C.P. No. 748

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Simulation of Ground Controlled Approaches with Reference to Certain Accidents

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1965

PRICE 9s. 6d. NET

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Simulation of Ground Controlled Approaches with Reference to Certain Accidents

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Communicated by Prof. A. V. Stephens

February, 1963

SUMMARY

This report deals with the simulation of ground controlled approaches and describes an investigation into possible defects in the system which might lead to accidents. Two such accidents are described and in both of these the aircraft built up long period expanding oscillations about the glide path. This motion is then investigated by simulation techniques and its causes determined. The trouble is found to be inherent in the technique of using the throttle to control height and the elevator to control speed. This is demonstrated by systematic use of the throttle in response to height errors according to various logical schemes. It is found that, in certain circumstances, entirely logical use of the throttle results in an oscillation of increasing amplitude no matter how successfully the pilot controls speed with the elevators. It is concluded that accidents have sometimes resulted from use of the throttle to control height.

Finally, a simple device is described, which led to a different flying technique giving much improved control of an aircraft making a blind approach. It consisted of an auxiliary spring-loaded throttle control. Flight tests of this device are strongly recommended.

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1. Introduction

One of the most important problems in aviation today is the guidance of aircraft in cloud so that they can be brought to a safe landing in bad weather. Current practice requires a minimum visibility at ground level of about a mile and a cloud base in the region of 200 to 300 ft. While the ultimate solution to this problem will lie in completely automatic controls coupled to electronic guidance systems the immediate aim is to reduce these distances. Improvements in technique which allow slightly worse weather to be tolerated may substantially decrease the number of flights which have to be cancelled, postponed or diverted and so confer considerable benefit upon aeroplane users.

Of the many guidance systems in use the best known and the most popular with the pilots is the ground controlled approach or G.C.A. In this system the aeroplane is 'talked down' by an operator on the ground who is kept continuously aware of the position of the aircraft by means of radar. He passes positional information and gives instructions to the pilot over the ordinary radio telephone so that no special equipment need be carried in the aircraft. Moreover, the pilot flies the aeroplane in the ordinary way and is free to make full use of the normal blind flying instruments. It is not surprising that the system is popular and that thousands of successful landings have been made by its use.

Despite its popularity the G.C.A. system has certain shortcomings which have occasionally led to serious accidents. These arise from the fact that the pilot is fed periodically with discrete pieces of error information whereas in making a visual approach he is continuously aware of his position relative to the desired glidepath. If the interval between successive pieces of information is not short compared with the period of any mode of the motion a linear extrapolation based on the last two items of information can be highly misleading as to the rate of change of error. Thus occasionally the pilot may be misled into believing that his error is increasing when he is already approaching the glide path - and so tempted into making corrections in the wrong direction. In general the next piece of information will not be misleading and the mistake will be quickly remedied. But it is easy to imagine that an exceptionally unfortunate choice of time interval between successive items of information and of their relationship to the phase of the aeroplane's motion could lead to the pilot being misled on several consecutive occasions. He would then undoubtedly use his controls to build up a motion of increasing amplitude. Another likely cause of instability lies in delay: if the controller is slow to pass on information to the pilot, or the pilot is slow to act on it, there is always a tendency for an oscillation to be built up.

Two accidents involving the crash of an aircraft at the conclusion of a ground controlled approach are well documented and the evidence leaves no doubt that oscillations of increasing amplitude about the glide path took place. But the cause of the accidents was not revealed by the detailed investigations which followed. In each case the mis-use of the controls which must have caused the oscillations to build up could only be attributed to rather vague combinations of possible errors and inaccuracies. No definite mistake in the information given by the controller or obvious error in the technique employed by the pilot came to light.

At the time of the investigation it was commonly supposed that the control of an aeroplane performing a ground controlled approach was effected by two entirely independent control loops, one on the ground and the other in the air. In other words it was assumed that the controller had but to provide accurate information, and the pilot to fly normally taking heed of it, for the aeroplane to maintain a close approximation to the desired glide path. Consequently, the investigators concentrated upon possible errors in the two domains: errors in the observation of the aeroplane's position relative to the glide path and its transmission back to the pilot: and mistakes on the part of the pilot himself. The third possibility that accurate information, if unfortunately timed, could be so misleading that entirely logical action by the pilot could lead to disaster does not seem to have been suggested. However, the experiments to be described in this report point the way to an explanation of both accidents on these lines.

2. Accidents to Stratocruiser and Vulcan

The final stages of the approaches which led to the accidents already mentioned are shown in Figs. 1 and 2. The first aircraft was a B.O.A.C.

Stratocruiser which was destroyed on Christmas Day 1954, when it struck the ground at the conclusion of a G.C.A. talk-down[2]. The other aircraft was the prototype Vulcan Mk 1B which crashed at London Airport on 1st October, 1956 when returning from a world tour[1]. In both cases there is a well-defined expanding oscillation with a period close to that of the phugoid of the respective aircraft. (The writer makes no claim to being the first to notice this, reference being made to it as long ago as May, 1957[2].)

These two flights might have been unique cases but Fig. 3 shows the last stages of two consecutive routine approaches selected at random from a large number of G.C.A. recordings. Both show marked oscillatory tendencies. This does not mean that the aircraft were in any danger on these occasions as it is not known when they broke cloud.

Thus it seems certain that this type of motion is quite common. Although comparison of its period with that of the phugoid has often been made, this can be misleading as it is not necessarily a phugoid motion. Indeed since the phugoid implies an exchange of airspeed for height at the rate of approximately 10 knots per 100 ft at speeds in the region of 120 knots it seems unlikely that the motion could be primarily a phugoid because the airspeed errors necessary to go with the flight paths shown would be too large to escape the pilot's attention. As will be shown later the motion is more likely to arise from deliberate throttle movements by the pilot while he keeps the speed reasonably constant. Thus it may be fortuitous that the period of the recorded motion was close to that of the phugoid although it may prove to be related to it.

The purpose of the present experiments was to discover the cause of this oscillatory motion and the factors which controlled its damping. There appeared to be four quantities which might affect the behaviour of an aircraft making a G.C.A. approach and these are listed below.

(i) The time interval between successive items of height information t_i.

(ii) The time taken for information to reach the pilot t_D.

(iii) The phugoid period of the aircraft T.

(iv) The time to half amplitude of the phugoid $t_{\frac{1}{2}}$.

Before discussing the experimental system it is worth considering what the normal values of these quantities are likely to be. The time interval is found to vary widely within the range 3 to 15 sec. It may depend largely on the difficulty being experienced in aligning the aircraft with the runway. In any case it varies with each controller. In the Vulcan flight record the time was found to be a very consistent 10 sec. If the aircraft is flying particularly close to the glide path the interval may even be as long as 30 sec.

It is rather more difficult to attach a value to the delay time t_D. In the absence of any direct evidence a reasonable estimate seems to be from 1 to 5 sec. It should not, however, be assumed that a pilot preoccupied with other tasks will always respond immediately to each new piece of information. Thus the effective delay time may sometimes be much longer than t_D as defined above[9].

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The period of the phugoid may vary between limits of roughly 25 and 50 sec for normal configurations. As the only laid down requirement for the phugoid is that it shall be damped, the time to half amplitude may range from 20 sec to several hundred seconds.

3. Experimental System: The Technique and Difficulties

The experimental set-up was based on the use of an analogue computer to simulate the longitudinal motion of an aircraft[5,6,8]. The 'pilot' had normal elevator and throttle controls and care was taken to simulate realistically the lag in change of engine thrust. No attempt was made to simulate 'feel' in the controls but the 'stick' was given a spring force of about 1.45 oz/in. and the throttle was restrained by a constant friction force of about 8 oz. In front of the pilot were instruments indicating rate of climb and airspeed and an artificial horizon. In addition for some tests there was an altimeter. The computed height above or below the glide path was presented to the 'controller' as a trace on a pen recorder. This enabled him to pass back to the pilot height information at predetermined time intervals and with a specified delay. Other provisions of the system included the ability to record either the throttle position, the stick position or the airspeed; a method of generating a predetermined vertical gust cycle[4], and the ability to simulate headwinds by altering the glide path angle. Fig. 4 shows a general view of the simulator showing pilot and controller at work.

Before discussing the results it is worth considering the limitations of this form of simulation. An important one is the necessity to use constant aerodynamic derivatives. This means that stability characteristics will not change with speed. In the cases simulated the nominal approach speed was slightly higher than the speed for minimum drag. Consequently, some of the special difficulties associated with flying at or below the minimum drag speed must have been absent. Nonetheless, to the writer at any rate, the simulator was still as difficult to fly as any aircraft within his experience and moreover the difficulties were of the same nature. It therefore seemed likely that the simulator would provide a valid means of testing a guidance system even if it was not fully representative of the aircraft type being simulated. Another shortcoming was the lack of complete instrumentation. The altimeter might have been thought essential but tests with it showed that the pilot seldom referred to it and preferred to rely on the controller for height information. More serious was the lack of direction indication and any controls for yaw and roll. This left the pilot free to concentrate on the pitch task and he could therefore be expected to perform this task much better than when dividing his attention among the three controls.

Despite its limitations this simple fixed base simulator was probably more effective for the purpose in hand than a much more elaborate and comprehensive system representing every feature of a modern aeroplane. More consistent results could be expected from a pilot giving his full attention to a specific task than from one subjected to a variety of distractions. In fact it seems reasonable to suppose that the results obtained with this simple simulator represented real trends and tendencies even if they had no precise quantitative significance.

4. Experimental Results

4.1 Using Wellington derivatives

Some preliminary tests were now made using the derivatives for a Wellington[3]. These tests were aimed at establishing any connection between the time interval between successive items of information, the period of the phugoid and the behaviour of the aircraft. As the time interval was increased from $\frac{1}{12}$ to $\frac{1}{4}$ of the phugoid period (3.8 sec to 11.3 sec) there was a slight deterioration in the pilot's performance but no special difficulty was associated with any particular value. Although his performance only deteriorated slightly this does not reflect the true situation as the pilot certainly had much greater difficulty when the time interval was long. The explanation of this lies in the remarkable ability of a pilot to perform difficult tasks nearly as well as simple ones with the expenditure of greater effort[7].

The effect of delay in telling the pilot his height error was also investigated briefly. A delay of 5 sec produced significantly worse results but delays of up to 3 sec produced no noticeable deterioration. Some of these preliminary approaches are shown in Figs. 5-9 and are discussed in greater detail later.

At this point it seems right to state that all these tests and a great many subsequent ones were made using only one pilot, in this case the writer. Only three pilots were used throughout and this is perhaps open to criticism: particularly the use of the writer, who might have been biased. However, it is the opinion of the writer that the number of variables in this sort of investigation must be kept to a minimum and there was no doubt that the use of one pilot produced far more consistent results. As the writer had, of course, far more experience in the use of the simulator and since it was frequently more convenient for him to spend the necessary hours of practice than for someone else, he performed many of the tests himself. All three pilots had had very similar flying experience consisting of some 200 hours on Chipmunks, including a fair amount of instrument flying and experience of G.C.A. talk-down under blind flying conditions. The writer had also acted as ground controller in practice talk-downs and spent some time watching 'live' talk-downs.

4.2 Using Vulcan derivatives

The next series of tests were conducted using the derivatives for the Vulcan Mk 1B. This was a much more difficult aircraft to fly as is evidenced by Fig. 10 which is a record of the first approach made in the simulator with these derivatives, after some hours of practice flying. Even Fig. 11 which shows a flight at a much later date when the pilot was completely familiar with the Vulcan, is much worse than any similar approach with the Wellington.

A study of the flight paths of the Wellington from the earlier tests had revealed two significant features. There was a comparatively short period oscillation about a series of mean straight lines. Secondly, these mean lines either diverged from, or converged with, the correct glide path. The slope of these lines seemed to be connected with the throttle setting while the short period oscillations appeared to result from conflict between speed and height information.

In order to isolate the short period motion some tests were made with the Vulcan derivatives in which the throttle setting was fixed at the correct value for an approach at 120 knots. The test started with the aircraft either 50 ft low or 50 ft high and the pilot was asked to do his best to keep the speed constant and to fly down the glide path. As these two demands were not immediately compatible it was thought that this would produce the necessary conflict between height and speed requirements to reproduce the short period oscillations. These tests were done with different values of time interval ranging from 1.7 sec to 10 sec in order to establish the connection, if any, between the time interval and the period of the resulting motion. Fig. 12 shows one approach at each of the time intervals and the periodic motion is clearly evident. The periods of this motion are summarised in Figs. 13 and 14. These figures were compiled by estimating the periods of each complete oscillation and counting the number of oscillations with periods in bands of 1 sec width.

The most probable period seems to be in the range 13 to 23 sec and it can be seen that there is no obvious connection between it and the time interval between items of information although with very short time intervals the most likely period does seem to be at the lower end of the group. These tests were all made with one pilot and a subsequent analysis of all flights made by another pilot, the writer, with the throttle in use is shown in Fig. 15. This shows the most probable period to be 10 sec and it therefore seems likely that the value of this period depends largely on the piloting technique, decreasing as the pilot makes bolder movements of the controls either because of greater familiarity with the aircraft or because of greater confidence in the talk-down.

The next stage in the investigation consisted of making approaches with the Vulcan configuration, recording the throttle movements in order to study the relation between the flight path and the throttle setting. Some of these are shown in Figs. 16-18 where the close correlation between throttle setting and deviation from the glide path is again apparent. Although little quantitative evaluation can be made from the results so far presented some valuable conclusions can be drawn on the nature of the motion of aircraft making G.C.A. approaches and the flying technique that gives rise to it. The next section of this report will be devoted to an analysis, with this aim in view, of the results so far obtained.

4.3 Analysis of motion and flying technique

For the regulation of speed and height the pilot has two controls; a stick connected to the elevators and a throttle. In the early stages of his training he is taught to control speed by use of the stick and height, via rate of climb or descent, by means of the throttle. This results in continuous use of the stick with occasional changes of throttle setting. Although this technique has to be modified for special purposes such as formation flying, it remains the basis of a pilot's method of control throughout his career. Moreover, this is the recognised technique for blind flying and is normally adopted on a blind approach.

The ideal approach is one in which the aircraft is always on the glide path and the airspeed is constant at the desired value. This requires exactly the correct throttle setting. If the throttle setting is not correct the approach could be made at a different airspeed without the aircraft leaving the glide path but the pilot will not tolerate this and therefore feels impelled to make adjustments until he finds the correct throttle position. The actual setting required will depend on several factors of which the all-up weight of the aircraft and the wind velocity are the most important.

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Let us now consider what the pilot does when making a G.C.A. approach. With the aircraft flying level at some specified height he is told that he is approaching the glide path. When he judges that the aircraft will just have settled down to its steady state by the time that it reaches the glide path he closes the throttle by an amount which he thinks will be correct in the prevailing conditions. His main guide to this setting is either the rev counter in a turbojet or the boost gauge in a constant speed propeller aircraft although other factors such as noise level may be of assistance to him. When the aircraft has settled down it can only be in one of four conditions.

(i) High with too great a rate of descent.

(ii) Low with too great a rate of descent.

(iii) High with too small a rate of descent.

(iv) Low with too small a rate of descent.

Of these four conditions the first and last are the most desirable since the aircraft will steadily approach the glide path if flown at the correct speed, whereas in the other two conditions it will diverge from it.

Following this initial throttle movement the pilot will fly the aircraft using the stick alone. If the throttle setting was incorrect the speed would steadily change if the aircraft were kept on the glide path. It may be some time however before the pilot can assess what throttle movement is required as speed also changes with errors in height. For some time therefore while using the stick control alone the pilot may be continually alternating between getting on the glide path and keeping the speed constant. This will give rise to the short-period oscillations evident in all the approaches made and is almost certainly the explanation of them. Although, as mentioned earlier, the period of these was not materially dependent upon the time interval, it was noticeable that the approaches in which the time interval was half the mean period of these oscillations tended to be either very good or very bad, depending on the initial stages of the approach. Thus it may well be inadvisable to give information at such intervals, but as the controller has no means of knowing this period the best he can do is to avoid giving the information at exactly regular intervals. However, these short-period oscillations associated with the stick control do not appear to be of great importance as they are of small amplitude because of their short period.

After some time has passed the pilot realises that the throttle setting needs adjustment and will alter it accordingly. However, in order to alter the rate of descent by 50 ft/min the throttle need only be moved one-sixteenth of the movement originally made to get the aircraft on the glide path. This is a very small movement indeed and so the pilot is quite likely to overshoot and the process will have to be repeated. It is in fact quite likely that he will never find the correct setting during the approach; and even if he does find it, gusts or flying at the wrong speed for some time will require him to alter it again. A 7 knot wind change for instance will require the rate of descent to be changed by 50 ft/min and if this is not done the aircraft would be in error by 150 ft, 15 knots or some combination of both by the end of the approach (assuming constant drag).

This correlation between throttle setting, mean glide path and short-period oscillations is clearly shown in all the approaches made on the simulator.

Most of what has been mentioned so far applies equally to visual approaches. The fundamental difference in a G.C.A. approach is that the pilot is provided with discrete items of position information from which he has to assess his rate of change of height. This assessment may sometimes be quite wrong; indeed it may be in the wrong direction even if the information given is entirely accurate. But naturally if the information is incorrect or is delayed the pilot's task is made much more difficult.

It is now possible to take a specific approach and analyse the pilot's reactions to the information he received. As an example the approach recorded in Fig. 8 has been taken. The flight path recorded by the pen recorder is plotted together with points representing the actual items of information as to height provided by the controller. These have been numbered. In this case there was no deliberate time lag but following normal practice height information was only given to the nearest 10 ft. Initially the pilot did not close the throttle enough and so the aircraft overshot the glide path. The information at (1) however was well timed so that he easily judged the correct time to close the throttle. Thus at (2) and (3) he was slightly high but by (4), probably due to trying to get the speed correct he was 20 ft high even though he had by now perhaps luckily found the correct throttle setting. One may suppose at this stage that he pushed the stick forward to lose the 20 ft surplus height and shortly afterwards closed the throttle slightly as the speed started to build up so that the aircraft started to go below the glide path being 25 ft low by (8). By pulling the stick back the aircraft came to within 10 ft of the glide path at (9) but (10) saw it 20 ft low again and the pilot realised that the throttle needed adjusting and so he opened it. The rest of the approach was made at this setting with the aircraft eventually becoming too high. The small oscillations were probably due to the pilot trying to hasten the return to the glide path by using the stick.

At this stage certain tentative conclusions can be made:

(i) Any long period variations in height probably arise from the pilot's difficulty in finding the correct throttle setting.

(ii) Short-period oscillations in height caused by stick movements appear to be an inherent part of the approach. Their period is largely dependent on piloting technique but may be influenced by the frequency of information passed to the pilot and by any delay in its reaching him. Their magnitude may also be affected by the timing of the information. Because of its relatively short period this mode does not appear to be dangerous.

(iii) Increasing amounts of delay in passing the information t the pilot lead to larger departures from the glide path.

5. Simulated G.C.A. Approaches on a Vulcan with Planned Throttle Movements

5.1 Continuous throttle movements

The problem of controlling the height of an aircraft under G.C.A. conditions is inevitably complicated by the fact that two controls, the throttle and the elevator are in continuous use and that three interrelated

variables,/

variables, speed, height and attitude, have to be controlled throughout. An error in height at any given moment may be due either to the cumulative effect of an incorrect throttle setting or to an error in speed. In the latter case being too low may be directly associated with excessive speed so that the height error can be immediately corrected with the elevator, kinetic energy being exchanged for potential energy as in a phugoid. However, if the excess of speed has been allowed to persist more work will have been done against drag, even if flying at the minimum drag speed, and so the correct speed and flight path can only be regained by opening the throttle even if it is already in the correct position for maintaining the desired flight path at the correct speed.

In practice both controls are used although elevator movements are more frequent. This is because the pilot finds it much easier to make immediate corrections to attitude rather than waiting for errors in attitude to build up errors in speed and height, and attitude is of course controlled by the elevators alone. However, when the throttle setting is altered it is normally necessary to make a co-ordinated movement of the stick if errors in height are to be corrected without overshooting and if the speed variation is to be kept to a minimum. The use of two different types of control (stick and throttle) to control a motion involving three variables (speed, height and attitude) not unnaturally gives considerable scope for variety in piloting techniques. There is no single correct method. Moreover, a considerable variety of actual control movements would produce substantially the same flight path without great variation in speed error. Consequently, experiments of the type so far described, although helpful in bringing home to the experimenter the nature of the problem, were not likely to lead to clear-cut results. Sometimes divergent height errors occurred, doubtless as a result of a momentary lack of concentration on the part of the pilot, but the same result was not obtained if the experiment was repeated under identical conditions. Moreover, factors which made the pilot's task more difficult did not necessarily lead to less accurate flying: he merely had to fly with greater concentration[7].

In view of these considerations and in order to eliminate the inevitable variations in performance arising from the state of mind of the pilot, it was decided to substitute a formal scheme of control movements for the 'natural' flying techniques which had been used so far. The formal drill would of course have to be based on a logical method of piloting and might be confined to one control, or one source of error information. If both controls were moved only in accordance with a formal scheme on the strength of errors in height and speed, the virtuosity of the pilot would be completely eliminated, and repeatable results obtained. Alternatively, part of the task might be left to the discretion of the pilot. In either case it seemed possible that a close enough approximation to natural control movements would be used to enable the factors leading to instability to be made clear.

The experiments in which planned control movements were substituted for normal piloting were all based on the standard technique of controlling speed with the stick and height with the throttle.

In the first series of tests it was assumed that the elevator angle was maintained constant while the throttle was altered in response to errors in height. This is of course an unrealistic assumption but it helps to separate the effects of the throttle from those of the elevator. It was further assumed that the throttle setting relative to the correct position for flight on the specified glide path at the desired speed was directly proportional to the height error. The changes in throttle setting could either oppose the height error, that is the thrust was reduced when the aircraft was high and vice versa, or they could be in sympathy with it. In either case the record of the throttle position was an exact replica of the flight path. In addition various amounts of time lag between the height error and the corresponding change in throttle setting were introduced. In order to do the experiment a single operator watched the pen record of the flight path and manually adjusted a potentiometer representing the throttle so that a second pen corrected with it produced an exactly similar record. Results obtained in this way were found to be entirely repeatable. They are summarised in Figs. 19-22. The tests covered all possible phase relationships between throttle setting and flight path and a wide range of the ratio between throttle movement and change in height. It can be seen that all throttle movements of this type had a destabilising influence on the flight path. This is startling as it seems reasonable to assume that any pilot's actual throttle movements must at least bear some resemblance to one or other of these piloting schemes.

5.2 Step throttle movements: fixed elevators

The pilot's use of the throttle would not, of course, be continuous but take the form of a series of steps. Consequently, a formal scheme using step movements was evolved. Once again the elevator angle was assumed constant. The pilot now moved the throttle only when the height had changed by some specified amount H_s. In response to each change H_s the throttle was moved so as to increase or decrease the thrust by an amount T_s depending on whether the height had increased or decreased. Thus when the aeroplane, starting from the glide path, reached H_s ft high the thrust would be decreased by T_s. If it continued to climb to $2H_s$ ft above the glide path the thrust would be reduced by a further T_s. When the aircraft returned to H_s ft high the thrust would be increased again so that it was only T_s below the correct value for flight down the glide path. As before the magnitude of the throttle movements was varied by altering the ratio T_s/H_s. The actual value of H_s was also varied and, of course, the previous control plan with continuous throttle movements was simply the limiting case of this one as H_s tends to zero. In this case however no delays were introduced and the throttle movements always opposed the height changes.

Because of the step nature of the control movements the results were not as consistent as the earlier ones. This was because small changes in any of the variables sometimes resulted in an extra control movement at an early stage and on other occasions made practically no difference. All these tests started with the aircraft flying parallel to the glide path either 30 or 60 ft high. The times to half or double this amplitude were estimated and these are shown in Table 1. They are inevitably approximate owing to the irregular flight paths resulting from step movements. In this case it is seen that very small throttle movements in certain circumstances improved the damping. However, large movements invariably caused it to decrease. In fact the system became negatively damped in all cases where T_s/H_s exceeded the value $0.00067\ T_{max}$ lb/ft.

So far these tests seemed to show that almost any throttle movements based upon height error had a destabilising effect upon the system. However, this conclusion rests on the assumption of a constant elevator angle and Fig. 23 shows that the speed changes which go with 100 ft error in height are large and similar in magnitude to the changes which occur in the phugoid, that is about 10 knots per 100 ft. Now a pilot making a blind approach would clearly endeavour to keep a close control of his airspeed and would certainly intervene with the elevator if the speed departed from the desired value by more than 4 or 5 knots. Such intervention would clearly be stabilising and so had to be represented in the tests before it could be safely concluded that the use of the throttle in the manner described would lead to divergent oscillations.

5.3 Step throttle movements: autopilot

Consequently, it was decided to see what would happen to the motion when the elevators were used to control the speed. In order to represent this a form of autopilot was employed in which a pitching moment proportional to the rate of change of speed was applied. The efficiency of this system is demonstrated in Fig. 24 which shows the responses of airspeed to a step throttle change for various magnitudes of the ratio $\frac{C_M}{du/dt}$. From this it can be seen that a good response was obtained with $C_M = 0.0290 \frac{du}{dt}$. In Fig. 25 several approaches are shown so that comparisons can be made between the flight paths with and without this amount of elevator control. This shows that even in an extreme case where $\frac{T_s}{H_s} = 0.004\, T_{max}$ and the aircraft started 60 ft high, the system is well damped. However, it transpired that this represents an upper limit to the damping which could be used as examination of the record of the third pair of approaches in Fig. 25 showed that the largest pitching moment used was nearly twice that available.

One other factor, although already discussed, remains to be considered in this context. This is delay in information reaching the pilot. Although this was investigated in the case of continuous throttle movements it had not so far been considered for step movements. Fig. 26 illustrates the effect of a delay of only $1\frac{2}{3}$ seconds on one of the approaches shown in Fig. 25. It can be seen that a reasonably well damped approach became negatively damped.

As there were five variables in the problem, T_s, H_s, $\frac{C_M}{du/dt}$, H_i (the starting height) and t_D (the delay time) it was decided to keep three of these constants (T_s, H_s and H_i) and to study the effects of delay time and autopilot gearing. With $T_s = 0.02\, T_{max}$, $H_s = 10$ ft and $H_i = 10$ ft, six values of t_D were chosen in the range 0 to 10 seconds and approaches were completed at each of these values with differing magnitude of elevator movement covering the range $C_M = 0$ to $C_M = 0.1 \frac{du}{dt}$. The times taken to reach 50 ft height error were estimated in each case and the results are quoted in Table 2 and plotted in Fig. 27. It is evident that increasing amounts of delay can be balanced by increasing magnitudes of elevator movement so that any particular degree of damping can be the result of numerous combinations of time delay and elevator movement. The rather non-continuous forms of the curves in Fig. 27 are due to the step nature of the motion as already explained. In general the mean lines through the points have been drawn as the discontinuities are mainly dependent on the value of H_s.

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Although Fig. 27 shows that different combinations of delay and autopilot gearing can produce the same degree of damping it does not show that the changes in airspeed and attitude which go with the flight paths are not the same. This is shown in Figs. 28, 29 and Table 3. Acting on the assumption that the airspeed changes in each approach were proportional to the height error the following figures were deduced. With no time delay and $C_M = 0.00628 \; du/dt$ when the height error reached 100 ft the corresponding airspeed error would have been 9.8 knots: with 5 seconds delay and $C_M = 0.0181 \; du/dt$, giving substantially the same time to 100 ft height error the speed error would have been 4.5 knots: and with 10 seconds delay, $C_M = 0.0438 \; du/dt$ again giving the same time to 100 ft, the speed error fell to 1.9 knots. This is of great significance for while it is difficult to imagine that a pilot would tolerate a 10 knot error in airspeed he would not only tolerate an error of 2 knots but would be well pleased with it. We have therefore demonstrated an instability arising from a logical set of throttle movements which never involve using an extra thrust of more than 20% of the total available. Even when applied to an aeroplane fitted with an autopilot making almost full use of the available elevator movement and keeping the speed within 3 knots of the correct value, they cause it to diverge fairly rapidly and become 100 ft too high simply because there was a delay of 7 seconds before the pilot acted on each piece of information.

5.4 Step throttle movements: human pilot

While it was useful to use an autopilot from the point of view of getting consistent results it was felt essential to see what happened when a pilot controlled the elevators to keep the speed constant while these throttle movements were being made. Fig. 30 shows the flight paths of some of these approaches and Table 4 summarises the results. It is seen that the pilot could keep the speed error much the same in all cases despite increasing time delays. The pilot, of course, knew nothing about the flight path or what was being done with the throttle. However, he was given a comparative score at the end of each run to show him how well he had performed. This was proportional to the mean of the modulus of the airspeed error.

With delays of up to 1.7 seconds the flight path was excellent and showed no particular characteristics, but with a delay of 3.3 seconds a fairly large amplitude oscillation with a 40 second period developed. This oscillation was neutrally damped. With longer delays negatively damped oscillations of 35-40 seconds period were observed. As in all the previous simulated flights short-period oscillations were superimposed on the long-period motion, further confirming that they are due to manual speed control. Thus we have now reached the stage of showing that in certain circumstances a completely logical set of throttle movements can lead to a divergent oscillation in height no matter how hard the pilot tries to keep the speed constant with the elevators.

6. Vulcan with Self-centring Throttle

It has been shown so far in this report that misuse of the throttle is the most likely cause of a build-up of height oscillations under G.C.A. control. This misuse arises for two reasons which have already been discussed; firstly, because the pilot has difficulty in finding the correct setting and secondly because, having found it, he is reluctant to move the throttle by more than a small amount. He has no such inhibitions about using the elevator. The principal difference between the stick and throttle controls is that the former

is/

is self-centring whereas the latter is friction-loaded. It was therefore decided to introduce a spring-loaded throttle with a variable datum position and to do comparative tests.

The spring loading had a rate of $1\frac{1}{3}$ lb per in. over a total range of $3\frac{1}{2}$ in. and the friction throttle required a force of 1 lb to move it. Adjustment of the zero in the spring loading was by means of a 2 in. diameter wheel behind the throttle. Simulated flights were made in the same manner as before, the pilot putting the aircraft into level flight before each run and having to judge the correct moment at which to close the throttle in order to arrive on the glide path. Root mean square height and speed errors were evaluated for each approach for a duration of 160 seconds immediately after the aircraft first came within 20 ft of the glide path. The spring-loaded throttle was initially set to the correct datum position to make an approach at 120 knots in zero wind conditions. The actual approaches were made in wind strengths ranging from 10 knots tail wind to 30 knots head wind and in the vertical gust pattern shown in Fig. 31[4]. This would have produced the flight path shown in Fig. 32 if no control had been applied. Neither pilot nor controller knew the phase of these gusts relative to the initiation of the approach and their complete cycle lasted 80 seconds so that the r.m.s. errors were evaluated over two complete cycles. Another quantity was also evaluated in each approach. This was the mean of the modulus of the throttle setting relative to that required for an approach in still air at 120 knots. In future this will be referred to as S_T, the throttle score. It is hard to attach precise significance to this quantity but it is felt that it should be as small as possible since a smaller number seems to indicate more economical use of the throttle and less pilot effort[7]. This score has been presented in the form

$$S_T = \frac{1}{240}\int_0^{240} \left| \frac{T_s - T_o}{T_{max}} \right| dt$$

where t is the time in seconds,

T_s is the thrust corresponding to the instantaneous throttle setting,

T_o is the thrust required for the ideal approach in still air,

T_{max} is the maximum thrust available.

Four series of approaches were made, the first two were exactly similar except for the use of different pilots, the first one being the writer. They consisted of 14 approaches, 7 with each type of throttle made in a variety of head winds in order to study the effect of these on the accuracy of the approach. They were all made with height information being given at 6.7 second intervals with no delay. The results of these approaches are presented in Table 5.

Throughout the two series there is a marked improvement in speed control and a slightly less marked one in height control. This is achieved in all cases with a lower value of S_T. Furthermore head winds, even up to 30 knots appear to have had little or no effect with either type of throttle. The pilots were told to alter the zero in the spring loading if necessary but both found that they neither wanted to alter it nor would they have known what alteration was required.

These/

These tests provided very strong evidence for the superiority of the spring-loaded control under a variety of conditions. However, a third series of 14 approaches was made with the second pilot. These were all made in a 15.5 knot head wind with gusts which gave rise to a maximum height change of 30 ft. The talk-down information was now given as often as the controller felt necessary, and every effort was made to help the pilot so that the height control was as good as possible. These approaches were made alternately with friction and spring loading so as to minimise the effects of learning and tiredness. The results are shown in Table 6 and summarised statistically in Fig. 33(a). In addition a fourth series of tests was made with the original pilot. This time instead of a G.C.A. talk-down an I.L.S. approach was simulated and the aircraft was provided with roll control. The pilot was required to maintain a constant heading, a task which was made more difficult by a disturbance in yaw similar to that in pitch giving rise to a change in heading of 10° over a period of 80 seconds. The pitch task was the same as in the previous series. In this series those tests made with the friction-loaded throttle were done separately from those with the spring-loaded throttle. This was to make it easier for the pilot to act objectively and also to make certain that he had time to develop the optimum technique for each type of throttle. These results are shown in Table 7 and are summarised in Fig. 33(b). Clearly the spring-loaded system is much superior, reducing the root mean square speed error by almost one half and the root mean square height error by one quarter, with a throttle score only half that recorded in the approaches made with friction loading on the throttle. These results establish clearly that the spring-loaded throttle is easier to use in these circumstances than the friction one. Both pilots very much preferred it once they had overcome its initial strangeness. And they were quite clear why they preferred spring loading; the effect was that the pilot could now concentrate on controlling height with the stick and keep the speed constant by using short bursts of power, knowing that the throttle would return to a sensible position as soon as he let it go. This is not possible with the friction-loaded throttle as too much concentration has to be applied to returning the throttle to its original position after each correction.

Two typical approaches from the third series are shown in Fig. 34. It is seen that in the approach made with the friction-loaded throttle there are large amplitude oscillations of speed with a period of about 40 seconds and this was evident throughout the series. This is interesting because in these approaches the pilot was concentrating on height control with very accurate and almost continuous talk-down information so that the height was controlled very much more accurately than would normally be the case. As height and speed are to a certain extent interchangeable it is probable that if the pilot were receiving very sparse height information these oscillations would appear in the flight path rather than in speed. This provides further confirmation of the cause of height oscillations and shows that the spring-loaded throttle may well provide a satisfactory cure for them.

In fact it seems likely that the conventional technique used in flying is not the best possible for the control of a modern aircraft making an approach. A much better technique would appear to be to use the throttle for speed control and the stick for height control. As is pointed out in Ref. 10 all autopilots and automatic landing systems use this method of control. The reason why this technique has never been adopted for manual control seems to lie in the inherent difficulty of operating a friction-loaded throttle. If this is so the introduction of a spring-loaded throttle could mean that the conventional flying technique would be abandoned and a new one, based on the use of the throttle to control speed introduced. For this reason it is felt that flight tests of the device are urgently required.

It should be emphasised that this self-centring throttle would be an auxiliary control. The normal throttle lever, or levers in the case of a multi-engined aircraft would be retained. The auxiliary spring-loaded control would open or close the throttles on all engines by the same amount. An arrangement suitable for a four-engined aircraft is shown diagrammatically in Fig. 37. In practice pre-loaded springs giving a finite break-out force would be fitted to ensure that the friction in the throttle lines was overcome when the auxiliary throttle lever was released. The self-centring control would only be used for tasks where close control of speed and height are essential. The approach is just one example: formation flying is another and there may be many more.

7. Conclusions

In this report two related matters have been investigated - the actual G.C.A. system and its possible faults, and the flying technique on approaches with G.C.A. control. These two aspects of the problem will be dealt with separately.

7.1 The G.C.A. system

While it is obvious from its excellent record and popularity that the G.C.A. approach aid is extremely safe there are several respects in which it could be improved. A potential danger lies in giving the pilot information which, although correct, leads him to postulate an incorrect rate of change of position. This is something which should be brought home to controllers during their training. The aim of the controller should be to give the pilot two consecutive bits of height information which enable him to forecast his return to the glide path accurately. It is not sufficient to tell him when he has returned to it because he will then overshoot. Further, the controller should not be tempted to act too quickly if the aircraft strays from the glide path as it may return of its own accord, if the departure was due merely to a speed error. Fig. 35 shows four examples of timing: two very good and two very bad.

The controller should be on the lookout for a build-up of oscillations throughout the approach. In this task he is not helped by the current presentation, for as can be seen in Fig. 36, while the Stratocruiser oscillations are quite evident when the presentation is of height above the glide path to a suitable scale they are not nearly so obvious when the scale is reduced to allow the actual height above the ground to be shown. They would be even more concealed by the lack of definition and impermanence of a radar trace.

It is therefore suggested that the presentation should be altered so as to show height above the glide path to a more suitable scale. Consideration should also be given to having a completely independent observer, preferably a pilot, monitoring each approach with overruling authority to order overshoot action. The controller would then be free to concentrate on giving accurate and helpful information all the time, while the observer could consider the safety of the manoeuvre as a whole.

While it may be argued that he would spend most of his time doing nothing it seems most unlikely to the author that an observer viewing a picture like Fig. 36(a) at either of the crashes would have allowed the approaches to continue beyond the '20 seconds to touch-down' point. However, the observer would need a convincing picture like that shown in Fig. 36(a): the current type of presentation would hardly suffice.

Looking at the actual accidents it can be seen in both cases that the aircraft was some 100 ft above the glide path with only 20 seconds to go. At this stage it was only 200 ft above the ground and should therefore have been breaking cloud. At this point the position must have seemed eminently safe to the pilots (100 ft too high with only 1000 yd to go); yet the aircraft would have hit the ground before reaching the runway had the same pattern of flight continued. Even so, had the pilot maintained a good view of the ground, it is most unlikely that he would have flown into it. It is felt that the actual crashes must have occurred because visibility was bad at this stage or the aircraft ran into another patch of cloud. It is because of the apparent safety of the situation as assessed by the pilot at the very moment when the aircraft is in greatest danger that it is particularly desirable to have an independent observer.

To sum up it is suggested that:

(i) In teaching the controller particular emphasis must be laid on the importance of providing the pilot with rate information as it is this which helps him to damp out any oscillatory motion.

(ii) The presentation be altered so that the controller has a more suitably scaled picture of the aircraft's height above the glide path. This could possibly take the form of a permanent pen recording.

(iii) An independent observer should be provided to monitor the approach and decide whether it should be abandoned at any stage.

7.2 The piloting technique

This report has shown clearly that quite apart from errors in the talk-down procedure long-period oscillations are likely to occur which can in some circumstances build up to large amplitude. These are caused by use of the throttle to control height. It is suggested that pilots be taught that during a blind approach the golden rule must be 'use the stick to control height and the throttle to control airspeed'. This is the reverse of normal flying technique but it is the writer's opinion that this is the best way of controlling a blind approach on a fast aircraft. It may well be that many pilots already use this rule, at least sub-consciously, and some have suggested that it should be formally adopted[10]. However, it is very strongly felt that a spring-loaded auxiliary throttle would be of great assistance and that given it any pilot would automatically adopt the proposed flying technique and find himself making blind approaches more accurately and with less effort. Flight tests of this device are strongly recommended. A possible arrangement for a four-engined aircraft is shown in Fig. 37.

References/

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Table 1/

Table 1

Step Throttle Movements: Fixed Elevator

$\frac{T_s}{H_s \times T_{max}}$	H_s	$t_{\frac{1}{2}}$ {starting at 30 ft}	$t_{\frac{1}{2}}$ {starting at 60 ft}	t_2 {starting at 30 ft}	t_2 {starting at 60 ft}
0.004	10			13.4	21.7
0.002	20			21.3	18.1
0.002	10			19.6	37.1
0.00133	30			31.1	45.2
0.001	10			46.1	72.4
0.001	20			50.4	68.8
0.00067	10			88.2	120
0.00067	30	60.7			123
0.00050	20	15.7			274
0.00033	20	30.5	36.8		
0.00033	30	15.7	41.3		
0.00022	30	30.5	25.5		

Table 2

Step Throttle Movements: Autopilot

Delay time t_D seconds	$C_M \div \frac{du}{dt}$	Time to reach 50 ft seconds	Delay time t_D seconds	$C_M \div \frac{du}{dt}$	Time to reach 50 ft seconds
0	0	41.5	1.67	0	38.7
	0.001445	51.1		0.00289	45.8
	0.00289	56.9		0.00578	68.3
	0.00578	85.5		0.00876	83.3
	0.00825	168		0.01155	173
	0.00876	206		0.01445	Damped
3.33	0	36.8	5.0	0	37.0
	0.00289	42.3		0.00289	41.7
	0.00578	47.8		0.00578	44.0
	0.00876	72.2		0.01155	69.0
	0.01155	87.7		0.01445	83.8
	0.01445	117.1		0.01701	93.6
	0.01701	141		0.02225	119.3
				0.02890	23.0
6.7	0	41.2	10.0	0	36.3
	0.00289	44.1		0.00578	40.6
	0.00578	47.0		0.01445	50.7
	0.01155	66.3		0.02225	53.3
	0.01701	94.3		0.02890	54.5
	0.02890	129		0.0402	580
	0.0413	150		0.0413	(61.7)(96.3)
				0.0578	96.8
				0.0963	103

Table 3/

Table 3

Airspeed and Pitch Changes for 6 Runs with Similar Times to Reach 50 ft

Delay time t_D seconds	$C_M \div \frac{du}{dt}$	Mean period T seconds	Time to reach 50 ft in (T_{50}) seconds	Amp of μ at T_{50} in knots	Amp of θ at T_{50} in degrees	Amp of C_M at T_{50}
0	0.00628	33.2	97.8	4.87	2.24	0.0117
1.67	0.00932	36.0	101.8	3.90	2.13	0.0146
3.3	0.01314	37.4	91.3	2.96	1.93	0.0153
5.0	0.01807	40.0	96.2	2.26	1.86	0.0168
6.7	0.01926	44.9	94.7	1.87	1.63	0.0170
10.0	0.0438	51.4	96.7	0.97	1.53	0.0175

Table 4

Pilot Controlled Elevators: Variation of r.m.s. Speed Error with Delay Time

No.	Delay time t_D seconds	r.m.s. speed error u knots	Score S_T (see text)	Remarks
1	0	1.67		
2	0	1.11		
3	0	0.68	30	Fig. 30(a)
4	1.67	0.97	52	Fig. 30(b)
5	1.67	0.79		
6	3.3	0.78	42	
7	3.3	1.42	78	Fig. 30(c)
8	0	0.60		Check on learning
9	5.0	1.64	78	
10	5.0	1.41	70	Fig. 30(d)
11	6.7	0.98	46	Fig. 30(e)
12	6.7	0.76	36	

Table 5/

Table 5

Comparison of Spring and Friction Loaded Throttles in Varying Wind Conditions
(Gusts 1.96 knots up to 2.64 knots down)

W/V	r.m.s. airspeed error (knots)		r.m.s. height error (ft)		Mean of $\left\lvert \frac{T_s - T_o}{T_{max}} \right\rvert \times 100\%$	
	Friction	Spring	Friction	Spring	Friction	Spring
-10.7	2.39	1.55	30.6	19.3	8.55	7.4
-10.7	1.82	1.48	19.2	19.7	9.75	7.55
0	1.77	1.49	22.5	22.8	12.2	7.6
0	1.62		20.0		10.2	
+10.3	1.64	1.20	29.9	21.3	8.8	4.0
+10.3		1.30		23.8		4.9
+20.3	1.72	1.26	29.1	27.0	9.4	7.4
+29.8	2.51	1.30	33.7	17.7	12.2	6.15
Mean	1.92	1.37	26.4	21.7	10.2	6.42
	Series II - Different pilot					
0	5.26	2.80	27.3	18.6		2.7
0	5.01	2.26	30.4	25.7	12.9	6.8
0.5	3.55	3.01	25.8	26.4	8.6	3.5
10.3	Very large	3.64	Very large	28.8	13.6	4.7
18.5	3.47	2.69	35.0	18.1	8.5	
18.5	3.91	3.19	26.5	26.3	11.2	5.1
29.8	4.26	2.23	36.5	38.6	11.6	5.8
Mean	4.24	2.83	30.3	26.1	11.1	4.76

Table 6/

Table 6

Comparison of Spring and Friction Loading
(15.5 knot wind with gusts 0.98 knots up to 1.32 knots down)
Pilot as in Series II

	r.m.s. airspeed error (knots)		r.m.s. height error (ft)		Mean of $\left\| \frac{T_s - T_o}{T_{max}} \right\| \times 100\%$	
	Friction	Spring	Friction	Spring	Friction	Spring
	3.67	1.43	21.6	13.7	9.7	4.1
	2.63	2.05	17.4	9.5	6.5	5.1
	3.22	2.03	16.2	14.8	7.8	6.4
	4.33	2.06	24.0	11.4	9.2	4.4
	4.75	1.82	27.8	17.5	9.1	6.3
	4.92	1.98	26.9	16.7	12.8	4.5
	3.17	1.18	12.0	17.5	8.9	4.1
Mean	3.81	1.79	20.8	14.4	9.14	4.98
Standard deviation	0.81	0.32	5.4	2.9	1.79	0.92

Table 7/

Table 7

Spring Throttle Compared with Friction Throttle
Direction Control and Pitch Control : I.L.S. Instrumentation:- Original Pilot

	r.m.s. airspeed error (knots)		r.m.s. height error		Mean heading error degrees	
	Friction	Spring	Friction	Spring	Friction	Spring
	3.22		30.9		1.79	
	3.07	1.38	26.3	19.6	1.84	1.37
	2.52	1.19	27.7	15.0	1.86	1.43
	2.72	1.08	26.9	18.0	1.63	1.50
	3.13	1.39	32.2	25.9	1.57	1.62
	2.82	1.52	27.8	25.1	1.51	1.33
	2.91	1.81	36.2	27.4	1.65	1.46
Mean	2.91	1.39	29.7	21.8	1.69	1.45
Standard deviation	0.23	0.23	3.3	4.6	0.13	0.09

APPENDIX I/

APPENDIX I

Derivatives of Aircraft Simulated in the Investigation

(a) Wellington

Speed $V = 115$ kt

Wing area $S = 840$ sq ft

Aspect ratio $A = 8.83$

Mean chord $c = 9.75$ ft

Wing lift curve slope $\dfrac{dC_L}{d\alpha} = 4.43$

Stick-fixed static margin $h_n = 0.04$

Zero lift drag coefficient $C_{D_0} = 0.027$

Moment of inertia in pitch $B = 97{,}200$ slugs ft^2

Induced drag factor $k = 1.39$

Tailplane area $s = 148$ sq ft

Tail moment arm $\ell = 31$ ft

Rate of change of downwash with incidence $\dfrac{d\varepsilon}{d\alpha} = 0.385$

Tailplane lift curve slope $\dfrac{\partial C_L'}{\partial \alpha'} = 3.2$

Rate of change of tailplane lift with elevator angle $\dfrac{\partial C_L'}{\partial \eta} = 2.11$

Non-dimensional equations:

u = change in forward speed in ft/sec
v = change in rate of descent in ft/sec
θ = change in angle of pitch in radians
ΔT = change in thrust in lb
$\Delta\eta$ = change in elevator angle in degrees

$\dfrac{du}{dt}$ /

$$\frac{du}{dt} = -\ 0.0365u - 0.0935v - 13.96\theta + \frac{\Delta T}{768}$$

$$\frac{dv}{dt} = +\ 0.331u - 1.083v + 211\theta + 9.53\,\frac{d\theta}{dt}$$

$$\frac{d^2\theta}{dt^2} = +\ 0.000674u + 0.00109v - 0.213\theta - 1.488\,\frac{d\theta}{dt} + \frac{\Delta\eta}{12.7}.$$

(b) Vulcan

Approach speed $V = 125$ kt

Wing area $S = 3446$ sq ft

Aspect ratio $A = 2.86$

Mean chord $\bar{c} = 34.81$ ft

Wing lift curve slope $\frac{\partial C_L}{\partial \alpha} = 3.0$

Stick-fixed static margin $h_n = 0.042$

Zero lift drag coefficient $C_{D_0} = 0.051$

Moment of inertia in pitch $B = 1.0597 \times 10^6$ slugs ft^2

Induced drag factor $k = 1.105$

Rate of change of thrust with speed $\frac{dT}{dv} = 5$ lb/kt

Maximum thrust $T_{max} = 42{,}000$ lb

Maximum pitching moment: Nose down $C_M = -\ 0.033$

Nose up $C_M = +\ 0.063$.

Thrust decays exponentially with time constant 5 seconds when throttle is closed.

Rate of climb. There is a lag of 3 seconds in the rate of climb indicator for a change in rate of descent of 100 ft/min.

Non-dimensional/

Non-dimensional equations:

u = change in forward speed in ft/sec
θ = change in pitch angle in radians
v = change in rate of descent in ft/sec
ΔT = change in thrust in lb
$\Delta\eta$ = change in elevator angle in degrees

$$\frac{du}{dt} = -\,0.0471u - 0.0399v - 23.8\theta + \frac{\Delta T}{3420}$$

$$\frac{dv}{dt} = +\,0.306u - 0.783v + 165.2\theta + 17.63\,\frac{d\theta}{dt}$$

$$\frac{d^2\theta}{dt^2} = +\,0.003585v - 0.755\theta - 0.893\,\frac{d\theta}{dt} + \frac{\Delta\eta}{50.4}.$$

<u>APPENDIX II/</u>

APPENDIX II

Specification of Computer Elements

Power supply:-	Two 300 volt D.C. stabilised power units	
	Maximum output current 500 mA	
	Stabilised ± 0.02%	
Amplifiers:-	Open loop D.C. gain	10^5
	Phase shift up to 100 c/s at unity gain	0.05°
	Drift correction factor	1000
	Long-term drift at unity gain - better than	25 μV
	Drift over 24 hrs at unity gain - better than	10 μV
	Input current	10^{-11} amps
	Maximum input capacitance for stability	2000 pF
	Maximum output capacitance for stability	10,000 pF
	Output at 10 mA	± 100 V
	Noise input	200 μV
Resistance elements:-	± 1% carbon	
Capacitance elements:-	± 1% silvered MiCA	
Instruments:-	± 50μA full-scale microammeters - ex aircraft instruments recalibrated	
	Two-channel pen recorder	
	Evershed and Vignoles Type QU/CRD 5	
	Oscilloscope. Solartron Type AD 557.	

D 31096/1/Wt.60 K4 11/64 XL & CL

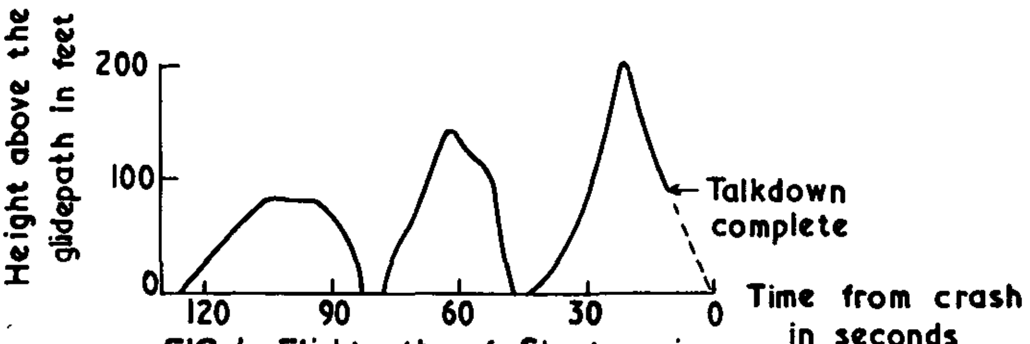


FIG. 1. Flightpath of Stratocruiser.

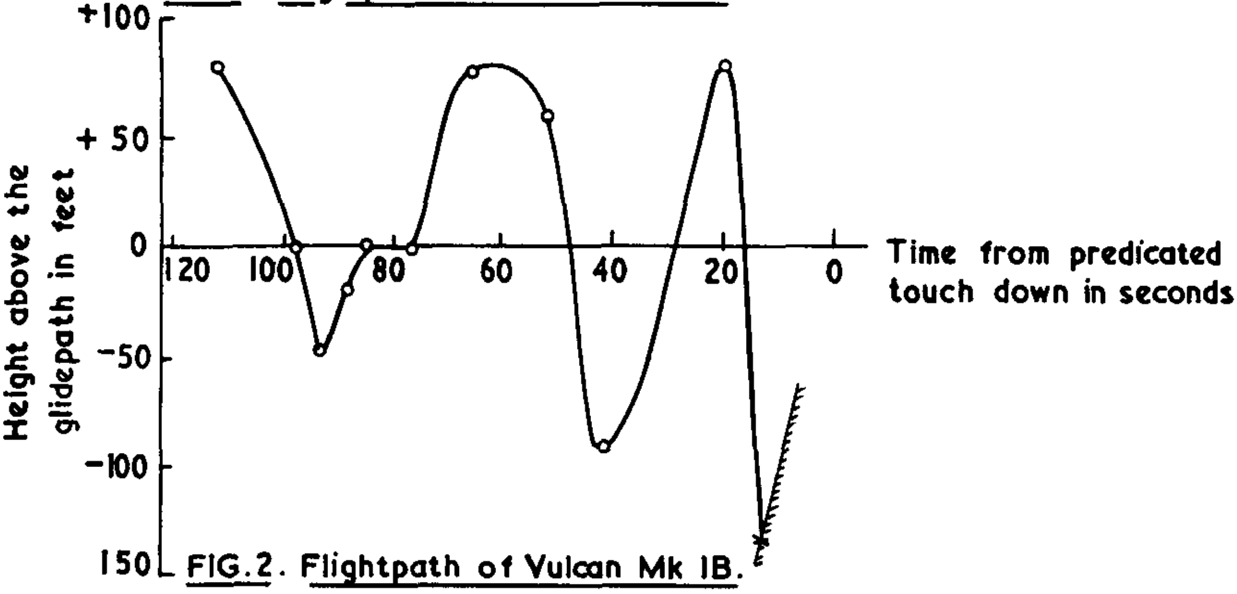


FIG. 2. Flightpath of Vulcan Mk IB.

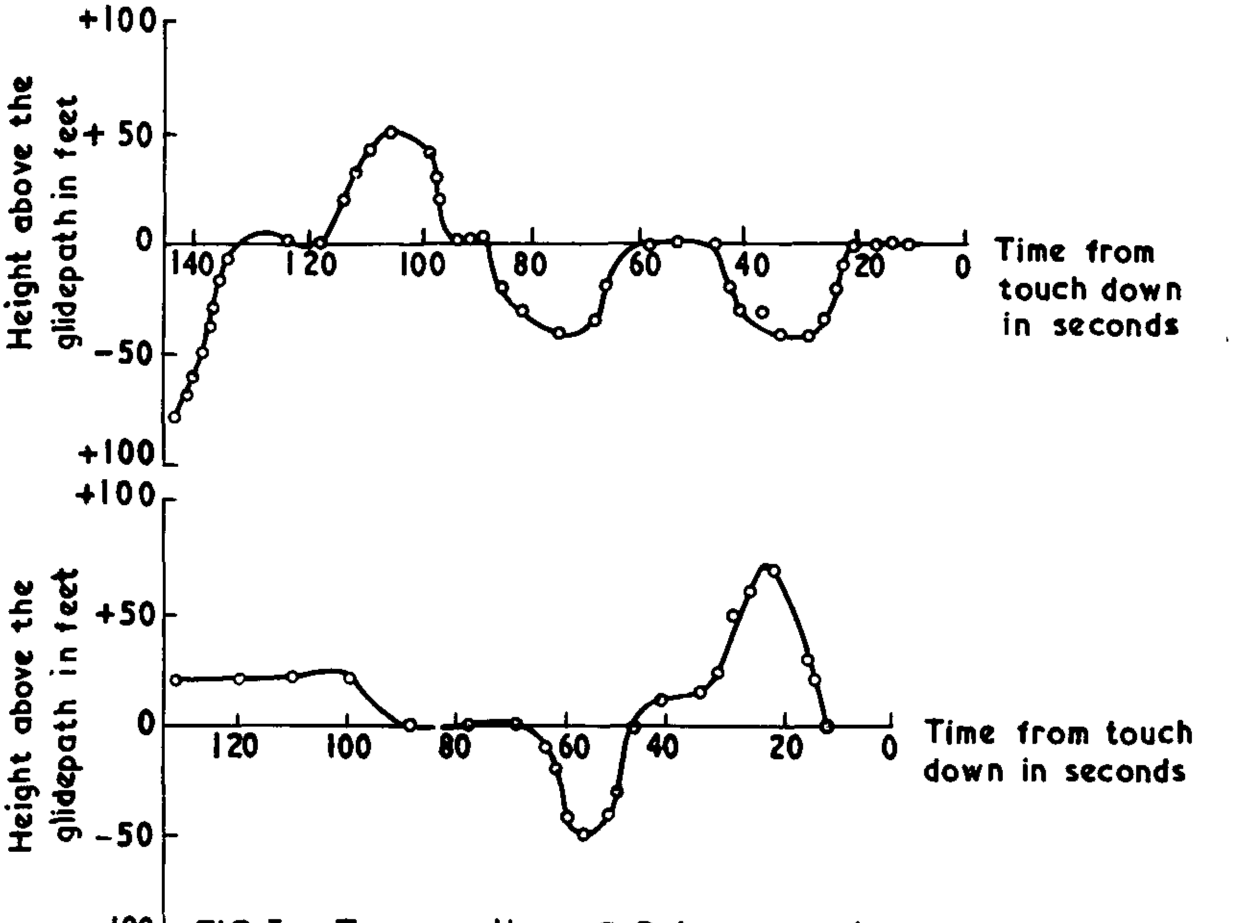
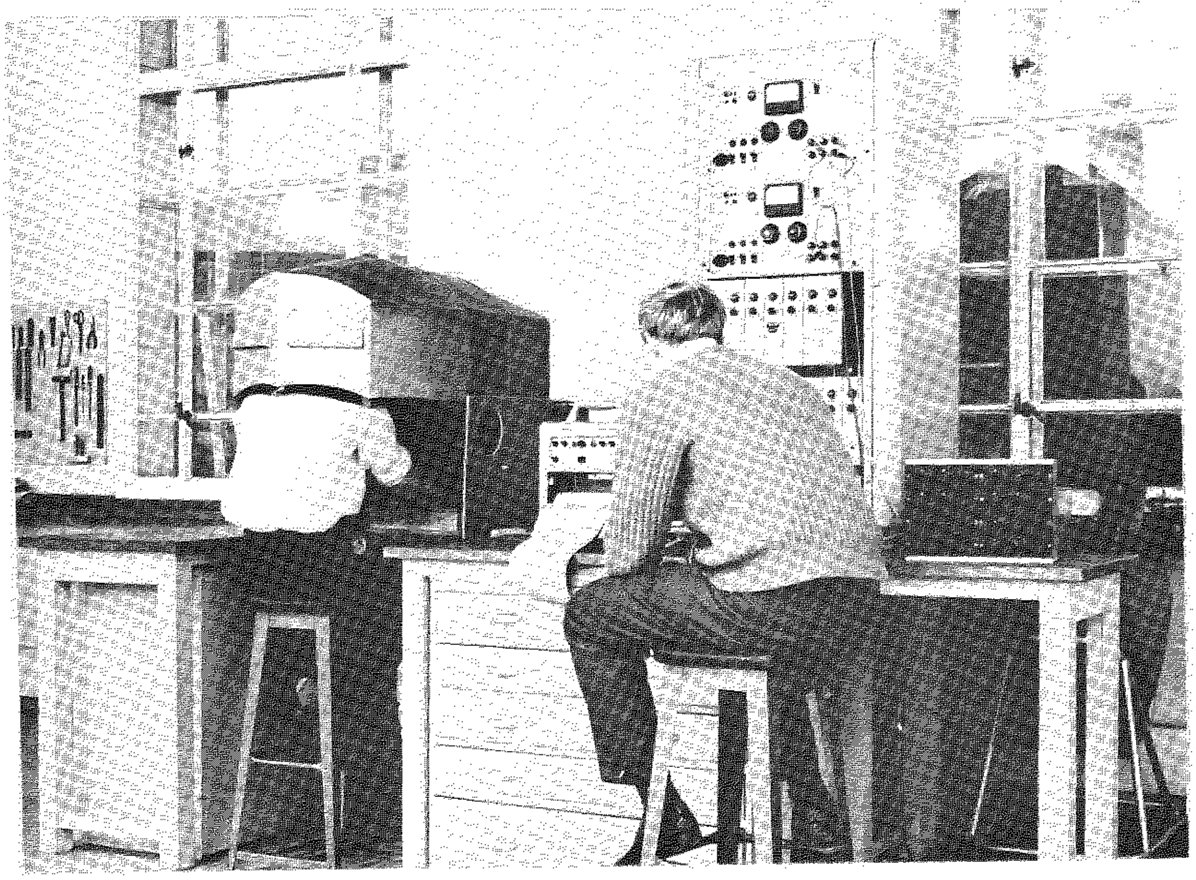


FIG. 3. Two routine G.C.A. approaches.

FIG.4



General view of simulator showing pilot and controller

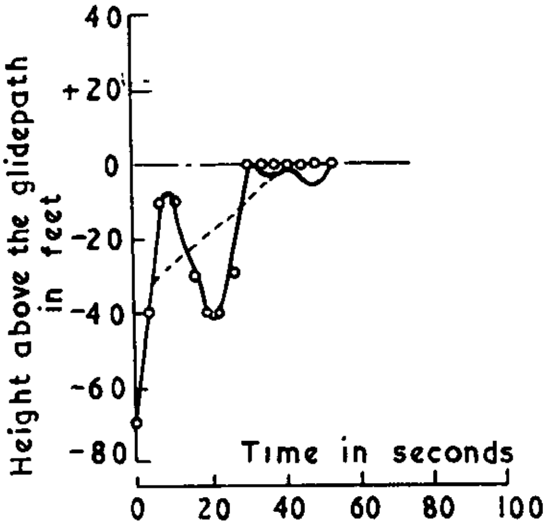


FIG.5 Simulated approach with Wellington. Time interval = $\frac{T}{12}$ = 3·8 seconds

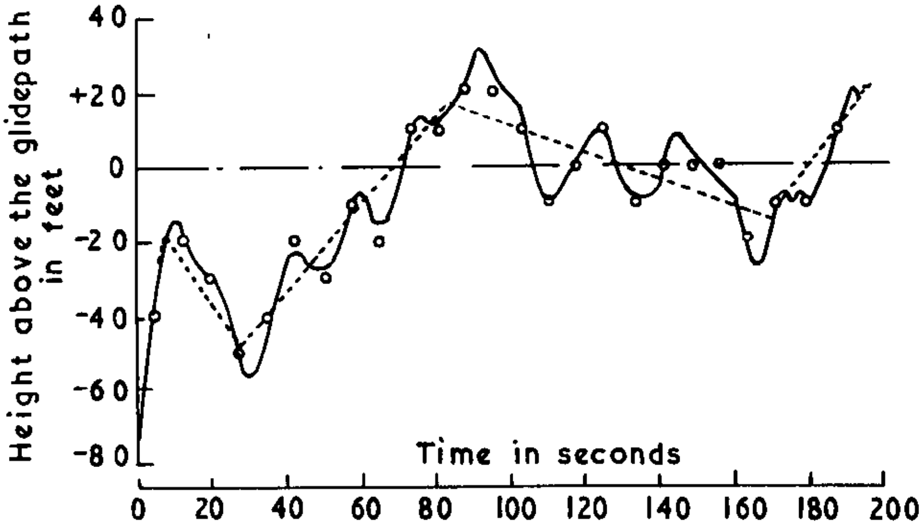


FIG. 6 Simulated approach with Wellington. Time interval = $\frac{T}{6}$ = 7·6 seconds

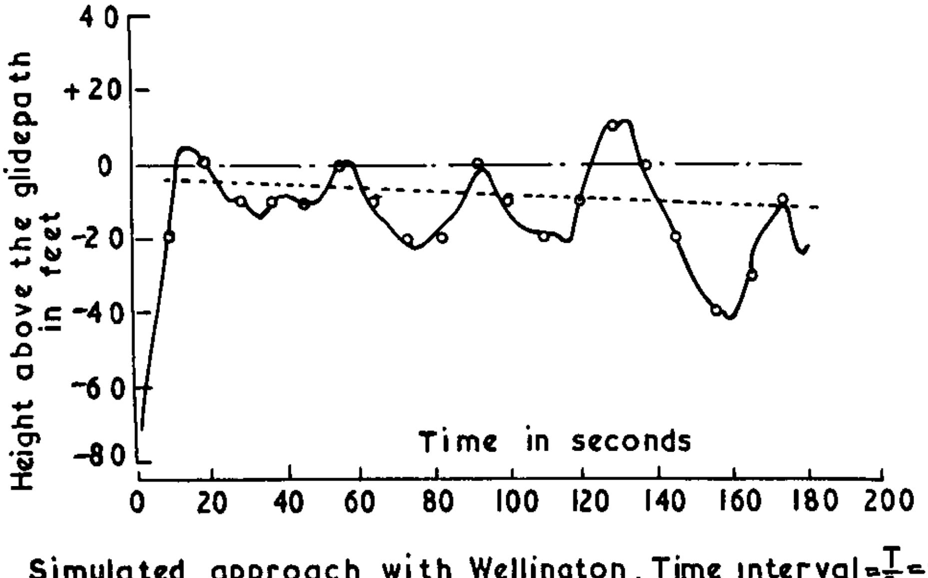


FIG. 7 Simulated approach with Wellington. Time interval = $\frac{T}{5}$ = 9·2 seconds

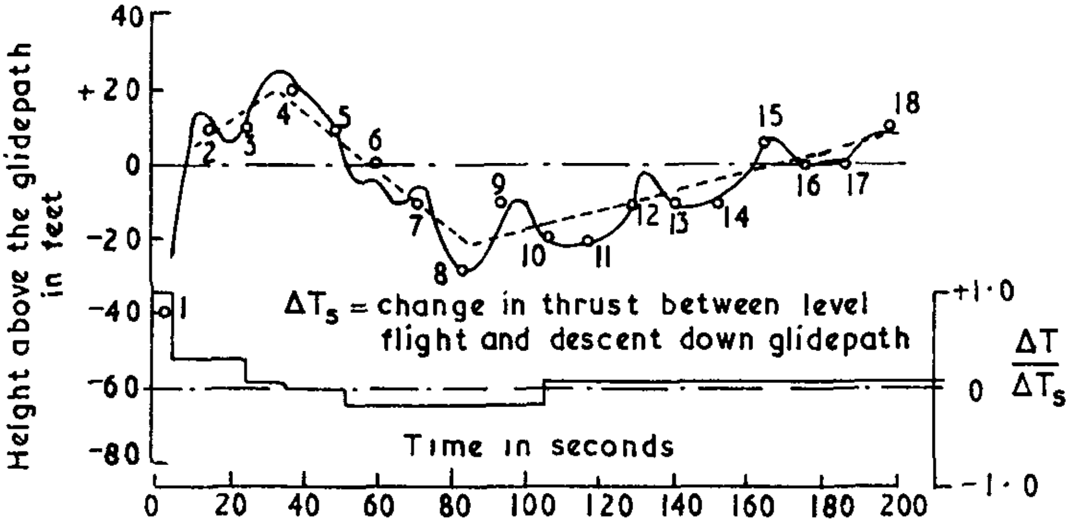


FIG. 8 Simulated approach with Wellington. Time interval $= \frac{T}{4} = 11{\cdot}5$ seconds

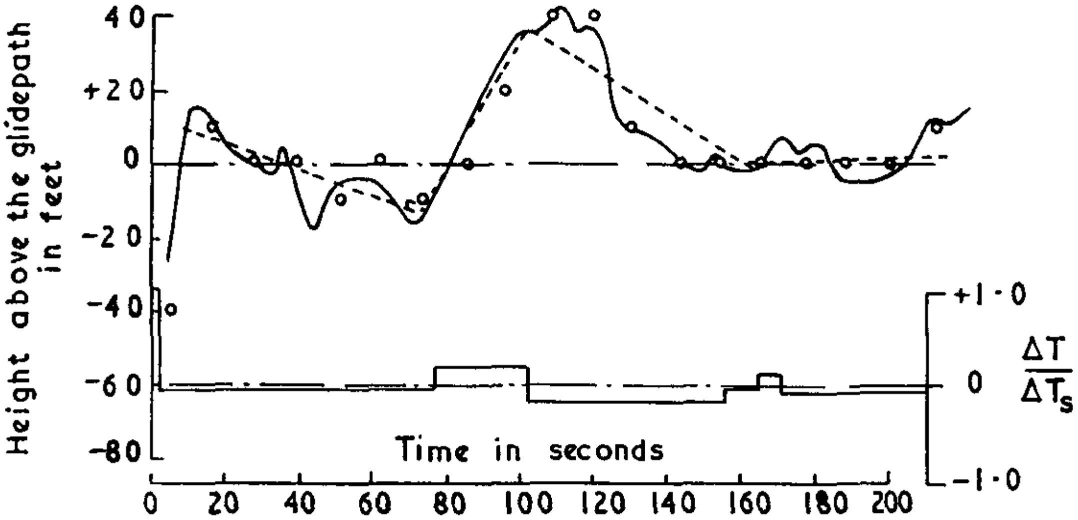


FIG. 9 Simulated approach with Wellington. Time interval $= \frac{T}{4} = 11{\cdot}5$ seconds Information 3·3 seconds late

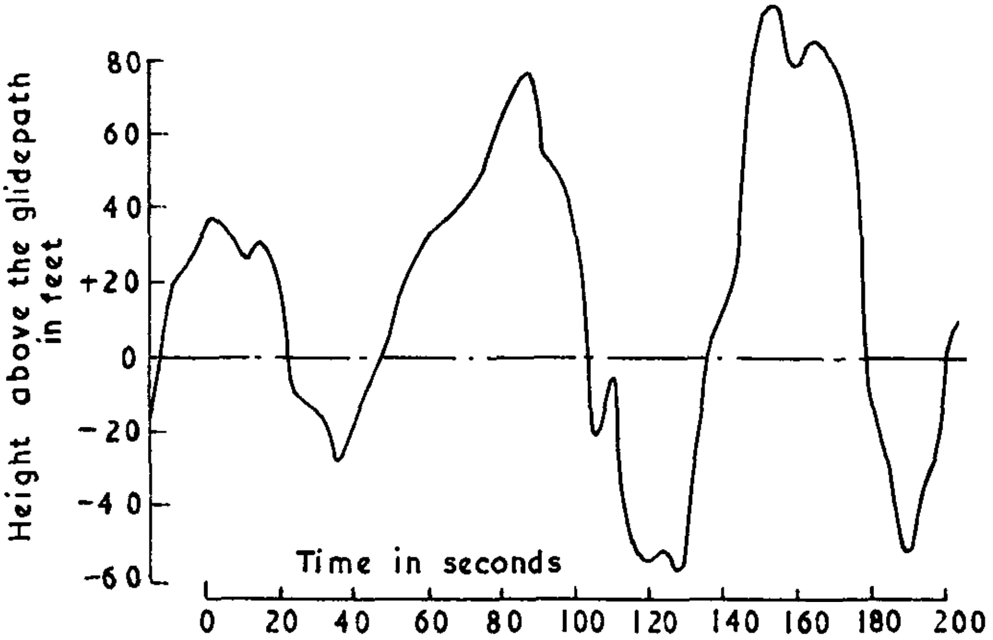


FIG. 10 First simulated approach with Vulcan. Time interval = 10 seconds; delay = 5 seconds

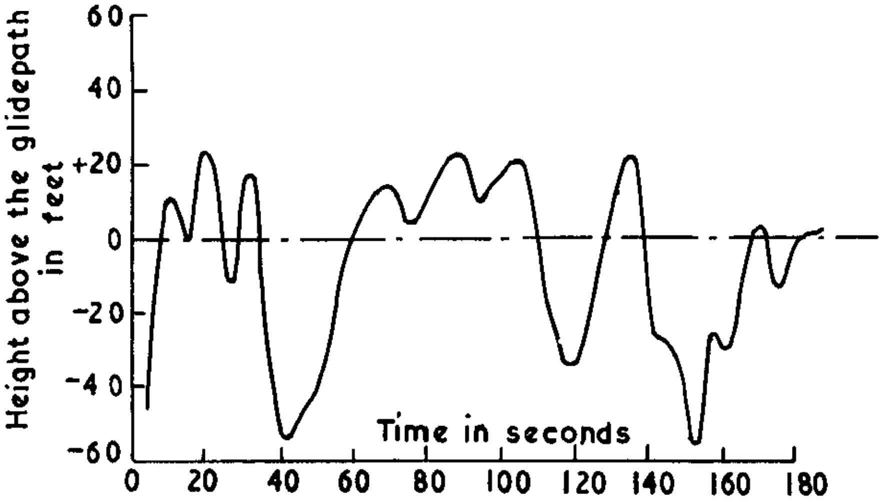


FIG. 11 Simulated flight with Vulcan after long experience. Time interval = 10 seconds; delay = 5 seconds

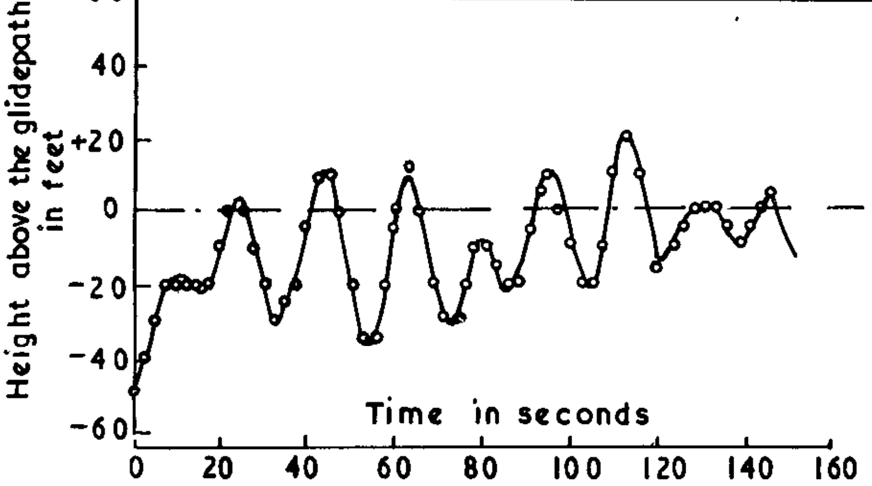


FIG. 12(a) Vulcan with fixed throttle. Time interval = 2·5 seconds

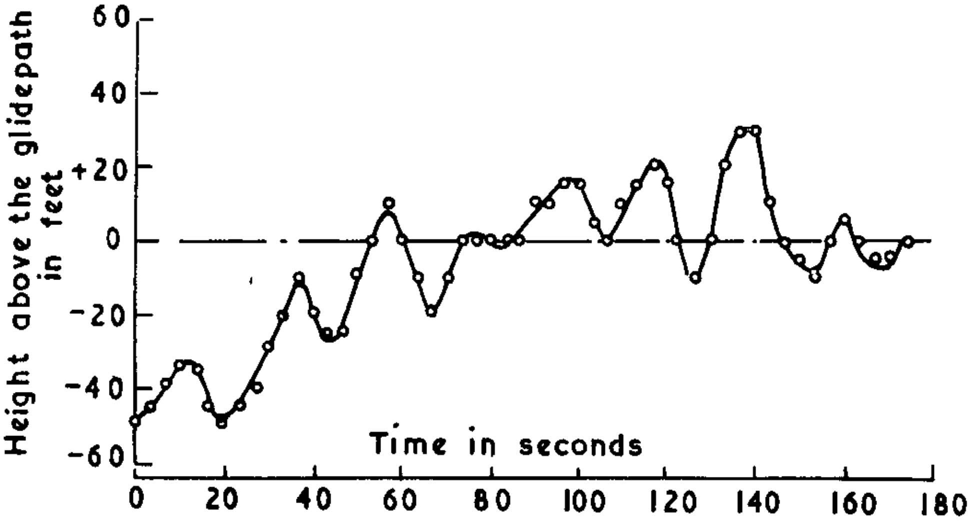


FIG. 12(b) Vulcan with fixed throttle. Time interval = 3·3 seconds

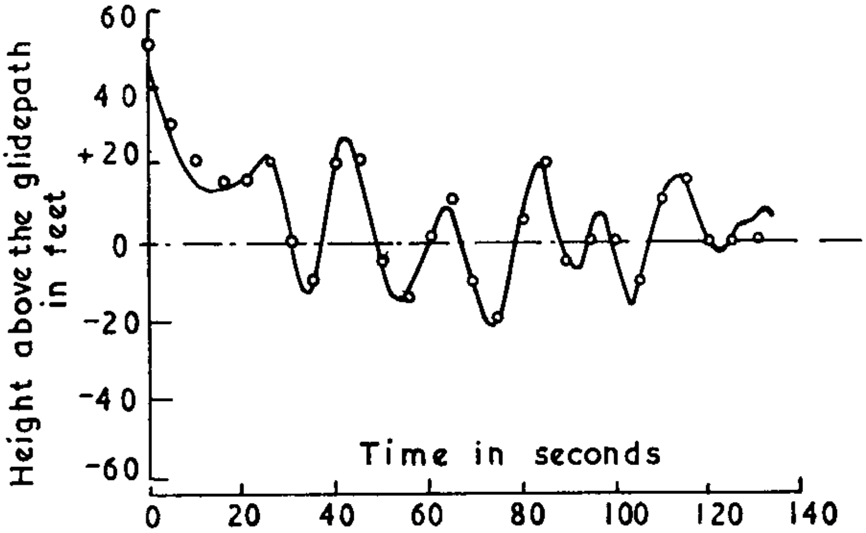


FIG 12(c) Vulcan with fixed throttle. Time interval = 5·0 seconds

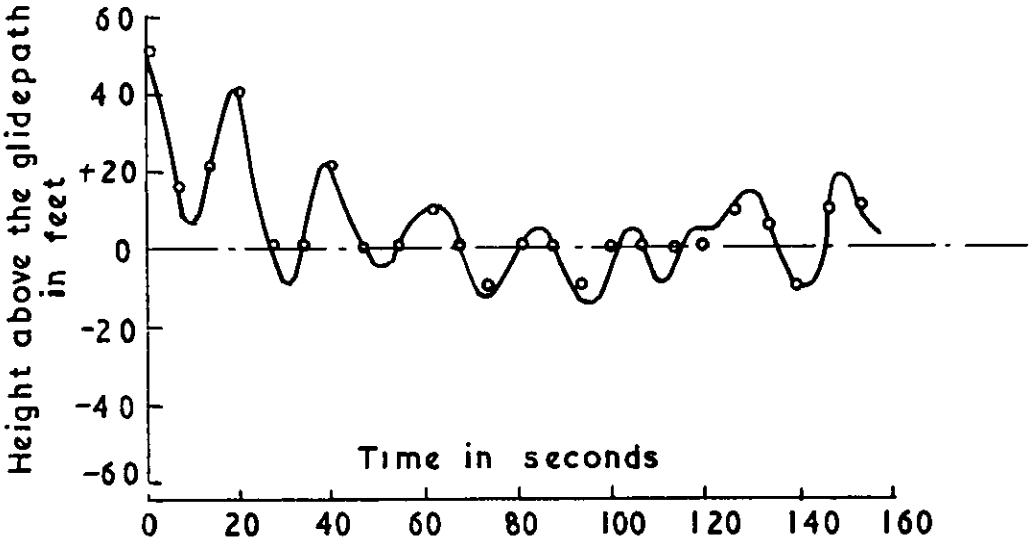


FIG. 12(d) Vulcan with fixed throttle. Time interval = 6·7 seconds

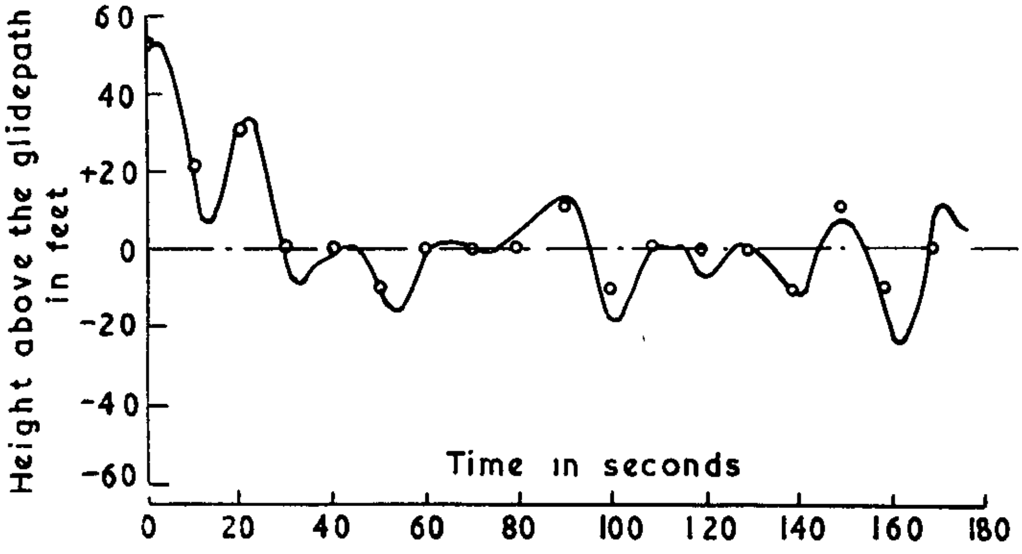


FIG. 12(e) Vulcan with fixed throttle. Time interval = 10·0 seconds

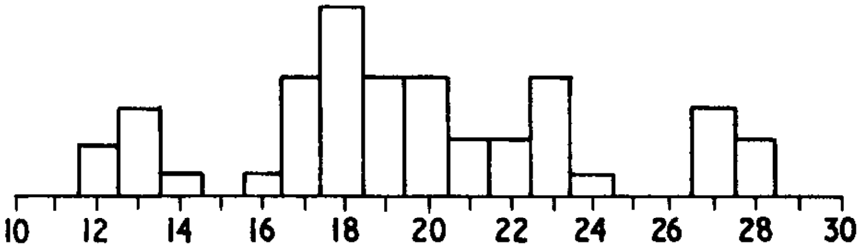


FIG. 13 Distribution of periods in motion of Vulcan with fixed throttle

(d) Time interval = 5·0 seconds

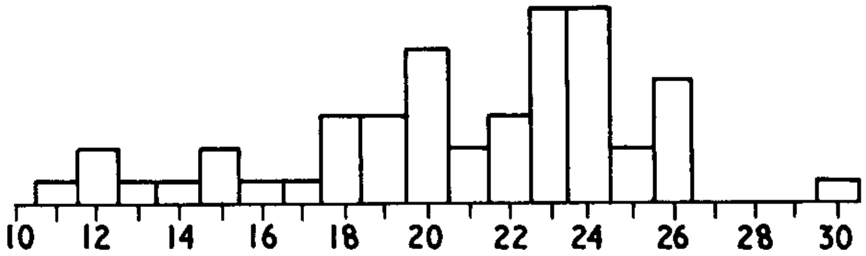


FIG. 13 Distribution of periods in motion of Vulcan with fixed throttle

(e) Time interval = 6·7 seconds

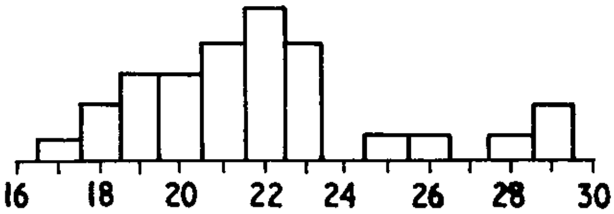


FIG. 13 Distribution of periods in motion of Vulcan with fixed throttle

(f) Time interval = 10 seconds

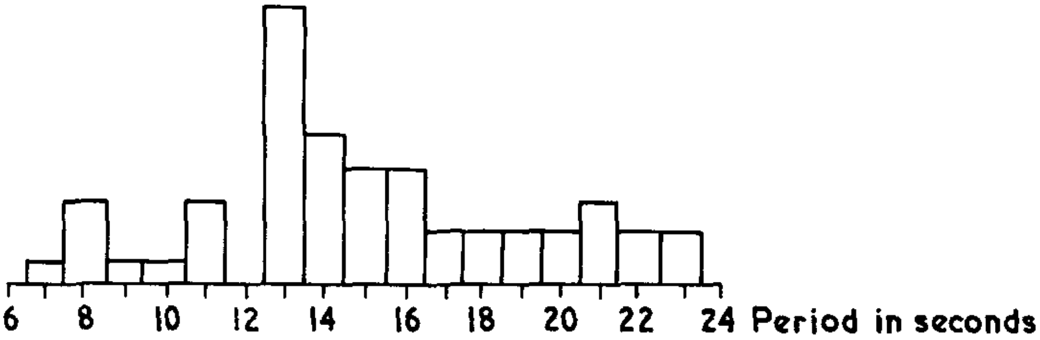


FIG. 13 Distribution of periods in motion of Vulcan with fixed throttle

(a) Time interval = 1·7 seconds

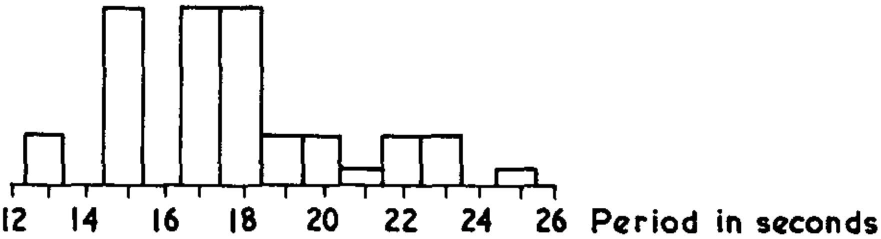


FIG. 13 Distribution of periods in motion of Vulcan with fixed throttle

(b) Time interval 2·5 seconds

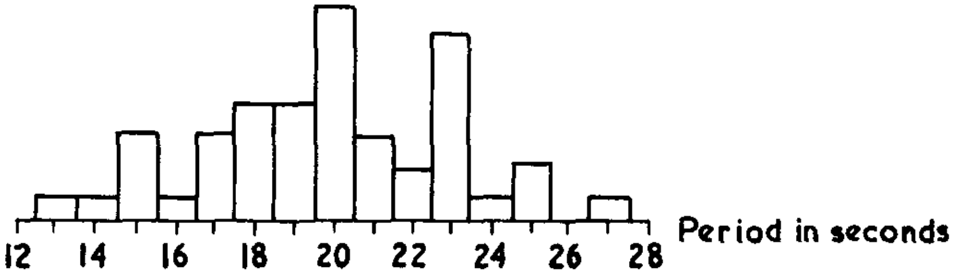


FIG. 13 Distribution of periods in motion of Vulcan with fixed throttle

(c) Time interval 3·3 seconds

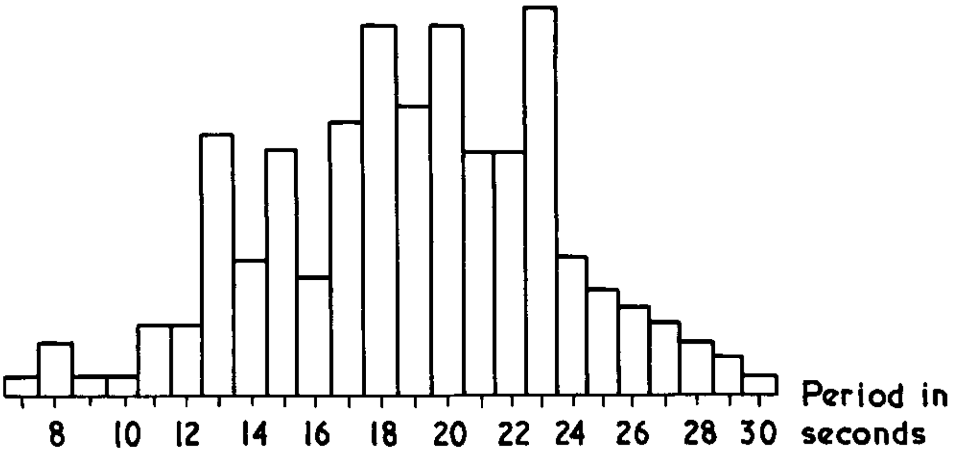


FIG. 14 Vulcan with fixed throttle – Distribution of periods in motion for all "flights" recorded

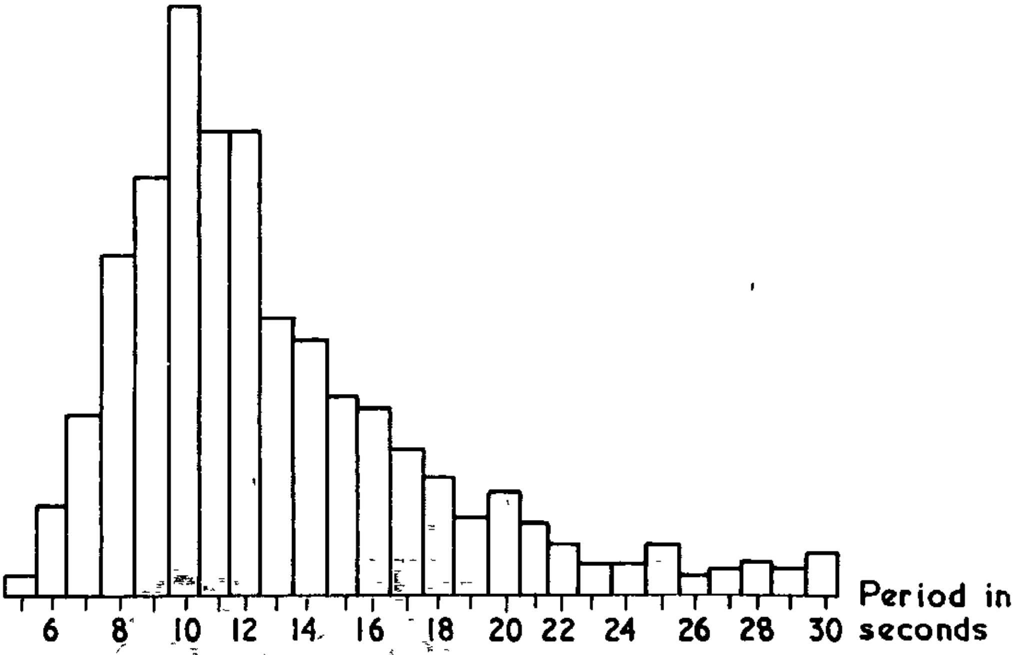


FIG. 15 Vulcan with moveable throttle – Distribution of periods in motion for all "flights" recorded – (Different pilot from Fig. 14)

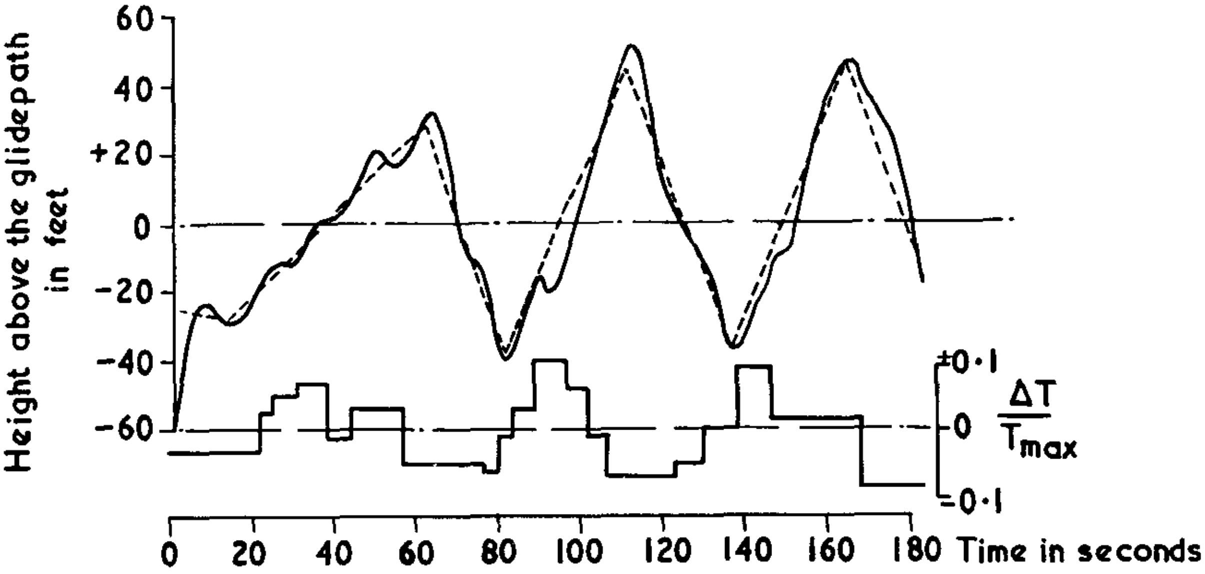


FIG. 16 Simulated Vulcan flight Time interval = 10 seconds

Time delay = 5 seconds

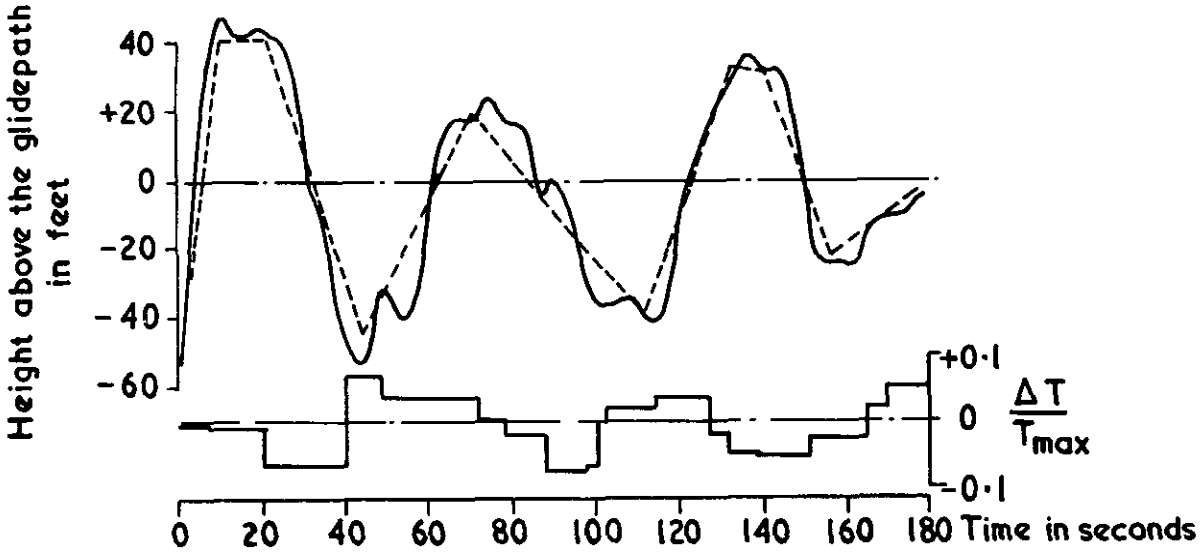


FIG. 17 Simulated Vulcan flight Time interval = 10 seconds

Time delay = 5 seconds

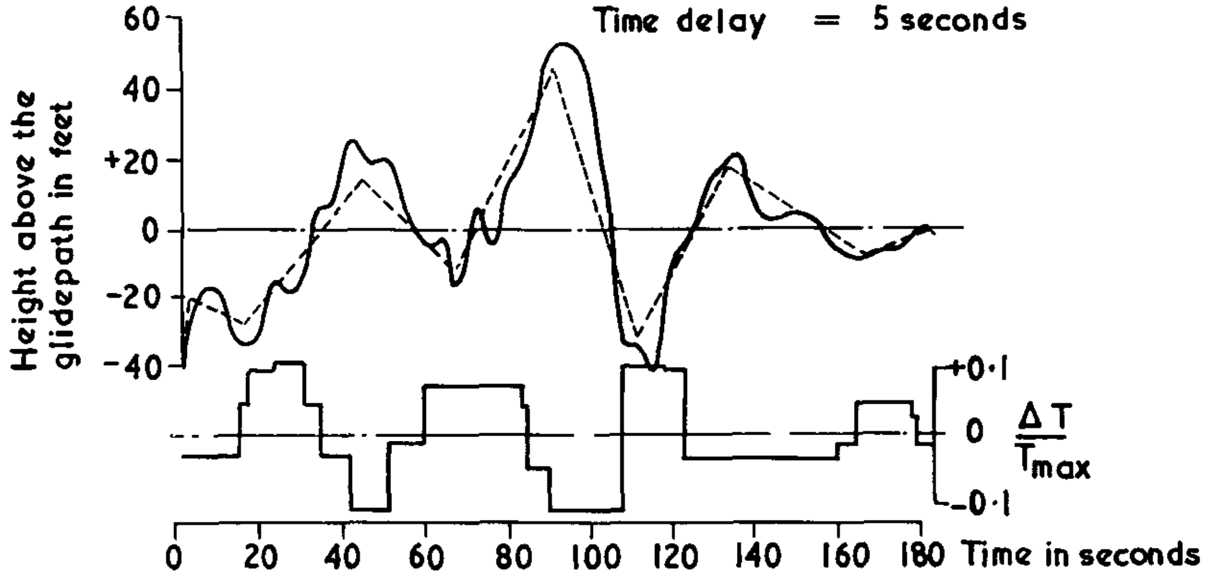


FIG. 18 Simulated Vulcan flight Time interval = 5·0 seconds

Time delay = 2·5 seconds

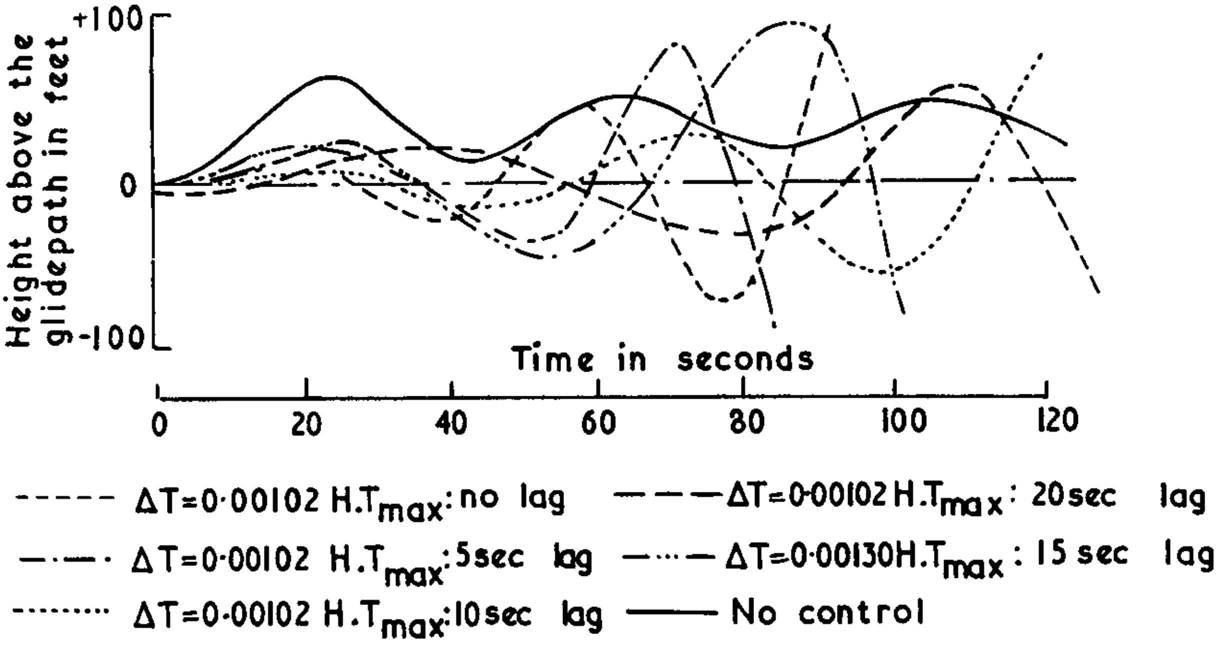


FIG.19 Continuous throttle movements: ΔT opposes H.

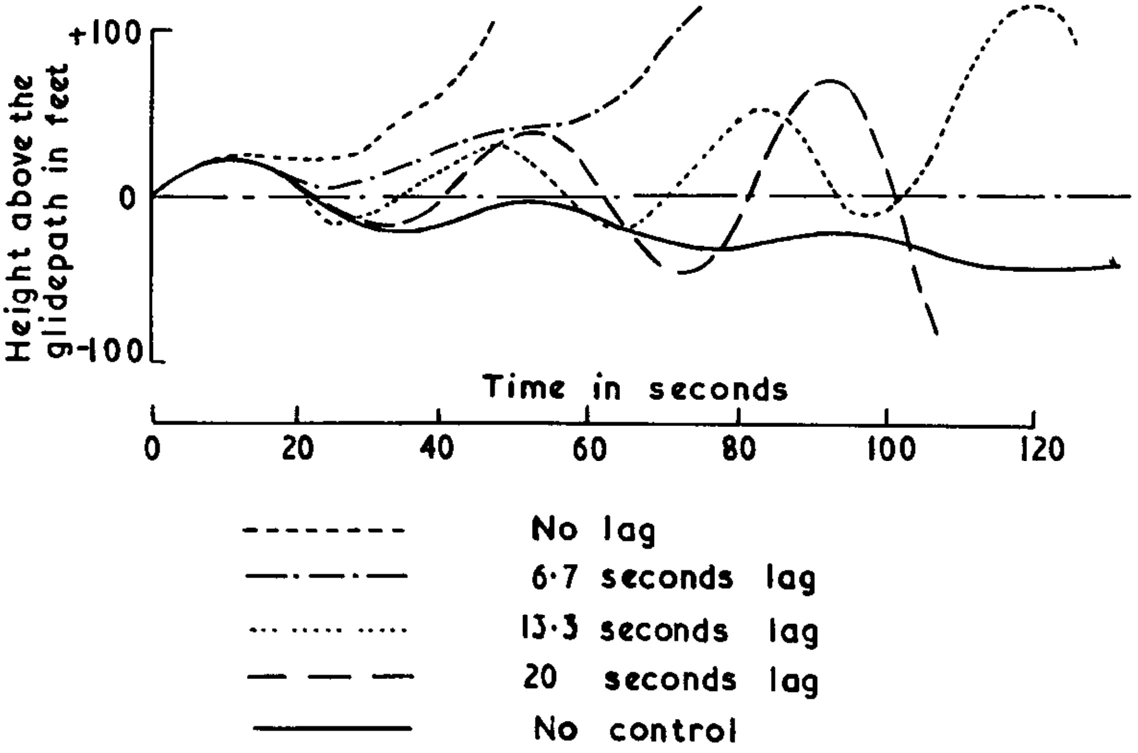


FIG.20 Continuous throttle movements : ΔT in phase with H
ΔT = 0·00102 H.T_{max}

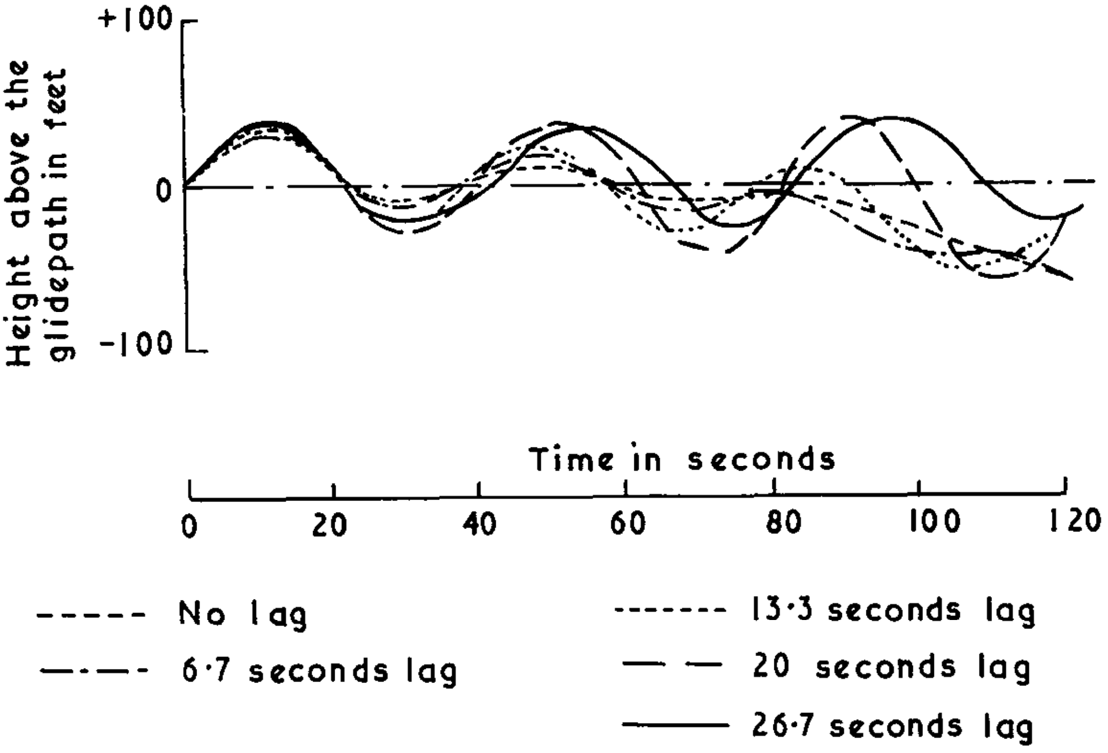


FIG. 21 Continuous throttle movements ΔT in phase with H
$\Delta T = 0{\cdot}000411\ H.T_{max}$

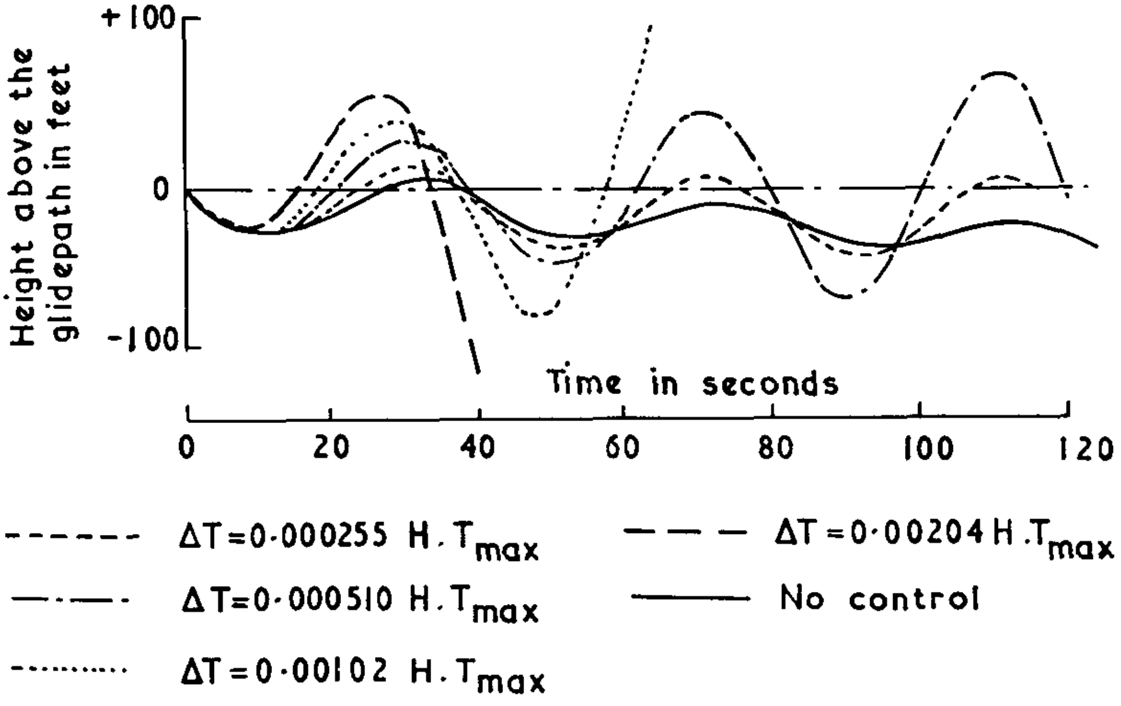


FIG. 22 Continuous throttle movements : ΔT opposing H : No lag

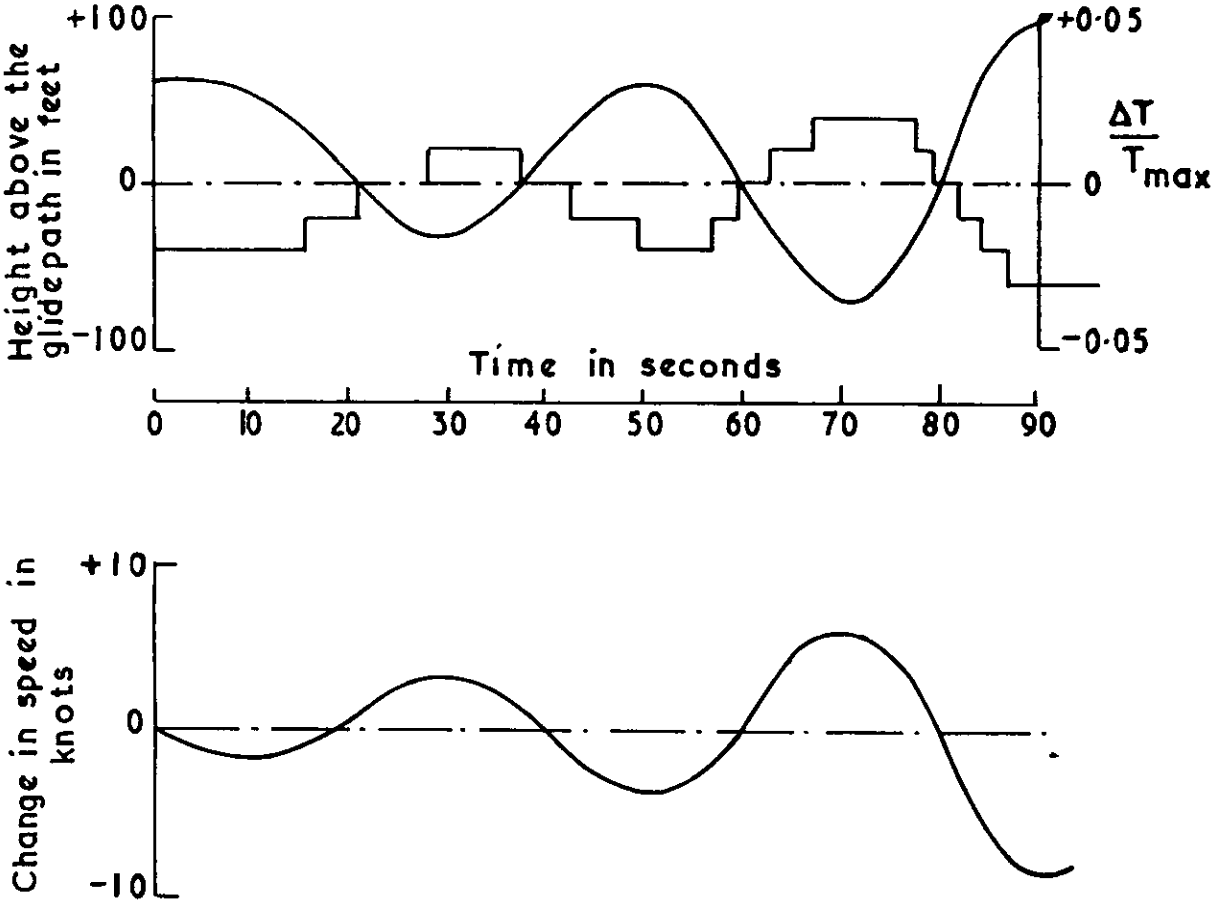


FIG. 23 Step throttle movements: $\Delta T_s = 0\cdot 01\ T_{max}$ per 20 ft

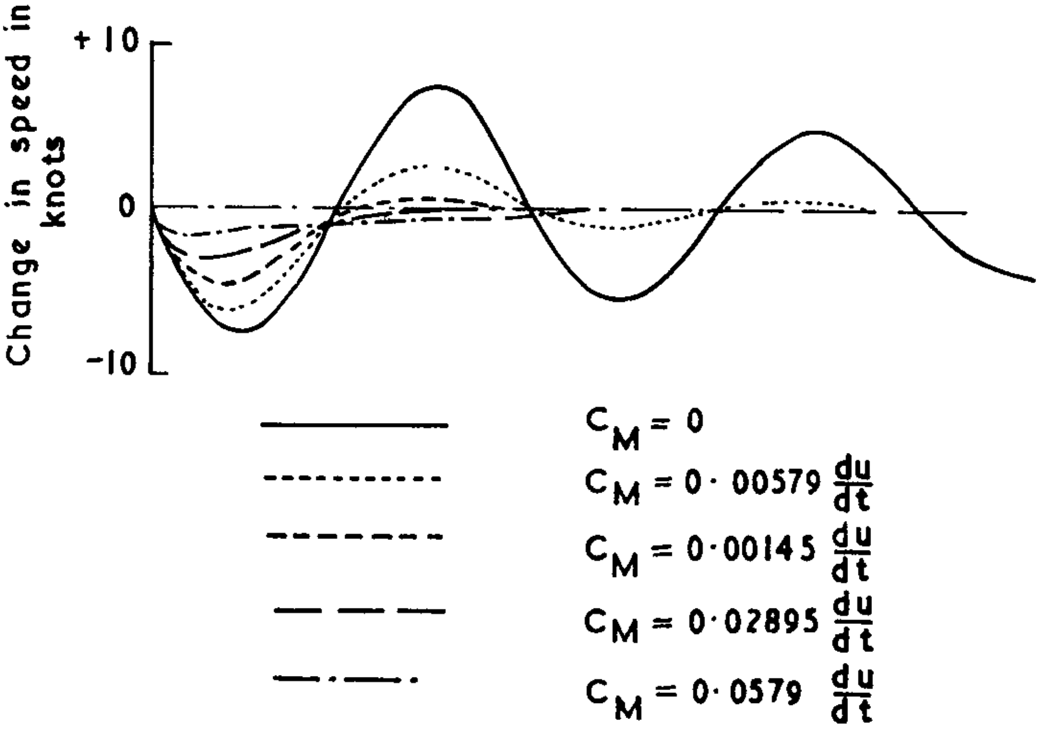


FIG. 24 Response to step throttle movement: $\Delta T = 0\cdot 02\ T_{max}$ for different autopilot gearing

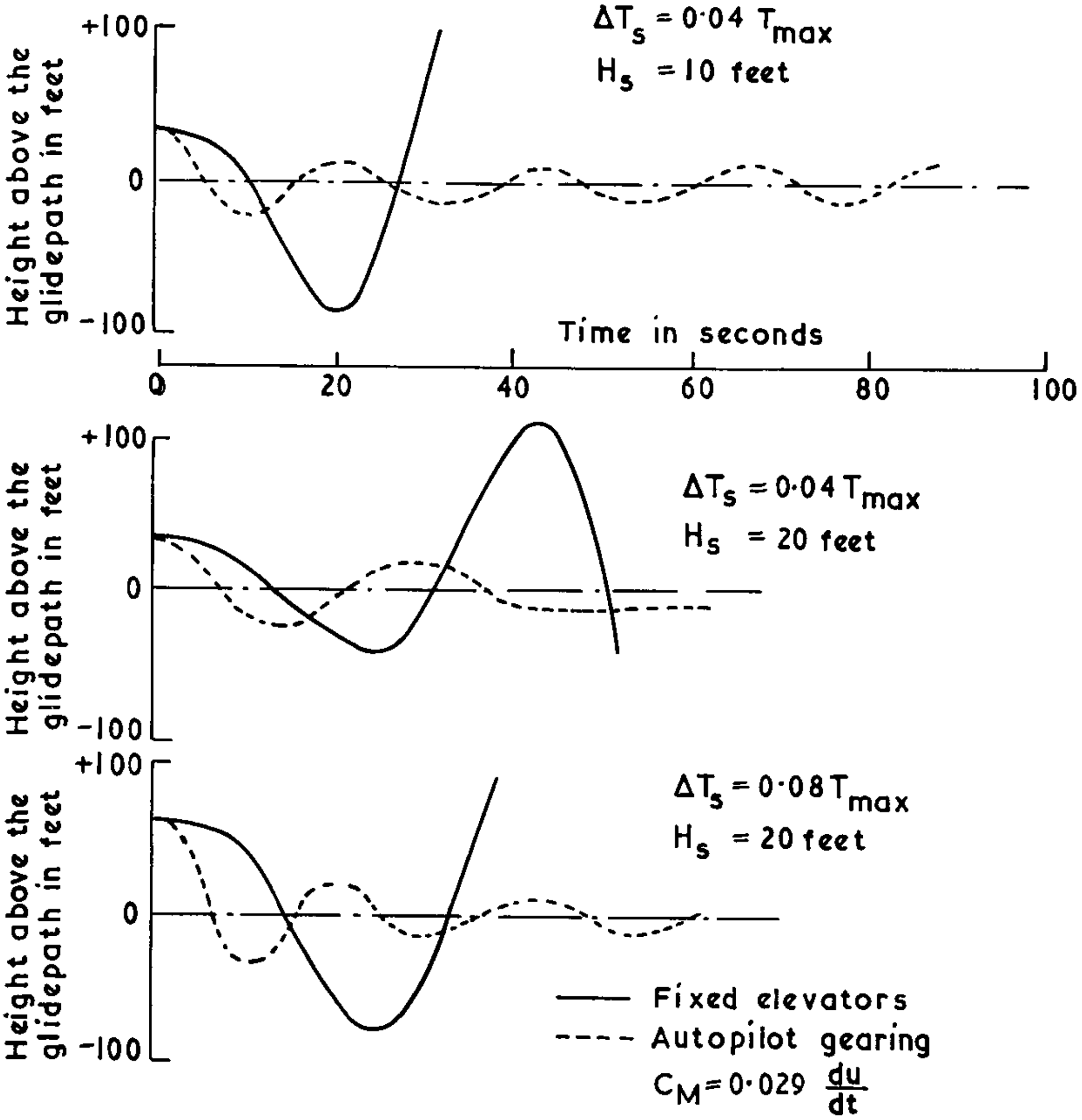


FIG. 25 Effect of an autopilot on several flight paths:-Step throttle movements

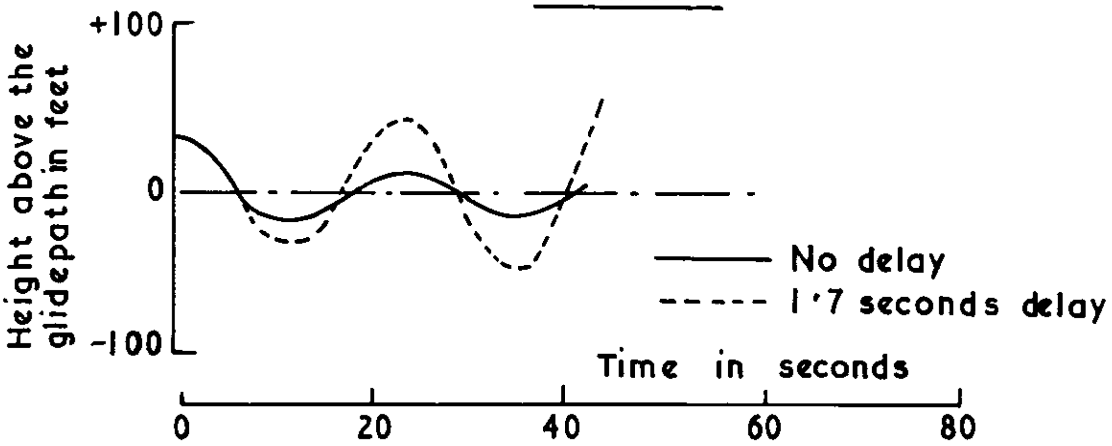


FIG. 26 Effect of delay in passing information .(Step throttle with autopilot)

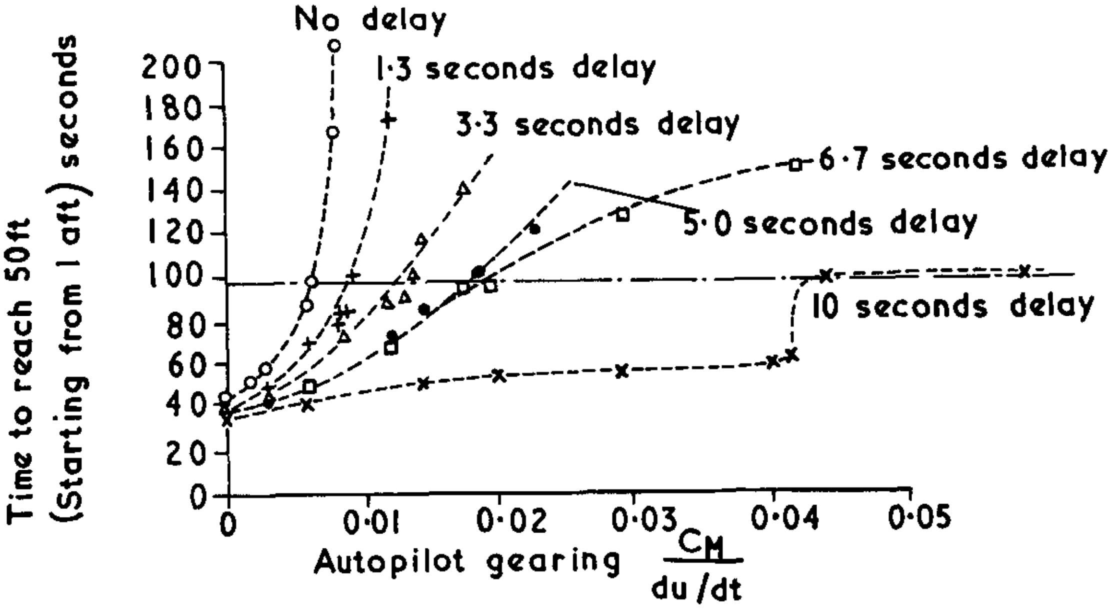


FIG. 27 Effect of delay and autopilot gearing

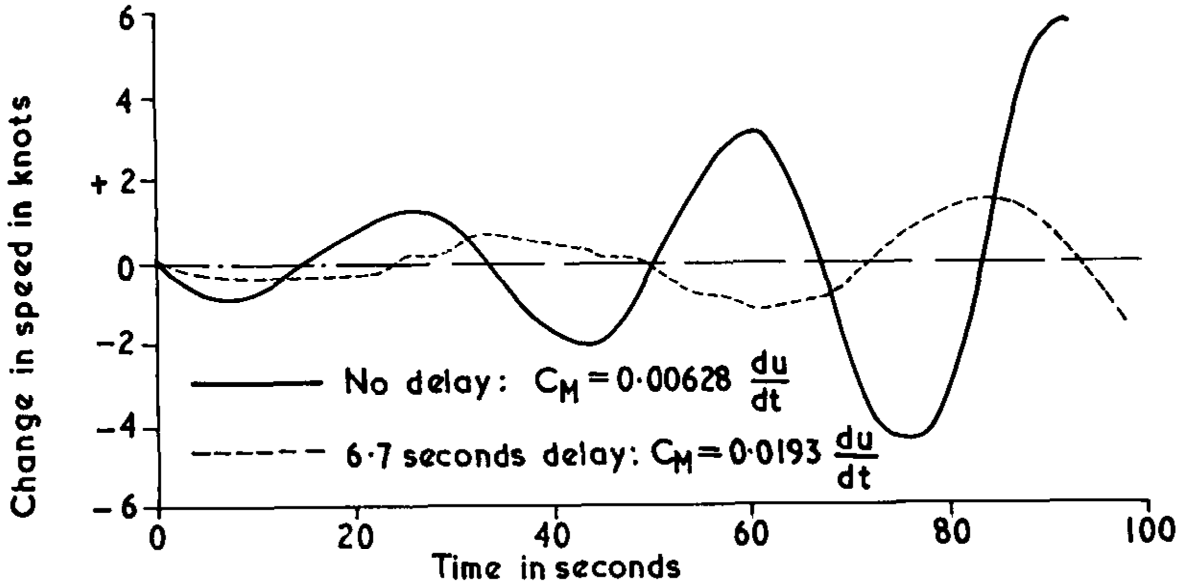


FIG. 28 Comparison of speed changes in two tests with same time to 50ft

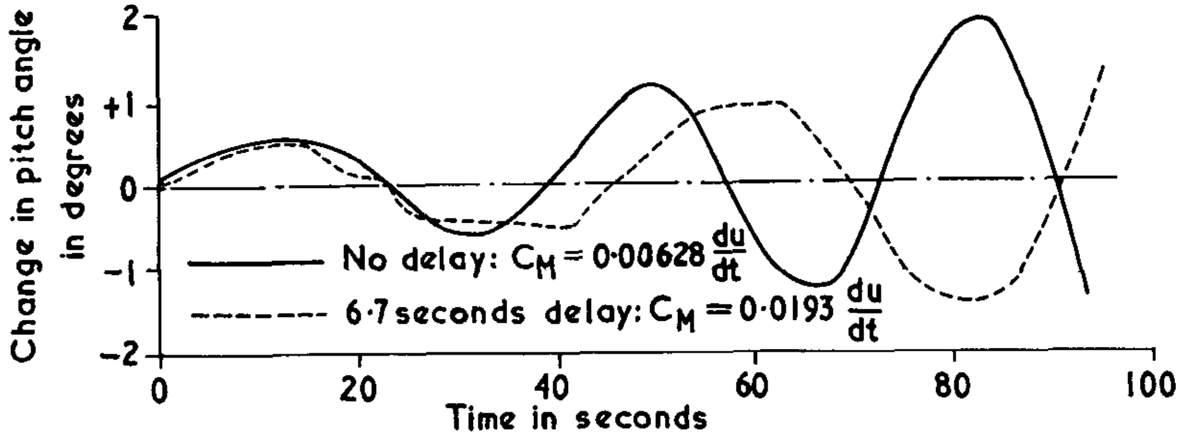


FIG. 29 Comparison of attitude changes in two tests with same time to 50ft

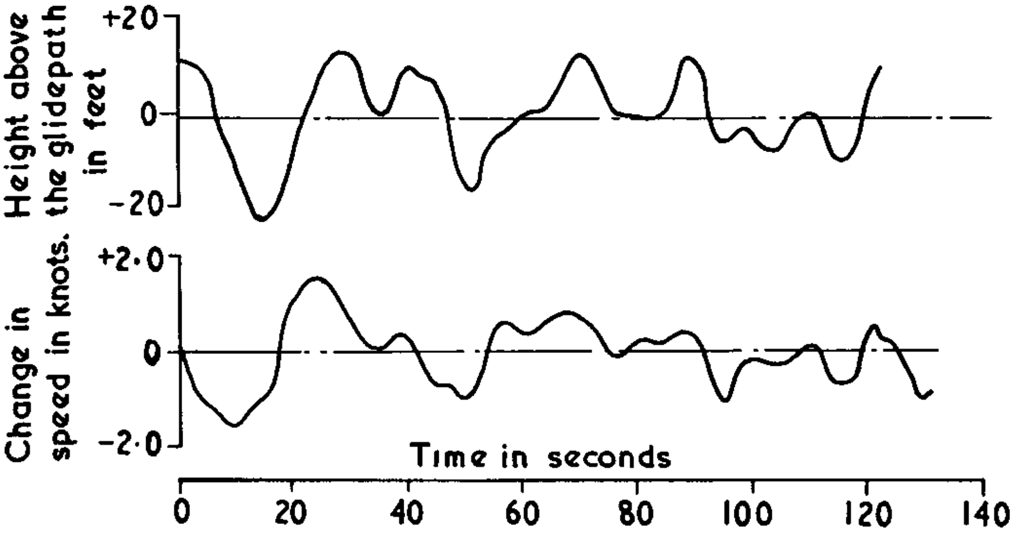


FIG. 30 Step throttle: pilot controlled speed (a) No delay

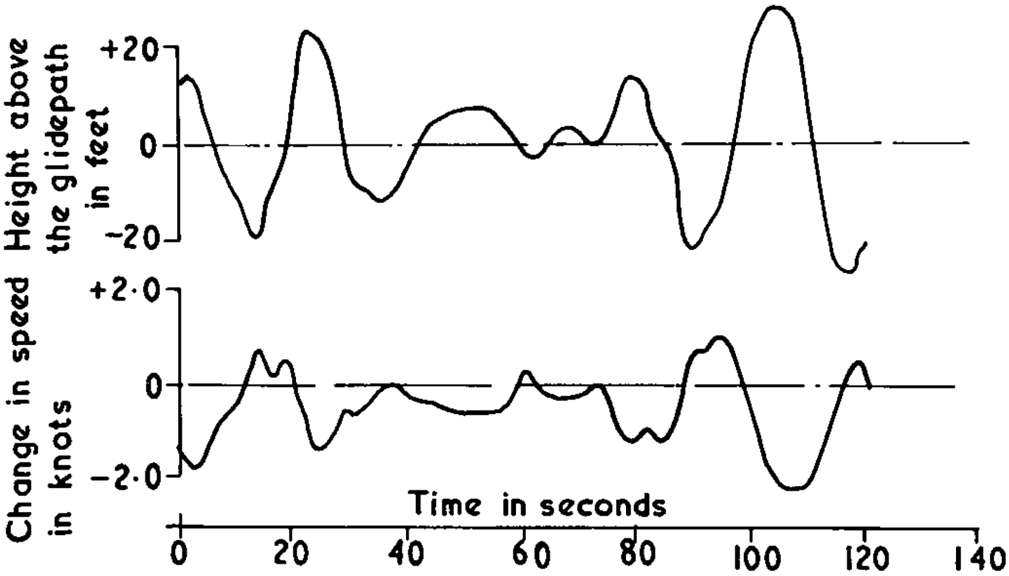


FIG. 30 Step throttle: pilot controlled speed (b) 1·7 seconds delay

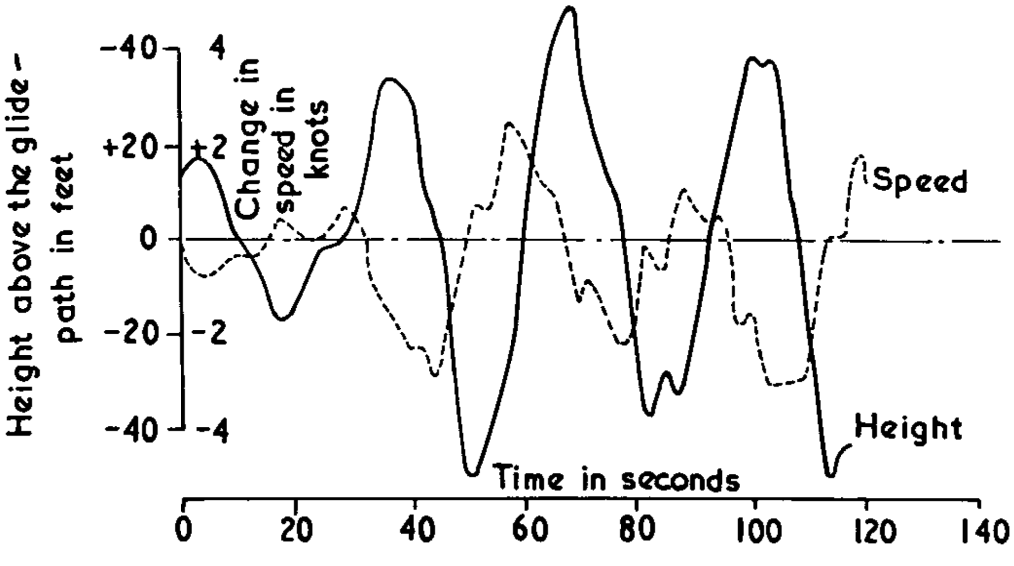


FIG. 30 Step throttle: pilot controlled speed (c) 3·3 seconds delay

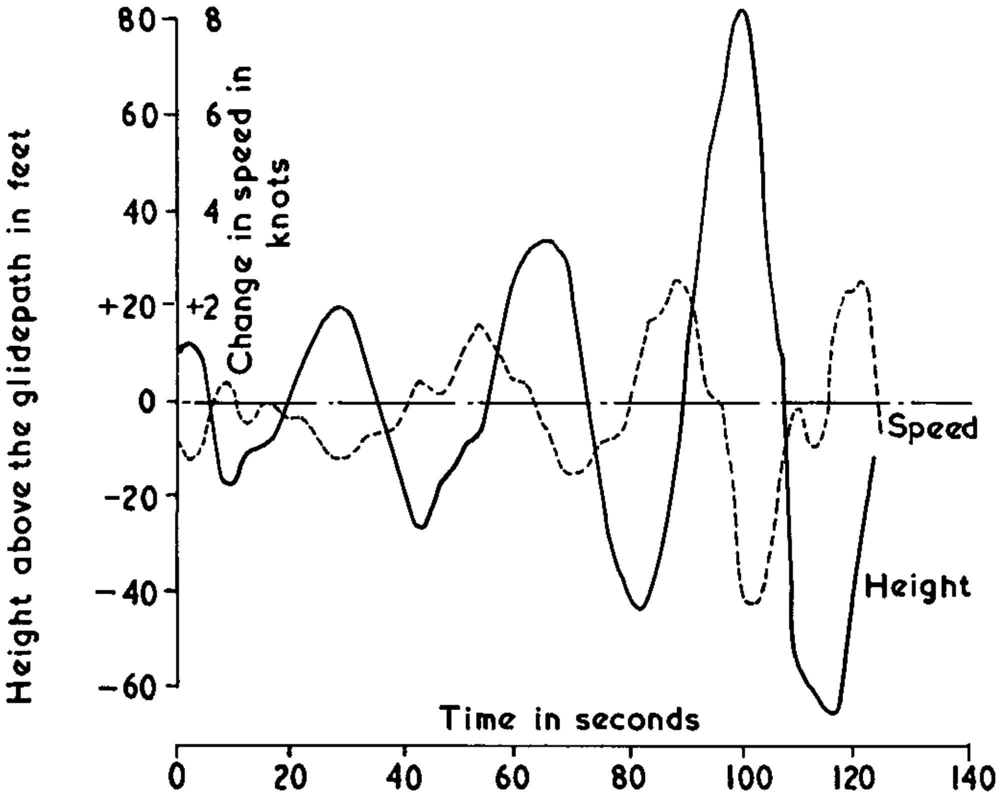


FIG. 30 Step throttle: pilot controlled speed (d) 5·0 seconds delay

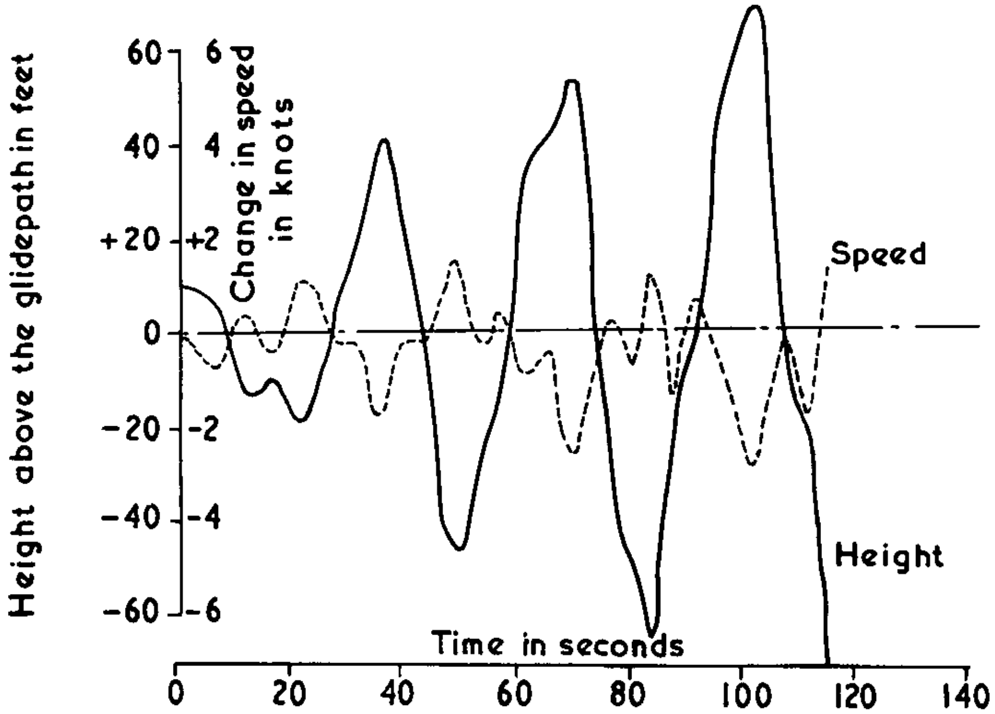


FIG. 30 Step throttle: pilot controlled speed (e) 6·7 seconds delay

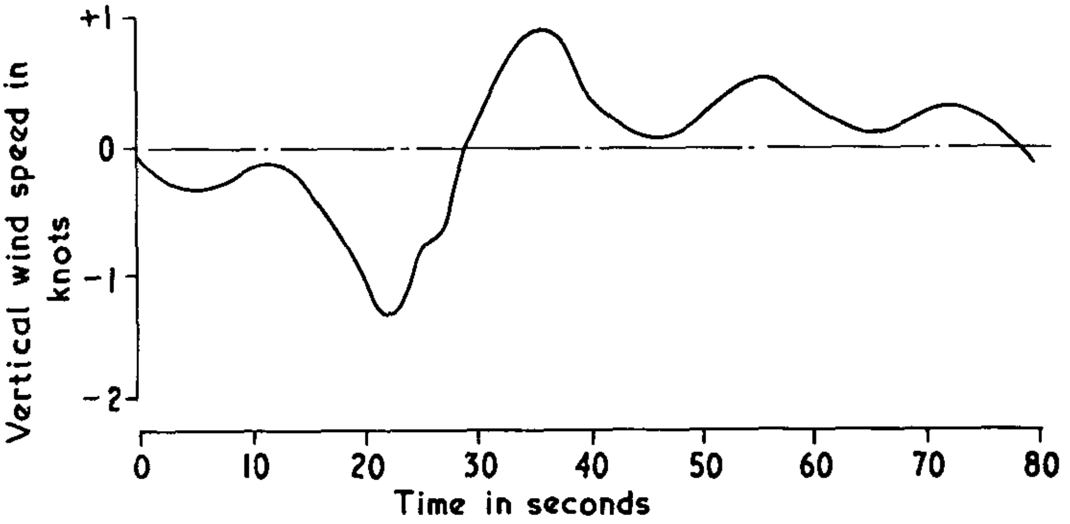


FIG. 31 Vertical gust pattern

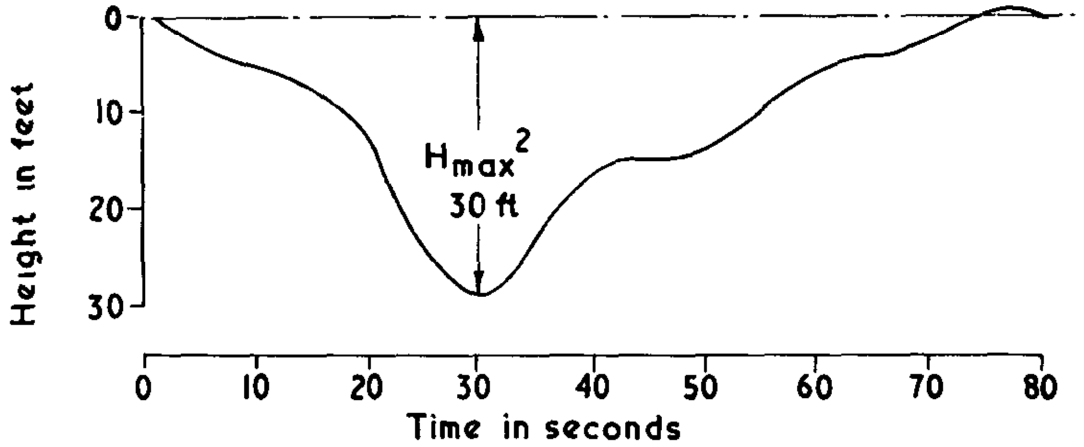


FIG 32 Effect of gusts on flight path

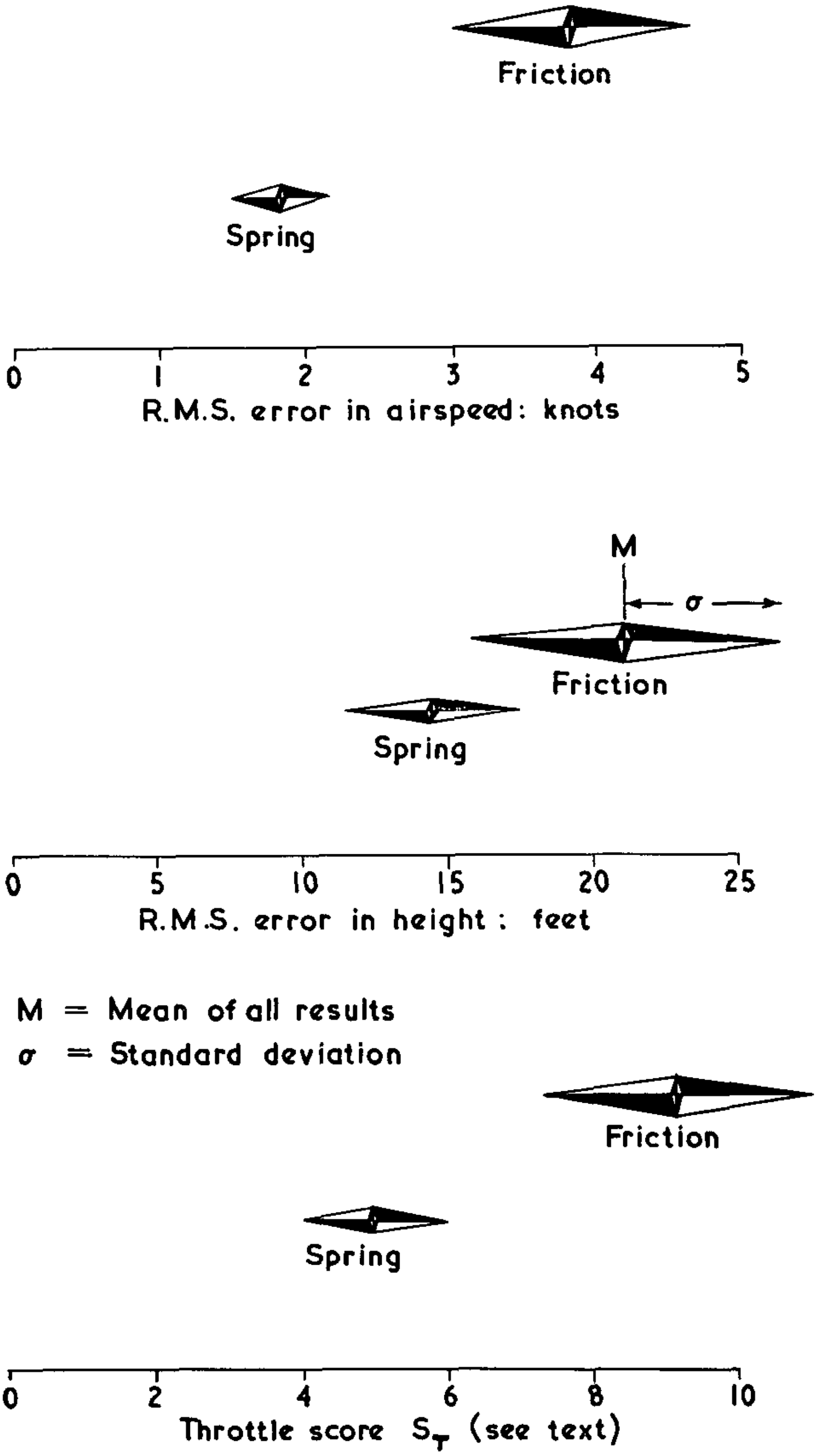


FIG. 33 (a) Statistical comparison of spring and friction loaded throttles

15·5 kt headwind:- gusts 0 98 kts up to 1·32 kts down

G.C.A. presentation with no roll controll

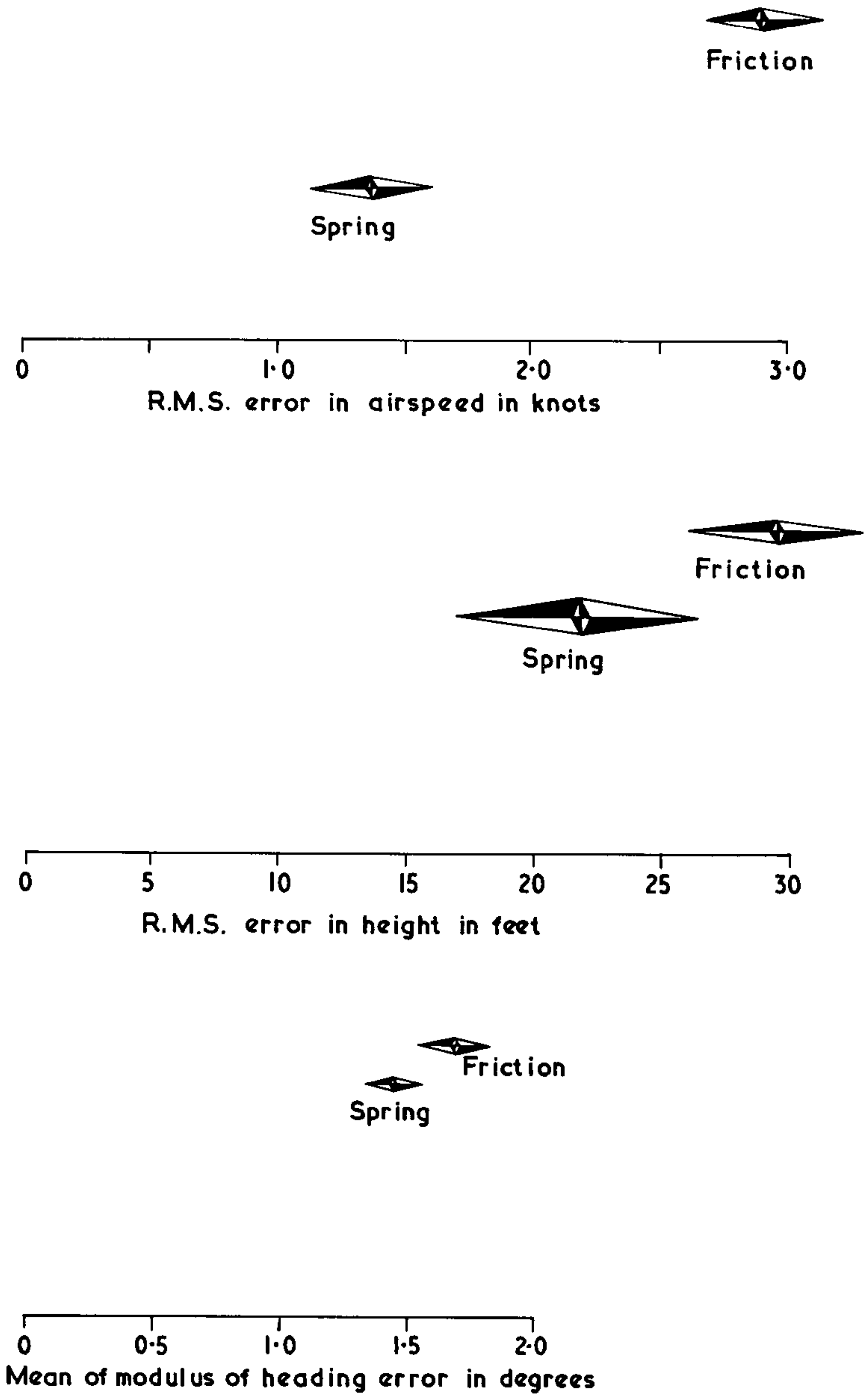


FIG. 33(b) Comparison of spring and friction loaded throttles

15·5 kt headwind —: gusts 0·98 kt up to 1·32 kt down
I.L.S. presentation with freedom in roll

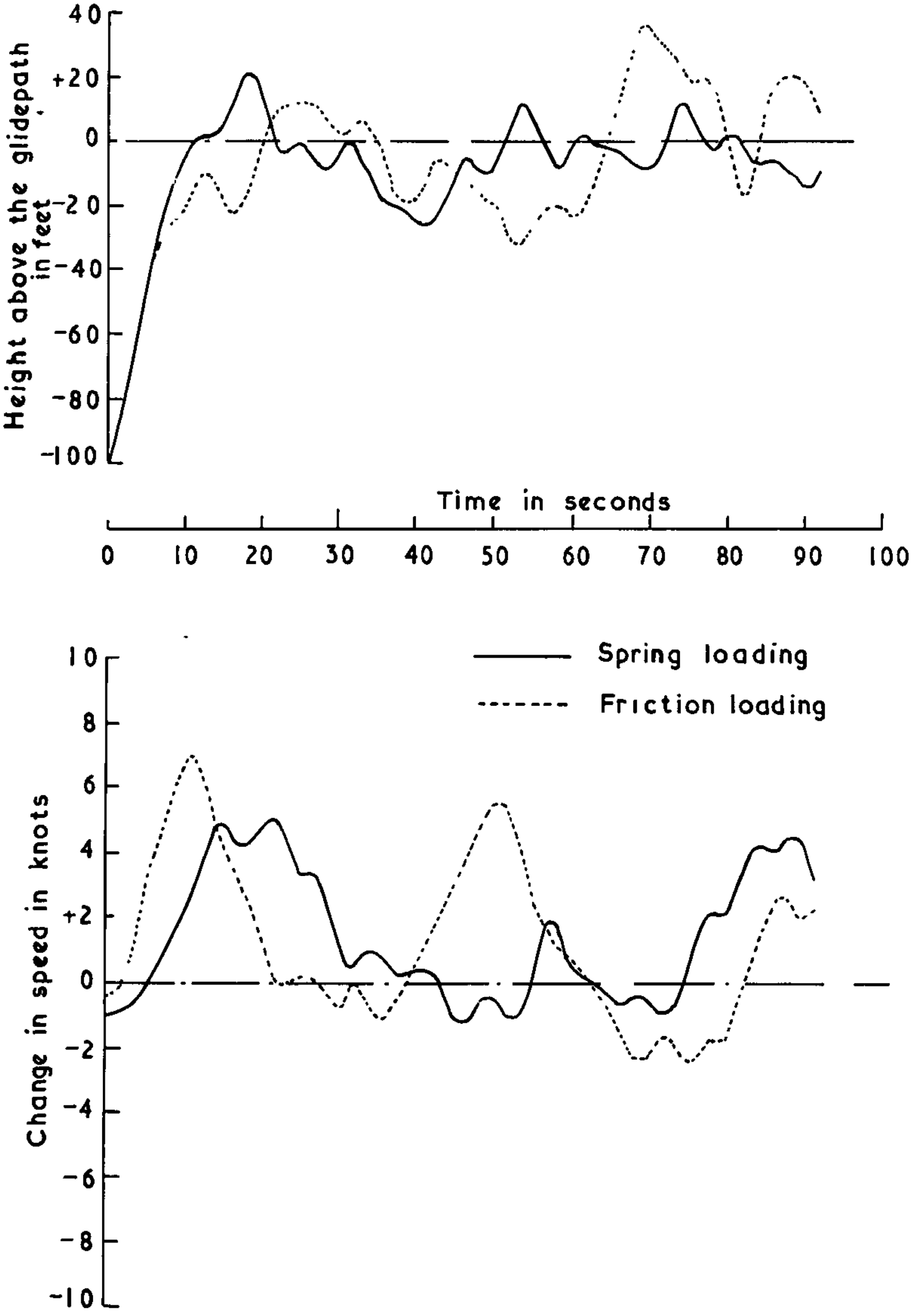


FIG. 34 Comparison of spring-loaded and friction-loaded throttles

15·5 kt headwind:- gusts 0·98 kt up to 1·32 kt down :-
(consecutive approaches)

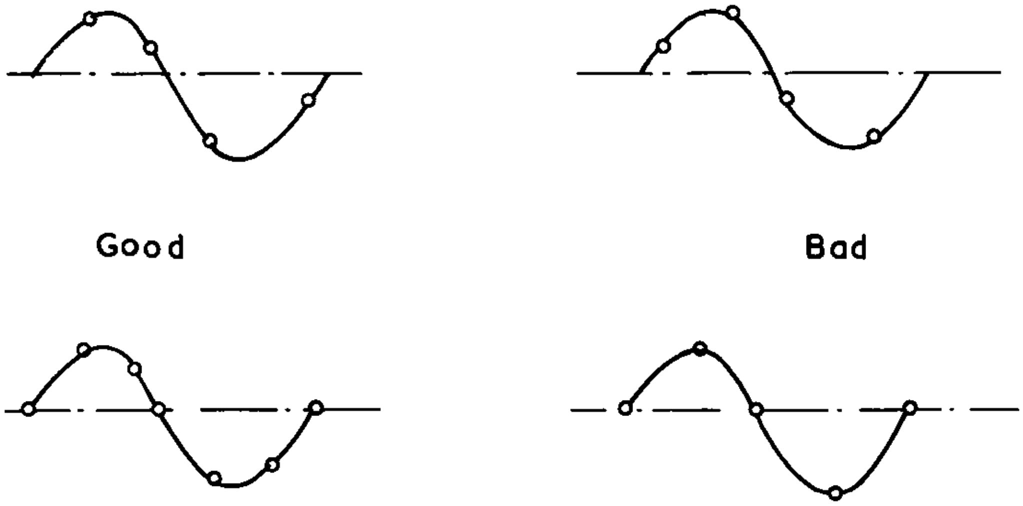
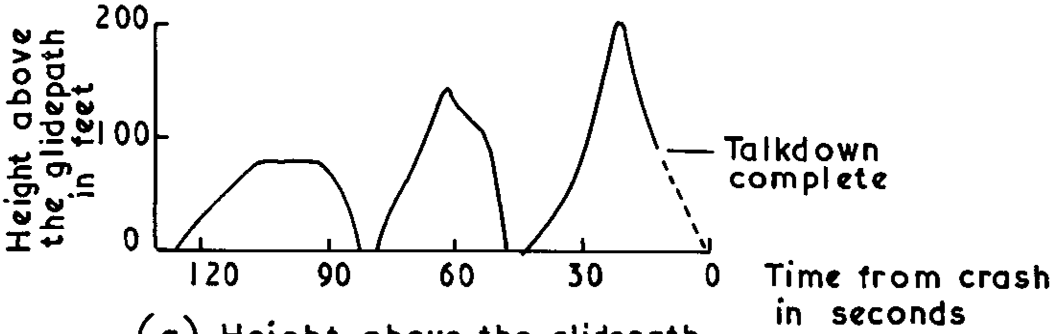
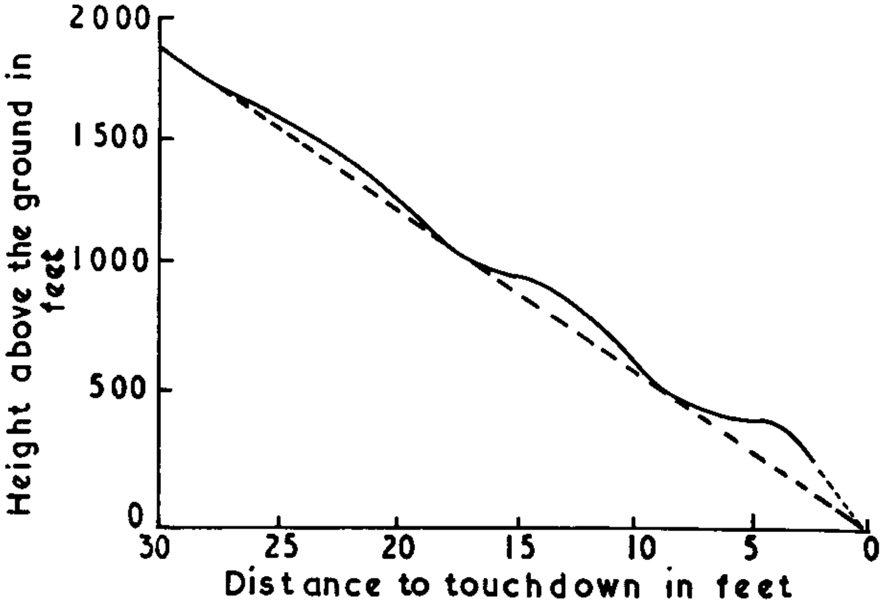


FIG 35 Illustration of the importance of timing information



(a) Height above the glidepath



(b) Height above the ground

FIG.36 Comparison of two methods of presenting height information

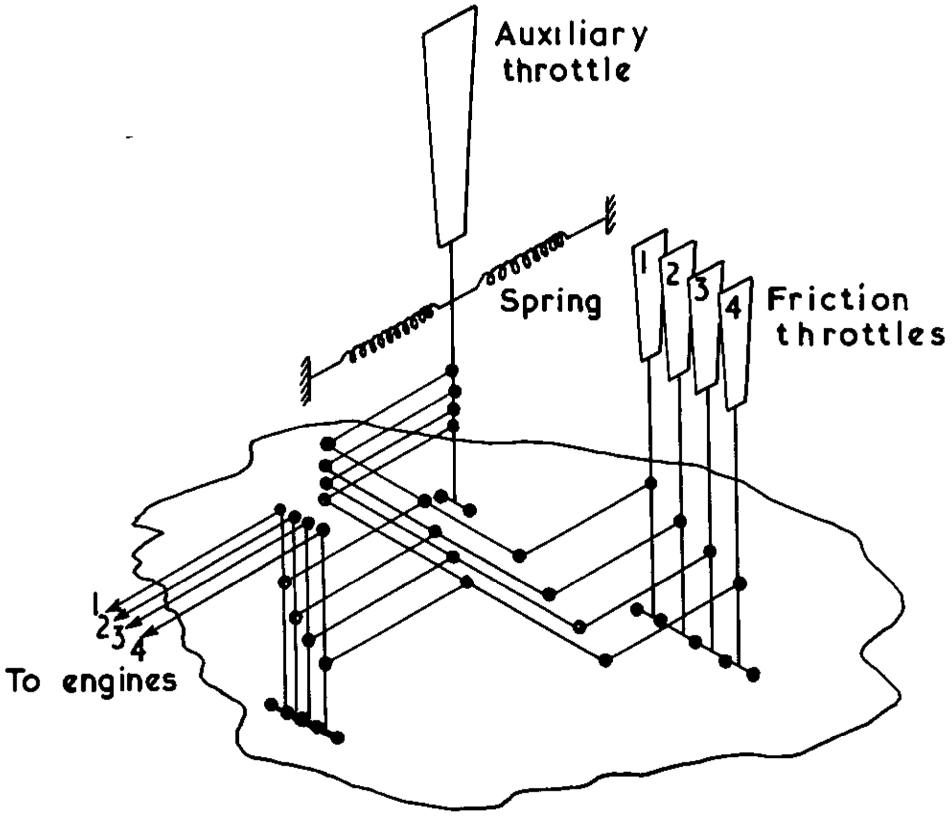


FIG. 37 Auxiliary self-centring throttle applied to four engines

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February, 1963
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SIMULATION OF GROUND CONTROLLED APPROACHES WITH REFERENCE TO CERTAIN ACCIDENTS

This report deals with the simulation of ground controlled approaches and describes an investigation into possible defects in the system which might lead to accidents. Two such accidents are described and in both of these the aircraft built up long period expanding oscillations about the glide path. This motion is then investigated by simulation techniques and its causes determined. The trouble is found to be inherent in the technique of using the throttle to control height and the elevator to control speed. This is demonstrated by

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systematic use of the throttle in response to height errors according to various logical schemes. It is found that, in certain circumstances, entirely logical use of the throttle results in an oscillation of increasing amplitude no matter how successfully the pilot controls speed with the elevators. It is concluded that accidents have sometimes resulted from use of the throttle to control height.

Finally, a simple device is described, which led to a different flying technique giving much improved control of an aircraft making a blind approach. It consisted of an auxiliary spring-loaded throttle control. Flight tests of this device are strongly recommended.

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