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Aircraft Loading Actions Problems - Proceedings of a Symposium held at Farnborough on 28th October 1966

Edited by

A. S. Taylor and D. J. Eckford

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AIRCRAFT LOADING ACTIONS PROBLEMS - PROCEEDINGS OF A SYMPOSIUM HELD AT FARNBOROUGH ON 28 OCTOBER 1966

edited by

A. S. Taylor

D. J. Eckford

SUMMARY

The symposium was held at the Farnborough Technical College on 28 October 1966 and was attended by representatives of the Aeronautical Research Council, Universities and Colleges, the Aviation Industry, the Air Transport Operators, the Air Registration Board, and Government bodies.

An Editorial Foreword, which sketches the background to the symposium, is followed by a Résumé of the Proceedings. The papers presented are then reproduced in full together with accounts of the ensuing discussions.

* Replaces R.A.E. Technical Report 67166 - A.R.C. 29965

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EDITORIAL FOREWORD

The idea for holding this symposium stemmed from some discussions of the Loading Actions Sub-Committee of the Aeronautical Research Council (A.R.C.) in the autumn of 1964. It was then felt that 'Loading Actions' was something of a 'Cinderella' subject whose scope and aims were not fully understood outside the circle of experts working in the field, and that it should therefore be accorded some publicity by means of a public lecture or a symposium. The latter was preferred since by inviting an audience partly from the ranks of those experts working within the Loading Actions domain and partly from those working in neighbouring areas one could contrive both to stimulate wider interest in the subject as a whole and to provide an opportunity of discussing the 'state of the art' in selected areas.

The general scope of the proposed symposium was discussed by an informal committee comprising representatives of the A.R.C., the Aviation Industry, the Air Registration Board, and the R.A.E. It was decided that proceedings should be limited to a single day and that, consequently, the field to be covered should be restricted to problems relevant to manned fixed-wing aircraft operating at Mach numbers of up to 2.5. Further, in pursuance of the twin aims of publicising the subject and of airing current problems, the first two papers should be aimed primarily at newcomers to the Loading Actions scene while the subsequent papers might have a more specialised appeal.

The symposium was held at the Farnborough Technical College on Friday, 28 October 1966, under the chairmanship of Mr. P.A. Hufton, Deputy Director (A), R.A.E. In all, 163 delegates, whose names are listed in Appendix A, attended; collectively they provided representation for the organisations listed in Appendix B.

Revised versions of the papers prepared for the symposium are reproduced herein in six self-contained sections and they supersede the original versions distributed prior to the event*. Within each section the text of the paper is followed by the relevant illustrations and an account of the discussion which followed its presentation at the symposium. (There was a combined discussion of Mr. Hovell's and Mr. Sturgeon's papers.)

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* The revised papers have been prepared by the editors in consultation with the authors. For the most part, only minor editorial changes of a non-technical nature have been made but Messrs. Vann, Sturgeon and Hall have taken the opportunity to incorporate additional material presented in their lectures.

Accounts of the General Discussion and the Chairman's Summing-Up are given in two further sections.

For the benefit of those who may wish to gain an overall impression of the symposium without necessarily reading all the papers and discussions, a résumé of the proceedings is given below.

RÉSUMÉ OF THE PROCEEDINGS

The Chairman opened the proceedings by outlining the reasons for the holding of the symposium. He said that a subject which he would like to hear discussed was that of the cost effectiveness of research and development in Loading Actions.

WHAT ARE LOADING ACTIONS?
by W. Tye, Air Registration Board

The problems lying within the scope of the subject were defined and certain of the principles underlying their solution were expounded. Next, the related topics of the accuracy which was required in predictions of loading actions and the balance of effort between Loading Actions and Stressing were discussed. It was suggested that there might be justification for directing more effort towards Loading Actions even if that available for Stressing was thereby reduced.

The history of the search for airworthiness requirements correct in form and in magnitude was outlined: this search had been laborious and the development of rational requirements had therefore seemed slow. The dependence of loading actions on four factors - the operational role of the aircraft, pilot behaviour, atmospheric conditions, and aircraft characteristics - was discussed.

As regards the determination of the distribution of load over the aircraft, the author believed that it was worthwhile to make specific estimates for each aircraft type, backed by model and full-scale flight tests.

Mr. Tye concluded with a stock-taking exercise, which summarised the 'state of the art' and pointed to possible lines of development.

Discussion

Much of the discussion centred around the topic of the behaviour of the pilot. It seemed to be agreed that lack of knowledge of this behaviour, whether premeditated, as in deliberate manoeuvres, or more instinctive, as in his reactions to atmospheric disturbances and emergency situations, was a fundamental weakness. There was, however, some argument as to the best way of remedying the situation. It was pointed out that advances in Flight Control were having an increasingly powerful influence on Loading Actions. Reference was made, in relation to the section of the paper which dealt with take-off and landing loads, to the possible importance of knowing how aerodynamic forces built up and decayed during these phases of operation.

LOADING ACTIONS FROM THE DESIGNER'S VIEWPOINT
by F.W. Vann, Hawker Siddeley Aviation Ltd., Hatfield

The processes involved in the derivation of the design loads for a typical modern high-speed airliner, the Hawker Siddeley Trident, were reviewed. The aim was to give an idea of the amount of work and the organisation necessary to obtain these loads, rather than to explain the methods used, although some of these were touched upon, particularly with reference to the complications associated with flexible aircraft. It was emphasised that, even in a computer age, 'engineering judgment' still played a major role in the determination of design loads.

Discussion

Over the years the Loading Actions specialists' concentration on determining the appropriate 'worst case' for a particular component had led to a proliferation in the number of cases to be considered: it was questioned whether this had been worthwhile in the sense of producing aircraft with larger factors of safety and/or of lower structural weight. The procedure which was adopted in designing for loading cases not 'in the book' was mentioned, with particular reference to the 'round-the-clock' gust case described in Mr. Vann's paper.

Other topics which arose in the discussion included the question of whether and how the Loading Actions picture for fighter aircraft differed from that for civil transports; differences between firms in their approaches to aeroelastic loading problems; the applicability of power-spectral techniques in Loading Actions work; and the loads due to buffeting and to landing.

A particular point in the paper that excited comment was the contention that the process of developing 'stretched' versions of a successful aircraft led ultimately to a situation in which one was calculating the aircraft to fit a given set of loads rather than calculating the structural loads for a given aircraft. It was suggested that one needed to produce sets of load calculations of differing degrees of sophistication, appropriate to the various stages of an aircraft's design and development.

AERODYNAMIC DATA FOR LOADING ACTION STUDIES
by H.H.B.M. Thomas, J. Weber, K.G. Winter, Aerodynamics Department, R.A.E.

This paper, presented at the symposium by Mr. Thomas, discussed the provision of the aerodynamic data which were essential to the discharge of the Loading specialist's task. The subject matter was dealt with under three main headings:

(a) Overall force and moment data.

(b) Pressure distribution data.

(c) The use of model experiments for the determination of Loading Actions data.

Particular emphasis was placed on swept-wing tailed aircraft and slender-wing aircraft, exemplified by the TSR2 and the HP115 respectively.

It was concluded that theoretical and experimental techniques currently available could provide reasonably reliable data. Development was desirable in certain areas: these included the measurement of pressure distributions under dynamic conditions, the experimental confirmation of calculations of the effects of distortion, and the treatment of problems relating to interfering components. It was envisaged that more effective use would be made of computers, both in tackling individual problems and in working towards the goal of integrated structural and aerodynamic analyses for the aircraft as a flying, deformable vehicle.

Discussion

It was suggested that more use could be made of experimental pressure-plotting techniques, which had been greatly facilitated in recent years by the automation of the various processes involved. Attention was drawn, however, to the considerable expense involved in the production and testing of pressure-plotting models, to the length of time needed for the assimilation of results, and to the difficulty of deciding at what stage of a developing design one should produce such models.

It was pointed out that an important feature of Loading Actions calculations was the fact that they usually related to limiting flight conditions, where the airflow might be separated and the aerodynamics decidedly non-linear in form. Even within the range of incidence for which linearity could be assumed, theoretical predictions of local loads, e.g. on a leading-edge slat, could be critically dependent on the assumptions made about behaviour at the leading edge. Such facts underlined the importance of experimental methods of measuring loads. The importance of scale effects in the interpretation of model results, especially when shock waves were present in the flow, was discussed.

The final point concerned the determination of the unsteady aerodynamic forces in transient conditions. It was stated that the forces of this type which were met in turbulence could now be derived from the vast accumulation of oscillatory aerodynamic data by the application of Fourier transform methods.

FLIGHT AND GROUND LOAD MEASUREMENTS
by P.B. Hovell, Structures Department, R.A.E.

The interpretational problems of flight and ground strain measurements were discussed in the separate contexts of structural integrity under design envelope conditions and of fatigue life assessment. Also discussed were the formidable problems yet to be solved in connection with the measurement of undercarriage loads as a means of demonstrating structural integrity in the landing cases.

OPERATIONAL RESEARCH ON LOADING ACTIONS
by J.R. Sturgeon, Structures Department, R.A.E.

In this paper the purposes of operational research were considered. Some recent studies of operational experience in turbulence, and its relationship to power-spectral theory, were then described. Further topics discussed included the pilot's contribution to loads in turbulence and the future of operational research that could be conducted with the aid of Mandatory Flight Recorders.

Discussion

It was suggested that the problems confronting structural engineers could be divided into three classes depending on whether they related to stiffness characteristics, to static strength or to fatigue behaviour. In all three, it was argued, the main sources of uncertainty were the environmental conditions postulated in design requirements, and the question arose whether enough full-scale research was being done to check their validity. A subsidiary question was whether, in the light of knowledge gained, any changes in requirements were desirable.

Attention was drawn to the fact that in current aircraft the contributions to structural weight of items other than the wing and fuselage were more significant than heretofore and it was questioned whether enough of the effort which was being applied to load measurements was being directed towards the greatest unknowns. In reply, it was suggested that the introduction of mandatory requirements for flight load measurements would ensure that effort was directed where it was most needed.

In relation to Mr. Hovell's paper, other topics discussed included the problem of extrapolating flight load measurements to limit load conditions and the relative merits of pressure-plotting and distortion measurements on the one hand and strain measurements on the other.

Reference was made to the essential difference between the 'discrete gust' and the power-spectral approaches to the problems associated with atmospheric turbulence: the former was based on the acceleration history of the aircraft, and therefore included the effects of pilot action, while the latter was based on the properties of the atmosphere. This difference was thought to be well illustrated by the operational records which Mr. Sturgeon had presented. These indicated that, during flight in turbulence, large negative acceleration increments occurred more frequently than did large positive ones, and it was suggested that this was due largely to the behaviour of the pilot.

Other points raised in connection with Mr. Sturgeon's paper concerned the relative merits of digital and of analogue recording, the use of operational records as a source of information on control surface usage, and the problem of changing requirements to take account of knowledge gained from such records.

ASYMMETRIC MANOEUVRES OF HIGH-SPEED AIRCRAFT
by G.D. Sellers, British Aircraft Corporation (Operating) Ltd., Filton Division

Recent developments in the manoeuvre load requirements for high-speed aircraft were discussed, with particular reference to asymmetric manoeuvres.

These developments were made necessary by the evolution of aircraft with aerodynamic and inertial properties which led to response characteristics which were fundamentally different from those of 'conventional' aircraft. The specification of an asymmetric manoeuvre for these modern aircraft would normally allow for response in five degrees of freedom and the use of all three primary controls. The consequent complexity of the calculation of such a manoeuvre rendered essential the use of automatic computing facilities. Mr. Sellers presented and discussed typical results for pilot-initiated manoeuvres, for recovery manoeuvres following engine failure, and for manoeuvres subsequent to asymmetric weapon release. Some of the calculations for pilot-initiated manoeuvres related to slender-delta configurations and some to rear-engined, swept-wing configurations; the calculations for the engine-failure cases were also for a slender delta.

It was pointed out that although handling and loading requirements were becoming more closely inter-related the manoeuvre levels on which they were based generally differed (the level being higher in the loading case). In these circumstances it was often difficult to specify control actions for the loading cases which could be interpreted rationally in the light of the handling requirements. It was suggested that for initial design simple rules of thumb were required and an example of such rules was given.

Discussion

Attention was drawn to the fact that in all the calculations presented by Mr. Sellers the stability augmentation system had been considered inoperative. It was suggested that, while such a system would normally decrease response, and therefore loads, in certain cases the addition of artificial stabilisation in one mode might lead to increased response in other modes.

In view of the rapid variation with Mach number of aerodynamic derivatives in the transonic regime, shown in one of Mr. Sellers's figures, it was asked whether six-degree-of-freedom calculations might not produce interesting results.

In the discussion of the relationship of Handling and Loading Actions it was suggested that steps could now be taken to reduce the artificiality of the control actions specified for some structural design cases and, in particular, that CAADRP records might indicate more realistic inputs for the engine-cut case.

A SURVEY OF GROUND LOAD PROBLEMS
by H. Hall, Structures Department, R.A.E.

Three main types of problem were identified; they were concerned respectively with the loads developed in the undercarriage, the response of the aircraft structure to ground-induced loads, and the loads produced at the ground. Most of the paper was devoted to a study of the 'state of the art' with respect to the first of these.

Sources of undercarriage loading actions which were currently being studied included main undercarriage shimmy, brake-induced vibrations, runway roughness and towing. Progress in these areas was reviewed.

The operational data relevant to ground loads which were being collected by CAADRP, by the R.A.E. and by the Aviation Operational Research Branch (A.O.R.B.) of the Board of Trade were discussed. It was thought that the time could be ripe for a rationalisation of design requirements, taking these statistics into account. The most pressing need seemed to be for an adequate fatigue load spectrum.

Research which was being conducted by the Structures and Mechanical Engineering Departments of the R.A.E. was described. Apart from some experimental work on the response of a model of a slender-wing aircraft to landing impact, this was mainly directed towards the problems associated with ground manoeuvres, and had the object of effecting improvements in pilot and passenger vibration environment levels, shock absorber design and braking characteristics.

Discussion

There was endorsement of Mr. Hall's views about the urgent need of a reliable fatigue spectrum; this was, in a way, more essential to the undercarriage designer, who still had to produce a safe-life structure, than to the airframe designer, who nowadays provided a fail-safe structure. One speaker argued that there was no fundamental difficulty in deriving such a spectrum from undercarriage load measurements in conjunction with the known use of the aeroplane; a large amount of work was, however, involved.

It was suggested that main undercarriage shimmy, which was characterised as a resonance or flutter-type problem, might be investigated by an adaptation of the normal airframe resonance test, in which the tyres would be inflated, and the wheels or undercarriages themselves excited by the trouble-causing loads. The major unknown in the problem was considered to be the tyre force developed under unsteady conditions.

The phenomenon of the multiple-bounce landing produced a discussion concerned with the separate influences of undercarriage rebound characteristics and aerodynamic lift forces. In a reference to the subject of landing load requirements, there came a plea for a reduction of the specified 10 ft/sec landing velocity, which was held to be unrealistic for many types of aircraft. It was pointed out that in the case of VTOL aircraft engine thrust was a factor that had to be taken into account as well as rate of descent.

GENERAL DISCUSSION

Time permitted only two contributions to the General Discussion. In effect, these two contributions (the second of which was by the Chairman), together with the Chairman's Summing-Up, constituted a review of the themes running through the symposium.

It was thought that the papers had pointed to two main objectives for the future - the establishment of a more comprehensive fund of knowledge of loading actions, and the application of that knowledge to the development of a rational design philosophy for aircraft structures. However, the acquisition of such knowledge was an expensive business and it was imperative that the cost effectiveness of the relevant research and development work be realistically evaluated, difficult though this might be. Also, it was necessary to ensure that the limited effort available was directed to the areas where it could do most good. It seemed desirable to explore the possibility of wider collaboration throughout world aeronautics in Loading Actions work, and to consider the benefits that might accrue from comparisons of problems relevant to aircraft structures with those in other fields of structural engineering.

There were said to be two main aspects of design philosophy - design against static failure, caused by the loads associated with rare events; and design against fatigue failure, caused by frequent low-intensity forces. The relationship between these two aspects was quite obscure: for example the rare intense loads might not belong to the same statistical family as the more frequent low-intensity loads.

It was considered that one of the greatest sources of uncertainty in Loading Actions calculations was imprecision in knowledge of the manoeuvres to which aircraft were subjected and, in particular, of the part played by the pilot. Resolution of these uncertainties had to be attempted although this would be a difficult subject to pursue and one which would involve questions of pilot psychology.

CHAIRMAN'S INTRODUCTION

Mr. P.A. Hufton, Deputy Director (A), R.A.E., said that Loading Actions was one of the areas which tended to fall between the two stools of Structures and Aerodynamics and that this had possibly led to a failure to give enough attention to the subject. The A.R.C., anticipating that some co-ordination would be needed, had set up a Loading Actions Sub-Committee some time ago: the present symposium stemmed from work initiated by it and also from the feeling that it was still necessary to impress upon people that the discipline of Loading Actions really warranted a good deal of attention.

The Chairman said that a point he would like to see brought out in the discussions was the question of how a value could be attached to the work that was done. He disliked using the O.K. words, but cost effectiveness of research work and development work had to be considered very thoroughly indeed, and one had to try to get a better feeling of the value of this kind of work to measure against the cost of doing it. He thought that it was going to be difficult to do this, but the attempt had to be made.

WHAT ARE LOADING ACTIONS?

by

W. Tye
(Air Registration Board)

CONTENTS

1 SCOPE OF THE SUBJECT

I know of no precise definition of the words 'Loading Actions'. This is not important so long as there is a generally accepted understanding of what the words are meant to convey. I think we can safely start by saying we are concerned with the systems of forces applied to structures. Clearly these forces include the external ones arising from motion through the air, from contact with the ground or water, or even from hail or birds. We are certainly concerned with the magnitude of these loads and their distribution over the surfaces of the aircraft.

These external loads may be self-balancing (e.g. thrust equals drag) or they may be balanced against the forces of gravity (e.g. lift equals weight) or they may cause acceleration, either linear or rotational. If the aircraft is in accelerated motion it is a handy convention to consider this as a quasi-static state of affairs in which each element of mass is replaced by an inertia force (of magnitude equal to mass times acceleration). The sum of these inertia loads provides the reaction equal and opposite to the unbalanced external loads. Thus a knowledge of the distribution of mass throughout the aircraft is also part of the study of loading actions.

These systems of forces, applied to the aircraft structure, permit the loads in individual elements and the stresses in these elements to be calculated but this I do not count as part of the subject of Loading Actions.

With the relatively stiff structures of early aircraft it was a pardonable approximation and a vast simplification to treat the aircraft as a rigid body. One advantage was that in assessing the air load distribution we were concerned only with the unique 'as designed' shape of the aircraft. With the modern flexible structure the loading is redistributed as the structure distorts. A classic case is that of control reversal. For instance, at aileron reversal speed, increase of aileron angle produces distortion of the wing sufficient to nullify the rolling moment normally accruing from aileron movement.

But even more important than these aero-elastic effects are the elastic-cum-inertial effects, i.e. the fact that a rapidly applied load causes a greater deflection, and hence greater stress, than the same load applied slowly. The artifice that the structure was a rigid body was equivalent to saying that external loads would be applied slowly in comparison with the natural period of the surface concerned. This first became patently untrue for gust loads on long flexible wings and for landing drag loads on long undercarriages.

Thus today the simple concept of the external loads being reacted by a set of easily calculable inertia loads, must be supplemented by a knowledge of the additional loads which arise from the elastic-cum-inertial properties of the structure.

Reverting once more to the question of what Loading Actions comprises; although the traditional problems of Aeroelasticity - flutter, reversal, divergence, control surface buzz - are not part of the Loading Actions problem, nevertheless, the fact that the structure is a set of masses elastically connected together must form part of the study of loading actions.

The application of loads to the structure results in stresses which may cause static failure or fatigue failure or creep. The mode of failure is not directly a matter of loading action, but in assembling data and prescribing loading actions regard must be paid to the kind of failure which we are attempting to prevent.

2 ACCURACY REQUIRED IN LOADING ACTIONS PREDICTIONS

It is not very original to say that if we are to construct aircraft with the requisite strength as economically as possible we need an exact knowledge of the loading conditions. But our knowledge is never exact and, as in most matters affecting design, compromise plays a part.

If the accuracy with which we know the loading conditions is relatively poor we can secure safety by including larger margins to counterbalance ignorance. Or we can preserve economy but at the risk of an unacceptable accident rate. Usually the demand for safety wins at the expense of the need for economy. Indeed, if the accident rate were to become excessive, the cost of the accidents would be, in itself, a dis-economy, certainly in the case of civil aircraft and possibly in that of military aircraft in peacetime.

A rough idea of the balance between risk of accident and of economy in terms of structure weight can be obtained as follows. If a typical design load is decreased by 10% this corresponds roughly to a 10-fold increase of frequency of occurrence of the load. Assuming that about half the structure weight is directly dependent on load (i.e. about 20% of the all-up-weight of the aircraft) then a 10-fold change of accident rate corresponds to about 2% difference in gross weight.

If, therefore, the predicted loading actions are subject to an inaccuracy of 10%, as we certainly cannot afford to risk a 10-fold increase of structural accident rate we pay a penalty of the order of 2% of the gross weight. This is not an impossible penalty but is serious enough for us to try to reduce it.

This kind of calculation, rough though it is, suggests to me that we are justified in maintaining the effort to increase our knowledge of loading conditions so as to avoid the penalty of large factors of ignorance. It also suggests that we have been right in concentrating most attention on the loading conditions which design the big structural items; the wing, landing gear and fuselage. In other words, the loads arising from gusts, pitching manoeuvres and landing and take-off deserve greater effort to obtain accuracy than do other loads.

3 BALANCE OF EFFORT

While considering the problem in these general terms, it should also be borne in mind that the accuracy with which we know the structural safety depends not only on our knowledge of the loading conditions, but also on the strength of the structure in relation to these loads. Similarly, an inefficient structure can arise not only from an over-estimate of the loads, but also from an under-estimate of its strength. In other words, accuracy of stressing plus testing is another facet of the overall matter.

It is my belief - though I recognise the difficulty of proving this view - that the accuracy of estimates of structural strength is better than that of estimates of the magnitude and distribution of the loads. The refinement of design associated with the elaborate processes of strength calculation and test programme seems to me to be well ahead of the basic loading conditions with which we start.

This point arises in an acute form when the designer, in seeking approval for a reserve factor of 0.99, points out that the loading condition specified in requirements is not known to better than 10% accuracy. The simple answer is that even if one ingredient is inaccurate, it is no excuse for compounding it with a known deficiency. But there is a deeper issue.

Are we devoting disproportionate effort to these two equally important elements of design? Should not we place more emphasis on Loading Actions even if this means less effort available for Stressing?

In my view, this merits careful consideration. Loading Actions work has tended to fall into a no-man's land between Aerodynamics and Structures. Recognition of Loading Actions as a subject in its own right has come rather late. It is now so recognised - the formation of the Loading Actions Sub-Committee of the A.R.C. being an outward sign. This Sub-Committee has, in the last few years, illuminated many problems, but committees rarely solve problems. This depends on the efforts of workers in the Establishments and Industry. Today we shall hear something of the problems and something of the efforts to solve them.

4 HISTORY

The airworthiness engineer seeks to ensure that requirements are of the correct form and the correct magnitude. If the form is incorrect, then it is likely that the level of airworthiness will vary from one application to another. If the magnitude is ill-chosen, all aircraft will be too safe or too dangerous. This search for correctness of form and magnitude is often called rationalisation.

In the aircraft structural field there has always been a conscious effort to find a rational form. Thus, from the beginning, strength was specified in terms of the manoeuvres it was visualised that aircraft would undertake. In retrospect, this can be seen as a superb effort of the imagination as it was a complete departure from previous structural practices.

The first attempts at specifying loading conditions (around the 1920s) were not, however, always consistent. For instance, the loads normal to the flight path were related to extremely violent manoeuvres which would break the aircraft, i.e. the ultimate load factor was specified. On the other hand, in the terminal velocity dive the associated loads were multiplied by a factor of safety to arrive at the ultimate load condition. Thus the concepts of load factors and factors of safety were sometimes confused.

Just before World War II, the next major step of rationalisation occurred. This was the introduction of the V-n diagram. The inner boundary of this diagram represented the combination of normal acceleration and air speed which could reasonably be expected to occur, albeit rarely. These conditions later became known as limit loads. The outer boundary corresponded to loads a given percentage above limit loads and represented ultimate loading conditions. The ratio of ultimate to limit load became established as 1.5 to 1.

These attempts to rationalise the form of requirements were made more difficult by lack of actual operational data. The fitting of the V-g recorder in the U.S.A. before the war and in Britain during the war gave the first valuable data. It became apparent that the envelope of an accumulation of V-g recorder results was, in fact, a real life V-n diagram corresponding to a certain frequency of occurrence. Thus the idea was born that the limit load boundary should be established to correspond to some selected frequency of occurrence.

This event was significant in the development of the approaches to all kinds of airworthiness problems. Prior to World War II the tendency was to pitch the requirements at a level which seemed reasonable, using whatever good judgment was available to decide on 'reasonable'. With the realisation that the level of a requirement could be related to the probability of occurrence of an accident, it became necessary to make more conscious decisions on what accident probability was acceptable. At root all safety questions are ones of statistical probability of occurrence, so it is basically sound, whenever our knowledge permits, to fix the acceptable probability and to contrive requirements which secure this probability.

I have described these developments in terms of the symmetric flight manoeuvre, but they permeated all fields of loading specifications. One other deserves particular mention - gust loading. The first simple specification was the sharp-edged gust. The aircraft was supposed to fly from still air into an ascending or descending air mass, and at first no account was taken of time effects. This clearly artificial idea of the atmosphere was soon replaced by the concept of a ramp-shaped gust. For some reason which is no longer clear a gradient distance of 100 feet was selected. Generalised calculations were made of the response of the aircraft when flying into such a gust, and this resulted in requirements which took some account of the aeroplane characteristics, in particular wing loading.

However, there remained the doubt about the statistical correlation between gust magnitude and gradient distance. This was not of great importance while aircraft were not too different from one another in size and flexibility. But with increasing flexibility, the stresses are greatly magnified when the time during which the gust is applied approximates to the quarter-period of the wing in bending. Thus it became important to assess the load for a variety of gust wavelengths. The eventual solution to this problem may lie in the use of power-spectral methods. The U.S.A. has done much work in this field. There has been considerable hesitation to use power-spectral methods in this country, the chief worry being whether the statistical model of the atmosphere on which the method is based truly reflects real life.

Looking back over this 40 or 50 year period one cannot fail to be struck by the relatively slow rate of development. Perhaps this is due to the fact that only to a limited extent will theoretical study advance the art. Much depends on amassing operational statistics, a slow and expensive process. For design purposes, we are concerned with very rare events. For instance, in civil aircraft the aim is a probability of catastrophic failure better than, say, 1 in 10 million flights. It requires a large fleet, flying for several years, to accumulate this number of flights. Hence the collection of data is essentially a laborious business.

5 APPROACHES TO THE GENERAL PROBLEM

I will now turn to the methods used for predicting loading actions. The loads encountered depend on four main factors:

- the operational role of the aircraft
- the way in which the pilot behaves
- the atmospheric conditions
- the characteristics of the aircraft.

The operational role of the aircraft determines broadly the kinds of manoeuvring which it is necessary to carry out and hence fixes approximately the level of loads which the aircraft needs to withstand if flown in an ideal way. For instance, the operational role provides a guide to the necessary normal acceleration in pull-up manoeuvres, the required rate of roll and the ability to make ground manoeuvres. A study of each main class of operational role thus provides some indication of some of the loading actions.

The behaviour of the pilot is a much more elusive problem. The pilot's intention is to make the aircraft follow a particular flight path, and he exercises the controls in a way intended to bring this about. But there is a great variety of ways in which the pilot can manipulate the controls as far as the control force/movement/time sequence is concerned, all of which more or less lead to the flight path he seeks to follow. But the precise way - for instance, whether the pilot applies the controls coarsely or smoothly - influences the loading conditions.

Similarly, in emergency conditions such as the failure of an engine, or in rough weather, the pilot handles the controls with the object of maintaining the attitude of the aircraft and, again, his control movements are not easily predictable.

By amassing data on pilot behaviour in operations and by analysing it statistically, it would theoretically be possible to estimate the force/movement/time sequences which might occur.

As regards the atmosphere, the features which affect loading actions are mainly turbulence and wind shears. These again are widely variable but are amenable to treatment by statistical analyses of amassed records.

Finally, the characteristics of the particular aircraft type are capable of assessment from wind tunnel or actual flight tests.

Thus a theoretically possible logical approach to establishing the loading actions for a particular type of aircraft would be to determine, from recorded data, the spectra of pilot behaviour and atmospheric conditions and to treat these as inputs. Given a knowledge of the aircraft characteristics the loading actions could then be determined as the output.

In fact, this approach is far too difficult to be of general use, chiefly due to difficulties of establishing the pilot input behaviour. The loading actions needed for design purposes are rare occurrences and abnormal behaviour is all the more difficult to predict. Moreover, pilot behaviour is conditioned by the operational role and the characteristics of the aircraft so it is not a truly independent variable.

Because of these major difficulties, the approach has often been to obtain statistical data on the output, i.e. the resultant flight behaviour, and to assume that this can be transferred from one aircraft type to another. The problem has been further simplified by studying one principal loading action at a time. A few examples will explain.

Consider the landing manoeuvre. A dominant design consideration is the velocity of descent at touchdown. The pilot's aim is to reduce this to some small value, say 2 or 3 feet per second. Due to imprecision in handling and to turbulence, the velocity achieved on rare occasions may be as high as 8 to 12 feet per second. For a given frequency of occurrence, say 1 in 100 000 landings, operational evidence indicates that the corresponding velocity of descent varies from type to type but broadly justifies a design value of 10 feet per second. This method of determining the design value lacks precision, but has the virtue of being straightforward. The alternative of assessing the statistics of the pilot's control movements at the moment of landing has not been attempted, but has all the appearances of being much more difficult.

For a second example, consider gust loading. The large scale accumulation of records of turbulence can be expressed as a spectrum which in effect relates gust amplitude and wavelength. For known aircraft response characteristics, the frequency of occurrence of loads of various magnitudes can then be assessed. This method of assessment gets close to a logical approach. However, it fails to take account of the pilot behaviour. If the pilot attempts to operate the controls he may reduce or increase the loads from the gusts. Ignoring pilot action is perhaps reasonable when considering short wavelength gusts, as the loads develop in a fraction of a second. For long wavelengths, the assumption becomes dubious.

As a third example, take symmetric pitching manoeuvres. Operational data recording provides information for each broad class of aircraft on the V-n diagram corresponding to a certain frequency of occurrence. Thus the end-product of the combined effects of operational duty and pilot behaviour is determined. This approach omits to take account of such features as the stability and control characteristics of the particular aircraft type. However, it is probably a reasonably good approximation so far as the important loading conditions on the wing are concerned.

It is less satisfactory in respect of tailplane and elevator loads. These loads are partly determined by the balance loads which relate directly to normal acceleration and speed and partly by the added load arising from the exact way in which the elevator is moved. Present civil airworthiness requirements give methods of calculation of these pilot-induced loads which, in effect, relate the pilot behaviour to characteristics of the aircraft. There remains at present a doubt about such a relationship.

Against the background of these examples, I would like next to consider whether our approach to the assessment of loading conditions is sound. I cannot prove what I am about to say - rather it is a matter of judgment with a lack of supporting data.

Consider first pilot-induced conditions. In general, I believe it would be too difficult to approach these by detailed study of pilot behaviour. It seems preferable to collect data on the end-product, i.e. the actual manoeuvres made, and, taking proper account of the operational role, to assume that these read across from one type to another. This, I believe, applies to such matters as the symmetric pitching manoeuvre, the rate of roll, the velocity of descent in landing, the speeds at which flaps and landing gear are extended, etc.

On the other hand, where the loading conditions are much more closely associated with pilot behaviour, and this is relevant to the design in the vicinity of the control surfaces, our present methods are too crude. A fuller study of the control force/movement/time history in operation might well help to refine these requirements.

As regards loads which are more closely related to environmental conditions, there are two main categories; atmospheric (gusts, wind shear, etc.) and ground loads when taxying. The development in recent years of measuring the spectrum of the external conditions and assessing the loads when the particular type is exposed to the environment seems the correct approach.

Finally, there is the question of treating each loading action more or less in isolation. By this I mean, for example, that we consider a high normal acceleration case without additional roll or yaw loads. Similarly, we consider large rudder loads only in steady flight conditions so far as pitch is concerned. In the reality of an actual manoeuvre, the loading conditions are much more complex. This practice is probably not so dubious as it looks at first sight. The magnitude of stresses in a particular part of the structure is often dominated by the loads arising from one component of the complicated motion. There is not a great loss of accuracy if the loads associated with some other component of motion are not taken into account with great precision. Nevertheless, this is one of the less satisfactory features of present requirements, and the most recent proposals (e.g. the TSS Standards for the Concord) include combined cases.

6 LOAD DISTRIBUTION

I have referred mainly to the magnitude of overall loads, rather than to their distribution over the surfaces, but the latter is important. In the early days attempts were made to provide, in requirements, generalised assumptions about load distribution. On the whole, this was not a satisfactory approach. The distribution depends so much on the particular aerodynamic shape that generalisation is subject to considerable inaccuracy. My belief is that if the accuracy of the assumptions regarding loading distribution is to match the accuracy of strength estimates, then it is worth the effort to make specific estimates for each type of aircraft. This may well involve not only model tests but full-scale flight tests. The full-scale flight test seems as necessary as full-scale strength tests.

7 STOCK-TAKING

I should like to finish by venturing an exercise in stock-taking. First there are the loading actions which are most important in the respect that they design massive pieces of structure.

Symmetric manoeuvres. So far as the principal design parameters, speed and normal acceleration, are concerned we are better placed than in almost any other area. A continued collection of routine data should serve to keep us up to date.

Gust loading. Improvements of general data, for instance at high altitude, are needed. But equally it is important to settle the previously mentioned problem of the correlation of gust magnitude and wavelength. For fatigue loading purposes the power-spectral approach seems to offer a basically sound description of turbulence, from which fatigue spectra could be derived. For static strength purposes, there remain doubts whether the rare high-magnitude gust is properly represented by the power spectrum, or whether it is not a member of the same statistical population. It might be better to retain, at least temporarily, the discrete gust form of specification but, if this course was followed, it would be important to specify ranges of wavelength corresponding to the various magnitudes of gust velocity.

<u>Landing and take-off loads</u>. The main design parameter in landing, the vertical velocity of descent, is reasonably well established but could probably be refined if operational statistics could be obtained. Of more immediate importance are the ground rolling and manoeuvring loads, firstly because they tend to design a considerable proportion of structure, secondly because fatigue failures are the predominant form of undercarriage trouble. A major effort is clearly needed in this field.

Turning to the loading conditions which design lighter, but still important, structural elements, we have the symmetric manoeuvres in relation to tailplane and elevator, and to the flaps, air brakes, etc; and the unsymmetric manoeuvres in relation to ailerons, fins and rudders. (It is, of course, realised that these loads find their way into main fixed structure.) Much effort has been put into defining the detailed loading actions on the tailplane and elevator consistent with the main symmetric pitching manoeuvres. But insufficient is still known about the control force/movement/time sequence and there is little doubt that operational statistics would enable improvements to be made in requirements. As regards the unsymmetric manoeuvres of roll and yaw, there is a dearth of operational data, not only of the pilot input, but also of the overall output (e.g. rate of roll, or yawing angles). So these again seem to qualify for attention.

There is, of course, a wide miscellany of loading actions to which I have not referred; buffeting, bird impact, crash landing, ditching, control system loads, acoustic loading. However, for one reason or another, these do not, in my mind, rate the same priority as the topics I have dealt with a little more fully. In any case, this symposium lasts only one day.

DISCUSSION

Prof. W.H. Wittrick, University of Birmingham (Chairman, Loading Actions Sub-Committee, A.R.C.) remarked that in the first sentence of his paper Mr. Tye had stated that he knew of no precise definition of the words 'Loading Actions' but that he had then gone on to give an admirably clear picture of what they implied and also a most valuable summary of what he regarded as the major problem areas. Prof. Wittrick said that he was particularly interested in the belief that the accuracy with which loads could be estimated fell short of the accuracy with which the structure could be designed for a given strength, and he thought that this emphasised the need for a symposium of the present nature.

As Mr. Tye had said, there was a Loading Actions Sub-Committee of the A.R.C. and Prof. Wittrick thought it was correct to say that over the past few years they had discussed, in some measure, most of the major problems that Mr. Tye had outlined, as well as some of the not-so-major ones. During these discussions several big question marks had cropped up with distressing regularity and he would like to mention one of these in relation to Mr. Tye's paper. This was the question of pilot action, especially in turbulence, and the related one of the adverse effects on the pilot of cockpit vibration in long-nosed aircraft. He recalled Mr. Tye's belief that it would be too difficult to approach the problem of pilot-induced loading actions by a detailed study of pilot behaviour and that it seemed preferable to collect data on the end-product instead, and said he would like to question this to some extent on the grounds that the end-product could only be measured on existing aircraft. Mr. Tye had pointed out that one would need to assume that the output data could be read across from one aircraft type to another and Prof. Wittrick wondered how valid this was, in that new generations of aircraft might have very different response and vibrational characteristics from their predecessors. He suggested that an attempt should be made to obtain some reliable fundamental data on just what a pilot does; although he appreciated the difficulties he felt that something ought to be done to fill in this vital gap in knowledge.

Another point raised by Mr. Tye was commented on by Prof. Wittrick, namely the question of treating each loading action more or less in isolation. Whilst he noted the reference to the combined cases in recent design requirements he would like to ask what good this was from the point of view of fatigue. Prof. Wittrick said that, not being a statistician, he had no idea what would be required in the way of correlation between individual load spectra or even whether it would be possible to define cross correlations that would serve the purposes of fatigue.

Finally, on the subject of the extent of the Loading Actions field, Prof. Wittrick was somewhat surprised that Mr. Tye had made no mention of kinetic heating and wondered whether it had been excluded because it gave rise to stresses without inducing loads.

Mr. Tye, in answer to Prof. Wittrick's last point, said that if he were asked to write down a programme for a committee to consider in terms of loading actions he would include kinetic heating: it seemed to him a justifiable candidate and its omission from his paper was probably an oversight. He thought that perhaps he had not expressed himself very clearly as regards the method of attacking the problem of pilot behaviour. He admitted that lack of knowledge of pilot behaviour was one of the fundamental weaknesses of the subject. He believed, however, that for certain conditions the statistical approach of measuring output quantities such as normal accelerations, speeds, and velocities of descent did not work badly in practice. Mr. Tye doubted whether even a very comprehensive study of pilot behaviour would lead to such accurate predictions of these quantities as were derived in approaching the problem in what was seemingly the wrong way round. On the other hand, in cases where the pilot behaviour had an intimate connection with the detailed loading, there was a need to treat this behaviour as a much more significant feature. For example, it was possible to achieve a certain normal acceleration with all sorts of time/motion histories of elevator movement and, correspondingly, to obtain all sorts of elevator loads. He thought, therefore, that in starting a programme of examining pilot behaviour one should relate it to particular aspects of Loading Actions rather than assume that one would be able to get quickly to a comprehensive set of loading actions via a knowledge of pilot behaviour.

Mr. Tye said that he would not comment on the question of stressing for combined cases rather than separate ones except to say that in the course of the day statements by various authors would show how much more elaborate were their approaches in terms of combinations of cases than the present requirements demanded.

Mr. C. Goldberg, Dowty Rotol said that in the section of the report which dealt with landing and take-off loads, Mr. Tye had said that the definition of the vertical velocities of descent was well established but could possibly be refined if operational statistics could be obtained. This was true but, while this refinement was taking place, one would like to discover how the lift forces disappeared as the aircraft touched down and, conversely, how they built up during taxying. These factors had an appreciable effect on the rate of growth of the ground reactions. He wondered if Mr. Tye could say whether any work was being done on investigating the disappearance of wing lift forces when an aircraft lands.

Mr. Tye said that he did not know whether or not any work was going on but that he was sure there would be someone present who did know. From the ensuing silence, Mr. Tye was inclined to infer that there was not - the Chairman, however, said that such an inference was not justified.

Mr. H.H.B.M. Thomas, Aerodynamics Dept., R.A.E. agreed with Mr. Tye that it was easier to define the manoeuvre which a pilot intended to do on a particular aircraft than to define how he actually achieved this. However, he was not convinced that there was such a wide variety of paths by which the pilot could reach the same end result and he wondered if there had been any examples that Mr. Tye could quote to support his statements.

Mr. Tye recalled that about twentyfive years ago he had performed calculations in which various assumptions were made about pilot behaviour and that he had been able to produce a variety of hypothetical time histories which had led to a certain value of normal acceleration. At that time he did not know whether these time histories realistically represented what pilots did in practice and he was afraid that the answer might still be unknown.

Mr. P.F. Richards, Air Registration Board felt that in discussing pilot action much depended upon whether intentional or emergency manoeuvres were being considered. He thought that as far as the intentional manoeuvres were concerned a very good attempt could be made at defining them, but that emergency manoeuvres lay in the realms of extremely remote probabilities where the pilot was obeying his instinct rather than his training. The A.R.B. believed that in these circumstances there was an infinite variety of possible control movements and that there could be no clear answer as to which would be actually applied.

Therefore, for requirement writing purposes, they had tried to define 'boundary' conditions and 'extreme' control movements to which the loading could be related and which they hoped would adequately cover the whole range of possible practical cases.

Mr. P.A. Hufton, Deputy Director (A), R.A.E. (Chairman) thought that one of the difficulties was that the pressures which forced us to get the utmost out of an aircraft were necessitating a more sophisticated approach. If told that we did not know how pilots used the elevator his instinctive reply would be "Nonsense, this has been known for ages; there have been millions of records.". However, he thought that what people were saying was that their current need was for a kind of probability diagram of the degree of likelihood that a pilot would respond in a certain way: some responses were impossible because the pilot was of only finite strength but between this limit and that of a very slow elevator application there were certain responses that gave rise to concern. There might, for example, be a pilot response to a gust which was only probable at a level of 1 in 100 or 1000 occurrences but which would increase the intensity of an already improbable gust load to a very high value. Mr. Hufton emphasised that a lot of knowledge had already been gained but that even more was demanded by modern levels of sophistication. He considered that the rudder, rather than the elevator, was the control that gave him most concern and said that he sometimes wished that rudder bars could be taken out and replaced by some other method of maintaining zero sideslip, e.g. by automatic controls, though he knew this would have additional implications.

Mr. D.J.M. Williams, A.O.R.B., Board of Trade referred to Mr. Goldberg's query about vertical velocities of descent and whether the attitude of the aeroplane, or the lift on the aeroplane, was being considered. He said that flight measurements of touchdown parameters were being made at Heathrow and that these could have a bearing on the subject. They were aware that the vertical velocity was not the only thing of importance at touchdown; rather, it was the energy to be absorbed in the undercarriage that was critical and this was now being studied.

Mr. W.J.G. Pinsker, Aerodynamics Dept., R.A.E. (Bedford) said that the disciplines of Stressing and of Aerodynamics had been given as those mainly involved in Loading Actions. He felt that before long a third would be a powerful influence - Automatic Flight Control. There had been a lot of discussion about the uncertainties of the actual applied loadings, especially those coming from the pilot. He pointed out that by applying such concepts as manoeuvre demand control one could limit the variety of things a pilot could do. Mr. Pinsker said that one area in which he had become involved in Loading Actions was that of inertia cross-coupling. There, a large amount of the trouble stemmed from allowing the pilot to use the controls in a way which was of no utility and very often it was possible to eliminate the problems altogether by putting stops on the control surfaces. He wondered whether many time-honoured concepts, even n_1 and so on, could not be revised very sharply if some means could be found to restrict the manoeuvres to those that were really necessary.

Mr. Hufton commented that this would be a less radical solution than getting rid of the rudder bar.

LOADING ACTIONS FROM THE DESIGNER'S VIEWPOINT

by

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SUMMARY

This paper gives a review of the methods used to determine the design loads for the structure of the Hawker Siddeley Trident.

CONTENTS

1 INTRODUCTION

The purpose of this paper is to give a review of the processes involved in deriving the design loads for a typical modern high-speed jet airliner, namely the Hawker Siddeley Trident. As far as possible, all mathematical formulae have been avoided and the paper is intended to give an idea of the amount of work and the organisation necessary to obtain the design loads rather than to explain any of the theoretical methods used, which are not particularly involved in any case. The additional complications associated with flexible swept wings play a large part in what follows, since it is due to aeroelastic effects that the derivation of the design loads for an aircraft like the Trident involves so much work.

A point which must be emphasised at the outset is the fact that even today, when computers are indispensible to obtaining the design loads, it is 'engineering judgment' which still plays the main part in determining these design loads. It has been said that no aircraft which fails to comply with the official design requirements can be satisfactory in service, but that conversely an aircraft which meets the requirements may be unsatisfactory in service. The requirements have always to be treated in a sensible way. Where it is considered that they may not produce adequate safety, the designer is justified in designing to higher loads than those given by the official requirements. On the other hand, where the requirements for any reason appear to penalise the aircraft unfairly, because of some peculiarity in its design which may not even have been envisaged when the requirements were drawn up for earlier types of aircraft, the designer will consult the official authority, in this case the Air Registration Board, and produce evidence to justify his asking for some relaxation of the written requirements. The whole process of determining the design loads is not a mathematical exercise carried out with computers in an ivory tower, but is basic to the whole design of any aircraft and is closely involved with all the other design considerations. We may use computers to assist in the purely mechanical work of calculating the loads, but considerable 'engineering judgment' is needed for the interpretation of the numbers which the computers produce. Ultimately the object of all work in 'Loading Actions' is to produce an aircraft which is safe in operation whilst still being economical to operate, and this consideration must be kept in sight throughout the whole process of producing the design loads.

2 DESIGN REQUIREMENTS

The Trident has been designed to comply with both the British Civil Airworthiness Requirements and the American F.A.R. since it was expected that the aircraft would be sold to customers requiring U.S. certification. The differences between the British and American requirements are, on the whole, not significant as regards the design loads. Since the design of the Trident commenced in earnest, in 1959, the differences between the two sets of requirements have been further reduced by the introduction in B.C.A.R. of the requirement of 2.5 g at V_D instead of 2 g and the revised gust load requirements which now coincide with the American F.A.R.

There are some features of the Trident which are not the subject of specific requirements in B.C.A.R. or F.A.R. Examples are the airbrakes, lift dumpers and slats which are not mentioned in the official requirements. The design cases for these components were settled by discussion between the designers and A.R.B.

3 DESIGN SPEEDS

The determination of the design speeds for the aircraft does not really enter into the scope of this paper. However, the speeds used for the different design cases are so fundamental in relation to the design loads produced that a brief mention of them must be made here. Fig.2 shows curves of the various stressing speeds and their variation with altitude.

The requirements define

$$V_A = V_{s1} \sqrt{n_1}$$

where V_{s1} = stalling speed at 1 g

n_1 = manoeuvring load factor.

Since $C_{L_{max}}$ falls off with increasing Mach number, it follows that this definition of V_A gives a lower value than the speed corresponding to a $2\frac{1}{2}$g stall. B.C.A.R. appears to be rather vague on this point since it calls for checked symmetric manoeuvres from 1 g up to the manoeuvre envelope load factor at V_A. This is less than n_1. However, it is obvious what is required here. The Trident is designed for $2\frac{1}{2}$g at V_A.

V_C is taken as equal to V_{MO}, the maximum operating speed, and hence is a practical limit. It will be noted in Fig.2 that V_C is reduced at altitudes below 6000 ft. This is a limitation imposed by bird impact loads on the windscreen and is no restriction in practice on the normal operation of the aircraft. At high altitude V_C is limited to M = 0.88.

V_D is fixed relative to V_C so that the margin between them is sufficient to cover inadvertent speed increases due to gusts, loss of control or variation of Mach number due to temperature fronts.

At high altitude the margin between V_C and V_D is narrow, amounting to 0.07 of Mach number. This smaller margin is adequate since there is a rapid drag rise at Mach numbers in excess of 0.88.

V_B is determined more by buffet boundaries than by pure $C_{L_{max}}$. One definition of V_B in B.C.A.R. is the intersection of the positive stall curve with the 66 ft/sec gust line but, in practice, $C_{L_{max}}$ is not very clearly defined at high Mach number and the onset of buffet becomes more critical.

As the Trident makes use of its flaps at a reduced angle for flying in turbulent atmospheric conditions, it has to comply with the requirements for flaps-down en route cases. In this case it is necessary to select V_B, V_C and V_D with flaps down at which the aircraft will meet 66 ft/sec, 50 ft/sec and 25 ft/sec gusts respectively. The considerations used to decide the flaps-down design speeds are similar to those for the flaps-up cases but are somewhat less severe as regards speed margins.

4 MANOEUVRE AND GUST ENVELOPES

Unlike low-speed aircraft, the Trident does not have one unique manoeuvre or gust envelope. Due to the variation of $C_{L_{max}}$ and the wing lift slope with Mach number, and due to the variation of speed with altitude shown in Fig.2, there is an infinite number of manoeuvre and gust envelopes. Typical envelopes for the Trident are shown in Figs.3 and 4.

In fact, these envelopes are of very little use in practice today, and appear usually only as a standard item in the aircraft Type Record as a matter of tradition.

5 DESIGN CASES FOR THE AIRCRAFT

It is convenient to categorise the design cases which have to be considered under the following headings:

(1) Airborne cases

(a) Manoeuvres (produced by pilot's actions)

(i) Symmetric (elevator-induced)

(ii) Asymmetric

Rolling cases (aileron-induced)

Yawing cases (rudder-induced)

(b) Gust cases (independent of pilot's actions)

(i) Vertical gusts

(ii) Lateral gusts

(iii) Head-on gusts.

(2) Ground cases

(a) Landing

(b) Take-off

(c) Ground manoeuvres (turning and swinging, dynamic braking, etc.)

(3) Miscellaneous

(a) Emergency alighting

(b) Loads due to pilot's effort

(c) Pressurisation loads

(d) Jacking

(e) Handling loads (Ground crew standing on doors, etc.)

6 CRITICAL DESIGN CASES FOR THE TRIDENT

The principal design cases which are critical for the structural design of the Trident are tabulated in Table 1.

It is immediately noticeable how many cases are critical for the design of the aircraft. In fact, the actual number of design cases is larger than is indicated by this summary since each case may produce design loads for a whole range of altitudes, speeds, weights and cg s. An item such as 'up-gust at V_C' may cover a light load case for the engine mounting, a forward cg case for the wing and an aft cg case for the tailplane. It will obviously be impracticable to investigate all the possible cases and, in the light of experience, the likely critical cases have to be selected by some comparatively crude criterion. These cases are then investigated in considerable detail. For instance, the critical altitude in the gust cases is determined by some simple criterion such as UVaK where:

U = gust velocity
V = aircraft speed
a = wing lift slope
K = gust alleviating factor of B.C.A.R.

A typical plot of this parameter is shown in Fig.5 for the '50 ft/sec gust at V_C' case. It will be seen that this quantity is not very sensitive to altitude in the critical region so that the design altitude can be selected without fear of missing the worst loads by a large margin. The same seems to be true of most of the design cases, luckily, so that there is normally a fair margin for error in selecting the design conditions.

The main reason why so many cases are critical for the aircraft structural design is the fact that the aircraft has been subjected to a continuous process of development since it was only a project. The operating conditions as regards weight, cg and speed have been changing continually in an effort to extract the maximum performance and economy from the aircraft. They have all been fixed by answering questions such as 'What is the maximum permissible V_C if we increase the zero-fuel weight by 2000 lb?' or 'What is the maximum permissible flap angle for en route conditions if the safe tailplane load is not to be exceeded?' The final result of this process is that the operating limitations for the aircraft have extended to fit the boundary of structural limitations at nearly all points. For example, the wing bending moment is the same within a very few per cent in the V_B up-gust, V_C up-gust, and 2.5g manoeuvre at V_A cases. Similarly there are half a dozen tailplane cases which give identical loads within a very close margin.

The development of 'stretched' versions of the aircraft leads to a point where the actual configuration of the aircraft depends on the design loads. For example, if it is desirable to improve the landing or take-off performance by increasing the wing span or by extending the flap area but without expensive modifications to the structure in the wing root, the final configuration of the wing will be determined by working back from the permissible structural loads to the permissible wing span and flap geometry. In fact, instead of calculating the structural loads for a given aircraft, we are calculating the aircraft which will fit a given set of loads. In the long run this leads to a highly efficient aircraft since all the design parameters such as speed and weight in all aircraft configurations have been thoroughly optimised.

As an example of this optimisation, the wing design bending moments for the latest 'stretched' version of the Trident are shown in Fig.6.

7 CALCULATION OF AIRCRAFT LOADS IN THE DESIGN CASES

If structural flexibility can be ignored, as it usually could be in the past, the calculation of the aircraft loads in any design case is a relatively simple matter. The total external air loads applied to the aircraft are calculated and the necessary balancing inertia loads due to linear and angular accelerations are determined. The net structural loads are the sum of the aerodynamic and inertia loads. The accelerations are obtained from the overall aerodynamic loads calculated from overall aerodynamic coefficients which define the total aerodynamic pitching moment, the aerodynamic centre, and the total lift and drag.

The internal structural loads such as shears, bending moments and torques are calculated from external air load distributions, and internal mass distributions. The only precaution needed, therefore, to guarantee a balanced consistent set of internal loads is that of ensuring that the external air load distributions correspond to the overall aerodynamic coefficients and that the internal mass distributions agree with the overall centre of gravity of the complete aircraft. This consideration may appear to be so elementary as to be scarcely worth mentioning, but in practice it is sometimes not as easy to achieve as might be expected, particularly at high-subsonic Mach number where the detailed distribution of air loads over the aircraft is not easily determined.

However, the introduction of aircraft with relatively flexible wings with pronounced angles of sweep has produced aeroelastic problems in connection with loading calculations. These problems are productive of most of the work on loading actions today and have, in fact, increased the amount of calculation needed to obtain the design loads to a different order of magnitude as compared with aircraft which are rigid or which can reasonably be assumed to be rigid.

The best way to appreciate the work involved in determining the design loads for a modern high-speed aircraft is to consider in detail the methods which are used for a particular aircraft. For this purpose, the methods used for the Trident are explained in general terms in the sections which follow.

7.1 Symmetric manoeuvre loads

The method used for obtaining loads in the symmetric manoeuvre cases has also been used for the loads in 1 g level flight, for the gust cases and for the symmetric loads associated with the asymmetric (rudder and aileron) cases.

The basic data required for the symmetric manoeuvre cases comprise the specification of the aircraft speed and altitude (hence Mach number), the manoeuvring load factor, the mass distribution including fuel and payload, and a statement of the aircraft configuration, i.e. flap setting and airbrake angle, if any.

When dealing with low-speed aircraft where Mach number effects are negligible, there will be a unique value for the aircraft pitching moment coefficient and aerodynamic centre position associated with any aircraft configuration. On modern high-speed aircraft, however, there is the added complication that the overall C_{M_0} and aerodynamic centre vary with Mach number and so do the distributions of lift and pitching moment over the wings, tailplane and fuselage. For the aircraft's complete range of operating Mach numbers, therefore, there is required a definition of the various aerodynamic load gradings over the whole aircraft together with the corresponding values of overall pitching moment coefficient and aerodynamic centre. In practice, the order is inverted since it is usually the overall coefficients which are derived from wind tunnel tests and the distributions have to be calculated to agree with the overall values.

As mentioned above, the introduction of aircraft with flexible swept wings has further complicated the calculation of the design loads on the wings in the symmetric manoeuvre cases. The Trident wing tip deflects about 60 inches under limit load. Since the wing is swept at 30° and the bending takes place along the swept flexural axis it follows that there is an 'in line of flight' change of wing incidence equal to the bending slope times the sine of the angle of sweepback. This change of incidence is zero at the wing root and amounts to about $1\frac{1}{2}^\circ$ per g nose down at the tip for the Trident. Lift is, therefore, twisted off from the outer wing and has to be recovered by increasing the overall incidence of the aircraft. The overall effect is to bring the spanwise centre of pressure of the wing inboard towards the root, and hence to reduce the wing bending moment for a given flight condition. This effect becomes larger as speed increases.

Due to the wing sweep, as the centre of pressure moves inboard it also moves forward so that the overall aircraft aerodynamic centre shifts forward by between 5% and 9% of the aerodynamic mean chord depending upon the aircraft speed. This has a significant effect on the tail load and, hence, on the wing lift, since the sum of the wing and tailplane lifts remains constant and equal to the aircraft weight times the manoeuvring load factor.

The calculation of the aircraft loads under these conditions can best be done by an iterative process which converges on the final state of equilibrium. The aircraft is first balanced out as if it were rigid and the wing bending moment, shear and torque are calculated. From these values, using the stiffnesses of the actual aircraft, the wing bending slopes and the torsional deflections can be calculated. On the Trident the effect of the wing torsional deflections is negligible compared with the wing bending slope.

Using this first approximation to the deflected shape of the wing, a revised lift distribution is obtained by the use of a Küchemann matrix of aerodynamic coefficients or by some less refined method. The modified aircraft aerodynamic centre is thus obtained and a second balance-out of forces is done based on the revised value. This gives a second approximation to the wing and tail loads. The whole process is then reiterated until two successive results agree within some acceptable limit.

This iterative process has been programmed for the digital computer. The programme outputs the structural loads for wing, fuselage and tailplane. The latest programme which is written for a KDF9 computer takes 2 minutes to produce the structural loads.

The aircraft is idealised as consisting of 38 elements. Each wing comprises 12 streamwise elements and the front and rear fuselage each comprise 7 'slices'. Each element is assumed to be of constant chord and all aerodynamic loads and masses are assumed to be uniformly distributed over the width of the element. The deflections and rotations of the wing elements are defined by a 24 × 24 flexibility matrix.

The data which have to be input to the programme comprise the mass of each element, its geometry, the aerodynamic load coefficients acting on it and its displacement under a unit load as defined by the flexibility matrix referred to earlier, together with the aircraft speed and manoeuvring load factor. The load distribution over the deflected wing is calculated by means of a 12 × 12 matrix of aerodynamic influence coefficients.

The output from the programme consists of the shear, bending moment and torque, the incidence and the final lift coefficient for every wing strip, the shear, bending moment and lift on every fuselage element and the total lift on the wing, fuselage and tailplane. The present programme does not output tailplane shears and bending moments but a later improved version of the programme will do so.

The maximum wing bending moments are obtained with maximum payload, but at a constant zero-fuel weight there is not much variation of wing bending moment with fuel load since the fuel is distributed along the wing in roughly the same shape as the basic lift grading and the fuel usage is such that fuel is drained from all the tanks simultaneously. Fig.7 shows the variation of wing bending moment with fuel loading for a typical case.

The effect of the aeroelastic deformation on the wing loads can be seen from Fig.8 which shows the variation of wing bending moment with aircraft speed for a given weight condition.

The programme described is also used to obtain the aircraft loads in level flight at 1 g since this is obviously only a specific instance of a symmetric manoeuvre with $n = 1$.

The other important symmetric manoeuvre cases, so far as the tailplane and rear fuselage are concerned, are the checked and the unchecked elevator-induced manoeuvres. In the case of the Trident these become tailplane induced manoeuvres since the aircraft has an all-moving tailplane.

This proves to be an embarrassment as regards the requirement of F.A.R. 23.4.23 which calls for a sudden deflection of the elevator to the stops at V_A. Applying this requirement to an all-moving tailplane produces very large loads since the aircraft acceleration produced is unlimited by the requirements.

The tail loads in the checked pitching manoeuvre cases have been calculated using the method given in B.C.A.R., which has been programmed for the computer. The programme outputs the complete time history of the tail load, tailplane acceleration factor, aircraft pitching acceleration and velocity, tailplane and trimming elevator angle as the aircraft performs the manoeuvre.

We here encounter for the first time a problem which becomes much more difficult in connection with the gust cases. Some items of the structure may have loads which are dependent upon a number of parameters such as tail load and aircraft linear and angular accelerations which are all varying with time. The problem is to find the critical time at which the component's load is a maximum although, perhaps, none of the parameters is itself a maximum at that time.

For example, it is an easy matter to choose the time when the tailplane bending moment is a maximum since it corresponds to the time of maximum tailplane air load. The rear fuselage of the Trident, however, is loaded not only by the tailplane air load but also by the inertia loads on the tailplane, fin and three heavy engines. When the tail load is a maximum the inertia loads are small and, conversely, when the inertia factors are a maximum the tail load has passed its peak. (See Fig.9.) In this case it is a relatively simple matter to find the worst loads but this type of problem becomes time-consuming in the gust cases where everything is varying with time and a search for the critical time interval has to be done for practically every item of the structure. This subject is discussed in more detail in a later section dealing with gust loads.

The checked manoeuvre cases have to be investigated also in the flaps-down en route and in the flaps-down landing configurations.

The symmetric manoeuvre cases produce design loads in parts of the wing and fuselage and design almost the whole tailplane.

7.2 Aileron cases

Lateral control on the Trident is effected by means of ailerons augmented by using the airbrakes differentially as spoilers. The original design of the aircraft incorporated inboard and outboard ailerons. The inboard ailerons only were to be used at high speed and the outboard ailerons were brought into play when the flaps were lowered. This introduced some interesting design cases for combinations of flap and aileron. However, it was found that the lateral control at low speed was adequate using the inboard ailerons only and the outboard aileron was deleted. The remaining inboard aileron is inset from the wing tip and extends from 60% to 80% of semi-span on the Series 1 Trident.

In calculating the loads in the aileron cases, the aircraft has been designed for a checked rolling manoeuvre at all speeds, the aileron angle being limited only by the effort available from the aileron jacks. The pilot effort required is no limitation in this respect. The effort available from the jacks is obtained by applying the maximum working pressure in the hydraulic system to the jacks. These aileron angles have been associated with aircraft normal accelerations of 0 to 1.67 g $(= \frac{2}{3} n_1)$ as required by B.C.A.R.

It is therefore impossible for the pilot to apply more aileron angle than the aircraft has been stressed for. The only way in which he can exceed the design case is by applying the maximum aileron angle available with more than 1.67 g. Fig.10 shows the reduction in aileron angle needed to stay within the aircraft strength limitations with manoeuvring load factors greater than 1.67. These limitations are based on limit loads so that there is still the safety factor of 1.5 in hand before structural failure actually occurs.

Fig.11 shows the boundary of aileron and load factor combinations to produce failure in the aircraft structure. Since the aileron angle is limited physically by booster effort, failure can most easily be produced by pulling 3.1 g whilst applying full aileron. This is at the very least an adequate margin. Fig.11 shows the envelope for V_C at 6000 ft. Similar figures can be drawn for other flight speeds and give similar results.

The calculation of the aircraft loads in the aileron cases has been done in accordance with B.C.A.R. except that, as said earlier, the aileron angle at any speed has been taken as the maximum available. The aircraft is assumed to have only one degree of freedom, roll about the centre line.

The up and down aileron angles obtained by operating the control are not equal; more up aileron than down aileron is obtained. Moreover, the airbrakes when used as spoilers can be effective on one side only, i.e. the spoiler is extended on the wing with up aileron only. By averaging and differencing the angles on the two wings, the case is split into two cases - one purely symmetric, the other purely antisymmetric.

The symmetric part is dealt with by the programme described in the preceding section on manoeuvre loads. The programme for the antisymmetric loads takes the stiffness data, aerodynamic and weights data for the wing elements defined as in the manoeuvre programme and outputs the rate of roll, the rolling acceleration, and the wing shear, bending moment and torque at any number of times selected during the rolling manoeuvre.

It is assumed that the aileron is moved to its maximum deflection, as limited by the stops or the maximum booster effort available, as quickly as possible. Thus, full aileron can be applied in about $\frac{1}{3}$ second. The aileron is then held at this deflection for a time which is determined by the condition that the angle of bank does not exceed 90°. This is considered to be a reasonably severe assumption for a civil aircraft. In any case, the time which results from this assumption is such that the aircraft has reached a condition of steady unaccelerated roll. The aileron is then fully reversed to the maximum deflection in the opposite direction and is held there until steady roll develops. The loads throughout this sequence of manoeuvres are calculated including the aeroelastic effects of wing deflection, and the maximum resulting values are used for design. The sequence of events is shown in Fig.12.

In general, the steady roll cases are more severe than accelerated roll cases as there are no heavy masses in the wing which are offset from the flexural axis and, therefore, the wing inertia loads do not produce large torques. The aileron cases are only important insofar as they produce torque in the wings, and they provide design cases for the outboard spar webs.

7.3 Rudder cases

The rudder-induced manoeuvre cases can be considered in three phases (see Fig.13):-

(1) Full rudder, zero sideslip.

(2) Full rudder, peak sideslip.

(3) Zero rudder, peak sideslip.

These three stages represent the successive states of the aircraft as a rudder manoeuvre is carried out. The aircraft has three degrees of freedom - lateral displacement, roll and yaw.

The rudder angle available to the pilot is restricted by a rudder limiter which reduces the attainable rudder angle as speed increases. The fin was designed for the maximum loads occurring in the side-gust cases (including dynamic overswing effects) and the rudder angle is artificially limited at all speeds so that the fin loads for the side-gust cases are not exceeded in the yaw manoeuvre cases.

The yaw manoeuvre case loads are calculated by considering the aircraft as a rigid body and balancing the external aerodynamic loads by the appropriate lateral, yaw and roll inertia loads.

As far as antisymmetric manoeuvre cases are concerned, Loading Actions seems to be lagging behind aerodynamic calculations on performance. Whereas, with modern high-tailplane aircraft, the cross coupling between yaw and roll, especially the so-called 'dutch roll', is a matter of detailed investigations by the performance engineers, loading actions are still based on the rather simple-minded approach of aileron cases and rudder cases as separate subjects. At Hatfield we have been looking into stressing cases which take into account the full response of the aircraft in all axes to combined rudder and aileron manoeuvres. Although, due to the severity of the simple cases which have been used to design the aircraft, the new cases investigated do not give any cause for doubt about the strength of the aircraft, it would appear that, in view of the new aircraft geometries which are now coming into vogue, future asymmetric manoeuvre cases should be related to a more realistic representation of the aircraft response to control movements.

7.4 Vertical-gust cases

The complications introduced into the manoeuvre and aileron cases as a result of wing flexibility are also present in the gust cases with the added problem of the dynamic response of the aircraft to suddenly applied gust loads. The primary effect of the wing deflection, as in the manoeuvre cases, is that some of the lift induced by the gust is twisted off and the wing loads reduced. This effect is more than counterbalanced, however, by the dynamic inertia loads in the wing which increase the wing bending moment so that the combined effect overall is that the wing bending moments are larger than those for a rigid aeroplane. The loads in the fuselage and tailplane are also increased due to dynamic effects.

The gust requirements stipulate a gust of $\sin^2$ shape. This can be considered as one cycle of excitation at a frequency determined by the length of the gust and the forward speed of the aircraft. If the gust length is chosen such that the equivalent forcing frequency is equal to the natural frequency of vibration of the wing, very large loads may be produced in the structure. For the Trident, it was agreed by A.R.B. that a minimum gust length of 100 ft should be used. This represents a forcing frequency of about 4 c/s at V_C at 20000 ft which is slightly higher than the wing fundamental frequency of about 3 c/s.

The introduction of gusts of varying lengths into the requirements has added another complication to the determination of the critical gust loads. In addition to selecting the most critical weight, cg and payload distribution, and the worst speed and altitude, a range of gust lengths has to be considered to match up the forcing frequency with the natural frequencies of different parts of the aircraft. For instance, the worst wing loads are produced by a 100 ft long gust on the inner wing, a 125 ft gust on the middle of the span, and a 150 ft gust at the tip. The engine loads are a maximum for 125 ft long gusts and the fuselage loads for a 100 ft long gust. The only way to get all the worst loads is to calculate the gust loads for a number of gust gradient lengths and to select the worst values from these.

It has been found from experience on the Trident that it is sufficient to calculate the loads for gust lengths of 100 ft, 125 ft and 150 ft in order to get all the critical loads in the aircraft structure. Fig.14 shows the variation of wing bending moment with gust length.

The gust load calculations for the Trident have been programmed for the digital computer. The aircraft is idealised as consisting of 48 elements. These comprise 12 streamwise wing strips per side, 5 streamwise tailplane strips per side, 7 front fuselage 'slices' and 7 rear fuselage 'slices'. The weight of each element is assumed to be uniformly distributed over its width. Hence, some care is needed in the selection of the elements so that the cgs of heavy items such as engines or undercarriages are not displaced from their true positions in the idealisation. As the assumption is also made that the air loads are uniformly distributed over each element, the elements have to be selected with an eye on the aerodynamic load gradings. Items such as the airbrakes and flaps produce sharp discontinuities in the air load gradings and it is convenient to arrange the wing elements so that their boundaries coincide with these discontinuities. In the end it usually transpires that the choice of wing elements is very restricted and they are almost fixed by the aircraft characteristics.

The stiffnesses of the elements are defined by considering each element as a beam with a definite flexural axis and specifying the bending and torsional stiffnesses. Where the structure is highly redundant, as in the case of the wing root and the fin-to-fuselage junction, it is necessary to devise an equivalent beam with the same stiffness characteristics as the actual structure. This involves some rough estimations being done for project work but there is no problem in development work on the aircraft when all the structural analyses have been completed.

Once a given aircraft loading case has been chosen for investigation and the masses of all the elements have been calculated, the normal modes of vibration of the aircraft are calculated. The aircraft elements have two degrees of freedom, translation and pitch.

The aircraft is then considered as flying through the gust specified by the requirements for the speed and altitude under consideration. The gust is assumed to be of $\sin^2$ shape. The aerodynamic loads induced by the gust are calculated using the appropriate aerodynamic lag functions (Küssner functions). The aircraft is given 8 degrees of freedom, rigid body translation and pitch and 6 modes of vibration. The aerodynamic damping due to motion is calculated by means of Wagner functions. No structural damping is assumed.

The 6 modes which are used are normally the 6 modes with the lowest frequencies. Investigations have been made into the effect of omitting some modes and substituting others of higher frequency to assess their effect on the structural loads. As a result it was decided to add 3% to the loads obtained from the calculations to cover the effect of the modes of higher frequency which have to be omitted due to limitations on the capacity of the computer.

The aircraft is assumed to meet a gust which is of constant velocity along a line parallel to the spanwise axis, i.e. normal to the direction of motion. Thus the root of the swept wing enters the gust first, followed by the wing tips after a time determined by the forward speed, and the tailplane enters the gust later still. The gust loads on the fuselage are assumed to act simultaneously with those on the wing root.

The equations of motion for the dynamic system are solved and, hence, the accelerations of all the elements are obtained. The net loads in the aircraft structure are then calculated from the external air loads and the inertia loads.

The computer programme outputs the loads in the structure for any desired number of time intervals. It is usually sufficient to consider time intervals of the order of 0.015 to 0.020 sec. The integrations are done by a step-by-step process and this size of time interval gives reasonable accuracy when using modes of frequency up to 10 c/s. The modes of higher frequency do not contribute much to the final loads, as stated earlier, so the loss of accuracy is small.

The computer output is usually obtained for 16 to 20 time intervals covering a total time of about a third of a second. This has been found to be long enough, in general, to include the time when the peak structural loads occur. For each time interval the computer outputs the shear, bending moment, torque, lift coefficient and linear and angular accelerations at each of the 48 elements. This represents the time history of the aircraft loads as the aircraft penetrates the gust. A typical set of output values is plotted in Fig.15.

The difficulties of sorting out the worst weight and cg combinations, the worst speed and altitude, and the critical gust length have already been mentioned. To these are now added the problem of determining the critical time interval. In some cases this is a simple matter. For instance, if we are considering a piece of equipment mounted in the fuselage, the design load on the attachments may be determined solely by the maximum inertia factor at the relevant fuselage station. It is a comparatively easy matter to read through all the output values for that station and select the largest one.

However, matters may be much more complicated in the case of, say, a wing stringer on the bottom surface. The loads in this may consist of:

(1) an end load dependent upon the wing bending moment,

(2) a lateral bending moment dependent upon external aerodynamic suction,

(3) a lateral bending moment dependent upon the inertia factor acting on the fuel in the integral tank above it.

It can be seen from Fig.15, where the timewise variation of these values is plotted, that the three values do not all reach a maximum at the same instant and the determination of the critical time depends on the contribution which each of these values makes to the final stress in the stringer.

Three different solutions to this difficulty have been tried at different times:

(1) to assume that the peak values of all three parameters occur simultaneously. This gives severe design loads and, hence, is a safe approach but it seems wasteful, to say the least, to carry out lengthy involved calculations on the response of an aircraft to gusts, and then to subject the results to this kind of heavy-handed treatment which invalidates the accuracy of all the preceding work. It would be more economical to use a much less sophisticated method from the beginning and obtain answers as accurate as those which result from distorting the results of the accurate approach.

(2) to calculate the stress in the stringer at a number of time intervals and plot the results in order to obtain the maximum value. This is a time-consuming process especially as it may have to be repeated for a vast number of aircraft components. However, it would be possible to arrange for the computer to process its own output in this way and output the design loads. This needs a lot of organisation of programmes to deal with all the data involved since it is approaching the ideal stage where the computer accepts overall aerodynamic and weight data for the aircraft and outputs the reserve factors on the structure. This possibility is being investigated at the moment.

(3) to calculate the stringer stresses at the three time intervals which correspond to maximum wing bending moment, maximum fuel inertia factor and maximum external air load. It is then assumed that any other time intervals will give loads only marginally worse ($< 2\%$) than the worst value from the three times investigated. This method has generally been used in deriving the Trident gust loads and checks using method (2) have shown that in the vast majority of cases it gives the correct design loads within a very small error. This is because usually one parameter outweighs the others in producing stress in the component.

Fig.16 shows the dynamic overswing factor for bending moments in the Trident wing. The factor shown plotted is the ratio of wing bending moment for a flexible aircraft divided by the corresponding bending moment for a rigid aircraft. The factor, therefore, includes not only the dynamic effects but also the relief due to aeroelastic 'twist off' of lift. As can be seen from the curve, the dynamic and aeroelastic effects almost exactly neutralise each other over the inner third of the span so that the bending moment for the flexible aircraft is only about 3% higher than that for the rigid aircraft. On the outer third of the wing, however, the dynamic increment far outweighs the aeroelastic relief so that, at the tip, the net bending moment is twice as great as that for the rigid aeroplane.

The total loads in the gust cases are obtained by adding the gust loads to the 1 g level flight loads to obtain the up-gust case loads. The down-gust loads are obtained similarly by subtracting the gust incremental loads from the 1 g loads.

The gust cases design a large part of the aircraft structure, including the wings, fuselage and engine mounting structure.

Most of the fatigue damage to the wing is also caused by flying in turbulence and the loads used in the fatigue calculations are obtained in the same way as described above for the 'static' gust cases.

7.5 Side-gust cases

At the time when the Comet was designed, some power-spectral analysis was done in connection with the fin loads due to flight through turbulence. It was decided to adopt the same approach to the fin loads for the Trident. The method used was basically as follows:

(1) Calculate the worst wing design loads using the B.C.A.R. discrete-gust approach.

(2) Using a standard spectrum of atmospheric turbulence, calculate, using power-spectral methods, the frequencies of occurrence of the wing design loads given by (1).

(3) Using the same spectrum of turbulence, calculate the fin load which occurs as frequently as the wing design load. This is equivalent to having the same probability of failure for the wing as for the fin.

The fin load thus derived is used for the design side-gust case. It was found that for the Trident this fin load was 20% greater than the load obtained by working to the discrete-side-gust method of B.C.A.R.

Once the fin load has been determined in this way, the method of calculating the design loads in the side-gust cases is basically the same as that used for vertical gusts except that the antisymmetric aircraft modes of vibration are used in determining the response of the aircraft.

The forcing loads due to the lateral gust are applied to the fin and fuselage using aerodynamic lag functions similar to those used for the wing loads due to up-gusts. Due to the position of the tailplane at the top of the fin, the side-gust produces a large tailplane rolling moment in addition to the fin side-load. This rolling moment has to be resisted by the fin and, in fact, contributes the larger part of the fin bending moment.

The tailplane rolling moment coefficient varies not only with Mach number but also with the symmetrical C_L on the tailplane at the time that the aircraft encounters the side-gust. This fact adds another difficulty to the problem of finding the worst fin loads since a large symmetric down-load on the tailplane is associated with a reduced tailplane rolling moment, and the net fin loads depend on both down-load and rolling moment. In order to obtain the maximum tailplane rolling moment it is necessary to have the maximum symmetric up tail load. This will occur with aft centre of gravity and hence full load in the rear fuselage. The inertia relief on the rear fuselage loads is, therefore, a maximum in this case and the maximum fuselage shears due to tailplane torque are associated with reduced direct shear loads since there is so much inertia relief. It is not easy to select the worst case from inspection of the overall loading conditions and several cases have to be investigated to be sure of obtaining the worst loads.

7.6 Head-on gusts

These cases design only those components whose loads are dependent solely on the forward speed. On the Trident such items are the flaps, airbrakes and lift dumpers. The flaps are designed for the loads corresponding to specified angles and speeds, and the speeds are augmented by the gust velocity to give the design conditions.

The airbrakes are designed for the loads which occur when they are opened to the maximum attainable angle as limited by the jack effort available. A rearward gust is then applied and the jack is unable to close because of the irreversibility of the hydraulic system. The jack load is, therefore, slightly higher than the load which it can exert when operated by the hydraulic system.

7.7 'Round-the-clock' gusts

In the past, aircraft have been designed for vertical and lateral gusts separately. At the time when the Comet was being designed, however, it was realised that a gust which hit the aircraft at some angle between the purely vertical and the purely lateral gust directions could produce higher loads than either the vertical or lateral gust separately.

If the stresses due to a vertical gust and a lateral gust, both of velocity U, are f_v and f_s respectively, the stress due to a gust of the same velocity coming along an axis at an angle θ to the vertical will be:

$$f = f_v \cos\theta + f_s \sin\theta .$$

By differentiating with respect to θ and equating to zero, it is easily shown that the maximum value of the total stress f occurs when

$$\theta = \tan^{-1}\frac{f_s}{f_v}$$

and that the maximum value of f is

$$f = \sqrt{f_s^2 + f_v^2}$$

and must, therefore, always exceed the stress due to a simple vertical or lateral gust alone.

In the worst case when the vertical and lateral gusts produce equal stresses in the structure, that is when

$$f_v = f_s ,$$

the maximum stress due to a gust of velocity U at 45° to the vertical and lateral axes is

$$f = 1.414\, f_v = 1.414\, f_s .$$

As the ratio f_s/f_v is usually different for each part of the aircraft, the critical angle θ also is different. For example, on the wing f_v is so much larger than f_s that there is negligible error in designing for up-gust conditions and ignoring the lateral gust component. This is certainly not true, however, for a component such as a high-mounted tailplane where the stresses due to a 50 ft/sec up-gust and a 50 ft/sec lateral gust may be nearly equal. The lateral gust produces a large tailplane rolling moment due to the presence of the fin and, hence, the fin and tailplane bending moments are large.

So far as loading actions are concerned, 'round-the-clock' gusts involve no more work than the simple vertical and lateral gusts. The aircraft loads for the vertical and lateral gust cases are calculated in the normal way described earlier, and it is the responsibility of the designer concerned with the relevant structure to decide which 'round-the-clock' gust produces the maximum stress in his component.

Some complications do ensue due to the fact that the vertical gusts excite the symmetric modes and the lateral gusts excite the antisymmetric modes. As a result, the peak loads in the two directions may not coincide. This alleviates the maximum loads. Also for most components either f_v is much larger than f_s, or vice versa, and the maximum stress is, therefore, not much greater than that in the simple case.

It was agreed with A.R.B., when design work on the Trident started in 1959, that the aircraft would be designed to meet the case of 'round-the-clock' gusts coming from any direction. The gust velocities were to be the normal values of 66 ft/sec at V_B, 50 ft/sec at V_C and 25 ft/sec at V_D. This has been done and it has been found that the case produces critical loads in the tailplane, fin, rear fuselage and engine mountings. The summary of design cases in Table 1 includes the vertical and lateral gust cases. They have, in fact, been combined as appropriate to each component so as to produce the critical 'round-the-clock' gust cases.

7.8 Landing cases

The landing cases are treated in a similar manner to the gust cases, except that the forcing loads are supplied by the undercarriage and are applied at localised attachment points only, whereas the gust loads are distributed over the whole aircraft.

The time history of the undercarriage loads is obtained from drop tests or from predictions. This load history is fed into the computer and the aircraft is again treated as a dynamic system which responds to the undercarriage loads. Aerodynamic damping appropriate to the flying speed at touch-down is included. At present, only symmetric modes of vibration are used so that the dynamic load increments are due to symmetric loads only. The loads due to side-load on the undercarriage are, therefore, rigid-aircraft loads only.

The rate of descent used for the dynamic landing cases is $8\frac{1}{2}$ ft/sec.

The computer programme output, as in the gust case, is a time history of the aircraft loads. The aircraft in the landing cases is assumed to be airborne at the moment of touch-down and the 1 g level flight loads have to be superimposed on the landing loads.

In addition to the dynamic landing cases at $8\frac{1}{2}$ ft/sec it has been agreed with A.R.B. that the aircraft should also be designed to meet the loads due to landing with a rate of 10 ft/sec but considering the aircraft to be rigid (that is, ignoring all dynamic effects).

It is hoped to develop in the near future more representative calculations for the landing cases. The main criticism which can be made of the present method is that the undercarriage and aircraft dynamic behaviours are not sufficiently coupled. The undercarriage reaction history is obtained from prediction or drop test on the assumption that the leg is attached to a rigid aircraft. This history is then applied to the flexible aircraft. It would obviously be more accurate to consider the undercarriage and the aircraft as a single dynamic system. It is also intended to include the anti-symmetric modes in the dynamic system.

The landing case loads are the design loads for a large part of the fuselage and centre-section, and for the structure in the wing root in the area of the undercarriage attachments.

7.9 Take-off cases

The loads in the take-off cases have been calculated on the assumption that the aircraft is rigid. The vertical reaction factor F specified in B.C.A.R. has been taken to be 1.70 in agreement with A.R.B.

The take-off cases provide the design loads for part of the undercarriage and the local attachment to the wing.

7.10 Ground manoeuvres

These cases are straightforward and do not require any detailed explanations. The turning and swinging case designs the undercarriage side stay, and the dynamic braking case gives design loads on the nosewheel.

7.11 Fail-safe cases

Apart from the consideration of fail-safe principles in designing the structure of the Trident, great emphasis has been placed on duplicated and triplicated control systems as a fail-safe measure. As a result, the loads in the structure have been calculated on the assumption that parts of the control system have failed.

The flap system will be considered as a typical example of this philosophy. The flaps run on curved steel tracks and are extended and retracted by two ball bearing screw jacks on each flap, one at each end of the flap span. With the whole system intact, the loads were calculated for the flap design speeds and settings with the effect of a rearward gust as specified in the design requirements. The normal ultimate factor of 1.5 is used.

In the fail-safe cases it is assumed that either of the two jacks has failed or become disconnected so that all the flap load is resisted by one jack only. In this case the design speeds and settings are unaltered but the ultimate factor is reduced to 1.00.

Each flap design case is considered three times, therefore:

(1) Both jacks connected. Ultimate factor = 1.50.

(2) Inboard jack failed. Ultimate factor = 1.00.

(3) Outboard jack failed. Ultimate factor = 1.00.

Similar principles have been used in designing the aileron which has triplicated jacks. It is assumed that the aileron has to meet limit loads after any single jack has failed. The same philosophy has been applied to the other control surfaces.

8 CONCLUSIONS

The only criterion which determines whether the load calculations for a particular aircraft are satisfactory is the question of whether they produce a safe aircraft whose operation is as economical as possible. In practice this optimum can never be attained. There will always be parts of the aircraft which are unnecessarily heavy due to inaccuracies in the load calculations.

It is interesting to consider the sources of these inaccuracies and what steps, if any, can be taken to eliminate or, at least, reduce them. It is to be hoped that the accuracy of the actual calculations has improved since the introduction of computers for this work. Apart from eliminating computational errors, computers make possible a much more detailed investigation of aeroelastic effects, for example, which could not have been done by hand.

The danger with computers is that one is led to believe, for example, that the accuracy of the calculated loads can be improved by increasing the number of degrees of freedom in the dynamic calculations. This is no doubt true to a limited extent but the methods used in doing the dynamic calculations are probably more accurate than the basic stiffness, weight and aerodynamic data on which they are based. Estimated structural stiffnesses can easily be 5% different from the final measured values. The assumptions about the behaviour of fuel under dynamic conditions are often inaccurate. The largest source of inaccuracy appears to be the aerodynamic data. Even basic values such as the overall aircraft pitching moment coefficient or aerodynamic centre cannot be determined to very close limits. Unless the accuracy of this basic information can be improved, it is pointless to develop more sophisticated methods of calculating the design loads.

During flight testing of the Trident many of the aircraft loads have been measured as a check on the calculated values. Good agreement has been obtained on such items as tail loads in manoeuvres. This confirms the aeroelastic calculations for the aircraft. Most of the control surface hinge moments have also been checked and give reasonable confirmation of the predicted values. At present a power-spectral analysis is being carried out on results of flight tests in continuous turbulence. Since the Trident was designed for single gust requirements these results do not give a direct check on the design load calculations but they do give a check on the behaviour of the aircraft under dynamic loading conditions. If the response of the aircraft to continuous turbulence agrees with the calculated response to the same atmospheric conditions, it is reasonable to assume that the design load calculations for single gusts are also correct. Results available to date show that the aircraft modes are excited as predicted and that the dynamic overswing factors on wing bending moments are a few per cent less than those predicted.

Table 1

CRITICAL CASES FOR LOADS IN THE TRIDENT AIRFRAME STRUCTURE

(1) WING CENTRE SECTION

(a) Flight cases

66 ft/sec up-gust at V_B
50 ft/sec up-gust at V_C
25 ft/sec down-gust at V_D
50 ft/sec down-gust at V_C
50 ft/sec side-gust at V_C
2.5 g manoeuvre at V_D

(b) Ground cases

Landing
Take-off
Ground manoeuvring

(c) Fatigue loads

(d) Miscellaneous

Pressurisation loads
Pilot's effort on controls
Emergency alighting

(2) INNER WING - RIBS 1 TO 8

(a) Flight cases

66 ft/sec up-gust at V_B
50 ft/sec up-gust at V_C
50 ft/sec down-gust at V_C
2.5 g manoeuvre at V_A
2.5 g manoeuvre at V_D
0 g manoeuvre at V_D
-1 g manoeuvre at V_C
-1 g flaps-down en route
Aileron cases at V_C
Flaps down 50° at V_F + rearward gust
Flaps down 20° at V_F + rearward gust

(b) Ground cases

Landing
Take-off
Braked taxying
Ground manoeuvring
Jacking

(c) Fatigue loads

(d) Miscellaneous

Flap-motor torque loads
Pilot's effort on controls
Spanwise g on moveable leading edge
Undercarriage retraction loads

(3) OUTER WING - RIB 8 TO TIP

(a) Flight cases

66 ft/sec up-gust at V_B
50 ft/sec up-gust at V_C
50 ft/sec down-gust at V_C
2.5 g manoeuvre at V_A
2.5 g. manoeuvre at V_D
0 g manoeuvre at V_D
-1 g manoeuvre at V_C
Aileron cases at V_C
Aileron cases at V_D
Flaps down 50° at V_F + rearward gust
Airbrakes open with rearward gust

(b) Miscellaneous

Pilot's effort on controls
Spanwise g on moveable leading edge

(4) MOVEABLE WING LEADING EDGE

2.5 g manoeuvre at V_A
-1 g manoeuvre at V_G
50 ft/sec up-gust at V_C
66 ft/sec up-gust at V_B

(5) FLAPS

50° flap at 190 kt + 25 ft/sec aft-gust
20° flap at 225 kt + 25 ft/sec aft-gust

Both cases considered with:

(a) Both jacks connected
(b) Inboard jack failed
(c) Outboard jack failed

(6) AILERONS

Maximum jack effort at any speed

(7) UNDERCARRIAGE

Landing
Landing with burst tyre
Spring-back
Braked taxying
Turn and swing
Rolling back
Take-off
Pivoting
Jacking
Rebound landing
Fatigue

(8) FRONT FUSELAGE

2.5 g manoeuvre at V_D
2.5 g manoeuvre flaps-down en route
- 1 g manoeuvre at V_C
50 ft/sec up-gust at V_C
50 ft/sec down-gust at V_C
Landing
Internal pressure
Emergency alighting
Fatigue

(9) FUSELAGE CENTRE SECTION

Landing

50 ft/sec up-gust at V_C

2.5 g manoeuvre at V_F flaps-down en route

- 1 g manoeuvre at V_C

Internal pressure

Emergency alighting

Fatigue

(10) REAR FUSELAGE

Landing

Take-off

50 ft/sec up-gust at V_C

50 ft/sec side-gust at V_C

2.5 g checked manoeuvre flaps-down en route

- 1 g manoeuvre at V_C

Internal pressure

Emergency alighting

Fatigue

(11) TAIL FUSELAGE

2.5 g checked manoeuvre at V_C

2.5 g checked manoeuvre flaps-down en route

50 ft/sec up-gust at V_C

50 ft/sec down-gust at V_C

50 ft/sec side-gust at V_C

25 ft/sec side-gust at V_D

Landing

Tail bumper loads

Emergency alighting

Fatigue

(12) TAILPLANE

2.5 g checked manoeuvre flaps-down en route

2.0 g checked manoeuvre flaps 45^o

2.5 g checked manoeuvre at V_D

2.0 g steady manoeuvre at V_F

50 ft/sec up-gust at V_C

50 ft/sec side-gust at V_C

(13) FIN

50 ft/sec up-gust at V_C

50 ft/sec side-gust at V_C

Yaw manoeuvre at V_C

2.5 g checked manoeuvre flaps-down en route

(14) ENGINE MOUNTING

2.5 g checked manoeuvre at V_A

50 ft/sec up-gust at V_C

50 ft/sec down-gust at V_C

50 ft/sec side-gust at V_C

Take-off

Emergency alighting

DISCUSSION

Mr. H.P.Y. Hitch, British Aircraft Corporation, Weybridge said that Loading Actions problems were approached in much the same way at Weybridge as at Hatfield. (He added that he did not have any direct responsibility for Loading Actions - there were present, however, certain representatives from his organisation who had.) He thought that this could be because they both dealt with the same type of aircraft and asked whether Mr. Vann had had any experience of dealing with fighter aircraft and, if so, whether the Loading Actions picture was different for these. It seemed to him that the Loading Actions specialist, partly as a result of pressure from the stress office, conducted a dedicated search for the 'worst case'. This search had led over the years to a large increase in the number of cases considered; for example, whereas fifteen years ago only two rolling cases were taken to be sufficient to demonstrate adequate strength this number had now been increased by a factor of 10 or more. Mr. Hitch wondered whether this was worthwhile and actually produced an aircraft with a larger factor of safety.

He thought that with Mr. Vann's paper following Mr. Tye's another point succinctly emerged. That was that those working in the Loading Actions field were split down the middle since, on the one hand, if they complied with the regulations they got their products passed, which was one of their fundamental objectives, while, on the other hand, if they chose to deviate they had to convince their own organisation that they were right. So on the one hand there was the 'legal' point of view and on the other what could be called the 'true' situation. He noted that while Mr. Vann had mentioned that point he had not said to what extent he found there was a fight within his organisation - that would be interesting to hear. Fundamentally, a reserve factor of 0.99 was complete and utter disaster but a reserve factor of 1.01 was conspicuous success! A lot had been heard about cases not 'in the book' and it was interesting to learn that a fin load 20% greater than that given by B.C.A.R. had been adopted for the design of the Trident. Mr. Hitch wondered how they had decided to tackle the 'round-the-clock' gust case and how they resolved the issue of whether to say that the component in one direction and the component in another direction should both be the maximum of 66 ft/sec or to say that the inclined value should be 66 ft/sec.

Mr. Hitch thought that the representation of the aircraft for aero-elastic calculations was perhaps the main source of difference between what was done by B.A.C. at Weybridge and Filton and what was done at Hatfield. He gathered from Mr. Vann's paper that they had chosen to describe the aircraft in terms of 48 elements, determine the first 6 vibration modes, and then use these modes in each of the cases of interest. At Weybridge they took each load distribution per se, found the variation due to static aeroelastic distortion, and then used this changed distribution in subsequent calculations. He wondered whether this point of view had been considered at Hatfield and whether Mr. Vann would like to comment on it.

As regards gust cases, Mr. Hitch asked Mr. Vann if he thought that the power-spectral-density technique could ever be of use as a design tool, since Mr. Tye had expressed some doubts on this point - this question seemed rather topical.

Mr. Vann had mentioned that the rough-air speeds could be dictated by buffeting and Mr. Hitch wondered whether he had considered the possibility that the buffeting could give rise to loading actions even greater than those which were being guarded against. He said that he, and he hoped others, would be very interested to know whether the loads in the $8\frac{1}{2}$ ft/sec landing case were greater or less than those in the 10 ft/sec case for the rigid aircraft. With respect to buckling or the time which it took for failures to occur, Mr. Hitch stated that a lot of thought had been given to this but the disappointing fact was that this time was of the order of the period of the local piece which failed, which could usually be assessed in milliseconds.

Mr. Vann said that it was ten years since he had worked on loading actions for fighters. The main difference was that they were largely designed by manoeuvre cases whereas civil aircraft were designed by gust cases. In consequence, the questions on pilot response were more important for fighters than for civil aeroplanes. He said that rolling cases had certainly become more complicated and he, also, sometimes wondered whether they produced a better aircraft than the two original cases. He felt that the point was that once you knew something about a set of cases you could not push this to the back of your mind and use old fashioned methods, so you hoped that the new methods produced aircraft that were lighter but just as strong. On the point of complying with requirements, he said that the only times arguments arose were when the A.R.B. were being asked to accept a less severe case than they called for in the requirements: if, on the other hand, a firm suggested more severe cases, the A.R.B. asserted that this was entirely the firm's decision. Mr. Vann could not recall any great arguments regarding Trident design cases. Describing their approach to 'round-the-clock' gusts, he said that they had assumed that the maximum gust velocity called for was that of a gust from any direction round a sphere. In fact the only cases that were significant were those where the gust was in the plane transverse to the direction of motion and in that case velocities of 66 ft/sec at V_B and 50 ft/sec at V_C had been assumed, directed from any point round the circle.

Mr. Vann said that the method of altering the load gradings to take account of aeroelastic effects on the wing had been applied in the case of the Comet but that for the Trident it was decided that a better way was the one he had described which involved calculations of the deflected shape under load and of the load on a twisted wing using a Küchemann matrix of aerodynamic coefficients.

Mr. Vann thought that, though it was undoubtedly the correct approach for deriving fatigue loads, power-spectral analysis would not in the foreseeable future become a method of designing for static loading. The difficulty was that, for example for gust loads, so much had to be known about the aircraft and, whereas at one time only the shape and the design speeds were required, nowadays all the stiffnesses and modes of vibration were needed; to cope with power-spectral analysis led further into this complication. He thought that it would be useful to apply power-spectral techniques to assess the true potentialities of a design and perhaps use it in subsequent optimisation processes but he could not see its being useful for initial design.

The effect of buffet on loads had been discussed with the A.R.B. who were of the opinion that there might be less risk to an aeroplane in flying faster than the rough-air speed, and so possibly undercutting the strength factor, since a significant gain in controllability in severely turbulent conditions could result. There could well be a greater danger of breaking the aircraft by losing control than by having direct structural failure. On landing cases, Mr. Vann said that some of the aeroplane was designed by the 10 ft/sec rigid aircraft case and some by the $8\frac{1}{2}$ ft/sec dynamic (flexible aircraft) case.

Mr. W.G. Heath, Hawker Siddeley Aviation, Woodford was fascinated by a remark of Mr. Vann's in which he had expressed, in the neatest possible way, a belief to which he himself would subscribe. This was that instead of calculating the structural loads for a given aircraft one calculated the aircraft which would fit a given set of loads. He thought that everyone realised that this was true, and that from the papers to be presented later it would also be discovered that nowadays one could not design an aircraft until one had flown it. This was rather like saying that one could not get a new pair of shoes on until one had worn them once or twice, but it was true nevertheless. He wondered, in view of the fact that an aircraft was always developed into the strength available, whether there was not a case for two standards of Loading Actions requirements. On the first level one would have a rather arbitrary set, the 'old fashioned' set about which Mr. Tye had spoken, to get the aircraft designed, built, and flown, while on the second level there would be a more sophisticated set to be used when all the aerodynamic and stiffness properties had been determined by tests; from the latter set of requirements a development set of loading actions could be derived.

Mr. B.J. Beele, British Aircraft Corporation, Preston agreed with the previous speaker and said that in many cases there was a continuing process, producing a multi-level set of calculations. Their own efforts were currently concerned with splitting this into a number of recognisable phases. There was an initial design phase in order to get a project going, and then a further issue of sets of loads which were used to produce drawings for the aircraft. Nothing further was then done until the check-stressing stage wherein the objective was to find out what the aircraft would really do: this enabled one to proceed to a flight test stage with reasonable confidence in the safety of the aircraft. Once the aircraft had been ground tested and flight tested one had even more information and one could, if necessary, go through the same exercise again to establish whether more could be extracted from the aircraft than was at first thought.

AERODYNAMIC DATA FOR LOADING ACTION STUDIES

by

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SUMMARY

The present paper considers certain of the aerodynamic aspects which form part of the Loading Actions problem. These are dealt with under the headings of overall forces and moments on the one hand and pressure distributions on the other, whilst in another section of the paper the extent to which the available experimental techniques are able to yield the necessary data is considered.

CONTENTS

1 INTRODUCTION

The purpose of the present paper is to show, mainly by means of example, the general level of achievement and the main directions in which progress may be expected in the problem of specifying the aerodynamics for the purpose of making Loading Action investigations.

So that we may the more easily identify the nature and extent of the claim of this work on the aerodynamicist's attention it is perhaps worthwhile (briefly, since this is dealt with fully elsewhere) to outline the various facets of the Loading Action worker's task. His main objective is to ensure safety of flight under all possible or usable flight conditions, with the added implication that this is achieved in the most economic manner as regards the structure weight.

Design procedures and requirements attempt to fulfil this aim by the provision of rational bases for the specification of critical flight conditions and by means of 'factors'. These latter reflect the other shortcomings of the approach to the problem of designing for adequate safety, and the accuracy to which the aerodynamic forces can be specified has a direct bearing on the degree of efficiency attained[34,35].

The Loading Actions investigation can usually be divided into two parts thus:

(a) The work on which specification of the (generally dynamic) flight condition rests. This is essentially the calculation of the response of the aircraft during prescribed deliberate manoeuvres and such inadvertent manoeuvres as those resulting from gust encounters, engine failures etc., or a combination of these as in recovery action by the pilot.

(b) The calculation of the distributions of the aerodynamic and inertial loads over the structure associated with the flight conditions as they come out of (a), and their application to the stressing problem and definition of a satisfactory structure.

The background work to (a) the Loading Actions man shares, to a not inconsiderable extent, with others interested in flight dynamics topics ranging over handling qualities, stability including automatic flight control systems, and flutter. It is not proposed to discuss this aspect of the work in the present paper, and its mention only serves to illustrate that there may be somewhat different formulations of the aerodynamics appropriate to the various stages of the work.

To be more specific, we may consider a simple case of an aircraft which for the purposes of conducting stage (a) of the work may be considered rigid. The classic approach to the aerodynamic problem is to use a linearised formulation of the aerodynamics in the form of quasi-steady derivatives of the forces and moments with respect to the response variables (u,v,w,p,q,r) for stage (a) and pressure distributions, associated with each variable, which may be linearly superimposed to obtain the resultant aerodynamic load distribution, for stage (b). Both the derivatives and the load distribution are considered functions of Mach number and Reynolds number, in general.

The extent to which present techniques, theoretical and experimental, meet the need of the Loading Actions investigator is discussed for two principal types of aircraft: the wing-fuselage combination in which the wing may be swept, but of moderate to large aspect ratio, such that the attached Kutta-Joukowski type of flow of the classical aerofoil forms the design basis; the other being the slender wing employing the separated type of flow with coiled vortex sheets above and behind the wing.

Even with some of the restriction that is implied in the foregoing remarks it is clear that, within the scope of a single paper, it is impossible to give an exhaustive survey of all the work done and possible future developments. Some of the references quoted themselves give broad surveys of certain topics[3,4,34,37] and so make up for this deficiency. Being more broadly based the present paper merely illustrates by example the main lines of progress, the order of accuracy achieved (comparisons of theory, wind-tunnel and free-flight test results are made) and the need for a more intensive attack on some aspects of the general problem.

For convenience the subject matter is dealt with under three main headings: the prediction of the overall forces and moments on the aircraft (Section 2), the calculation of pressure distribution over component parts of the aircraft (Section 3) and some discussion of experimental techniques (Section 4).

Although the methods and techniques, experimental and theoretical, apply more generally, the present paper is confined to the application of these to the problems of aeroplanes with an upper Mach number limit of 2.5.

Certain other topics such as the repercussion of the aerodynamics and the response of the aeroplane on the formulation of the most critical manoeuvres, having regard to the structural integrity of particular components, are excluded from the discussion, as are also gust and buffet inputs.

2 OVERALL AERODYNAMIC FORCES AND MOMENTS

As mentioned in the Introduction it would be out of the question to give anything approaching a detailed account of the present position on the estimation of the aerodynamic derivatives, or any other formulation of the overall forces and moments on an aeroplane. In any case, an attempt to outline the position as it then was has been made in a paper by Thomas[4]. In the bibliography appended to this paper further papers relevant to the subject are listed.

Comments on the general position and possible lines along which improvement may be sought are made below as they refer to particular types of aircraft.

2.1 Swept-wing, tailed aircraft

Within this class of aircraft we have at one end of the scale the subsonic, large-aspect-ratio transport type of aircraft and at the other the high performance military aircraft with wings of moderate to small aspect ratio ($4 \geq A \geq 2$, say) and high angle of sweep. From the viewpoint of the estimation of their aerodynamic derivatives, these represent extremes in degree rather than type.

The relatively smaller body diameter to wing span of the former permits certain relaxations to be made in the calculation of the derivatives; for example, for many derivatives the component contributions may be considered additive. On the other hand the relatively bigger body to wing size in the latter case precludes any such simplification. Here we must seek a more integrated approach to the aerodynamics of the assembly of wings, fuselage and tail surfaces. Nevertheless, the first step is to obtain methods which adequately predict the forces and moments on isolated components. Hence a good deal of effort has been expended for some time in the quest for a reliable lifting-surface theory to deal with the type of wing under consideration. Much has been achieved already, but there is evidence that a yet greater degree of accuracy may be attained. Garner, in some recent work, has demonstrated that even within the general framework of existing lifting-surface theories greater accuracy follows from a specialised distribution of collocation points. Other work by Hewitt and Wallace[6]* aims at a renewed attack on the problem embodying some fundamentally different concepts. Notwithstanding these future possible developments, the existing methods are judged to be capable of providing overall forces and moments with accuracy sufficient to meet the needs of the early stages in the design procedure.

The fuselage, which is usually a near-body-of-revolution, has been the subject of a number of studies. No entirely satisfactory treatment has emerged and there is undoubtedly need for further work here.

Fundamentally, the tail surfaces may be treated along the same lines as the wing. The important point here is that under no circumstances may we entirely neglect the interference between the wing and these surfaces. Strictly speaking, we are concerned even in the simplest case with aerofoil surfaces operating within a field of flow which is non-uniform. Even though it is possible in many cases to average out the non-uniformity of flow it is as well to bear in mind that, handled on a digital computer, the calculation of the force on a tailplane or a fin for a completely arbitrary distribution of incidence may be lightly undertaken. The comparative ease with which the flow field surrounding a wing and the action of this on aerofoil surfaces immersed in it can be calculated has not been sufficiently exploited or so it would seem.

Thomas and Spencer[5] indicated the possibilities in calculations relating to the tailplane contribution to damping-in-pitch. More recently, Hewitt[6] has made more extensive comparisons covering downwash and sidewash at specific points in the neighbourhood of the wing and again damping-in-pitch. Some of his results are shown here as Figs.1 and 2. We shall return to this topic again in Section 3.

In the meantime, having outlined some of the general trends, we consider the level of accuracy achieved in prediction of the derivatives for the broad class of aircraft under discussion. We choose a rather extreme case, for which test results are available from both wind-tunnel and free-flight model tests[52], see Fig.3. In Fig.4 the derivatives z_w and m_w as estimated by the available theories are compared with the wind-tunnel and free-flight test results. The two sets of experimental results are in good agreement generally, although there are differences in z_w at transonic speeds, for

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* This work is being conducted by B.A.C., Warton under an M.O.A. contract.

which there is also more scatter in the free-flight results. Similar remarks apply to the stiffness-in-pitch derivative, m_w. Part of the scatter in the free-flight results may reflect the non-linear character of the pitching moment variation with incidence, since the models flew at somewhat different lift coefficients or trimmed incidence. The theoretical estimate for z_w is in good agreement with the experimental values, but at subsonic speeds the estimate for m_w shows an appreciable discrepancy, probably due to the inadequacy of methods for estimating the downwash at the tail.

It is, of course, a feature of many test techniques that damping derivatives are yielded in combination as they occur in the damping characteristics of a mode. For this reason Fig.5 shows a comparison of $(m_q + m_{\dot{w}})$ as determined by experiment and theory. The experimental results give a nearly constant damping in pitch at high subsonic Mach numbers. This somewhat unusual feature is not present in the calculated values, which are otherwise in good agreement with experiment.

During the same free-flight experiments lateral stability derivatives for the same models were obtained. These are compared with estimates and wind-tunnel measurements, where these are available. The general level of agreement is not uniform and in some cases there are appreciable discrepancies between tunnel and flight as well as between experiment and estimates, see Figs.6, 7 and 8. For ℓ_v, the estimate includes incidence effects appropriate to the model which yielded the experimental points indicated by the circles in Fig.6, and the agreement is remarkably good. The sideforce and yawing moment due to sideslip, y_v and n_v, depend largely on the fin effectiveness, and the estimate, including wing, body and sidewash interference effects, gives much larger values than obtained experimentally, Fig.6. An analysis of several configurations suggests an empirical factor of between 80 and 90% on fin effectiveness, but it is seen that 85% fin effectiveness gives results which are still greater than the experimental values of n_v. (It may be noted that a large reduction in n_v was indicated in the same series of tests for models flying at higher C_L s.) On the whole, the agreement between experiment and theory is good for ℓ_p and n_r.

2.2 Slender-wing aircraft

As indicated in the Introduction the aircraft based on the slender-wing concept belongs to a distinctive class. The type of flow employed here is typified by coiled vortex sheets above and behind the wing.

The calculation of the flow about a wing at uniform incidence is a formidable task. Not unnaturally the first attempts to tackle the problem have made the assumption of conical flow. Even so, real progress has only recently been made in dealing with an entirely ab initio calculation of the flow field and the shape of the coiled vortex sheet.

It is not surprising, therefore, that the estimation of the various aerodynamic derivatives has rested to a large extent on the predictions of lifting-surface and slender-body theories empirically modified as necessary on the basis of a number of systematic tests. The procedure is discussed fairly fully elsewhere[4], and so we content ourselves here with some comparisons of theory and experiment to illustrate the present status of estimation methods, based in the main on Refs.1, 2 and 7 to 22.

Before passing on to discuss these, it is worth remarking that the most recent work by Smith[31] does take us some way toward the complete framework of theory such as we have been exists for the swept wing.

We first consider the wing-fin arrangement shown in Fig.9, for which free-flight model test results are available covering a number of derivatives[33]. Wind-tunnel test results are also available for the damping-in-pitch derivative ($m_{\dot{\vartheta}} = m_q + m_{\dot{w}}$).

In Fig.10 are plotted the variations of z_w and m_w with Mach number as predicted on the basis of a number of theoretical solutions. The circled numbers indicate the curve or point yielded by the method given in the reference of corresponding number. Apart from the near-sonic conditions the estimates are in fair agreement with experiment. For the damping in pitch the estimates consistently lie above the measured values from tunnel and free-flight tests. There is appreciable scatter of the experimental results. More is said of the experimental techniques involved in a later section.

Turning to the lateral derivatives of this layout we see from Fig.11 that the side-force derivative, y_v, is predicted with good accuracy. For this arrangement the yaw-stiffness derivative, n_v, has a comparatively high value throughout the Mach number range covered by the tests and is reasonably well predicted by the calculations (Fig.11). In contrast the rolling moment derivative, ℓ_v, is numerically small at these Mach numbers and at the incidences encountered in the tests. Consequently the prediction is at the mercy of opposing effects (see Fig.12), one of which is of questionable accuracy. The general level of the experimental results as well as the trend of the variation with Mach number are, nevertheless, reproduced.

To illustrate the essential difficulties relating to the estimation of the derivatives of this type of aircraft, namely the prediction of their dependence, often quite strong, on incidence, we now discuss the experimentally determined and predicted derivatives of the HP115 aircraft (see Fig.13).

The comparisons are made in Figs.14, 15 and 16. Departure of the estimates from the measured values tends to become more marked as incidence is increased. The only means by which the estimates can be brought into closer agreement with experiment is to account for the effect of the flow separation at the leading edges. In particular, the wing contribution to the derivatives y_p and n_p arises from the suction forces along the leading edges, which are zero if the flow is completely separated. Reasonable agreement between theory and experiment has been obtained (Figs.15 and 16) by applying a factor derived from the experimental values of induced drag, which lie between the theoretical values for attached and separated flows.

The recent progress in the calculation of the loading for symmetrical flight conditions at uniform incidence holds out hope that a rational basis can be found for dealing with pitching, rolling, yawing and sideslipping conditions also.

3 PRESSURE DISTRIBUTION

Underlying the estimation of the overall forces and moments is the problem of calculating the pressure distribution over aircraft components in combination as a flying vehicle. Basic to this in turn is the calculation of the pressure distributions on the various components in isolation.

This is of particular importance to the Loading Actions investigator as we have mentioned already. He is fundamentally concerned with the loads generated by the air as it flows around the structure of the aircraft. More specifically, we shall here discuss the pressures exerted by the air on, and their distribution over, the external surfaces of aircraft shapes. These can be conveniently expressed in the form of a pressure coefficient $C_p = \frac{p - p_o}{\frac{1}{2}\rho_o V_o^2}$, where p_o and ρ_o are the ambient pressure and density and V_o is the flight speed (or free-stream speed).

Ideally, one would like to be able to estimate $C_p (x,y,z,t)$ as a function of the space coordinates of the surface and of time for all manoeuvres and conditions that are likely to occur during flight. Apart from the time dependence introduced through the dynamics of the manoeuvre, the local pressure must be expected to fluctuate with time, under all conditions of flight, as a result of excitations by turbulence in the boundary layer, by noise from jets or propellers, or by other unsteady flow phenomena. Here, we would like to be able to estimate the amplitude and frequency spectrum of the oscillations as well as the phase correlations. To obtain a complete and consistent answer, account must be taken of the fact that the structure responds to these air loads and deforms, thereby introducing changes in the loading. Clearly, we are still a long way off being able, as a matter of course, to undertake estimates of such generality. Nevertheless, the integrated aerodynamic and structural analysis of the flying vehicle must remain an important aim of future research work.

3.1 The swept-wing aircraft

We consider first the swept-wing-fuselage combination. It may be assumed that the wing-fuselage layout has been designed to have a certain pressure distribution in the cruising condition and that the wing shape is cambered and twisted accordingly.

An important feature of this class of aircraft is the fact that, to a first order and over nearly all the usable incidence range of the aircraft, the loading due to incidence may be taken as additive to that of the warped wing. Furthermore so long as we are dealing with attached flow the aerodynamic load distribution due to incidence is nearly independent of the value of the lift coefficient and may thus be scaled up and down accordingly.

Here again we can do no more, within the compass of this paper, than give some illustrations, and refer to documents wherein the existing information may be found in greater detail.

A typical design loading for a swept wing at cruising condition is shown in Fig.17. This is largely determined by the desire to obtain nearly straight isobars (not generators!) at least over the upper surface of the wing. Performance considerations lead to a fairly large load over the rear of the section and also to some peak load near the leading edge. Again for reasons of performance, the spanwise loading is nearly elliptic. A typical loading for a swept wing at an angle of incidence is shown in Fig.18, where that of an unswept wing is also shown for comparison. This exhibits the characteristic changes in the chordwise loading due to sweep (with larger loads over the rear near the centre of the wing and sharp peak loads at the leading edge near the tips of the wing); and also the characteristic loss of lift in the spanwise distribution near the centre and the increase of lift near the tips. Existing methods for calculating these loadings are fairly well documented, and we refer here to Thwaites[3], Bagley[23], Pearcey[24], Lock and Bridgewater[25], and especially the Data Memorandum[2] prepared by the Royal Aeronautical Society. Thwaites's book, in particular, also refers to methods for calculating the effects of boundary layers; of slats and slots; of joining bodies (such as intersecting wings, wing-fuselage and wing-nacelle combinations); of non-uniform mainstreams (in the spanwise and in the lift direction); and also some non-linear effects (such as those caused by tip vortex sheets). All these effects produce some characteristic changes in the load distribution.

Thus far we have discussed the design of the wing to have some desired pressure distribution and the calculation of the pressure distributions at uniform incidence. It is implicit in these that we can deal with other distributions of incidence. In dealing with the loadings produced in quasi-steady manoeuvres reasonable approximations may be obtained, within the framework of theory outlined above, by taking account of the sideslip and angular velocities, by forming additional incidence distributions associated with the kinematics, e.g. py/V_0 for rolling.

The same methods are available for dealing with the tail surfaces provided due account is taken of the field of flow in which these surfaces operate, as indicated in Section 2. For dealing effectively with such calculations it is necessary to make the fullest use of the capacity of present-day computing machinery.

Founded on the same basis, methods have been developed, and continue to be improved upon, for calculating the pressure distribution on oscillating wings. Under certain circumstances (high values of the frequency parameter, transonic Mach numbers) the pressure distributions are markedly frequency-dependent. A wide range of frequency can in principle be covered.

To date most of the work has centred around the oscillation-in-pitch motion, but there would seem to be no fundamental reason why the application of the techniques should not be broadened.

3.2 The slender-wing aircraft

A typical design loading for a slender wing is shown in Fig.19, taken from Ref.32. This is largely determined by imposing the condition that the attachment line lies along the leading edge (and in consequence there is zero load there) and by the desire to have low vortex and wave drags. It is also necessary to achieve a certain position of the centre of pressure to keep the trim drag as low as possible. In an actual design the wing may, at cruise, operate at a larger angle of incidence than that for which the attachment line is along the leading edge.

Fig.20 shows the loading due to incidence on an uncambered wing at supersonic speeds. A rough approximation to the loading on the cambered wing at cruise incidence may be obtained by combining the loadings of Figs.19 and 20.

In Fig.21 the load distributions on a delta wing at various angles of attack and at low Mach numbers are shown. It is seen that with increasing incidence the vortex moves inwards and the peak suction produced under it moves inboard. This may be contrasted with the state of affairs for the swept wing (see Fig.18), for which a single curve is obtained.

For attached flow along the leading edge the surface or load may be calculated - as for the swept wing - from linear theory. When the leading edge vortex sheets are present, however, it becomes necessary to account for their presence - and more or less faithfully reproduce their strength and their location - before a reasonably sound estimate of the loadings can be obtained. Some recent progress along this road has been made.

Treating the flow as conical, J.H.B. Smith[31] has obtained a solution in which the shape, position and strength of these vortex sheets is determined and in consequence the pressure distribution calculated. Some of his results are compared with measured values in Fig.22. A point to note is that the other comparisons made with experiments indicate that the position of the vortex and its core is given with reasonably good accuracy by this theoretical calculation.

Extension to non-conical flows and wings with thickness is considered possible and is currently being looked into.

All this holds out hope that, in time, more rigorous methods of dealing with wings in sideslip or rotating in roll, yaw or pitch will become available, as will also improved methods of dealing with the wing oscillating in pitch.

To give some idea of the types of pressure and load distributions theory will have to cope with we give some further illustrative cases in Figs.23, 24 and 25. In Fig.23 is given the load distribution on a delta wing of aspect ratio 1 and in Fig.24 that of a gothic wing of the same aspect ratio to show the effect of planform. Fig.25 demonstrates the variation of the pressure distribution with Mach number.

With regard to the structural aspects of these loadings, we note that both the swept wings and the slender wings have loadings which are far from uniform and also quite unrelated to the expected weight distribution. In both cases, a good deal of the lift is generated by high localised suction forces. These are generally lower in the case of slender wings, and there is a possibility, as yet unexplored, of designing warped slender wings with a view to obtaining a better match with the weight distribution and to achieving more favourable stress distributions in the curved surfaces near the drooped leading edges.

4 THE USE OF MODELS

The consideration of the application of model techniques to Loading Actions problems virtually embraces the whole of some fifty years development of aerodynamic testing and a complete survey is beyond the scope of this paper. A fairly broad survey of some of the current experimental techniques has been given by Taylor[37] and the application of model tests to a particular aircraft is well illustrated by the article by Webber[38] on the VC 10. The approach adopted here is to consider the applicability of some model techniques to the determination of manoeuvres and the resulting loading. A fuller study would include many other aspects where model tests could contribute; for example, the representation of gusts[58], the determination of buffet boundaries and loads[59] and other effects arising from unsteady airflow[60,61]. The special techniques developed for V/STOL and high-lift model testing[62] are a subject in themselves, as also are the means of representing engines[63], and are not discussed. Three classes of aircraft only are considered, the high-aspect-ratio subsonic transport, the slender-wing supersonic transport and the 'manoeuvring' aircraft.

4.1 Test requirements

It has been pointed out by Molyneux[39] that the full representation in model tests of all the possible parameters defining the fluid motion and the structural behaviour of an aircraft is so formidable a task that complete similarity becomes possible only when the model and the aircraft are identical. From a practical point of view it is therefore necessary to introduce many restrictions. Attention is directed mainly to rigid models and no consideration is given to representing thermal conditions. Basic aerodynamic loading data usually stem of necessity from tests of rigid models. As noted by Taylor, attempts are being made to simulate flight conditions on complete aeroelastic models in a wind tunnel. How far this attempt is worthwhile and whether the proper simulation of inertia and gravity loads is possible must be debatable.

It would appear more profitable to develop and improve methods of prediction of aeroelastic effects (which must in any case be used in design) by reference to experiments in which the problem is treated step by step; for example by testing under steady conditions and making elastic only a component of a model such as a wing on a stiff fuselage.

For rigid models the parameters considered are generally reduced to two, namely Mach number and Reynolds number. It is usually essential to represent Mach number correctly* and it should be pointed out that this is true in some instances even at very low speeds, for example in stalling tests, where local high peak suctions may lead to compressibility effects. Generally the representation of full-scale Reynolds number is not possible but some minimum Reynolds number may be defined, above which the character of the flow is little changed. This minimum will depend upon the type of flow. Some particular types are discussed.

For full-scale aircraft with high-aspect-ratio wings transition from laminar to turbulent flow may be assumed to be near the leading edge. The minimum acceptable test Reynolds number is then that for which transition may be brought forward on a model without using a trip of excessive size. Experience suggests that this is of the order of two million based on wing chord. The flow will then be qualitatively similar to that at the large full-scale Reynolds number but some quantitative correction will be required. As an example Fig.26 shows the dependence of lift curve slope, at low speed, upon Reynolds number for an unswept aerofoil of 11 degrees trailing edge angle, as given by Spence[41] and by the R.Ae.S. data sheets[1]. There is some

* In subsonic flow when shock waves are absent so-called analogous models may be used in which change of Mach number is represented by change in thickness[40].

discrepancy (which has been discussed by Beasley[42] but not resolved) in the absolute level of lift curve slope but fair agreement in the change with change of Reynolds number. The effect of increasing angle of sweep may be expected to increase the Reynolds number dependence, and there is a need for more work both theoretical and experimental on the effect of sweep. For wings near maximum lift the stall, particularly for thin wings, may be very sensitive to leading edge conditions and thus the use of trips (to try to fix transition) may be undesirable. Williams and Kirkpatrick[43] suggest that for testing near maximum lift the minimum Reynolds number may consequently need to be increased to about 6 million.

For slender wings with sharp leading edges, as might be used for a supersonic transport aircraft, the main scale effect likely to be significant in the context of Loading Actions is the behaviour of the secondary separation on the upper surface at high incidence. If the boundary layer is laminar the peak suction is smaller than for turbulent flow and occurs further inboard[44]. There is thus a dependence of the spanwise loading distribution upon boundary layer conditions. However, provided the Reynolds number based on mean chord exceeds about two million, particularly if a transition trip is used, the loading appears to follow the turbulent pattern and little change of the flow occurs with further increase of Reynolds number. There is also no evidence of any significant scale effect on vortex bursting (in some ways akin to the stall on high-aspect-ratio wings). Good agreement has been found between tunnel and flight on the HP 115 slender-wing research aircraft.

For bodies of revolution it is not easy to define a simple minimum scale condition. For bodies at incidence the flow is dependent both upon a longitudinal scale and upon a transverse scale. The transverse scale can be related to the flow conditions on a cylinder normal to an airstream. By use of this correlation a dual condition may be devised. An example of the correlation is shown in Fig.27, extracted from Ref.45, for a body of fineness ratio 10 tested at a Mach number of 1.61. At incidences up to about 14 degrees the crossflow Mach number is less than 0.4 and the Reynolds number is sufficiently high for the smaller turbulent crossflow drag to hold. For higher incidences the crossflow Mach number increases and produces a higher crossflow drag (as in laminar flow) resulting in a larger normal force coefficient. When a long body is combined with a low-aspect-ratio wing the effects shown in Fig.27 may be magnified because of the interaction of the vortices shed from the body with the wing. However, Fig.27 implies that if the longitudinal flow can be made turbulent then the loading will be qualitatively the same as for higher Reynolds numbers at the same Mach number. There is generally no problem in establishing transition near the nose of a body of revolution.

4.2 Static measurements

The essential loading information in the design of an aircraft comes from static testing, in wind tunnels, of pressure-plotting models and of models on which are measured overall forces. It is thus of interest to see how far the wind-tunnel model can cover the flight envelope over which loadings are required. A simple representation of the flight envelope of an aircraft can be obtained as a lift coefficient - Mach number boundary. Fig.28 shows such boundaries taken as being typical of three classes of aircraft. Positive lift coefficients only are considered since the loading requirements at negative lift are less stringent. For these boundaries, aerodynamic loadings, for wind-tunnel models about five feet long which meet the minimum requirement of wing chord Reynolds numbers of two million, have been plotted. Strictly, if tailplane or fin loads are required very accurately, some increase in Reynolds number, and consequently loading, would be required to maintain sufficiently high Reynolds numbers on the appropriate surfaces. The examples are based on specific models but their application is probably fairly general. The models are sting-mounted and manufactured of high tensile steel. All three models were designed for the minimum practicable distortion due to the sting support, and had completely internal six-component balances. As a result, the load limitation is that of the balance rather than the model. Nevertheless it is clear that, within the scale requirements suggested in Section 4.1, the loading requirements can be met. For pressure-plotting models the strength reduction due to the installation of tubing runs will reduce the model loading limit, but not below that for the sting, so that the picture is not materially affected. As model size is reduced, loadings will be increased to maintain a given Reynolds number, and an increase in the model distortion to accommodate the sting and balance may be inevitable.

The figures are drawn for aircraft without high-lift devices. Representing take-off and landing configurations would of course increase the lift coefficients required at low speeds, and the increased Reynolds numbers suggested for stalling tests involve further increases in model loading. The loadings at Mach numbers up to 0.2 are, however, small and a fivefold increase could be tolerated except for the subsonic transport which would require a stronger sting and balance. The Reynolds number requirement of 6 million at a Mach number of 0.2 would be hard to meet in existing facilities on a complete model.

Fig.28 shows only design loading boundaries and omits other boundaries which may have significance both full scale and model scale. For example the subsonic transport may have a buffet boundary at a lower value of lift coefficient than that taken for the design loads. It is unlikely that a highly loaded wind-tunnel model could be tested without mishap beyond the buffet boundary. This shortcoming is academic since the aircraft also would be unlikely to survive far beyond its buffet boundary.

Techniques of measuring loads and pressures under steady conditions are so well established as to need almost no comment here. With the introduction of strain gauges it is possible to obtain loads on almost any component or part of a component as desired. There are, however, problems of model support which need careful consideration. Taking an example from Fig.28, for which models with minimum distortion were selected, corrections are still required. Fig.29 shows the effect of the sting fairing on a model of a supersonic transport aircraft. The results plotted were obtained by measuring the loads on a single sting mounting, and then making additional tests with the model so supported that loads on the rear part only, with and without the sting fairing and a dummy sting, could be measured. In the longitudinal plane there is a change in C_{m_0} and a change of about $\frac{1}{2}$% chord in aerodynamic centre. There are also changes of about 20% in n_v and about 10% in y_v.

Other undesirable effects may arise from tunnel constraint corrections on high-aspect-ratio wings. It has been common practice to apply a simple incidence correction to lifting models to account for wall constraint. Recent work by C.R. Taylor has drawn attention to the spanwise variation of this correction and the additional incidence variation across the span caused by bending of a swept wing. Fig.30 shows the variation of the correction to incidence across the span for a 30-degree swept wing made of steel and of span equal to two-thirds tunnel height. For a tunnel with solid walls as plotted, the two effects almost cancel for a Reynolds number of 4 million at M = 0.2 and for 2 million at M = 0.8. Increase of Reynolds number to 4 million at M = 0.8 introduces some 3% variation in the incidence corrections across the span. For a transonic tunnel with ventilated walls the situation is worse in that the constraint correction is of opposite sign and is additive to that due to the wing bending.

One aspect of pressure plotting may be of some interest. Pressure-plotting models take longer to design and build than balance models and there is thus a reluctance to commit pressure-plotting models at an early stage in a project, and furthermore the primary aims in the early stages are to assess stability and performance. Webber[38] suggests that loading data are produced in four stages.

(1) At the early project stage when simple estimates and experience are used.

(2) Reappraisal of (1) in the light of performance and stability model tests.

(3) Using data from specific loading tests combined with estimated stiffness and inertia data.

(4) Corrections to (3) from the results of flight testing.

It may be helpful at stage 2 to be able to make some limited pressure distribution measurements. An attempt has been made to do this using pressure-plotting tubes external to the model. (This is not new in principle. The use of creeper static tubes attached to wooden models has been a standard technique in low-speed wind tunnels for many years.) Fig.31 shows a pressure-plotting rake used on a model aircraft fin. The rake was so designed that the static pressure tubes would lie in contact with the model surface, and the rake could be traversed in the longitudinal direction. The arrangement is obviously difficult to use in regions of high curvature or near leading edges. It is too expensive in tunnel time to be used extensively but may have applications over limited regions in the suggested context.

A direct check of the accuracy of pressure measured with the rake is not available. Fig.32 shows a comparison of pressures measured in a conventional fashion, on a fin and dorsal extension, with pressures obtained from the static rake on a straight-leading-edge fin. Other differences are a change in the position of the wing relative to the fin and a change in the sweep of the fin trailing edge. The trailing edge is supersonic in both cases and the change in sweep will have small effect on the pressures. The dorsal extension will, however, increase the loading near the leading edge, and the change in relative position of the wing flow field will have a small effect on the fin pressures. The agreement between the two measurements is thus probably as good as could be expected but a specific comparison is clearly desirable.

4.3 Oscillatory derivative measurements in wind tunnels

For a review of possible model techniques for the extraction of aerodynamic derivatives the reader is referred elsewhere, for example to Bratt[46]. One specific technique only is discussed here. This is the method devised by Thompson and Fail[47] which has been as highly developed as any other, and in which the aim has been to produce a self-contained equipment not dependent upon the use of a special wind tunnel or model support. Measurements have been made in three wind tunnels, the ARA 9 ft × 8 ft Transonic Tunnel, the R.A.E. 13 ft × 9 ft Low Speed Tunnel and the 8 ft × 8 ft Tunnel, together covering a range of Mach numbers from zero to 2.8. Provided the geometry of the model support is suitable for the sting mounting used in the equipment, and is of adequate stiffness to avoid the development of undesirable modes of oscillation, there seems no reason why any tunnel of adequate size should not be used.

There are, however, restrictions on the acceptable model loading. Testing has been confined to slender aircraft shapes and for such shapes the maximum loadings are about 0.4 psi for longitudinal derivative measurements increasing to about 1.6 psi for lateral measurements for models of the same size as the supersonic transport model used in Fig.28. There is thus a restriction of either lift coefficient or Reynolds number for longitudinal derivatives.

Recent developments in the equipment have been described in Ref.47. In its present form five degrees of freedom (oscillations in the axial direction are not included) are covered in two stages, pitch-heave as one stage and roll-yaw-sideslip as the other. The technique is one of forced oscillation at the natural frequency of each mode, measurements being made of the amplitude and phase of the excitation force and moment and of the accelerations. The model inertias are derived by calibration. The equations of motion are then treated in either two or three degrees of freedom as appropriate, and the aerodynamic derivatives are determined as differences between results wind-on and wind-off.

The derivatives are defined with respect to earth-fixed axes in the mean position of the oscillating model, and are as follows (in the notation of Ref.47):-

Longitudinal

Stiffness	m_θ	m_z	
	z_θ	z_z	
Damping	$m_{\dot\theta}$	$m_{\dot z}$	
	$z_{\dot\theta}$	$z_{\dot z}$	

Lateral

Stiffness	n_ψ	n_y	n_φ
	y_ψ	y_y	y_φ
	ℓ_ψ	ℓ_y	ℓ_φ
Damping	$n_{\dot\psi}$	$n_{\dot y}$	$n_{\dot\varphi}$
	$y_{\dot\psi}$	$n_{\dot y}$	$n_{\dot\varphi}$
	$\ell_{\dot\psi}$	$\ell_{\dot y}$	$\ell_{\dot\varphi}$

The stiffness derivatives with respect to θ, ψ and φ are obtained as a by-product in the dynamic tests and can be checked against results from static testing. Additional checks can be made using $\dot y$ and $\dot z$ derivatives which are equivalent respectively to ψ and θ derivatives e.g. $\ell_\psi = -\ell_{\dot y} \cos \alpha$. Acceleration derivatives with respect to $\ddot y$ and $\ddot z$ cannot generally be determined with any accuracy. Unless a range of frequency of oscillation is studied, they cannot be distinguished from derivatives due to displacements y and z (which in principle are zero), and with some exceptions appear as very small changes in effective stiffness. The direct-damping derivatives,

$m_{\dot\theta}$, $n_{\dot\psi}$ and $\ell_{\dot\varphi}$, are relatively easy to measure, being determined by the change in excitation with and without airflow. The cross-damping derivatives are more difficult to obtain and show a fair amount of scatter. Examples for results of the important cross-damping derivatives $\ell_{\dot\psi}$ and $n_{\dot\varphi}$ are shown in Fig.33 for a model of the HP 115 slender-wing aircraft. Other cross-damping derivatives, $z_{\dot\theta}$, $y_{\dot\psi}$ and $y_{\dot\varphi}$, required for transferring to an axis origin other than that used for the measurements, show similar amounts of scatter.

As a further example of results obtained, values of ℓ_p, n_r and y_p for a model of the HP 115 are compared in Fig.34 with those deduced from analysis of the dutch roll oscillation of the aircraft[48]. The Reynolds number of the tunnel test based on mean chord is about 3 million compared with full-scale values of the order of 20 million. There is fair agreement in values of ℓ_p and y_p but gross disagreement in n_r. The flight values of n_r are dependent upon assumed values of n_p. A brief reanalysis of flight data at an incidence of about 13 degrees where the biggest disagreement occurs, using tunnel results for n_p, has been made. The results shown are in good agreement with the tunnel data*.

The natural extension to the extraction of oscillatory derivatives from model testing is the measurement of pressures and this is almost an essential pre-requisite to the establishment of satisfactory methods of prediction. Little experimental work has been done in this direction mainly because of the lack of suitable pressure-measuring devices. The work of Bergh[49] at N.L.R. offers a means of circumventing some of the difficulties and possibly opens up a new field in Loading Actions studies.

4.4 Rocket-launched models

The rocket-powered model may be regarded as being complementary to the wind-tunnel model. The advantages it offers are the absence of any modification to the model shape because of model support requirements, the absence of the wind tunnel constraint corrections and the ability to attain high Reynolds number. For models of typical size, chord Reynolds numbers in excess of 10 million can be obtained at supersonic and transonic speeds. The range of lift coefficients which can be obtained is, however, limited because

* Very recent work has shown a dependency upon frequency parameter of n_p measured in the tunnel. Further work is required to clarify the effect of this upon the comparison shown.

of the low wing loading inevitable on models. For similar structures wing loading will be proportional to scale size, though the model wing loading will be increased by using solid material where space permits. At a given lift coefficient the normal acceleration of a model compared with the full-scale aircraft will be given by

$$\frac{n_m}{n_a} = \frac{q_m}{q_a}\frac{\rho_a}{\rho_m}\frac{\ell_a}{\ell_m}$$

where subscripts a and m refer to aircraft and model, q is kinetic pressure, ρ density of model or aircraft and ℓ is length scale. At a given Mach number the kinetic pressure for the model will be greater than for the aircraft (because the model is flown at low altitude) and may be assumed to cancel any increased density of the model. Thus the normal acceleration of the model will be increased over that of the aircraft inversely as the scale. For a manoeuvring-type aircraft the model would be about one-twelfth scale. By flying models in a barrel roll, large normal accelerations can be maintained but the limits are about equivalent to level flight on the full-scale aircraft.

Derivatives are extracted from flight tests by analysing the decay of disturbances produced by 'bonkers'. The methods of analysis are discussed by Hamilton and Hufton[50], and by Turner[51].

Reference has already been made to Fig.9 which compares free-flight data for pitch damping derivative from Ref.33 on a slender-wing research model with unpublished data obtained by Thompson and Fail in two wind tunnels. The data are all at or near zero lift. The Reynolds number of the free-flight experiment is some four times that of the tunnel but no particular trend with Reynolds number is apparent. The data from the two tunnels have an unexplained disagreement which is roughly the same as the scatter band of the free-flight data. The tunnel data were measured about an axis some 12% root chord aft of that shown and the results quoted allow for this and so include some scatter from the measurement of normal force derivative.

4.5 Use of models as analogues

Free-fall models

The use of freely flying models as an analogue to complex motions which cannot easily be synthesised has been long established in the particular context of spinning. More recently there has been increased interest[53] in their application to other types of motion and in the extraction of derivatives from analysis of the motion. The aim of the work has been to study the handling problems of slender-wing aircraft at low speeds but it is worth considering whether a more direct contribution in the Loading Actions field might be made in respect of response characteristics.

For slender-wing models adequate Reynolds numbers can be obtained. Bisgood[53] shows that for dynamically similar models flown at the same height as the aircraft the ratio of model to full-scale Reynolds number is equal to the (model scale)$^{3/2}$. Taking as an example unpublished work by Bisgood on a quarter-scale model of the HP 115, a Reynolds number of about 3 million is obtained. Fig.35 shows that the motion of the model appropriately scaled agrees very closely with that of the full-scale aircraft. Static lateral derivatives are given in Fig.36 which also agree tolerably well with those for the aircraft[48] and from wind-tunnel tests[54].

Wind tunnel-flight dynamics simulator

An alternative approach to freely flying models is that proposed by Beecham, Walters and Partridge[55]. In this scheme a model is supported in a wind tunnel in a conventional manner and the static forces and moments so measured are used in conjunction with continuously computed gravitational, inertial and aerodynamic damping terms to solve the equations of motion for the three velocity components along the model axes. The velocity components are then used to control the tunnel speed and model incidence so that a continuous flight path may be generated. The accuracy of this type of simulation depends upon the significance of the damping terms and the accuracy to which they can be estimated and computed. The technique has so far been applied only in a small supersonic wind tunnel but could, in principle, be used in any size of tunnel so that the Reynolds number obtainable may be considered to be the same as for steady static testing as shown in Fig.28. Other uses for the simulator have been suggested such as the simulation of store release[56,57], in the determination of trim boundaries, where the problem is essentially static, but where, when motion in more than one plane is involved, analytical determination requires very extensive data and analysis.

Aeroelastic static tests

As suggested earlier, it is considered that aeroelastic static testing is likely to be more profitable as applied to component parts of an aircraft rather than to the aircraft as a whole. An example is the work of B.A.C., Filton on fin and rudder effectiveness. The model fin (Fig.37) is manufactured of light alloy spars covered with an etched light alloy skin stabilised by inserting preformed foam plastic blocks. Leading and trailing edges are made of balsa wood. The rudder hinge and jack stiffness is represented by machined flexures and the aft fuselage is made of a light alloy cone incorporating etched stringers covered with moulded plastic foam with a finishing surface of gelcoat.

The essence of the design is the bulking of the aircraft structure so that the stiffness can be represented by local spars in the model. The stiffness ratios are then at a given Mach number

$$\frac{(EI)_m}{(EI)_a} = \frac{q_m}{q_a}\left\{\frac{\ell_m}{\ell_a}\right\}^4$$

and the skin thickness ratio is

$$\frac{t_m}{t_a} = \frac{q_m}{q_a}\,\frac{\ell_m}{\ell_a} .$$

The stiffness of the rudder mounting scales as

$$\frac{r_m}{r_a} = \frac{q_m}{q_a}\left\{\frac{\ell_m}{\ell_a}\right\}^3 .$$

For the fin shown a ratio of $q_m/q_a = 0.8$ was chosen and for an assumed tunnel stagnation temperature of 35°C the range of tunnel conditions for full-scale loading simulation are shown in Fig.38. With a tunnel capable of being pressurised to two atmospheres a wide range of aircraft conditions can be simulated, in fact well beyond the design speed. At the lower speeds the results must be in some doubt because of the low Reynolds number - the stagnation pressure for fin chord Reynolds number of 2 million is shown. However, at the lower equivalent speeds, data can be compared with tests on rigid models at higher Reynolds numbers.

5 DISCUSSION AND CONCLUSIONS

There are clearly many aspects of the wide Aerodynamics field which may enter into the deliberations of the worker in the Loading Actions field and a good number have not been discussed herein. This is inevitable in a topic so wide that it could not possibly be brought within the scope of a short paper.

Perhaps more important is that in the preceding text we have tended to gloss over the fact that, as the Loading Actions calculation is oft-times concerned with some limiting flight condition, we shall go beyond the point where the aerodynamics are linear in form. For the slender-wing aircraft the aerodynamics are essentially non-linear over a wide range of incidence except where the attachment line lies along the leading edge. Generally, however, these non-linearities become important when a large incidence - angle of attack or sideslip, or both - is involved. To date the only available convenient formulation to cope with these more trying conditions has been the coefficient form of the forces and moments, which could be expressed as some function of the variables as determined by experiment. There has been no theoretical counterpart of this, but some work is in progress on problems of this nature.

Attempts have been made to provide methods which analyse flight data on the motions of aircraft - model or full-scale - on a non-linear basis.

However, within the framework of the more usual theory as outlined, much remains to be done.

From the few illustrative cases quoted, and the general background of knowledge contained within the various references given, it is concluded that:

(1) Though this paper omits many interesting applications of model techniques it is shown that, with the combination of the few standard techniques discussed, the essential Loading Action information can be obtained.

(2) There is scope for more direct application of both tunnel and free-flight model techniques to the manoeuvre part of the Loading Actions requirements.

(3) The measurement of dynamic pressures as an adjunct to dynamic derivatives is worthy of more attention than hitherto.

(4) There is a need for work on a broad basis on the experimental confirmation of loading calculations including the effects of distortion.

(5) The available methods (theoretical and semi-empirical) of predicting the forces and moments, although falling short of what is ideally needed, do provide a reasonable basis for early design work.

(6) More could probably be got out of the available theory by a more efficient harnessing of the computer to the problems, particularly those relating to interfering surfaces, e.g. wing-tail problems.

(7) Improvements in the basic lifting-surface theory and that for the flow with vortex sheets are likely and such basic progress should bring in its train developments in the more general manoeuvring case.

(8) A long-term aim must be the development of an integrated aerodynamic and structural analysis of the complete flying vehicle as a deformable body, making full use of modern computers.

(9) Some aspects of flight testing of full-scale aircraft have been touched on, but there is a self-evident case for more broadly based tests, to aid the Loading Actions procedure in particular cases and to give the ultimate check on the various stages of the prediction process. The scope and nature of such tests are considered in some detail in Refs.36 and 37.

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DISCUSSION

Mr. R. Hills, Aircraft Research Association stressed the point, mentioned in Mr. Thomas's written paper but not discussed by him, that Loading Actions calculations were often concerned with limiting flight conditions, which went beyond the region where the aerodynamics were linear in form. This meant that, if possible, calculations should be continued into regions where the flow was separated: some of Mr. Thomas's slides had shown that for slender wings something was being achieved in this respect. However, there was still a lot to be done particularly with regard to Mach number effects at high-subsonic and transonic Mach numbers. He thought that this stressed the importance of experimental methods of measuring loads.

Looking at this from the point of view of someone who ran a large wind tunnel, where a lot of work had been done for foreign customers as well as for British firms, he had found that foreign firms seemed to require a lot more pressure plotting on complete models than did the A.R.A.'s member firms in this country. He wondered whether the Loading Actions people had been pressing hard enough for data. Five years previously pressure plotting had involved laborious measuring of pressures on manometers, and results had taken a long time to work out. This was no longer the case. A complete model could have 400 to 500 pressure points and be tested right through the transonic speed range; results could be worked out, plotted and integrated all on the computer, to give detailed loads over the whole model. He suggested that this technique should really be used more in this country to cover regions, such as transonic speeds and high incidences, where the flows would tend to be separated.

Mr. Hills pointed out that one did have to be very careful in interpreting the results of wind-tunnel tests. Mr. Thomas had dealt in his written paper with the question of test Reynolds number and had suggested that if this were of the order of 2 million, based on wing chord, then one would generally get the same sort of wing flow as at full scale. Mr. Hills thought that recent evidence both in Britain and in America suggested that when shock waves were present there might be some quite appreciable differences between model results and what happened on the full-scale aircraft. It had been found that the shock waves might be further back on the latter which, in turn, would imply considerably greater rear loadings and hence, for swept wings, considerably larger torsions. Whilst it could normally be assumed that wind tunnels would give pessimistic answers as far as performance aspects were concerned, the same might not be true for loadings. Individual cases had to be looked at very carefully and in this, again, pressure distributions helped one in deciding whether they were applicable to full scale. He said that for $C_{L_{max}}$ there was a known scale effect at low speed and noted that Mr. Thomas had suggested that for determining this quantity one required a Reynolds number of about 6 million.

Mr. Hills said that this completed his comments, except that he would compliment Mr. Thomas on his achievement in dealing with a subject, which really required a book, in a very readable report and a lecture of 20 minutes.

Mr. H.C. Garner, National Physical Laboratory said that in his paper Mr. Thomas had referred to some work of his (Garner's) in which he had used specialised distributions of collocation points. He thought that he ought to make it clear that in fact this work did not use anything very special by way of collocation points. However, he had read recently a paper by van de Vooren which did so: a novel spanwise distribution of collocation points was used and this seemed to be particularly relevant to T-tails and, possibly, to swept-wing junctions. He thought this might prove to be quite important. (The reference to this paper is:- A.I. van de Vooren Some additions to lifting surface theory. Mathematisch Instituut Universiteit Groningen. Report TW-35.)

Mr. B.J. Beele, British Aircraft Corporation, Preston took up Mr. Hills's point about pressure-plotting models. He said that people in Britain were by no means averse to using them but pointed out that there was a great deal of expense involved in the production and testing of such models and a great deal of time involved in assimilating the results. Consequently, one had to compromise in several respects. The time when the information was needed was at a fairly early stage in the designing of an aircraft, which was the very time when least was known about its actual shape. Hence one had two alternatives: either one did testing at an early stage, on a model which one accepted would probably turn out to be unrepresentative, or one left it until very late on, by which time it would be rather late to incorporate the results into the design. He considered, therefore, that while pressure-plotting models were useful one also needed to have a method for modifying any pressures that had been measured on one configuration when one changed to another. Mr. Beele said that a further problem was that if pressure information was desired on wing, tailplane, and fin then the size of model was often prohibitive for a lot of the available tunnels.

Reverting to Mr. Thomas's statement that in many cases one could get quite reliable estimates of pressure distributions on wings, Mr. Beele recalled Mr. Hills's point that one was often concerned with regions where things were no longer linear and said that he would, himself, like to emphasise another point which they had come across quite recently. This was that, even in a linear region, the assumptions made by most theories about the behaviour at the leading edge became of importance if one had a leading edge slat, even though they might not matter very much as far as the wing as a whole was concerned. It was then crucial that one knew in detail the pressures around the very nose of the wing: if one was not able to make any reasonable assessment of these values then the loads predicted by theory would be wildly out.

Mr. Thomas said that he accepted all Mr. Beele's remarks and that he hoped he had not painted too rosy a picture. He had stressed that his remarks applied to the range of incidence where linearity could be assumed. It had always been a source of some amazement to him that in Loading Actions one did in fact get away with so much on this assumption because, since critical cases were being dealt with, it would have been reasonable to suppose that one would be knocking up against that limit all the time. He supposed that it was all hidden somewhere in 'that factor of 1.5'. He agreed that this type of problem furnished the reasons for continuing to work on such topics as thick wings as opposed to thin wings, the effect of large incidences as against small incidences and so forth.

Mr. C.H.E. Warren, Structures Department, R.A.E. said that Mr. Thomas's paper was concerned mainly with aerodynamic forces and loadings in steady and quasi-steady situations. There was also the very big problem of knowing the aerodynamic forces in transient and other unsteady conditions such as one met with gusts. It might be thought that in this situation one would be faced with the task of calculating directly the aerodynamic forces in these transient conditions. He said that he would like to bring to the attention of those present an alternative approach which they had been looking at. In the study of flutter they had had to amass a vast amount of aerodynamic information appropriate to the case of oscillatory motion and they now had very extensive programs for calculating the aerodynamics of wings of a large variety of geometries, for quite a wide range of Mach numbers, and over the highly relevant range of frequencies. As was well known, if the aerodynamics of a wing were known for various frequencies then, in theory, the powerful methods of the Fourier transform enabled one to derive the variation of the aerodynamics with time in a transient situation. Mr. Warren guessed that this might have been looked into in the past but that it would not have been a practical proposition because the aerodynamics had not been known for a sufficiently large range of frequencies: strictly, the Fourier transform method required this to extend from zero to infinity. He said that in recent work it had been possible to derive the aerodynamic forces that occurred in gusts by using the vast body of information available for oscillatory aerodynamics. In other words, the method did work in the cases at which they had looked - he thought that this might not be generally known.

FLIGHT AND GROUND LOAD MEASUREMENTS

by

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CONTENTS

1 INTRODUCTION

There is a good chance of some misunderstanding arising from the term 'load measurement'; on occasion it has merely meant the measurement of the acceleration at the centre of gravity. However, in this Paper, concerned mainly with structural interests, the expression is used in two ways. It can denote either the measurement of the net external loads, i.e. the algebraic sum of the aerodynamic and inertia loads, acting on a major component, in order to check that the loads used in the design calculations or applied to the static strength specimen are reasonably representative of the flight loads, or the measurement of the internal load distributions in the structure for the assessment of fatigue life. For the latter purpose it is necessary to establish the magnitudes and frequencies of occurrence of these internal loads and their associations with the environments expected during the operational life of the aircraft. In general this latter task can be done only by strain gauges attached to selected structural members. The alternative of measuring accelerations and aerodynamic pressure distributions would be precluded because the relevant loads in the members would be obtainable only via theoretical stressing analysis from the measured external loads. This would be a most formidable exercise involving the investigation of a multiplicity of flight conditions each of which may be significant at a particular point in the structure.

The interpretations of flight and ground strain measurements for these two purposes are discussed in this Paper.

2 INTERPRETATION OF THE STRAIN MEASUREMENTS

2.1 Design envelope conditions

The most widely used and successful technique for flight load measurement has been the statistical method[1] developed by the N.A.C.A.: although, until a few years ago, it had rarely been used in British experiments. The early attempts to utilise flight strain measurements involved the comparisons of the measured values with those either calculated in the stressing or measured at similar positions on a strength test specimen. The conversion of gauge responses into stresses involves assumptions of gauge sensitivity and modulus of elasticity and these quantities can vary about their mean values. The calculated stresses are usually subject to some simplifying assumptions and, as in the case of stresses measured on the test specimen, they will be known only for a limited number of design conditions which will not necessarily match the particular flight condition. The derivation of the overall load parameters - bending moment, torque and shear - at selected sections of the major structural components from the measured flight stresses introduces further inaccuracies from the uncertainties regarding the effective areas and moment areas associated with the stresses.

These difficulties are overcome by the use of a statistical method[1] which interprets the flight responses by means of a regression fitted to the response data of selected gauges obtained from a comprehensive calibration by a series of individual loads applied to the structure. The regression is applied to the distributed loading on the basis that the latter is a combination of individual loads each of which can be estimated by the regression. Thus the validity of the procedure requires the structure to conform with the principle of superposition. Theoretically the regression, which can be chosen to estimate bending moment, torque or shear, can be used over a limitless range of distributed loadings but in practice the accuracy of prediction will vary with the position of the centre of pressure. The standard error associated with the regression - that is the statistical error of the regression operating on the sample - is not reliable for indicating the error for the distributed load but, in general, acceptable accuracy, say 2 to 3%, is obtained on medium- to high-aspect-ratio structures. The procedure requires gauge installations that respond predominantly to each of the loading parameters - bending moment, torque and shear - and regression analysis is introduced because generally an installed gauge will respond to two or more of the parameters. Laboratory tests on a Lightning fin showed that the standard errors were unacceptably large for a multi-spar construction of low aspect ratio and the method was modified[2] by changing to a sample of distributed loadings with their appropriate response data. In this case the justification for using the regression is based on the flight loading being within the sample. The increase in accuracy is obtained by limiting the movement of the centre of pressure. The standard error then has some significance and can be used to estimate the reliability of the forecast of a flight loading. However, in the flight trials on the Lightning fin it was necessary to cater for comparatively large movements of the centre of pressure and the regressions were based on a mixed sample of distributed and individual load data. Figs.2 to 4 show the residuals of the forecasts by the regressions on each item of the sample shown in Fig.1. The use of the regression and the acceptance of the indicated accuracies would be justified by comparing the distribution of the flight responses with the appropriate member of the sample.

The particular exercise on the Lightning fin did not introduce any support problems - the calibration loads on the fin were reacted at the main undercarriages. However, it was necessary to obtain calibration response data for loads inboard of the measuring section. These data were included in the matrix with an associated zero input for the individual load sample and were automatically taken into account in the obtaining, by superposition, of the responses associated with the distributed loads. When the gauge responses are affected directly by the reactions at the supports it is necessary to obtain calibration data for loads acting anywhere on the structure. For any flight condition the distributed loads must be in equilibrium (i.e. the aerodynamic loads must equal the inertia loads) and the effects of the supports will vanish.

The relevant flight parameters - speed, altitude, accelerations, rates of pitch, roll and yaw, control surface positions etc.- must also be measured to identify the particular flight condition. In general it should be necessary only to investigate a limited number of flight conditions matching the critical modes of major structure failure and ideally it would be desirable to compare directly the flight loads with the unfactored loads of the structural strength test programme. However, this may not always be possible and the measured flight loads would be then used to establish confidence in the Loading Action calculations. The shortcomings arise from two sources. Firstly, it may be physically impossible to match flight and design conditions or it may be too hazardous to simulate an emergency condition specified for the aircraft. Secondly, there are difficulties from the choice of datum levels from which the gauge readings will be interpreted. Recordings taken at ground static conditions do not always correspond to zero load levels in the component and the estimation of the relevant ground loads introduces some uncertainty. In early stress investigations the use of the ground zero readings was very dubious because of the drifts of the gauges and recording equipment. Some improvement is effected by temperature-compensated systems such as half or whole bridge installations and further gains accure from the use of 'selective-melt' gauges whose temperature characteristics are matched with those of the structural material. An American technique establishes datum levels of zero stress in flight but it involves acceptance of the assumptions that 'zero-g and zero-q' conditions produce zero stress throughout the structure and that the corresponding gauge responses can be extrapolated from measurements taken during roller-coaster manoeuvres at various air speeds. Thus it is not uncommon to interpret only the incremental gauge responses from the 1 g level flight condition, it being assumed that the loading appropriate to this condition is known to reasonable accuracy. This does not entirely preclude the use of ground static levels when there is evidence of the stability of the instrumentation but the increments from these levels may then include thermal loads as well as the usual external loads. It is envisaged that the gauge installations will be internal and thus protected from any rapid changes of temperature but doubtless the guages would respond to any self-equilibrating loads induced by differential expansions of the structure. However, in the time scale of a manoeuvre or the sampling of flight in turbulence it is most unlikely that the 1 g level flight datum levels would change and thus there are many advantages to be gained from the use of incremental strains (from level flight zeros) for the estimation of the aerodynamic and inertial loads.

When the thermal loads are important in the structural clearance of the aircraft it is probably more accurate to measure the thermal loading action directly by means of temperature measurements rather than by strain measurements. The stress distributions could then be investigated in suitable laboratory simulation tests.

2.2 Fatigue life substantiation

The above methods can supply the time histories of the bending moments, torques and shears at selected sections to a reasonable accuracy but this knowledge may be of little assistance for fatigue studies. A successful assessment of fatigue life will depend on the identification of those regions where local damage may occur and initiate a major structural failure. The damage could arise from the fluctuating stresses induced by local or remote external loads and the detail design of the structure can be a dominant factor. The magnitudes of the local stresses and the relative frequencies of occurrence are both important and, because there is no reason to expect the local stresses to maximise throughout the structure at the same instant of time in any loading action, the processing of the time histories of the overall loads to provide the local load data would be an impossible task.

It would also appear to be unprofitable to attempt to measure the local stresses for a direct fatigue life assessment from an appropriate S-N curve. If the physical difficulty, or often impossibility, of installing a gauge at the significant position is ignored, there would be inaccuracies from the averaging of the strain over the area of the gauge and from the variations in gauge sensitivity and Young's modulus. Another method would be to measure the local load adjacent to the stress concentration but, additional to the possibility of the errors previously mentioned, this implies a knowledge of the effective area to be associated with the measured strain and also a reasonably uniform uni-axial stress distribution. This latter condition is only to be found some distance from the stress concentration but, if existing, it would allow multi-gauge installations which would maximise the bridge output from the gauge station and improve the temperature compensation.

Many investigators, such as Rhyne and Murrow[3], used the response from a steady symmetric manoeuvre for the interpretation of the gauge responses from flight through turbulent air. This procedure allows the comparison of the root mean square (rms) of the centre of gravity accelerations with the rms of equivalent accelerations at each gauge station. These comparisons then indicate the degrees of amplification arising from the dynamic response of the aircraft to the disturbances and, for a large flexible aircraft, the amplifications of bending strain varied from about 1.1 at the root to about 2.0 at the midspan of the wing. The internal loads induced by the steady manoeuvre can be estimated by normal stressing procedures and the flight responses can then be converted into loads. The overall accuracy depends on a knowledge of the aerodynamic and inertia loads of the manoeuvre and on the accuracy of the stressing calculations. Nevertheless the derived fluctuating loads and some appropriate detail tests may be satisfactory for the analytical assessment of the endurance of the structure. Some guidance, based on technical appraisal or practical experience, is required on whether the local chordwise and/or spanwise loads attributable to shears and/or bending moments should be measured. In general the 'known' distribution of the external loads of the manoeuvre would not be suitable for direct application to a complete structural test specimen and major modifications to the distribution might be necessary to ensure that the various regions were adequately tested during the fatigue test.

The previous interpretations have not necessitated the load calibration of the structure. When this has been done the gauge installations, preferably fully active bridges responding to shear or bending moment, would provide measurements of the internal loads at a number of stations in the structure. The procedure would not necessitate the interpretation of the gauge responses as either stress or local loads. The gauge responses and cg accelerations would be recorded as continuous traces under manoeuvre and turbulent flight conditions at selected speeds, altitudes and weights consistent with the flight plan of the operational aircraft. The severity of the turbulence or manoeuvre in these samples would be assessed from the cg accelerations and thus related to the average expectations implicit in the flight plan. The continuous trace records at each station would be analysed by the counting method most appropriate to fatigue considerations and then extrapolated to the average flight plan by the relationships obtained from the cg acceleration data. Thus at every station gauge response spectra for manoeuvre and turbulence conditions can be assembled. In general these spectra will vary throughout the structure, especially when the dynamic response is significant. In the conventional fatigue test the continuous distributions of magnitude and frequency of occurrence are represented by a limited number of loads whose magnitudes and frequencies of application are selected to produce equivalent fatigue damage. The particular load distributions to satisfy these conditions could be obtained by an iterative procedure using superposed calibration data. In some cases it may be sufficiently accurate to dispense with the calibration of the flight aircraft and use the responses of similar gauge installations in a test specimen under the test loadings.

It is tacit in the method that there will be an accompanying full-scale fatigue test and that there will be a little significant error in accepting the interpolated conditions for the remainder of the structure from the conditions obtained at the point of measurement. As the structural design becomes more redundant and the dynamic response more complex, there may be a need to monitor chordwise as well as spanwise loads. If the fatigue life of a particular component is governed by both chordwise and spanwise fluctuating loads or by the combined action of fluctuating shear and direct loads, the phasing of the various loads becomes important. The flight installations would of necessity become more specific and detailed. This could be undertaken but naturally it would not overcome the severe problems then inherent in the fatigue test.

2.3 Undercarriage clearance

The gauge installations outlined above could be used for general structural load measurements under landing and ground manoeuvring conditions. There still remains, however, the need to establish the structural integrity of the undercarriage. The landing cases have always been difficult to investigate experimentally - partly because pilots are reluctant to land at vertical velocities near the specified value and partly because of the problems of measurement.

Despite the apparent simplicity of the average undercarriage structure the measurement of the three load parameters - vertical load V, drag load D and side load S - presents many formidable problems, especially for the landing conditions. The three loads do not act through a common point: the vertical load acts through the hub, the side load through the point of tyre contact and the drag load through the hub or the point of tyre contact according to whether the load is from spin-up or from an application of the brakes. In many practical cases the side and drag loads are deduced from bending strain measurements and thus the geometry of the undercarriage, which changes under the action of the various loads, and the attitude of the aircraft relative to the ground must be known before a reliable estimate can be made of the ground loads. The system behaves in a non-linear fashion because of damping and generally at least two of the load parameters use the same load path. The time history of the drag load is dependent on the horizontal speed and the local conditions of friction whereas that of the vertical load depends on the rate of vertical descent and the characteristics of the shock absorber system. Thus the two loads will not usually maximise at the same or related times after touch-down, and the processing of any practical measurements can be most complicated. However, it should be satisfactory to achieve reasonable accuracy only at the maximum load conditions and the appropriate geometries would then be needed for a very limited number of conditions.

The procedure adopted in previous investigations has been to select the more promising positions for the strain gauges and then to calibrate the system for various geometries by the separate application of static loads V, D and S at their appropriate positions. If reference axes in the undercarriage are adopted the calibrations must include moments about the chosen axes as well as loads along them. There is a consequential need for additional gauge stations to cater for the moment determination but some advantage accrues because the need to measure the attitude of the aircraft vanishes. However, this latter measurement is still required if the ground loads are to be established. In some experiments the undercarriage components have been individually calibrated and the relationships between the various parameters and the gauge responses are based on the geometry of the assembly. The use of separate loads or calibrated components can mask significant interaction effects: for example the estimate of a drag load from a bending strain may be inaccurate because of the added bending moment induced by a vertical load acting on a structure deflected by the drag load. For such reasons and to allay doubts that the static calibration procedure can cater adequately for dynamic conditions it is recommended that the accuracies of estimation should be checked with gauge response data obtained from drop tests of the undercarriage on a calibrated platform which provides independent measurements of V, D and S.

It is evident from the preceding discussions that the processing of the data could be most time-consuming, and as an alternative it might be expedient to introduce statistical methods and to establish relationships between the load parameters and the gauge responses by regression analysis. The sample data could be obtained in one of the following ways:

(a) from a series of drop tests on a calibrated platform in which drag and side load conditions would be simulated by pre-rotation and moving platform techniques (the wedge technique would be unsatisfactory because it produces drag or side loads which are directly correlated with the vertical load throughout the impact cycle);

(b) from a number of static calibrations in which various combinations of V, D and S are applied to an undercarriage;

(c) from the superposition of response data obtained from component calibrations and a knowledge of the geometries of the undercarriage.

It would be most convenient if the regressions could be used universally but it is more likely that acceptable accuracies will be obtained only for a limited range of geometry. Thus samples to match particular ranges would be required.

The preceding discussion has been written with the single- or twin-wheel undercarriage in mind. For these the selection of the critical conditions from the time histories of the load parameters should not be unduly difficult. In the case of bogie undercarriages, either the front or rear wheels contact the ground initially and the bogie beam rotation is controlled by a shock absorber until eventually the other wheels impact with the ground. Thus, in general, the critical ground loads will be deduced from the time histories of three loads and three moments at each end of the beam and from the shock absorber load. A further complication will arise from the fairly large changes in geometry. The loads from ground manoeuvring should be easier to determine because the rates of changes of the loads and of the geometries will not be so high.

With uncertainties regarding the positions of likely fatigue failure similar to those discussed in Section 2.1 it is evident that the fatigue life substantiation of an undercarriage must be based on local strain measurements under typical operating conditions rather than by the inspection of overall load measurements.

3 CONCLUSIONS

The interpretational problems of flight and ground strain measurements in the interests of structural integrity have been discussed for design envelope conditions and for fatigue life assessment. The latter presents the greater difficulties because there is an increased number of modes of structural failure and these are dictated by the frequencies of occurrence as well as the magnitudes of the local loads. It is suggested that for fatigue life substantiation the local internal loads in the structure should be monitored for a sample of operational conditions by suitable gauge installations. The validity of the associated fatigue test can then be established by comparing the gauge responses for the test loadings with those estimated to produce fatigue damage equivalent to that produced by the spectra of gauge responses assembled from the flight data and the operational data for the typical aircraft. The responses for the test loadings may be obtained directly from similar gauge installations in the test specimen or from superposed data obtained during a calibration of the flight aircraft. With systematic arrangements of gauges at sections of the main components the calibration data can be used either directly or by superposition as distributed loadings to supply regressions for the estimation of the overall loads acting on the components.

The measurement of undercarriage loads introduces many formidable problems and it is unlikely that these programmes will be as successful as measurements to establish the integrity of the other major structural components.

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OPERATIONAL RESEARCH ON LOADING ACTIONS

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CONTENTS

1 INTRODUCTION

Design requirements for aircraft have developed largely as a result of theory, experiment and experience of operational reliability. Loads may be predicted by theoretical methods, working to an error of, typically, less than 1%, or determined by experiments which can be in error by less than 10%; operational loads are, however, seldom known to such accuracies. It may be considered that the main purpose of operational research is to increase the efficiency of aircraft design and usage by providing a more accurate model of the aircraft environment and behaviour. Inevitable by-products are improved design requirements and reduced accident risk.

With current operational research techniques, cost and available man-power usually limit general operational research studies on any one aircraft type to about 10000 flying hours. Nevertheless, when specialised techniques or instruments are developed, studies of one aspect of operational research can be made on a larger scale at an acceptable cost.

The small sample of flight experience normally available is not a serious limitation when fatigue damage is the design problem, and valid quantitative information can be produced; when ultimate strength and accident risk design requirements are being studied, the sample is so small that quantitative estimates lean heavily on extrapolation of data. Then defect experience must be used to assess the numerical values to be inserted in the requirements but operational research may still shew that the form in which the design requirement is drafted has a poor correlation with the physical phenomena which create the requirement.

It is seldom possible to design operational equipment which measures significant parameters directly, as simplicity and reliability of instrumentation is an overriding consideration. Therefore, operational parameters should be measured with similar instrumentation during experimental flying and correlated with the comprehensive measurements made during the experimental flight programme.

Operational research to aid Structural and Aerodynamic Design probably began with the V-g recorder. This instrument measured extreme aircraft accelerations and associated speeds, thus providing information for symmetric manoeuvre and gust strength requirements. The need for fatigue loading information led to the development of V-g-h continuous trace recorders in the U.S.A. Subsequently, Counting Accelerometers and Fatigue Load Meters were developed in the U.K. to provide operational information on symmetric loads and gust velocities; current work is producing operational evidence of the reduction in structural loads due to the use of storm-warning radar and is monitoring the usage of fatigue life. Information from Fatigue Load Meters is to be presented to aircrew in flight to assist them in developing techniques for conserving fatigue life.

The Civil Aircraft Airworthiness Data Recording Programme was initiated in 1962 with the purpose of obtaining a wider understanding of operating procedures in civil airlines and their relation to design requirements by the use of continuous trace recording.

2 CIVIL AIRCRAFT AIRWORTHINESS DATA RECORDING PROGRAMME

This is a co-operative programme involving the A.R.B., B.O.A.C., B.E.A., Aero and Structures Departments, R.A.E. Speed, acceleration, height, control-surface movements, aircraft attitude and a number of auxiliary signals are recorded on photographic paper for subsequent study and numerical analysis. Super VC 10 and Trident aircraft are currently fitted with recorders; recording on Boeing 707 and Comet 4 aircraft is nearing completion. Records are being obtained at a rate of about 10000 flying hours per year: about 50000 hours have already been obtained.

CAADRP records provide a valuable new source of information on the nature of problems that are met in airline service, which can become a guide to future experimental and theoretical research. In particular, new information is being obtained on the reasons for severe loading due to gusts, manoeuvres, landing impact and high-speed taxying.

The data recorded include vast quantities of information in a form which is expensive to analyse and the prime difficulty in running the programme is to decide which aircraft operating characteristics should be studied with the limited resources available. All flight records are inspected by staff of degree standard with a wide range of background experience, e.g. A.R.B., Airline, Aerodynamics, Structures. The objective of this inspection is the development of a mental picture of the normal characteristics of the trace records and then to select, for subsequent analysis, all periods of flight which appear abnormal. It will be appreciated that this form of activity is not amenable to computer programming except when simple events, e.g. a large gust or excessive speed, are detected. These abnormal periods of flight have provided the main guidance for directing the effort spent on analysis but assistance from aircraft and equipment manufacturers, pilots and accidents investigators is needed.

A wide range of special studies is being made. These include cockpit acceleration levels; elevator, aileron and flap operation; take-off, descent and landing procedures including auto-flare trials; observance of placard speed limitations and emergency descent procedures. Turbulence and undercarriage performance investigations are of particular interest to Structures Department but most investigations have some Loading Actions implications. It is hoped that further studies of control surface movement may lead to improved design requirements for check manoeuvres and asymmetric manoeuvres.

2.1 Turbulence investigations

Gust frequency and fatigue damage caused by turbulence cannot be derived economically from CAADRP records and they continue to be recorded by counting accelerometers and fatigue load meters. Attention has been directed to a study of the behaviour of aircraft in severe turbulence of the type met about once per 100 to 1000 hours. Figs.1, 2 and 3 are examples of records obtained in operational encounters with turbulence. The original records shew more detailed information than can be reproduced.

Current design requirements are based on the assumption that turbulence consists of discrete gusts and there is an interest in replacing this by a power spectrum of turbulence. A study of 3284 hours flying by Comet and Boeing 707 has shewn that the extreme accelerations are met in turbulence with power-spectral characteristics but that extreme values are about 30% larger than predicted by a Rayleigh distribution; whether this is due to the atmosphere, pilot or aircraft cannot be resolved from the records.

Fig.1 illustrates a prolonged encounter with turbulence of an intensity such that significant fatigue damage will be produced but there will be a negligible risk of achieving a static design load. The steady airspeed and the limited elevator activity shew that both pilot and aircraft functioned efficiently but that speed was not reduced to the rough air speed.

Fig.2 is a record of the most severe clear air turbulence event recorded in 50000 hours. A 150 knot jet stream was encountered over the Atlantic at night. The root mean square acceleration is about 0.23g (13 ft/sec equivalent gust velocity). Two peaks of -0.8g and -0.85g (46 and 49 ft/sec equivalent gust velocities) occurred. On the assumption that acceleration followed a Rayleigh distribution, peaks of 0.65g would have been expected: the probability of the recorded peaks being achieved would be only about 1%. The aircraft did not reduce speed to the rough air speed. The elevator oscillations with a period of about 30 seconds indicate that there was some difficulty in maintaining constant pitch attitude.

Fig.3 illustrates a typical encounter with severe turbulence, over Borneo, with a duration of 15 seconds. The peak acceleration was -0.95g (67 ft/sec equivalent gust velocity) and airspeed was reduced only after the event. The aileron activity is considerable and it is probable that the autopilot was in height lock and heading modes at the time of the incident.

Severe turbulence appears to be of short duration, mostly between $\frac{1}{4}$ and 2 minutes. Speed was reduced during only 9 of the 24 severe turbulence events so far recorded. Further work is needed on a larger sample of flying, perhaps using Mandatory Flight Recorders. Records from VC 10 and Trident aircraft include pitch and roll attitude traces; these will produce more information on the causes of the extreme values.

2.2 Landing and undercarriage performance

Undercarriage design is dominated by a design requirement to meet a specified rate of descent onto a smooth runway with the aircraft weight supported by wing lift; it is also required that the rebound energy shall not be more than 33% of the descent energy. This encourages undercarriage designers to produce systems with low damping and CAADRP records shew that multiple bounces occur on most landings; also, heaving and pitching oscillations occur during high-speed taxying. Theoretical research on undercarriage damping is being co-ordinated with operational information with the aim of specifying new requirements. These will represent real conditions more accurately and influence designers to provide more damping. This should lead to considerably smaller vertical load fluctuations on tyre and undercarriage and may lead to an alleviation of the loads causing fatigue damage.

B.L.E.U. are actively co-operating with CAADRP and the A.O.R.B. to aid in certification of the auto-flare facilities on Trident aircraft. This work includes a comprehensive study of manual landing procedures as operational knowledge is required for comparison with the safety standards achieved with auto-flare.

2.3 Manoeuvres and handling characteristics

Autopilots appear far from satisfactory when flying in turbulence and it is now common to insist on manual flight through turbulence, partly to assist in crew training. It is clear that both pilots and autopilots increase fatigue damage rates and that considerable improvement in fatigue life could be obtained with autopilots or blind-flying instruments capable of producing stable flight paths. Aircraft systems frequently oscillate in pitch at a frequency of 10 to 30 seconds per cycle in instrument flight conditions and on autopilot in the height lock mode. These oscillations are of such small amplitude that they produce negligible fatigue damage in still air but, when they are combined with mild turbulence, the increase in fatigue life consumption is significant. Fig.4 is a record of a severe form of this behaviour during approach on a glide path. The oscillation has an amplitude of 0.2g and a period of 20 seconds, which indicate an oscillation in rate of descent with an amplitude of 1200 ft/minute.

As the period of the oscillations does not correspond to known aerodynamic characteristics of the aircraft it may be profitable to expend more effort in studying the handling properties of aircraft in instrument flight conditions. It seems likely that these oscillations may only be reproduced in experimental flight conditions if the operational attitude to maintenance of prescribed altitude and airspeed is simulated by the test pilot.

3 MANDATORY FLIGHT RECORDERS

Mandatory Flight Recorders are now carried on all large British civil aircraft and provide records of height, speed, normal acceleration, pitch attitude and heading up to the time of an accident. It is fortunate that Airline Management decided to purchase recorders suitable for operational research as well as accident investigation. As a result many of the recorders have a considerably higher accuracy and recording capacity than specified in the mandatory requirements. The value of this was demonstrated in the Vanguard accident inquiry.

Operational research with Mandatory Flight Recorders is likely to be of considerable value in the future as it promises to provide information on the character of rare events which define the strength requirements of aircraft. A case can already be made for using them with slight modification to obtain more information on turbulence and landing loads. When considering many other strength or safety requirements no automatic method of identifying relevant data is known; further work with CAADRP and accident investigations may lead to a solution of this problem.

Mandatory Flight Recorder information from accidents and major incidents is likely to appear frequently in the future from civil and military aircraft. It is probable that a significant proportion of all accidents could be prevented by a study of alarming incidents which may precede an accident. These incidents may erroneously be attributed by the crew to turbulence, action of a crew member or aircraft malfunction, but expert study of Mandatory Flight Records would lead to more accurate diagnosis. Identification of these incidents seems impossible except with the aid of a pilot reporting procedure.

4 CONCLUSIONS

Operational research information from civil aircraft is being collected at a rate of 10000 flying hours per year by use of continuous trace photographic recording. Therefore, the nature of loading actions which occur less frequently than once in 10000 hours is not known. Loading actions, if based on these data, therefore presuppose that the structural accident risk is produced by more severe forms of the events already discovered.

Progress has been made in understanding the loading actions produced by turbulence, manoeuvres, landing and high-speed taxying.

Loading actions defining the strength of an aircraft are based on events which occur once in 1 000 000 or more hours. Mandatory Flight Recorders are already recording data on an appropriate scale but the data are destroyed 30 days after being recorded. Thus accurate information on loading actions is now within reach if data retrieval can be organised at a reasonable cost.

As improved knowledge on operational loading actions becomes available new methods of alleviating the loads by improved design, operation and maintenance procedures emerge and can lead to improved safety or reduced structure weight.

DISCUSSION

Mr. R.M. Hare, Hawker Siddeley Aviation, Hatfield first congratulated the speakers on their papers. He said that it could be seen that a lot of valuable work was being done on the measurement of loads on aircraft. Much of this was obviously fraught with difficulties, one of which was that when measurements were taken one had to decide how well they could be extrapolated to design conditions.

He considered that the tasks confronting a structural engineer could be divided into three categories. Firstly there were those related to the stiffness characteristics, secondly those related to static strength conditions, and thirdly those related to fatigue behaviour. In each category one could regard the work as the balancing of two sides of an equation. The right-hand side dealt with the properties of the materials used, the calculation of the load distribution in the structure, the derivation of the stresses resulting from these loads, and the calculation of the allowable stresses. He said that this right-hand side seemed fairly well understood since in addition to the large amount of theoretical knowledge available there was a wealth of experience in dealing with structures - it was possible to carry out experiments relatively easily and there was already a large accumulation of test evidence. Thus this was a reasonably satisfactory state of affairs. The left-hand side dealt more particularly with the environmental conditions which were set up by the various design requirements: it was in this field, where data were often lacking, that the measurements referred to by the speakers would help to produce less vagueness. His first question, therefore, would be "Do you think that enough effort is being spent at the moment in producing the evidence which is required to check the validity of the design conditions?" If the answer was that there was enough then he would also ask "Are the present design conditions satisfactory or would you like to see any changes?"

Mr. Hare said that in designing an aircraft there were varying amounts of effort applied to the various portions of the structure and that in the past much of this had been applied to such main items as the wing and fuselage, largely because the weight of these items was a large percentage of the total structural weight. However, with high-lift devices such as slats and flaps and particularly with the heavy components one now had at the rear of an aeroplane - all of these items constituting large, dense pieces of structure - the percentage of the total structural weight concentrated in the main wing box was becoming a much smaller one than it used to be. Therefore his last question would be "Is enough of the effort which is being applied to load measurements being directed towards the greatest unknowns?"

Mr. J.C. Chaplin, Air Registration Board said that he would like to comment on Mr. Sturgeon's paper in particular. Mr. Sturgeon had shown three slides relating to flight in turbulence and on two of these he had shown some large peaks in g which were not part of the general family. Mr. Chaplin had noticed that all these were negative peaks and he wondered whether this was fortuitous or whether there was some significance in this fact. He had the impression that there was a tendency for the large peaks in g to be negative ones rather than positive ones and he wondered whether there was any evidence on this point. Also, the slides emphasised the difference between the discrete gust approach and the power-spectral approach and made it clear that the term 'discrete gust approach' was a misnomer since this approach was really based on the acceleration history of the aircraft and might not say much about the atmosphere, whereas the power-spectral approach was based entirely on the atmosphere and did not say much about what the aeroplane-pilot combination did. This point was made clear to him, when looking at these records, by the movement of the elevator which clearly showed that the pilot was playing an important part in producing some of the peaks. Here, perhaps for the first time, it would be possible to build up a comparison of the two approaches and perhaps to begin to understand how to combine them. Mr. Chaplin said that he would also like to comment that although Mr. Sturgeon had stated that the pilot did not change the airspeed the records showed, nevertheless, considerable fluctuations in airspeed and so one wondered whether some account should be taken of this when considering the strength of an aeroplane in turbulent conditions.

A final point was that Mr. Sturgeon's fourth slide had shown movements of the elevator and of the ailerons, combined in some phasing or other, associated with very big fluctuations in normal acceleration. Various speakers had mentioned the need for work on control surface usage and Mr. Chaplin queried whether it was not this sort of record which gave the type of evidence needed to commence such work.

Mr. P.F. Richards, Air Registration Board said that he would like to direct two questions to Mr. Hovell. It seemed extremely desirable that in making flight load measurements one should manoeuvre to limit load conditions. One did, however, get a firm impression that pilots were not prepared to do this, and one could certainly sympathise with them. Therefore it would help to know to what extent one could extrapolate from a manoeuvre of reasonably low severity to limit load conditions and he would ask if Mr. Hovell could give any idea of this, taking into account the possibility that one was not able to make the extrapolation in a linear fashion because of distortion effects and so forth. Also, Mr. Hovell had not mentioned other methods of recording information, in particular pressure plotting, nor the possibility of measuring distortions by optical means. Mr. Richards invited him to comment on these.

Mr. B.J. Beele, British Aircraft Corporation, Preston had three questions to put to Mr. Hovell. The first, which was purely for interest's sake, was concerned with some illustrations which showed the Lightning fin with centre of pressure positions well ahead of the actual fin; would Mr. Hovell like to comment on the practical significance of these cp positions? The second query was that, while in his paper he had mentioned that it was important in certain cases to consider loads applied inboard of a gauge station it was not clear how this sort of approach could be used on an aircraft such as Concord where it was presumably difficult to distinguish between the contributions of the fuselage and of the wing. Also, he asked what sort of accuracy Mr. Hovell would expect and what degree of calibration he would have to do for an aircraft of this type. Mr. Beele said that in his third question he was following the lead of the Chairman in inviting comment on the cost effectiveness of the flight measurements proposed, particularly as regards fatigue. An additional point was that he noticed that the records reproduced in Mr. Sturgeon's paper were entirely analogue ones. He presumed that the degree of analysis required on such records must verge on the prohibitive if one wished to investigate a large number of aircraft. Mr. Beele asked if there was a proposal to replace this by digital recording and let machines compile the data.

Mr. Sturgeon referred to Mr. Chaplin's first point that the high peaks in g were all negative ones. He stated that it was known from counting accelerometer records that, at the higher levels, positive peaks were slightly more common than negative peaks but it was clear from CAADRP records that at least half of these positive peaks were due almost entirely to events which were incontrovertibly manoeuvres, i.e. events lasting for 2 or 3 seconds. Therefore there was, in fact, some possibility that in heavy turbulence negative peaks were more common than positive ones and he would suggest, in contradiction to one of the morning's speakers, that this might be due to a belief of the pilot that when he was in turbulence it was safer to apply a lot of negative g than a lot of positive g. Thus he might tend to push his elevator control forward sharply when he was alarmed whereas he might be very doubtful about the safety of severe backward movements. Mr. Sturgeon said that this was speculation, and he would say that in general there was a reasonable number of positive peaks occurring in severely turbulent conditions. Admittedly, the worst peak of all he had shown - equivalent to a 67 ft/sec gust - was a negative one.

Mr. Sturgeon said that the problem of changing requirements to fit in with the knowledge that was gained from operational records continually taxed resources and mental capacity. It was found that real events did not fit the requirements very easily, but one had to remember that operational research, at least in this country, had only begun on its present scale about four years ago. Certainly, he said, he felt a beginner compared with many of the experts who had talked on related subjects and who could perhaps refer back to many years of experience helping them with their activities. Control surface usage was of vital interest and information on this was being gained: the difficulty was to program a measuring process which would give useful information. This related to Mr. Beele's question on digital versus analogue recording since if one knew, in a qualitative sense, exactly what it was desired to discover then one should have digital records and employ a computer to do the quantitative work. However, from the very small sample of data that had been presented in the slides it could be seen that if a computer were programmed to find out from operational data the numerical values which should be inserted in existing design requirements one could be led severely astray. This was a very serious difficulty. Referring to control surface usage, he said it was clear on the fourth slide that there was some form of mild oscillation of a servo-loop, which almost certainly included the pilot but of which the other parts were not known, since it could not be said with any confidence which instruments were dominating the pilot's actions when he was descending in that particular manner. He said that, even so, some information on control surface usage had been derived for a Boeing 707 and it was hoped to extend the methods used, when they had been further developed, to all the aircraft on which data had been obtained.

Mr. Hovell, answering Mr. Hare's point on whether enough effort had been spent on checking the validity of the design conditions, said that he liked to think that the flight load measurements and the operational data recording system were somewhat complementary in that for the interpretation of the one the other was needed. He did not think that anything could be done in the way of modifying design conditions until flight load measurements were started: at the moment they were possibly the best guesses that could be made and had been modified after each accident or incident. For this reason he would duck the question as to whether they were satisfactory. As regards the direction of enough effort to the greatest unknowns, he said that Structures Department, R.A.E. would favour a mandatory requirement for flight load measurements which followed the methods in use in the U.S.A. where they required measurements of bending moment, torque and shear force at a number of wing stations and a number of fuselage stations, tail loads, fin loads, etc. He thought that out of these programmes would come attention to the greatest unknowns because these would surely be where the differences between the measured loads and the estimated loads were greatest. On Mr. Richards's question of extrapolation to limit load conditions, Mr. Hovell said he understood that in the U.S.A. aircraft were flown to limit load conditions and that the loads measured at these conditions were applied to their strength test specimens. He said that the question of pressure plotting versus strain measurement was a perennial battle that Structures Department had fought from its point of view; his own opinion was that structural loads were the quantities with which they were concerned, although they did arise from aerodynamic and inertial loads. The trouble with pressure plotting seemed to be that in order to get a reasonably accurate measurement of overall load a large number of measuring points was necessary. One was then forced to a multiplexing type of instrumentation which then limited one to investigating quasi-steady conditions and not the transient ones which might be of importance in the design. Mr. Hovell thought that the measurement of distortions was a more or less immediate consequence of a decision to adopt pressure plotting since any discrepancies between pressures measured in flight and in a wind tunnel had to be explained and the most convenient explanation lay in the differences in stiffness between the aircraft and the model. Answering Mr. Beele's question about the centre of pressure lying off the fin, Mr. Hovell referred to his Fig.1 in which was seen a cluster of positions on the fin which corresponded to somewhat mistaken ideas of where the centre of pressure would be in the flight trials, which were essentially for measuring fin loads in formation flying. However, that flight programme was preceded by a series of manoeuvres and steady sideslips wherein the centres of pressure did lie off the fin. He would not say that any of the measured centres of pressure were at points 1, 4 or 7, or 2, 5 or 8 but these were included in the statistical sample just in case they occurred in the programme. As regards inboard loads, Mr. Hovell said that these produced gauge responses and therefore had to be taken into account in the interpretation of the total responses. The statistical method as described would determine the total loads outboard of the chosen section. Mr. Hovell felt that he would leave the question of cost effectiveness, which was a political one as well as an economic one, to others.

ASYMMETRIC MANOEUVRES OF HIGH-SPEED AIRCRAFT

by

G. D. Sellers

(British Aircraft Corporation (Operating) Ltd., Filton Division)

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1 INTRODUCTION

Airworthiness codes specify a number of circumstances (flight manoeuvre, gust and ground conditions) for which the structure shall have minimum properties. For flight manoeuvre cases these circumstances may be specified in terms of pilot's action, control surface movements or in terms of the overall motion of the aircraft.

From a knowledge of the aerodynamic derivatives and of the characteristics of the control systems, calculations must be carried out to establish the response of the aeroplane in sufficient detail so that, at the critical times, the various parameters affecting the loading are known. These include angles of attack, control angles, rates of motion, acceleration factors etc. These data, together with appropriate pressure distributions and mass distributions, provide the basis on which sets of external design loads are obtained for the various components of the structure.

In this Paper an attempt is made to indicate some of the features which have led to developments in the manoeuvre load requirements following the introduction of modern high-speed aeroplane configurations.

2 EXISTING REQUIREMENTS

The provisions of existing published structural requirements (Av. P. 970, B.C.A.R.) for pilot-initiated manoeuvres are briefly outlined in Fig.1. The pilot's action is given in general as a control movement of the elevator, aileron, or rudder - each on its own - and the calculation of the behaviour of the aeroplane requires not more than two degrees of freedom. The control angles may be limited by any of the following:-

(a) maximum pilot effort

(b) control stops

and (c) maximum hinge moment provided by a servo-control jack.

The pitching case used to ask for consideration of loads to balance a pitching acceleration given in terms of aeroplane speed and maximum normal acceleration factor; in fact F.A.R. 25 is still in this form. British civil and military codes now give the elevator action to be considered and the control displacement is limited to keep the normal acceleration in the manoeuvre to the design value of n_1. The design value of n_1 is obtained

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For the asymmetric manoeuvres the situation is rather different; there is less information regarding the manner in which ailerons and rudder are used, particularly in emergency. There is no natural pilot deterrent like 'g' and the airworthiness requirements cannot so readily provide a limit to the results of the pilot action as in the case of symmetric manoeuvres.

For the rolling cases current rules prescribe either an aileron angle or a rate of roll for each of two conditions, acceleration in roll or steady rate of roll. These give incremental loads which are added to those from a symmetric manoeuvring condition.

In the yawing cases a rudder application is specified - the civil requirement defining three particular cases during the manoeuvre and the military requirement defining the rudder action only - and the design cases are selected from a study of the resulting response. Pilot recovery action following engine cut also needs to be considered.

For conventional aeroplanes these structural design conditions appear to have been satisfactory from service experience but as aeroplane speeds and their characteristics change it is necessary to examine whether procedures found acceptable in the past will continue to be so at the present time.

3 EFFECT OF NEW CONFIGURATIONS ON RESPONSE CHARACTERISTICS

A more complete study of the response of the aeroplane to the previously specified control movements is called for. The symmetric pitching manoeuvre requirements need a response study introducing the necessary degrees of freedom and, having been developed more recently, are already at a standard which appears to meet the situation. Attention at the present time is therefore concentrated more on the asymmetric manoeuvres.

3.1 Rudder-induced manoeuvres

A comparison of the response to rudder application for a conventional and a high-speed aeroplane, obtained using three degrees of freedom in the calculation, is shown in Fig.2. As the sideslip builds up the high-speed aeroplane develops much larger bank angles than does the conventional aeroplane and possible pilot action to correct the roll must be considered.

The increase in the resulting roll follows from the tendency of the high-speed configurations to have reduced roll inertia in comparison with the pitch and yaw inertias and the effects of inertia cross-coupling are likely to be greater and must also be studied. A calculation with five degrees of freedom is required and the results of such a calculation are shown in Fig.3 in comparison with those for three degrees of freedom. The change in incidence during the manoeuvre and the resulting variation in normal acceleration will affect the stressing condition to be considered, and pilot action to correct the pitch response may be introduced. The effect on the lateral loads on the fin and rudder may, however, be relatively small as shown in Fig.4.

3.2 Suppression of roll in rudder-induced manoeuvres

The effect of aileron application to suppress the resulting roll is indicated on Fig.5. The reduction is most significant if the aileron is introduced early in the manoeuvre. For the aeroplane configuration shown, the fin lies in the pressure field caused by the aileron, and increased lateral loads on the fin and rudder result if the corrective aileron is applied before maximum sideslip is reached, as is indicated in Fig.6. At the peak load the components due to sideslip, rudder angle and aileron angle each result from different aerodynamic pressure distributions and this will be taken into account in the structural analysis.

3.3 Form of rudder application

For the rudder application manoeuvre the form of the application and its duration are significant parameters. The resulting peak fin and rudder loads for step, ramp and triangular time histories are compared in Fig.7 where the load is plotted against base time. The curves plotted for step and ramp applications are the envelope of points marked X on Fig.6. When the base time is long and the control is returned to zero after the time of maximum sideslip the maximum load is that for rudder deflected and held. The most severe ramp type will be that when the rate of control displacement is a maximum.

4 FIVE-DEGREE-OF-FREEDOM RESPONSE CALCULATIONS

We have seen that, in general, asymmetric manoeuvres involve five degrees of freedom, with all controls playing a part and design offices involved in the design of high-speed aeroplanes must develop procedures for dealing with these problems. As the number of degrees of freedom increases the number of parameters about which information is needed also increases as illustrated in Fig.8. In the early stages of design all these data will not be available and designers must have recourse to some relatively simple rule-of-thumb method; this is discussed later.

4.1 Computing facilities

The complexity of the calculations to give five-degree-of-freedom response data is such that the use of a modern computing facility is absolutely essential; in fact, without this the task would be almost impossible. A typical sequence, starting from the basic data for the aeroplane and ending with loads for stressing, is outlined in Fig.9. The actual response calculation is shown as being carried out by either an analogue or a digital facility. The elapsed time for the calculation tends to be shorter using a digital computer but the analogue computer has advantages in that trend investigations can be more readily carried out. An output of structural loading data in addition to the aircraft response quantities can be obtained using either process.

In the data preparation process the weight, centre of gravity, speed and altitude are specified and the initial calculation for trim in pitch is done. The basic aerodynamic data, usually given about a reference position, are converted to the specified cg and where the derivatives are functions of lift coefficient the initial values for the case are calculated. The effect of aeroelastic distortions on, say, the fin terms is established for the flight case under consideration and new total derivatives, including this effect, are computed.

4.2 Typical variations of parameters

Typical variations of some of the more important aerodynamic parameters needed for computation of asymmetric manoeuvres are shown on Fig.10. They are dependent on the lift coefficient, particularly at high Mach numbers, and this effect is indicated. Flexibility effects can be important, particularly at high EAS, and in calculation of total derivatives for the complete (flexible) aircraft they can be allowed for by applying 'quasi-static' corrections to the rigid-aircraft values of component contributions, as appropriate. Modifications to the loading distributions are required to account both for this effect and for the resulting changes to the stressing cases considered in design.

On the high-speed aeroplane, the range of speed, altitude, etc. to be considered is greater than was the case on earlier conventional aeroplanes and the number of points to be examined is very much larger. Consequently the total amount of work involved in a complete study can be quite prodigious.

4.3 Manoeuvres initiated by rudder deflection with subsequent aileron deflection

Typical computer results for manoeuvre cases involving rudder and aileron at low and high Mach numbers are given on Figs.11 and 12. The rudder is returned to neutral at the static equilibrium angle in yaw and corrective aileron is applied when the bank angle is about 15°. The elevator is fixed at the level flight trimmed position. The frequencies of the motion at high and low Mach numbers are different as the natural frequencies for the mode involved are different.

The maximum fin and rudder load occurs in association with a normal acceleration greater than 1.0 in these cases and this will affect the design loads for the rear fuselage, under the combined lateral bending, vertical bending and torsion. It was the practice in the past to associate 1.0 g vertical bending loads with the lateral loadings.

The effect of lift coefficient on the derivatives has been referred to earlier. The effect on the response and loads following rudder application is shown on Figs.13 and 14. Two initial 'g' conditions were considered for a small delta aeroplane. A significant effect on the fin loads is indicated in Fig.14.

4.4 Engine failure conditions

Engine failure conditions are likely to provide structural design criteria when the engines are installed in outboard positions and the corrective action could be expected to involve all three controls. Airworthiness rules ask for rudder application at the maximum sideslip angle unless the time to reach this angle is large, in which case a reasonable time delay is accepted. Calculations have been made with the following assumptions:

(a) rudder applied at 3 seconds and held;

(b) aileron applied when the bank angle reaches 15°, held for a short time and returned to neutral;

and (c) elevator applied when Δn = 0.25 and returned after a short time to the n = 1.0 trimmed position:

results are given in Figs.15 and 16. The response and loads are shown for cases when the rudder alone is applied, when the rudder and aileron are applied, and when all three controls are used. The thrust decay was of exponential form, reducing to zero in 2 seconds. The pilot's action is not very realistic (it arises from the assumptions fed into the computer) but the calculated results do serve to illustrate the effects on response and loads. If corrective action to reduce the roll and pitch is effective the sideslip and, consequently, the fin and rudder load are increased.

The timing of the pilot's action is all-important and in an actual design case one should introduce, as far as is possible, a realistic action particularly with respect to the aileron and elevator. This is difficult to judge and a study of flight simulator results would be helpful in giving a guide to the probable action. Some early results from engine failure simulations carried out for a slender delta aeroplane with a fixed-base simulator suggest that the pilot applies rudder and aileron at about the same time, the rudder generally preceding the aileron, with the delay from start of engine failure being around $1\frac{1}{2}$ to 2 seconds. In some cases the correction was initially by aileron action and the yaw was trimmed out some 7 or 8 seconds after engine failure.

The engine thrust line for the subject aeroplane is below the cg and the initial feature of the response to engine failure in pitch is a nose-down attitude (indicated by the initial reduction in n on the upper part of Fig.16). In the simulator studies no elevator action was taken until some time after the engine failure and it is probably relevant to repeat that the simulator was fixed-base.

Note that the pilot's corrective actions compared in Fig.15 in no way take account of the existence of autostabiliser devices fitted to the aircraft. The significance of these is discussed later.

4.5 Hinge moment limitations

Requirements allow the control movement to be limited by stalling load in a servo-control jack. If such a limitation is relevant for a rudder jack in the pilot-initiated manoeuvre, the initial control angle applied can be reduced. As the response builds up the jack is allowed by the reducing hinge moment to achieve the angle demanded. This is illustrated diagrammatically in the lower left of Fig.17.

In the case where rudder is used following engine failure and is applied before maximum sideslip is reached, the hinge moment increases during the continuing response, where hinge moments due to sideslip and due to rudder are additive. Values above the stalling hinge moment could then occur as indicated on the lower right of Fig.17. This could be significant for design loads on the rudder itself and the earlier the rudder is applied the more severe is the result.

4.6 Manoeuvres initiated by aileron deflection

The yawing motion induced by roll is important from a Loading Action point of view since it could provide the critical condition for fin and rudder lateral loads. To establish the response of the aeroplane to aileron application it is again necessary to carry out five-degree-of-freedom response calculations. The results of a typical calculation on a slender delta configuration are given in Fig.18. The aileron is applied, held for a short time and then returned to zero, with the aeroplane initially in the wings-level conditions at $n = 1.67$ and with constant rudder and elevator angle during the manoeuvre.

A further illustration of the response in the same type of manoeuvre is given in Fig.19 for a rear engined configuration. Three different aileron time histories are considered and different maximum angles of bank and of sideslip result in each case. Fig.20 shows the results obtained when the ailerons are held until after the maximum sideslip angle has occurred: a different maximum bank angle results for each time history, since the rate of roll attained is modified subsequent to the point where the sideslip angle is a maximum.

As stated earlier, previous airworthiness requirements considered the condition of acceleration in roll following a step application of aileron and also the resulting steady rolling condition. To calculate the latter the aircraft was assumed to respond in roll alone. These conditions correspond to the points marked A and B on the dashed curve in Fig.21, which shows the single-degree-of-freedom roll response to step aileron application. Fig.21 also shows (solid curves) the results of a five-degree-of-freedom calculation of the response to a ramp-shaped time history of aileron application. For this case the aeroplane is initially flying in a steady turn at $n = 1.67$ (angle of bank about 53°); the ailerons are deflected and returned to zero so as to bank the aeroplane into a turn in the opposite direction. The maximum rolling acceleration occurs at point C and this is smaller than at A, while the maximum rate of roll occurs at point D and is smaller than that for the step aileron.

The yaw developed in rudder-fixed rolls modifies the maximum rate of roll, and its variation with time, and in their turn, the development of yaw and the maximum value attained are dependent not only on the aileron angle applied but also on the length of time for which it is applied (i.e. the final angle of bank attained). Thus a full estimation of the magnitude of yaw which develops in rolling pull-outs, and its effect on the loading of the aircraft, depends on the manoeuvre which is specified.

The previous method in use for establishing loads is an unsatisfactory basis if the effects of yaw are important because no specific manoeuvre which the aeroplane must perform is implied by the method.

The points C and D of Fig.21, together with a case at the maximum sideslip angle, derived from the calculated response data, provide a basis for obtaining the loads on the aeroplane since a specific manoeuvre has been considered. It may also be necessary to consider a condition where the manoeuvre is performed with yaw suppressed as far as is possible by suitable rudder application.

4.7 Asymmetric weapon release

A condition which may be of interest on military aircraft is the combined yawing and rolling manoeuvre associated with asymmetric weapon release. The aeroplane is in a symmetric pull-up at some 'g' when the weapon on one side is released. This applies a yawing moment to the aeroplane giving response in yaw and roll. Rudder is applied to correct the yaw and at the same time aileron is applied to roll the aeroplane away. The results of a calculation for such a manoeuvre are shown on Fig.22. The elevator is assumed held at the value required for the entry 'g'. This condition could well give rise to an overriding design case for the fin and rudder and the 'g' limit for weapon release could be defined by the fin strength in the subsequent breakaway manoeuvre.

5 DEVELOPMENT OF REQUIREMENTS

The structural design requirements for an aeroplane must provide a structure sufficiently strong to cater for all the various conditions it can meet during its lifetime with an acceptably low probability of failure. Many different kinds of asymmetric manoeuvre are required, amongst which are the following: level roll, rolling turn, sidestep, engine failure correction, erroneous rudder application; and special manoeuvres which apply to military aeroplanes only, such as the weapon release condition described above. Autopilot or stability augmentation system runaways will also give rise to asymmetric manoeuvring conditions.

The configuration of the modern high-speed aeroplane is such that the application of the aileron or the rudder induces responses which may require use of all three controls and the previous requirements, which considered one control at a time, are not sufficient.

To provide a basis for setting up structural design cases, a more complete definition of the manoeuvre, which is representative of actual pilots' behaviour, is required and handling and stressing become more interrelated.

In general, handling requirements are based on manoeuvre levels below those considered for the strength cases where, in the past, controllability was not defined. The interpretation of control actions in the strength cases is then rather difficult and a study of several likely actions must be carried out. On military aircraft operational requirements may well give overriding design cases and handling requirements can coincide with the strength requirements as, for example, in the 'g' limit for weapon release, which could be defined by the fin strength in the breakaway manoeuvre. This is less likely to be the case on civil aeroplanes where the strength cases are, in general, related to the very rare circumstances which occur in emergency, following an upset due to turbulence, for instance, and about which there are hardly any data.

The definition of the worst control movements is difficult and the tendency is to consider full travel on aileron and rudder and restrictions on their travel, e.g. by stops, may be required to protect the aeroplane. Roll rate limitations are somewhat nebulous and the peak roll rate may differ from the mean in strongly coupled manoeuvres. Use of the aileron in stopping the roll is more difficult. The use of the longitudinal control during rolls, intentionally or inadvertently, is difficult to establish. Experience on one military aeroplane type suggests that a longitudinal control input which would produce about 1.0 g normal acceleration (incremental to entry 'g') could occur at any time during the manoeuvre. This may not, of course, have any relevance to civil aircraft. The use of rudder in rapid rolling manoeuvres is discouraged since it may well increase the sideslip in strongly coupled manoeuvres.

The use of the feel system to restrict control angles is an approach which can give rise to undesirable handling features in that excessive forces may be required in other more normal circumstances.

The most recently published requirements (TSS 8) take as their starting point the control applications previously specified and extend these by considering the action which the pilot might be expected to take to eliminate the undesirable features of the resulting response. Until more information is available from flying experience this approach seems the most logical since we might expect that, when these conditions are applied to conventional aeroplanes, the design cases which were formerly used would result. In a particular case where the handling requirements require investigation of inertia cross-coupling effects, an extension of the handling requirement is introduced into the structural requirement.

6 THE USE OF RULE-OF-THUMB METHODS IN DESIGN

Asymmetric manoeuvre conditions can give critical structural loading cases for a number of parts of the aeroplane. These include the fin and rudder, the tailplane and elevator (or the moving tail or elevons, depending on the configuration), rear fuselage, the outer portion of the wing including the ailerons and, for military aircraft, external stores.

Examination of the response in asymmetric manoeuvres requires five-degree-of-freedom calculations and a considerable quantity of data must be available before these can be performed. As stated earlier, this will not be possible at an early stage in the design and recourse to a rule-of-thumb method must be had. This is particularly relevant to the fin where all the design cases derive from the asymmetric conditions and an example of the rules of thumb a designer might use is as follows.

The ultimate design mean pressure on the fin and rudder clear of the body for a number of aeroplane types, plotted against the maximum design EAS, namely V_C for civil aircraft and 0.9 V_D for military aircraft, is given in Fig.23 and this could form the basis of a rule-of-thumb approach.

Having once committed himself to a stressing design figure, the designer will use the more complicated studies which will be carried out as more data for the aeroplane become available, to provide a basis for judgment as to the adequacy of the selected figure. This process will be repeated several times during the design.

Limitations such as autopilot and stability augmentation system authorities will initially be set to be within the design strength when runaway conditions are considered and these will be continually checked. A similar approach could be followed with regard to control-stop limitations.

In the early stages of flight trials, limitations will be established which provide margins to allow for uncertainty in the knowledge of the aerodynamic derivatives and other relevant parameters. These will gradually be changed as more information becomes available.

The stability augmentation system is likely to have the effect of reducing the response and consequently the loads, and throughout this Paper the effect of such a system has been omitted in all the typical results of response calculations presented. The reliability of such a system is the crucial issue and, unless complete reliability can be shown, manoeuvre conditions with the system inoperative will require examination.

DISCUSSION

Mr. T. Czaykowski, Structures Department, R.A.E. remarked that the characteristic behaviour of the aircraft, in the many cases presented by Mr. Sellers, was mainly due to the proverbial inertia coupling and aerodynamic coupling effects. He thought that if he had to introduce this subject to someone unfamiliar with it he would refer him to Mr. Sellers's Fig.13 where one found the case of a rudder angle application for one second which had forced the aircraft not only to yaw to a maximum of 4° but also to bank, the angle of bank reaching something of the order of 90°. This was due to rudder application only. On the other hand Fig.18 showed a case of aileron application which had forced the aircraft not only to roll but at the same time to sideslip to something like 6°. This impressed even him! He noted that it had been stated that all the cases had been calculated without automatic stabilisation and he thought that, while automatic stabilisation might reduce the response of the aircraft and therefore also the loading, in some exceptional cases, if one added artificial stabilisation and particularly static stability in one mode of motion, there might be an increased response in other modes. He wondered if Mr. Sellers had any experience on that point.

In connection with Fig.10, where it could be seen that the aerodynamic derivatives changed their values fairly rapidly around Mach 1.1, Mr. Czaykowski asked whether calculations for six degrees of freedom might not show something interesting. He thought all the derivatives seemed to do something there and he wondered if Mr. Sellers had any results. Referring finally to a diagram, in the top corner of Fig.10, which showed the flexibility effect, Mr. Czaykowski confessed that he was not clear how it should be understood or applied and he asked Mr. Sellers to comment.

Mr. Sellers replied that the simple answer to Mr. Czaykowski's first two questions was "No: he did not know". He was prepared to take Mr. Czaykowski's advice that automatic stabilising with respect to one degree of freedom might increase the response in other senses. He himself had no experience in that respect but, clearly, in the designing of an aircraft, that would be the kind of thing which would be investigated in the course of time. With regard to the introduction of six degrees of freedom he really had no experience. The flight simulator, which was really a six-degree-of-freedom device, might provide such experience but he had not investigated this. With regard to the little picture in Fig.10 labelled 'flexibility effect' he said that this was intended to illustrate a quasi-static way of allowing for the effect of flexibility on that part of a particular term which was due to the fin rather than its effect on the total term.

Mr. W.J.G. Pinsker, Aerodynamics Department, R.A.E. (Bedford) remarked that Mr. Sellers had spoken about an area where Handling and Loading Actions were entirely intermingled and he said that it always distressed him somewhat that some of the structural design cases seemed to be based on very artificial control applications. He would have thought that in some areas one ought by now to be able to put in some more realistic inputs. An example was the engine-cut case where the structural designer worked entirely on some assumed pilot reaction. He thought that in the CAADRP exercises, extending over some 50000 hours, an engine must have cut at some time and he wondered if one could derive some help from the records in seeing how a pilot would react and what the actual aircraft response would be to this event. He thought that as an alternative it was high time that some flight test work be devoted to that area to put it on a more solid basis. Another point was that, in an area where aircraft stability and loading were interacting as in the inertia-cross-coupled manoeuvres, the effect of the aerodynamic derivatives on the loading had become more important than appeared at first sight because, for example, variations in the aerodynamic derivative n_v did not only cause a proportionate effect on the loads on the fin by itself but could also cause a disproportionate effect on the response of the aircraft to pilot action. Therefore one was required to know these derivatives to a much better degree of precision than the actual Loading Actions aspect by itself would suggest.

Mr. Pinsker said that difficulties had been met, for example, with the derivative n_v which was one of the most difficult ones to determine in wind tunnels because one usually had to distort the rear end of models. Consequently, it was customary to employ some empirical correction when going from tunnel data to flight data. The empirical correction was simply based on a comparison of some flight tests and tunnel tests. One found that flight data, which were invariably obtained by dutch rolls of very small amplitudes, might give quite a misleading answer about the n_v applicable to large amplitudes. This was due to the possible occurrence of a rather insignificant-looking non-linearity which only came out if one did an extremely careful and very finely spaced wind-tunnel test over a range of sideslip at intervals of possibly $\frac{1}{4}^{\circ}$. He said that unless this was done one might obtain very misleading answers.

Mr. Hufton, Deputy Director (A), R.A.E. (Chairman) asked Mr. Sturgeon if in his CAADRP work he had any data involving engine cuts as distinct from engine shut-downs.

Mr. Sturgeon referred the question to Mr. J.C. Chaplin, Air Registration Board who said that he was not aware of any.

Mr. Hufton thought that this was significant.

Mr. Sellers said that it would be a brave man who crossed the engine-cut case out of the requirements.

Mr. Hufton queried one of Mr. Pinsker's remarks about non-linearity close to the origin. He said that if it was as close to the origin as Mr. Pinsker suggested he was surprised that it had much significant in the kind of area being discussed. This suggested to him that fins and rudders ought to come off very much more frequently. He understood that when one was trying to make precise measurements one could get disturbed answers but he wondered if this was really relevant to what was being discussed.

Mr. B.A. Tyler, British Aircraft Corporation, Preston commented that the important thing was how one extrapolated the data to high-load conditions and not what happended in the area round the origin.

A SURVEY OF GROUND LOAD PROBLEMS

by

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CONTENTS

1 INTRODUCTION

Interest in fundamental design principles has been renewed of late because over the past few years there has been an increase in the number of undercarriage failures. This increase has emphasised the need to design future undercarriages with longer lives. With this in mind, work is now proceeding aimed at a better understanding of the loads developed in the undercarriage. The response of the aircraft structure to ground-induced loads is of great importance, especially for slender-wing aircraft, and this facet of aircraft operation is also being studied, the aim being to ensure that structure, occupants and equipment are subject to acceptable vibration levels. Finally, the loads produced at the ground are of prime importance for the airfield engineer.

Most of this paper is devoted to a study of the 'state of the art' in respect of the undercarriage loads, but some mention is made of the other aspects noted in the preceding paragraph.

2 CURRENT PROBLEMS

The following is a list, by no means complete nor in any specific order of importance, of problems that are occupying workers in this field at the moment.

(i) Shimmy.

(ii) Brake-induced vibrations.

(iii) Runway roughness.

(iv) Towing.

2.1 Shimmy

In the past, shimmy has been confined to nose and tail wheels; the wheels, having the facility to rotate in their steering capacity, are free to oscillate. The stiffness is provided entirely by the tyre. The problem is reasonably well understood and ad hoc cures adopted have been dampers in the steering mechanism and the introduction of friction in the system. Recently, shimmy of main undercarriages has occurred and this problem is much more complex involving, as it does, freedoms in bending and torsion of the leg. The prediction of this type of motion is hampered by the fact that there is inadequate knowledge regarding the tyre forces involved, and of the importance of the parameters that govern these forces. It is necessary to determine lateral stiffness, torsional stiffness, relaxation length and footprint length. A programme of measurements has been started at R.A.E. by British Aircraft Corporation (Operating) Ltd., aimed at improving our understanding of the tyre forces involved and the prediction techniques for the tyre forces and the structural oscillations. This work, which is being done under contract for the Ministry of Aviation, was initiated by Mechanical Engineering Department, R.A.E. which continues to monitor it.

The work so far accomplished has been concerned with a study of the effects of stiffness and inertia variations on the shimmy speed for a specific aircraft leg. In the experimental study severe shimmy cases have been found and it has proved difficult, up to this stage, to correlate the experimental results with the existing theory. Even under reasonably controlled conditions the shimmy does not manifest itself in a consistent manner.

2.2 Brake-induced vibration

Two separate types of problems are involved here and they are:

(a) those involved with brake linings, and

(b) those associated with automatic anti-skid braking systems.

Type (a) is mainly concerned with properties of materials. Solutions are normally sought on an empirical basis. The typical problem is of non-linear lining characteristics. Rigid body motion of the aircraft on the oleos may be excited and complications in regard to brake cooling may occur. Tyre forces are known to affect this type of vibration and it is hoped that the measurements mentioned in Section 2.1 will yield useful information in this respect also. The uneven operation of anti-skid type braking systems can lead to significant torque loads on undercarriage legs. Specific modifications are usually adopted to cure problems of type (b) and a call has recently been made by the Oscillation Sub-Committee of the Aeronautical Research Council for an analysis of a typical aircraft system The publication of the results of such an analysis would be a significant addition to the literature on the topic.

2.3 Runway roughness

Since the requirement for V/STOL operation from rudimentary forward airfields was formulated by Defence Staffs, great efforts have been expended in assessing the performance of existing systems and in devising undercarriage systems that will operate successfully on such surfaces, in specifying the degree of roughness that is acceptable and in devising alternative artificial surfaces that will extend operational capabilities beyond the naturally occurring areas. Movement on a particular surface is dependent on the geometry of that surface and the soil characteristics. The study of the behaviour of soils under dynamic loading is still very much in its infancy. The effect of surface roughness can only be determined from a study of the interaction between the aircraft and the runway surface.

During the Summer of 1965 a test area was laid down at Waterbeach Aerodrome to standards suggested in a J.A.C. paper. Ten artificial undulations were set up of 150 ft wavelength and ±6 inches amplitude. A Beverley aircraft was taxied at varying speeds, 10-68 knots, over these undulations. Subsequent to the high-speed run, structural damage was found at the wing root-fuselage joint. The tests were discontinued at this stage. It was felt that the number of regular undulations was unrepresentative of what happened in practice.

This year tests have been made on an Andover aircraft at Boscombe Down over similar undulations but reduced in number. Three separate strips have been prepared, each of which has three undulations with wavelengths of 50, 75 and 150 feet, as specified in J.A.C. Paper 855, but with amplitudes reduced to two-thirds of those recommended. There is, apparently, limited evidence that three is the maximum number of undulations that will occur in succession naturally. The most significant parametric variation measured in these tests was that of the nose leg end load. Maximum values of this load, depending on the piloting technique, could approach proof load during operations over the two longer-wavelength profiles and operation over the 75 foot length waves could lead to an extremely uncomfortable pilot environment which, subjectively, was considered to be limiting. Take-off has proved to be possible from the 150 foot waves. Mention should be made of the fact that these tests were made on an extremely hard surface with a California Bearing Ratio (CBR) of more than 15%. Further tests have been made over a soft, stony surface with a CBR of 3 to 4%. Apart from heavy tyre wear there is apparently nothing to suggest that this aircraft cannot operate in these conditions.

A Sub-Committee of the Short Term Airfield Research and Development Committee has been set up to formulate and advise engineering officers in the field, in relation to acceptable standards of ground in regard to surface conditions, runway lengths, overall runway gradients, overruns and shoulders, approach zones and taxiways and aprons.

Some theoretical work concerned with approach paths and related aerodynamic effects has been completed. Experimental work to date has involved slow-flying aircraft in steep approach patterns and more full-scale work is required. Theoretical work is needed to relate, on a statistical basis, the ground loads with variations in approach paths and techniques.

Prefabricated surfacing materials have been developed by MEXE to permit operation from soft surfaces. Extruded aluminium alloy mats and neoprene-coated nylon membranes have been tested and show promising results in regard to support characteristics but the latter have limitations in regard to the low coefficient of friction developed.

The question of the effect on fatigue life of operating from short-term rudimentary airfields remains to be considered.

The problem of runway roughness has so far been discussed mainly from the point of view of V/STOL operation. It is of course important also for normal operation from commercial or military airfields. It is appropriate in this context to mention some work proposed by the late J.K. Zbrozek in what was possibly his last paper[1]. He came to the conclusion, from a study of American experimental work, that it should be possible to establish on a power-spectral basis different levels of runway roughness as they affect the aircraft response. The American work shows that the spectra of cg acceleration for large and small aircraft, when measured on the same runway and at comparable speeds, are similar enough to allow extrapolation from one aircraft to another. The suggestion is, therefore, that measurements of cg acceleration even on a small aircraft can be a reasonably good measure of runway roughness and it is possible that such measurements can be extrapolated to larger aircraft.

2.4 Towing

So far little consideration seems to have been given to towing as a significant ground loading action. It has become known recently as a result of operational control problems that aircraft are being towed quite significant distances from servicing areas to stands at major airports. There seems to be a high probability that this operation, made under unskilled control, will lead to the development of loads of magnitude and frequency that were never considered in the design.

3 DATA COLLECTING

Some three years ago the Civil Aircraft Airworthiness Data Recording Programme began. The programme has been described adequately in the paper by Sturgeon and all that remains to be said at this stage is that large quantities of data concerning the landing and take-off of aircraft are becoming available. The information that is obtained is in the form of the acceleration measured at the cg of the aircraft. Certain special events are singled out for detailed analysis: these include the occurrence during the landing phase of incremental accelerations in excess of 1 g, and the occurrence in the ground role of (positive or negative) increments greater than $\frac{1}{2}$g in amplitude.

Operational events at London (Heathrow) Airport are being monitored by the Aviation Operational Research Branch of the Board of Trade. They are studying, with the aid of cameras and radar, the landing and take-off of aircraft and are making a further study of manoeuvres actually carried out on the ground at the airport. It has been evident for some time that such manoeuvres give rise to a significant proportion of the fatigue loads to which an undercarriage is subjected.

For some time, efforts have been made at R.A.E. to devise a fully automatic airborne rate of descent recorder measuring the change in vertical velocity during landing. Our current view is that the production of such an instrument is impracticable. Despite this, much useful information has been obtained in the attempt and this corroborates results obtained in the course of CAADRP.

With the help of the information gathered from these programmes it may be possible to devise a better fatigue load spectrum to which undercarriages should be designed.

3.1 Results obtained in these data collecting programmes

With regard to landing, both CAADRP and the R.A.E. programmes have shown that there are two classes of landing. The first comprises normal light landings which are common in practice, such as is illustrated in Fig.1. An initial landing at a vertical velocity of 3 ft/sec or less may be followed by a second landing, more severe than the initial impact, which is experienced about one second after the first. The second class comprises heavy landings which may involve one or more touchdowns of which the second is frequently of about the same severity as the initial landing. This is illustrated in Fig.2. These characteristics may well contribute significantly to undercarriage failures and should certainly be taken into account in future undercarriage stressing and life assessment. It is of great interest that the French airworthiness requirements mention that the designer should consider the possibility that the vertical velocity of descent on a second or subsequent impact may be greater than on the first. There is no such British or American requirement nor any rider in them to this effect.

The A.O.R.B. studies have produced some interesting results and amongst these we may list the following:

(i) that all landings are one-wheel, and

(ii) that, on the basis of limited samples, (a) for an instrumented landing system approach in a 5 knot headwind, 1 in 10 landings will involve bounce, and (b) for manual control of approach in a 30 knot crosswind, 1 in 3 landings will involve bounce. If these figures can be substantiated in bigger samples then there will be a strong case for the modification of requirements that certainly do not reflect statistics such as these.

In the taxi phase of operation, typical Airline Operational Records obtained during the course of CAADRP show that large oscillations may be set up in the aircraft during ground operations. The recorded parameter of interest is the acceleration at the centre of gravity. A typical record is shown in Fig.3. It can be seen that low frequency oscillations at about 1 c/s, corresponding to rigid body motion of the aircraft on the undercarriage, are excited by ground roughness.

4 DESIGN CONSIDERATIONS

Probably the most pressing problem is the provision of an adequate fatigue load spectrum that will provide a satisfactory basis for design. The only paper that gives guidance on the appropriate loading conditions for all aspects of ground operations is an old one by McBrearty[2]. A serious limitation in the spectrum is that side load data, appropriate to both landing and taxying, were derived from information that was suspect in quantity and quality. Past American estimates of fatigue loads resulting from runway roughness have employed power-spectral techniques. Recent analysis has shown that the spectra on which these estimates were based are suspect and that they do not extend to the longer wavelengths that are becoming more important.

Reference has been made in the paper by Hovell to the difficulty of measuring ground loads and, until these difficulties have been resolved, little progress is likely in the provision of a realistic spectrum for lifing the undercarriage. Work is in hand at present to measure undercarriage loads on the following aircraft: Victor, Herald, Vulcan, Comet, and the R.A.E. is participating to some extent in all these programmes. A satisfactory load measurement scheme will enable one to estimate the importance of phase lags between the vertical, drag and side components and, further, to decide how such loads should be associated in any realistic spectrum. Most of the aircraft noted above have bogey undercarriages and the application of a fatigue load spectrum derived from a consideration of earlier, less complicated mechanisms to such units seems somewhat doubtful. Ultimately it may be found that variations between individual combined aircraft-undercarriage systems are so great that the provision of a general fatigue load spectrum would be meaningless. The most that would be possible in these circumstances would be to make sure that the loads applied in a fatigue test were based on strain measurements on the particular aircraft. In any event, it seems important that areas where high stress concentrations are likely should be adequately strain-gauged as a matter of course.

From time to time it has been suggested that current requirements, which have gradually evolved over the years, should be put on a more rational basis. These suggestions arise because, with their historical background, the requirements are largely arbitrary in today's context. Particular requirements have led individual manufacturers to query them as difficulties were encountered in design. Among such requirements we may list the turn and swing case where sideloads, it is said, are not distributed as suggested in the requirements; the asymmetric braking case which was written around the single-wheel nose undercarriage whereas most are now twin-wheeled; the bump factor in the take-off and landing cases, which was derived on the basis of measurements on grass fields many years ago. Despite limitations of this nature the general strength level determined by these requirements seems to be satisfactory. As we have seen earlier there is now a certain amount of statistical operational evidence accumulating that particular parts are not soundly based and the time is probably ripe for a rationalisation exercise to be attempted.

5 RESEARCH AT R.A.E.

It has been noted that many problems today are associated with manoeuvring on the ground and some of the work at present being done is concerned with this phase of operation. There are three facets of this work:-

(i) To improve pilot and passenger vibration environment levels.

(ii) To improve shock absorber design.

(iii) To improve braking characteristics.

The work under (i) has been triggered off because American calculations show that rms accelerations at the pilot station during operations under typical conditions could be as high as 0.25g for a high-subsonic jet and 0.54g for a supersonic transport configuration. Acceleration values recorded in CAADRP bear out the result on the subsonic jet. The supersonic transport configuration studied is not dissimilar to Concord and this naturally caused alarm that acceleration levels on the latter might prove to be unacceptable. Structures Department are at present assessing the response of the Concord to passage over a rough runway. A digital computer programme which involves step-by-step integration of the equations of motion has been written by A.J. Sobey. Part of a take-off run has been simulated using profile measurements for two American rough runways as the basis for derivation of the excitation force. This process has been adopted as power-spectral techniques have been found inadequate, to date, when dealing with inputs of this nature. The application of statistical techniques to non-stationary, non-linear dynamic response problems requires further study. The output from this programme will be used to produce a tape that will drive the cockpit simulator at Weybridge and thus provide a positive check of a pilot's capacity to work in this specific environment. This part of the work will be organised by Mechanical Engineering Department, R.A.E. The study is at the moment confined to the take-off run when, patently, the pilot must have absolute control. It is hoped to publish the programme, in due course, in a form that will allow dynamic analysis of aircraft with similar two-stage bogey undercarriage mechanisms to be made.

If this study should prove that the vibration level is unacceptable then alternative approaches to undercarriage design may have to be considered. This may involve providing softer springing in the neighbourhood of the static loading. Present designs, due to the non-linearity of the airspring, have high stiffness under static loading conditions. Another approach is to consider anew the question of the damping that is required in an undercarriage and to see whether it can be improved to deal more effectively with oscillations produced in ground operation.

Orifice damping has been employed in the past because it was necessary to provide high energy absorption for the design vertical velocity of descent case. Such dampers have coped adequately with the design case but, by their very nature, damping being proportional to square of stroking velocity, will not cope particularly well at the low stroking velocities that occur in the taxi phase of operation. We have seen in the rest of this report that problems associated with ground manoeuvring are becoming increasingly important.

Starting from the above the writer has made some calculations on a simplified aircraft-undercarriage combination to compare the performance of two struts, the first having the conventional square-law damping characteristics, and the second a linear damping relationship. A two-degree-of-freedom system, comprising a sprung mass on top of an unsprung tyre-wheel combination, was studied. A typical light aircraft was considered, approximately 5000 lb weight, and the orifice damper was of a conventional oleo pneumatic type. The strut employing linear damping was designed to have the same stroke as the conventional one in the high descent velocity case. The results that are shown in Figs. 5 and 6 are for taxi at 100 ft/sec over the fairly rough runway profile illustrated in Fig.4. It can be seen that, with the new design, the force amplitude is reduced and that any disturbance is damped down more effectively. There still remains the question of how such dampers compare in the landing cases and this is illustrated in Fig.7. At high descent velocities the new strut shows a slight, 10 per cent, reduction in maximum force compared with the original. There is a corresponding slight penalty at low, normal descent velocities but, even so, the 1 g level is not reached. Enough has been said to indicate that there may be promise here for future landing gear development and this is receiving consideration.

Mention may also be made of studies concerning the response to landing impact of slender-wing planforms that have been proceeding at R.A.E. and are now nearing fruition. A scaled model of an early Concord design has been fitted with model undercarriages whose stiffness and damping characteristics may be varied. The undercarriages have been instrumented to measure force input at the three undercarriage attachment points and the response of the structure is monitored by accelerometers mounted at stations of interest. The model response to landing impact at certain stations has been shown to involve modal contributions up to at least the 9th symmetric mode. Calculations are proceeding to determine how accurately the model response may be predicted from the known input forces.

Mechanical Engineering Department are carrying out work at present on aspects of retardation and this takes two forms:-

(a) Stopping an aircraft on overshoot, or soft ground arresting.

(b) Improving braking on the runway proper.

A good deal of attention has been focussed on (a) recently in the Press and, apart from mentioning the method of arresting, which is by running into a bed of gravel, there is probably no need to say more than that the method shows great promise. Work under (b) is aimed at improving the frictional characteristics of runway surfaces, particularly in the wet. The required surface should improve frictional characteristics without increasing tyre wear. Tests have been made on a super-porous surface constructed from large aggregate material that allows drainage of surface water. To date this surface has shown a slight improvement in frictional characteristics over a standard Marshall surface. Drop testing onto various specimens indicates that wear is least on a standard motorway textured surface which gives drag coefficients roughly equal to those obtained on the open graded surface.

6 CONCLUDING REMARKS

This survey outlines many areas in which our knowledge and understanding of ground loads problems is lacking. As we have seen, steps have been, and are being, taken to improve this situation but resulting studies have not so far come to fruition. We may expect that with the great interest that there is currently in undercarriage and ground load problems, significant developments will emerge shortly. It is hoped that this Paper will stimulate discussion of the more vital problems and their relative priorities.

One final thought. Will the American air cushion landing gear do away with all our problems? Messrs. Spurr and Barnes of Mechanical Engineering Department, R.A.E. have made an appreciation of the problems involved in the production of such an undercarriage. They conclude that many practical problems require solution before such a design could become a realistic proposition.

REFERENCES

No.	Author	Title, etc.
1	J.K. Zbrozek	A proposal for simple measurements of the 'effective' roughness of runways. Unpublished R.A.E. Technical Memorandum Aero 949, (A.R.C. 28394) (1966)
2	J.F. McBrearty	A review of landing gear and ground loads problems. AGARD Report 118, (1957)

DISCUSSION

Mr. E.D. Keen, Dowty Rotol said that Mr. Hall's paper was a fair representation of the things which an undercarriage designer still needed to know. He said that he would like to endorse the statement that, of everything that was still unknown, the provision of a fatigue spectrum caused most anxiety. Everyone knew that, particularly with transport aircraft, the fatigue problem had reared its ugly head and that it was no longer sufficient to design aircraft to limit and ultimate loads. He had been somewhat puzzled during the day that no-one else had been badgering those concerned with operational research to provide them with better and better fatigue spectra until he had suddenly realised that aircraft Chief Designers were now in the wonderful position of having fail-safe structures. Hence he would submit that the accuracy of the fatigue spectra did not now assume the importance which it did in the days of safe-life structures such as those of certain well-known aircraft with concentrated spar booms. Mr. Keen asked that a thought should be spared for the undercarriage designer who seemed to be stuck with a safe-life structure and suggested that all V-g recorders should be moved from the aircraft structure to the undercarriage - the undercarriage designer had the greater need of them.

He said that another area mentioned by Mr. Hall in which one seemed to be stuck with other people's problems was that of past experience with undercarriage excitations emanating from anti-skid unit operations and cyclic brake torque variations, and here one could do little other than accept them. The whole horrible combination had now led to an occurrence which had never even been dreamed of - shimmy of the main undercarriage. Mr. Keen said that shimmy was no stranger to him as he had wrestled, in the early days of the war, with nose-wheel shimmy. In that case the shimmy was mainly torsional and the efforts of many people, including Dr. Temple, had shown that this problem could be lived with and beaten with the aid of friction damping. However, main-undercarriage shimmy was undoubtedly the sort of thing which the airframe designer would class as a resonance or flutter problem and so it seemed that everyone was in this together. He thought that it was a little sad that the method of progress towards either a rational explanation of this phenomenon or a set of design rules to prevent it was far from clear. Mr. Keen said that he had had one idea, and he would be glad to know if anyone had tried it already, which stemmed from the thought that for the whole aircraft one laboriously did pre-flight resonance tests in which one vibrated the aircraft to find its modes of vibration. Now these had usually been done with the tyres deflated, in order to get the natural frequencies of the whole aircraft correct, but Mr. Keen wondered whether anyone had thought of inflating the tyres to the correct pressures and then exciting the wheels or undercarriages themsleves with the side and torsion loads that were the causes of trouble. He did not know if here he was proposing something that was already commonplace but if it was not then he would consider it as worthy of thought.

Mr. Keen said that another point made by Mr. Hall concerned the severity of the second landing but that in his firm they were not sure what this really meant or how it arose and they would like a little more explanation. Were undercarriages without an adequate rebound characteristic causing this problem?

Naturally, he said, everyone in the undercarriage business was interested in the soft ground arresting experiments now going on and they wondered what damage to their own pet child would result. He asked if Mr. Hall had any values of the decelerations which were imposed on the undercarriage and if he could say what damage had resulted in the experiments.

Mr. Hall said that he had no knowledge of any experimental investigation of the shimmy problem in which the undercarriage had been excited in the manner of resonance tests as suggested by Mr. Keen. He said that the bouncing that he had mentioned seemed to occur on all the types involved in the various programmes he had described. He did not think that any particular undercarriage was worse than any other in leading to this problem. As he had said in his Introduction, some aspects of the work described in the Paper were really in Mechanical Engineering Department's field and he thought he would refer the question on soft ground arresting to representatives of that Department present in the audience.

Mr. H.G. Spurr, Mechanical Engineering Department, R.A.E. said that the decelerations that were being aimed at in the soft ground arresting trials were about 0.7g and that at present the indications were that this could be achieved and, if necessary, exceeded. There had been no structural damage on aircraft engaged in this work. He thought that there would be possible risk to the nosewheel on large transport aircraft but that this might be accepted in preference to the risk of complete disaster if there were no such arresting gear.

He stated that resonance testing of the proposed type had in fact been done, since one had to know the torsional and lateral stiffnesses and frequencies in order to be able to apply any sort of theoretical analysis to the main-undercarriage shimmy problem. The major unknown in this problem was the tyre force developed under unsteady conditions, which was analogous to the unsteady aerodynamic force in flutter but much less well documented. He thought that, until more information was gained on these tyre forces and the extent of their variability, one could not make headway with the problem. The object of the work now going on was to obtain shimmy of an undercarriage under controlled conditions and to see whether existing theoretical methods, using existing information on tyre forces, would match the experimental results. Mr. Spurr said that the main problems were at present concerned with developing a satisfactory rig but he was confident that as this work, which was at a very early stage, progressed solutions would be found. He emphasised again that the major problem area was that of the tyre forces.

Mr. Sturgeon, Structures Department, R.A.E. said that he would like to consider the subject of the multiple bounce landing and its relationship with rate of descent measurements and with requirements. The requirement for undercarriage design stated that at the time of impact the lift corresponded to 1 g and that the runway was smooth: what appeared to be a reasonable rebound energy was specified for these conditions. However, operational research results showed quite clearly that these conditions were totally inadequate, firstly because at the time of impact on a heavy landing it was much more likely that the lift corresponded to 1.1 or 1.2g, which inevitably increased the size of the rebound. Secondly, the runway was not smooth and it was almost certain that one would hit the runway in such a way that its roughness fed more energy into the rebound at the time of the first impact. Thirdly, pilots had certain views about the correct use of the elevator when landing and were willing to admit that, for instance, on a Stratocruiser if you did what you would like to do a 'porpoising' motion would develop; therefore, it was likely that elevator activity would also produce more rebound energy. For these reasons Mr. Sturgeon thought that it would be necessary to specify undercarriage requirements more realistically and he was sure that when this was done undercarriage designers would have to be asked to reduce the rebound energy.

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Turning to the topic of rate of descent, he said that the above facts cast doubt on the possibility of making a meaningful rate of descent meter because it was not possible to define which rate of descent the Structures or Loading Actions expert wished to measure. As he saw it, if on a heavy landing there was 0.2 g excess aerodynamic loading then in the last second before impact the rate of descent changed by 6 ft/sec while in this time the aircraft might have descended about 10 ft; hence, unless the rate of descent could be measured during the last foot or two of the descent, the quantity measured was not what was required. Additionally, the question arose as to a basis for measuring rate of descent since one would wish to measure it relative to the part of the runway on which the aircraft was going to land rather than to the part on which it was not going to land. For these reasons, he would say that he did not believe a rate of descent recorder could be made. Nevertheless he thought that, provided one could make digital recordings of normal acceleration at a rate of about 20 samples/sec during the landing, a computer program could be written which would enable quantitative statements to be made about the severity of the landing and help in assessing structural loads.

Mr. C. Goldberg, Dowty Rotol said he was interested in Mr. Sturgeon's remark about asking undercarriage designers to improve their rebound ratio in an endeavour to solve the problem, which was also aerodynamic, of keeping the aircraft on the ground at touch-down. When an aircraft landed some of the energy was stored in the oleo spring, some in the tyres and the rest dissipated by the damper. In recoil nearly all the tyre energy was returned so there was a limit beyond which rebound ratio could not be reduced with existing tyres.

He thought that when people referred to the phenomenon of bounce they possibly meant that daylight could be seen between the tyre and the ground. All aircraft bounced on landing, so that there was always some rebound ratio. When a large gap was visible between tyre and ground it could mean that the shock absorber was rather too well damped in recoil and was thus extending rather slowly. High damping in recoil reduced rebound ratio but adversely affected recovery of the shock absorber which was necessary to cater for the second touch-down. Thus undercarriage designers could do only a limited amount to reduce rebound ratios.

He cited some recent results of drop tests on a nosewheel wherein, at first, a rebound ratio of 0.3 was measured. The recoil orifice was then closed down and the rebound ratio reduced to 0.25. However, daylight could then be seen between tyre and platform and so it could be erroneously deduced that the second situation was worse than the first.

Mr. Goldberg said that it was necessary when altering requirements to be certain that one foresaw all the consequences, and on the proposal of reducing rebound ratios one consequence might be that the second touch-down could take place with an almost fully compressed shock absorber.

[Since the symposium, Mr. Sturgeon has contributed the following reply to Mr. Goldberg.

Our calculations confirm that closing down the recoil orifice would not significantly improve the rebound ratio on an undercarriage. Therefore, improved operational performance must be sought elsewhere, probably by increasing the ratio of dissipated energy to stored energy during the working stroke. This may result in a small structural penalty in meeting the current design requirements.]

Mr. H.P.Y. Hitch, British Aircraft Corporation, Weybridge thought that it was the landing loads part of the exercise which was least well understood. He said that he would very much like to see the 10 ft/sec landing velocity reduced, at any rate in those aircraft which are expected to have a sedate life. He felt that if a velocity of 10 ft/sec were actually to be achieved then something would have significantly gone out of control in that landing and any other velocity, above or below 10 ft/sec, could just as easily have been achieved. He said he would like to see this figure reduced so that the weight of material thereby released could be used to make the undercarriage a better device for its real purpose, which was to facilitate a proper comfortable landing and to enable the aircraft to manoeuvre on the ground under normal operating circumstances. He thought that undercarriage designers had been too restricted in the past because the specified rate of descent was too high.

On the subject of rough runways, Mr. Hitch said that the only evidence available to most people was that relating to the fourteen runways measured by AGARD but it had recently come to his notice that there were quite a few about which airlines actually complained. For example there was a place called Whenuapai in New Zealand where every pilot, on landing, said his aircraft had square wheels. (This was curious because the runway was actually made in octagonal pieces.) Also, pilots taking off from Kansas City airport sat with their teeth gritted waiting for the rotation speed because life then became comfortable again. He had been told that in South Africa, where they hoped to sell a number of aeroplanes, the runways were absolutely shocking. Mr. Hitch said he would like to see the R.A.E. or some other body actually measuring a few of these interesting places from which civil aircraft actually flew.

Regarding shimmy he thought that when some of the results had been looked at the correlation between theory and the R.A.E. experiments would not turn out to be so bad. He said this with the background that in the original case that engendered this series of tests a theoretical exercise had in fact led to a successful solution.

Mr. Rochefort, Hawker Siddeley Aviation, Kingston expressed appreciation of Mr. Hall's Paper and said that the author was to be congratulated on summarising the whole situation. There was one paragraph which was of great interest to those concerned with determining the fatigue spectrum of the undercarriage. Mr. Hall had said "The most that would be possible in these circumstances would be to make sure that the loads applied in a fatigue test were based on strain measurements on the particular aircraft". Mr. Rochefort thought that this was too pessimistic since the fatigue spectra were obtained and, he felt, should be obtained, from undercarriage load measurements in conjunction with the known use of the aeroplane. He did not think there was anything unknown about this. The problem was rather that an enormous amount of work was necessary to do this. However, they had done this once for the Kestrel and had obtained a fatigue spectrum that was thought to be very satisfactory and representative. He said that, incidentally, a feature of the landings was the double bounce. Strain-gauge analysis showed that a double application of large loads on landing almost always occurred. This could be because a lot of lift was dumped on the first bounce.

Continuing, Mr. Rochefort said that he would like to add to some remarks made in Mr. Hall's Paper and elaborated upon by Mr. Sturgeon, by stating that if one dealt with a VTOL aircraft another important factor had to be accounted for in addition to the rate of descent etc. This was engine thrust. If during vertical landing the engine was cut one foot from the ground then there was an enormous extra energy to absorb - equal to the weight of the aeroplane times one foot which, on conventional aircraft, one would have neglected. This made nonsense of ordinary energy absorption requirements based solely upon a vertical landing velocity of so many feet per second.

Another point to which, Mr. Rochefort said, he would like to draw attention concerned the drag associated with the vertical load. Analysis of landing records showed that the drag was a load in its own right and would be applied independently of the vertical load, possibly at a later stage, so that one could not relate the drag loads or, for that matter, the side loads to the vertical loads by means of a factor. This meant that there were three loading actions to be separately determined and a fatigue spectrum for the undercarriage had to include these three separate loading actions.

GENERAL DISCUSSION

Prof. A.H. Chilver, University College, London thanked the Chairman for the opportunity to make a general comment and congratulated him on the scope of papers presented. The general paper by Mr. Tye and the other papers which covered a wide range of particular topics had shown the breadth of interest in Loading Actions. In the Loading Actions field the concern was with loads in structures and this implied a concern with the structural environment. There was a tendency to treat the environment in special senses, such as aerodynamic loading and the impact of an aircraft with the ground, but more generally the whole of the structural environment, including kinetic heating, should be included.

It seemed that two main themes had emerged from the papers which had been heard: one was concerned with the clear need to establish knowledge of loading actions and the other with the use of that knowledge in the development of a design philosophy for structures. The search for knowledge of loading actions had proved extremely costly and one had to face the crucial problem of the effectiveness of any Loading Actions studies that were made. He thought that there should be exploration of the possibility of wider collaboration throughout world aeronautics in the study of loading actions, perhaps on the lines on which major airline companies shared their knowledge about the maintenance of aircraft. He thought that great benefit could be derived from comparisons of Loading Action problems in the aircraft field with those in other fields; the statistical nature of the maximum bending moments experienced by ships was similar to that of the heavy gusts experienced by aircraft, which in turn was similar to that of the gusts experienced by tail buildings. Aircraft landing loads had statistical similarities to the loads experienced by structures in earthquakes. He felt that more general studies should be made of loading actions throughout the field of structural engineering to develop general ideas, covering the whole structural field. He thought that design philosophy was aimed at two main areas; one was design against static failure and the other design against fatigue failure. Knowledge of loading actions was at present not really extensively applied in other fields. The types of loads that caused static failure were rare events while, at the other extreme, fatigue design was dictated by frequent low-intensity forces. One important point that emerged was that these two fields did not seem to be tied together very effectively in that one did not seem able to treat rare intense loads as members of the same family as the more frequent low-intensity loads which caused fatigue.

He felt that the main question raised by the papers that had been heard was that of cost effectiveness, and there he would have liked to have seen more calculations of the sort described by Mr. Tye. Mr. Tye had mentioned that a reduction of load would entail an increase in the frequency of that loading and that this would in turn possibly lead to a higher frequency of failure. He wondered whether a deeper knowledge of loading could mean a reduction of loading without an increase of frequency of failure, in which case there would be very great advantages in learning more of loading actions.

Finally, in thanking the Chairman and the staff of Structures Department for arranging the symposium, which had afforded those present the opportunity of meeting and discussing the problems of Loading Actions, Prof. Chilver expressed the opinion that perhaps the subject had not yet come of age - it was probably still very much in its teens.

Mr. P.A. Hufton, Deputy Director (A), R.A.E. (Chairman) said he would like to go back to the question of getting a clearer view of the value and the cost of increasing our knowledge of loading actions. He could call for one of these symposia on almost every other subject in aeronautics and he was sure that everyone would produce similar kinds of problems wanting more solutions. However, the effort available in the Research and Development Establishments was undoubtedly fixed and the problem to be faced was whether the Establishments had got the distribution of effort right. Both of the components of cost effectiveness were extraordinarily difficult to determine. How much it was really worth to prevent one accident in ten years' flying was itself difficult to evaluate. Again it was difficult to assess the cost of trying to do this.

Mr. Hufton said he had gained the impression that Loading Actions workers were uneasy about the nature of the manoeuvres that were inserted into calculations and uncertain whether these were completely pilot-induced or whether they were gust-induced with some pilot assistance. Unfortunately this subject, which was most responsible for their uncertainty, was the very one which would be most difficult to pursue. Difficulty arose not only on account of cost but because the foundations for the study of pilot manoeuvres clearly lay in pilot psychology. The basic understanding of the relationship between the task and how, on a kind of frequency spectrum basis, the man was likely to go about it, was completely non-existent. He thought that this knowledge had to be built up afresh on each aeroplane and so there was not much opportunity to make forecasts. Hence this was a difficult subject. He felt that a big attempt had to be made to get this straight.

Mr. Hufton said it was necessary to ensure that the available effort was directed to where it would do most good: this might not be, as appeared at first sight, the area of the greatest possible uncertainties. It might not be possible to do anything about such an area since the fact that it was an area of uncertainty indicated that it was one where progress had been difficult. He referred to Prof. Chilver's statement that Loading Actions was just coming of age. Although it might then have been called a different subject, he had been reminded, in the discussion about the rebound ratio of tyres, that it was almost twentyfive years since he had written a paper about the interactions between aerodynamics, the rebound ratio of tyres and undercarriages and the difficulty of landing naval aircraft. He thought, therefore, that Loading Actions had well and truly come of age.

At this point, Mr. Hufton invited contributions from the floor. None was forthcoming, however, and he therefore proceeded to his 'summing-up'.

CHAIRMAN'S SUMMING-UP

Mr. Hufton suggested that Prof. Chilver had summed up people's feelings very well and since he had just expressed his own views he did not wish to add a great deal. However, he hoped that those who had attended would agree with him that it had been an extremely useful meeting. He would personally like to see the development of an organisation whereby there could be more and deeper discussions about more restricted subjects. However, that implied that one would run a continuous series of symposia and never do any work, which he did not think would be a very effective way of conducting one's enterprises. He felt that the day's discussions had been very useful and to the point. He thanked everyone who had attended the meeting for making their contributions.

Appendix A

LIST OF DELEGATES

Adams, P.D.	Structures Department, R.A.E.
Anstee, R.F.W.	Structures Department, R.A.E.
Appleyard, D.C.	Scientific Research (Air)/Structures, M.O.A.
Argyris, Prof. J.H.	Imperial College, London
Atkinson, R.J.	Structures Department, R.A.E.
Baines, R.	Hawker Siddeley Aviation, Hatfield
Baldock, J.C.A.	Structures Department, R.A.E.
Barnes, J.R.	Mechanical Engineering Department, R.A.E.
Beele, B.J.	British Aircraft Corporation, Preston
Betts, R.B.	Electro-Hydraulics
Bishop, Prof. R.E.D.	University College, London
Bramwell, Dr. A.R.S.	The City University, London
Brown, H.	Hawker Siddeley Aviation, Hatfield
Buchanan, S.	The City University, London
Bullen, N.I.	Structures Department, R.A.E.
Burns, Mrs. A.	Structures Department, R.A.E.
Burt, M.E.	Road Research Laboratory
Cardrick, A.W.	Structures Department, R.A.E.
Chaplin, J.C.	Air Registration Board
Chilver, Prof. A.H.	University College, London
Clark, W.M.	Hawker Siddeley Aviation, Kingston
Clarkson, Prof. B.L.	Southampton University
Coles, W.W.	Hawker Siddeley Aviation, Hatfield
Cornall, P.N.	British Aircraft Corporation (Guided Weapons), Filton
Crabtree, Dr. L.F.	Aerodynamics Department, R.A.E.
Curran, J.K.	Structures Department, R.A.E.
Currie, J.P.	British Aircraft Corporation, Weybridge
Czaykowski, T.	Structures Department, R.A.E.
Davies, Dr. G.	Imperial College, London
Davies, I.C.	A.O.R.B., Board of Trade

LIST OF DELEGATES (Contd)

Day, A.	R.D.T.2, Ministry of Aviation
Dickinson, R.P.	D(R.A.F.)B, Ministry of Aviation
Dovey, J.	British Aircraft Corporation, Preston
Dow, W.T.	Hawker Siddeley Aviation, Hatfield
Elms, P.	Hawker Siddeley Aviation, Hatfield
Evans, J.Y.G.	Aerodynamics Department, R.A.E. (Bedford)
Evans, R.G.	British Aircraft Corporation, Weybridge
Ewing, H.G.	Structures Department, R.A.E.
Fisher, I.A.	Aeroplane and Armament Experimental Establishment
Foster, D.N.	Aerodynamics Department, R.A.E.
Fox, W.A.	Hatfield College of Technology
Fraser-Mitchell, A.H.	Handley Page
Gandy, R.W.	Secretary, Aeronautical Research Council
Garner, H.C.	National Physical Laboratory
Goldberg, C.	Dowty Rotol
Grinstead, F.	A.D./P.S.M. 2, Ministry of Aviation
Guyett, P.R.	Structures Department, R.A.E.
Haile, A.V.	Farnborough Technical College
Haines, A.B.	Aircraft Research Association
Hall, H.	Structures Department, R.A.E.
Ham, Dr. A.C.	Structures Department, R.A.E.
Hancock, Dr. G.J.	Queen Mary College, London
Hare, R.M.	Hawker Siddeley Aviation, Hatfield
Harris, D.	Handley Page
Harris, Dr. G.Z.	Structures Department, R.A.E.
Harris, K.D.	College of Aeronautics
Hawkins, F.J.	Structures Department, R.A.E.
Heath, W.G.	Hawker Siddeley Aviation, Woodford
Heath-Smith, J.R.	Structures Department, R.A.E.
Heaton, A.D.	British Aircraft Corporation, Filton
Henniker, H.D.	British European Airways

LIST OF DELEGATES (Contd)

Henwood, M.J.	Structures Department, R.A.E.
Heron, K.H.	Structures Department, R.A.E.
Hills, R.	Aircraft Research Association
Hitch, H.P.Y.	British Aircraft Corporation, Weybridge
Hopkin, H.R.	Aerodynamics Department, R.A.E.
Houghton, E.R.	Hatfield College of Technology
Hovell, P.B.	Structures Department, R.A.E.
Howard, H.B.	Loading Actions Sub-Committee, A.R.C.
Howe, J.M.	Hatfield College of Technology
Hufton, P.A.	Deputy Director (A), R.A.E.
Hunt, G.K.	Aerodynamics Department, R.A.E.
Keen, E.D.	Dowty Rotol
King, G.E.	Structures Department, R.A.E.
Kirkby, W.T.	Structures Department, R.A.E.
Kitchenside, A.W.	British Aircraft Corporation, Weybridge
Kite, R.J.	Structures Department, R.A.E.
Knell, K.A.J.	R.D.T.2, Ministry of Aviation
Knight, T.A.	Structures Department, R.A.E.
Küchemann, Dr. D.	Aerodynamics Department, R.A.E.
Lambourne, N.C.	National Physical Laboratory
Landon, R.H.	Aircraft Research Association
Lang, J.A.	Aeroplane and Armament Experimental Establishment
Lethem, Sqn. Ldr. D.A.	Experimental Flying Department, R.A.E.
Lewis, D.R.	Structures Department, R.A.E.
Mabey, D.G.	Aerodynamics Department, R.A.E. (Bedford)
Maine, R.	D./F.S. Ministry of Aviation
Mair, Prof. W.A.	Cambridge University
Mangler, Dr. K.W.	Aerodynamics Department, R.A.E.
Marsden, P.	Aircraft Research Association
Maull, Dr. D.J.	Cambridge University
McElhinney, D.M.	British Aircraft Corporation, Weybridge
McKenzie, P.J.	Hawker Siddeley Aviation, Kingston

LIST OF DELEGATES (Contd)

Mead, Dr. D.J.	Southampton University
Mitchell, C.G.B.	Structures Department, R.A.E.
Morris, B.	British Aircraft Corporation, Weybridge
Needham, D.	Hawker Siddeley Aviation, Brough
Oaks, J.K.	Structures Department, R.A.E.
Ormerod, A.O.	Aerodynamics Department, R.A.E. (Bedford)
Owen, Mrs. E.M.	Structures Department, R.A.E.
Pankhurst, Dr. R.C.	National Physical Laboratory
Parkinson, Dr. A.G.	University College, London
Parks, M.J.	British Aircraft Corporation (Guided Weapons), Filton
Pendlebury, H.	Electro-Hydraulics
Pinsker, W.J.G.	Aerodynamics Department, R.A.E. (Bedford)
Pope, Dr. G.G.	Structures Department, R.A.E.
Purslow, D.	Structures Department, R.A.E.
Reddaway, J.L.	Cambridge University
Redmayne, C.	Structures Department, R.A.E.
Richards, P.F.	Air Registration Board
Ridland, D.M.	Aerodynamics Department, R.A.E.
Ripley, E.L.	Structures Department, R.A.E.
Roberts, T.A.	Structures Department, R.A.E.
Rochefort, H.E.J.	Hawker Siddeley Aviation, Kingston
Rose, R.	Aerodynamics Department, R.A.E. (Bedford)
Ross, Dr. A.J.	Aerodynamics Department, R.A.E.
Rossiter, J.E.	Aerodynamics Department, R.A.E.
Russell, J.B.	The City University, London
Samson, D.R.	Hatfield College of Technology
Seal, A.C.G.	Air Registration Board
Seddon, Dr. J.	D./S.R.(A), Ministry of Aviation
Sellers, G.D.	British Aircraft Corporation, Filton
Sharpe, W.E.	British Aircraft Corporation, Preston

LIST OF DELEGATES (Contd)

Smith, J.H.B.	Aerodynamics Department, R.A.E.
Spurr, F.A.	Aeroplane and Armament Experimental Establishment
Spurr, H.G.	Mechanical Engineering Department, R.A.E.
Starkey, R.D.	Structures Department, R.A.E.
Stone, Dr. D.E.W.	Structures Department, R.A.E.
Strange, K.A.	British Aircraft Corporation, Filton
Sturgeon, J.R.	Structures Department, R.A.E.
Symmons, R.W.	Structures Department, R.A.E.
Talbot, P.	Structures Department, R.A.E.
Taylor, A.S.	Structures Department, R.A.E.
Taylor, C.R.	Aerodynamics Department, R.A.E. (Bedford)
Taylor, J.	Aerodynamics Department, R.A.E.
Taylor, R. Hain	Mechanics Committee, A.R.C.
Templeton, H.	Mechanical Engineering Department, R.A.E.
Thomas, H.H.B.M.	Aerodynamics Department, R.A.E.
Thomas, Dr. K.	Imperial College, London
Thompson, J.S.	Aerodynamics Department, R.A.E. (Bedford)
Tye, W.	Air Registration Board
Tyler, B.A.	British Aircraft Corporation. Preston
Udall, H.	The City University, London
Vann, F.W.	Hawker Siddeley Aviation, Hatfield
Warren, C.H.E.	Structures Department, R.A.E.
Webb, D.R.B.	Structures Department, R.A.E.
Webber, D.A.	Structures Department, R.A.E.
Weber, Dr. J.	Aerodynamics Department, R.A.E.
Williams, Dr. D.	Structure Sub-Committee, A.R.C.
Williams, D.J.M.	A.O.R.B., Board of Trade
Williams, Dr. J.	Aerodynamics Department, R.A.E.
Winter, K.G.	Aerodynamics Department, R.A.E.
Wittrick, Prof. W.H.	Birmingham University
Wolfe, Dr. M.O.W.	A.D./A.D.R., Ministry of Aviation

LIST OF DELEGATES (Contd)

Wood, F.S.	R.A.F./A., Ministry of Aviation
Woodcock, D.L.	Structures Department, R.A.E.
Wright, M.D.	The City University, London
Yeomans, D.G.	British Overseas Airways Corporation
Young, Prof. A.D.	Queen Mary College, London

Appendix B

LIST OF ORGANISATIONS REPRESENTED

Aeronautical Research Council

Council

Standing Committees:	Aerodynamics Committee
	Mechanics Committee
	Propulsion Committee
Operational Committees:	Civil Aircraft Research Committee
	Naval Aircraft Committee
Committees:	Gust Research Committee
	Noise Research Committee
	Powered Lift Committee
Sub-Committees:	Fluid Motion Sub-Committee
	Hypersonics Sub-Committee
	Performance Sub-Committee
	Stability and Control Sub-Committee
	Loading Actions Sub-Committee
	Oscillation Sub-Committee
	Structure Sub-Committee
	Heat and Mass Transfer Sub-Committee

Computer Panel

Universities and Colleges

Birmingham University
Cambridge University
The City University, London
College of Aeronautics
Farnborough Technical College

Universities and Colleges (Contd)

Hatfield College of Technology

London University: Imperial, Queen Mary and University Colleges

Southampton University

The Aviation Industry

Aircraft Research Association Ltd.

British Aircraft Corporation (Operating) Ltd.: Filton, Preston, Weybridge and Guided Weapons Divisions

Dowty-Rotol Ltd.

Electro-Hydraulics Ltd.

Handley Page Ltd.

Hawker Siddeley Aviation Ltd.: Brough, Hatfield, Kingston and Woodford

Air Transport Operators

British European Airways Corporation

British Overseas Airways Corporation

Air Registration Board

Government Bodies

Board of Trade:	Aviation Operational Research Branch
Ministry of Aviation:	Headquarters
	Aeroplane and Armament Experimental Establishment
	Royal Aircraft Establishment (Aerodynamics, Experimental Flying, Mechanical Engineering, and Structures Departments)
Ministry of Technology:	National Physical Laboratory
Ministry of Transport:	Road Research Laboratory

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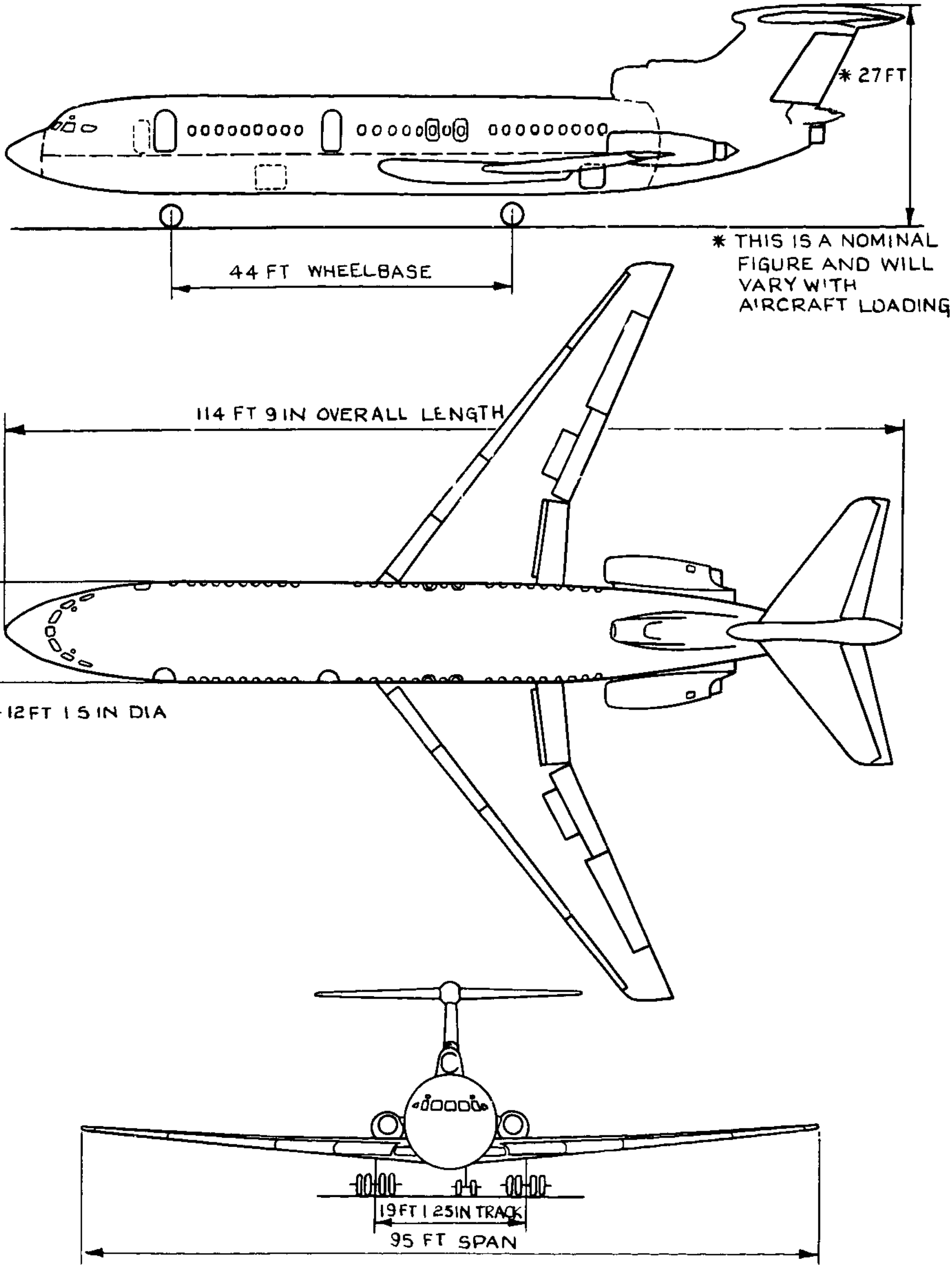


FIG. 1 GENERAL ARRANGEMENT

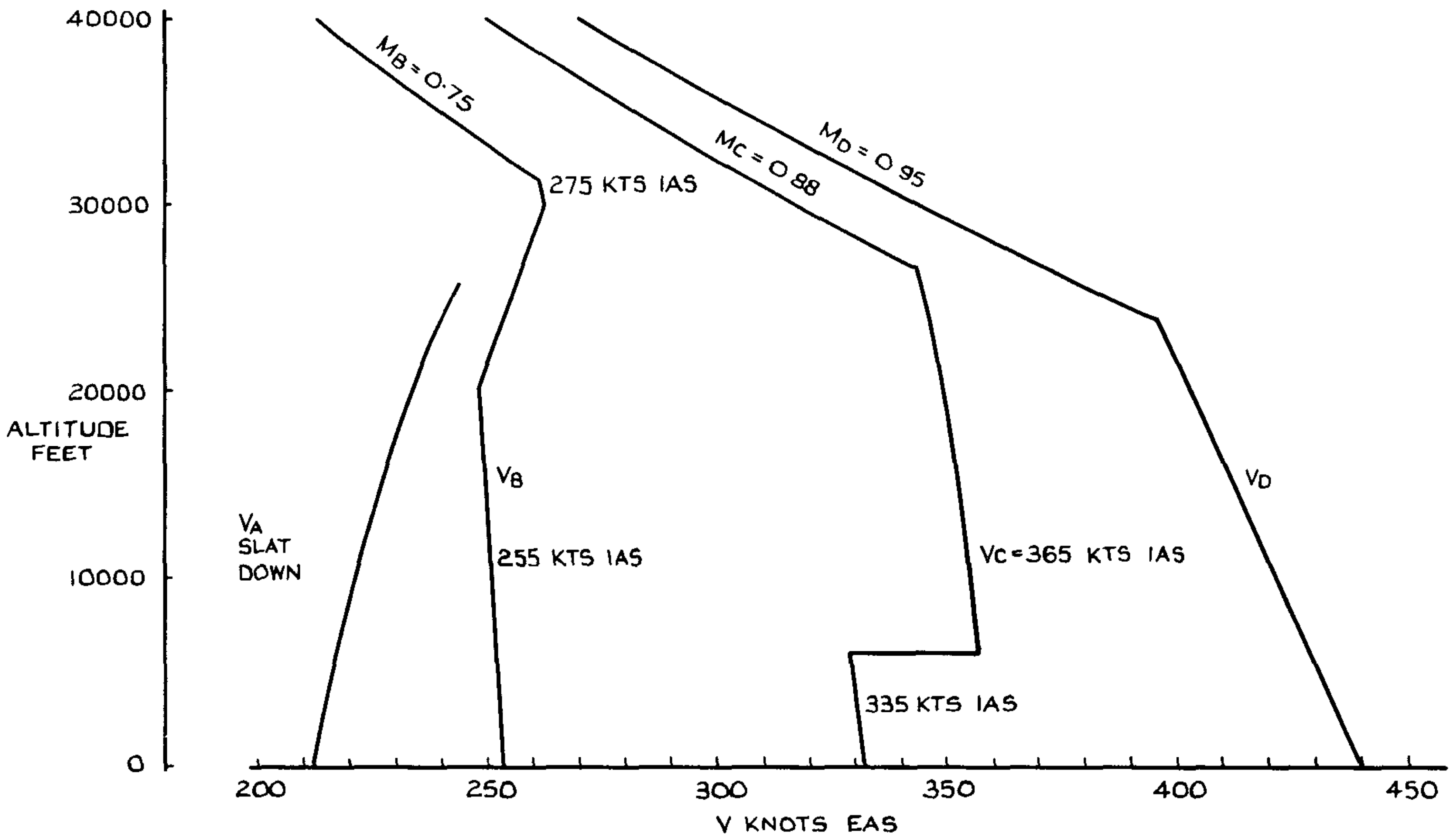


FIG. 2 VARIATION OF DESIGN SPEEDS WITH ALTITUDE

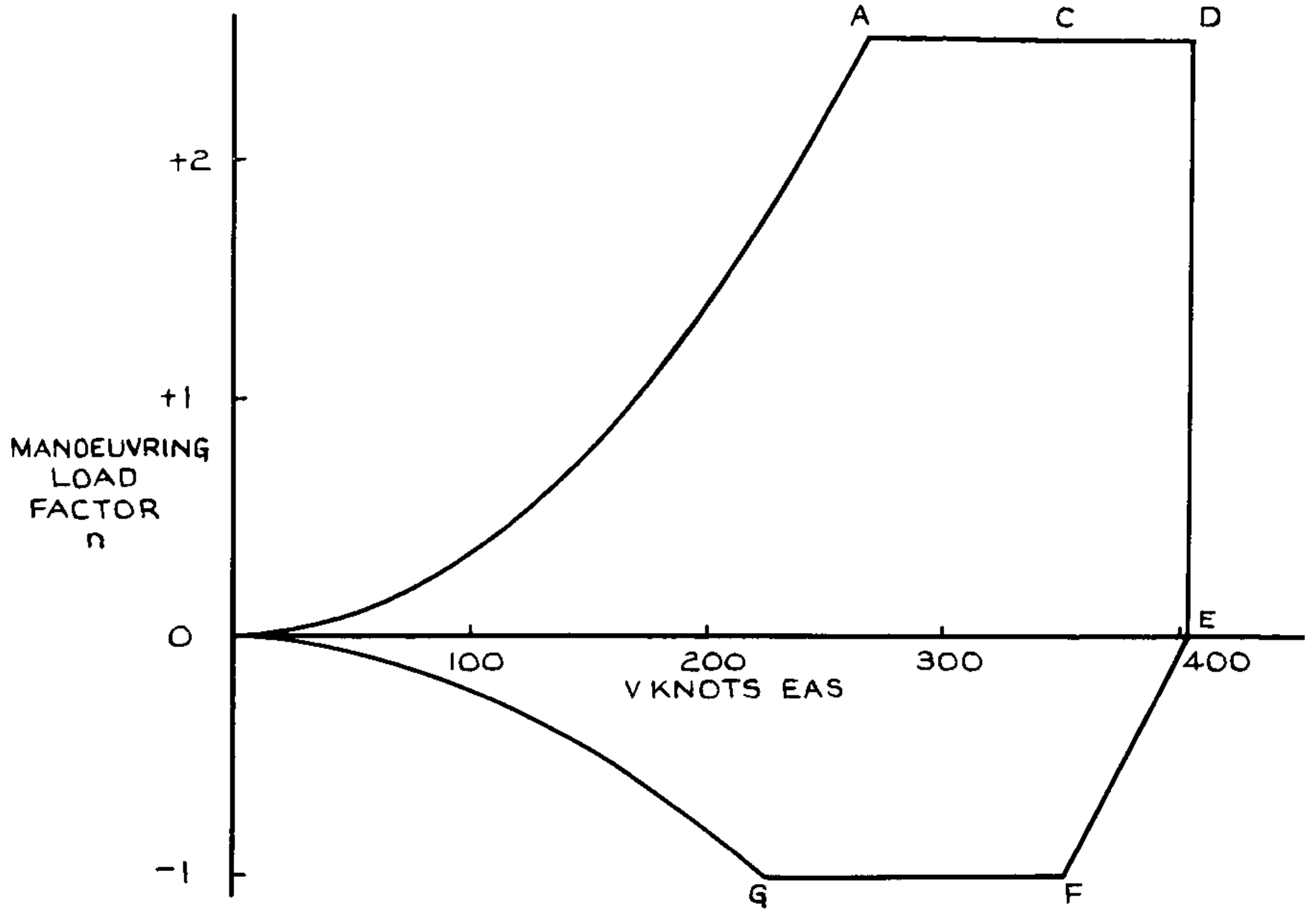


FIG. 3 MANOEUVRING ENVELOPE FOR HAWKER SIDDELEY 'TRIDENT' ALTITUDE 20000 ft

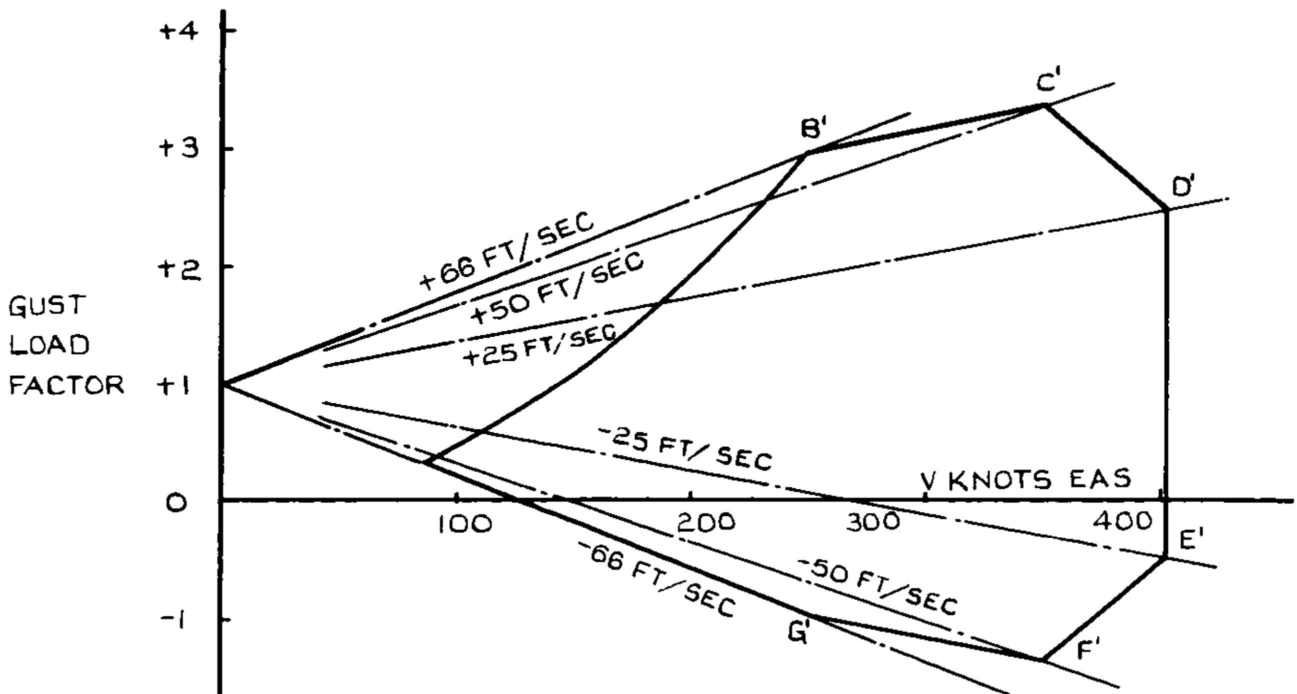
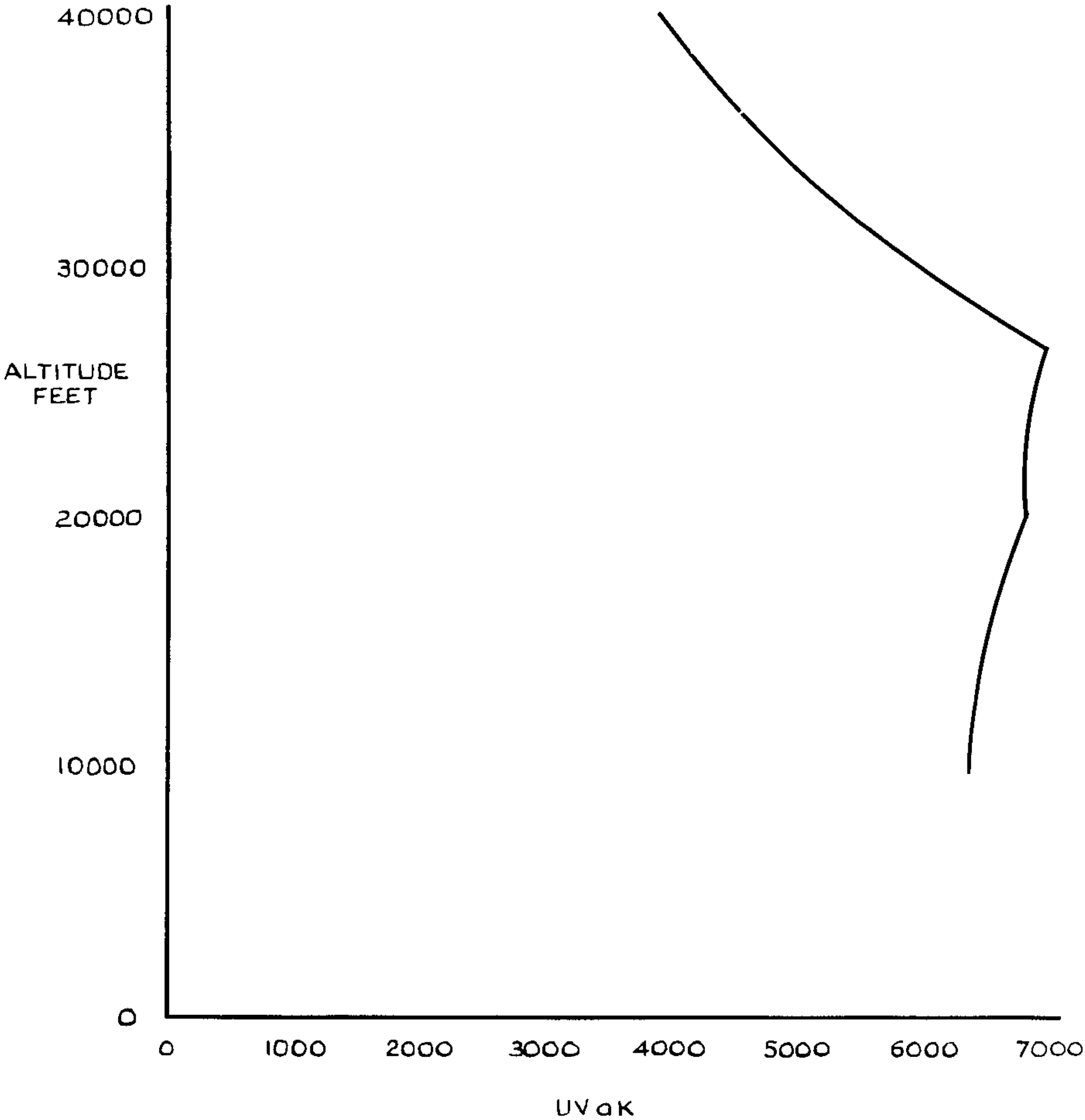


FIG.4 GUST ENVELOPE FOR HAWKER SIDDELEY 'TRIDENT' AIRCRAFT WEIGHT 99500 lb ALTITUDE 20000 ft



U = GUST VELOCITY ft/sec

V = CRUISING SPEED KNOTS EAS

a = WING LIFT CURVE SLOPE

K = GUST ALLEVIATING FACTOR

FIG. 5 CRITICAL ALTITUDE FOR 50 ft/sec GUST LOADS

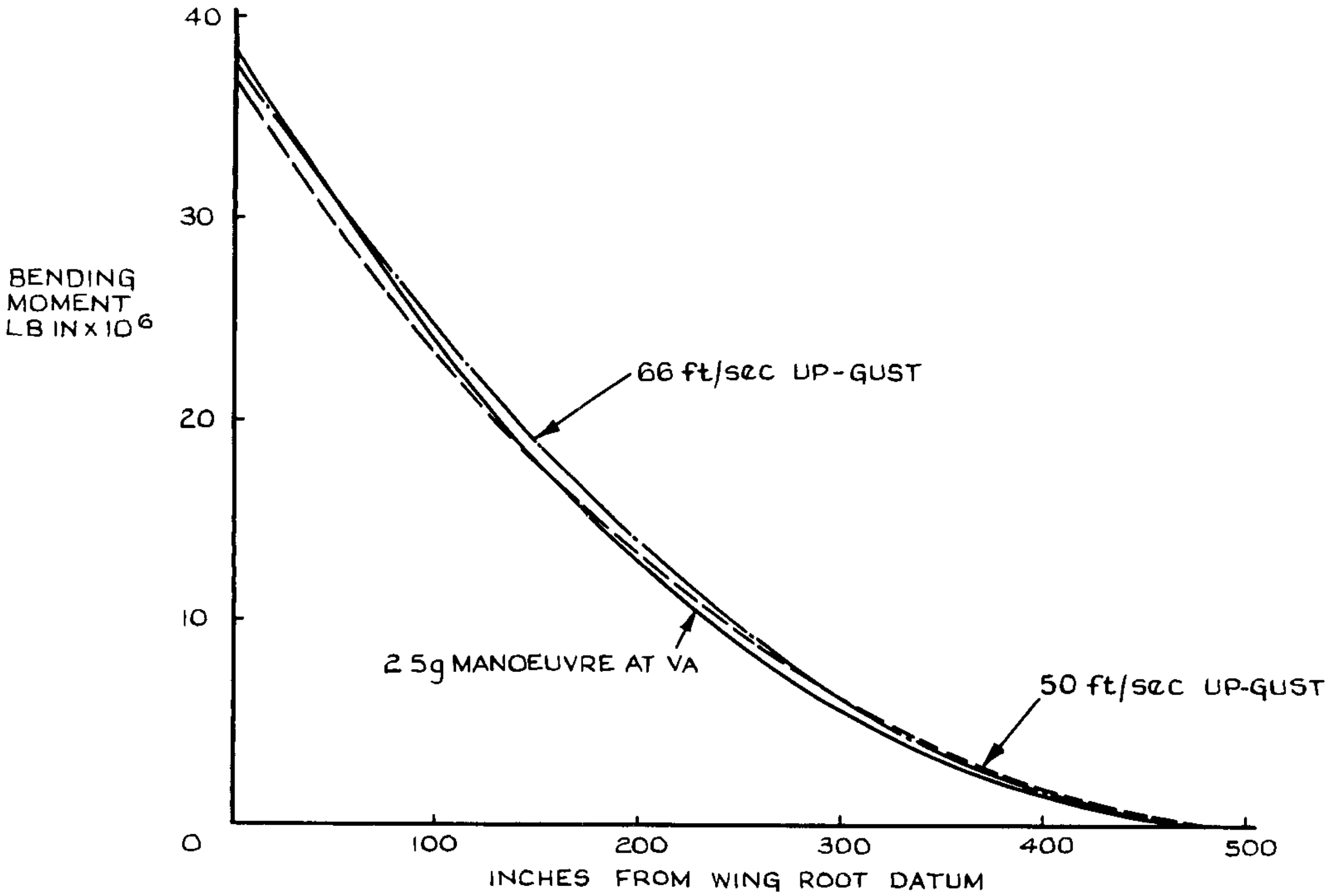


FIG. 6 DEVELOPED VERSION OF 'TRIDENT'-WING BENDING MOMENT DESIGN CASES

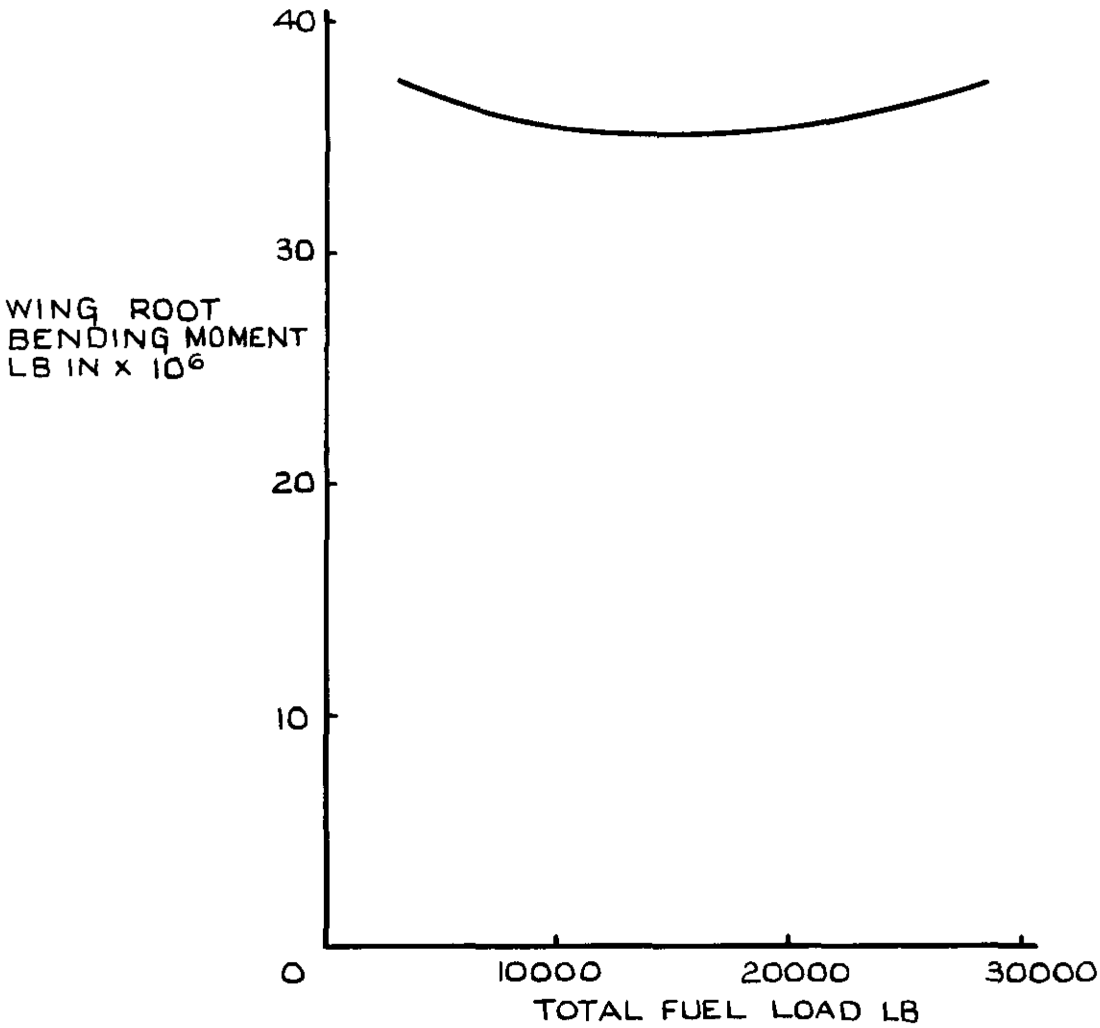


FIG. 7 VARIATION OF WING ROOT BENDING MOMENT WITH TOTAL FUEL LOAD IN WINGS
66 ft/sec UP-GUST AT V_B

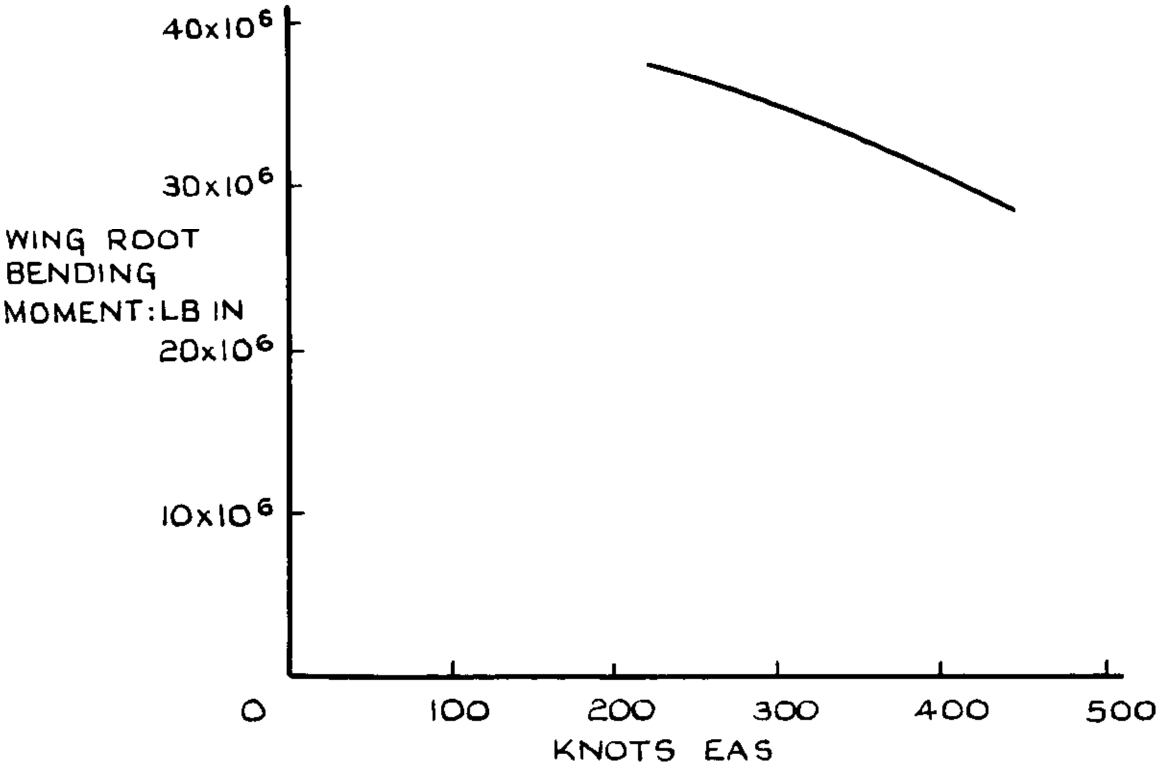


FIG.8 VARIATION OF WING ROOT BENDING MOMENT WITH SPEED: 2·5g MANOEUVRE AT SEA LEVEL

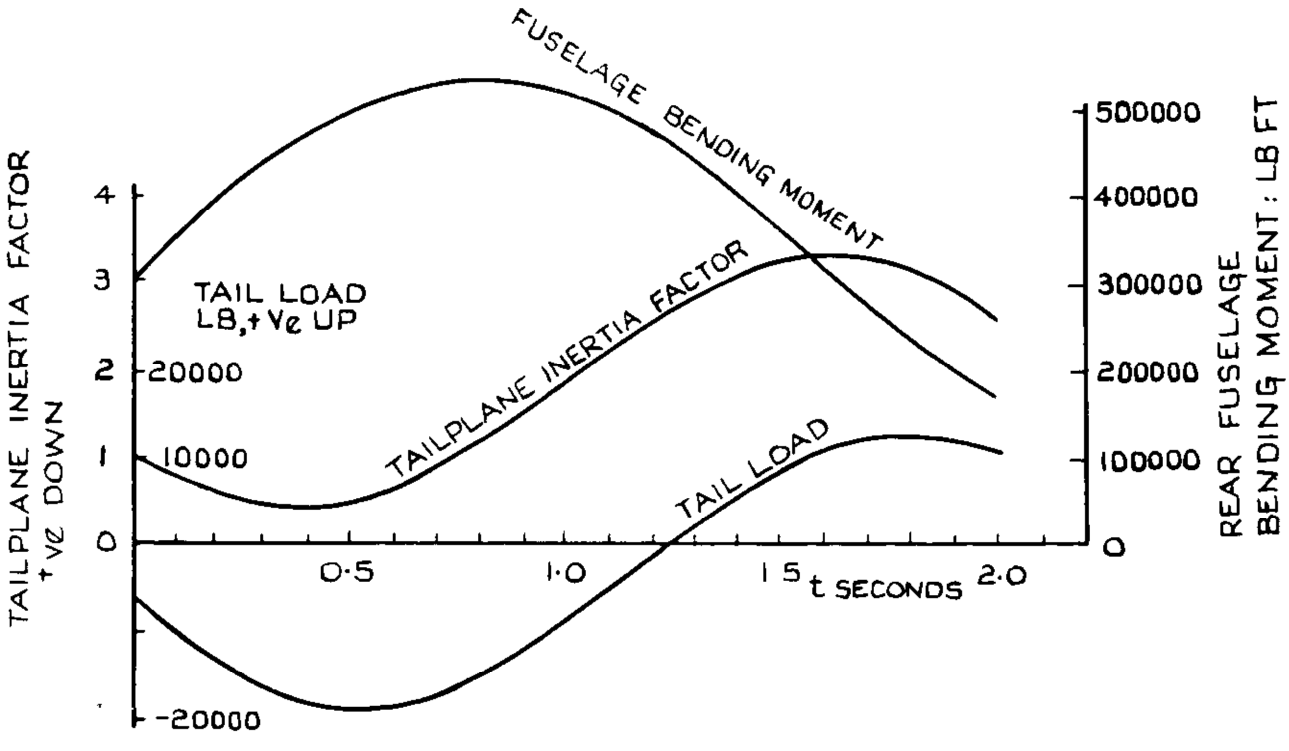


FIG 9 REAR FUSELAGE LOADS IN CHECKED MANOEUVRE CASE AT V_A

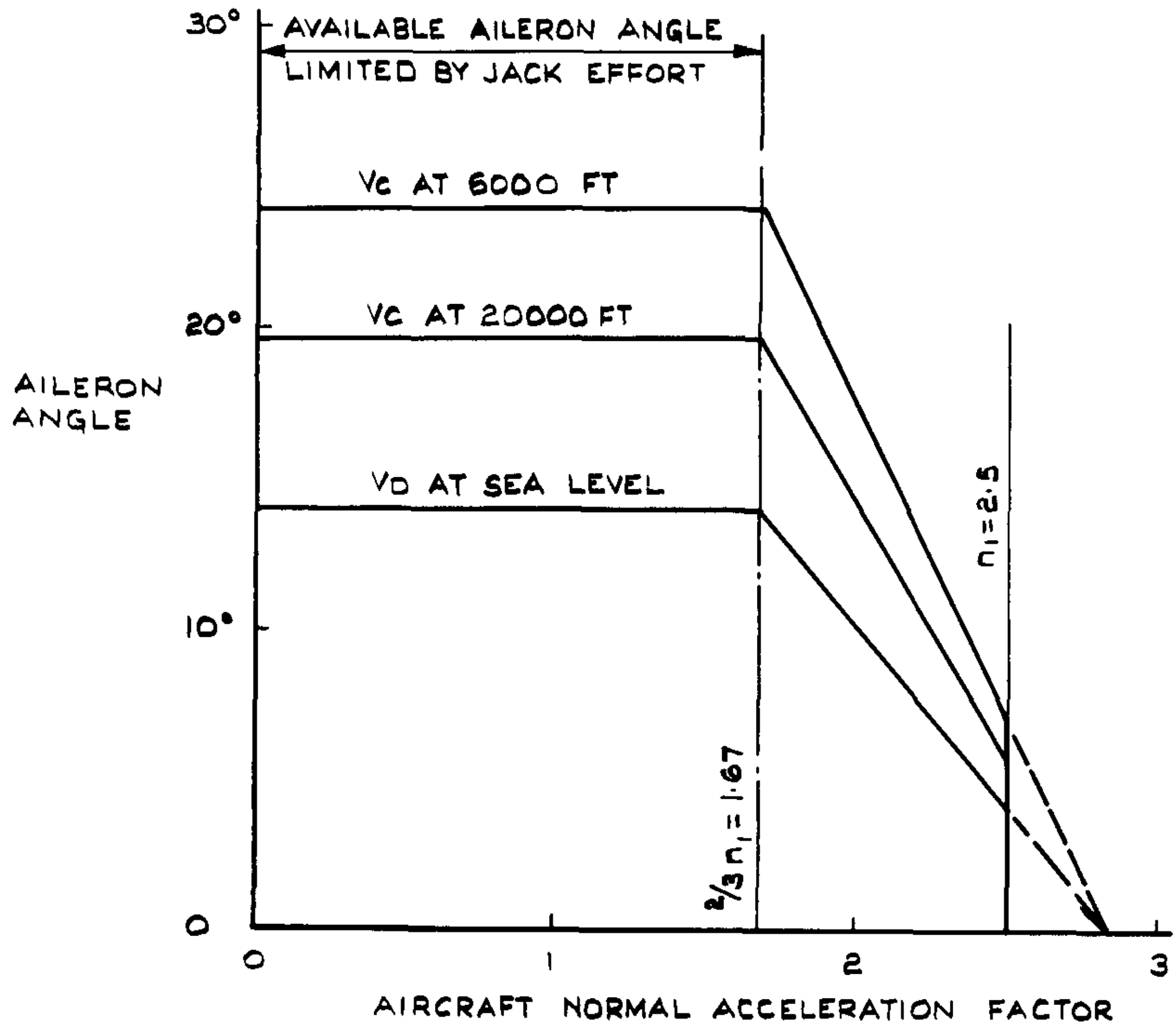


FIG.10 COMBINATIONS OF AILERON ANGLE AND G TO PRODUCE LIMIT LOADS IN THE WING

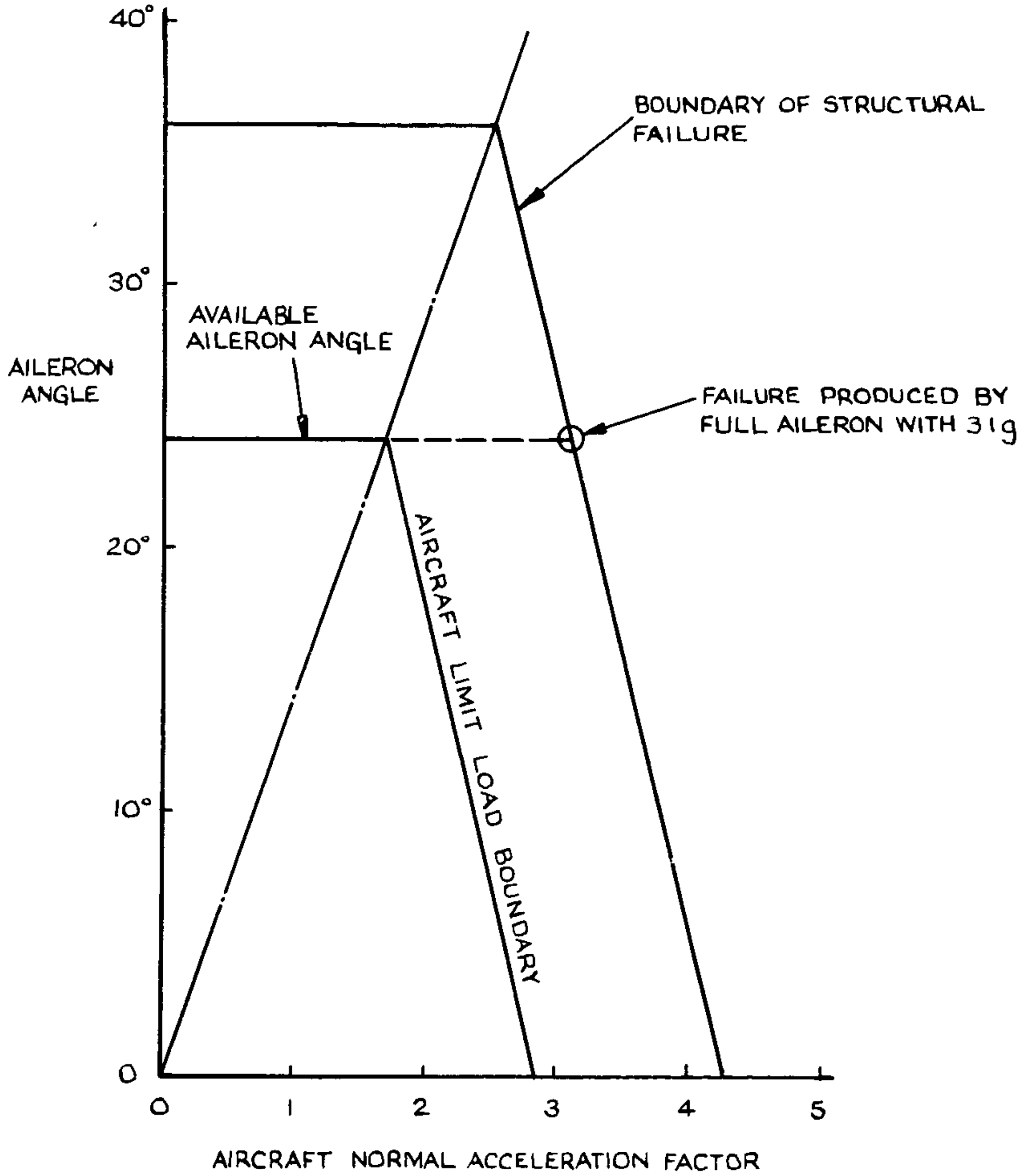


FIG.11 COMBINATIONS OF AILERON ANGLE AND G TO PRODUCE STRUCTURAL FAILURE OF WING AT Vc AT 6000 ft

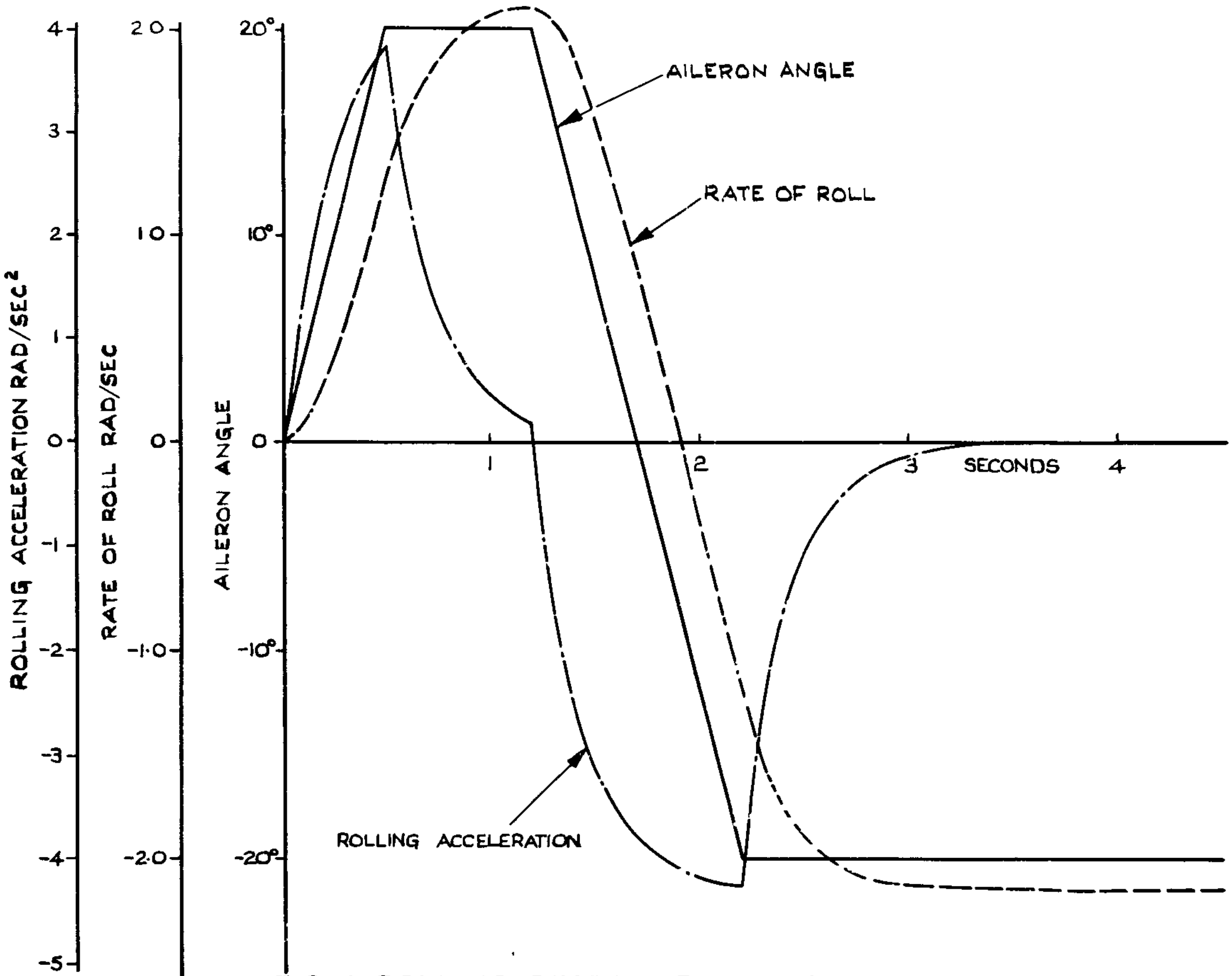


FIG 12 ROLLING RESPONSE IN AILERON CASES

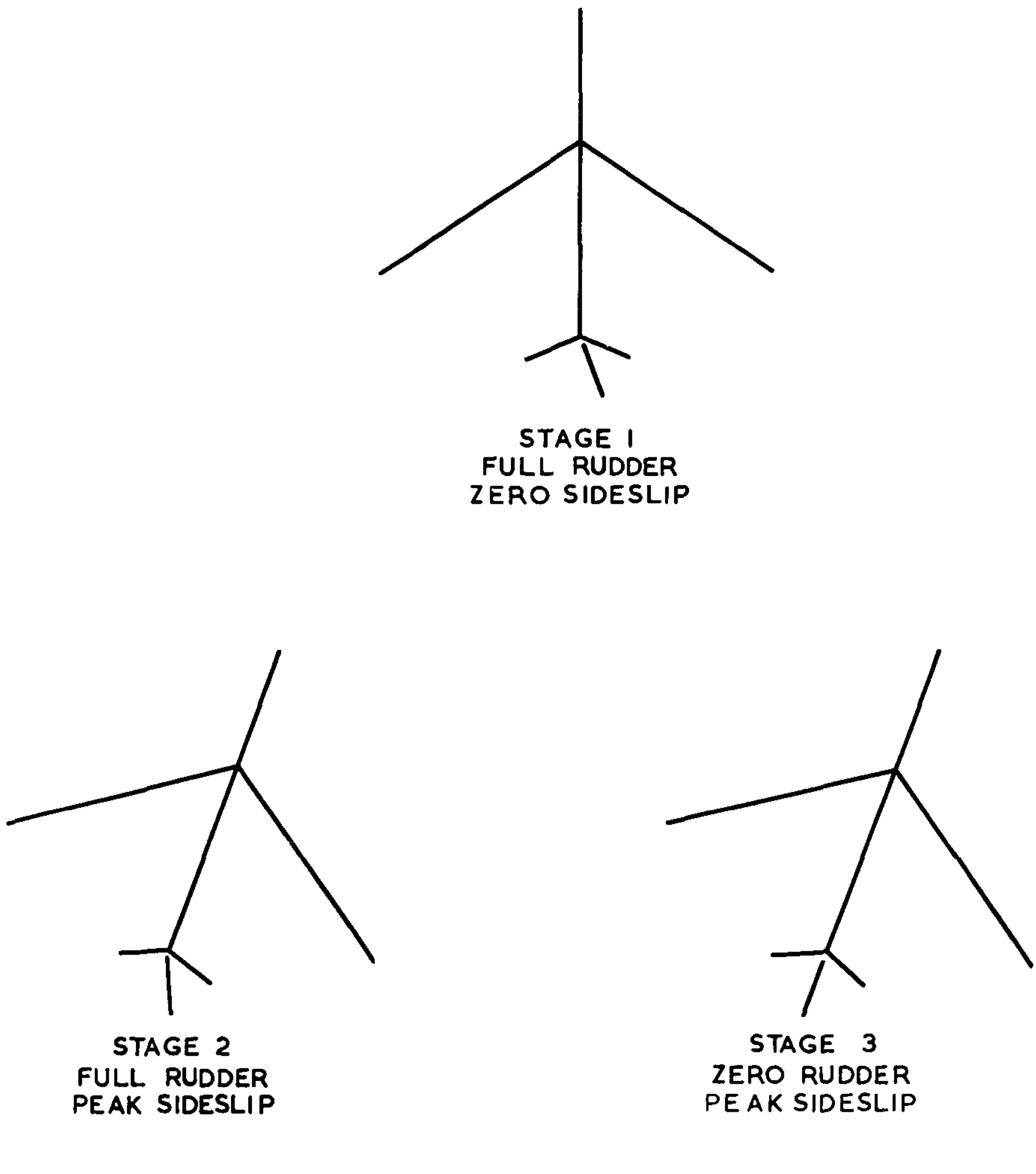


FIG 13 SCHEMATIC DIAGRAM OF AIRCRAFT ATTITUDE IN YAW MANOEUVRE CASES

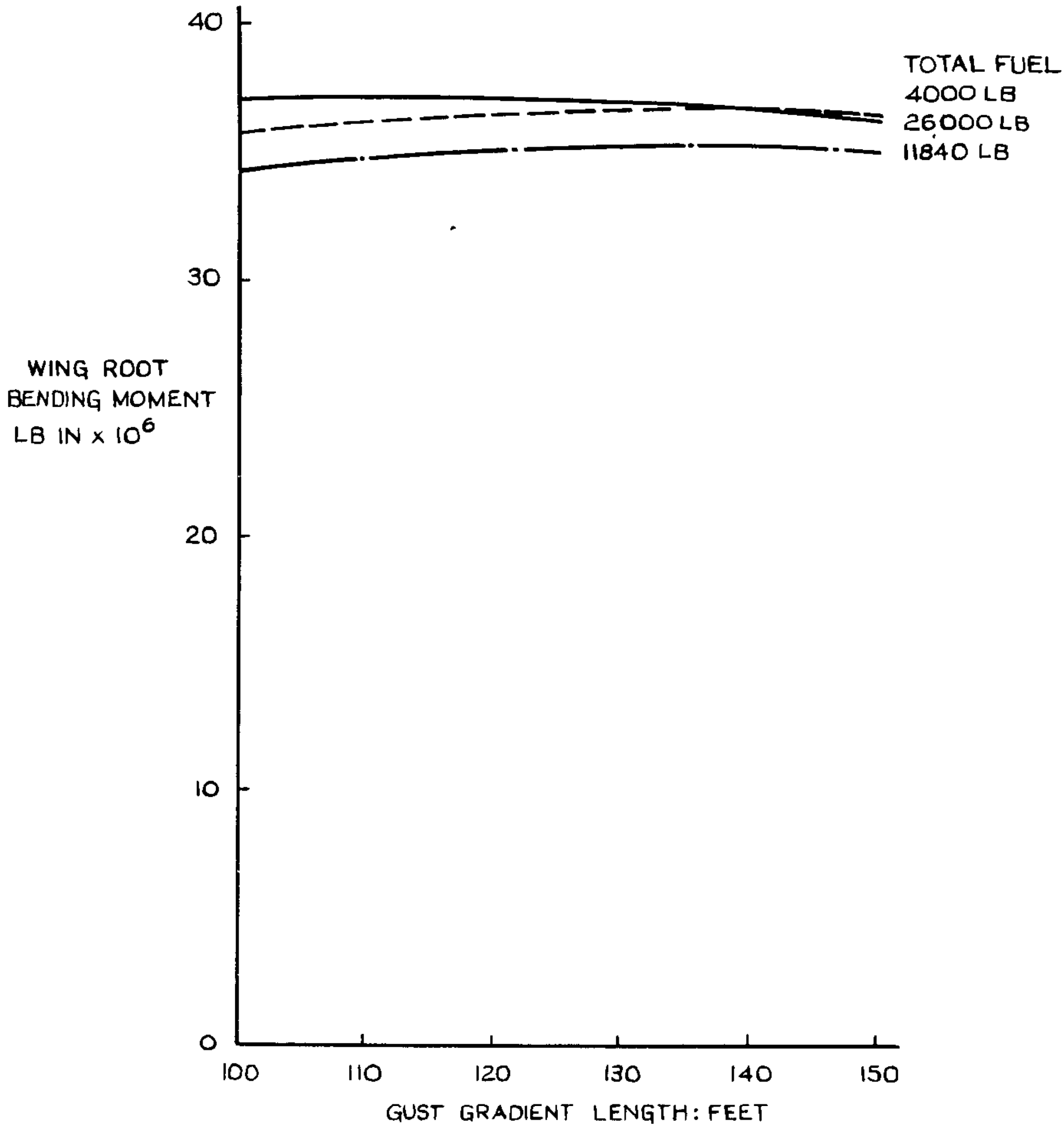


FIG 14 VARIATION OF WING ROOT BENDING MOMENT WITH GUST GRADIENT LENGTH
66 ft/sec UP-GUST AT V_B

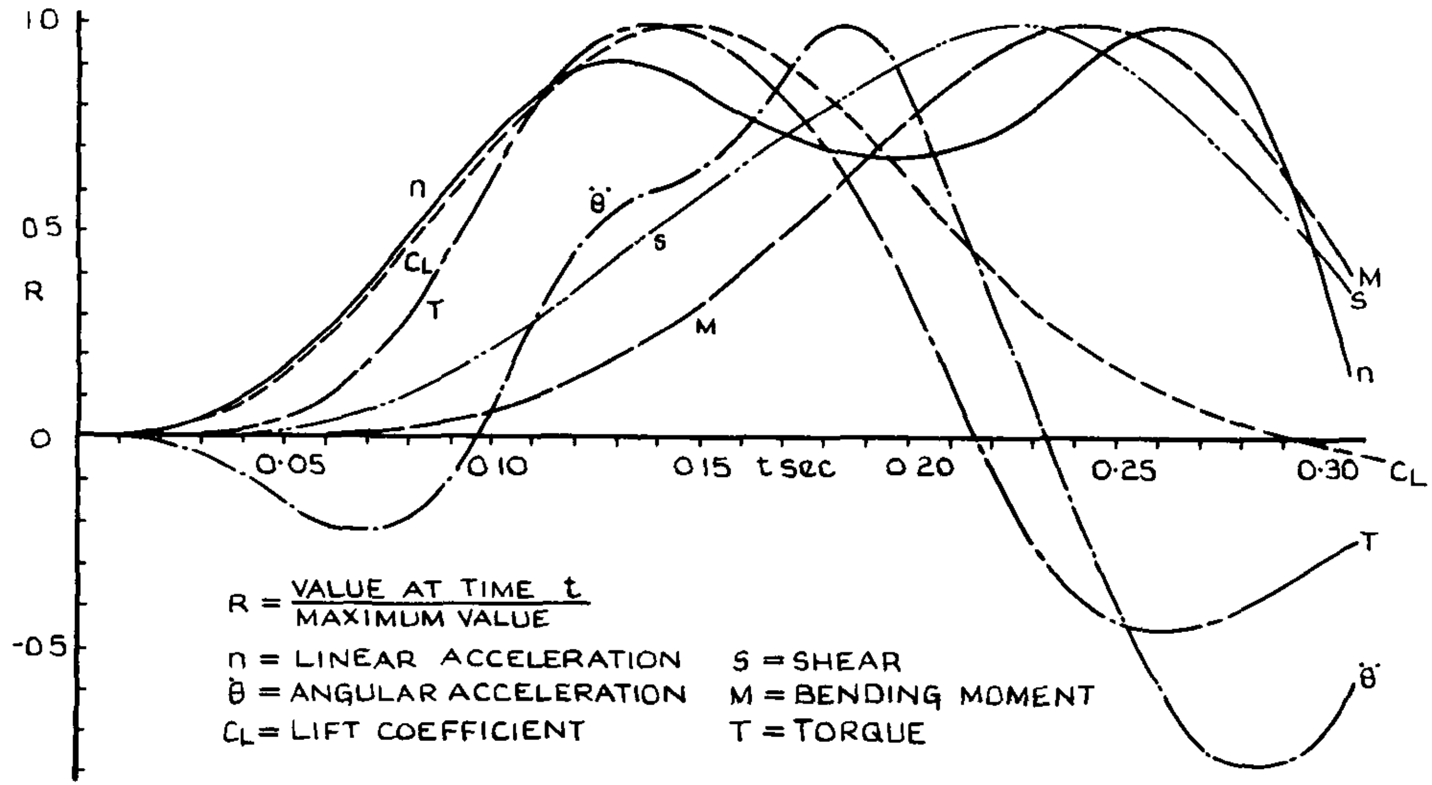


FIG. 15 TYPICAL VARIATION OF WING LOADS DUE TO UP-GUST WITH TIME

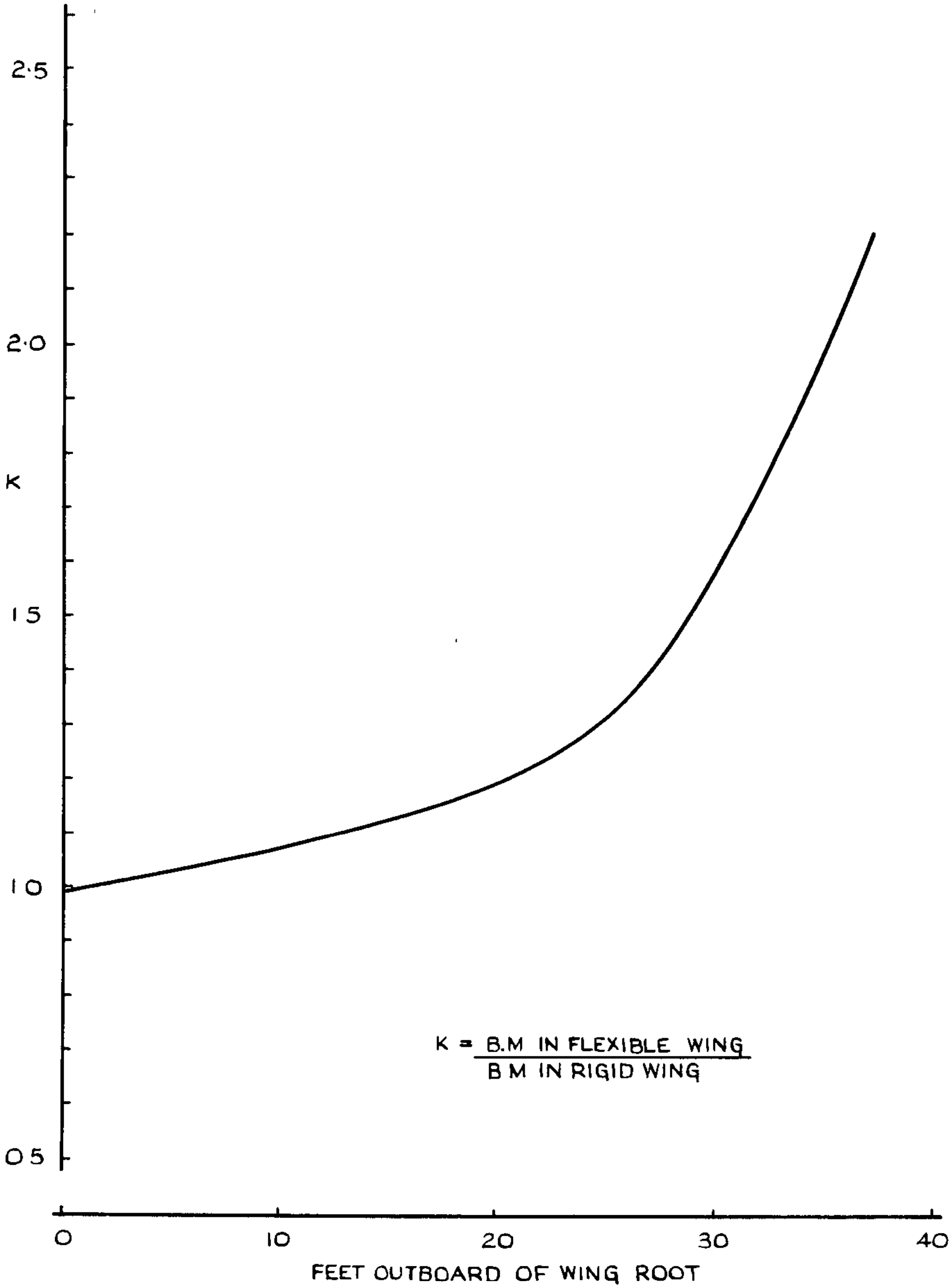


FIG.16 OVERSWING FACTOR ON WING BENDING MOMENT DUE TO VERTICAL GUST

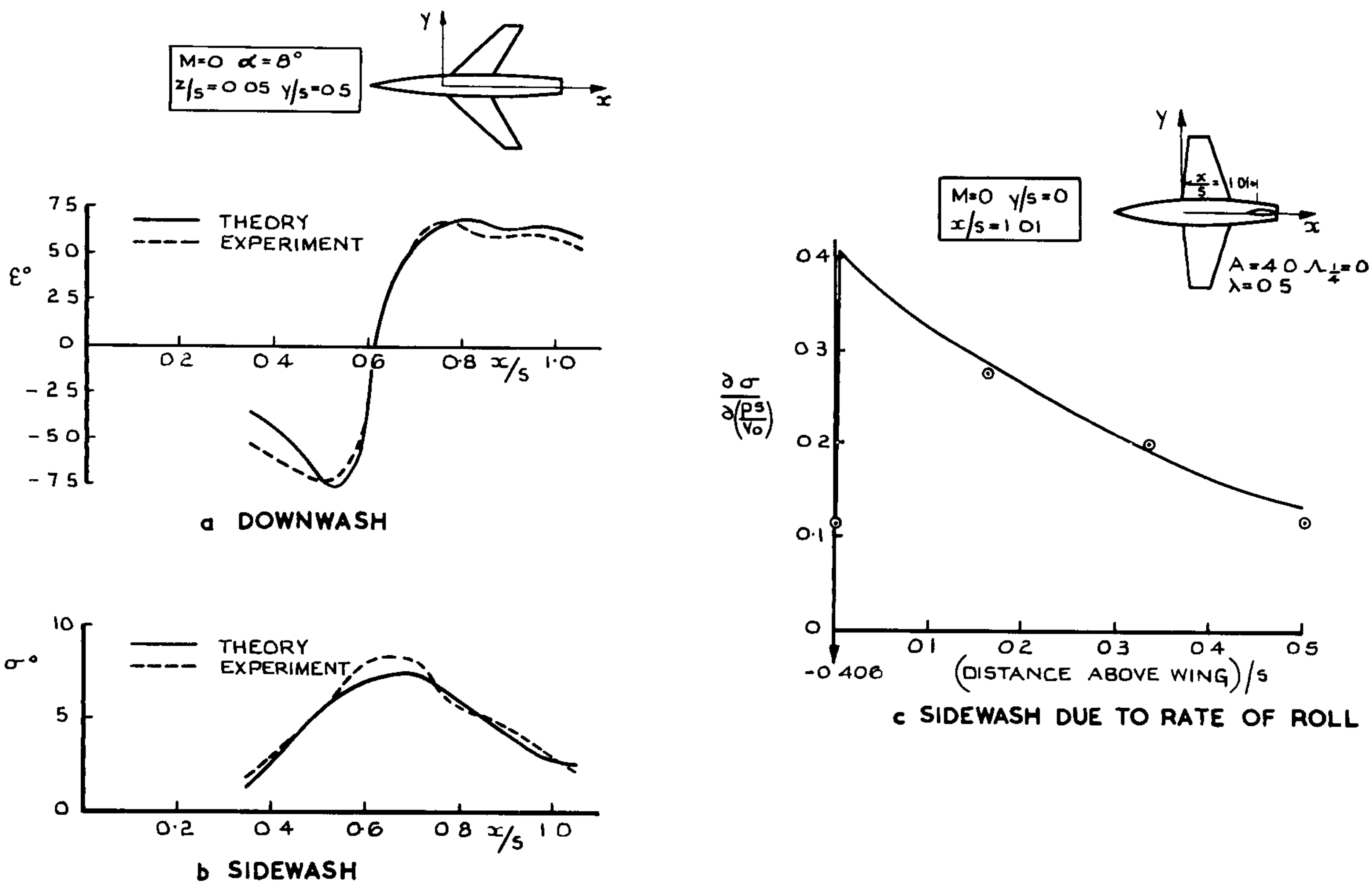


FIG.1 a-c COMPARISON OF CALCULATED AND MEASURED DOWNWASH AND SIDEWASH ANGLES

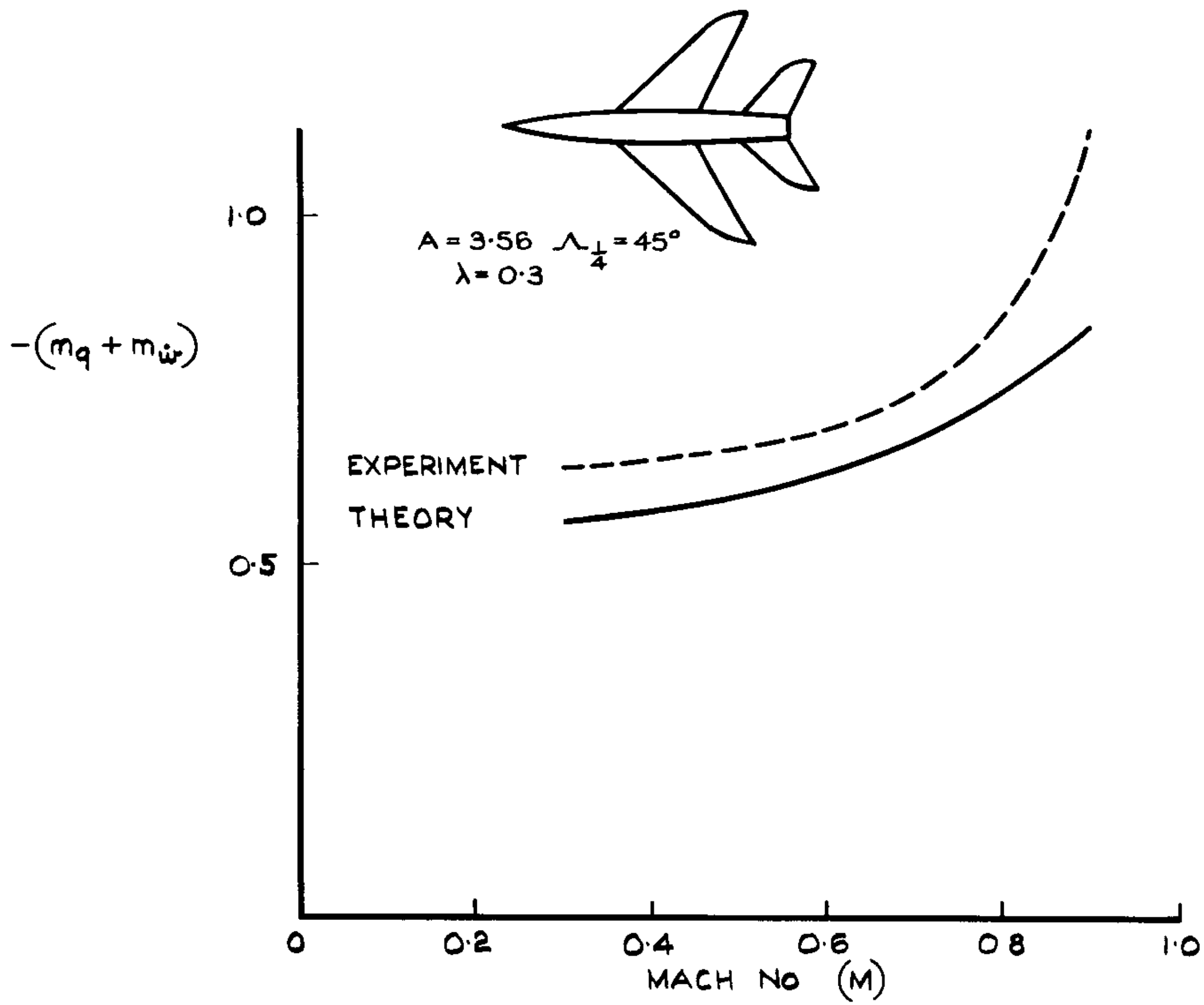


FIG. 2 TAILPLANE CONTRIBUTION TO THE TOTAL DAMPING-IN-PITCH DERIVATIVE

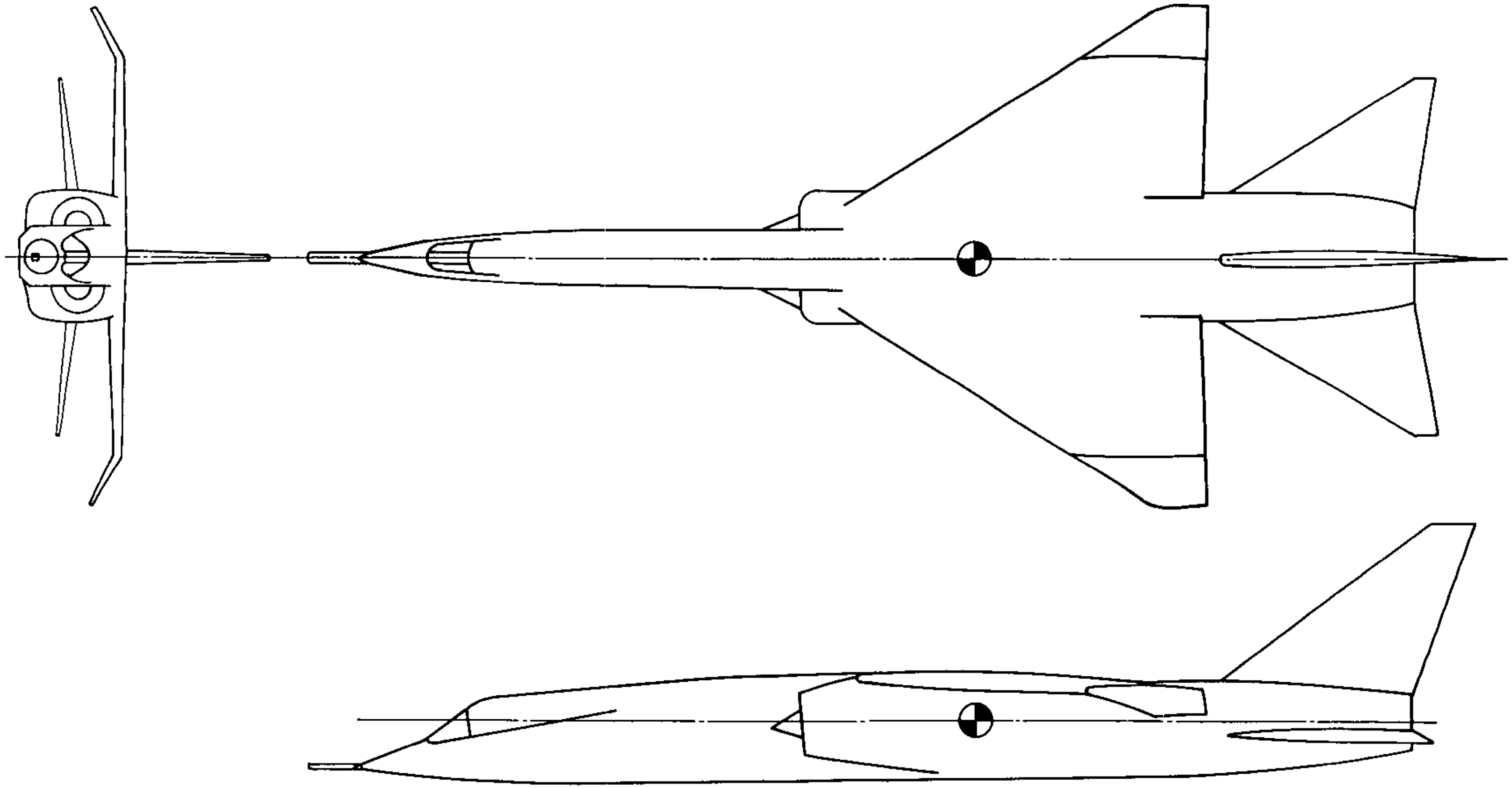


FIG. 3 GENERAL ARRANGEMENT OF MODEL

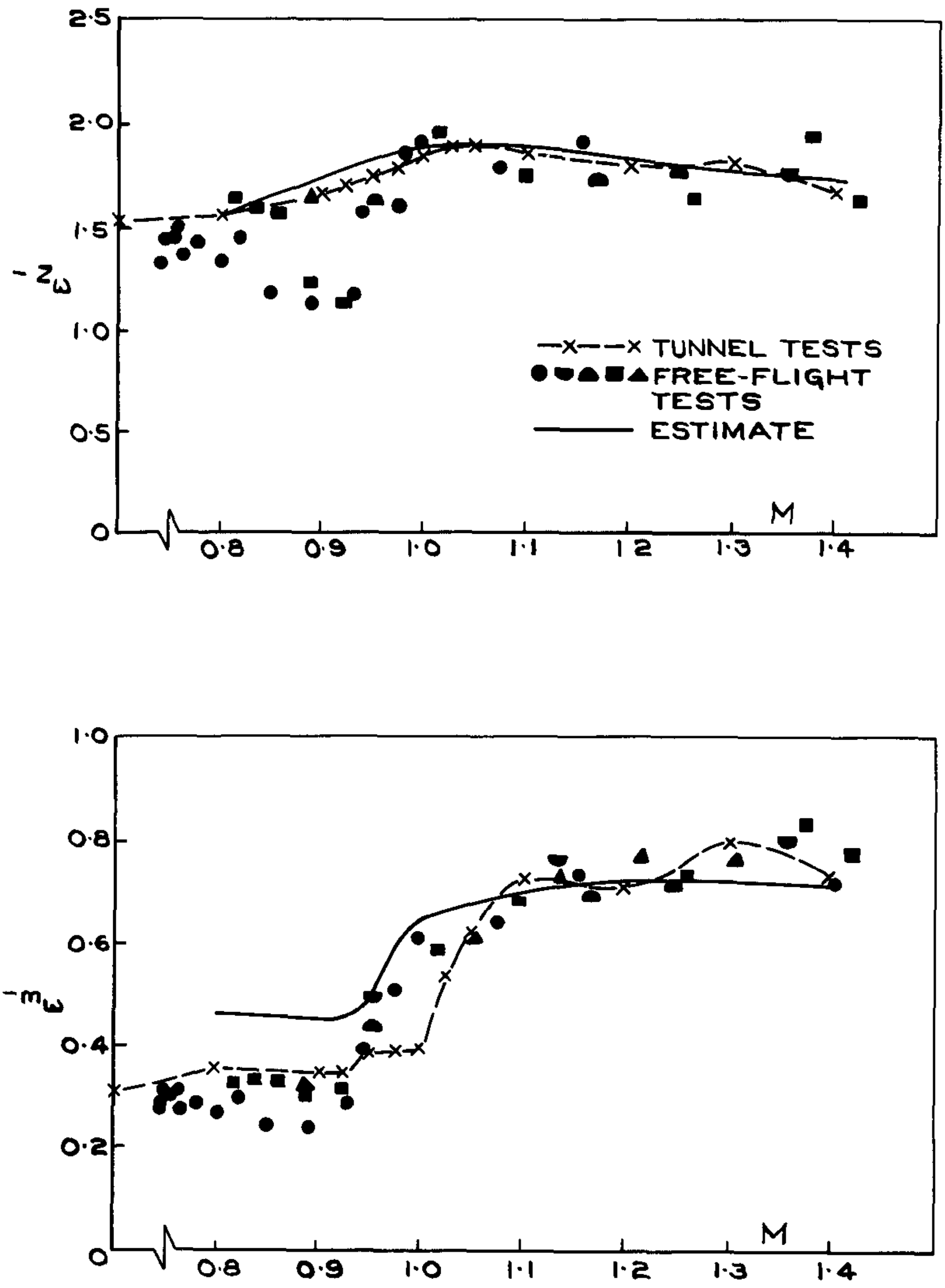


FIG. 4 MODEL OF FIG. 3 –
Z-FORCE DERIVATIVE DUE TO INCIDENCE, z_w
AND PITCHING MOMENT DERIVATIVE DUE TO INCIDENCE, m_w

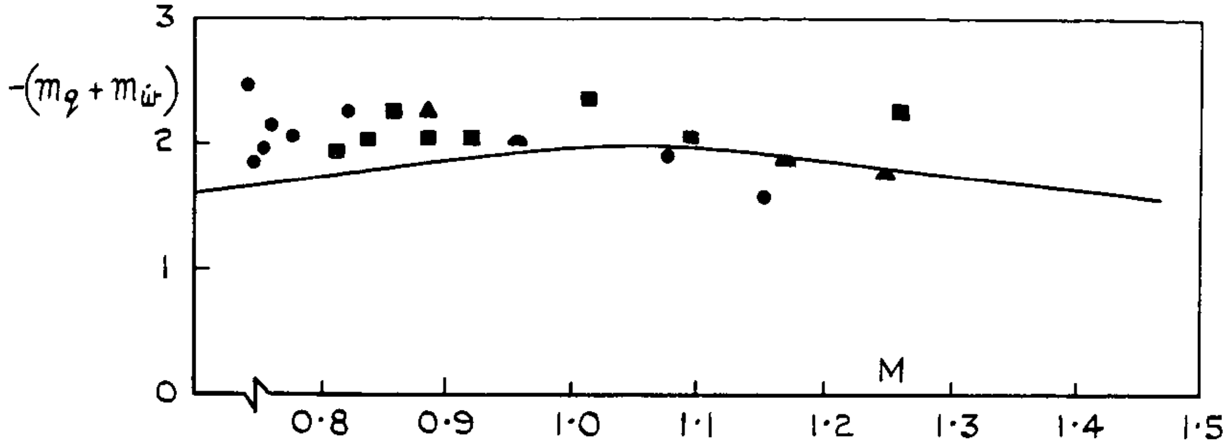


FIG. 5 MODEL OF FIG 3. ROTARY DAMPING-IN-PITCH DERIVATIVE, $-(m_q + m_{\dot{w}})$

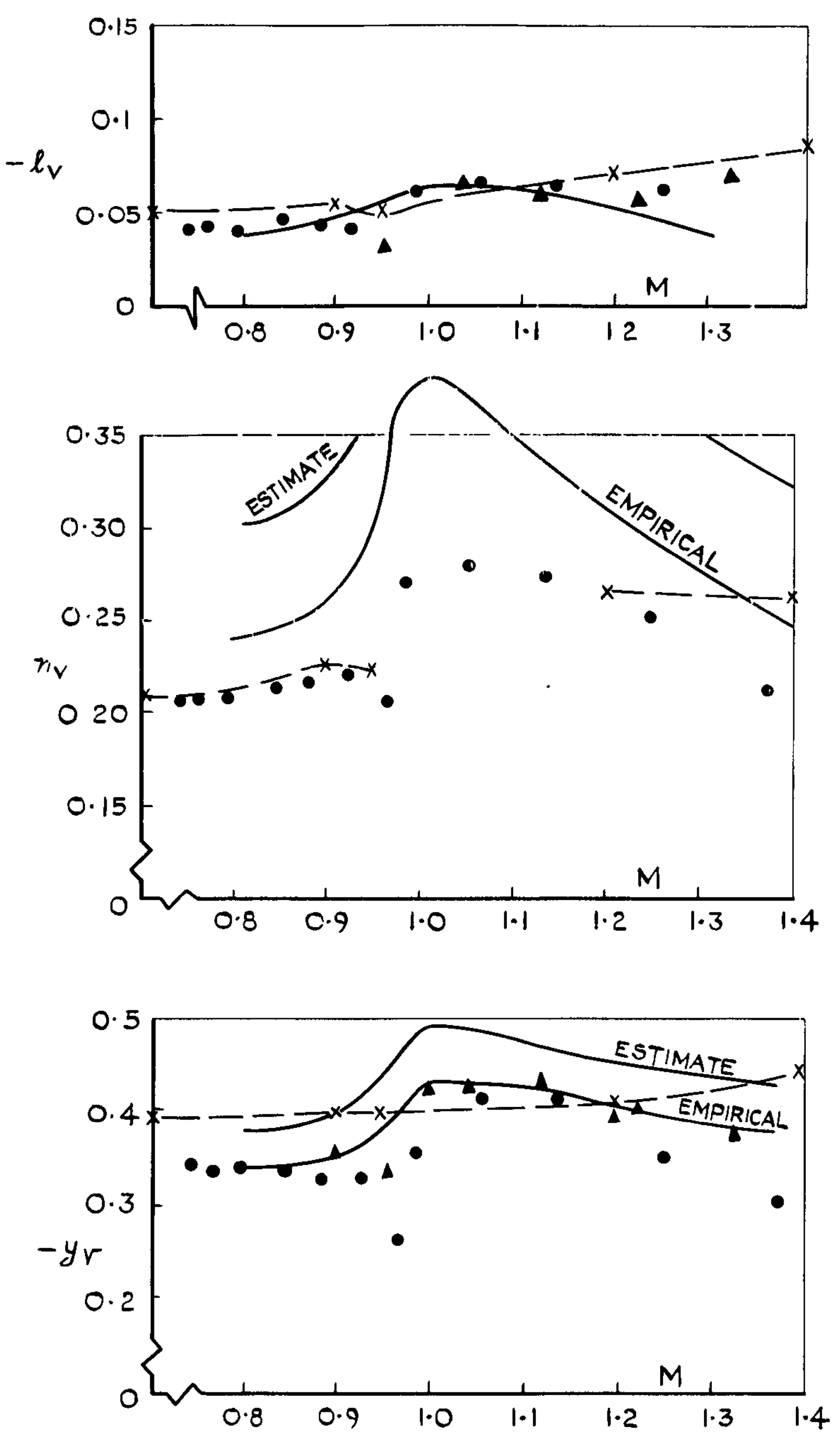


FIG.6 MODEL OF FIG. 3. SIDESLIP DERIVATIVES l_v, n_v, y_v

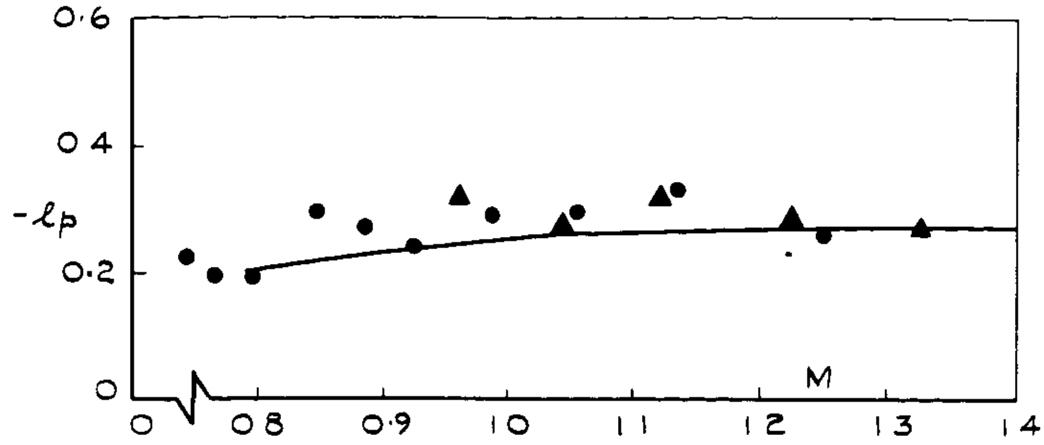


FIG 7 MODEL OF FIG 3. DAMPING-IN-ROLL DERIVATIVE, ℓ_p

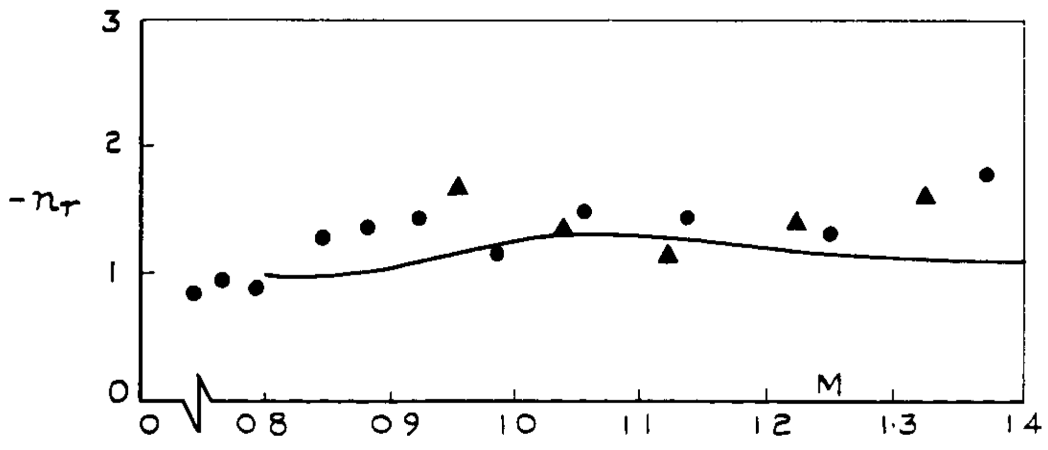


FIG 8 MODEL OF FIG 3. DAMPING-IN-YAW DERIVATIVE, n_r

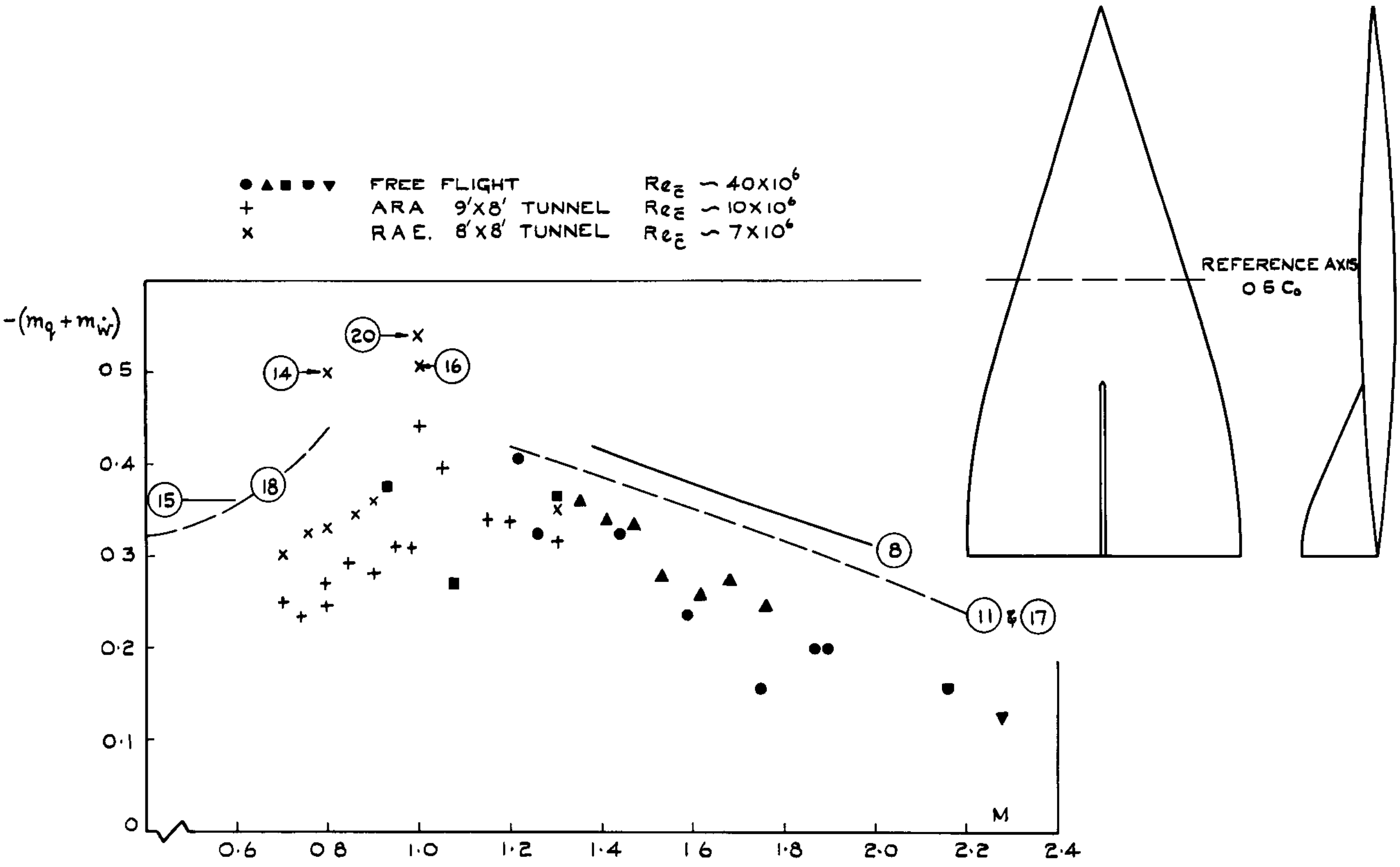


FIG. 9 DAMPING-IN-PITCH DERIVATIVE, $(m_q + m_{\dot{w}})$

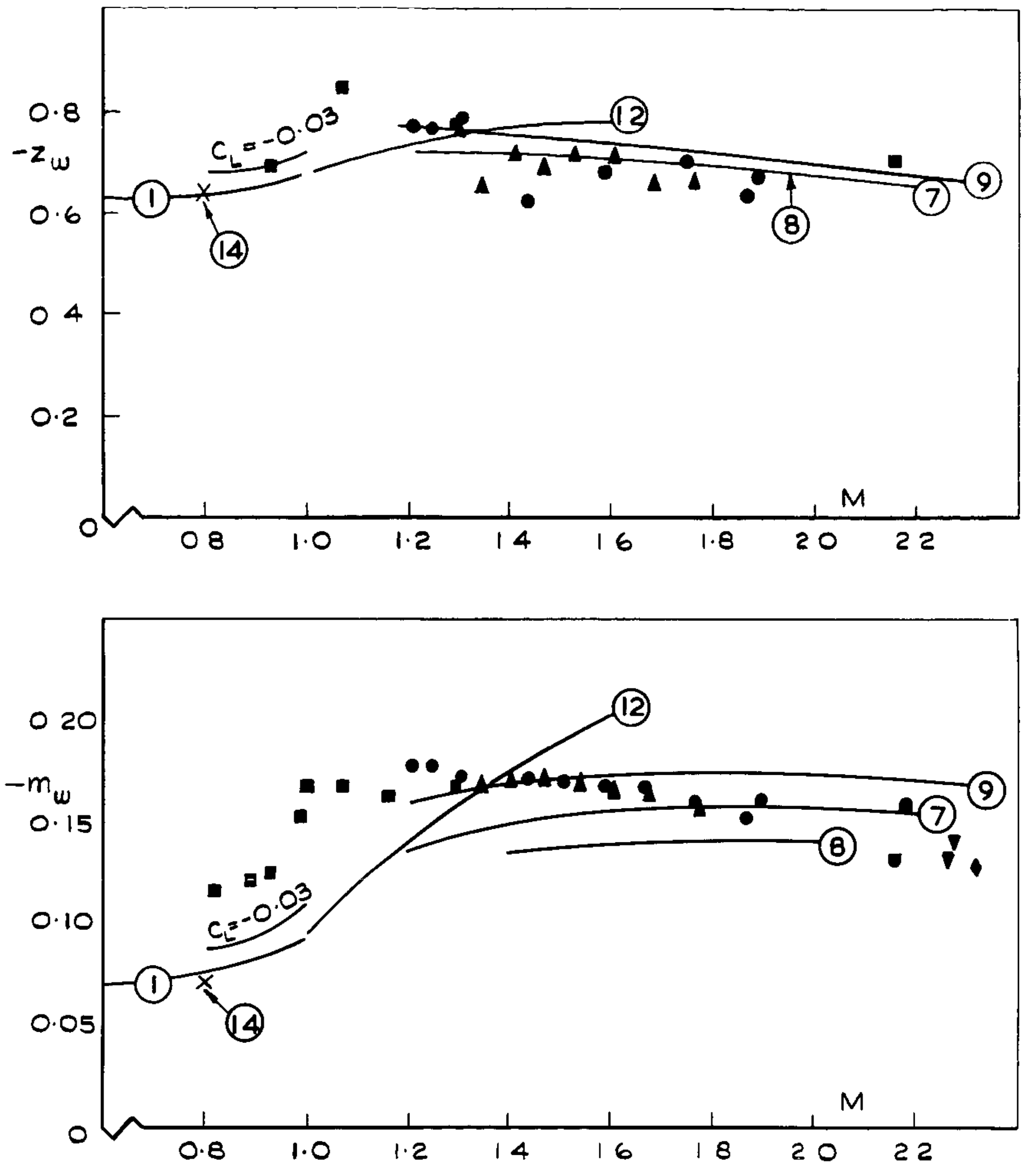
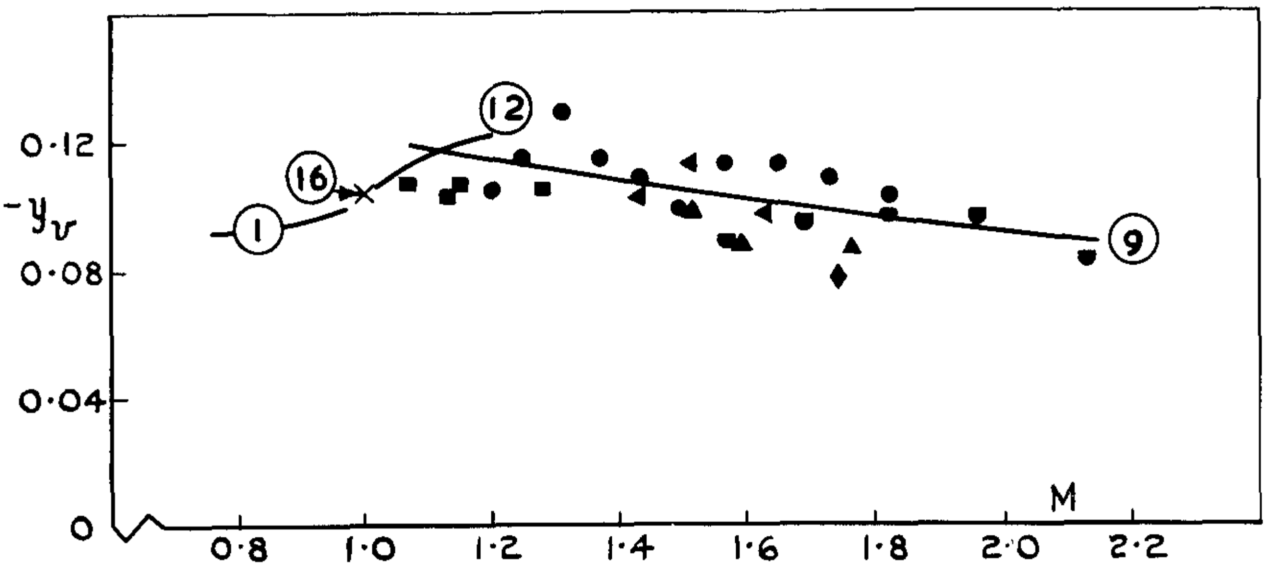


FIG 10 Z-FORCE DERIVATIVE DUE TO INCIDENCE, z_w AND PITCHING MOMENT DERIVATIVE DUE TO INCIDENCE, m_w



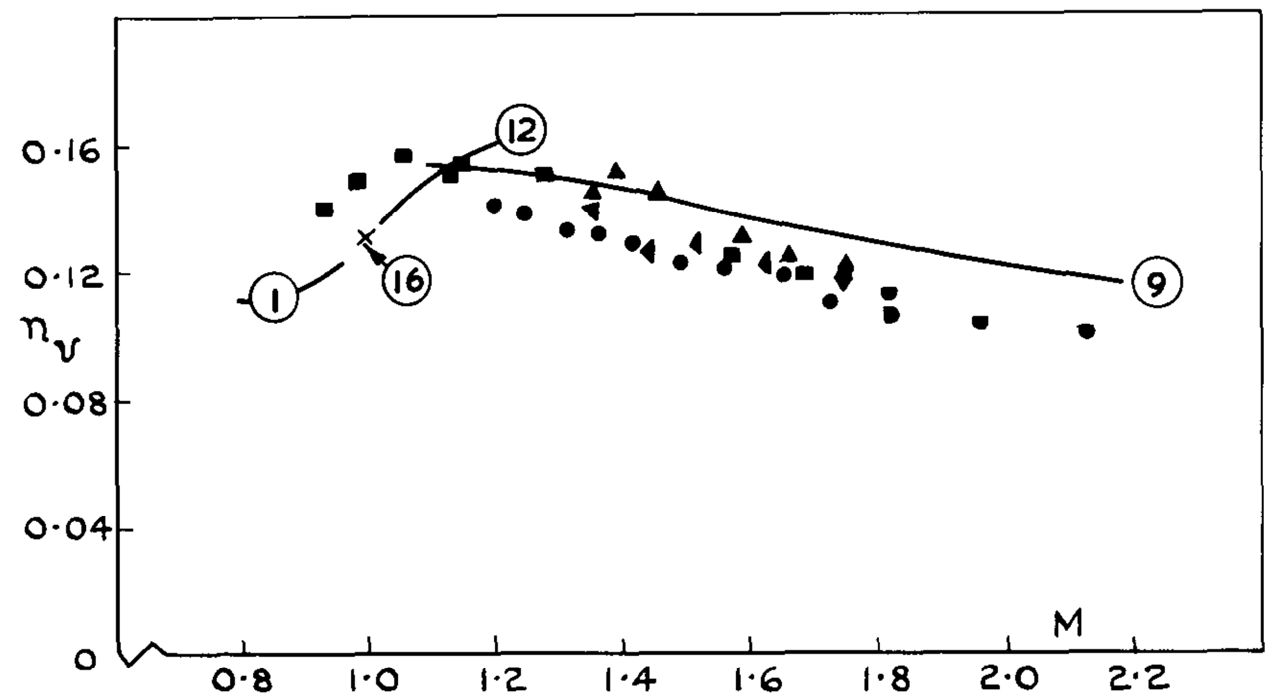


FIG.11 SIDEFORCE DERIVATIVE DUE TO SIDESLIP, y_v AND YAWING MOMENT DERIVATIVE DUE TO SIDESLIP, n_v

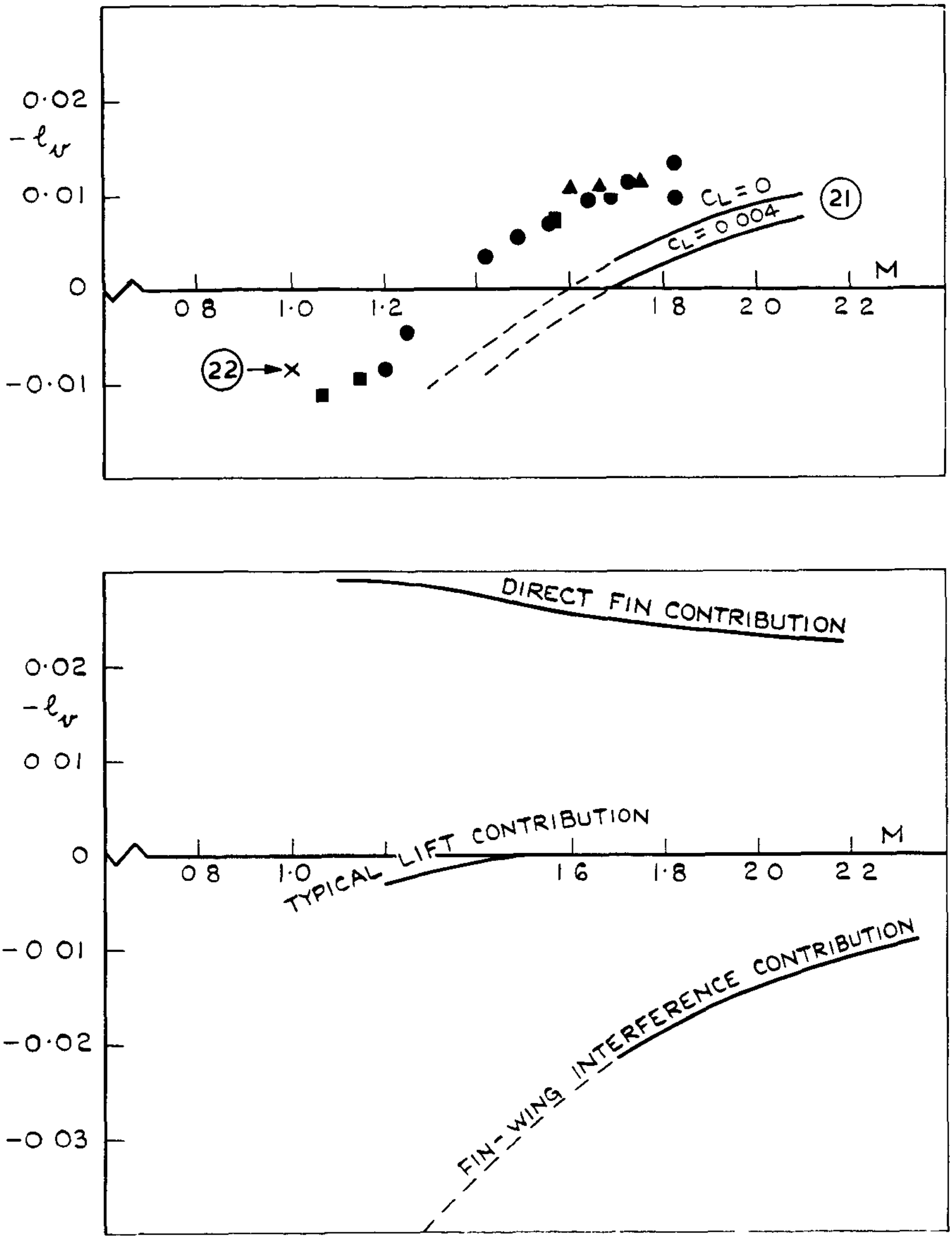


FIG 12 ROLLING MOMENT DERIVATIVE DUE TO SIDESLIP, ℓ_v AND BREAKDOWN OF CONTRIBUTIONS TO ℓ_v

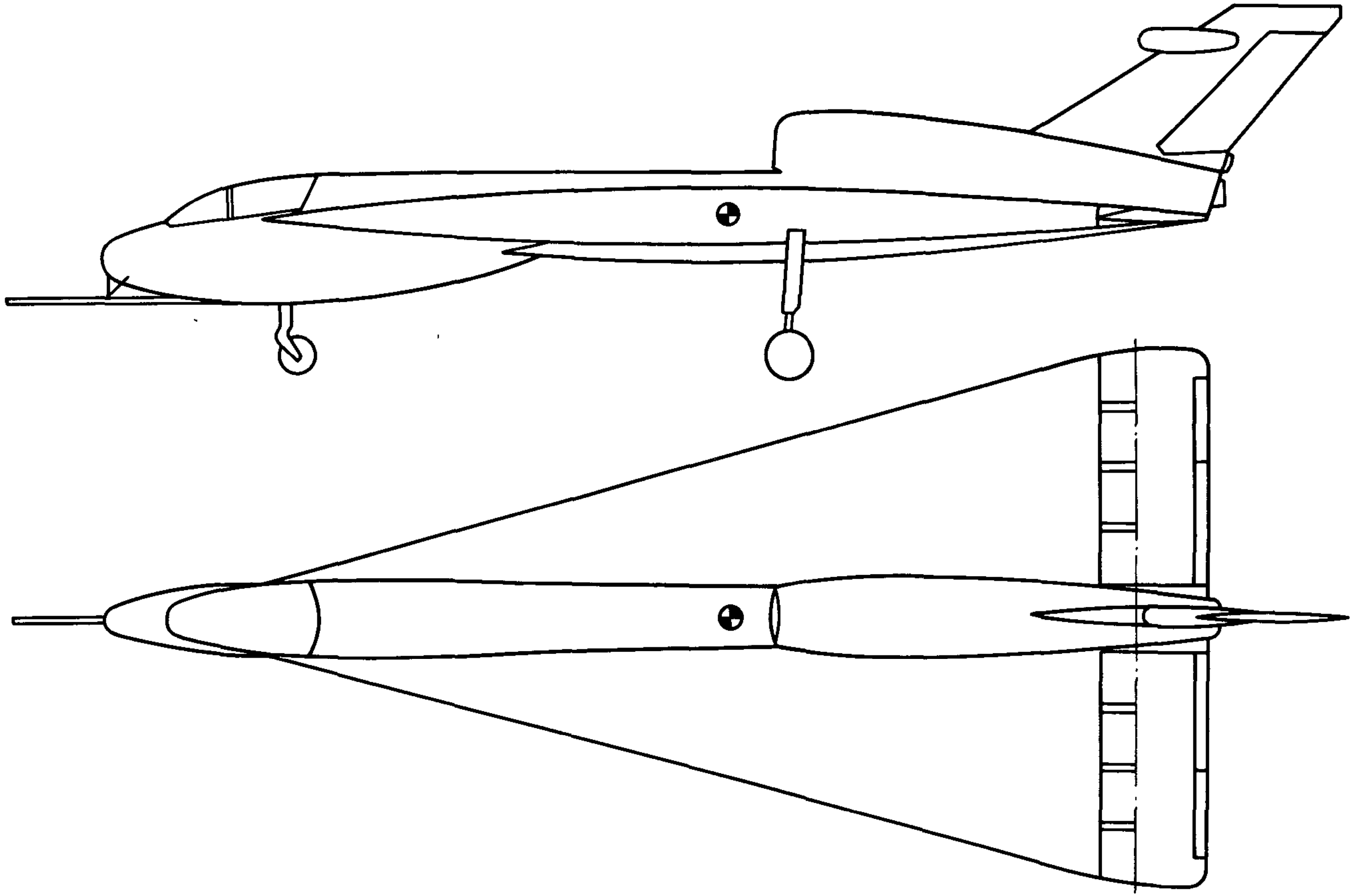


FIG. 13 GENERAL ARRANGEMENT OF H.P. 115

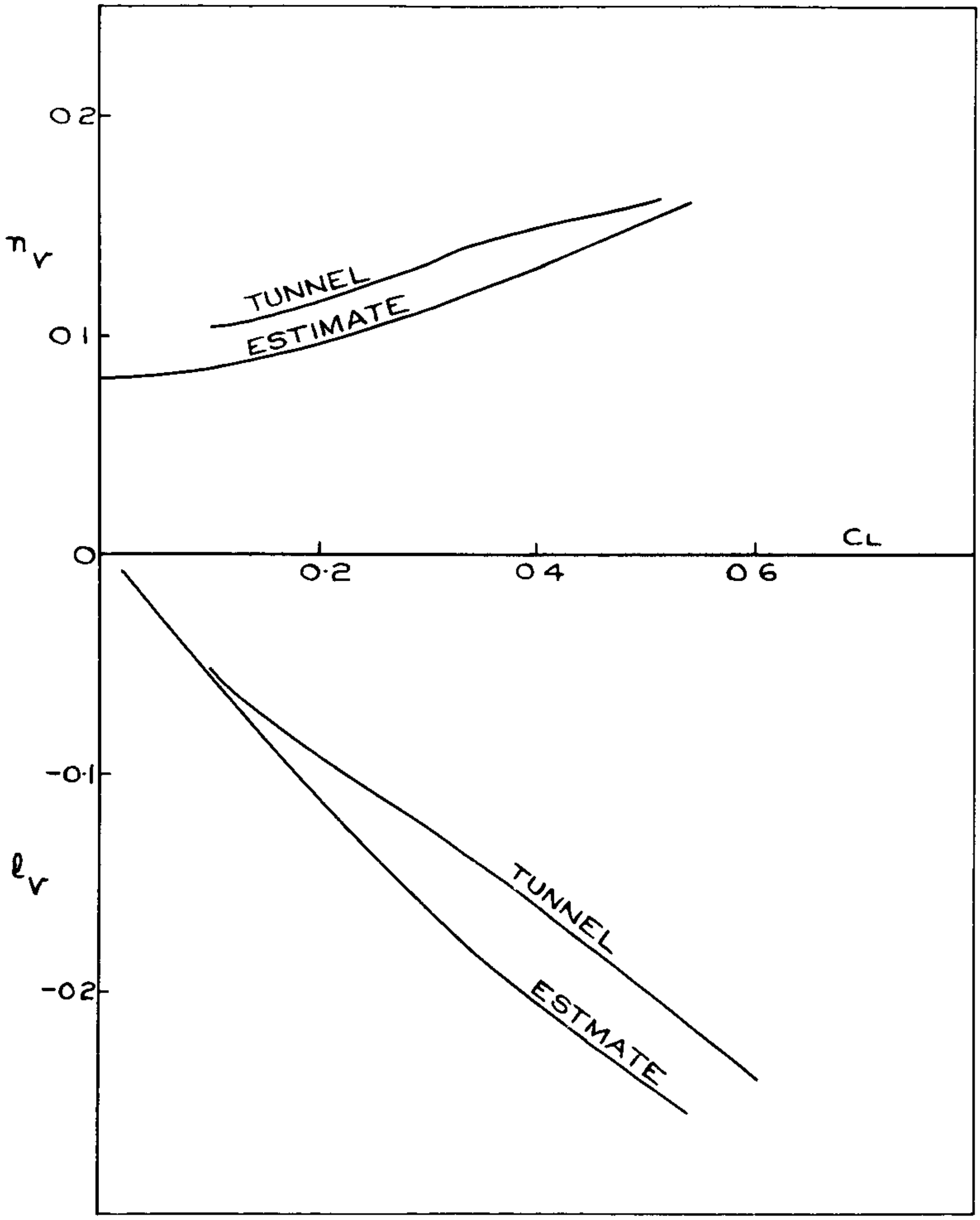


FIG 14 H.P. 115. STATIC LATERAL DERIVATIVES: COMPARISON OF WIND-TUNNEL RESULTS AND THEORY

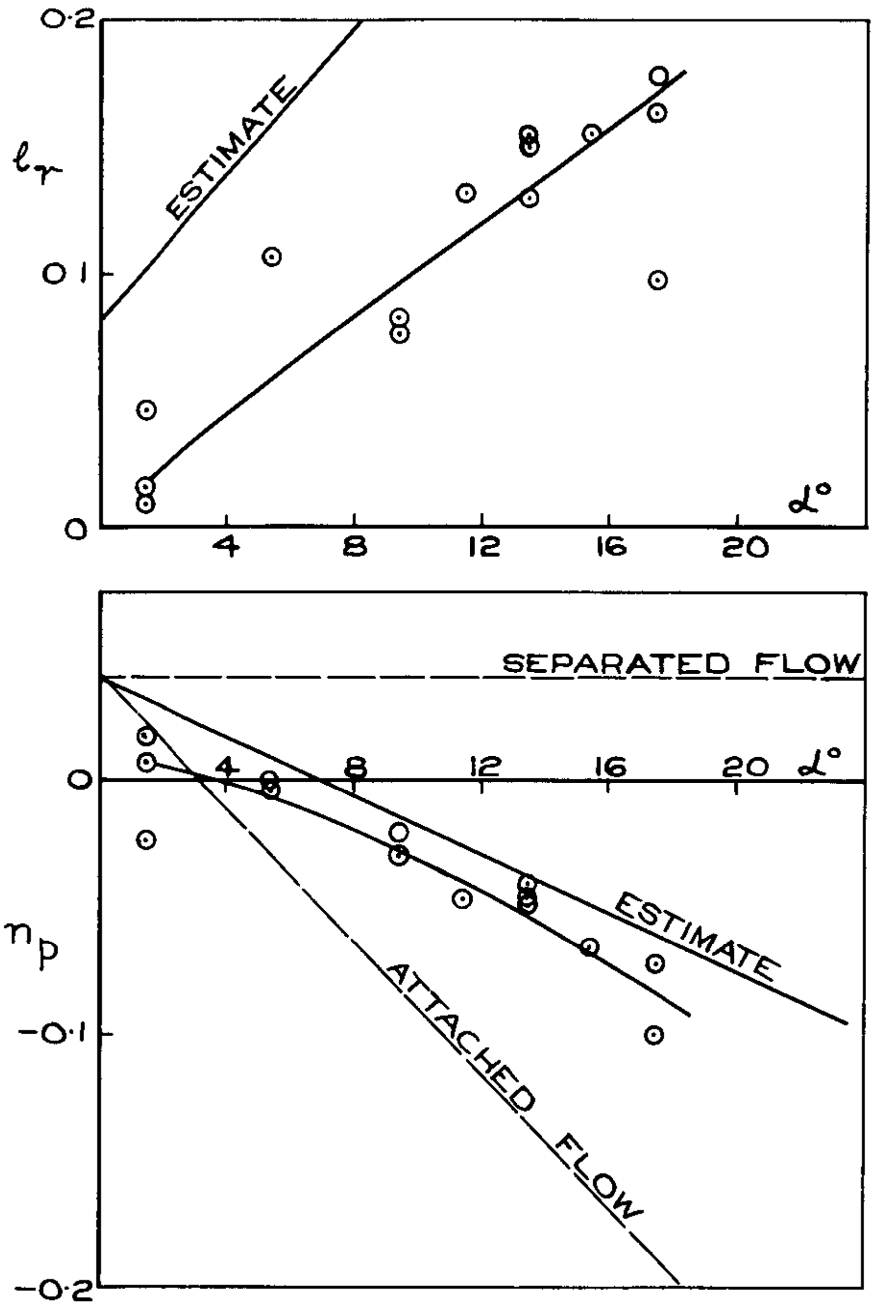


FIG. 15 H.P. 115. LATERAL CROSS-DAMPING DERIVATIVES: COMPARISON OF WIND-TUNNEL RESULTS AND THEORY

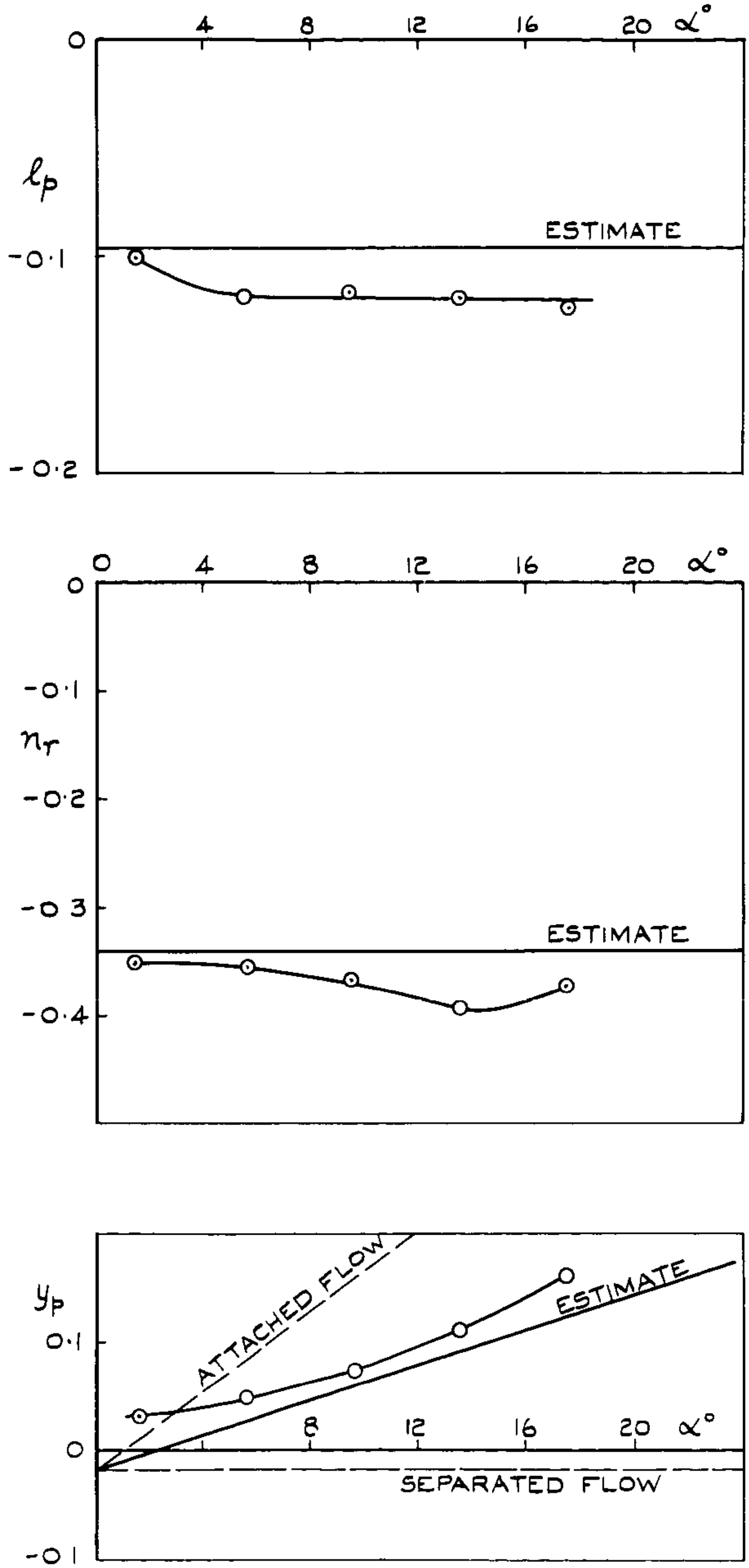
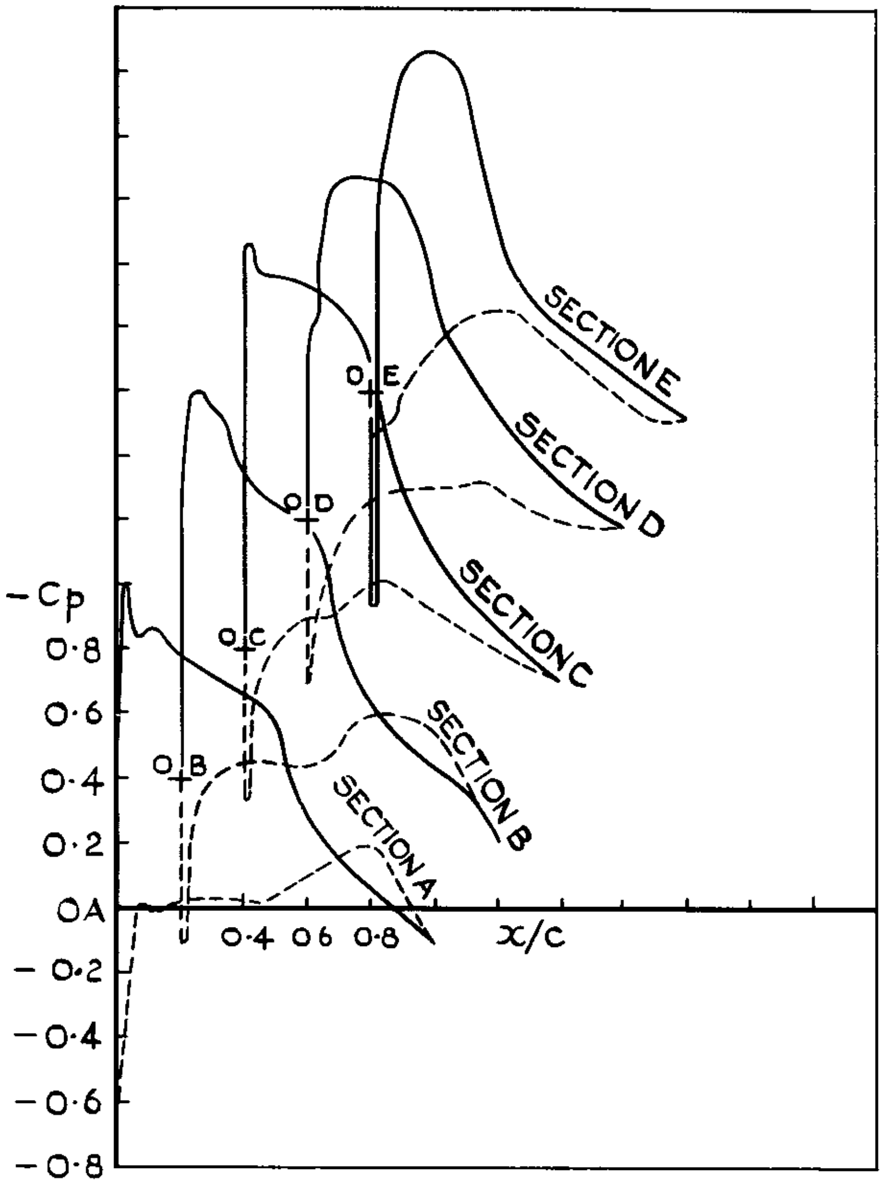


FIG.16 H.P. 115. LATERAL DAMPING DERIVATIVES: COMPARISON OF WIND-TUNNEL RESULTS AND THEORY



M=0·85 , $\alpha = 4°$

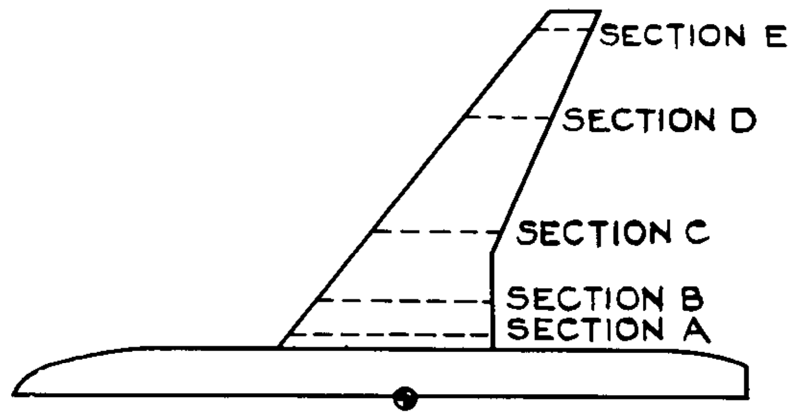


FIG. 17 CHORDWISE PRESSURE DISTRIBUTIONS AT DESIGN CRUISE CONDITIONS FOR A TYPICAL SWEPT-BACK WING

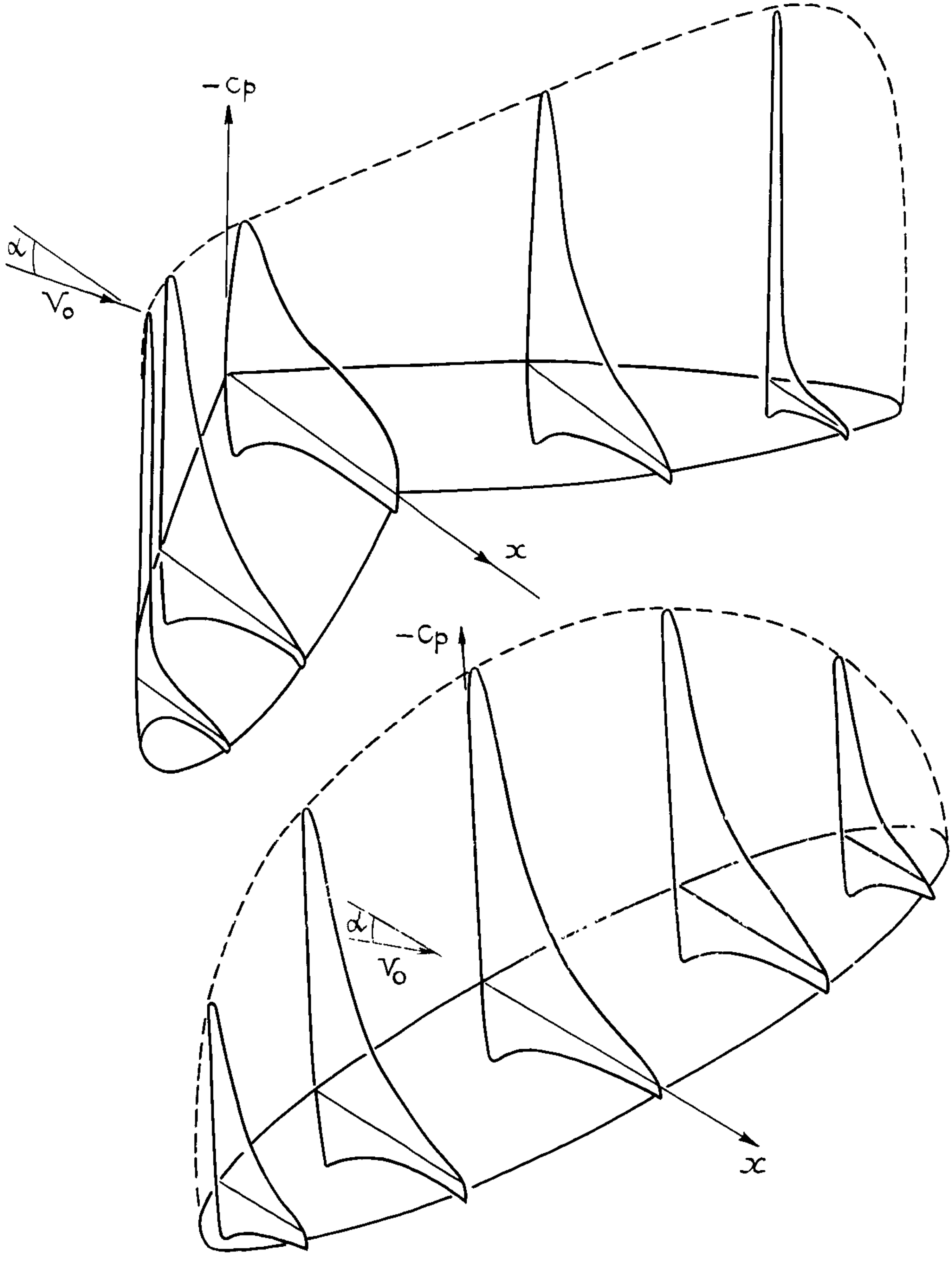


FIG 18 PRESSURE DISTRIBUTION DUE TO INCIDENCE ON SWEPT AND UNSWEPT WINGS

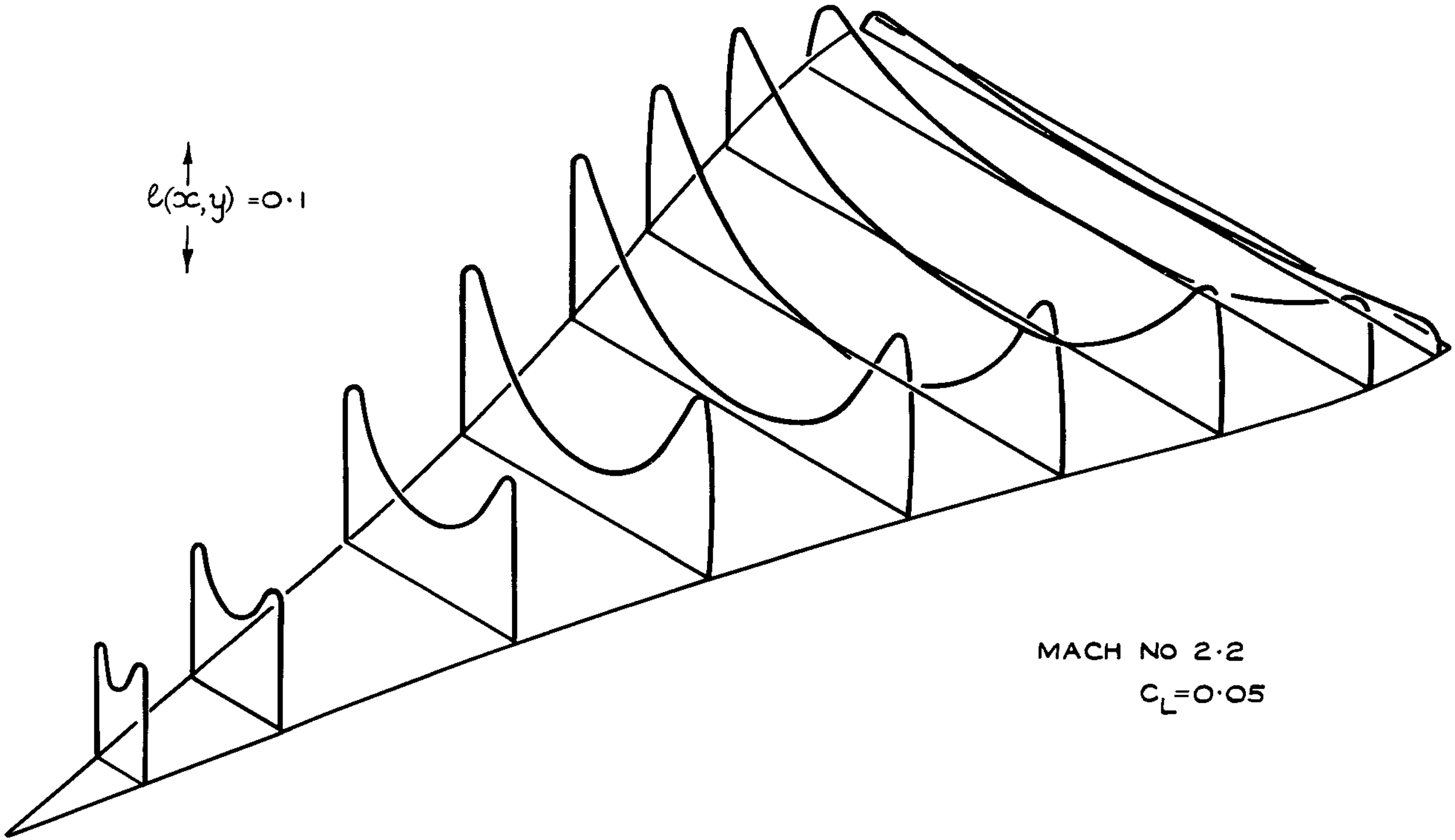
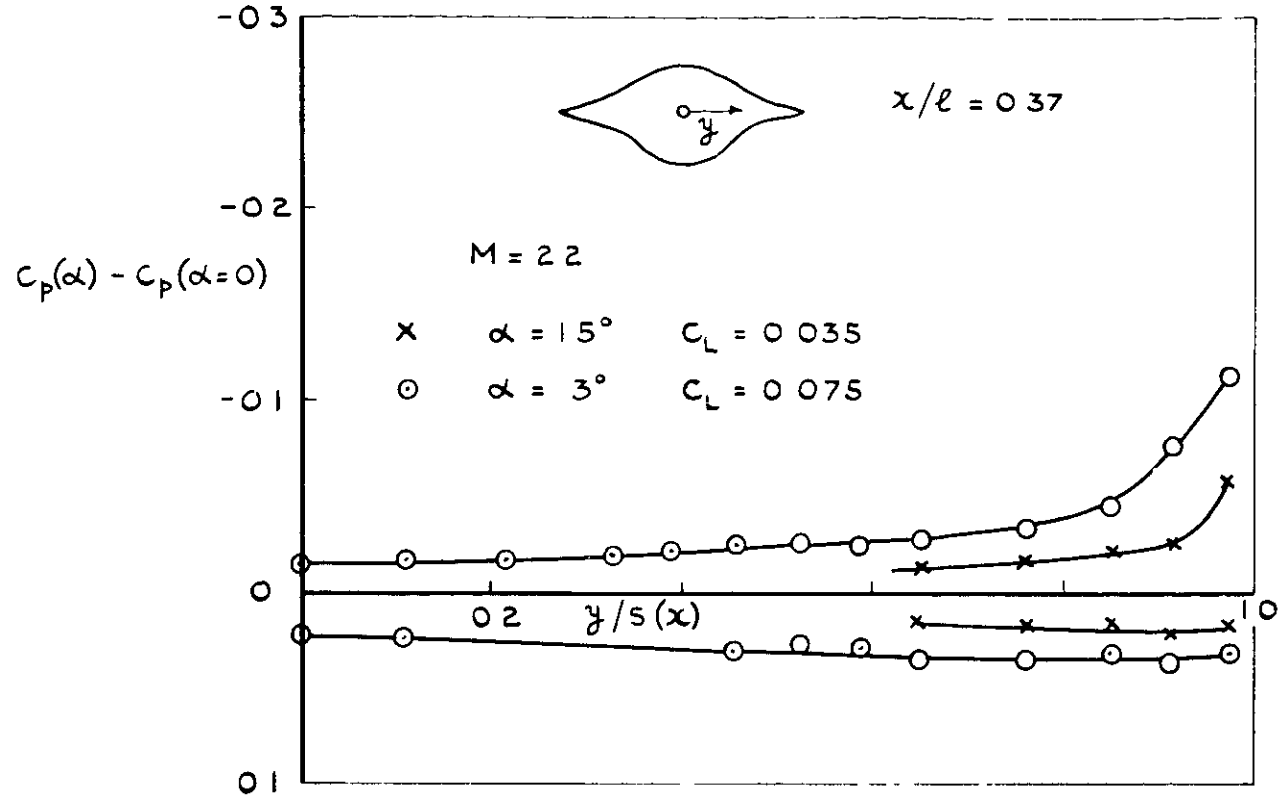


FIG.19 LOCAL LOAD COEFFICIENT ON A WING AT ATTACHMENT INCIDENCE



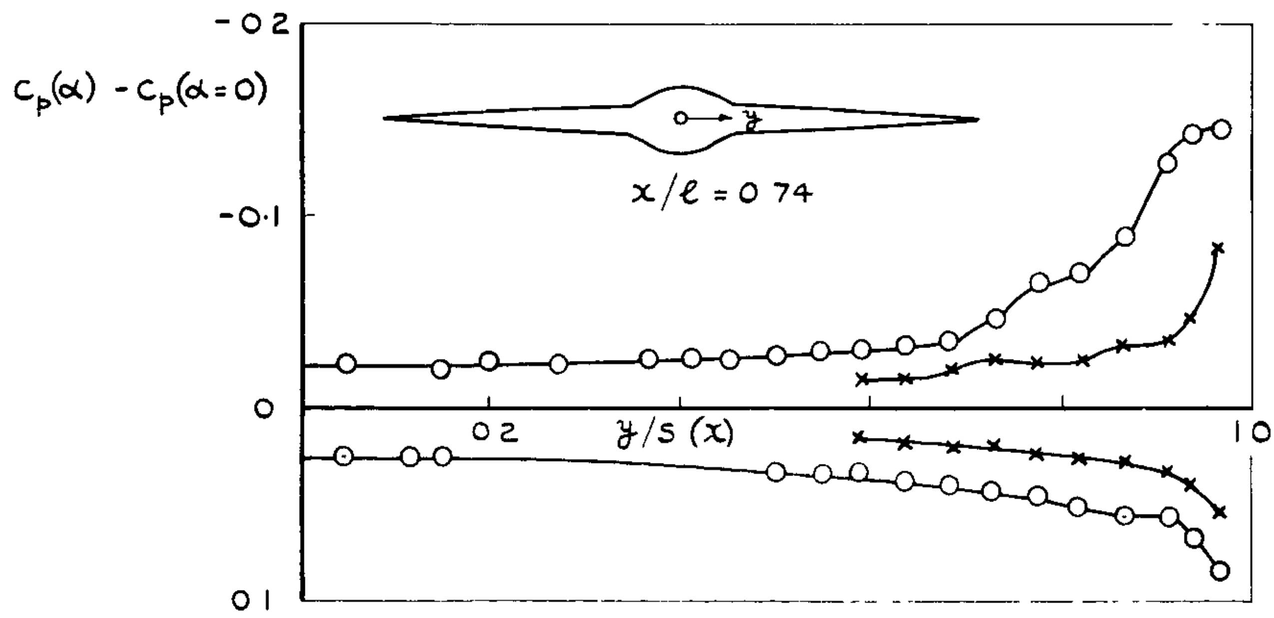


FIG. 20 PRESSURE DISTRIBUTIONS ON A SYMMETRICAL WING OF THE SAME PLANFORM AS IN FIG 19

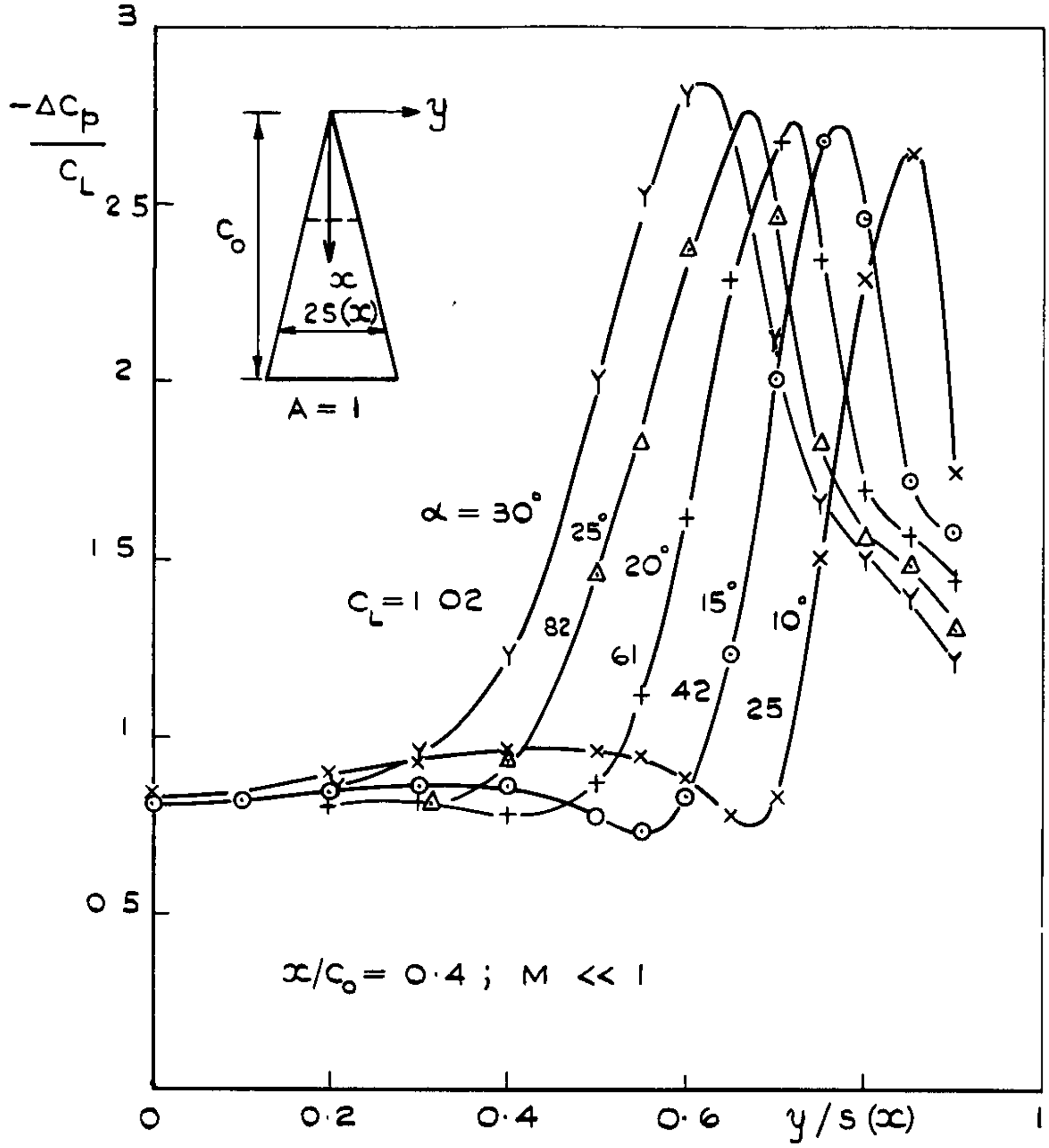


FIG. 21 LOAD DISTRIBUTIONS ON A DELTA WING, WING B OF REF. 30, AT LOW SPEED

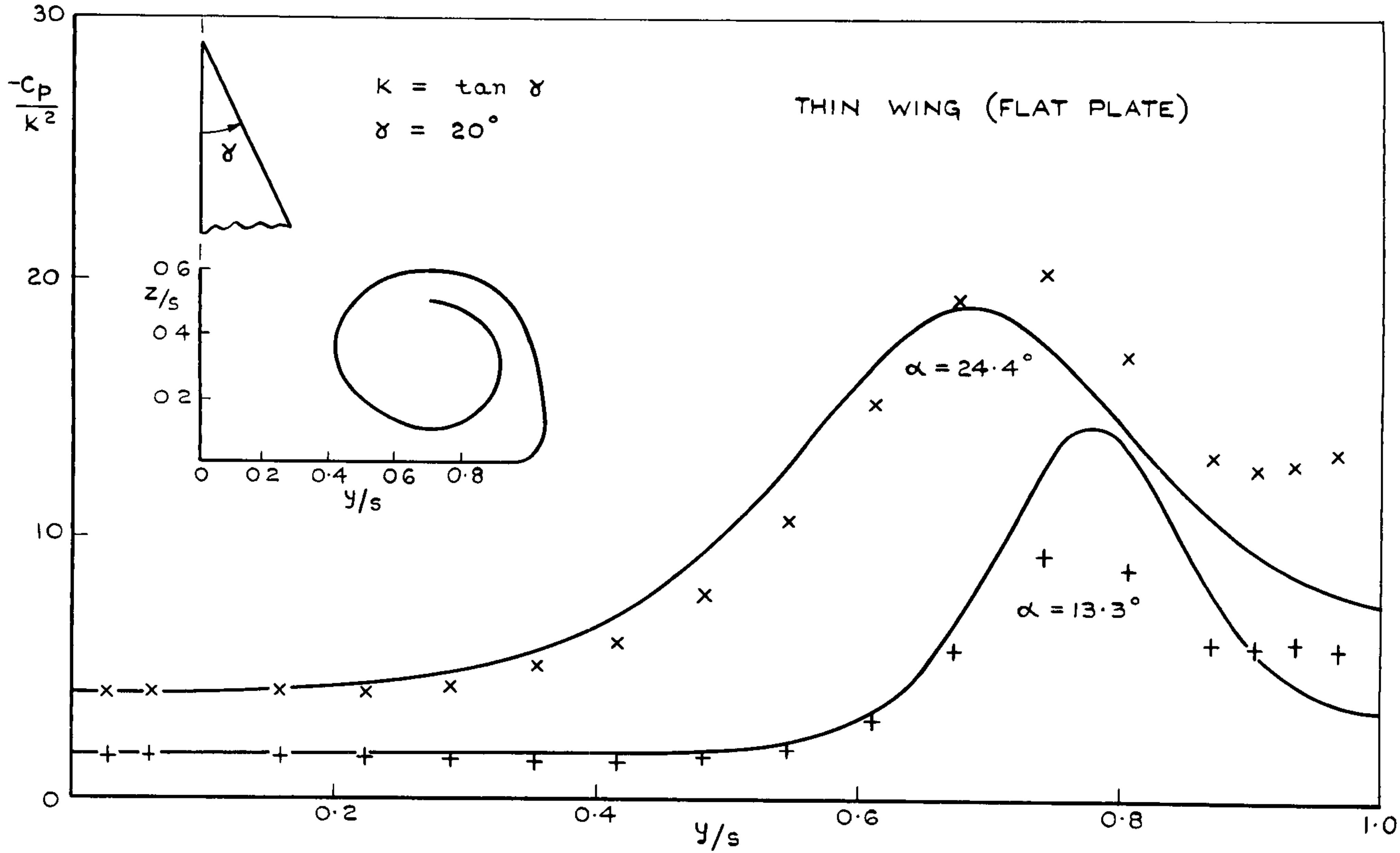


FIG 22 PRESSURE ON WING UPPER SURFACE, THEORY AND EXPERIMENT

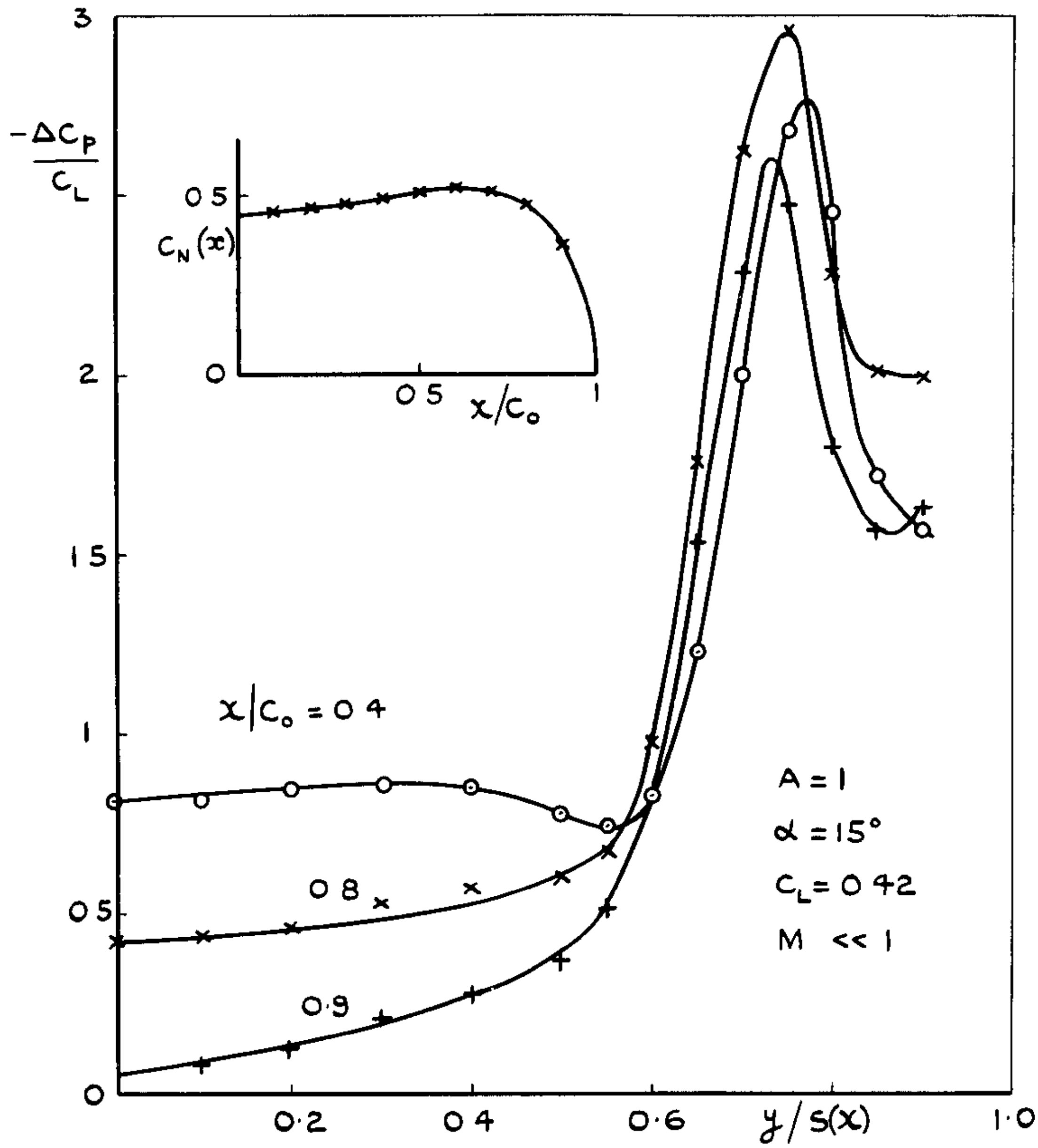


FIG 23 LOAD DISTRIBUTIONS ON A DELTA WING, WING B OF REF 30, AT LOW SPEED

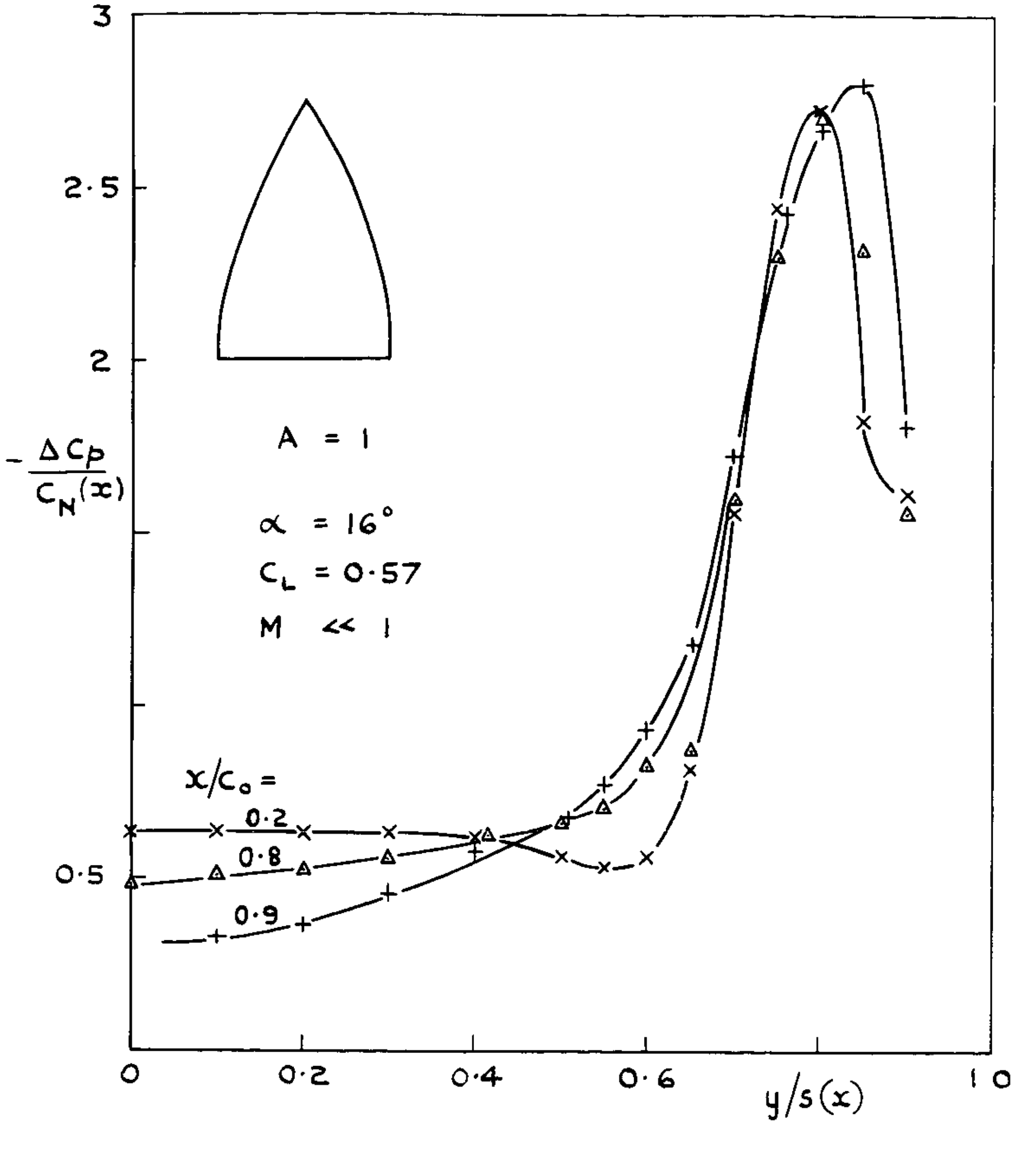


FIG 24 (d)

FIG. 24 LOAD DISTRIBUTIONS ON A GOTHIC WING, WING A OF REF 30, AT LOW SPEED

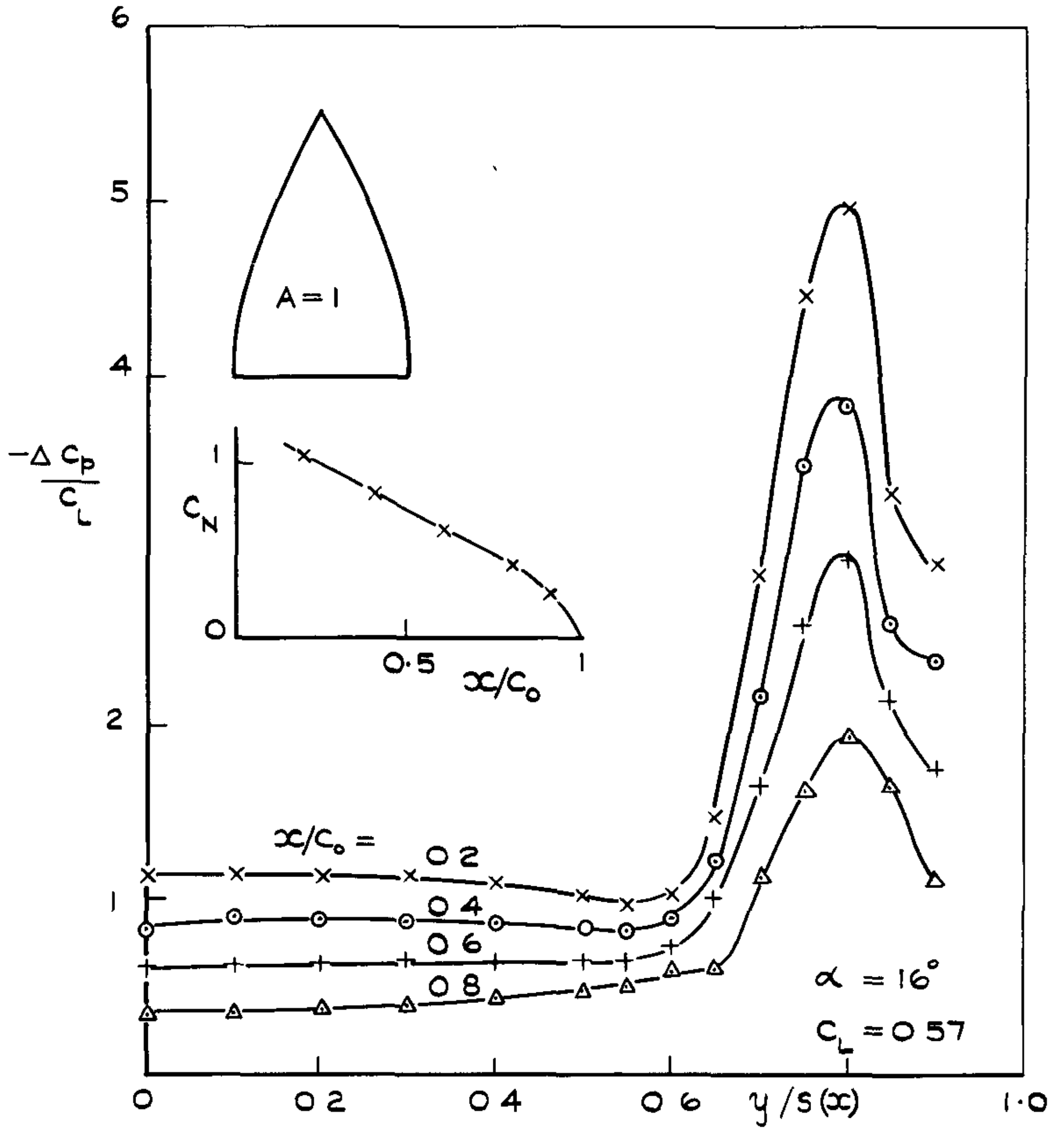


FIG. 24 (b)

FIG. 24 (CONT'D) LOAD DISTRIBUTIONS ON A GOTHIC WING, WING A OF REF 30, AT LOW SPEED

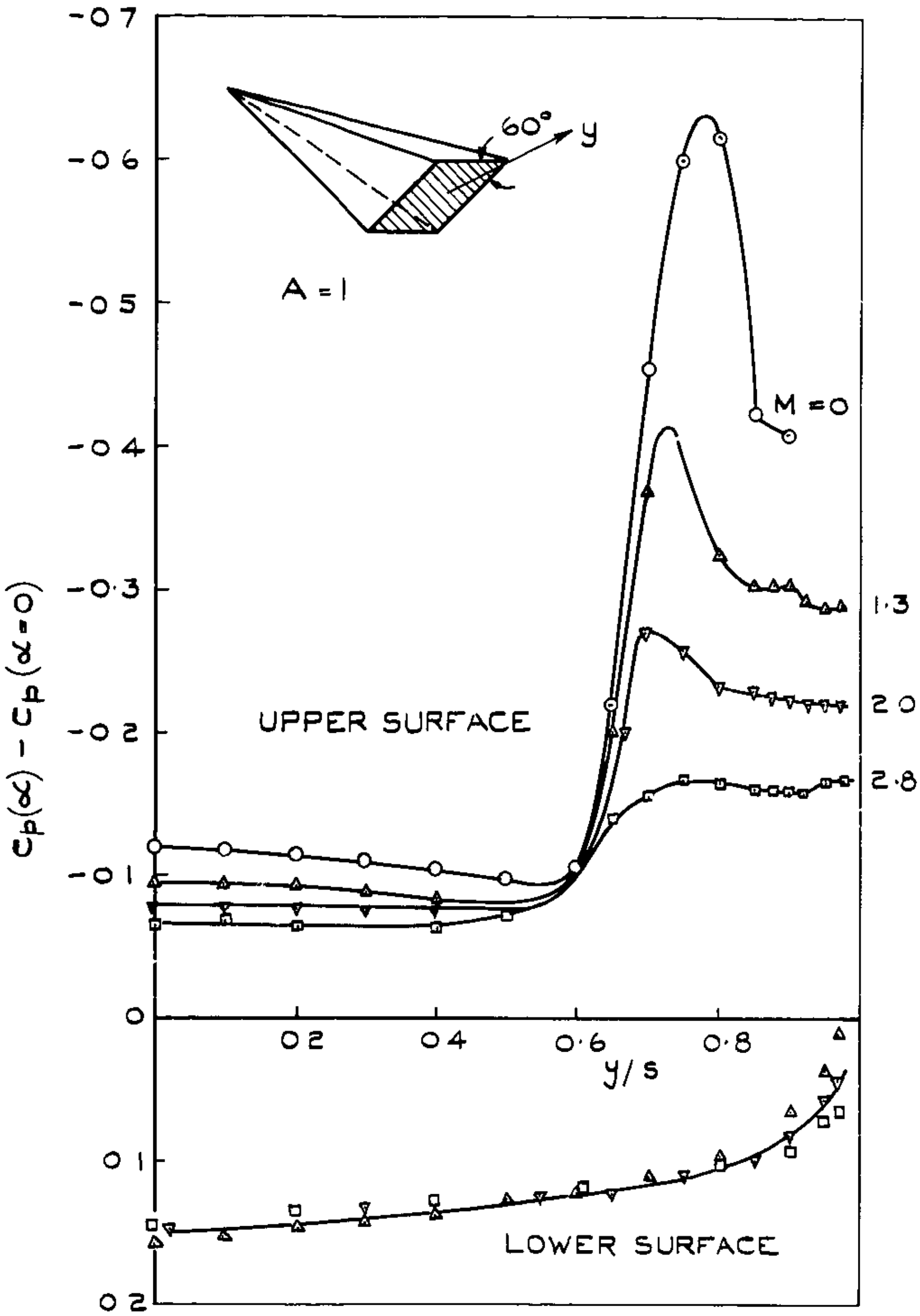


FIG. 25 PRESSURE DISTRIBUTIONS OVER A CONICAL BODY WITH RHOMBIC CROSS-SECTIONS AT $\alpha = 10°$ MEASUREMENTS BY KEATING AND BY BRITTON [27]

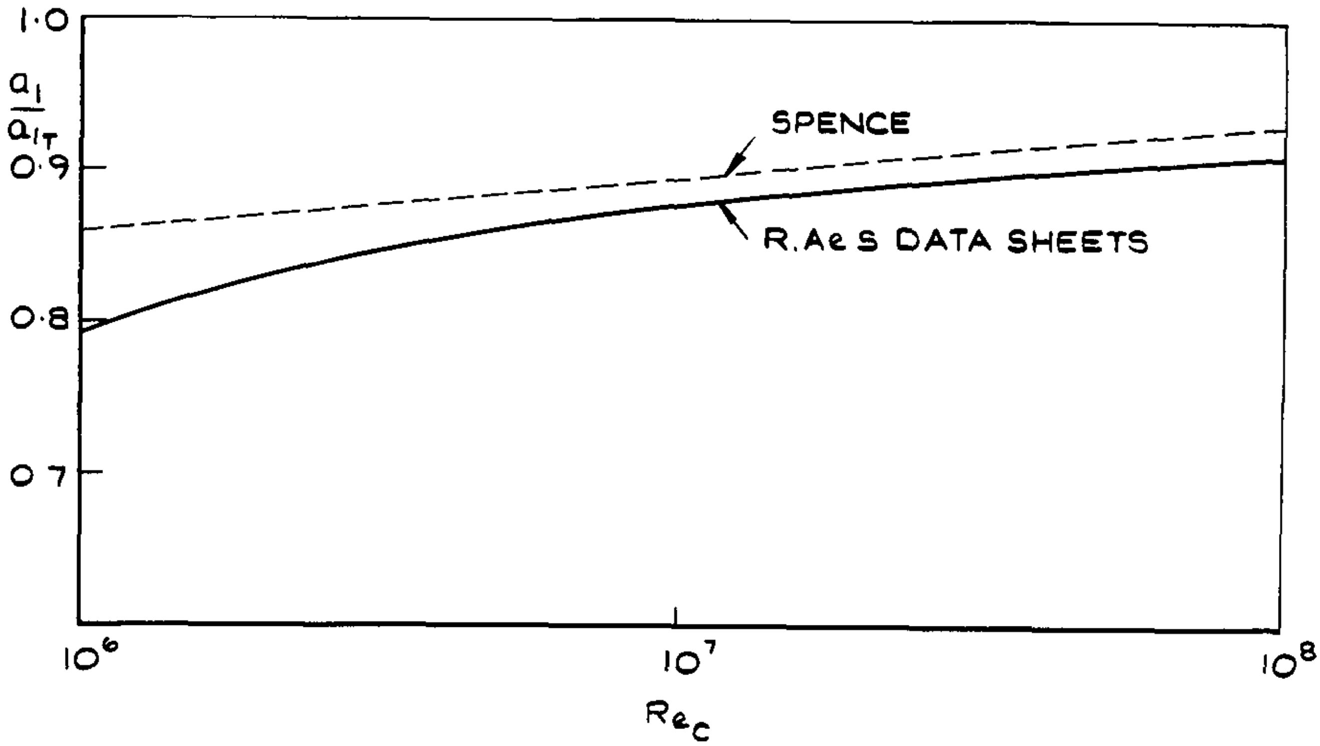


FIG.26 EFFECT OF REYNOLDS NUMBER ON LIFT CURVE SLOPE

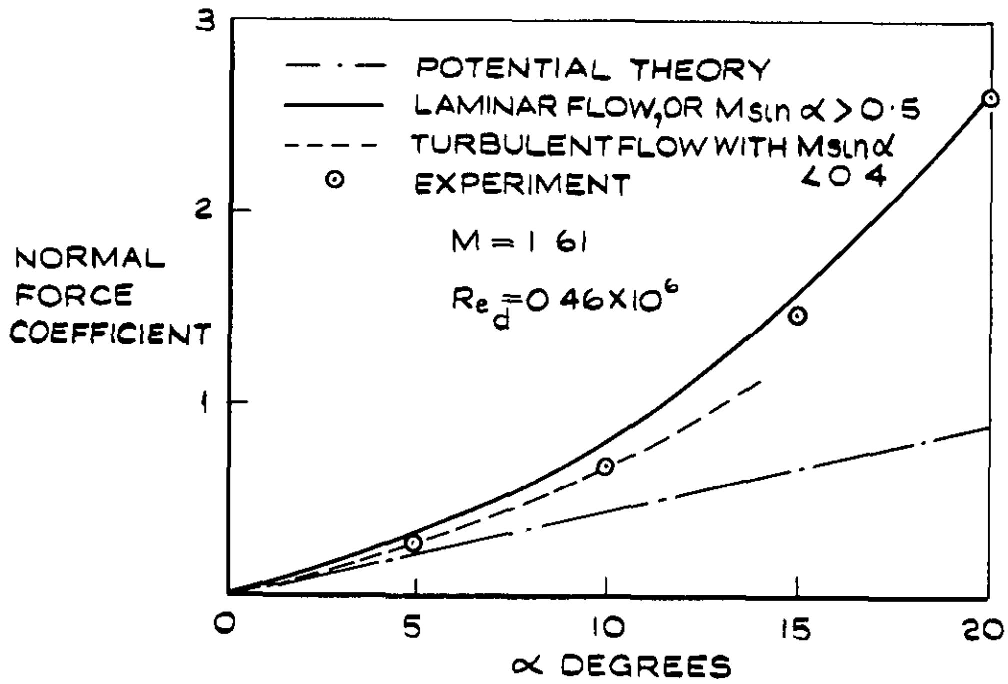


FIG.27 NORMAL FORCE ON A BODY OF REVOLUTION, REF 45

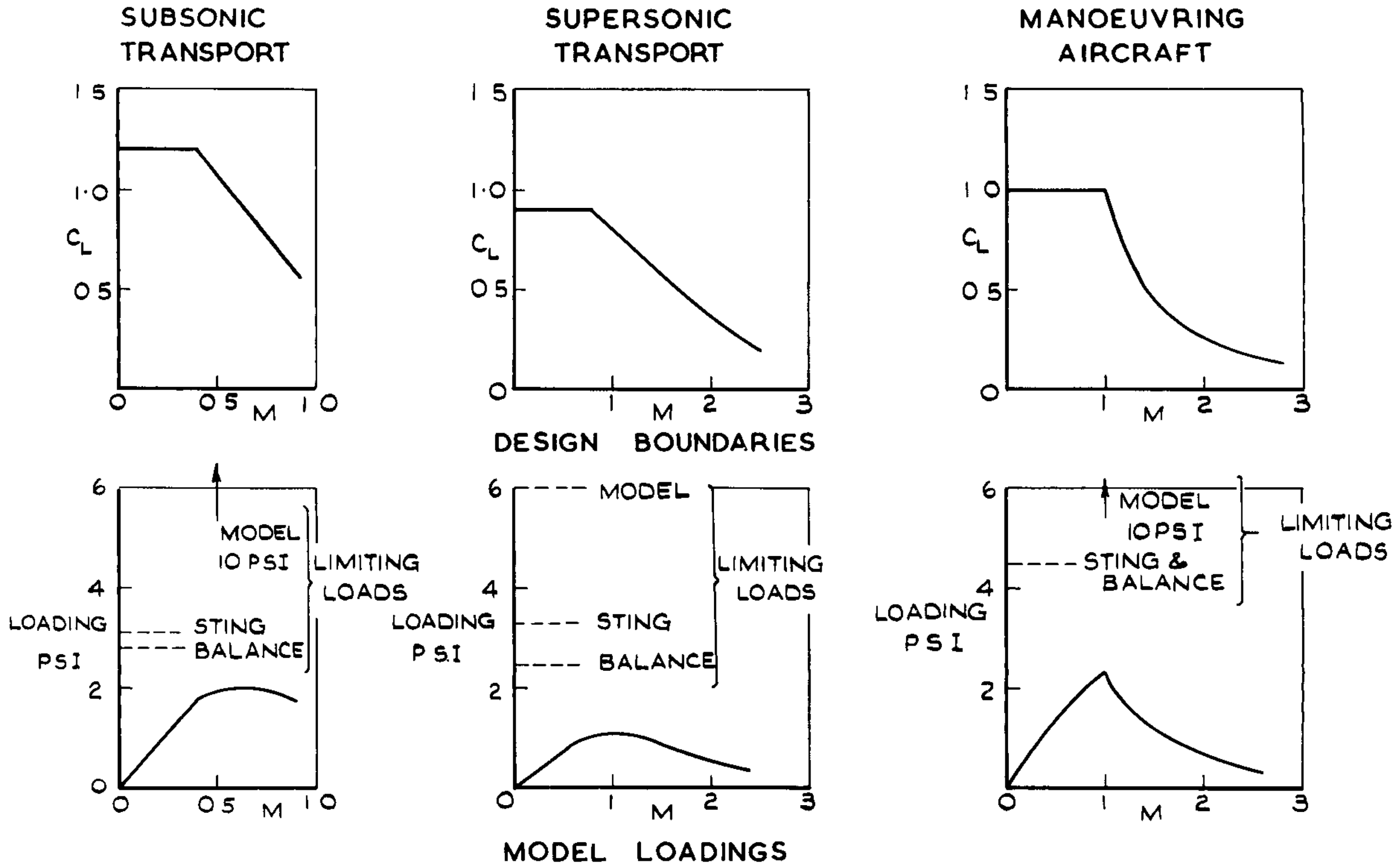


FIG.28 LOADING REQUIREMENTS FOR WIND-TUNNEL MODELS

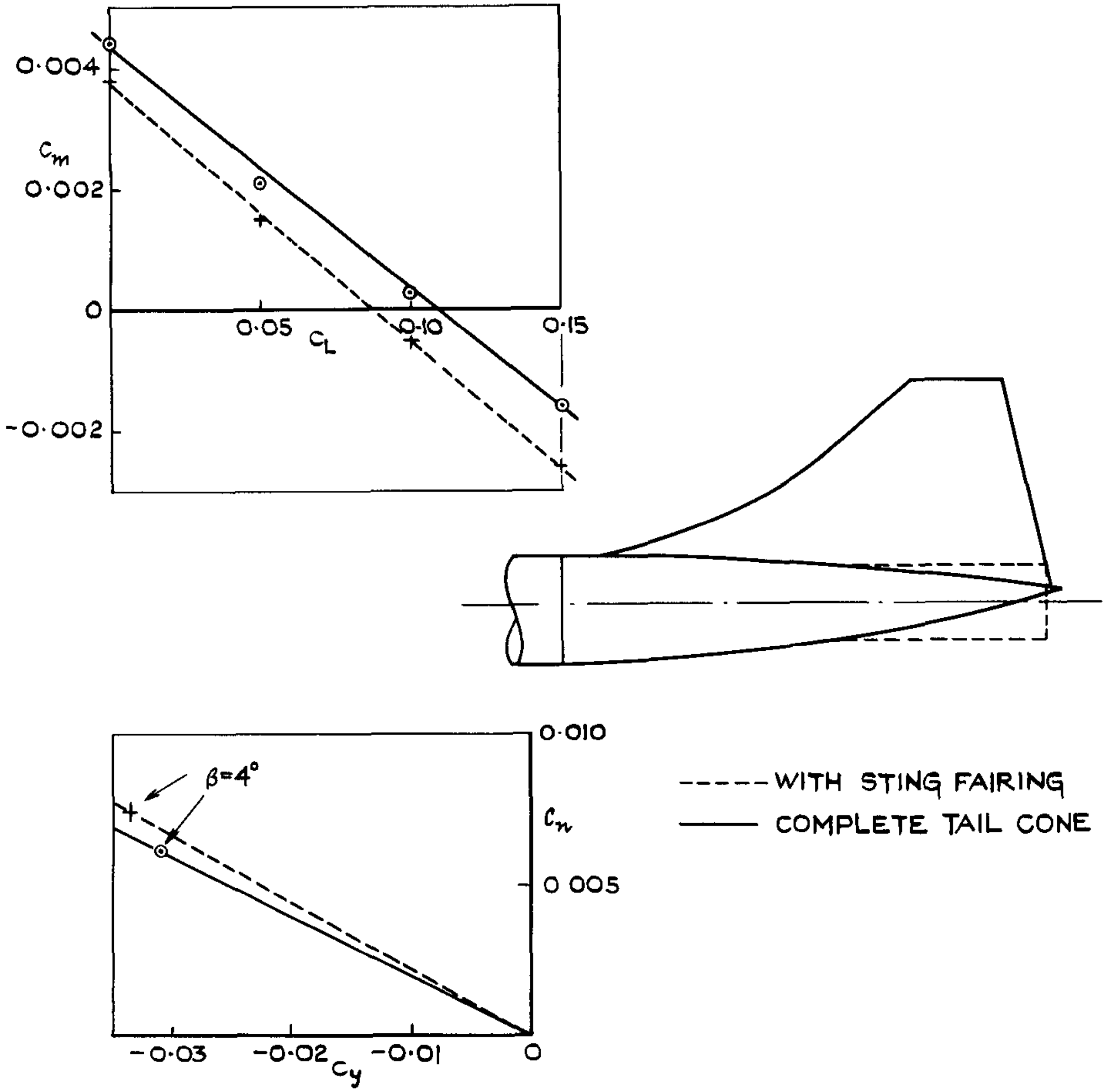


FIG.29 EFFECT OF MODEL SUPPORT ON STATIC STABILITY
M = 1·8

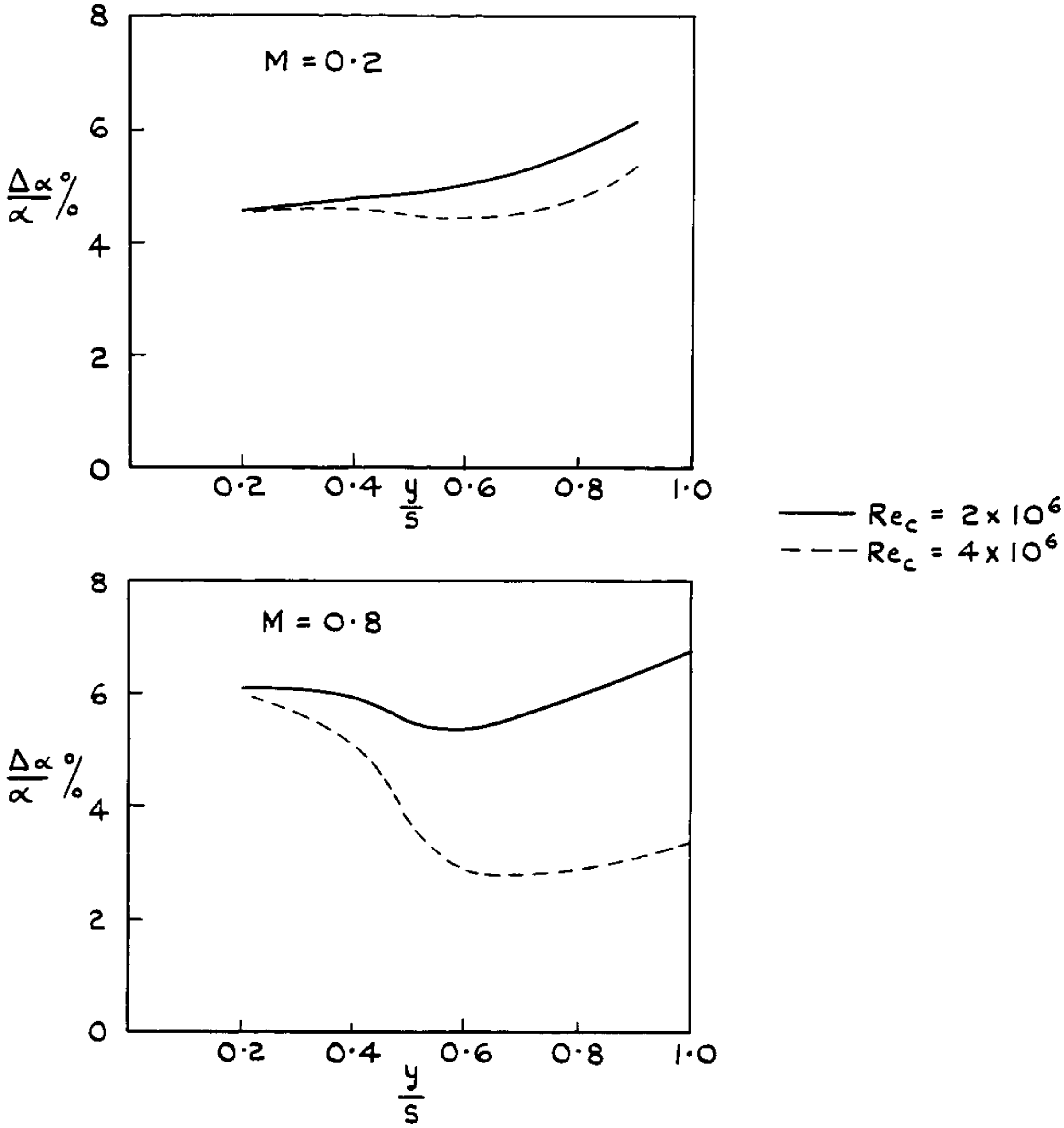


FIG. 30 SPANWISE VARIATION OF INCIDENCE CORRECTION DUE TO TUNNEL CONSTRAINT & LOADING FOR 30° SWEPT WING

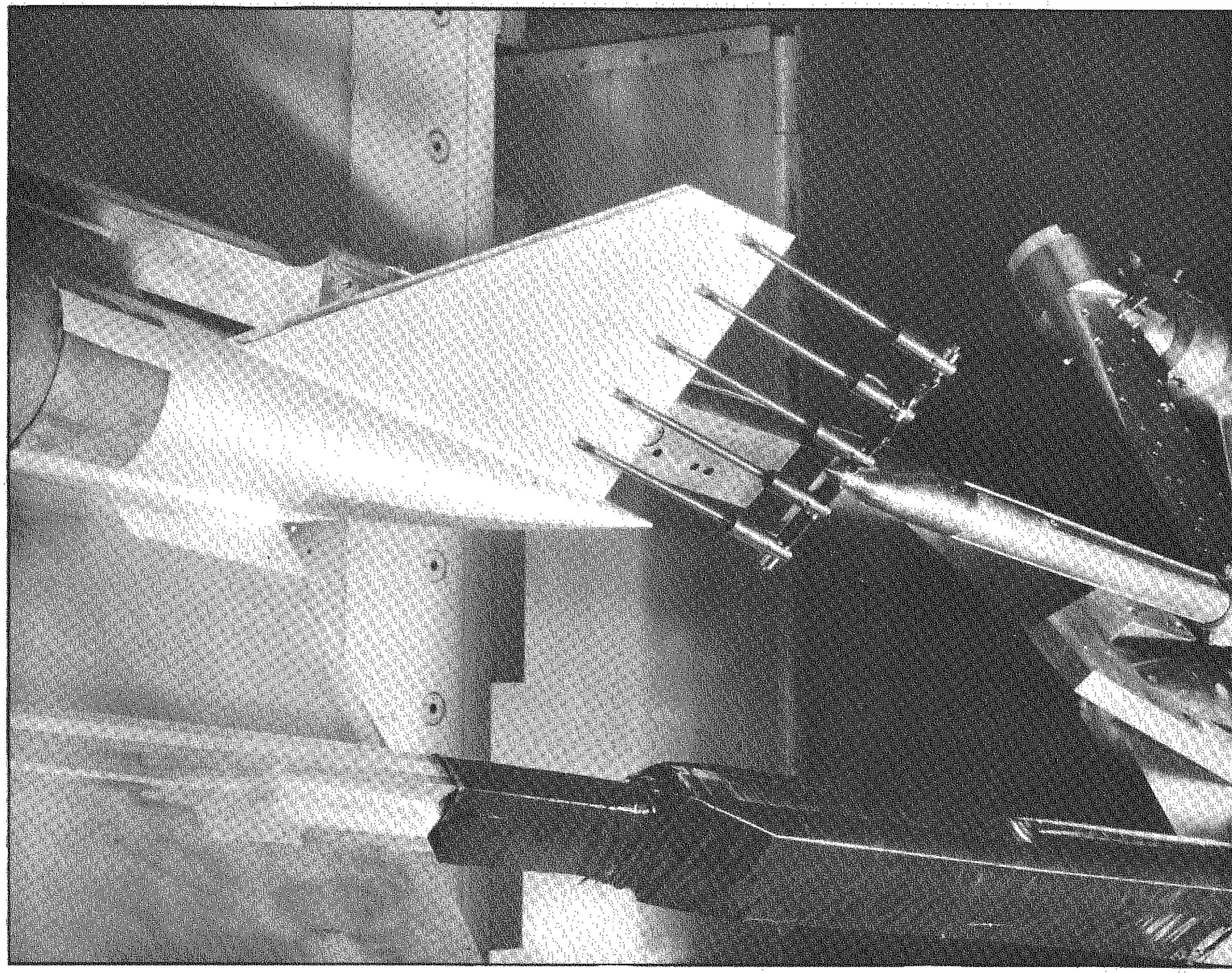


Fig.31 External pressure-plotting rake

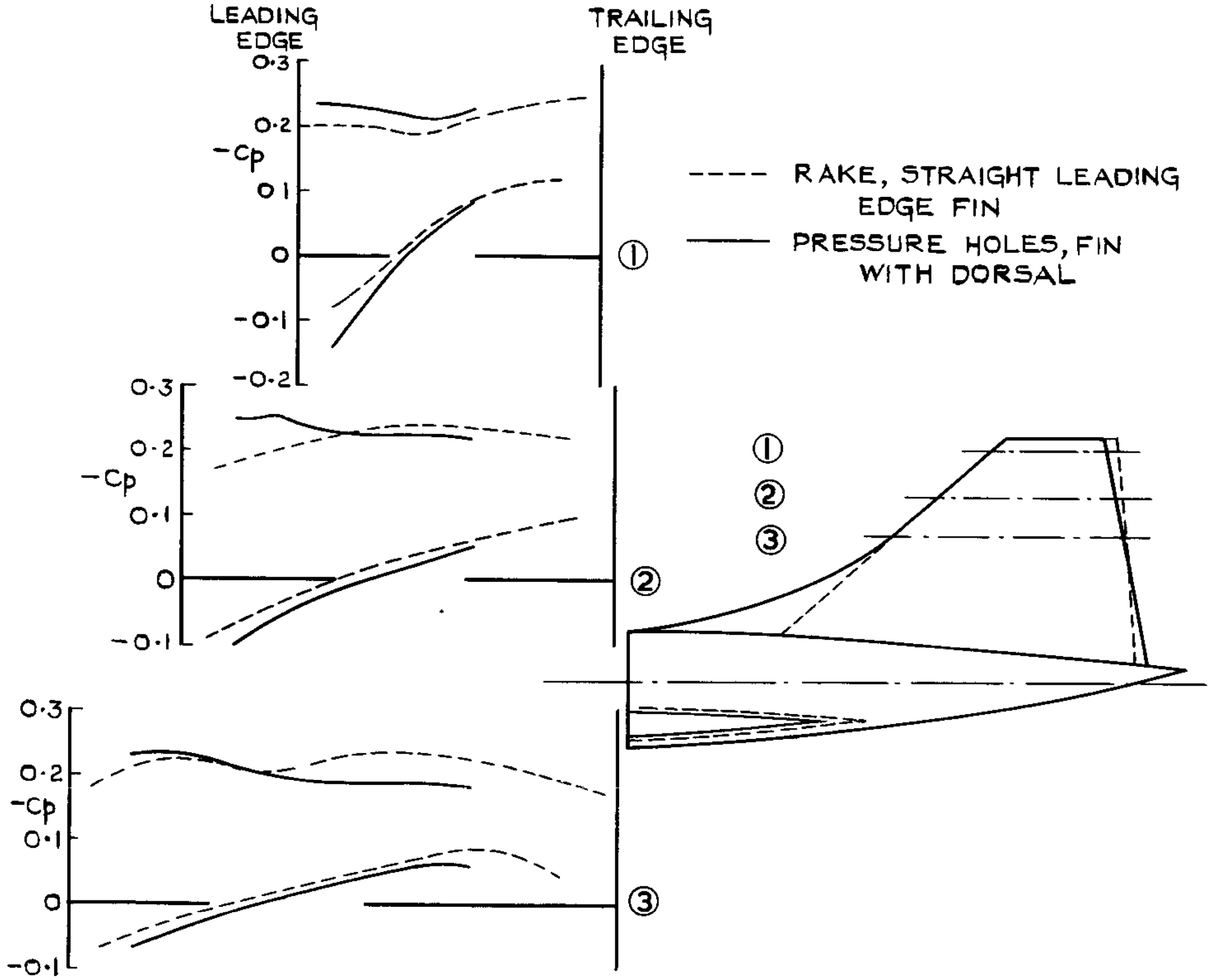


FIG. 32 PRESSURE DISTRIBUTION AS MEASURED ON FIN BY RAKE & ON MODIFIED FIN WITH STATIC PRESSURE HOLES
$M = 1 \cdot 6 ; \beta = 4^{\circ}$

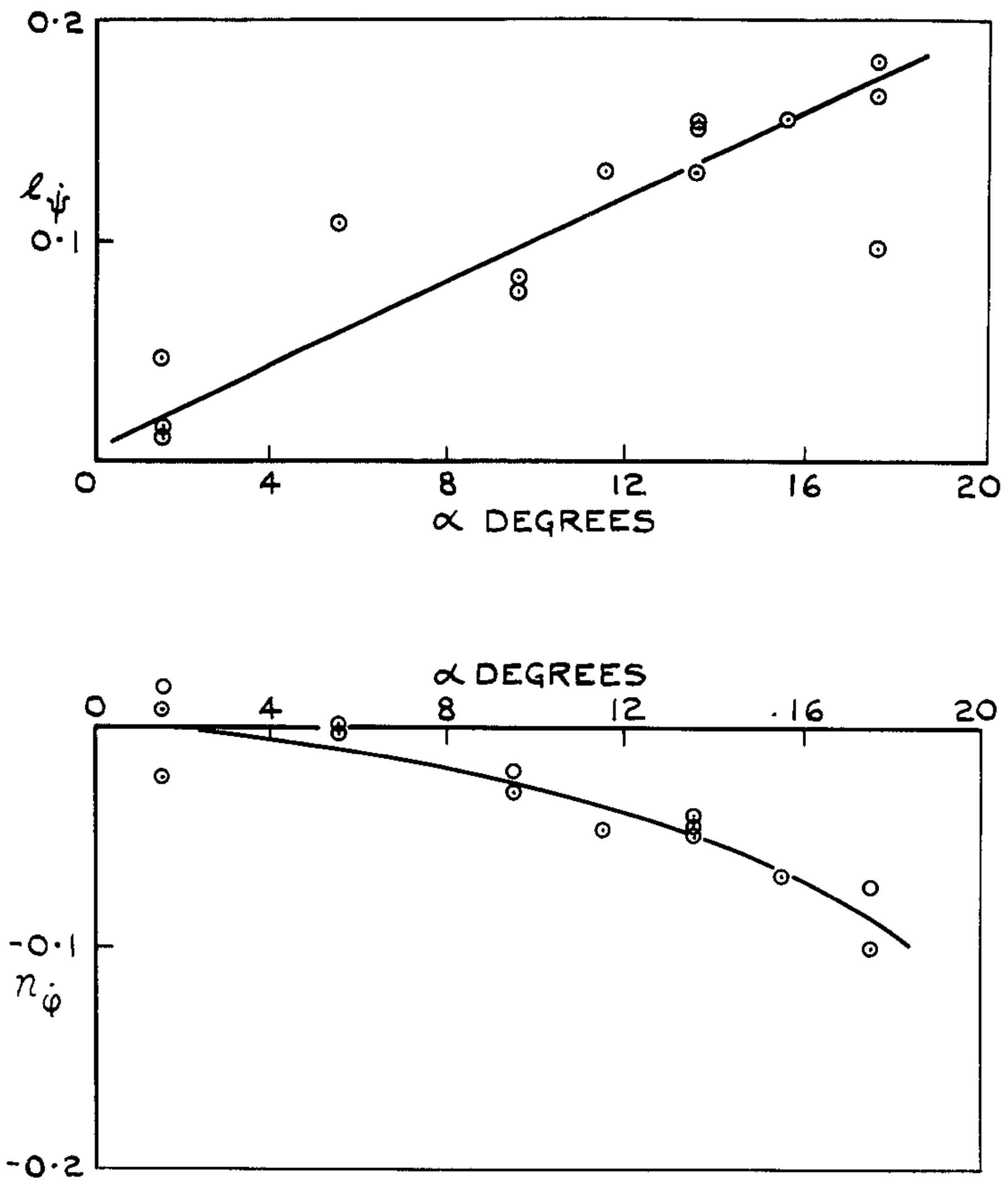


FIG.33 H.P. 115 CROSS-DAMPING DERIVATIVES FROM MODEL TESTS (STING AXIS)

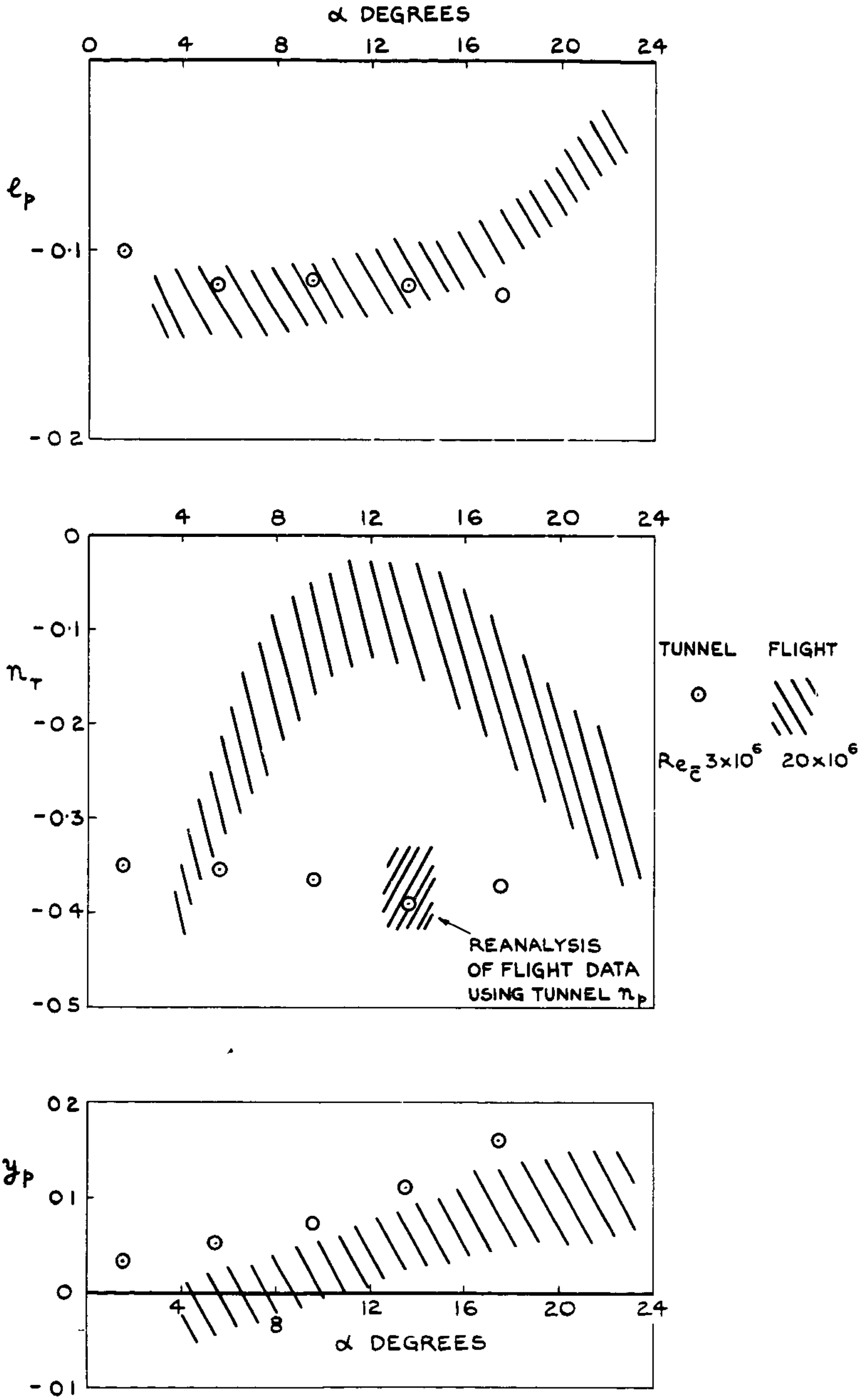


FIG.34 H P 115 TUNNEL & FLIGHT DAMPING DERIVATIVES

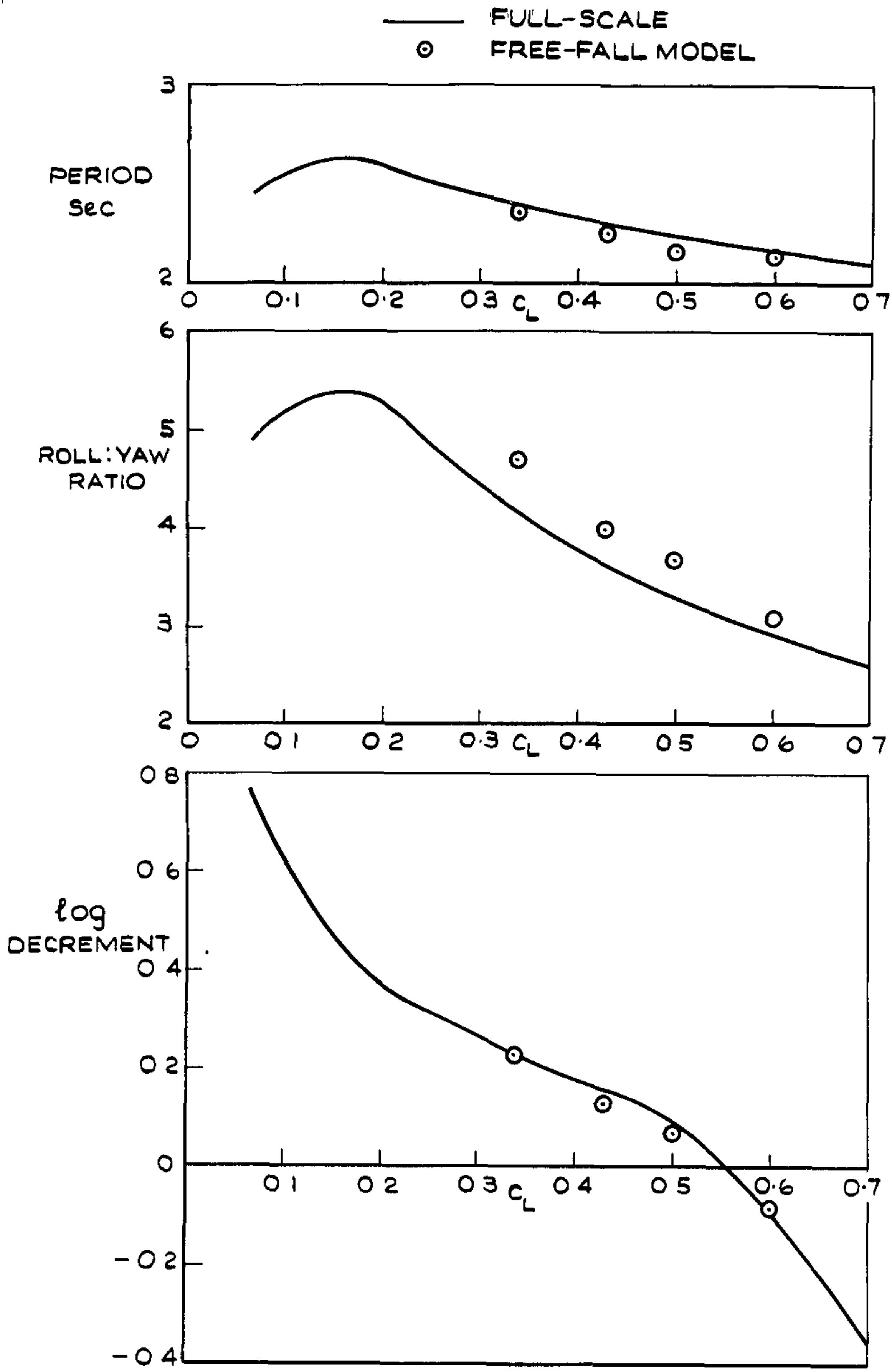


FIG.35 HP.115 COMPARISON OF BEHAVIOUR OF DUTCH ROLL ON AIRCRAFT AND $\frac{1}{4}$-SCALE MODEL

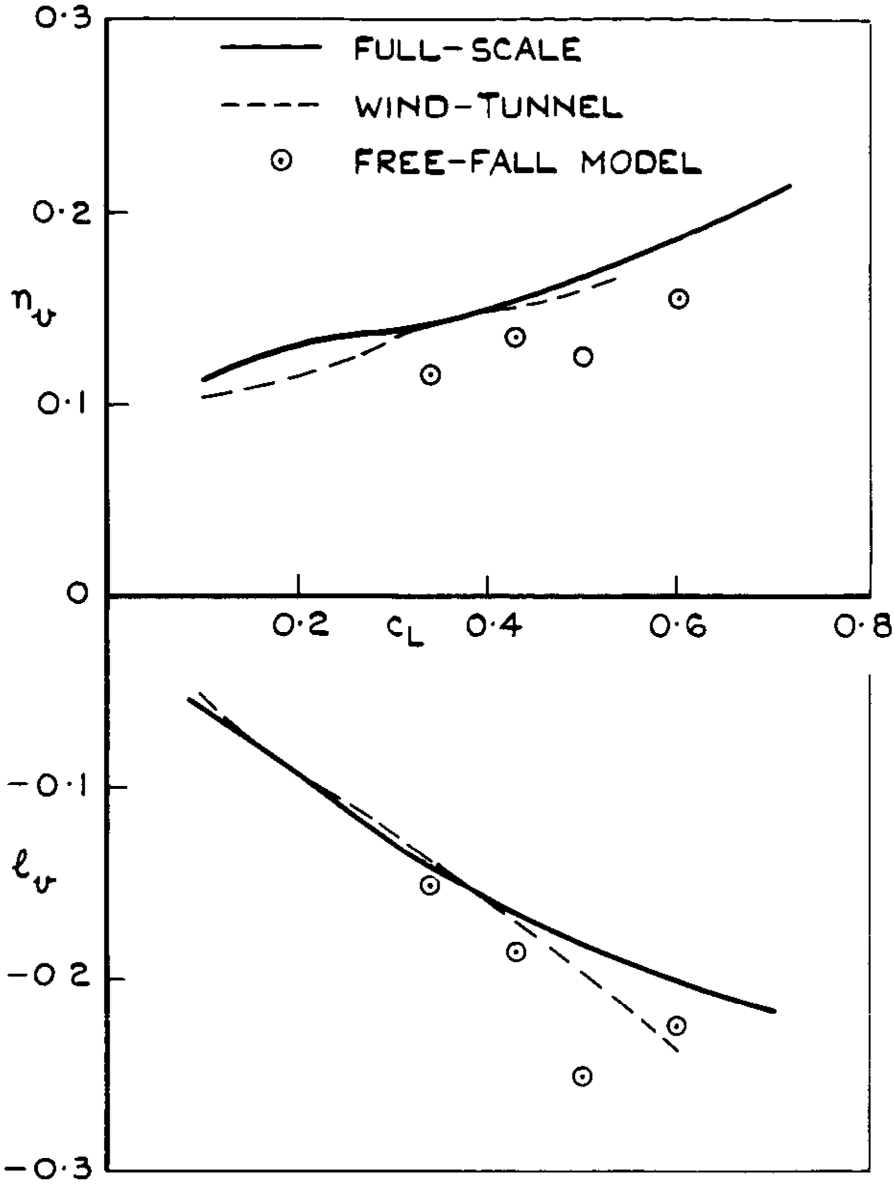


FIG. 36 H.P. 115 STATIC LATERAL DERIVATIVES - COMPARISON OF FULL-SCALE, FREE-FALL MODEL & WIND-TUNNEL MODEL

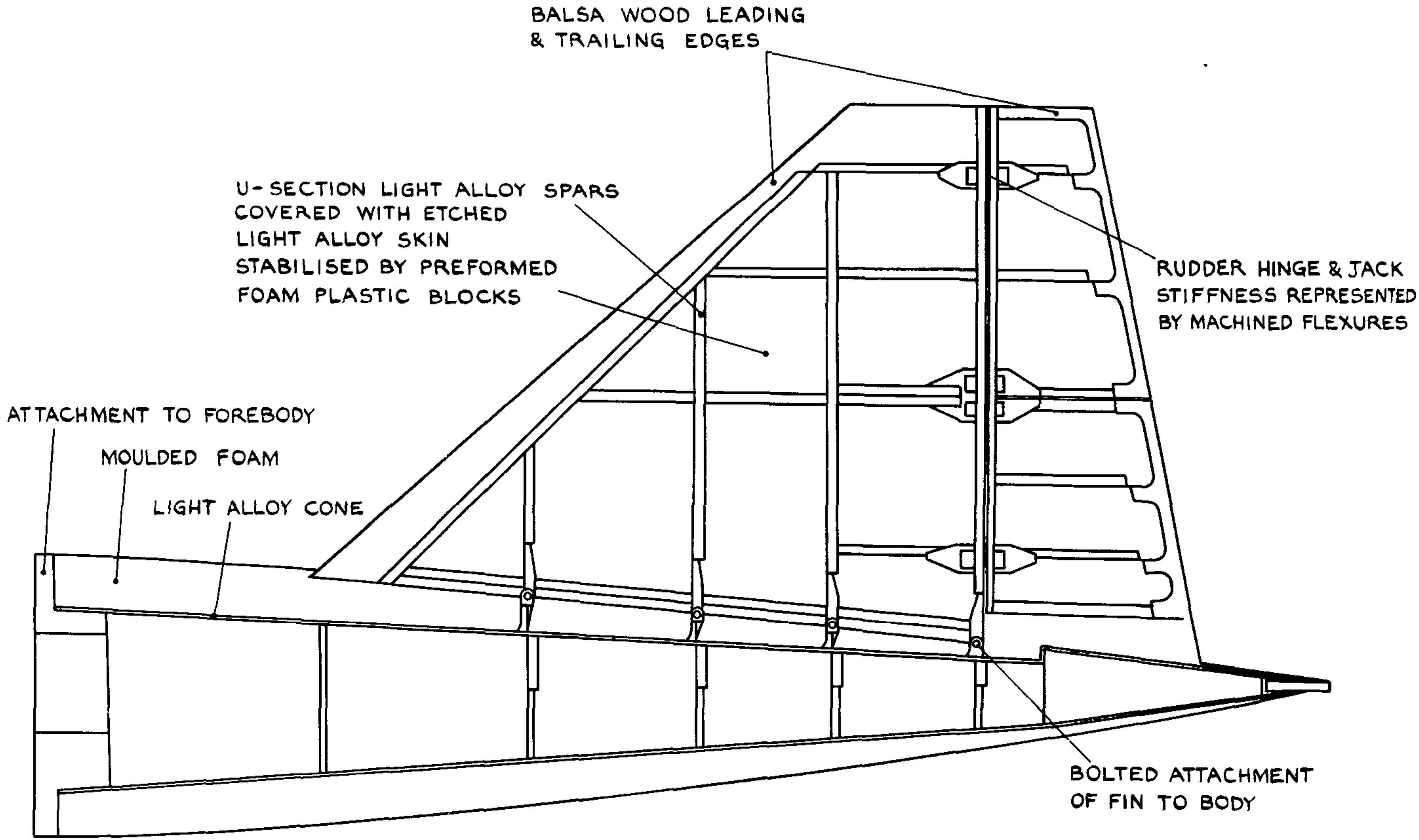


FIG. 37 FLEXIBLE FIN MODEL

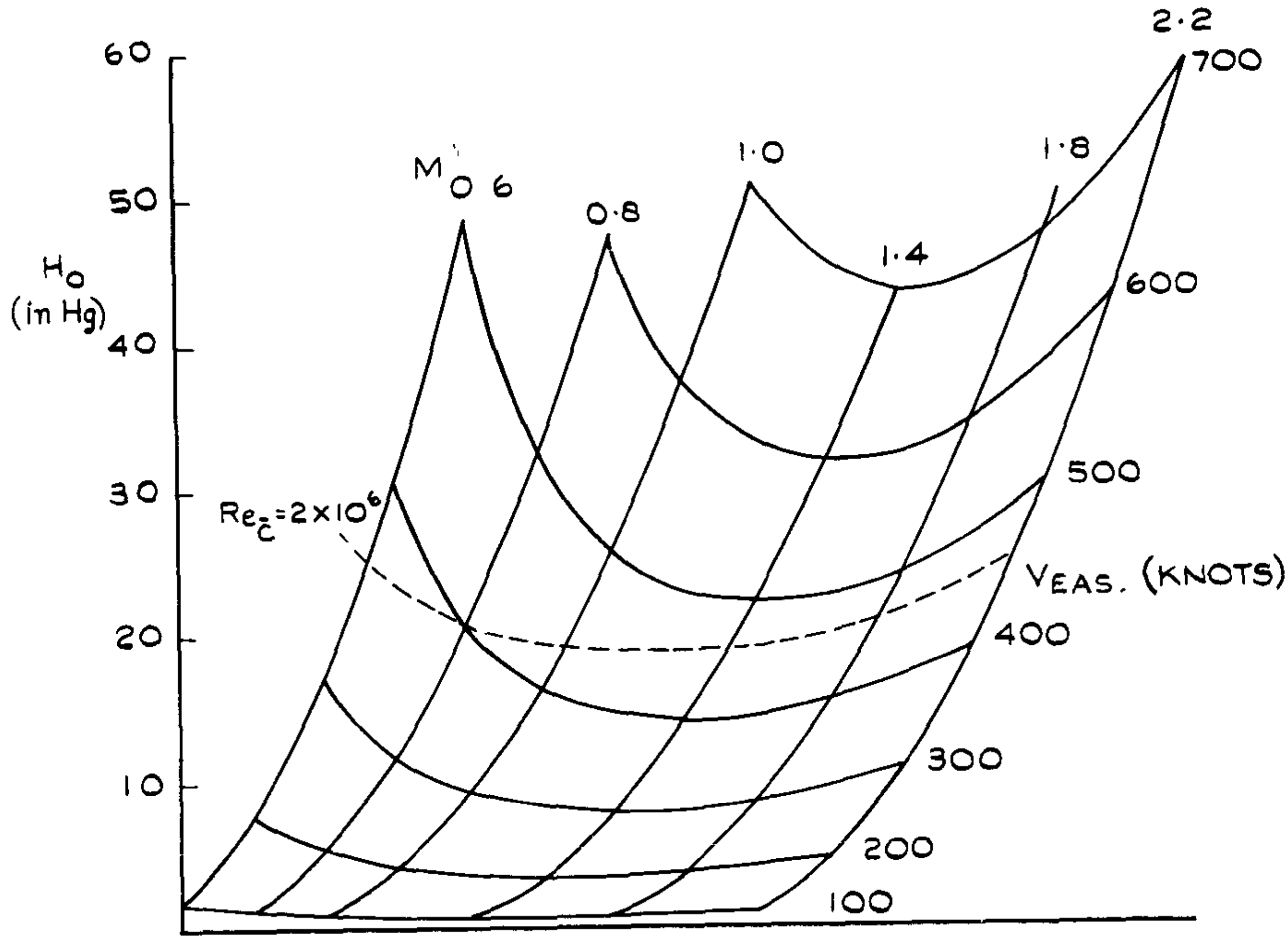


FIG 38 TUNNEL CONDITIONS FOR SIMULATING FULL-SCALE LOADING

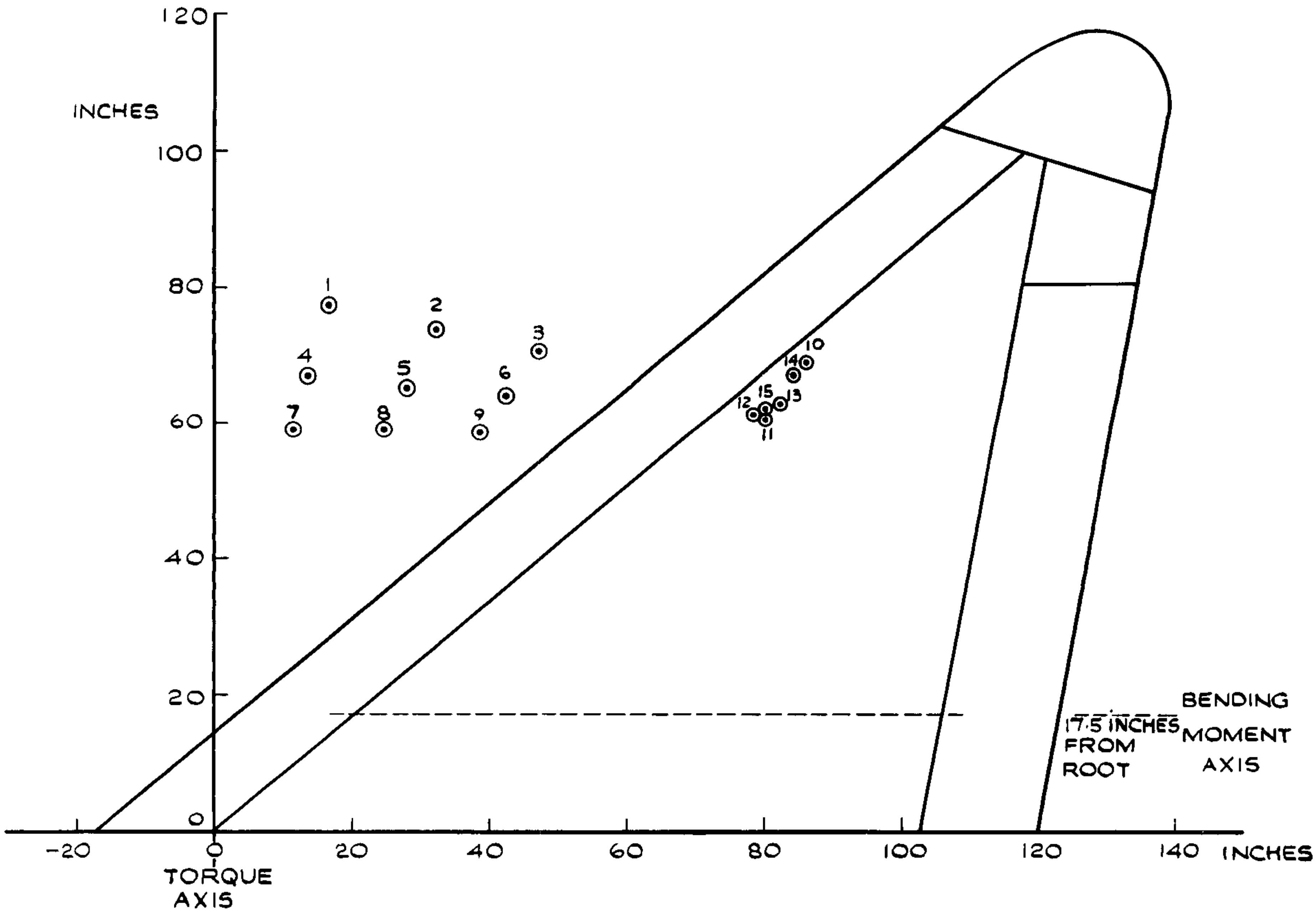


FIG.1 CENTRES OF PRESSURE OF LOAD DISTRIBUTIONS

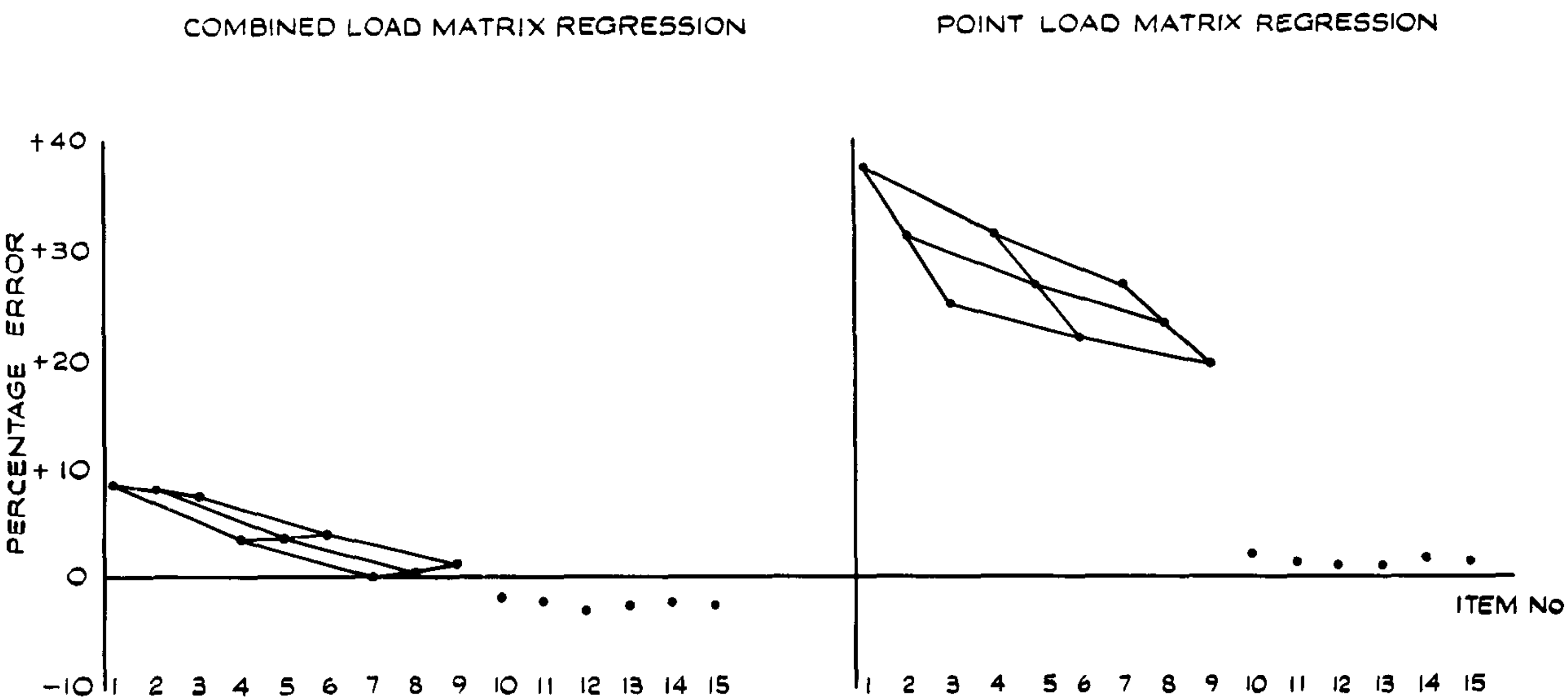


FIG.2 ERRORS IN PREDICTION OF SHEAR

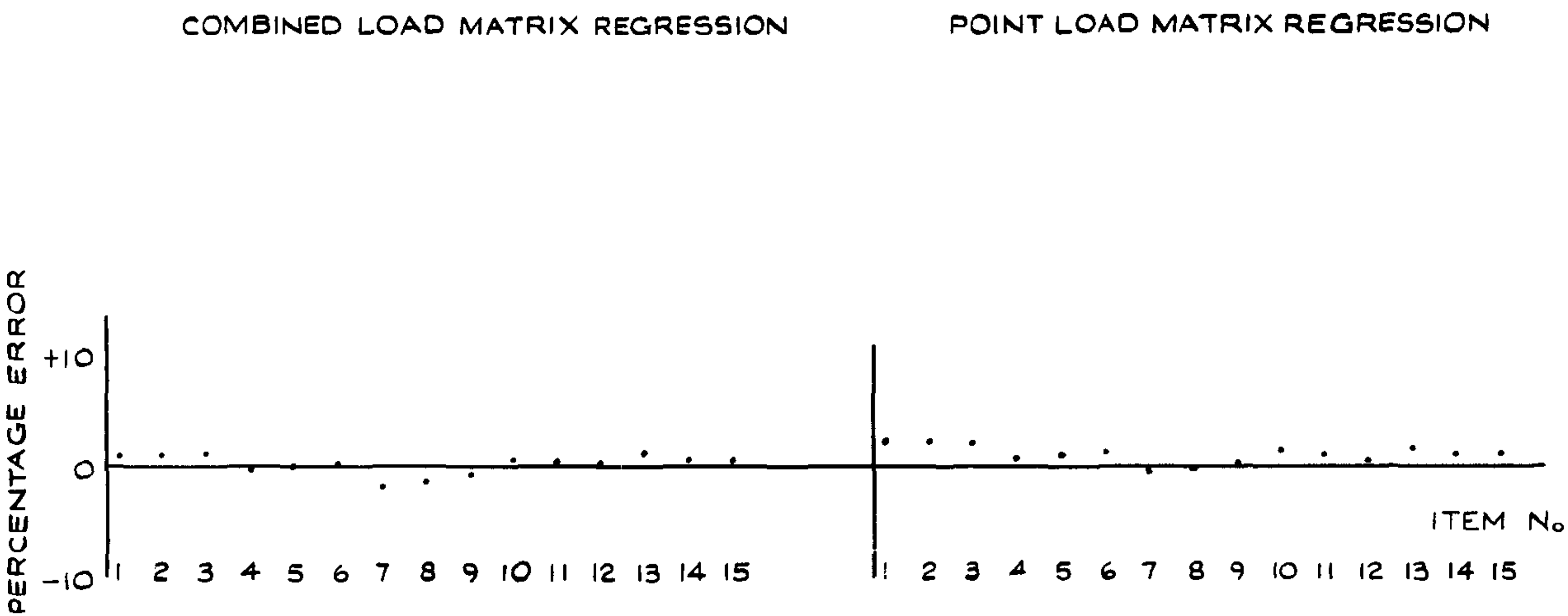


FIG.3 ERRORS IN PREDICTION OF BENDING MOMENT

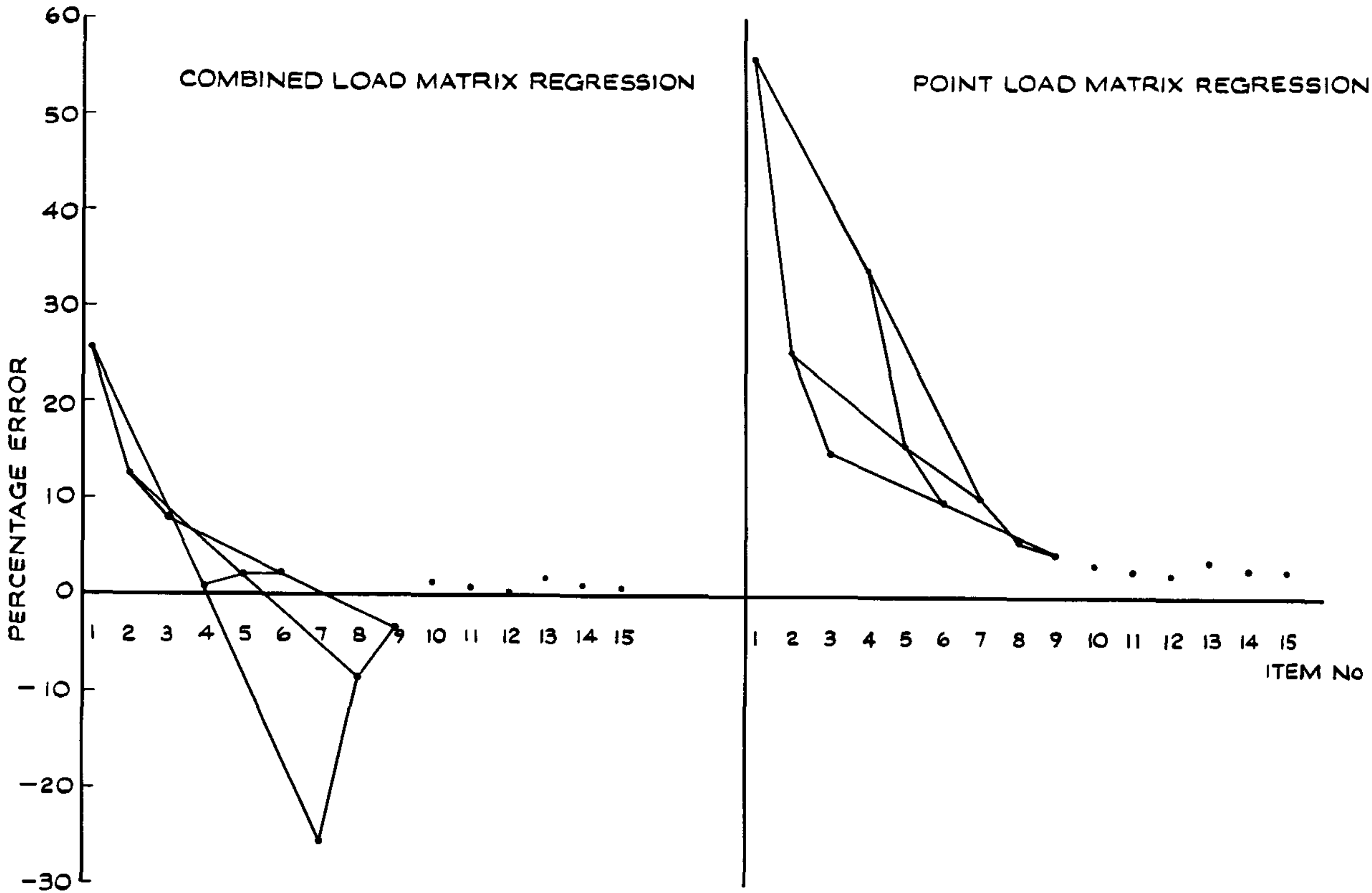


FIG.4 ERRORS IN PREDICTION OF TORQUE

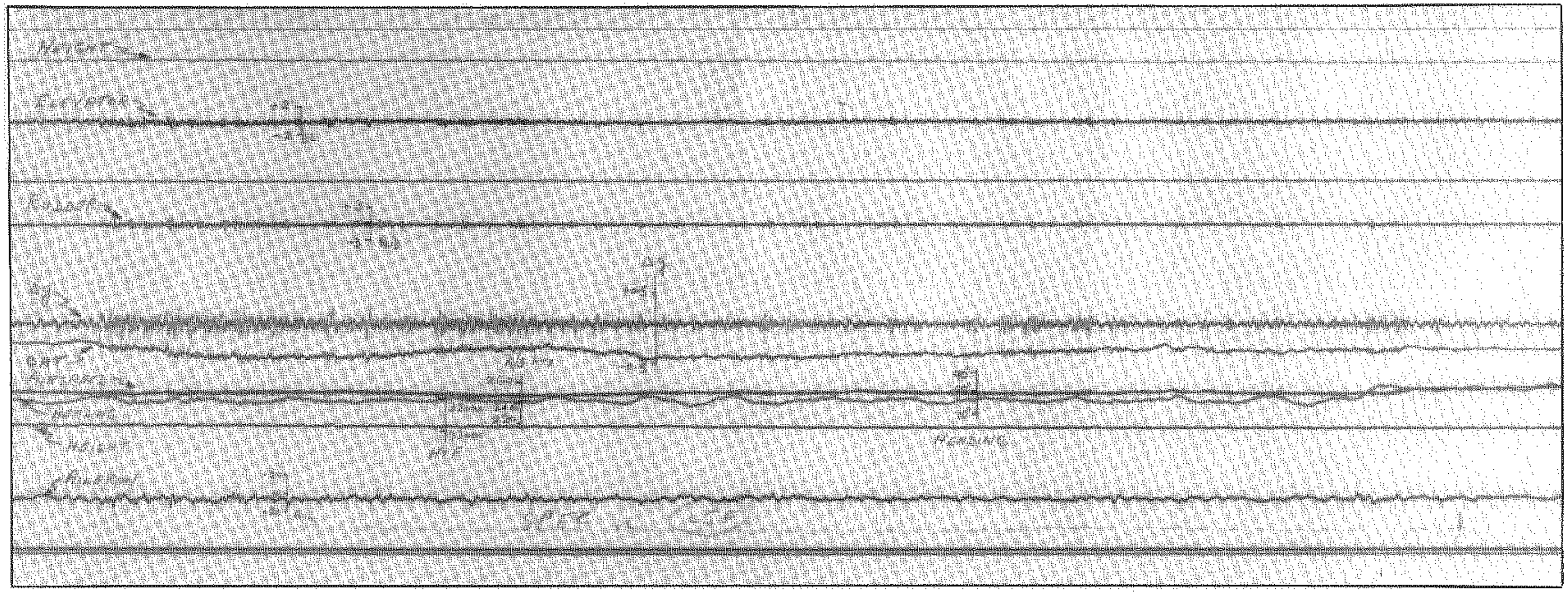


Fig.1 Prolonged encounter with turbulence of moderate intensity

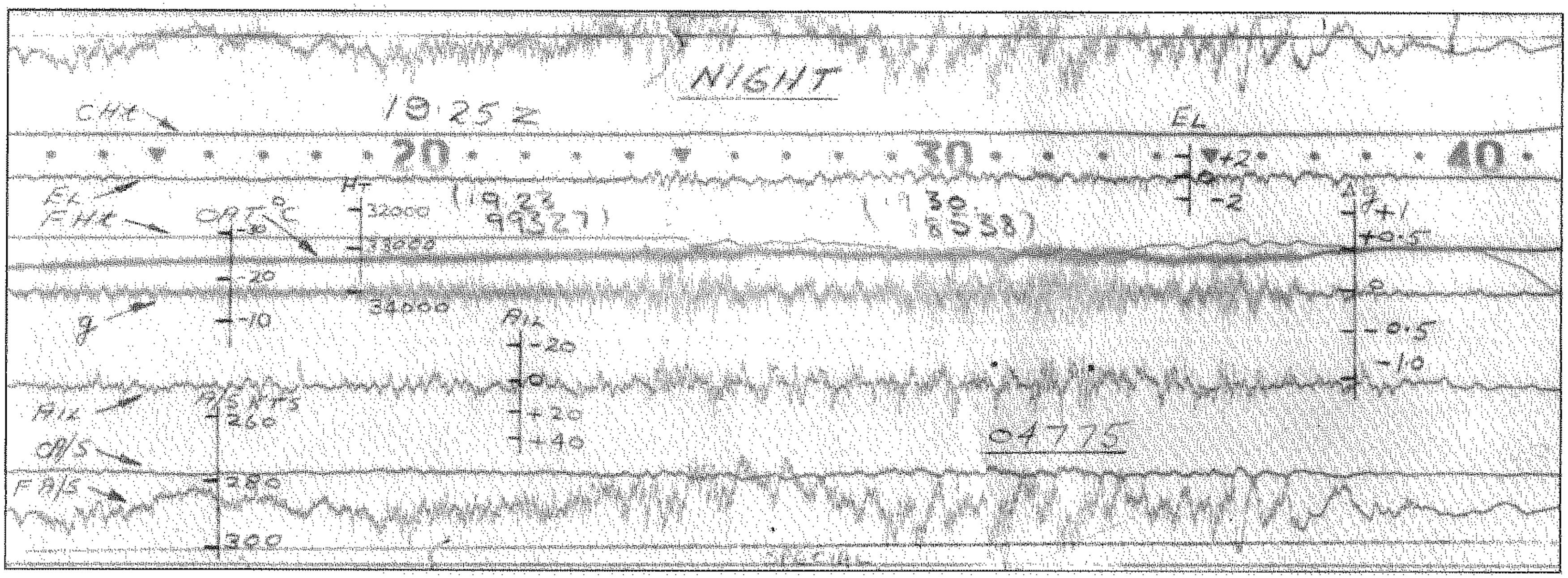


Fig.2 Encounter with severe clear air turbulence

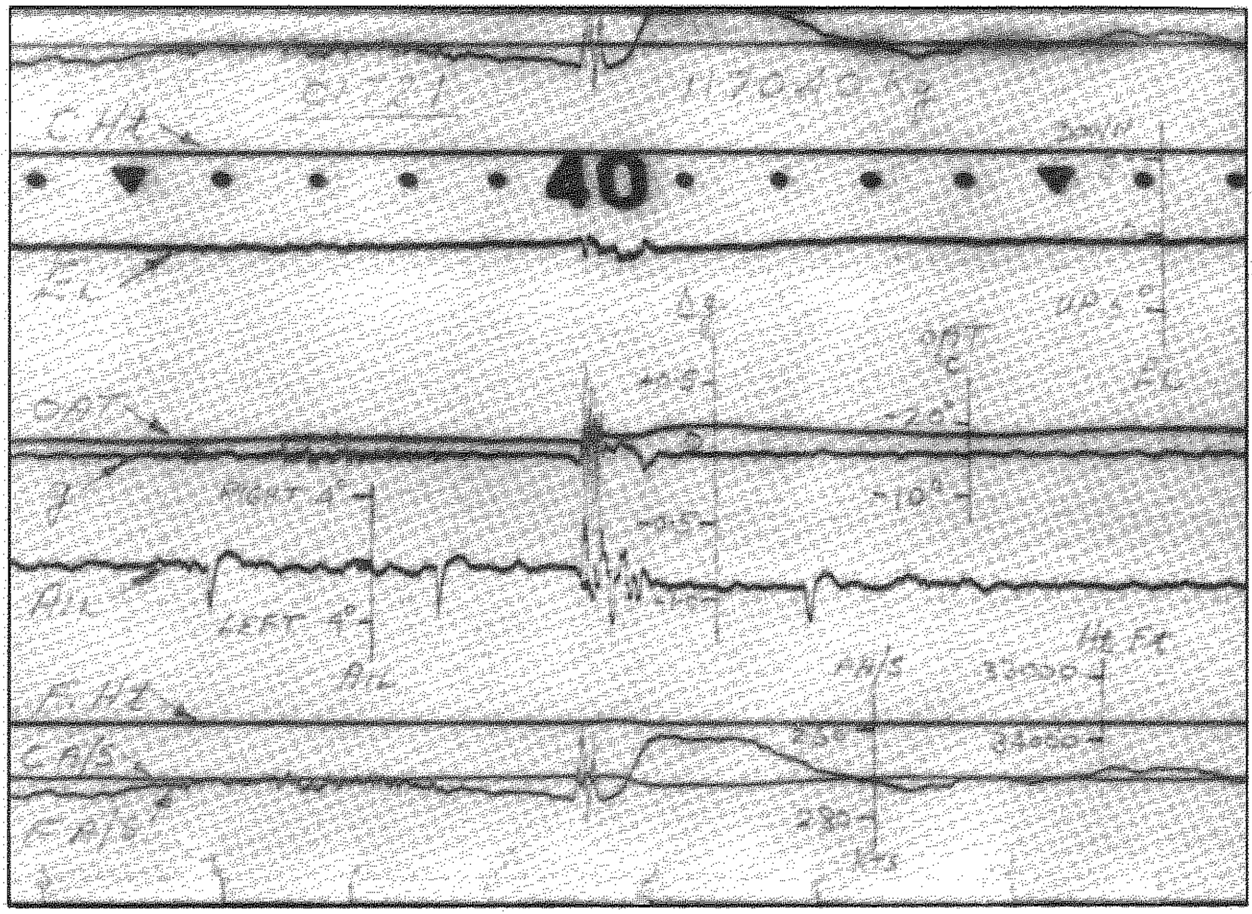


Fig.3 Encounter with severe turbulence

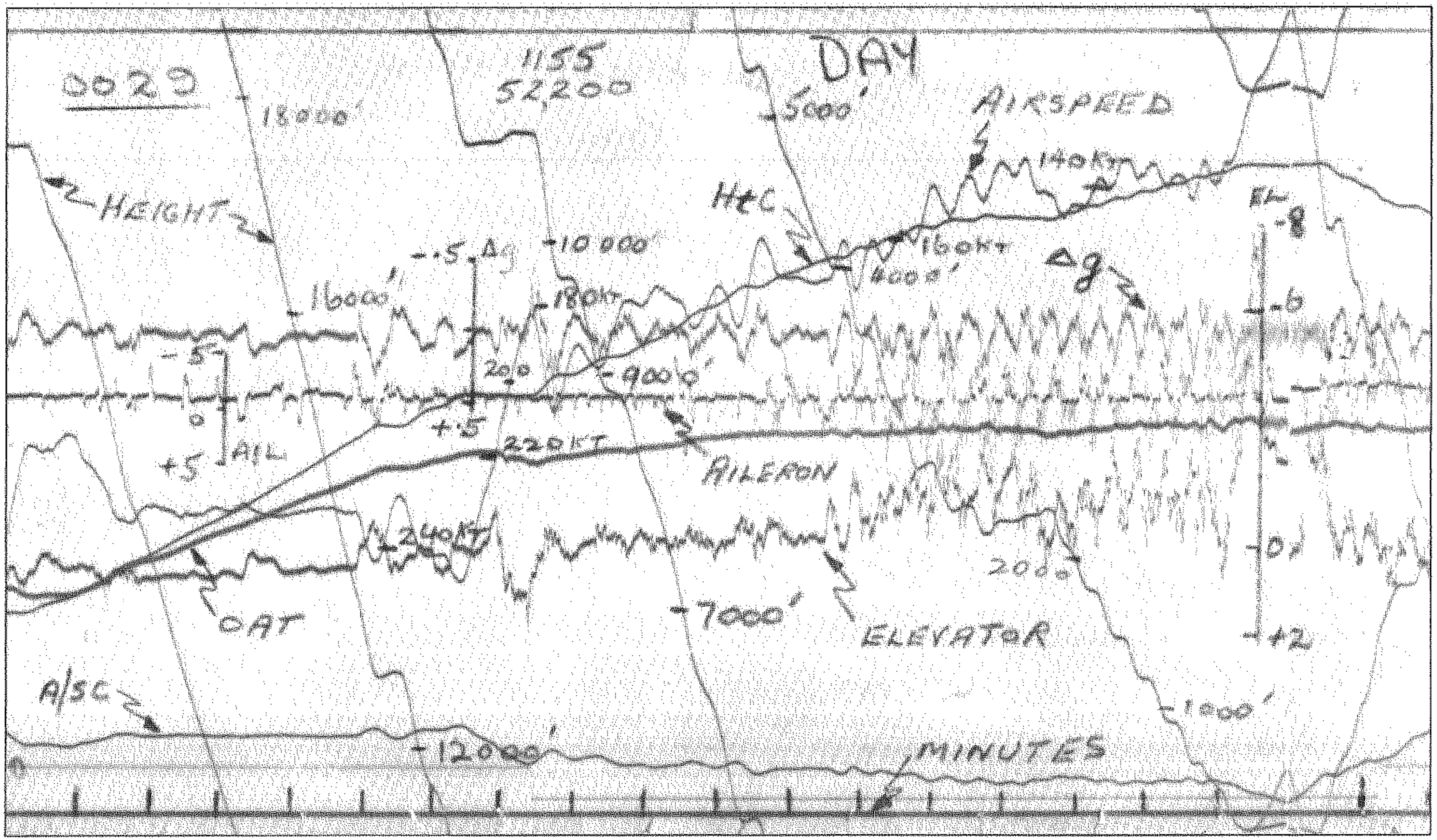


Fig.4 Pitch oscillations during approach

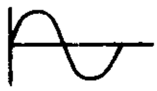
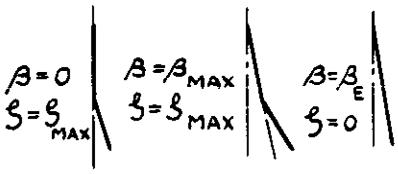
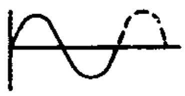
PITCH	TO LOADS FOR GIVEN STEADY n ADD TAIL LOADS DUE TO A PITCHING ACCELERATION GIVEN AS A FUNCTION OF V AND n_1	MANOEUVRE FROM n = 1·0 TO n = n_1 AND FROM n = n_1 TO n = 1·0 ELEVATOR FUNCTION DEFINED,  OR 
ROLL	FROM n = 0 OR $\frac{2}{3}$ n_1, EITHER FOR DEFINED AILERON ANGLE OR FOR DEFINED RATE OF ROLL, EACH OF TWO CONDITIONS (1) ROLLING ACCELERATION WITH ZERO RATE OF ROLL AND (2) STEADY RATE OF ROLL WITH ZERO ROLL ACCELERATION	
YAW	RUDDER ANGLE GIVEN AS A FUNCTION OF SIDESLIP,  $\beta = 0$, $\zeta = \zeta_{MAX}$; $\beta = \beta_{MAX}$, $\zeta = \zeta_{MAX}$; $\beta = \beta_E$, $\zeta = 0$	RUDDER ANGLES GIVEN AS FUNCTIONS OF TIME  AND 
	ENGINE FAILURE WITH PILOT'S RECOVERY ACTION	

FIG.1 REQUIREMENTS FOR STRUCTURAL LOADING CASES - PILOT-INITIATED MANOEUVRES

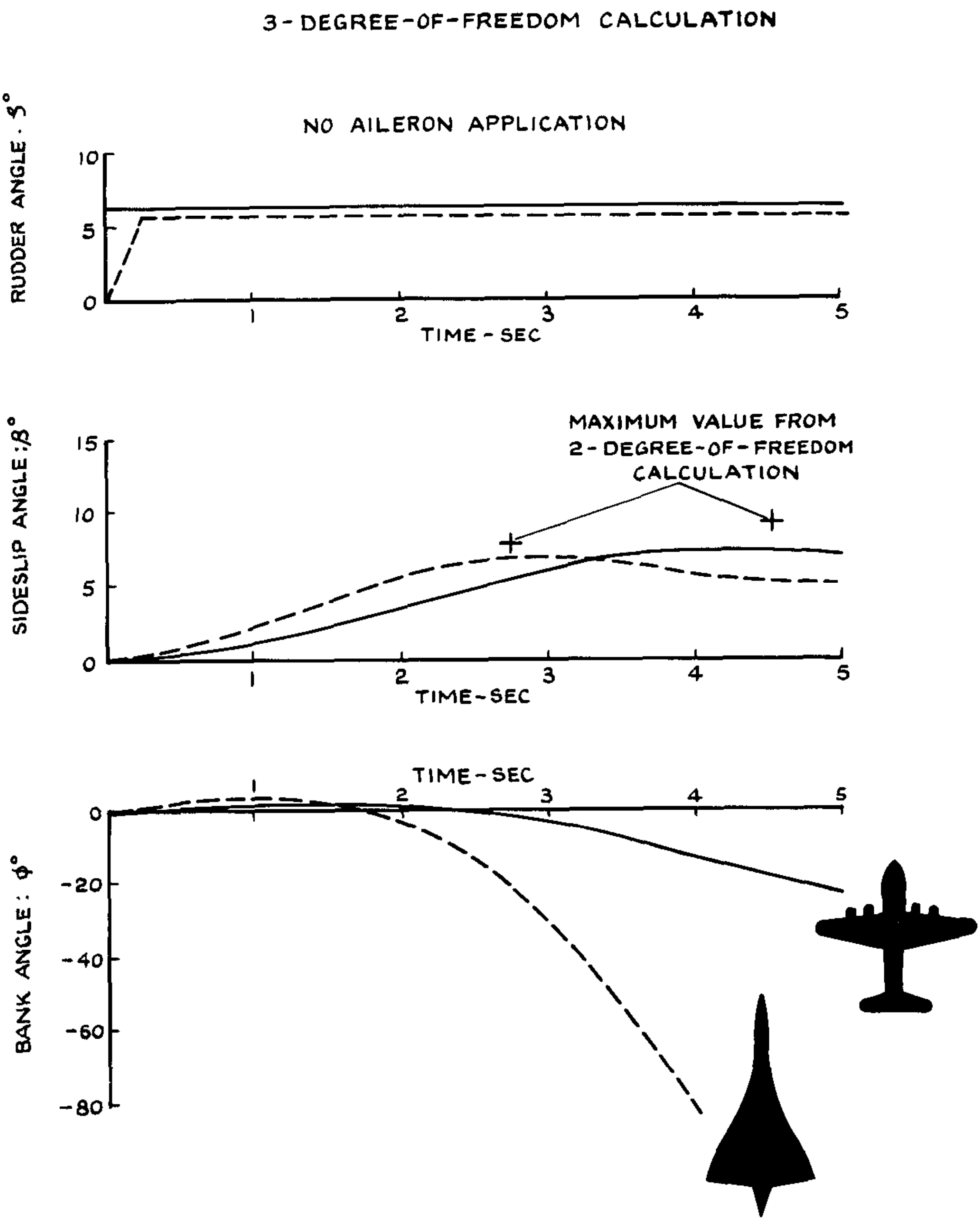


FIG. 2 COMPARISON OF RESPONSES TO RUDDER APPLICATION ON CONVENTIONAL AND HIGH-SPEED AEROPLANES

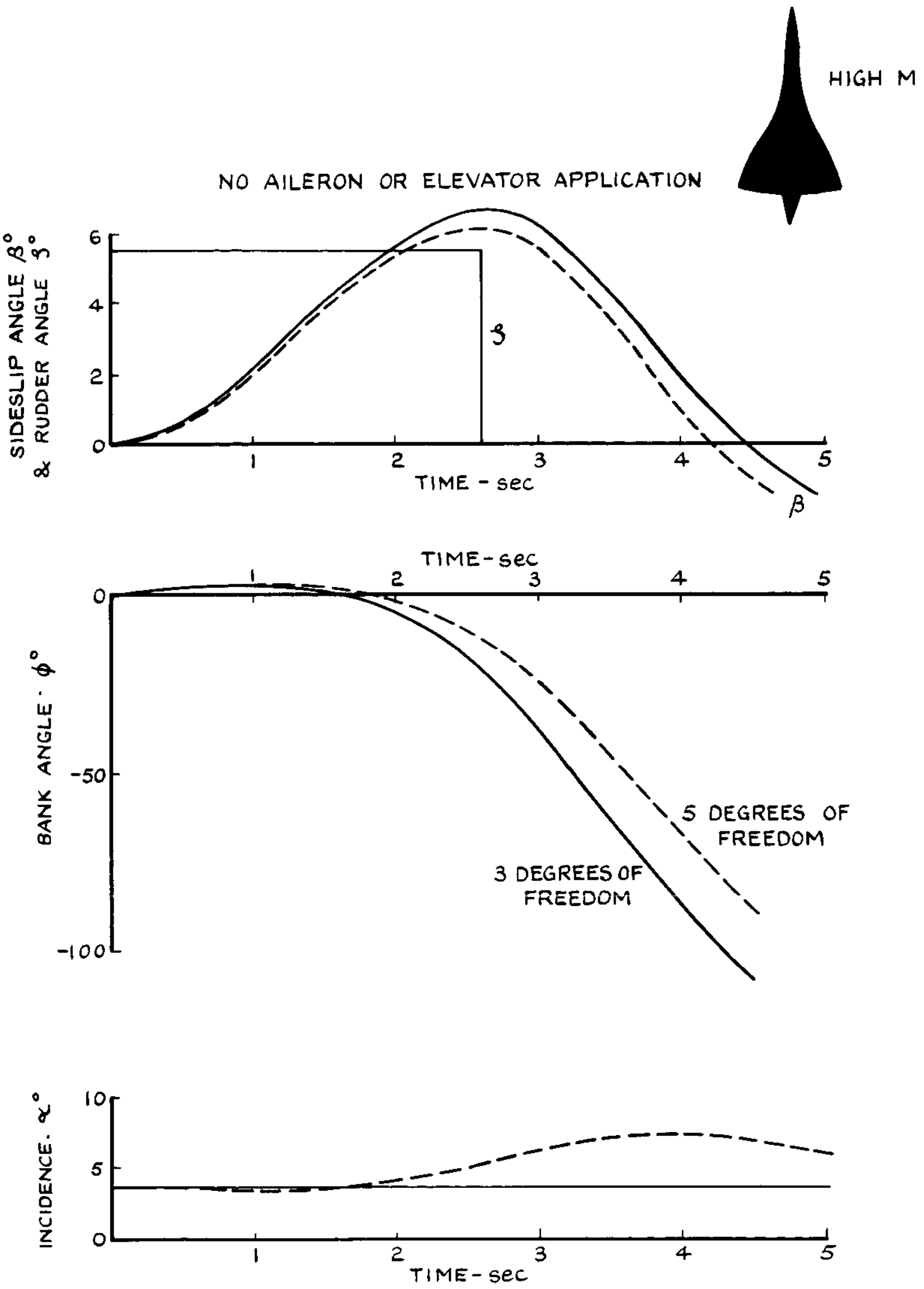


FIG. 3 COMPARISON OF 3-AND 5-DEGREE-OF-FREEDOM CALCULATIONS: RESPONSE PARAMETERS

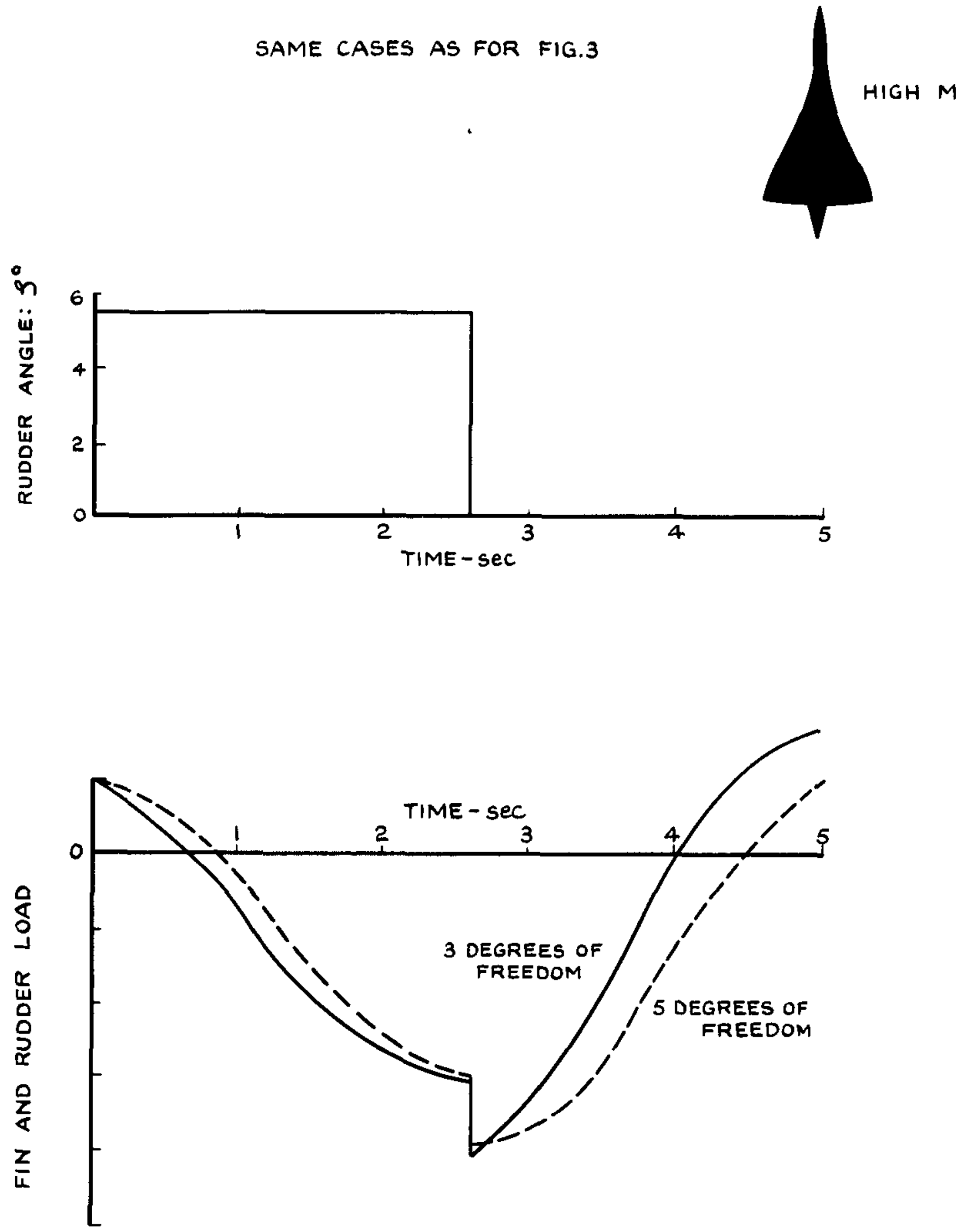


FIG. 4 COMPARISON OF 3 - AND 5 - DEGREE - OF - FREEDOM CALCULATIONS: FIN AND RUDDER LOADS

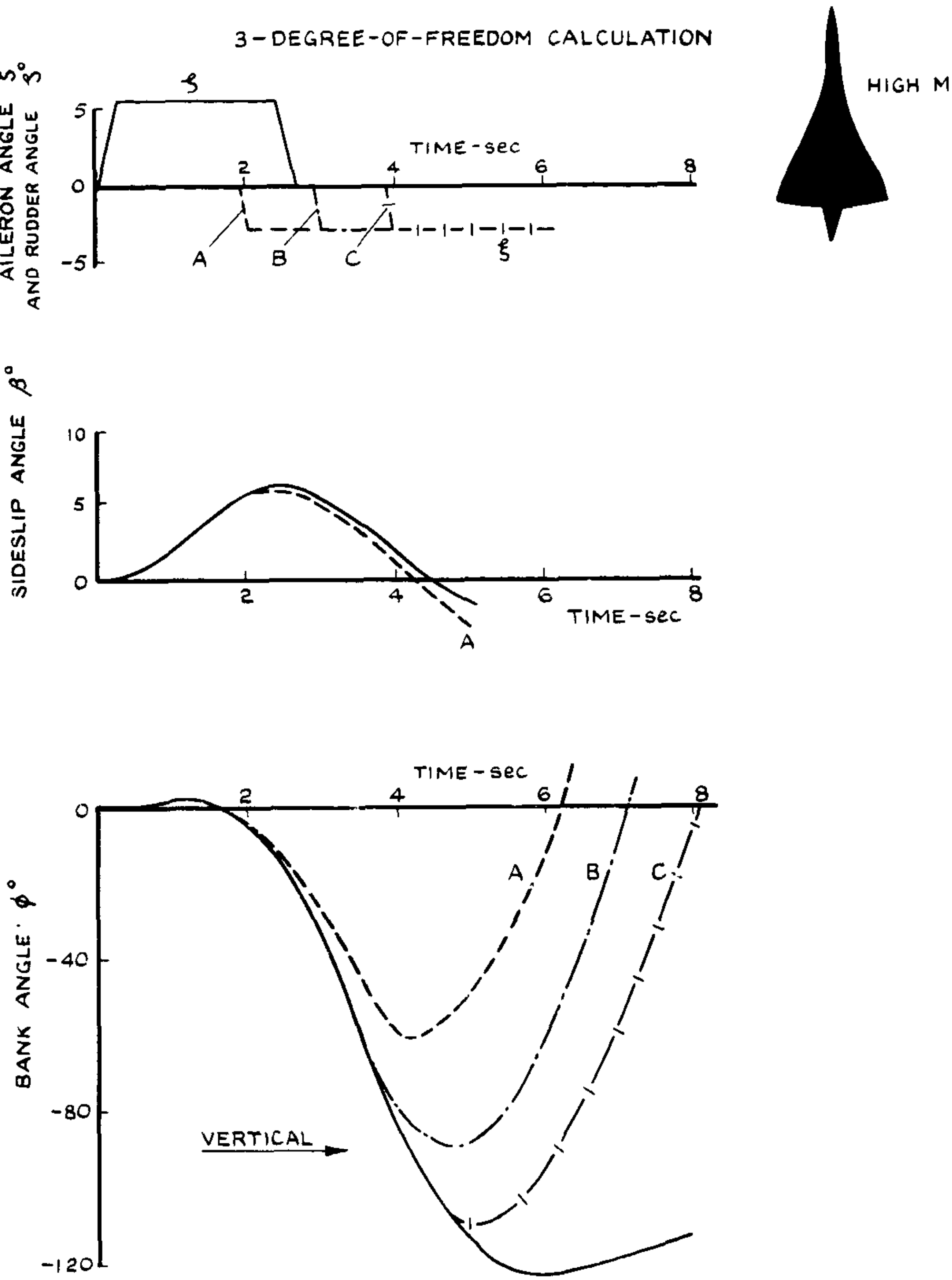


FIG.5 EFFECT OF AILERON APPLICATION ON RESPONSE PARAMETERS IN A RUDDER-INDUCED MANOEUVRE

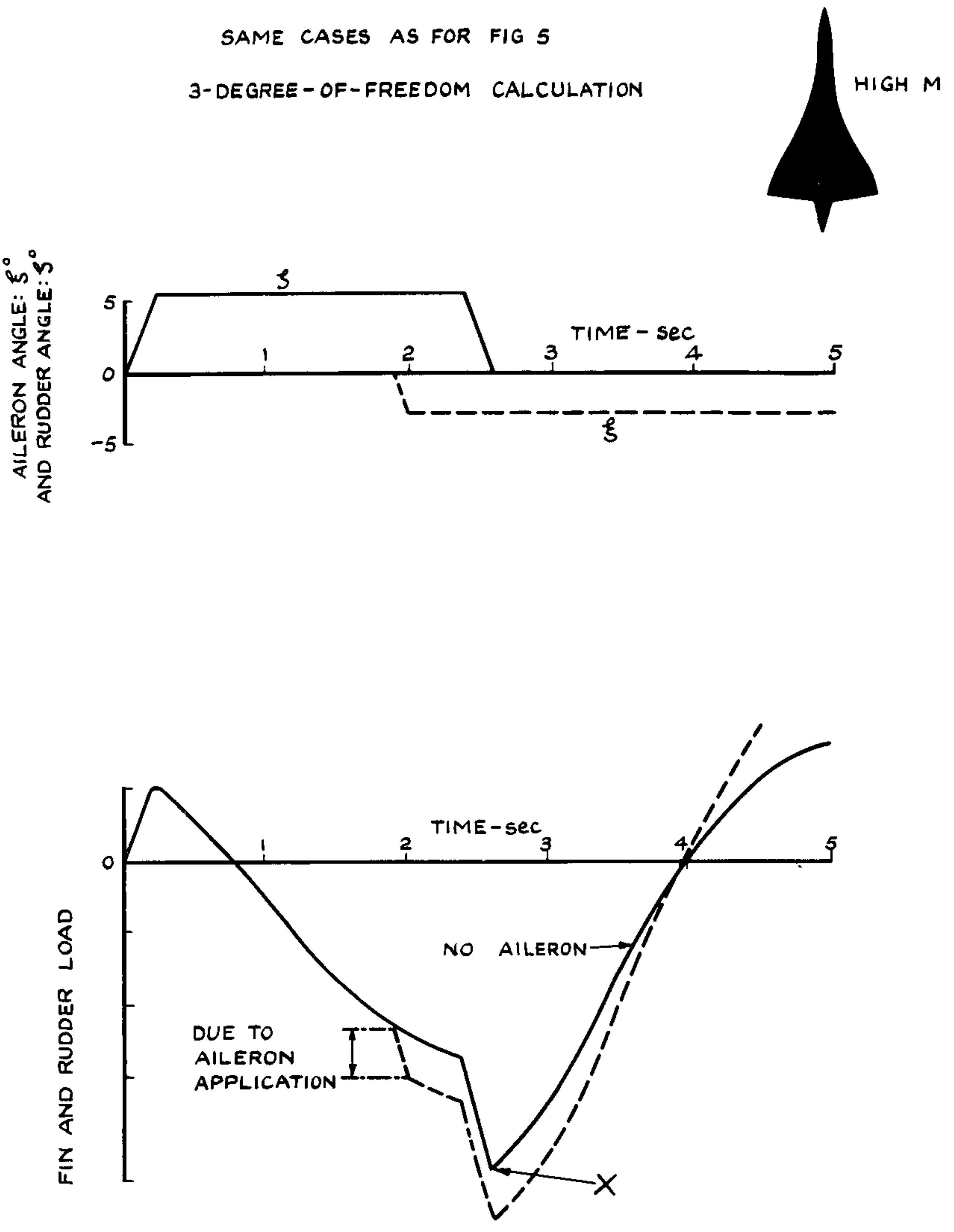


FIG. 6 EFFECT OF AILERON APPLICATION ON FIN AND RUDDER LOAD IN A RUDDER-INDUCED MANOEUVRE

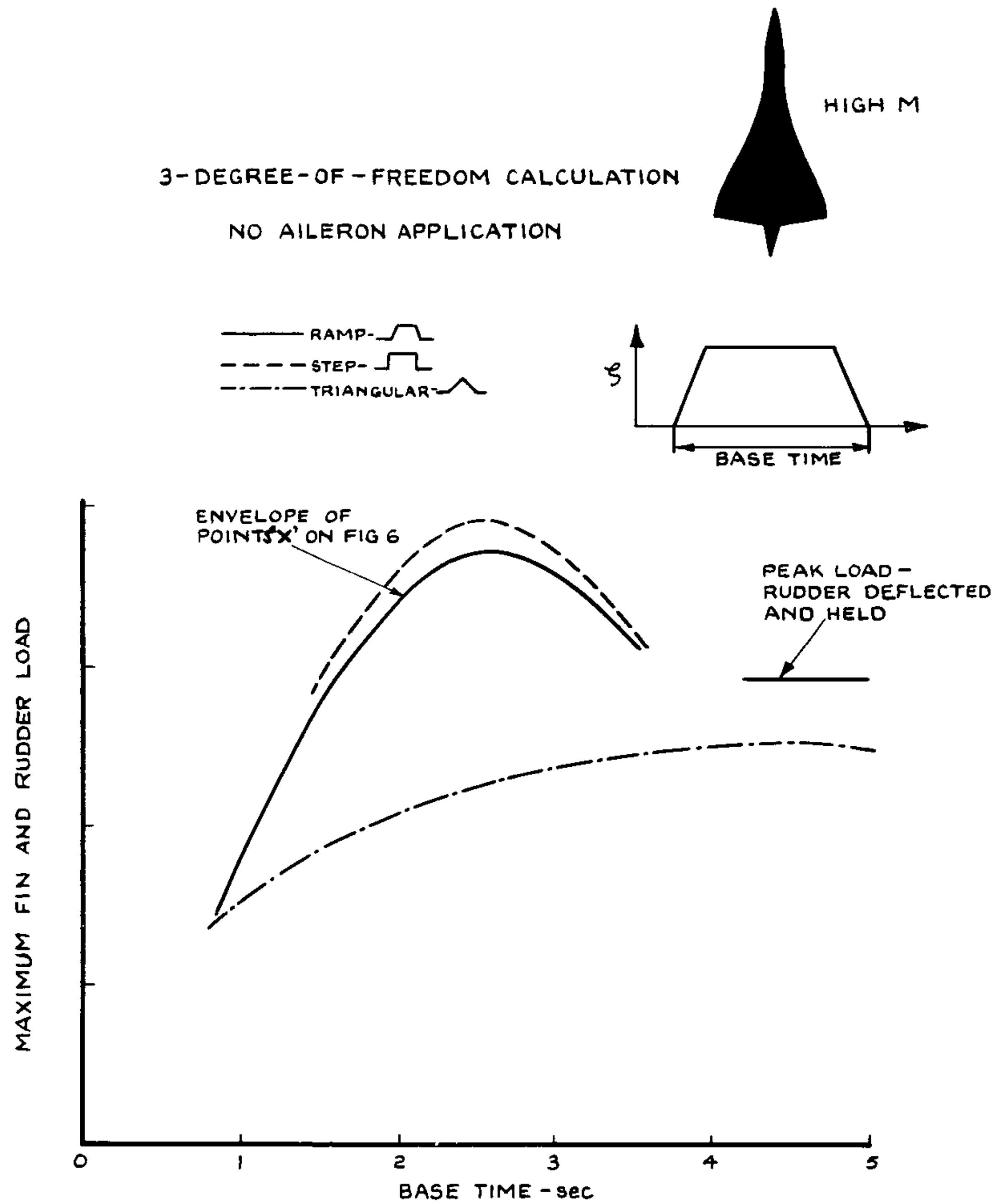


FIG 7 MAXIMUM LOAD ON FIN AND RUDDER FOLLOWING DOUBLE RAMP, STEP, AND TRIANGULAR RUDDER APPLICATIONS

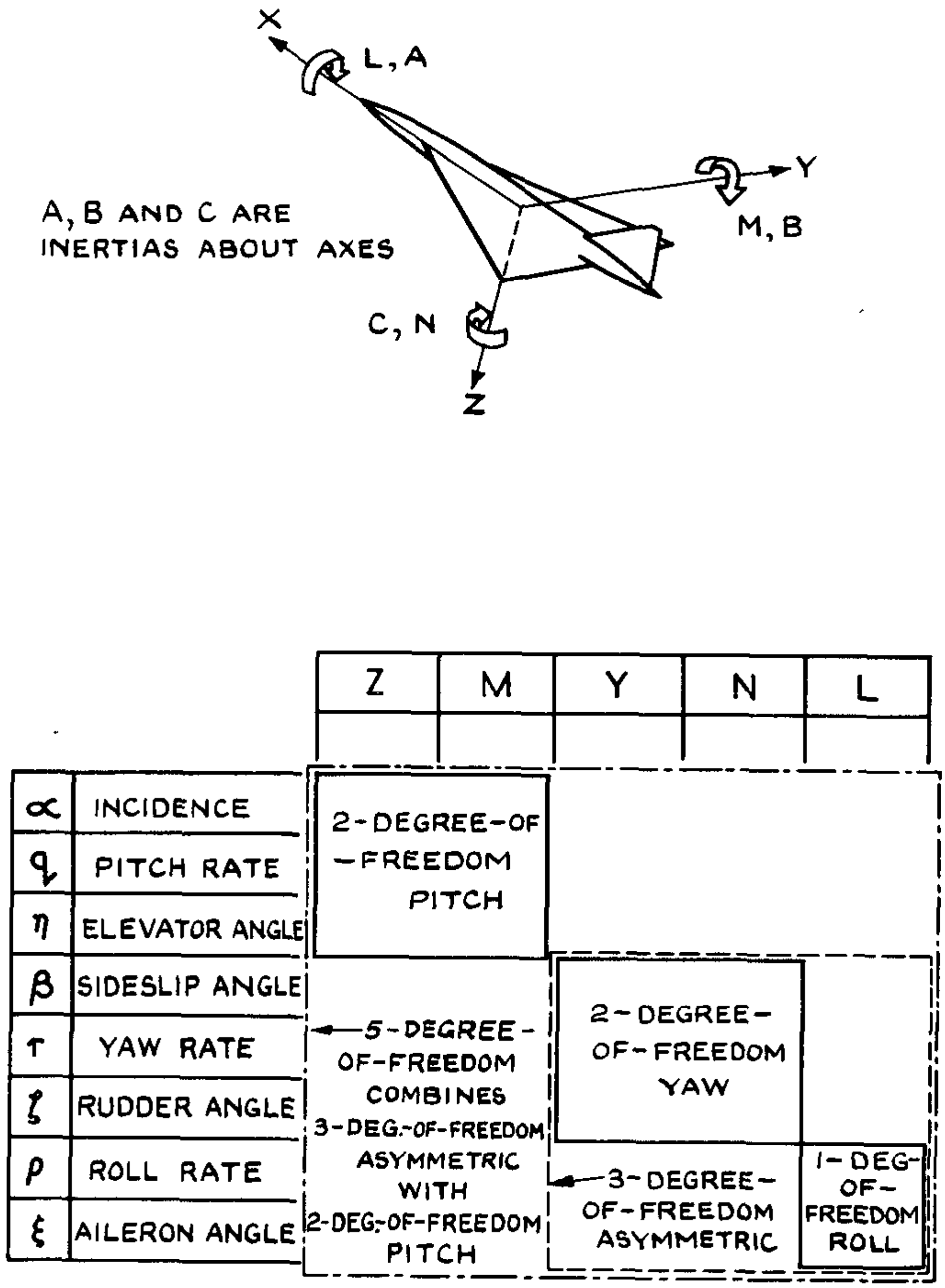


FIG. 8 AERODYNAMIC PARAMETERS USED IN RESPONSE CALCULATIONS

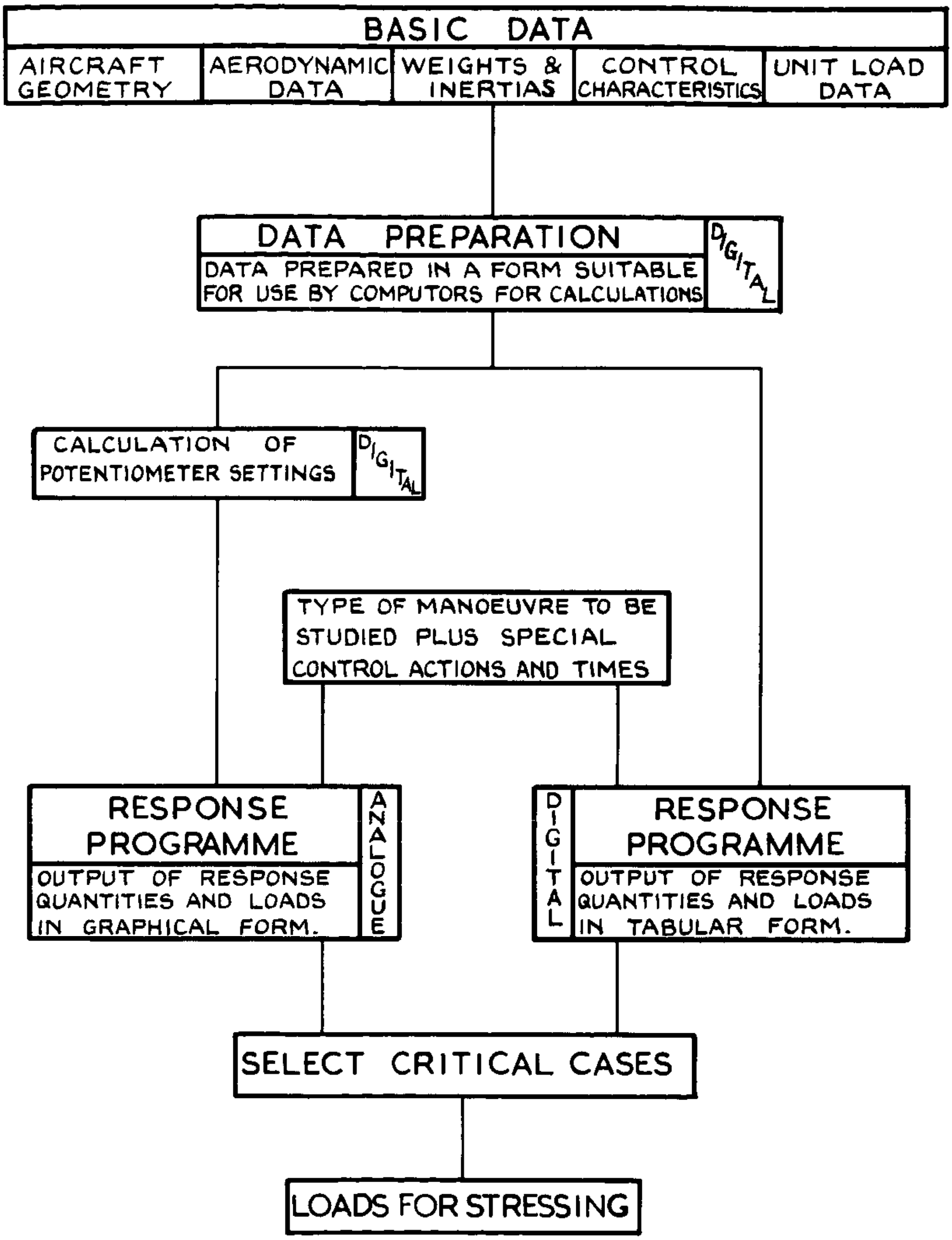


FIG. 9 SEQUENCE OF OPERATIONS IN CALCULATION OF DESIGN LOADS

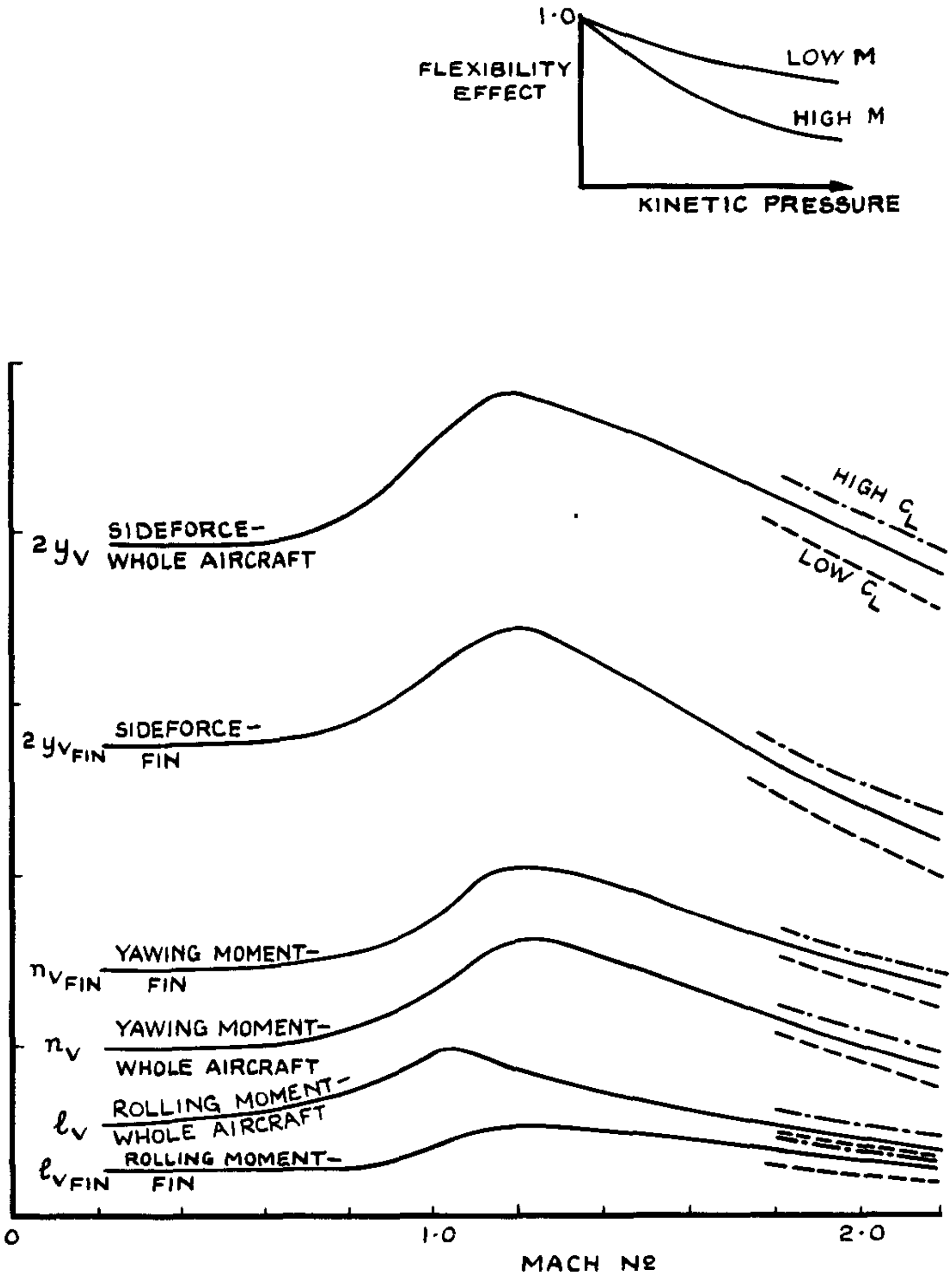


FIG. 10 VARIATION OF TYPICAL AERODYNAMIC PARAMETERS WITH MACH NUMBER

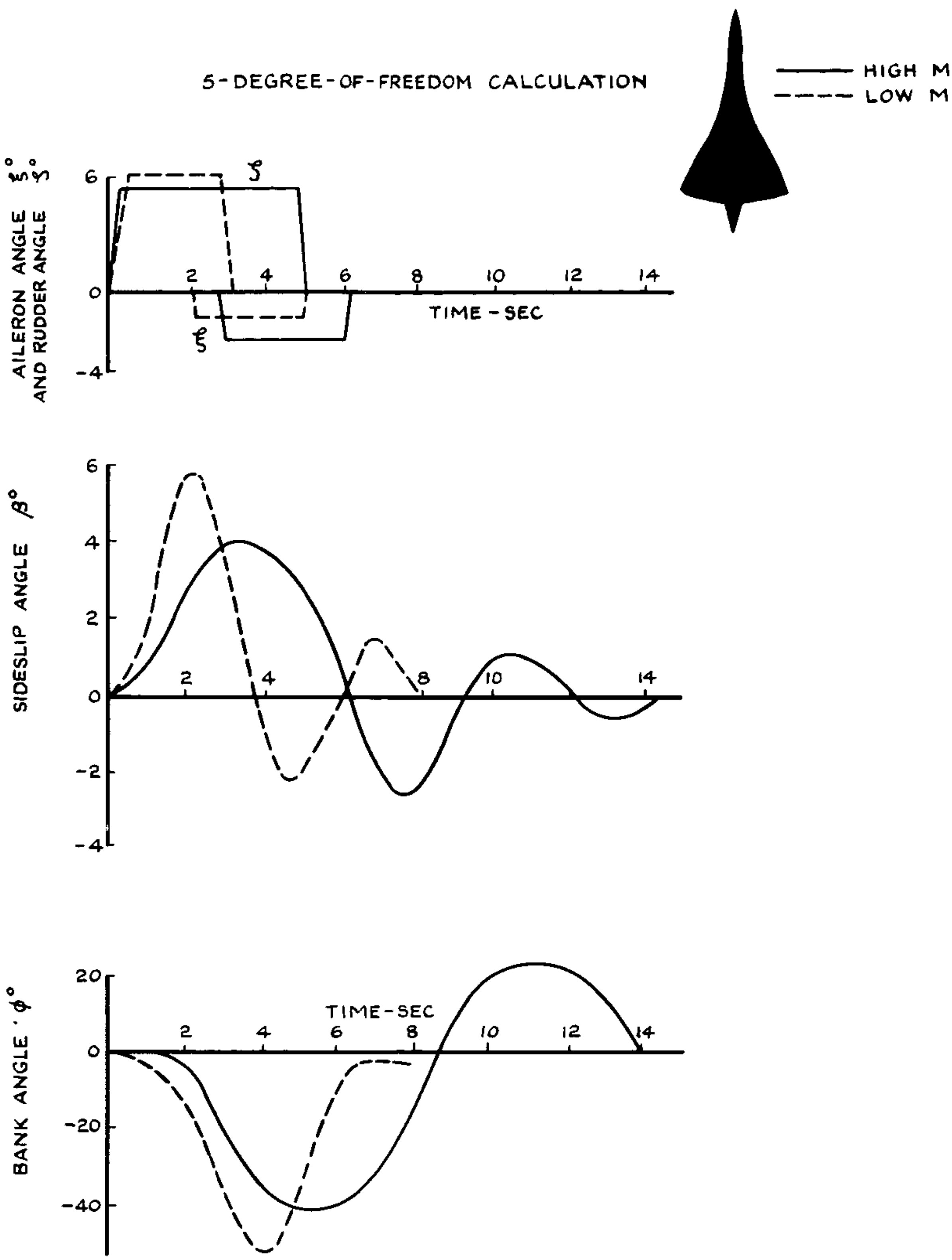


FIG.11 RUDDER-INDUCED MANOEUVRES WITH CORRECTIVE AILERON APPLICATION: SIDESLIP AND BANK

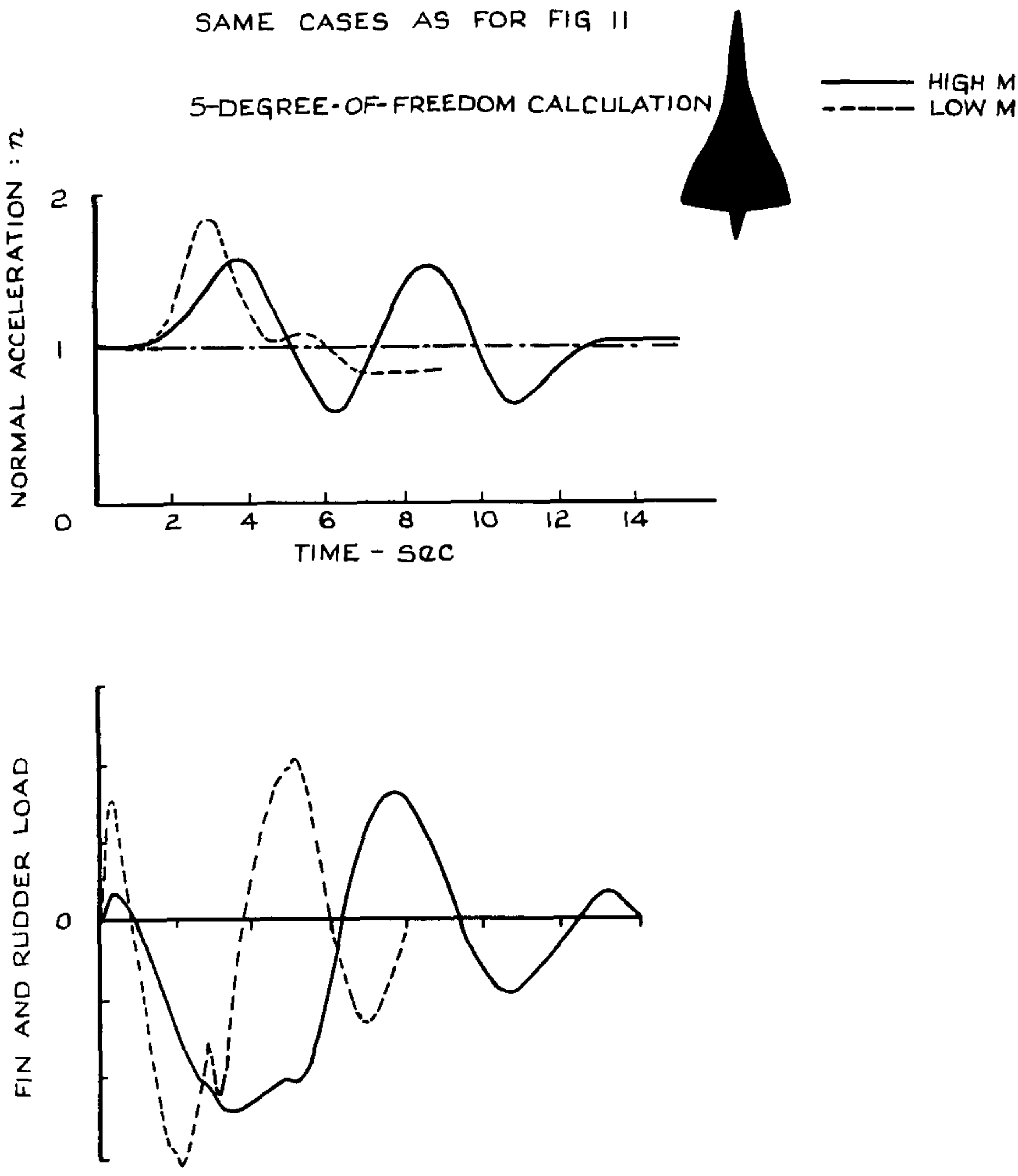


FIG.12 RUDDER-INDUCED MANOEUVRES WITH CORRECTIVE AILERON APPLICATION: NORMAL ACCELERATION AND FIN AND RUDDER LOAD

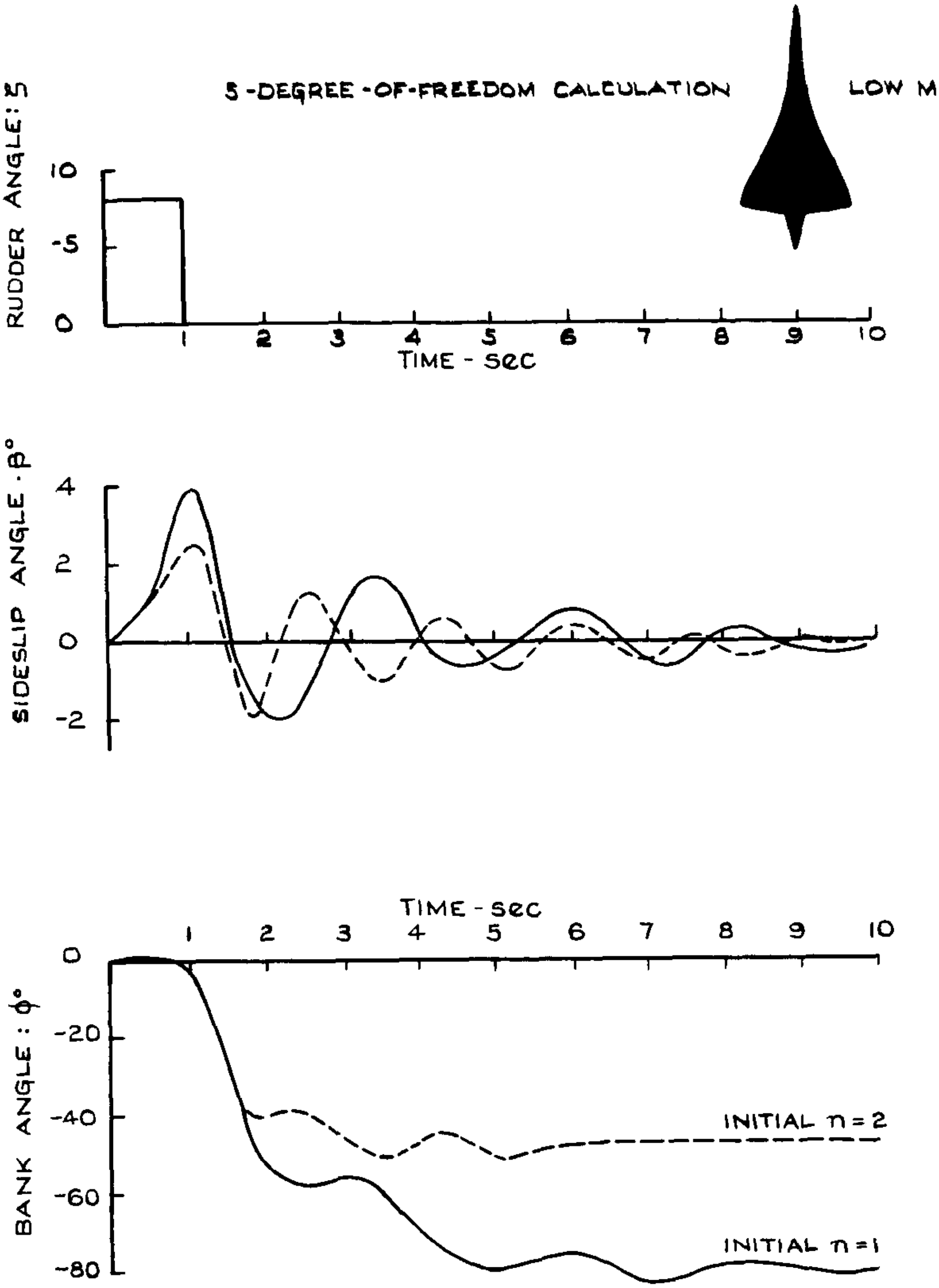


FIG.13 EFFECT OF LIFT COEFFICIENT ON RUDDER-INDUCED MANOEUVRE: SIDESLIP AND BANK

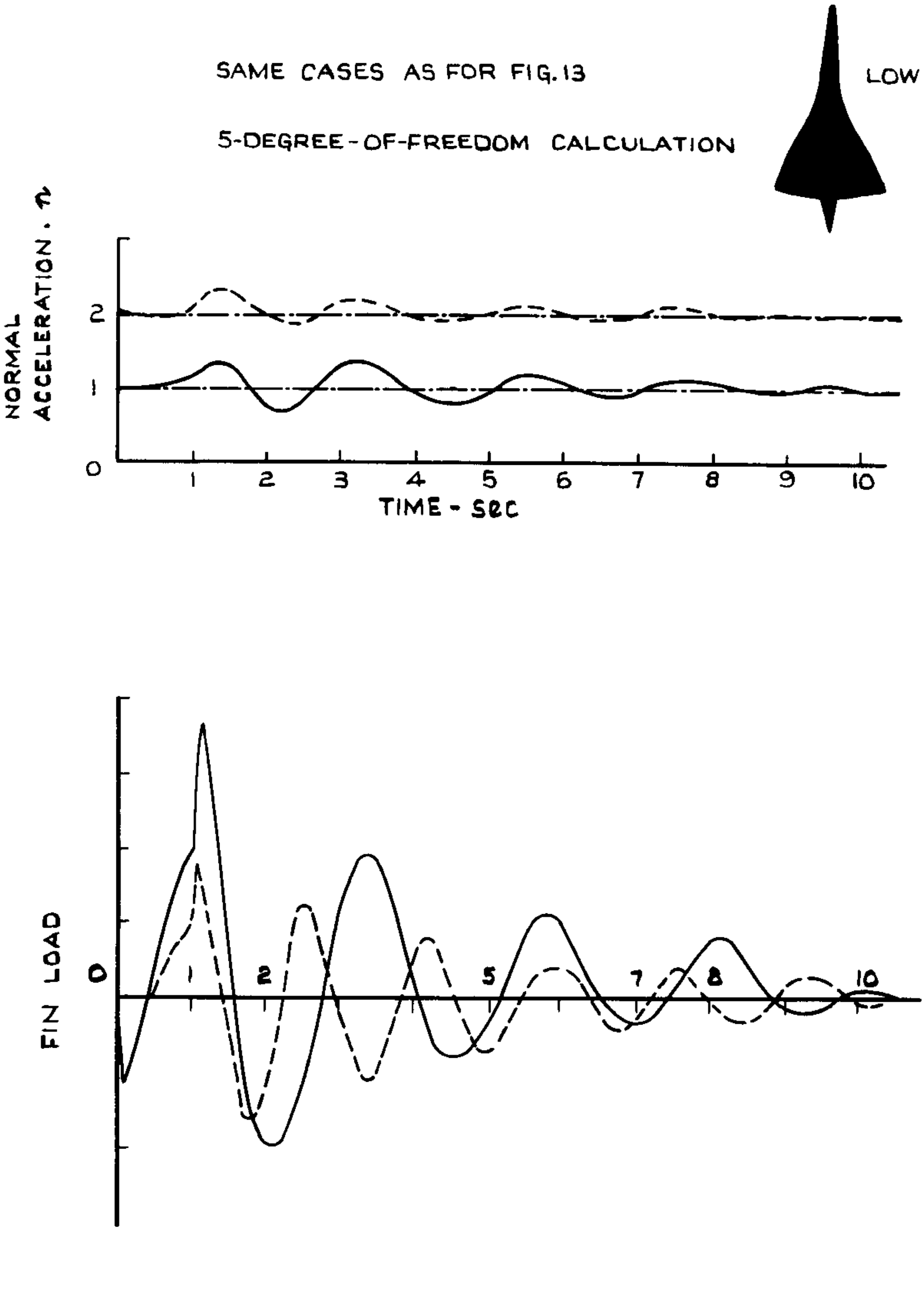


FIG.14 EFFECT OF LIFT COEFFICIENT ON RUDDER-INDUCED MANOEUVRE:NORMAL ACCELERATION AND FIN AND RUDDER LOAD

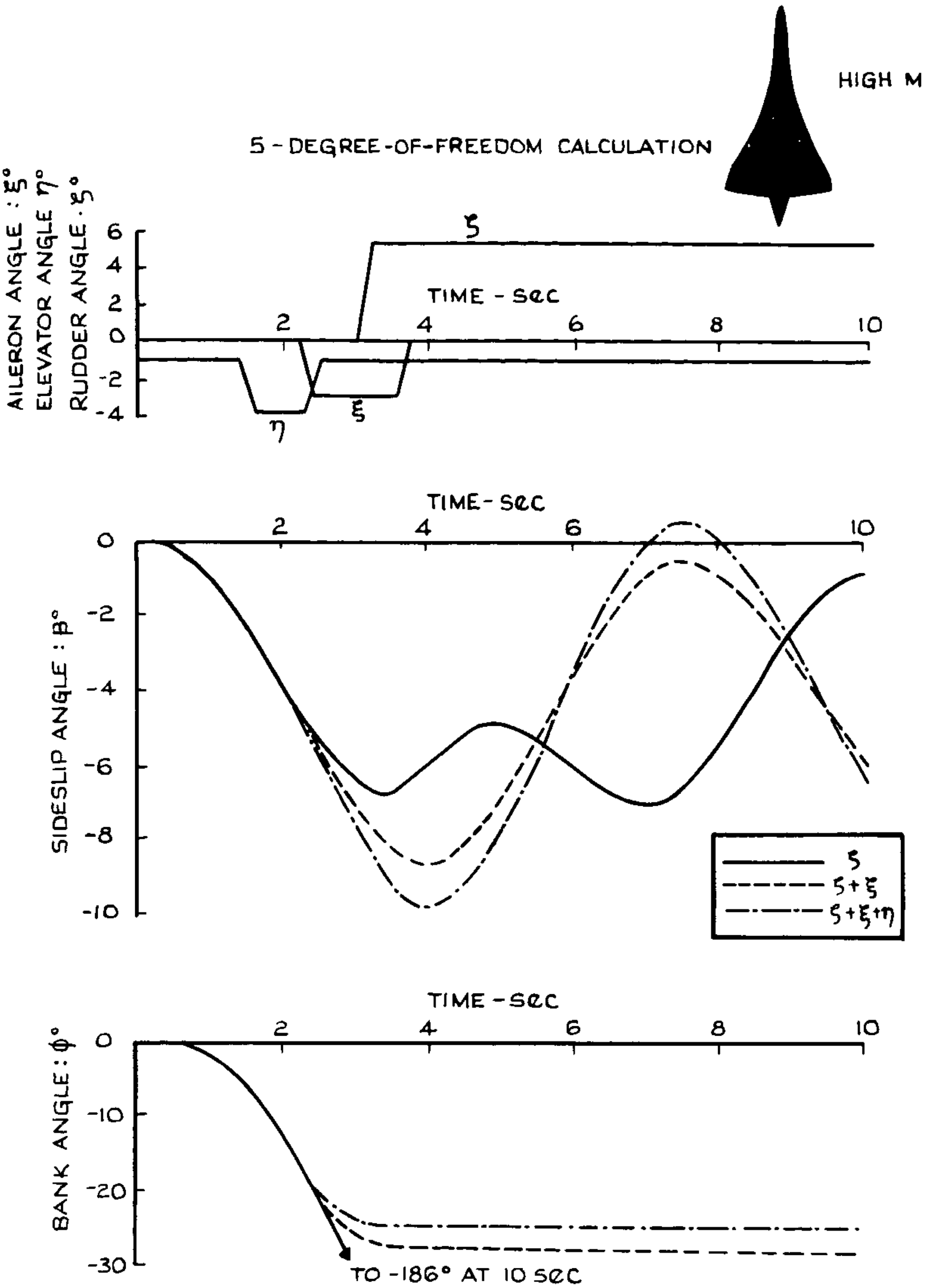


FIG.15 ENGINE FAILURE CASE WITH CORRECTIVE CONTROL APPLICATIONS: SIDESLIP AND BANK

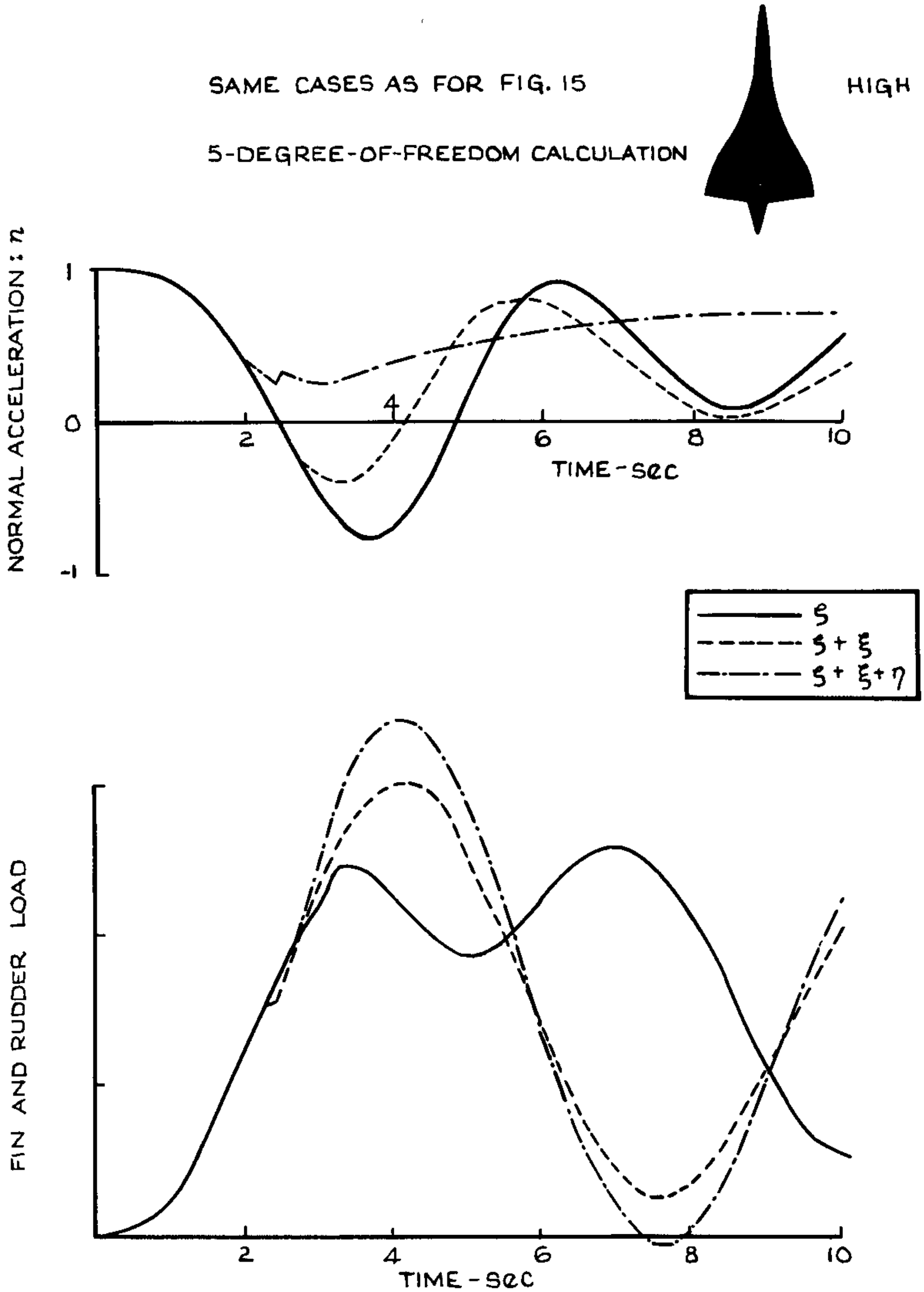


FIG. 16 ENGINE FAILURE CASE WITH CORRECTIVE CONTROL APPLICATIONS: NORMAL ACCELERATION AND FIN AND RUDDER LOAD

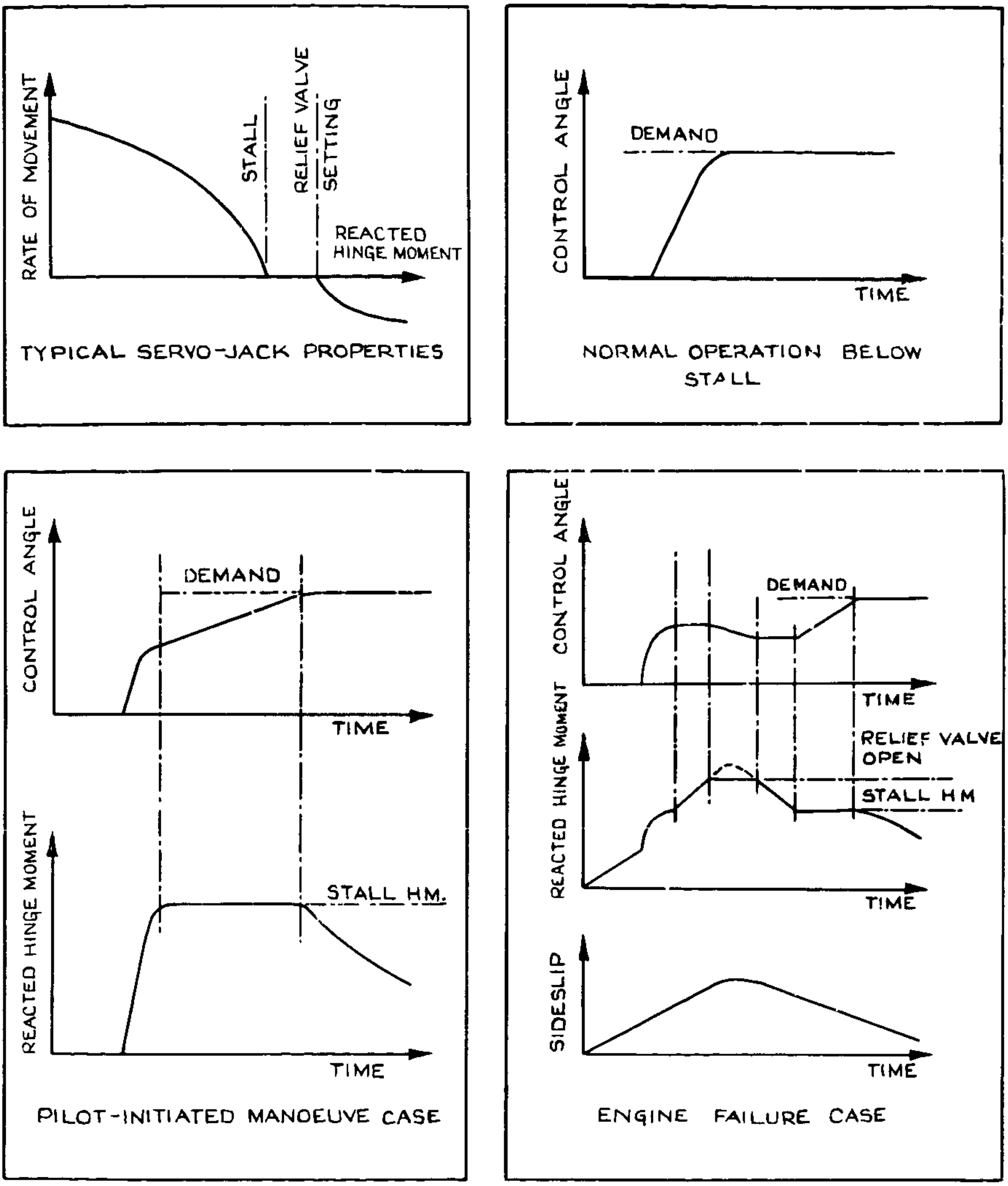


FIG.17 SERVO-JACK PROPERTIES AND HINGE MOMENTS

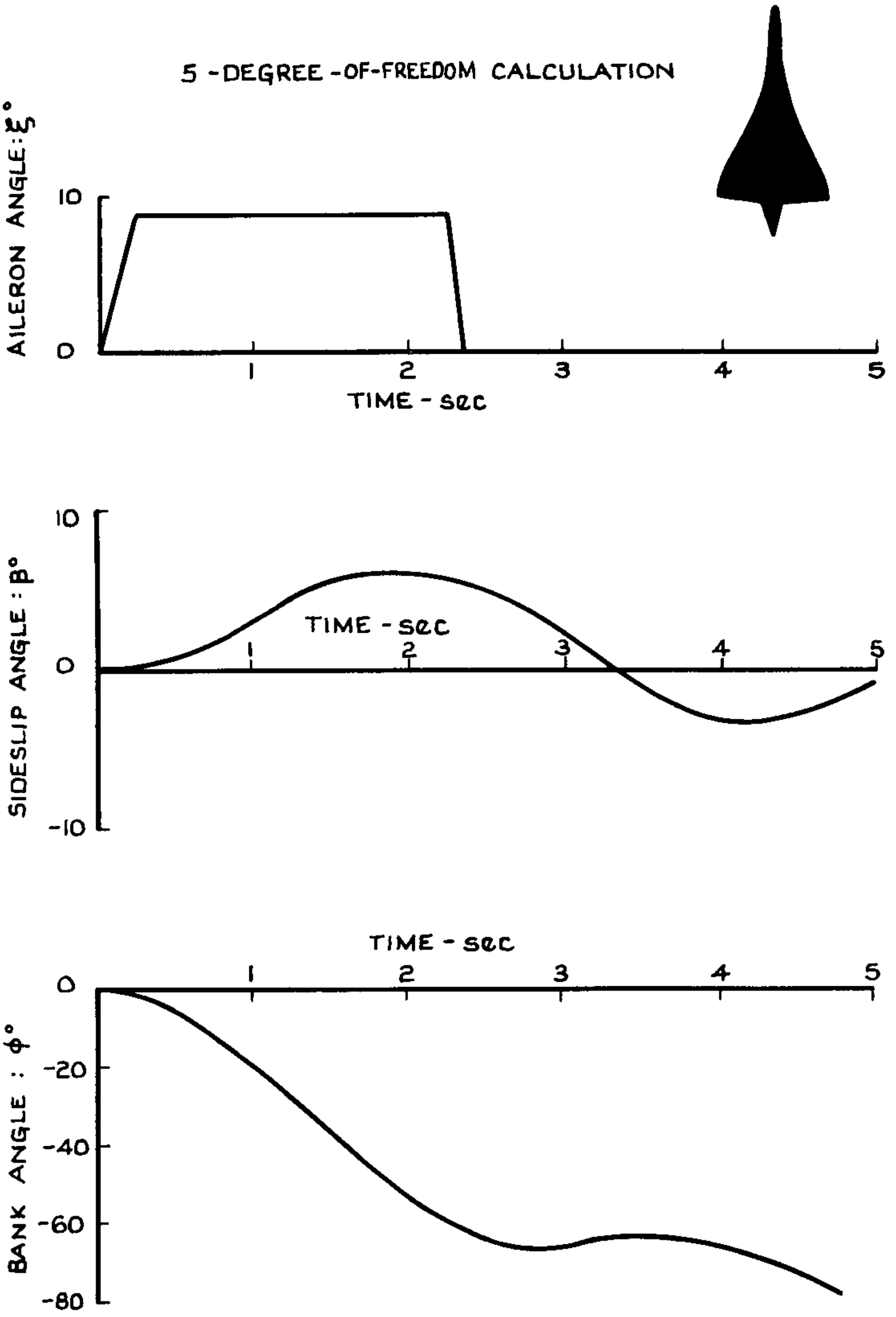


FIG.18 RESPONSE OF SLENDER DELTA CONFIGURATION TO AILERON APPLICATION

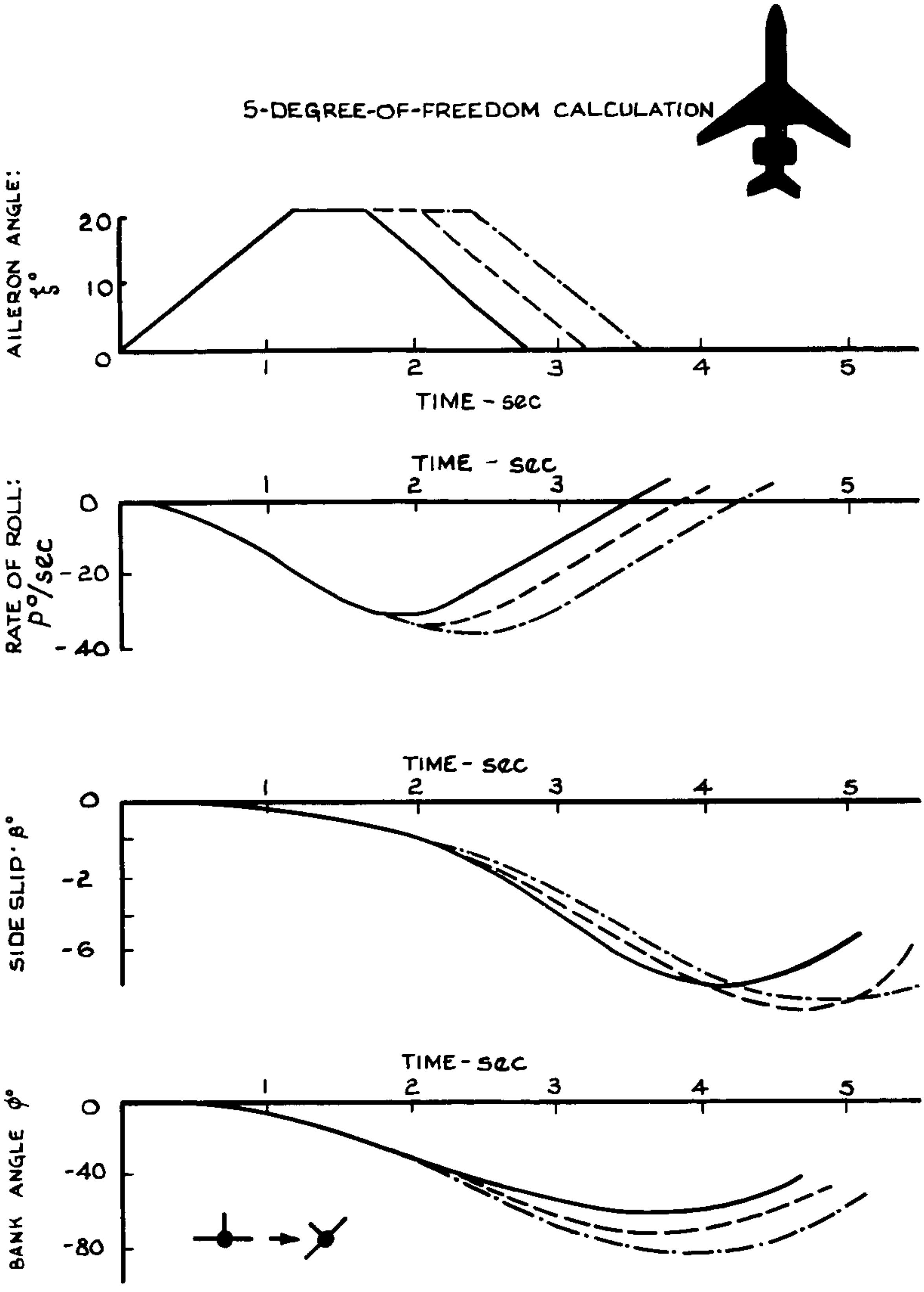


FIG.19 RESPONSE OF REAR-ENGINED CONFIGURATION TO AILERON APPLICATION: CONTROL REMOVED BEFORE MAXIMUM SIDESLIP

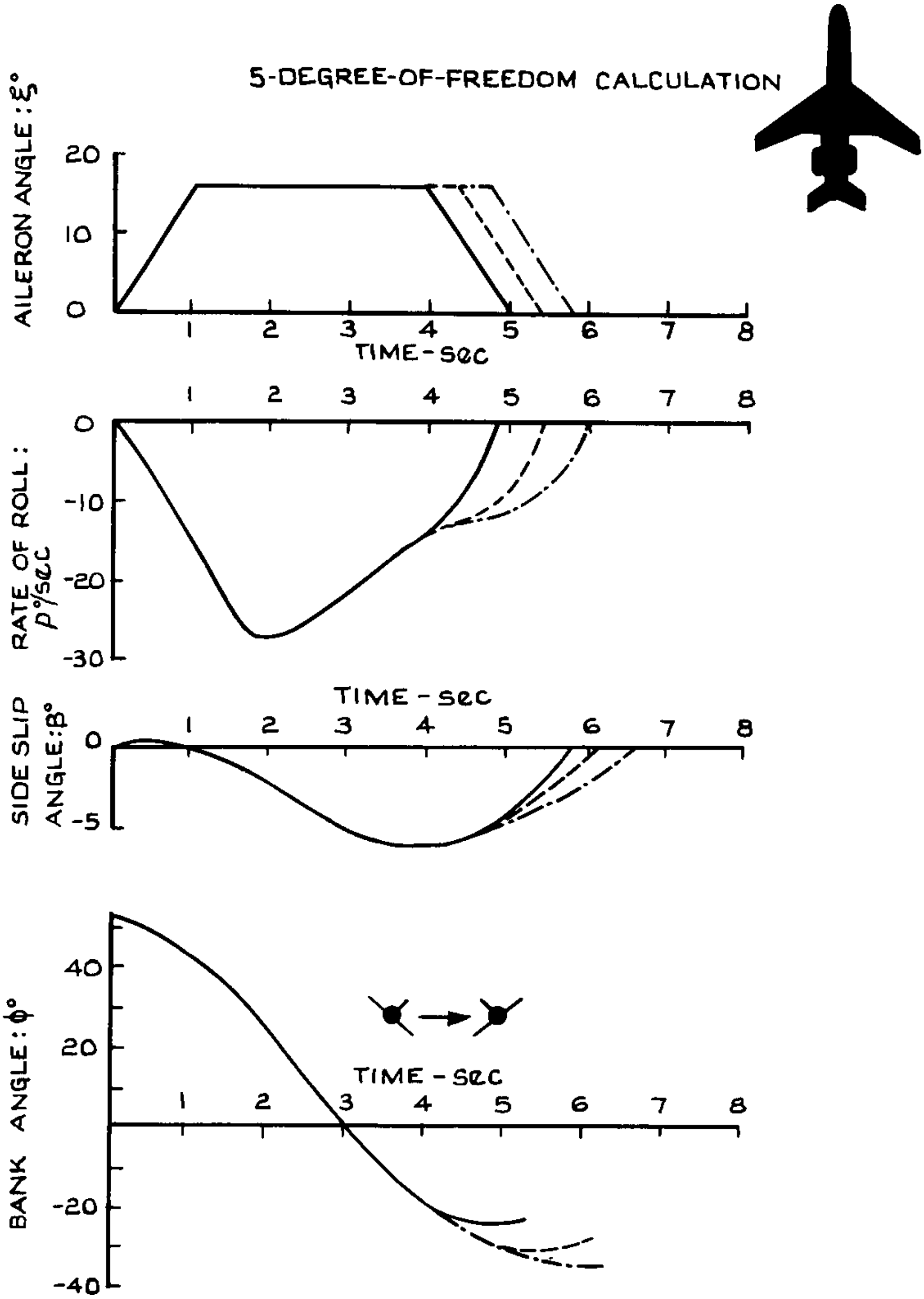


FIG 20 RESPONSE OF REAR-ENGINED CONFIGURATION TO AILERON APPLICATION : CONTROL REMOVED AFTER MAXIMUM SIDESLIP

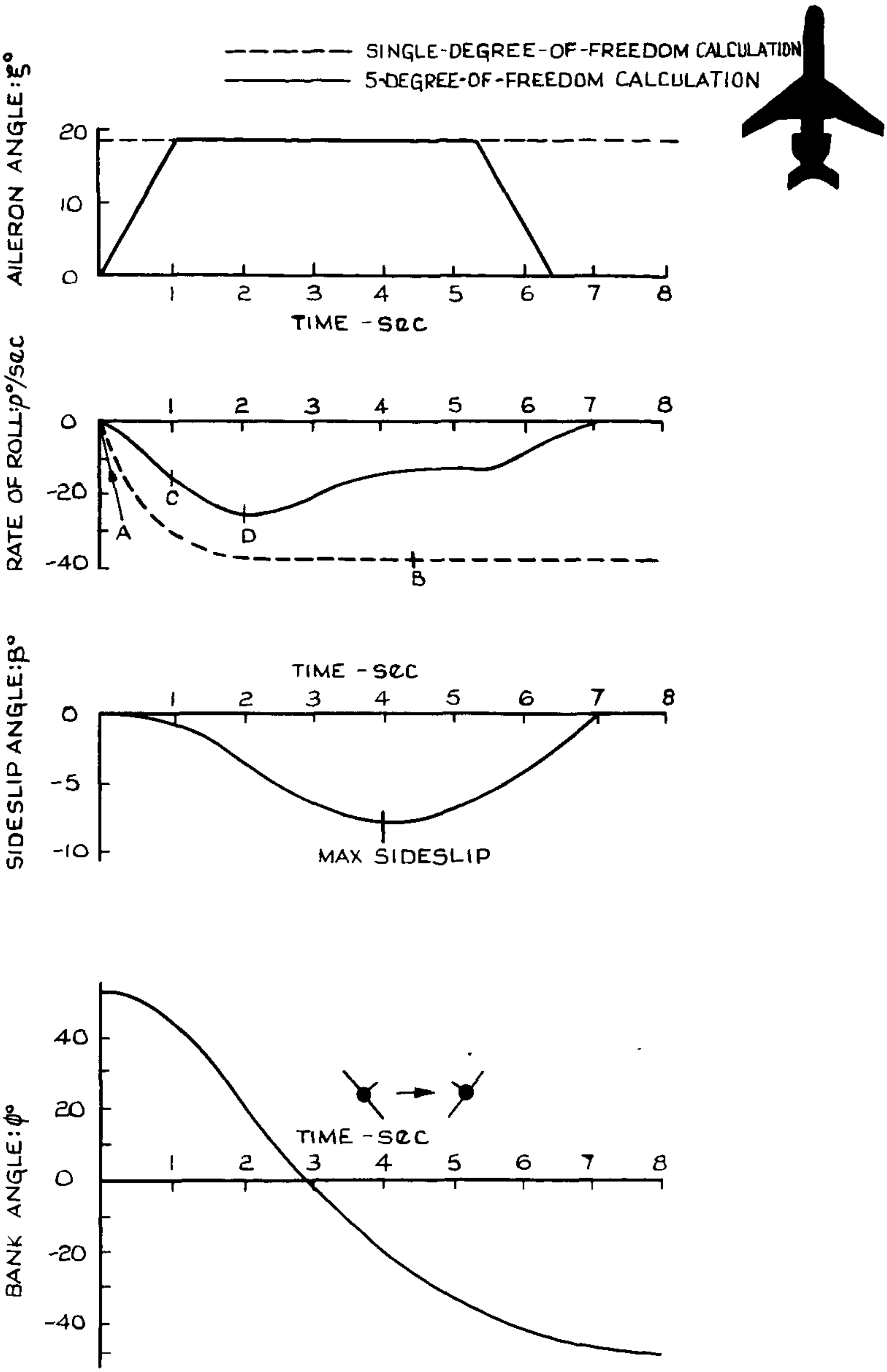


FIG. 21 PILOT - INITIATED ROLLING MANOEUVRES : ILLUSTRATION OF EXISTING AND PROPOSED DESIGN CASES

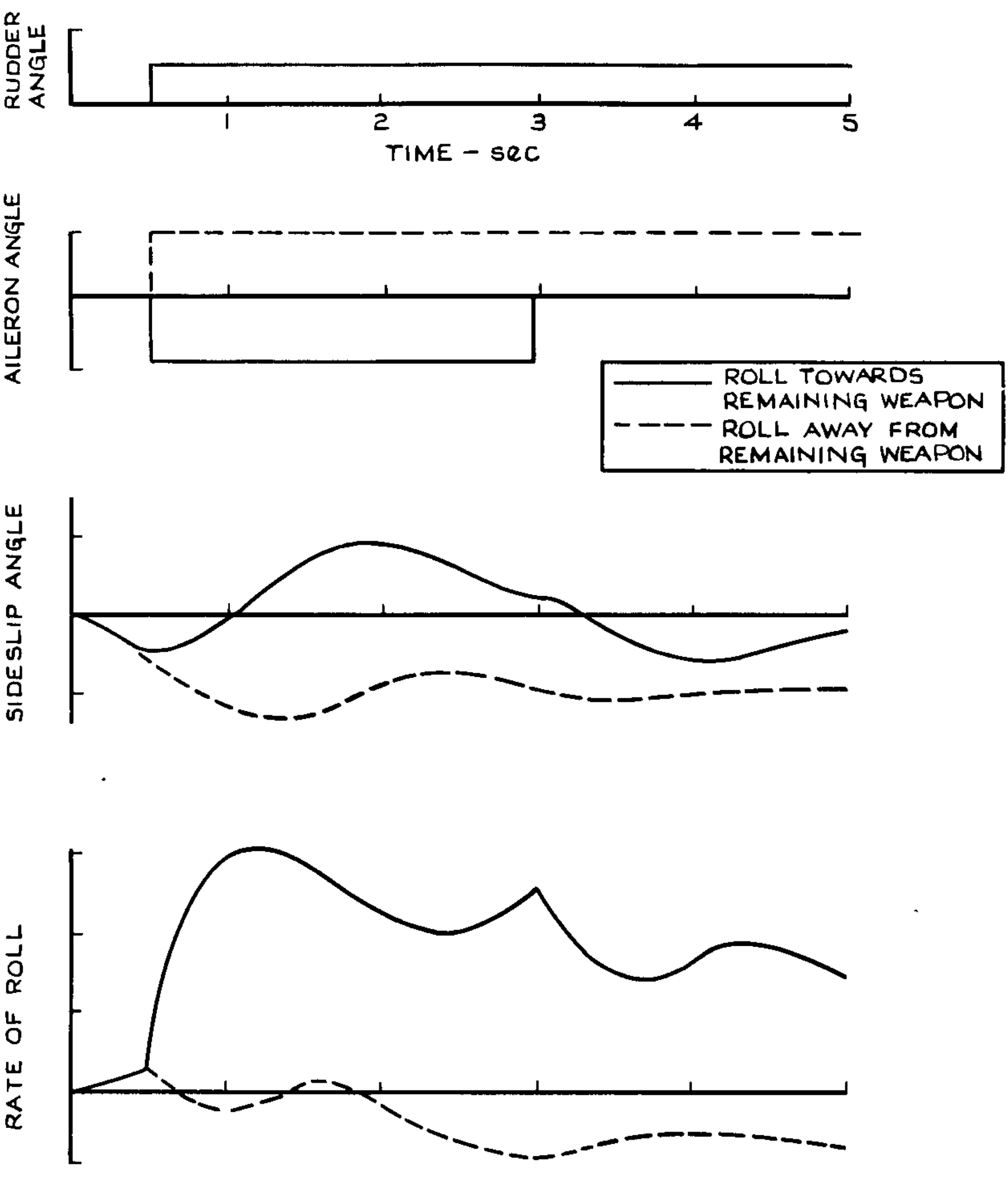


FIG. 22 RESPONSE TO ASYMMETRIC WEAPON RELEASE AND IN BREAK-AWAY MANOEUVRE

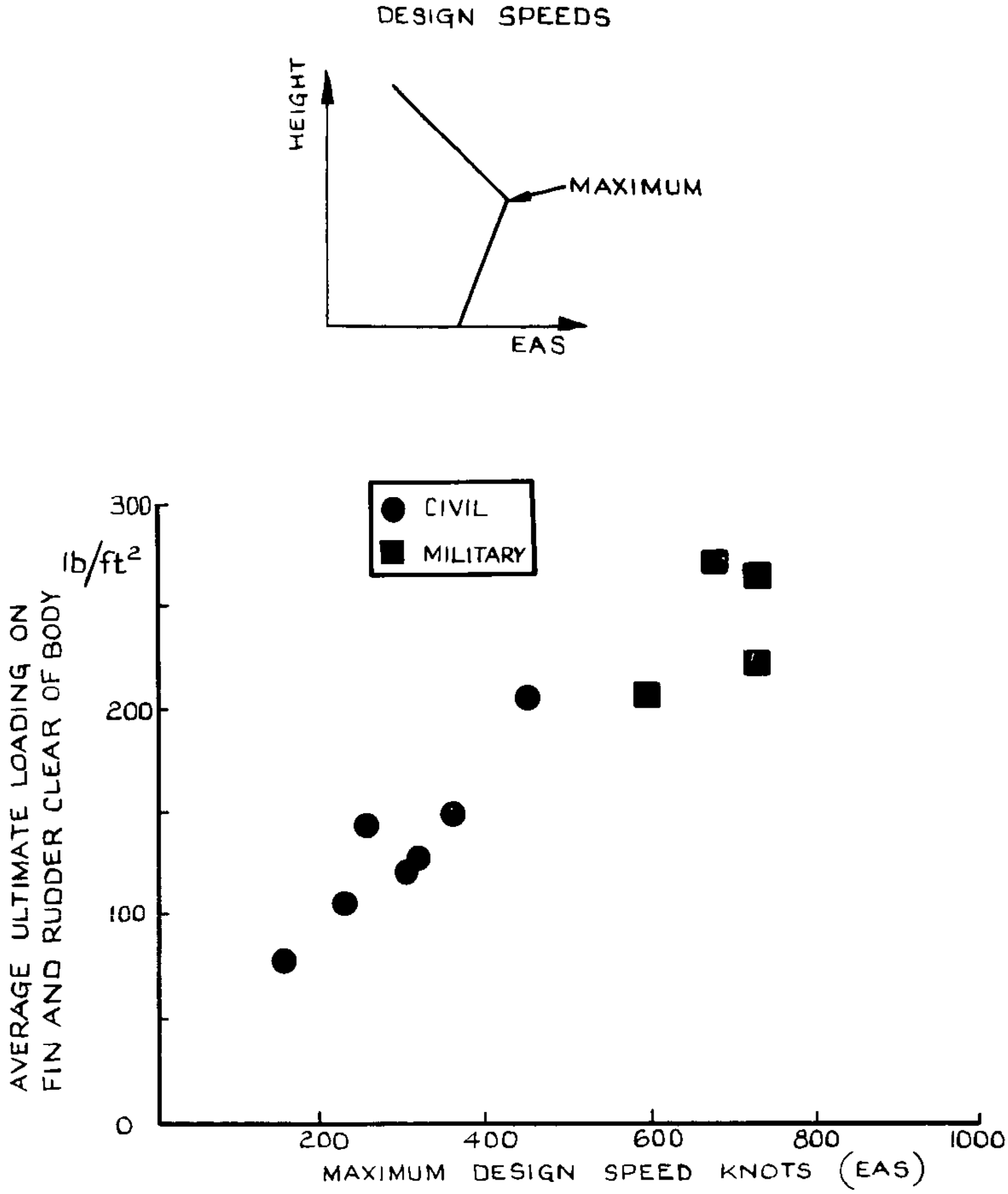


FIG 23 FIN AND RUDDER DESIGN LOADS

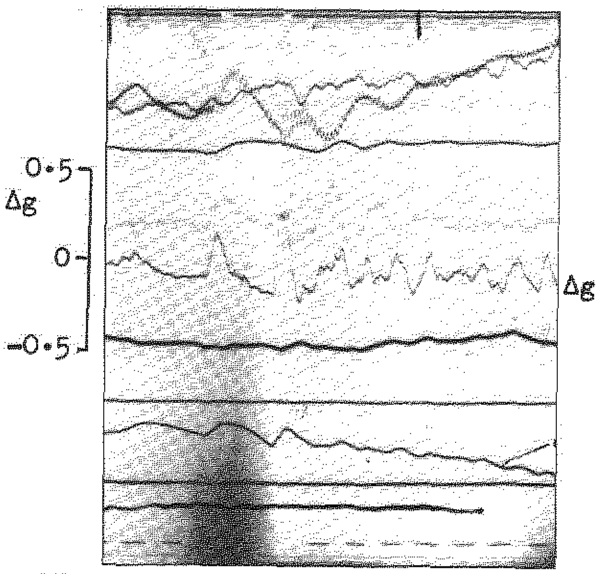


Fig.1 Example of normal landing

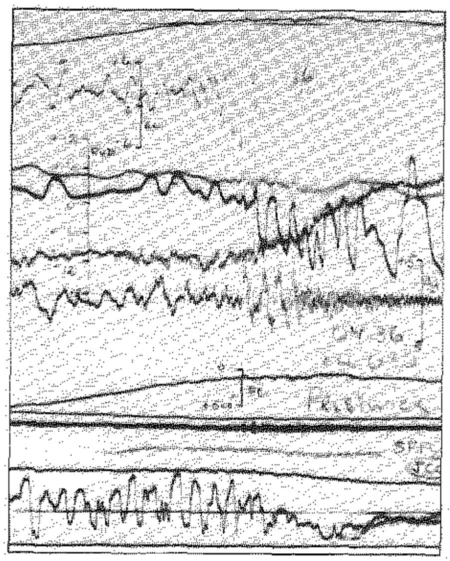


Fig.2 Example of heavy landing

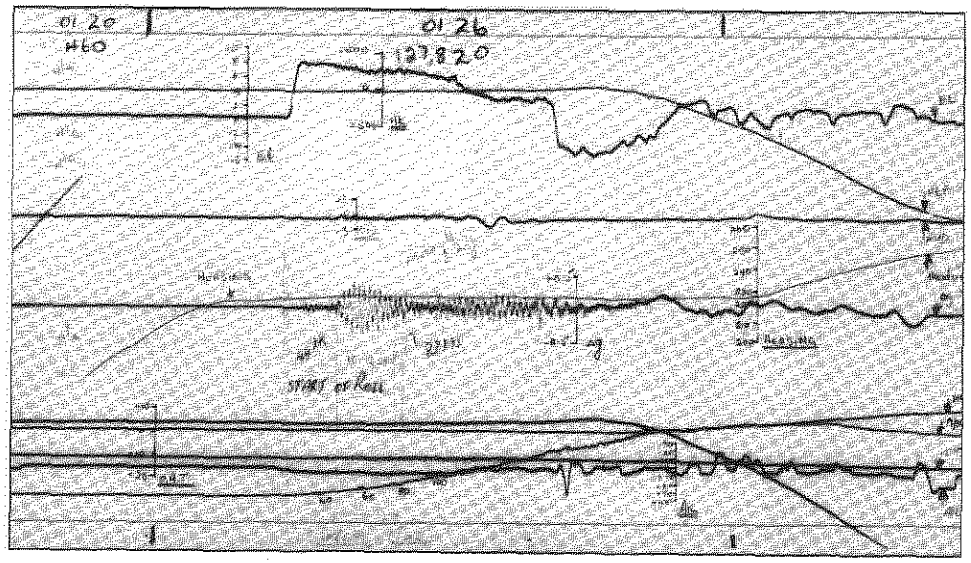


Fig.3 Centre of gravity normal acceleration during taxying

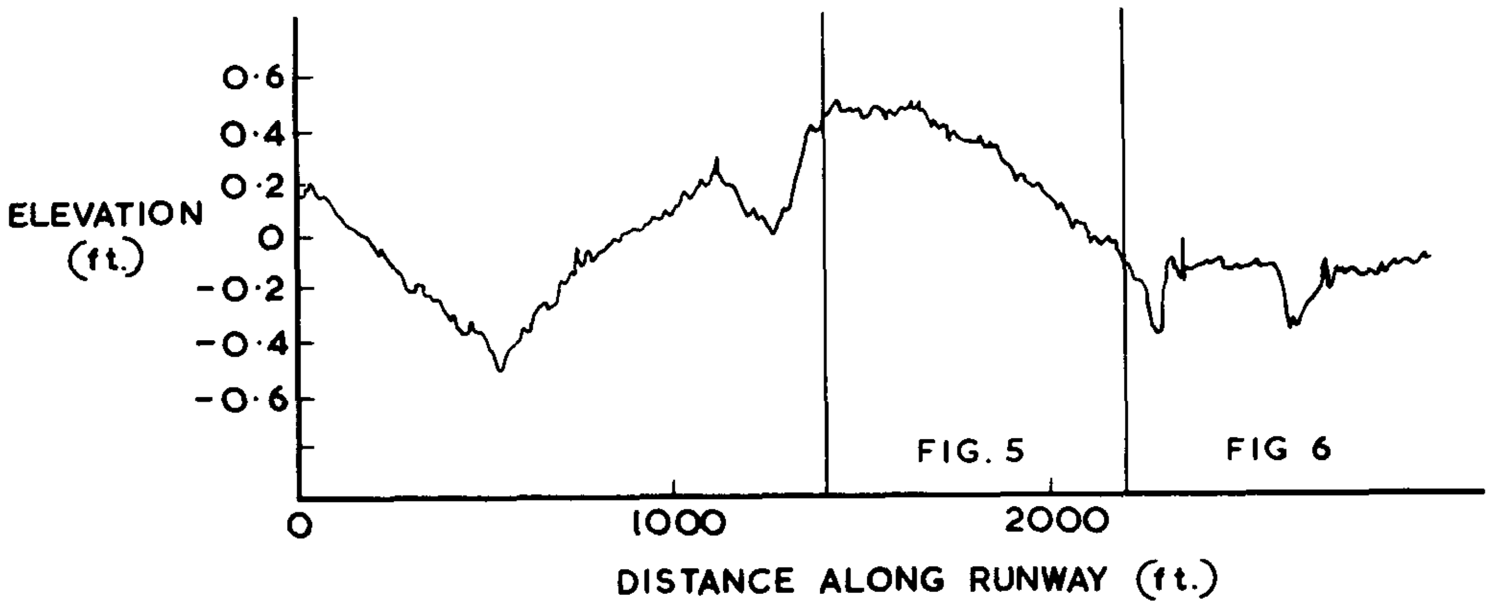


FIG. 4 PROFILE OF RUNWAY

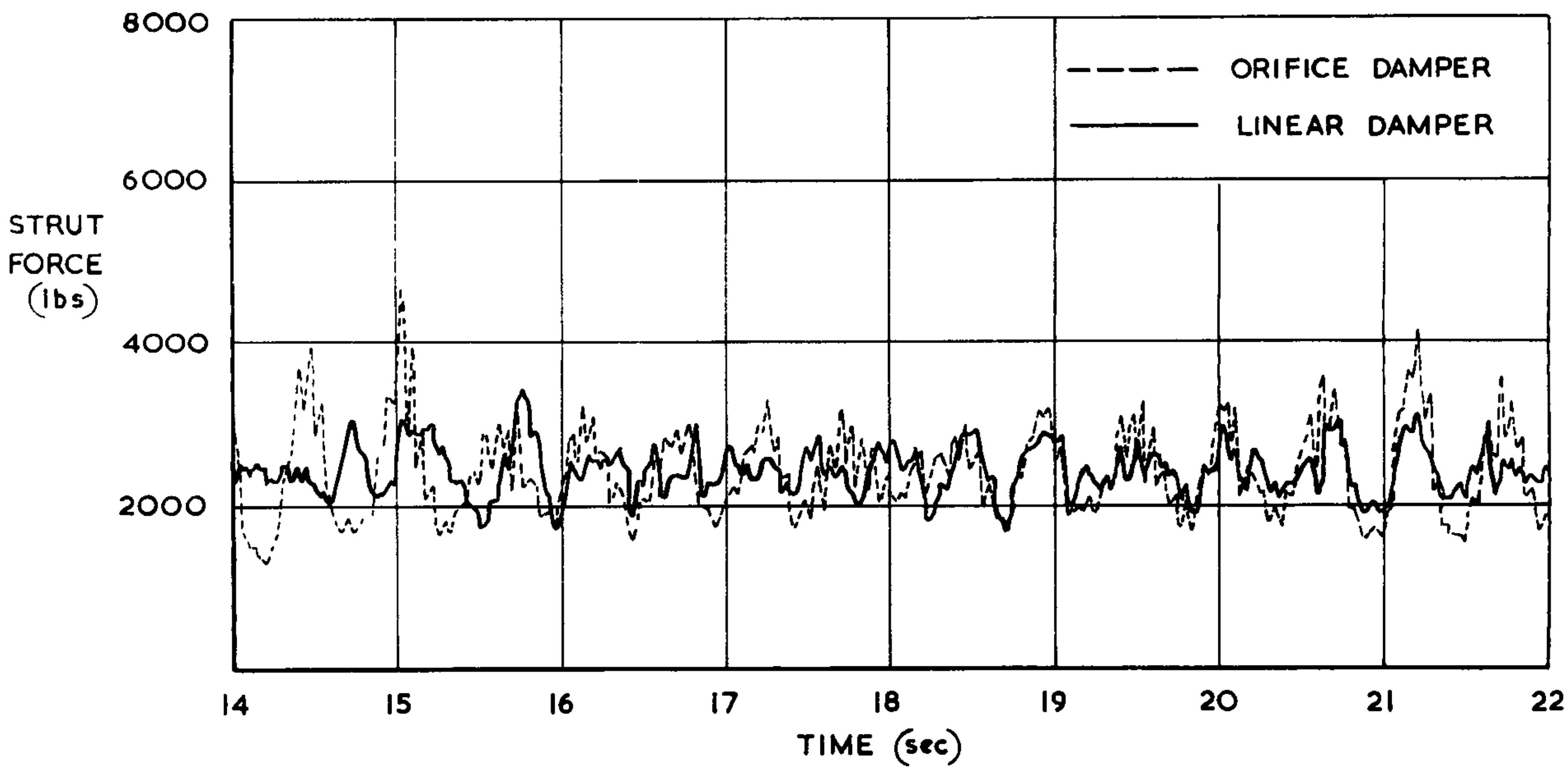


FIG. 5 STRUT FORCES DURING TAXYING FOR ORIFICE AND LINEAR DAMPERS

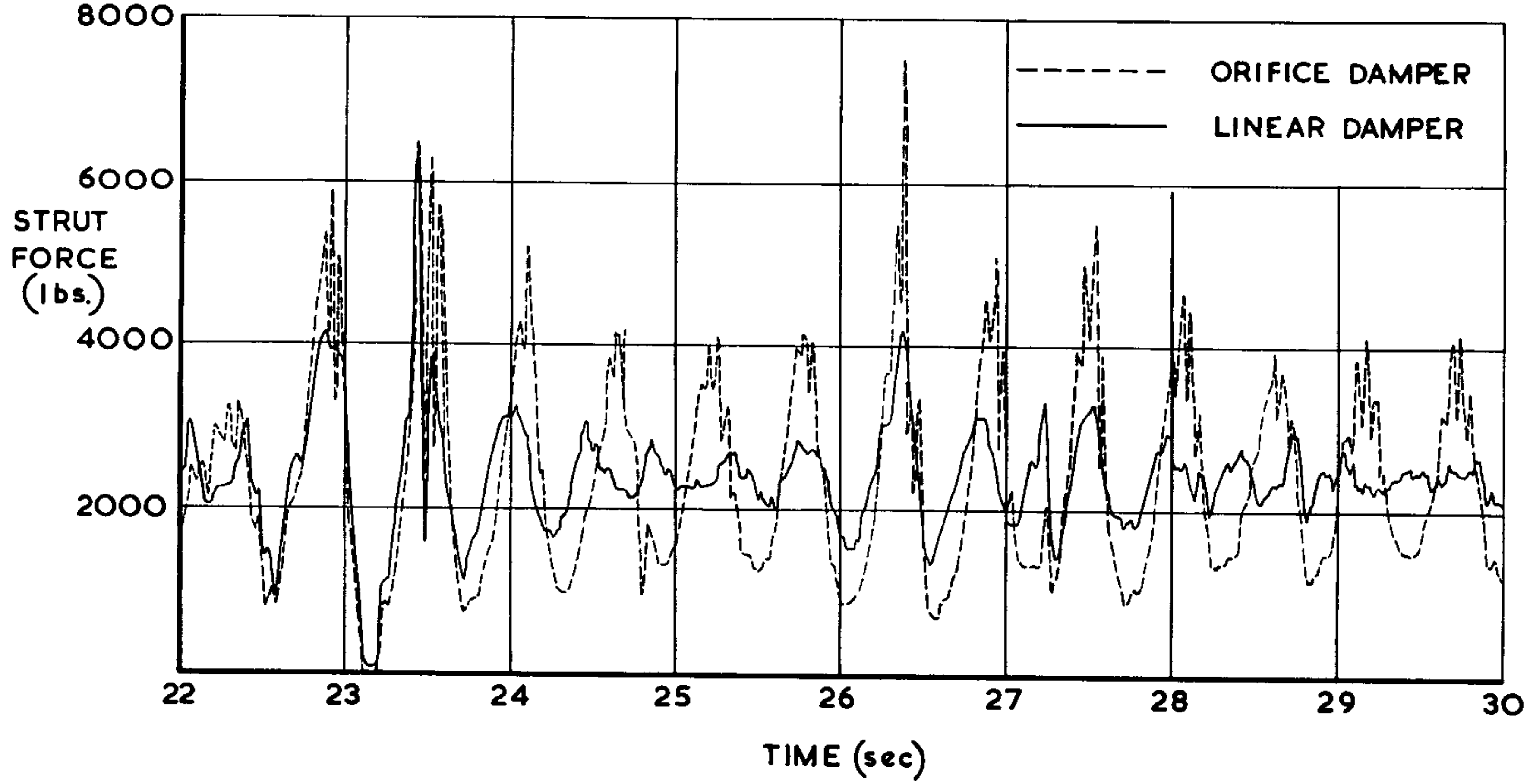


FIG. 6 STRUT FORCES DURING TAXYING FOR ORIFICE AND LINEAR DAMPERS (CONTD)

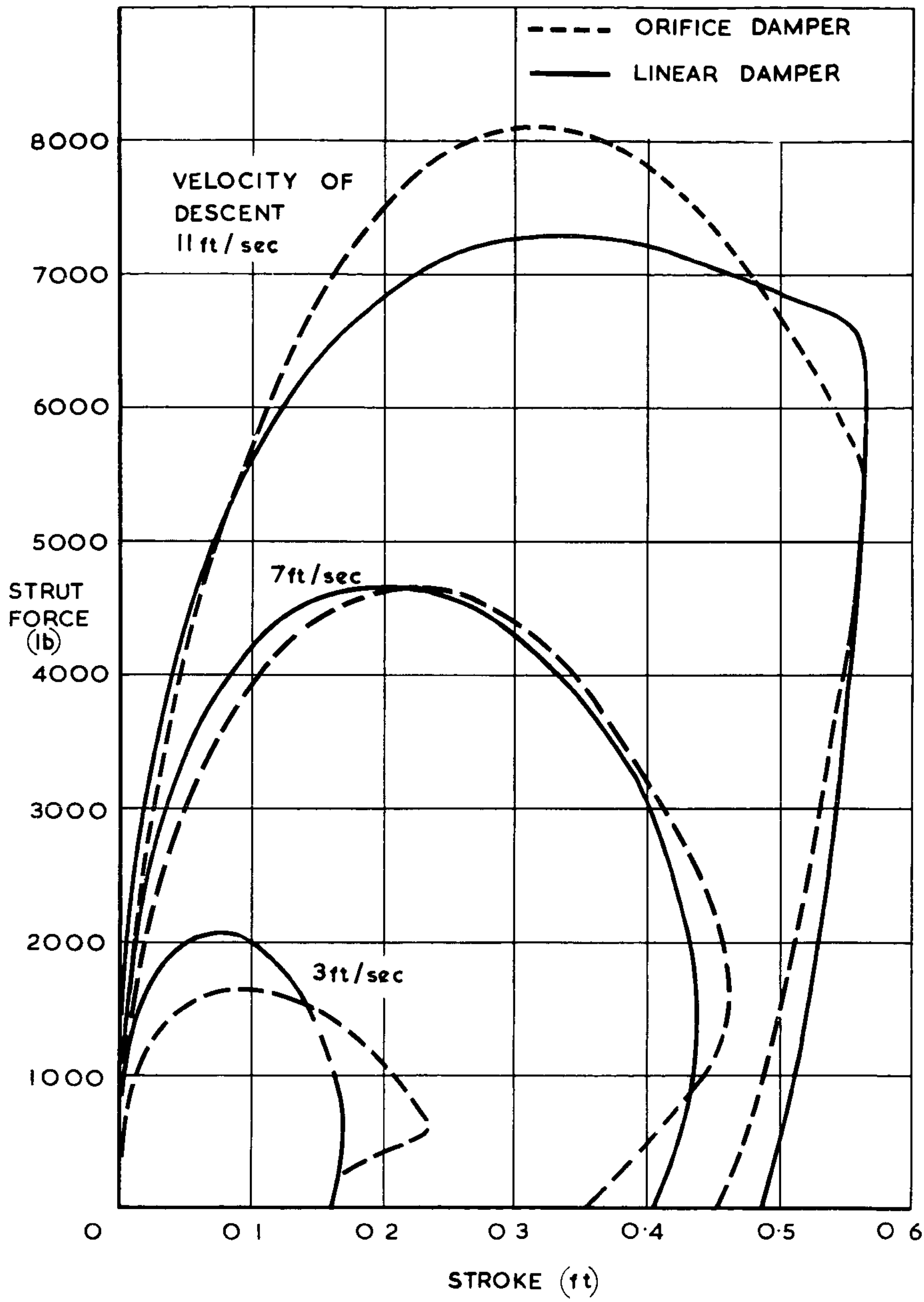


FIG.7 STRUT FORCES DURING LANDING FOR ORIFICE & LINEAR DAMPERS

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