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SOME FLIGHT AND WIND-TUNNEL LONGITUDINAL STABILITY MEASUREMENTS ON THE BAC 221 SLENDER-WING AIRCRAFT

by

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SUMMARY

Preliminary flight measurements of the longitudinal trim and dynamic stability of the BAC 221 aircraft have been made. The flight measurements are of reasonable quality in spite of difficulties associated with the aileron control system, an early instrumentation standard, and the handling characteristics of the aircraft at high incidence. Useful comparisons with wind-tunnel results are made, and the agreement is generally reasonable, although some unexplained differences remain. Flight and wind-tunnel tests to investigate the differences are planned.

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* Replaces R.A.E. Technical Report 70054 - A.R.C. 32330.

CONTENTS

1 INTRODUCTION

The BAC 221 ogee-wing research aircraft, Figs.1 and 2, was built for the investigation of the aerodynamic and handling characteristics of a slender aircraft over a wide speed range from subsonic to supersonic speeds. The early research flying on the aircraft at R.A.E., Bedford was concerned mainly with an assessment of the handling characteristics of the aircraft at very low airspeeds below its normal minimum level flight speed[1]. This exercise, which was planned in direct support of the Concorde programme, was done well in advance of the first flight of that aircraft. Considerable confidence in the expected handling characteristics of the Concorde at low speeds was derived from the successful tests on the BAC 221.

During the handling investigation, specific items such as cross-wind landings and sidestep manoeuvres on the landing approach[2], and recovery from flight at speeds below the zero-rate-of-climb speed[3], were investigated. In addition, preliminary data on the longitudinal trim and dynamic stability of the aircraft were derived from measurements made during the handling tests. These data, and a few measurements at rather higher speeds, are the subject of the present report; they provide a valuable addition to the limited flight data already available on slender aircraft, and a comparison with measurements made in wind tunnels[4,5,6] is therefore included.

Mention should be made at this stage that, due to an early standard of instrumentation and of aileron controls, and also to the difficulty of flying the BAC 221 steadily at very low speeds[1], the flight results are of lower quality than would normally be expected. These difficulties, and the measures taken to overcome at least some of them, are discussed in the report. Suggestions for further more extensive tests are made.

Some leading particulars of the aircraft are given in Table 1. The aircraft is described in more detail in Ref.1.

2 AILERON-CONTROL-SYSTEM CHARACTERISTICS

Before discussing the tests made, and the results obtained, it is worthwhile describing briefly the difficulties experienced with the aileron-control-system. (The aircraft has separate aileron and elevator control surfaces.)

Firstly, as described more fully in Ref.1, the aileron-control linkages are flexible and the servo-valves in the powered flying controls required relatively high operating forces. These factors resulted both in a lag of control-surface movement behind stick movement, and also in small stick movements failing to produce any control surface movements at all. Precise control in roll was, therefore, difficult and there was a tendency for a pilot-induced 'lateral rock' to occur*.

Secondly, the ailerons move slightly in the elevator sense as altitude changes during a flight. It is believed that this is due to differential expansion, between the steel control rods in the aileron circuit and the light alloy aircraft structure, as the ambient temperature changes with altitude. At zero anti-symmetric deflection, both ailerons are nominally symmetrically rigged 2° up to reduce hinge moments at transonic speeds. Changes from this nominal setting measured before, during and after flight are shown in Fig.3 and it is seen that all the data points from the low speed flights collapse reasonably well when plotted as a function of altitude. The reason for the difference between the measurements taken before flight and immediately after landing, is assumed to be that the complete aircraft does not attain ambient sea-level temperature until some time after landing. Corrections to the measured data, for the pitching moment changes due to the aileron movements in the elevator sense, were necessary, and are discussed at the appropriate places in the text.

3 TEST PROCEDURES

3.1 Instrumentation

The instrumentation was the same as that used for the handling assessment[1]. Continuous trace photographic records of incidence, sideslip, angle of bank, accelerations along and angular rates about three body-datum axes, control angles, and free-stream pitot and static pressure and total temperature were made. Fuel used was recorded on an automatic observer. The quality of this instrumentation, whilst satisfactory for the handling assessment, was not sufficiently high to allow a full analysis for the extraction of stability derivatives.

In particular, the outputs of the wind vanes used to measure aircraft incidence were temperature sensitive**. Incidence was, therefore, calculated

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*The aileron-powered-flying-control units have now been replaced by two-stage-linearised-valve units requiring significantly lower operating forces; a considerable improvement in the aircraft lateral handling characteristics at normal flying speeds has resulted, but the handling at very low speeds has yet to be re-evaluated.

**The wind-vane outputs have since been made independent of temperature.

from a pendulum level which measured the apparent aircraft attitude. Corrections were necessary, firstly for acceleration effects, to give the true aircraft attitude, and then for the flight path angle. The latter was obtained from the aircraft rate of descent and true airspeed, which were themselves calculated from the measured free-stream pitot and static pressures and total temperature. This process is much less accurate than a direct measurement, mainly because the accuracy of the flight path angle calculation was poor, but reliable results are believed to have been achieved, albeit with a scatter of about $\pm 1.5^{\circ}$.

3.2 Flight tests made

Most of the tests entailed steady reductions in speed starting at an altitude of about 35000 ft. They were, in general, made in descending flight at a constant throttle setting. At low speeds it was not possible to stabilise speed and height, since the drag exceeded the available thrust. During these tests some limited measurements of the aircraft's response to elevator-stick jerks were made. The characteristics of the engine air intakes at very high incidence were unknown since no intake-model tests had been made under these conditions. Accordingly, because of the possibility of engine flame-out due to poor intake flow, a ram-air turbine, which supplies emergency hydraulic power in the event of engine failure, was deployed for all tests at speeds lower than 135 kt (69 m/sec) ias. A detailed description of the technique used to extend the flight envelope to lower speeds, and higher incidence, is given in Ref.1.

The lowest speed attained during the handling assessment was 114 kt (59 m/sec) ias, corresponding to an incidence of about 22°. Flight at this incidence was rather unsteady and the highest angle of incidence at which longitudinal trim data could be derived was about 20° with the aircraft in both the clean and approach configurations*. The corresponding lowest angles of incidence were 3° and 15° respectively. The range of altitude within which results were obtained was about 19000 to 35000 ft.

3.3 Handling difficulties

The unsteadiness of flight at very high incidence was mentioned briefly in section 3.2. The main reason for this unsteadiness is the low directional stability of the aircraft under these conditions. The aircraft tends to

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*In the approach configuration the aircraft undercarriage is lowered and the fuselage nose is drooped through an angle of 8° about a hinge aft of the cockpit.

wander, if not to diverge, in sideslip and continual control inputs are necessary to keep sideslip to a minimum. The aileron-control-system characteristics, discussed in section 2, made the pilot's task more difficult. There is also some effect of sideslip on the pitching moment and, to a lesser extent, on lift. Consequently, the aircraft was rarely in a perfectly trimmed condition both longitudinally and laterally. Some lateral motion was present for most of the data points for which incidence was greater than about 18°, although results are only presented in this report for points where elevator movement and the pitch rate and acceleration were negligibly low, and the aircraft was therefore trimmed longitudinally.

4 RESULTS

4.1 Trimmed normal force

Fig.4 shows the trimmed normal force variation with incidence for the aircraft in the clean and approach configurations. The clean configuration results include test data up to a Mach number of 0.7. The trimmed normal force coefficient, C_N, rather than the lift coefficient, is shown, since the former follows directly from the normal accelerometer reading and the aircraft weight. To obtain the lift would require a significant correction for engine thrust at high incidence, but the thrust was not measured during the tests. No corrections were necessary for the aileron movements in the elevator sense described in section 2, as the effect on the normal force was very small. The scatter on the results is consistent with the expected accuracy of the calculated incidence.

Also shown in Fig.4 are results from low-speed wind-tunnel tests on a 1/7 scale model at BAC, Filton[4] and from tests at the Aircraft Research Association on a 1/12 scale model[6] at $M = 0.7$. The comparison between tunnel and flight is discussed in section 5.1.

4.2 Elevator angles to trim

Fig.5 shows flight and tunnel[4,6] values of elevator angle to trim, as a function of normal force coefficient, for the aircraft in the clean and approach configurations. The elevator angles measured in flight have been corrected for the asymmetric aileron movements discussed earlier, so that both flight and tunnel data refer to a configuration having both ailerons symmetrically rigged 2° up from the wing chord. Unpublished low-speed wind-tunnel measurements of aileron pitching power were used in deriving the corrections, which were of the order of −1° throughout the incidence range.

It is noteworthy that there is only a very slight difference in elevator angle to trim in flight between the clean and approach configurations; in the latter case perhaps about 0.3° more up elevator is needed to trim the aircraft, although this small difference is less than the scatter on the results. It is considered that, including the correction for symmetric aileron movements, the flight elevator angles to trim are accurate to about ±0.3°. Tunnel tests[4] have shown that pitching moment, and hence elevator angle to trim, is rather sensitive to sideslip at constant incidence on the BAC 221. As noted earlier, some lateral motion, including sideslip, was present for many of the data points and this may be responsible for some of the scatter on the flight measurements.

The comparison between flight and tunnel results is discussed in section 5.1.

4.3 Longitudinal dynamic stability

There are only a few flight results available and, mainly because of the relatively high damping of the longitudinal short-period oscillation which reduces the analysis accuracy, but partly because of poor instrumentation, no attempt has been made to extract stability derivatives. Fig.6 shows the measured period and damping of the oscillation compared with predictions, based on tunnel data[5], using simple theory[7]. The possible reasons for the difference between flight and predictions are discussed briefly in section 5.2.

5 DISCUSSION OF RESULTS AND COMPARISON WITH WIND-TUNNEL DATA

5.1 Static measurements

In view of the expected scatter on the calculated flight incidence, it is difficult to make a useful comparison between the tunnel and flight measurements shown in Fig.4. Agreement is reasonable within the scatter on the results.

A much better comparison can be made between the elevator angle to trim data shown in Fig.5. It should first be noted that the centre of gravity of the aircraft moves aft about 2 inches (0.051 m) and down about 5 inches (0.127 m) on lowering the undercarriage and drooping the nose. The wind-tunnel data have been corrected to the appropriate centre of gravity position.

In the clean configuration, up to $C_N = 0.65$ approximately, there is a constant difference of about 0.4° in elevator angle to trim between low-speed tunnel results[4] and flight results, although the agreement at low C_N (and higher speeds) with the more appropriate tunnel results[6] at $M = 0.7$ is very good. At high C_N, above 0.65, there is a progressive divergence between flight and tunnel results, and the flight results show no sign of the predicted pitch-up. (The pilot, however, did report a mild pitch-up at about $\alpha = 22^\circ$, $C_N = 0.85$ approximately, but further flights were not made to confirm this since the tests were then terminated for safety and other reasons.)

In the approach configuration the agreement is poor; at high C_N, below the predicted pitch-up, the tunnel shows a large difference in elevator angle to trim of about 1° less up-elevator in the approach than in the clean configuration. In flight the difference is about 0.3° more up-elevator. The reason for the discrepancy is worth considering.

Taking first the flight results, when the aircraft is changed from the clean to the approach configuration the following changes in moments occur:

(i) The aerodynamic forces which were previously trimmed about the centre of gravity in the clean configuration must now be trimmed about the approach configuration centre of gravity.

(ii) There is an additional moment from the drag of the undercarriage legs, wheels and doors and from that of the drooped nose.

(iii) Due to the lower centre of gravity, there is a change in the moments from momentum of the engine intake air and the jet thrust. Except for the results at low incidence in the clean configuration, all the trims were obtained at constant engine throttle setting in steady descending flight, and there was no increase in throttle setting to balance the increased drag in the approach configuration.

(iv) Drooping the nose may cause an additional moment associated with a change of fuselage lift.

Taking the above four points in order, calculations show that the effect, on elevator angle to trim, of transferring the aerodynamic moments from the clean to the approach configuration centre of gravity is negligible. It was assumed that the lift versus incidence curve is the same for the clean and approach configuration; Fig.4 shows that there may be a small difference but it is not sufficient to affect the calculations.

Evaluation of the pitching moment due to the drag increase in going from the clean to the approach configuration was felt to be relatively reliable for the undercarriage legs, wheels and doors, but the line of action of the drag increment due to drooping the nose is very uncertain and makes this part of the calculation difficult. However, use of manufacturer's data for the drag of the undercarriage[8], together with the measured total drag increase in the low-speed tunnel[4], suggests that the resulting change in elevator angle to trim will be very small. This change could, however, be either positive or negative depending on the assumptions made regarding the drag of the drooped nose. The poor accuracy of the calculated incidence and flight path angle prevented any useful calculation of the drag increase when the undercarriage and nose were lowered at constant engine throttle setting.

Since the engine throttle setting for the majority of the tests was constant, the only relevant systematic difference between the clean and approach configurations is the change of thrust moments due to the centre of gravity movement. However, since the tests were made in descending flight, the increase in thrust with decreasing altitude, at constant throttle setting, could introduce scatter into the results. Data from in-flight engine performance measurements on the Fairey Delta 2 aircraft[9], from which the BAC 221 was converted, were used to determine the moments due to intake momentum effects and to jet thrust. The engine installation of the BAC 221 is identical to that on the Fairey Delta 2 except for the intakes, and a representative intake efficiency for the former aircraft was obtained by extrapolation of data from intake model tests at a lower incidence[10]. The results of these calculations show that the total thrust moment about both centre of gravity positions was virtually the same, at the same altitude, but that over the range of altitude employed in the tests, a scatter of about $\pm 0.1^{\circ}$ in elevator angle to trim could be caused by the change of thrust with altitude.

The effect on the fuselage lift, of drooping the nose, is unknown. The data in Fig.4 suggest that any effect on normal force is small, but it does not necessarily follow that the effect on pitching moment, and hence on elevator angle to trim, is also small.

The accuracy of the calculations made to evaluate the first three possible sources of trim changes mentioned above is difficult to assess, but it is unlikely to be worse than an equivalent scatter on elevator angle of $\pm 0.3^{\circ}$. Since there is no reason to doubt the validity of the flight measurements shown in Fig.5 it is concluded that the small difference, perhaps about 0.3°, between the elevator angles to trim measured in flight for the clean and approach configurations is genuine. This conclusion incorporates the assumption that the pitching moment associated with a change in fuselage lift when the nose is drooped is small. It is considered, therefore, that the reason for the large difference between flight and tunnel results shown in Fig.5 for the approach configuration must be sought in the tunnel measurements.

The only obvious fundamental differences between flight and tunnel, apart from scale effects, are that there was no simulation of the ram-air turbine or of the engine in the tunnel tests, although the engine air intakes were open and there was flow through the model. Assuming that the intakes were running full in the tunnel, calculations show that the intake conditions in tunnel and flight were reasonably closely scaled at high incidence; any associated pitching moments should thus be approximately the same in tunnel and flight. Estimates of the pitching moment due to non-representation of the jet flow in the tunnel suggest that the elevator angles to trim will be more positive (less up) in the tunnel by about 0.2° and 0.6° in the clean and approach configurations respectively at $\alpha = 20^{\circ}$. At lower incidence these increments will be smaller since, at the higher speeds implied, the elevator becomes more effective relative to the thrust moments. This picture is complicated, however, since the tunnel intake flow would be less representative at higher flight speeds. Although the ram-air turbine was not represented in the tunnel tests referred to here, earlier unpublished tunnel results showed that its effect on trim is negligible.

Due to the uncertainties, it is not felt worthwhile to correct the tunnel results to representative engine flows, but it is clear that the agreement between tunnel and flight would be improved slightly for the clean configuration and significantly for the approach configuration. However, in the latter case the agreement would still not be good and the reason for this is not known. Tunnel tests[4] do show significant differences in elevator pitching power between the clean and approach configurations at moderate and extremely high incidence, but in the range of this flight/tunnel comparison, mainly $\alpha = 13^{\circ}$ to 20°, the difference is not significant in terms of elevator angle to trim, except at a few points at higher speeds for which comparison with the A.R.A. results[6] is more appropriate.

A possible source of the difference between tunnel and flight might be scale effects on flow separations associated with the undercarriage, its doors, or its wheel wells, and possibly with the drooped nose. In particular, the

Reynolds number based on undercarriage leg diameter is sub-critical for the tunnel model and super-critical for the aircraft.

Finally, it should be noted that no corrections for the effects of aeroelastic distortion to either the aircraft or the model have been made. However, at the low speeds and dynamic pressures of the tests, it is believed that such effects will be very small and would in any case be similar for both the clean and approach configurations.

Further low-speed tunnel tests have been made at R.A.E. to investigate the differences between tunnel and flight but the results are not available at the time of writing.

5.2 Dynamic stability

It is seen from Fig.6 that, within the scatter of the flight results, the agreement of these results with the values of the period of the longitudinal short-period oscillation predicted from tunnel tests[5] is reasonable. The damping measured in flight is rather less than that predicted by the tunnel. The longitudinal short-period oscillation has both pitching and heaving degrees of freedom and consequently both the damping in pitch derivative and the lift curve slope contribute to the damping of the oscillation. Accurate knowledge of the moment of inertia of the aircraft in pitch is also necessary, and this has yet to be measured. It may be significant that for the Fairey Delta 2 aircraft, from which the BAC 221 was converted, the manufacturer's estimate of the inertia in pitch was nearly 20% too low[11].

Until better quality flight measurements are obtained, and until the inertia in pitch is measured, it is not considered possible to determine the origin of the discrepancy in damping.

6 CONCLUSIONS

Low-speed measurements have been made in flight of the trimmed normal force coefficient and elevator angle to trim, in the clean and approach configurations, up to an incidence of about 20°. Above about 18° incidence it was not possible for the pilot to set up very steady conditions, but nevertheless fairly consistent results have been obtained. The aircraft longitudinal static stability remained positive up to the highest incidence of measurements, although the pilot reported a mild pitch-up at an incidence of about 22°.

Comparisons have been made with low-speed tunnel tests at BAC, Filton on a 1/7 scale model and with tests at $M = 0.7$ on a 1/12 scale model at the

Aircraft Research Association. Agreement for normal force data is fair within the scatter of the flight results. For the clean configuration, the agreement between the flight and tunnel results for elevator angle to trim is quite good, although the mild pitch-up occurs at a slightly higher normal force coefficient in flight. In the case of the approach configuration results the agreement is not good, although some of the discrepancy can be explained by non-representation of the engine jet in the tunnel.

A very small number of flight measurements were made of the longitudinal short-period oscillation characteristics. Agreement with tunnel data is fair for the period but poor for the damping.

Further flight measurements of longitudinal stability, using improved instrumentation, are planned; ground-based measurements of the moment of inertia in pitch of the aircraft will be made. It is hoped that the results of these measurements, used in conjunction with the results from further low-speed wind-tunnel tests at R.A.E., will provide more information on the discrepancies discussed in this report.

Table 1

LEADING PARTICULARS OF THE BAC 221

Length	57.6 ft	(17.56 m)
Span	25.0 ft	(7.62 m)
Aerodynamic mean chord	25.0 ft	(7.62 m)
Wing area	490 ft^2	(45.5 m^2)
Mass, empty of fuel	511.0 slug	(7458 kg)
Mass, fully-loaded	621.1 slug	(9063 kg)

Pitch inertia for mass = 574.5 slug (8392 kg):

Clean configuration	37900 slug ft^2	(51400 kgm^2)
Approach configuration	53700 slug ft^2	(72800 kgm^2)

SYMBOLS

C_N	Normal force coefficient
M	Mach number
α	Incidence, degrees
η	Elevator angle to trim, degrees

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Fig.1 View of BAC221 in approach configuration

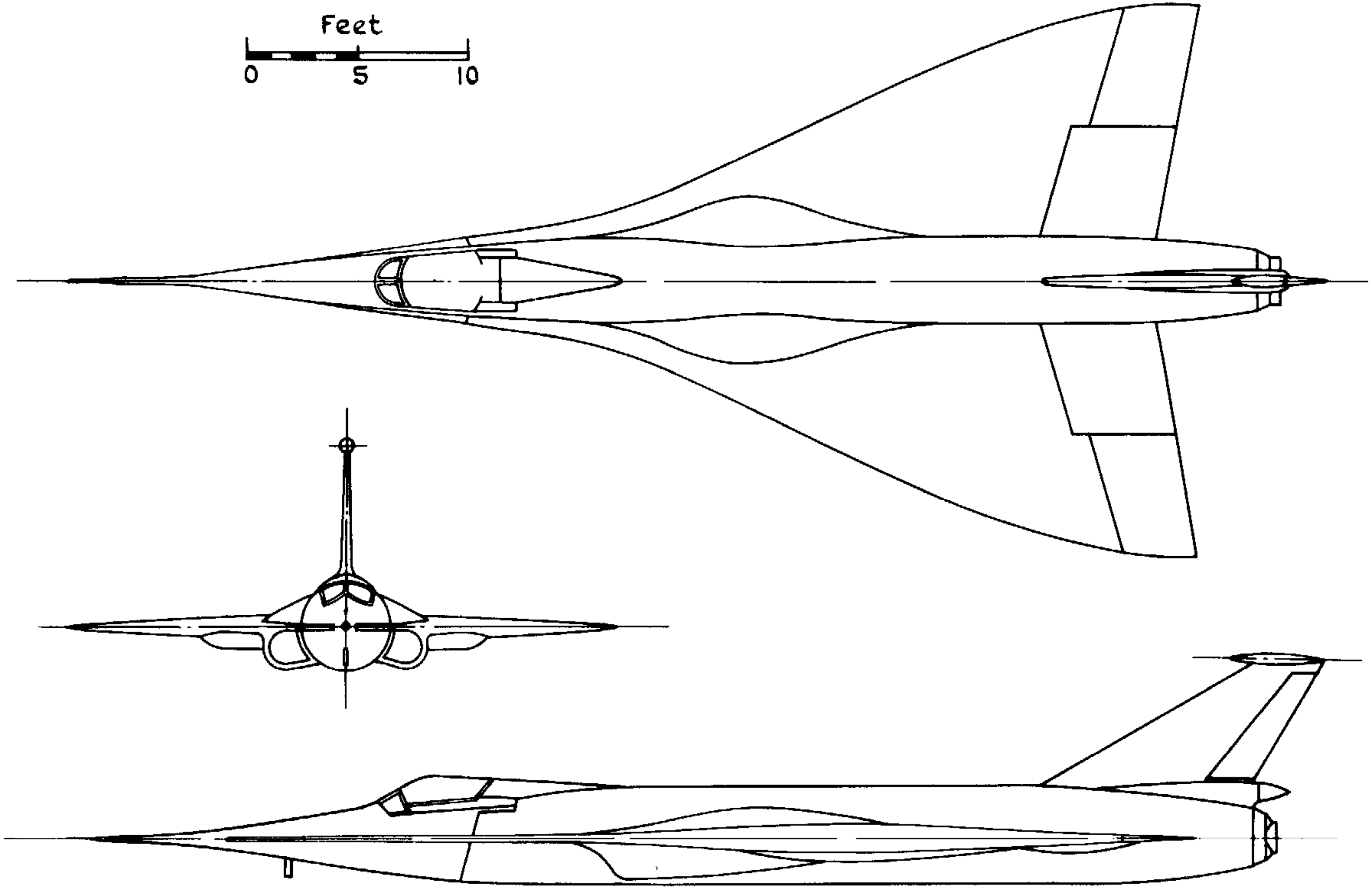


Fig.2 BAC 221 general arrangement, clean configuration

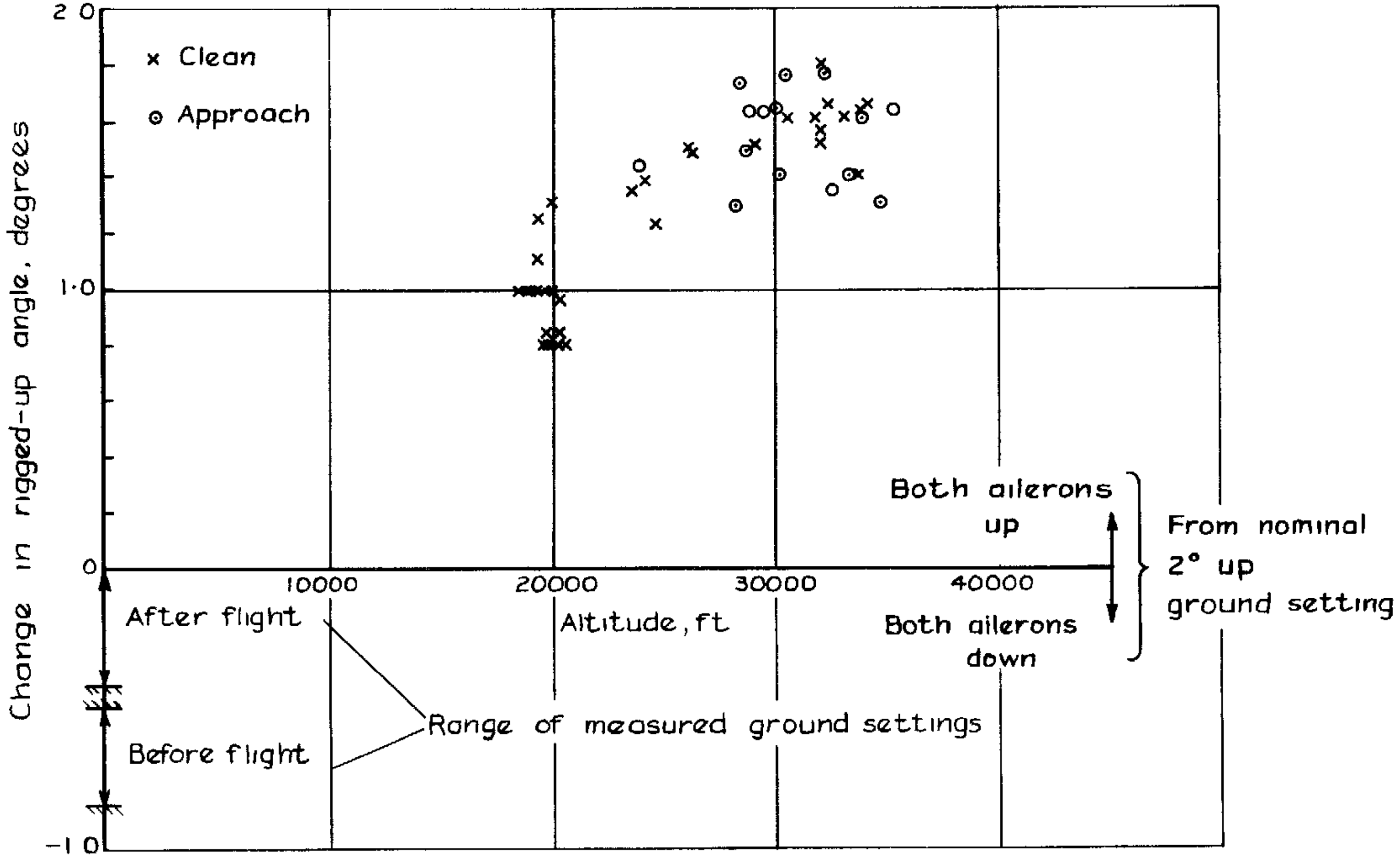
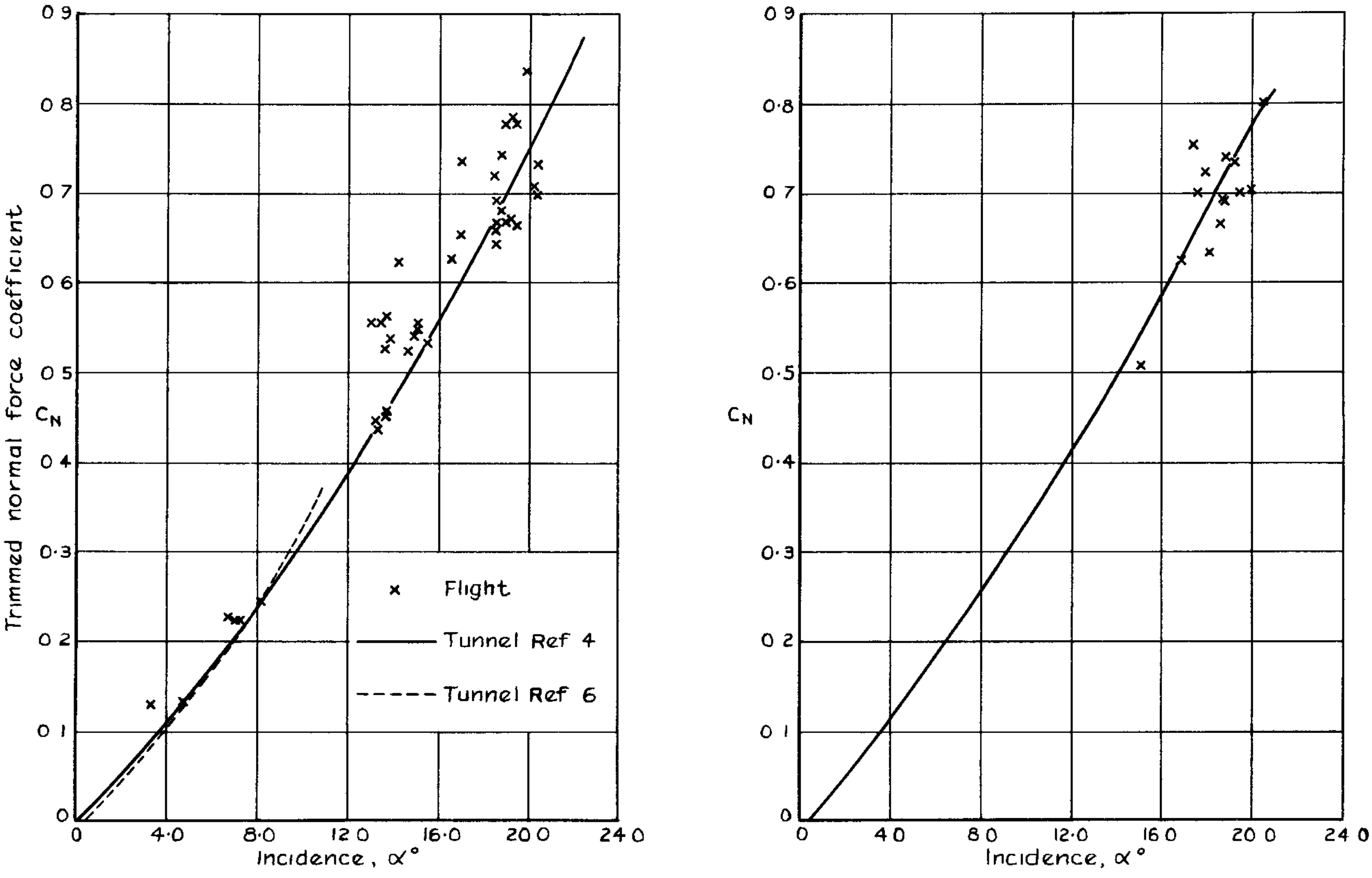


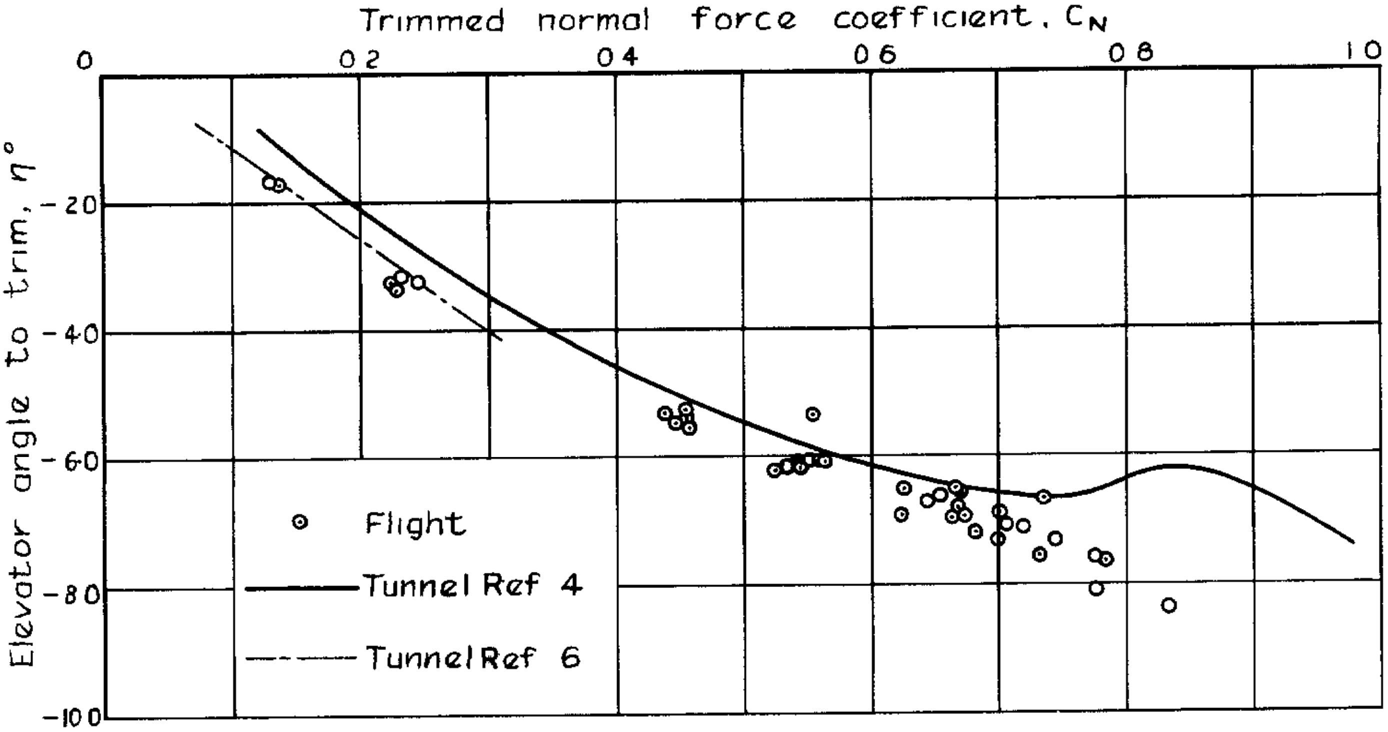
Fig. 3 Changes in aileron rigged-up angle with altitude



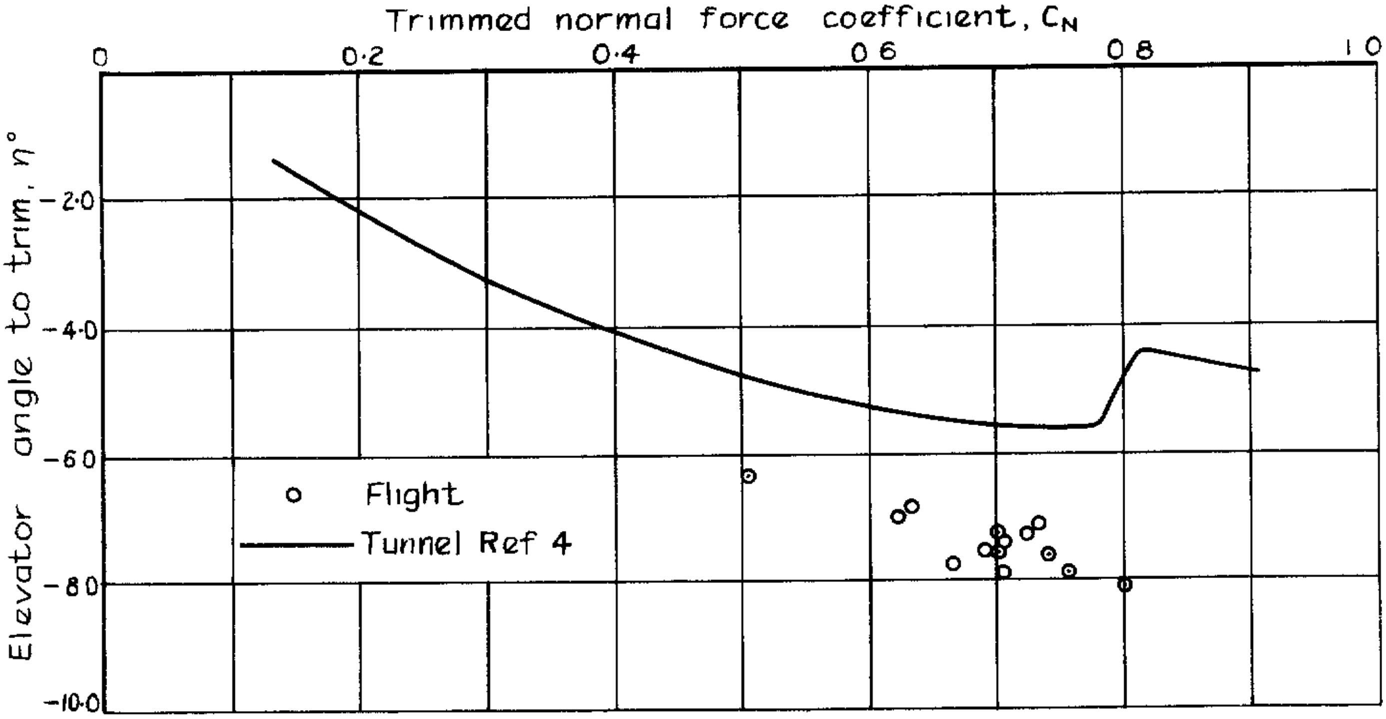
a Clean

b Approach

Fig. 4 a & b Trimmed normal force coefficient versus incidence

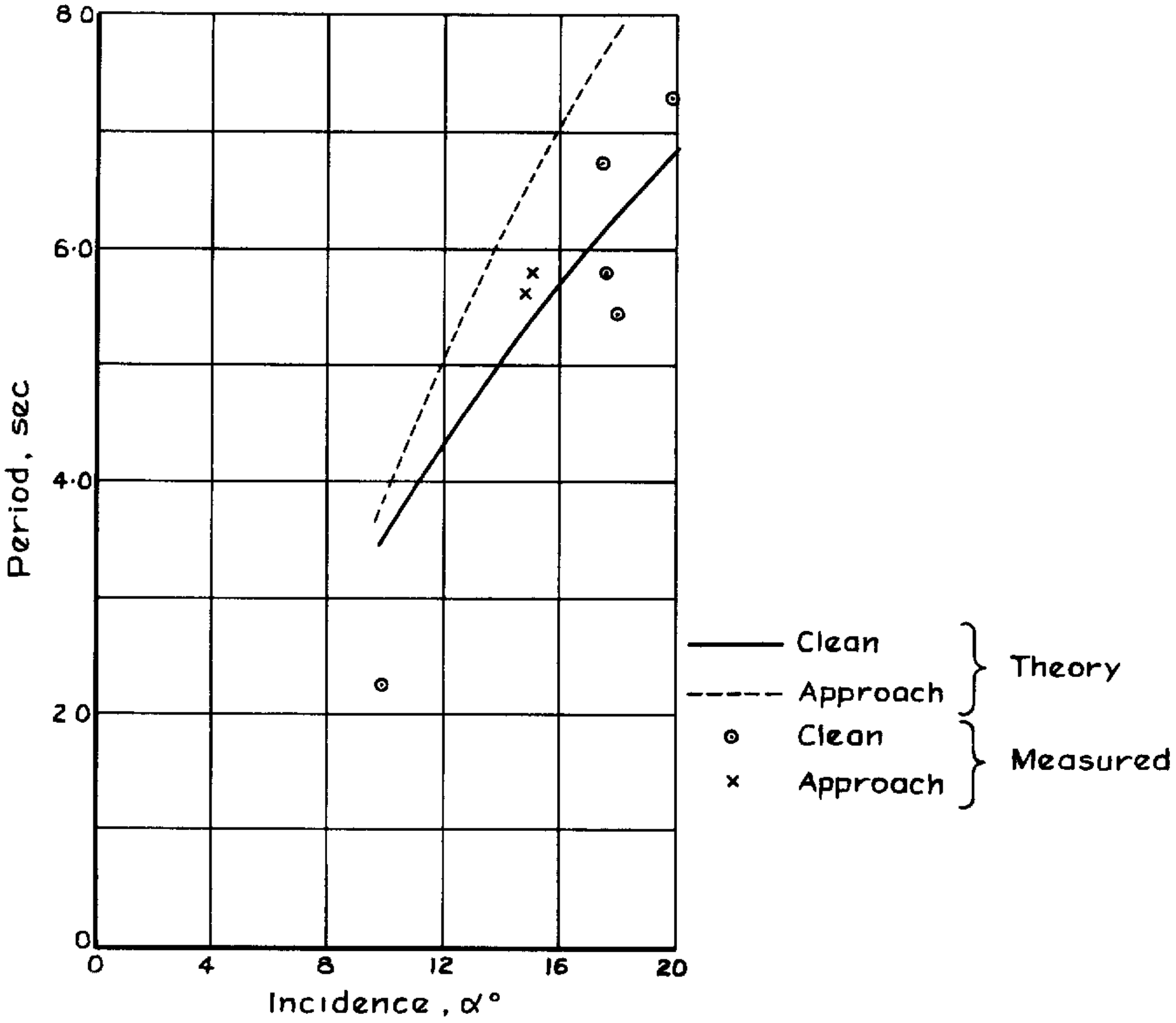


a Clean

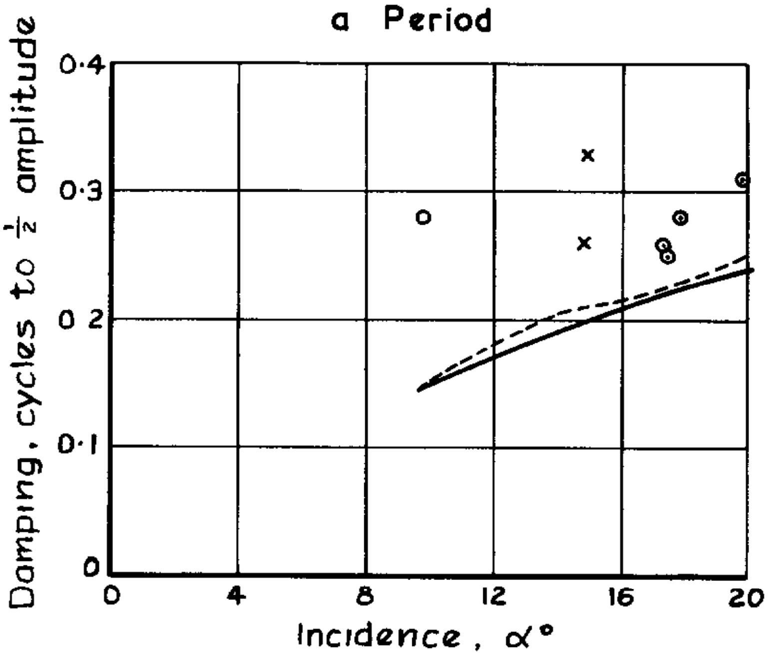


b Approach

Fig. 5 a & b Longitudinal trim comparison, flight results corrected to aileron rigged-up angle = 2°



a Period



b Damping

Fig. 6 a & b Period and damping of the longitudinal short period oscillation

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