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Speed Stability and the Landing Approach with an Appendix of Avro 707A Longitudinal Characteristics

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Summary.

The effect of speed stability on pilot workload and accuracy on the approach has been investigated with the Avro 707A research aircraft. Speed instability was simulated by a reversed autothrottle which applied thrust in response to changes in airspeed, or in airspeed and incidence.

No correlation was found between the speed stability parameter and the accuracy achieved in speed holding and flight path control. The pilot's throttle usage, however, varied consistently with the speed stability time constant, and was little affected by the type of talkdown control used. Marked changes in throttle usage corresponded well with pilots assessments of the difficulty of the task.

Results of flight measurements of the longitudinal characteristics of the aircraft in the approach configuration are also included in an Appendix.

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*Replaces R.A.E. Technical Report 67 322—A.R.C. 30 362. This Report is an expanded and refined version of AGARD Report 420 presented at the Take-off and Landing Specialists Meeting in Paris, January 1963.

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1. *Introduction.*

The ever increasing performance of aircraft has led to the employment of wings with large sweepback and/or small aspect ratio. One of the consequences of this trend has been a steady increase in the speed for minimum drag, which in many cases is now well above the speed that might otherwise be usable on the approach. It is generally known that below minimum drag speed a speed instability is experienced if the pilot attempts to control closely the approach path. Clearly one of the factors influencing the pilot in his selection of an approach speed is his ability to control speed and rate of descent. This problem is likely to predominate when an aircraft is flown below minimum-drag speed but above the speed range where there is a deterioration in other aircraft characteristics, such as a general reduction in stability or control response, proximity to the stall, vision from the cockpit, etc.

Several investigations[1,2,3,4] of the problem have been made in the past by progressively reducing the approach speed on a given aircraft to determine a minimum comfortable value, but have inevitably been hampered by simultaneous changes in other characteristics of the aircraft. The present tests used a 'reversed autothrottle' to provide variations in the apparent 'drag-speed' characteristics by changing engine thrust with speed, or with a combination of speed and incidence, and this allowed use of a constant nominal approach speed; the other aircraft characteristics were therefore unchanged. The tests were designed to find some measure of the effect of the drag-speed relationships on the difficulty of the approach task, so that the results could be applied to aircraft other than that used for the present investigation.

The bulk of the present investigation was devoted to variations in the speed stability characteristic but some brief tests have also been made to investigate the effect of lag in the engine response, and changes in the static margin. Clearly it would also have been desirable to consider other general aircraft handling and control system characteristics and their interaction with the speed stability and with each other; such an extended programme was well outside the scope of the present investigation. Section 2 discusses in general terms the problems of longitudinal control during the landing approach under conditions when drag-speed variations may be important, and gives a brief outline of the theory of speed stability. Section 3 describes the experimental system, including the autothrottle control system and the rather unusual theodolite approach path control used for most of the tests. Sections 4 and 5 describe the instrumentation and test programme. Section 6 gives a brief resumé of the aircraft longitudinal characteristics; detailed results are given in Appendix A and have been included to define fully the pertinent characteristics of the Avro 707A in the landing configuration so that comparisons can be made with similar investigations on other aircraft. Section 7 discusses the effect of various terms in the autothrottle law on the realism of the simulation and on the phugoid oscillation. The statistical tests used in the analysis and the rating table used in pilot assessments are also described. Section 8 presents the results of the flight experiment, which are discussed in Section 9. Here we try to relate the pilots assessments of the difficulty of the approach task at various levels of speed stability to the measurements of workload, in these tests indicated only by control usage, and to the approach accuracy, in terms of speed and glide-path holding.

2. *Basic Theory of Speed Stability.*

During the approach to landing the pilot is required to control the flight path and the speed of the aircraft. This definition of the pilot's task might be applied to flight in general, but the tightness of control demanded during the approach forces the pilot to act in a manner which is capable of altering substantially the apparent stability of the vehicle, and, as a consequence, to experience flight characteristics which he does not meet in general flying. The control problems are not then necessarily explained by conventional 'stability' parameters, and indeed serious longitudinal control difficulties are often encountered on aircraft with perfectly satisfactory 'stability'.

One phenomenon, which is often associated with such difficulties, is the so-called 'speed divergence' below minimum-drag speed, which results from the fact that below this speed the aircraft drag in trimmed rectilinear flight increases as the speed decreases. If then the speed departs from the trimmed value associated with a given thrust, the drag variation will tend to increase further the speed error unless an appropriate thrust adjustment is made. This condition of constrained rectilinear flight, is not considered in conventional stability theory, which is concerned with the response of the aircraft to disturbances from trimmed flight with controls either fixed or free, but not controlled by the pilot. Rectilinear flight at a fixed thrust described above requires that the pilot must apply elevator so as to suppress deviations from the flight path, a condition clearly not treated by conventional theory.

If, however, we postulate that a pilot is restraining the aircraft in a specified way, of which one, but not the only, example is that given above, then the stability of the aircraft in this special condition can again be treated by conventional calculus. Neumark[5] has considered this problem for the longitudinal motions under the following 'constraints':

(i) Rectilinear flight under elevator control.

(ii) Flight at constant speed under elevator control.

(iii) Rectilinear flight under throttle control.
(iv) Flight at constant speed under throttle control.
(v) Flight at constant attitude under elevator control.
(vi) Flight at constant altitude under throttle control.

Before the results of such an analysis can be applied to a realistic flight situation it is necessary to consider which—if any—of these various assumed constraints can be exercised in practice by a pilot. On the approach, as distinct from all other flying, the pilot is frequently required to guide the aircraft along a sharply defined flight path, whether prescribed directly by a visual glide slope indicator, or indirectly by GCA instructions or an ILS indicator. To follow this path the pilot is forced to constrain the aircraft flight path; therefore either (i) or (iii) should apply. At the same time, however, the pilot is equally concerned with speed holding, a condition which again can be achieved by either elevator or thrust control. Obviously, if one assumes these constraints to be satisfied simultaneously by the pilot controlling flight path with elevator and speed with throttle, or *vice versa*, the problem is eliminated by the assumption and no further assistance can be obtained by analysis.

There is, however, a distinction between the two constraints of fixed flight path or constant speed. An ideal pilot, with perfect skill and instantaneous reactions, is in theory capable of achieving almost perfect flight path control by use of elevator (assuming the time for response to control is small), since no conceivable disturbance can produce an immediate flight path error, but only forces to initiate such an error; these, such a pilot can counter. On the other hand, speed errors can arise from fore and aft gusts without involving a true response of the aircraft and by no mechanism, other than the availability of infinite thrust, can speed be held constant (in relation to an instationary atmosphere). The physical impossibility, in the real world, of maintaining constant speed gives some justification for selecting a fixed flight path as the more plausible restraint. Using the same reasoning it is evident that only elevator control allows effective constraint of the short term response; control by throttle is indirect, since it requires a change in speed to produce initially a normal acceleration, and is not really effective when the task is very tight.

The pilot is obviously best qualified to answer the question as to how, in fact, an aircraft is controlled. Such an enquiry unfortunately reveals a difference of opinion, some pilots claiming to control flight path by elevator and speed by the throttle whereas others profess to use the opposite technique. Inspection of their actual performance (Section 9) in flight shows that both groups use the same technique, co-ordinating the use of the controls to maintain both speed and flight path. Apparently, one pilot thinks he controls the flight path with the throttle but, appreciating that a thrust change will initially cause a change in speed, makes an elevator adjustment in anticipation; another thinks he controls flight path by elevator but makes a compensatory throttle adjustment, and so on. There may be interesting psychological distinctions but they have little relevance to the present investigation.

It is also of some interest to note a distinction between the use of controls for long term trim and their use for short term control. If a constant mean speed over a period of time is required then it is the elevator position which determines this speed, and at any one time, in the absence of a pitching-moment change due to thrust variation, a given speed corresponds to a unique elevator position irrespective of the flight path, provided the latter is not too inclined. Similarly, over a period of time, it is the throttle which trims the glide-path. For control, however, we require quick application of the force to provide the appropriate acceleration. For the flight path the elevator gives a normal acceleration response dependent on the pitching oscillation of the aircraft whereas the throttle provides such a response through the phugoid motion, normally of much longer period. The throttle, on the other hand, provides directly a force approximately along the flight path with little initial affect on the normal acceleration.

We shall therefore consider in detail flight path constraint because, in the real world, it is the only constraint which is capable of achievement, and to apply the constraint we shall use the elevator because it provides the more direct control. In fact, this assumption leads to a theoretically predictable control problem that appears to correlate with pilots' complaints. The experimental work reported later is of course designed to test this hypothesis more rigorously.

Displacement in elevation being precluded by the constraint the aircraft has only one freedom of longitudinal motion left, i.e. fore and aft motion. Linearised for small perturbations the response of the aircraft is described by the first order solution,

$$u = u_0 e^{-t/\tau} \tag{1}$$

where u is the speed error,

u_0 the initial error,

and τ a time constant.

The analysis due to Neumark[5] shows that an approximate expression for this time constant, in level flight, is:

$$\frac{1}{\tau} = \frac{g}{W}\left(\frac{\partial D}{\partial V} - \frac{\partial T}{\partial V}\right) \tag{2}$$

or

$$\frac{1}{\tau} = -g\left(\frac{\partial T/\partial V}{W} - \frac{\rho}{W/S} C_{D_0} V_0 + \frac{W/S}{\rho/4} \frac{1}{V_0^3} \frac{\partial C_D}{\partial C_L^2}\right) \tag{3}$$

C_{D_0}, the parasitic drag coefficient gives a stabilising term, whereas the induced drag $\left(\frac{\partial C_D}{\partial C_L^2}\right)$ is destabilising, the latter contribution increasing as speed is reduced. $\partial T/\partial V$, the thrust term, is usually negligible for jet engines and in this case, the aircraft is speed-stable at speeds above that where

$$\frac{\rho}{W/S} C_{D_0} V_0 > \frac{W/S}{\rho/4} \frac{1}{V_0^3} \frac{\partial C_D}{\partial C_L^2}. \tag{4}$$

This is the speed where $\partial D/\partial V = 0$, i.e. the minimum-drag speed. Below this speed the solution becomes unstable, i.e. the pilot when constraining the aircraft to a rectilinear flight path with the elevator will experience a speed divergence.

Equation (3) also shows that by varying thrust with V the time constant of this mode can be altered readily and this fact has been utilised for the present tests. The use of an automatic throttle servo provided a range of values of $\partial T/\partial V$ by changing thrust in response to speed.

It should also be noted that, because of the unique relationship between incidence and speed in rectilinear flight, the introduction of a term $\partial T/\partial \alpha$ provides an alternative way of changing the speed stability, equation (3) then becomes:

$$\frac{1}{\tau} = -g\left(\frac{\partial T/\partial V}{W} + \frac{\partial T/\partial \alpha}{W} \frac{1}{V_0^3} \frac{W/S}{\rho/4} \frac{1}{a} - \frac{\rho}{W/S} C_{D_0} V_0 + \frac{W/S}{\rho/4} \frac{1}{V_0^3} \frac{\partial C_D}{\partial C_L^2}\right). \tag{5}$$

The second term is analogous to the induced drag term, whereas $\partial T/\partial V$ simulates a variation in the parasitic drag. Although equivalent in their effect on the restrained motion these two simulated drag terms will alter the general aircraft response quite differently. For this reason changing thrust with incidence was also investigated as it removes the difficulties in gust response associated with the $\partial T/\partial V$ term and improves the phugoid damping. A more detailed discussion is given in Section 7.

3. *Description of the Experimental System.*

3.1. *The Aircraft.*

The test vehicle was the Avro 707A (WZ 736) single seat research aircraft powered by one Derwent Mk. 8 turbo-jet engine with a single jet pipe and wing root intakes. Relevant geometric details are in

Table 1, a general arrangement drawing at Fig. 1 and photographs at Fig. 2.

The aircraft was tailless with an approximately cropped delta wing of aspect ratio 2·86 and 50° leading edge sweepback. The trailing edge contained inboard trim flaps and irreversible power operated elevators and ailerons. Both elevators and ailerons had simple spring feel, with additional 'q' feel on the elevators. The rudder was unpowered. Two-position airbrakes were located inboard on the upper and lower surfaces.

3.2. *The Autothrottle and Throttle Control System.*

The experimental apparent drag characteristics were derived by a throttle servo capable of applying thrust in response to either indicated airspeed and/or incidence. Airspeed was sensed by a nose boom pitot-static head and incidence from a hole on the wing undersurface at approximately 29 per cent semi-span and 5 per cent local chord. Transducers, connected to the pressure sources*, provided electrical signals to drive the throttle through the system shown diagrammatically in Fig. 3. These signals, the gain of which could be changed by the pilot in the cockpit, drove a constant speed servo motor *via* a magnetic amplifier, a centre stable polarised relay and two slave relays, which determined the direction of throttle movement. The motor was connected to the throttle by a magnetic clutch and a weak link, which could be sheared by the pilot should the system fail to disengage electrically. Snatch at engagement was avoided by the follow-up servo provided to zero the control demands; this was disengaged with the main system operating. The automatic system had authority over almost the complete throttle range. After engagement the throttle was rigidly connected to the servo so that the pilot could not operate the throttle lever. To restore engine control to the pilot an additional lever was installed adjacent to the original one and provided an electrical signal in parallel with those from the pressure sensors. The gain of this auxiliary throttle could also be changed by the pilot but was set throughout these tests so that the demanded main aircraft throttle-lever movement was the same as the auxiliary throttle-lever movement.

The servo could move the aircraft throttle over the complete range in five seconds. This limited in practice the response of the system to error signals and by necessity also the engine response to pilots' demands with the system engaged. In order to investigate the effect of engine response poorer than this an additional lag was introduced between the auxiliary throttle and the main servo system. This consisted of a lag servomotor, driven by signals from the auxiliary throttle *via* its own system of magnetic amplifier, polarised and slave relays, and driving a potentiometer from which the signal for the main system was obtained. With this system in use the main aircraft throttle took eight seconds to traverse the full range. It should be noted that the pressure signals were unaffected by the lag, so that the simulated drag changes were unaltered.

The system performed satisfactorily throughout the test programme. A number of fatigue failures of the weak link occurred and occasionally it was inadvertently sheared by the pilots. On no occasion was it necessary to shear the link deliberately due to failure of the electrical system to disengage.

3.3. *Landing Approach-Path Control.*

As difficulties due to speed instability were expected to be most prominent on a closely controlled glide-path, guidance had to be provided. An ILS system would have been appropriate but its installation in the test aircraft proved impracticable. An alternative technique, providing close control of elevation, was devised in which the aircraft was tracked by a theodolite, and continuous verbal error information, displayed to a controller by a meter, was passed to the pilot *via* a radio link. The elevation error signal was also recorded on a Hussenot A22 trace recorder. The pilot thus knew his deviation, in units of 1/32 deg, from the specified 3° glide-path, and by virtue of the continuous commentary, had an indication of its rate of change. This type of control, called here 'tight' control, provided a powerful constraint on the glide-path and frequently towards the end of the approach the controller was unable to speak rapidly enough to

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*The output of both transducers connected to the pressure sources was approximately proportional to the square root of the applied pressure. The output from the nose boom head thus varied nearly linearly with speed and that from the hole varied linearly with C_L and hence α (*see* Fig. 4).

cover every interval of 1/32 deg; at one mile from touchdown the interval represents about 3 feet height deviation.

It may well be that the control of glide-path by aural instruction as distinct from visual means—ILS, glide slope indicator, etc.—affects the ease with which the pilot accomplishes the task. This is discussed further in Section 9.

Limited tests were also made with a so-called 'loose' control, in which the controller communicated with the pilot only when his elevation had changed by 1/4 deg from the previously reported position.

The pilots were asked to intercept the glide-path at about 5 miles from touchdown (a height of about 1400 feet) and control started as soon as the aircraft had been accurately located by theodolite, usually about 4 miles from touchdown (1100 feet). When under theodolite control azimuth was uncontrolled, i.e. the pilot had to 'look out' and visually control alignment with the runway.

Flights were also made in which the aircraft was tracked by the theodolite but controlled by the normal airfield ground controlled approach facility. In this case the pilot was given information on azimuth and elevation corrections using precision approach radar, known as 'P.A.R.' control. In this type of control the pilot is normally given heading changes aiming towards alignment with the runway extended centre-line but only general information about his elevation relative to the glide-path, e.g. 'slightly above', 'well above' or 'approaching' the glide-path. He is also given his range from touchdown in miles or half miles. The information is provided infrequently by 'tight' control standards, and at the discretion of the controller.

4. *Aircraft Instrumentation.*

A pitot-static head on a nose boom supplied all the experimental pressure instruments and one on a port wing tip boom supplied the pilots' instruments. The nose boom also carried an incidence vane.

An automatic observer photographed by an F.57 camera firing at ½, 1 or 2 second intervals contained, among others, instruments indicating the following quantities:

(a) Airspeed.

(b) Altitude.

(c) Port and starboard elevator angles.

(d) Port and starboard trim flap angles.

(e) Port and starboard airbrake extension.

(f) Port and starboard elevator trim tab angles.

(g) Fuel contents.

(h) Engine rpm.

(j) Jet pipe temperature.

(k) Jet pipe pitot pressure.

(l) Flight and camera shot numbers.

(m) Time, by clock.

(n) Event marker and autothrottle engage lights.

Two Hussenot A22 recorders, running at 0·2 inch or 1 inch per second, gave continuous trace records of the following:

(p) Airspeed.

(q) Starboard elevator angle.

(r) Pitch attitude, by pendulum and by position gyroscope.

(s) Rate of pitch.

(t) Aircraft and auxiliary throttle positions.

(u) Jet pipe pitot pressure.

(v) Aircraft incidence.

(w) Vertical acceleration.

(x) Event, autothrottle engage and camera firing markers.

Synchronisation between the airborne and tracking theodolite recordings was obtained by event marks on command from the controller. The difference between the clocks, aircraft and ground was negligible.

Calibration of the autothrottle $\partial T/\partial V$ at various gain settings was done by trimming the aircraft in level flight at 120 knots equivalent airspeed and then, using elevator alone, trimming to rectilinear flight at various greater and lesser airspeeds, measuring the thrust at each condition by the standard single jet pipe pitot method. Variation of position error, Fig. 5, with airspeed was thus accounted for, but not the variation of position error with incidence at a fixed speed. The latter effect is small, but not completely negligible, amounting to about 4 per cent of $\partial T/\partial V$ per degree incidence change. The wing hole was also calibrated in flight, Fig. 4, from which, knowing the lift-curve slope and the thrust change with transducer signal (from the $\partial T/\partial V$ calibration), it was possible to determine $\partial T/\partial \alpha$ at various gain settings.

5. *Programme of Tests.*

The measurements described here were originally conceived as part of a larger investigation involving many other aircraft. The present tests were made in order to achieve a better understanding of the parameters influencing the pilot's control of the landing approach and, in particular, to define the measurements needed to allow an assessment of the difficulty of the pilot's task. With the larger programme in mind it was necessary to determine accurately the longitudinal characteristics of the test aircraft; the details are given in Appendix A to give future investigators all the data on the characteristics of this particular vehicle. The results are introduced into the main text as necessary.

Four pilots, A, B, C, D, participated in the initial approach investigation during which measurements of performance were made and analysed. An additional four pilots, E, F, G, H, made a subjective assessment of the difficulties at various autothrottle settings at a later date. In these later tests more severe levels of speed instability were investigated and engine lag was incorporated; measurements of performance are presented, but without analysis.

The conditions tested are given in the following tables, where the forward cg is at 0·234 $\bar{c}$ and the aft cg at 0·287 $\bar{c}$.

Pilots A, B, C, D

*Range of speed stability covered: $\partial T/\partial V$ only $1/T_2 = -0{\cdot}017$ to $0{\cdot}17$
$\partial T/\partial V + \partial T/\partial \alpha$ $1/T_2 = -0{\cdot}017$ to $0{\cdot}23$

Stability term / Type of control \ cg	$\partial T/\partial V$ only		$\partial T/\partial V + \partial T/\partial \alpha$	
	fwd	aft	fwd	aft
Tight	X	X		X
Loose				X
P.A.R.		X		X

*See footnote on p. 9.

Pilots E, F, G, H

*Range of speed stability covered: $\partial T/\partial V$ only $1/T_2 = -0{\cdot}017$ to $0{\cdot}45$
$\partial T/\partial V + \partial T/\partial \alpha$ $1/T_2 = -0{\cdot}017$ to $0{\cdot}62$

cg at aft position

Type of control \ engine \ Stability term	$\partial T/\partial V$ only		$\partial T/\partial V + \partial T/\partial \alpha$	
	no lag	with lag	no lag	with lag
Tight	X	X	X	X
P.A.R.	X	X	X	X

Pilots were asked to intercept the glide-path at about 5 miles from touchdown, i.e. a height of about 1400 feet and, when under ground control, to make as accurate an approach as possible in terms of speed and glide-path holding, without giving undue attention to one at the expense of the other. They were aware that the accuracy with which both were controlled would be used in the analysis of the difficulty of the approach task. On all approaches the target speed was 120 knots equivalent airspeed and the aircraft was in the landing configuration of undercarriage down, trim flaps fully up and airbrakes fully extended.

6. *The Aircraft Longitudinal, Speed Stability and Thrust Characteristics.*

The detailed description of the measurements of the longitudinal characteristics of the aircraft is given in Appendix A. The results are summarised in Tables 2 and 3.

The flight measurement of speed stability would require a speed disturbance from the trimmed condition and then precise suppression of displacements from a rectilinear glide-path by use of elevator alone; this is not practicable[13]. Calculations of the speed stability have therefore been made from the measured drag polar of the aircraft and the calibrated values of autothrottle gains $\partial T/\partial V$ and $\partial T/\partial \alpha$, Section 4, using the formula (5), Section 2. These calculations assume instantaneous thrust response to speed and incidence changes and therefore overestimate (*see* Appendix C) the degree of speed instability produced by the autothrottle. The results for this so-called *nominal* speed stability are shown in Fig. 6 for the forward and aft cg positions with $\partial T/\partial V$ alone and with $\partial T/\partial V + \partial T/\partial \alpha$.

The autothrottle had authority over 2200 lb of thrust. The trim position varied slightly with aircraft weight but was generally near the middle of the range so that the available ΔT was approximately ± 1100 lb. With $\partial T/\partial V$ alone, Fig. 6 therefore also allows the calculation of speed errors for saturation of the system, these being, for example, ± 24 ft/s at $1/T_2 = 0{\cdot}2$ and ± 11 ft/s at $1/T_2 = 0{\cdot}45$.

Fig. 7 shows a cross plot of the relationship between speed stability and damping of the phugoid oscillation. The speed stability was obtained from Fig. 6 at various autothrottle gain settings and measurements of the phugoid damping at low and moderate gain settings, *see* Appendix A, were extrapolated to high gain settings by calculation because of the violently divergent oscillations. The figure shows the.

*The results are presented as the reciprocal of the time to half $1/T_{\frac{1}{2}}$, or time to double, $1/T_2$, amplitude of the speed error. These are related to the time constant, τ, section 2 by:

$$\frac{1}{T_{\frac{1}{2}}} = -\frac{1}{T_2} = \frac{1{\cdot}443}{\tau}.$$

rather small, improvement in phugoid damping, at a given speed stability, due to adding $\partial T/\partial\alpha$ to the basic case of $\partial T/\partial V$.

Fig. 8 shows the engine thrust response, measured in flight at 120 knots equivalent airspeed, to rapid inputs of main aircraft throttle and of auxiliary throttle, with and without the lag system. Following an aircraft throttle movement there is a time delay of 0·2 second before the thrust starts to change. Following an auxiliary throttle input there is a time delay of 0·3 second before the aircraft throttle starts to move followed by a further 0·2 second before the thrust starts to change. The rate of increase in thrust is lower than with an aircraft throttle input due to the slower rate of aircraft throttle movement. The lag system causes a further 0·4 second delay in aircraft throttle movement; thus no thrust change occurs for 0·95 second following the pilot's input and the rate of change is lower than in both the other cases.

7. *The Simulation and Methods of Assessment.*

7.1. *The Realism of the Simulation.*

Under the particular conditions of constraint discussed in Section 2, the aircraft motion is completely defined by the stability of the speed subsidence or divergence mode, and with respect to this mode the effects of $\partial T/\partial V$ and of $\partial T/\partial\alpha$ are completely interchangeable. However, in real flight when the constraint exercised by the pilot may be much looser, the two terms have quite different effects on the response of the aircraft. For example $\partial T/\partial V$, representing a reduction in C_{D_0}, greatly affects the response to a horizontal gust, so that with a head gust, the speed loss is less relative to the undisturbed air than would otherwise be the case. But there is no initial response, with $\partial T/\partial V$, to pilots elevator control. On the other hand $\partial T/\partial\alpha$ responds to elevator control but not to a fore or aft gust. The addition of $\partial T/\partial\alpha$ in some of the tests simulates an increase in induced drag and thus represents more directly the effect that is normally responsible for the occurrence of speed instability in a real aircraft. Indeed, with $\partial T/\partial V > 11$ lb ft^{-1} s^{-1} the effective $C_{D_0} < 0$, i.e. representing an aircraft with negative parasitic drag, a clearly impossible physical condition. Unfortunately it was not practicable to use sufficiently high gains for $\partial T/\partial\alpha$ to obtain the desired range of speed instability and so it was used only to supplement $\partial T/\partial V$, keeping the ratio $\partial T/\partial\alpha$ to $\partial T/\partial V$ constant for each series of tests. It is worth noting, however, that from this point of view the results from these tests are likely to be pessimistic in that, for example, a head gust produces a displacement above the glide-path and a rather higher speed than would be the case in a real aircraft. A position of high and fast is less favourable than one of high and slow, or, in other words, energy has been added to the simulated system which the pilot must remove, and which does not occur in the real case.

It might also be argued that simulation of speed instability by thrust variation gave additional clues to the pilot either audibly, due to the change in engine noise, or visually *via* the rpm indicator. The pilot could then suppress the action of the speed destabiliser by attempting simply to hold engine power constant. The pilots were asked not to use the rpm indicator for this purpose and stated that they did not do so. They admitted however, to being aware of changes in engine noise, but were doubtful of the value of this clue, concentrating as they were on the glide-path information which was also provided audibly.

The damping of the phugoid oscillation, Section 6 and Fig. 7, may also be of some importance. The speed stability mode is only involved if the pilot attempts flight path holding by tight closed loop control. He may however elect to make only occasional discrete adjustments to the elevator or throttle setting, particularly if he has allowed a large displacement to occur, with the aim of recapturing the glide-path with less haste. The aircraft then flies for a time with fixed controls and its response is governed by the phugoid characteristics. The period of this oscillation, about 35 seconds, is such that only about 4 cycles would be completed during a landing approach from 5 miles. The oscillation is therefore unlikely to be forced by the pilot unless glide-path information is given only at rather long intervals. Nevertheless, a strongly divergent phugoid oscillation, as occurs at the higher autothrottle gain settings, may be important since large errors can arise in less than one cycle.

A corollary of the phugoid motion and manner of modifying the speed stability is the response to elevator input. In the first half cycle of the oscillation following a step input, the response follows closely the theoretical behaviour assuming no speed change. However, subsequently, the speed does change in practice and the response differs from the theoretical, and this difference is more marked when $\partial T/\partial\alpha$

is included as an autothrottle term. This altered behaviour with $\partial T/\partial \alpha$ is unlikely to be important in the present tests, and of course has no general applicability to other aircraft. The tests are described in Appendix A.4 and the results shown in Fig. 27.

7.2. *The Method of Measurement and Analysis.*

In the final reckoning the acceptability or otherwise of a given level of instability must depend on the subjective assessments of pilots. In this sense the present tests will only lead to a qualitative result. Nevertheless an attempt has been made to find some quantitative measure of the difficulty of the approach task. Since the physical effort of controlling the aircraft, even in the most unstable condition, is relatively small, the pilots' assessment must reflect essentially the mental effort involved. In the absence of a reliable indication of cerebral activity it is debatable whether the measurement, however defined, of the pilots input in terms of throttle and elevator actions (or the output in terms of speed and glide-path holding) necessarily provides a good indication of the difficulty of the task, though one might hope that the mental effort might be translated into physical action. Nevertheless, it is possible that the task may be rated equally difficult when in one case the input, as defined above, is high and the output low (i.e. good speed and glide-path holding achieved by great effort) and in another case when the input is low and the output high (poor performance with little expenditure of effort). Under these circumstances, a similar measure of difficulty for the two cases could only be hoped for from a parameter which weighs both the pilot effort and the achieved performance simultaneously, called here the 'total measure'. An additional variable, over which no control is possible, and for which in the present experiment no quantitative measurements is available, is the atmospheric turbulence.

It remains to define the method of quantifying the measurements. Of the possible methods the most satisfactory would probably be a complete spectral analysis. Unfortunately the instrumentation was hardly adequate for such an analysis, nor was the effort available to carry it out effectively and it lacks the virtue of simplicity for use in, and comparison with, other tests. Another possibility, which was examined, was counting the frequency of elevator movements, and to a lesser extent of throttle movements and speed fluctuations. The glide-path, however, changed only slowly and any high frequency content was filtered by the theodolite tracker. The combination of the individual contributions from these sources seemed to indicate more the atmospheric turbulence combined with general pilot-noise rather than the difficulties due to speed instability. Consequently, the measure chosen was the amplitude of the deviations from the mean, so that the average value of the square of each half second deviation from the mean gave the variance of the measured contribution, i.e. the contribution from elevator, throttle, speed and glide-path. The square root of the variance gives the standard deviation, which very nearly equals the root mean square. The variances were obtained in a miscellany of units from the four parameters, involving degrees for elevator and glide-path, inches for throttle and knots for speed, and required scaling for addition into total input, total output and total measure. While many methods of scaling could be devised, and some were considered, that chosen was the simplest. The highest variance for any parameter obtained by one pilot in a series of tests in a given configuration* was divided into each of his other variances for the same parameter to give the so-called scaled variance. The scaled variances were therefore non-dimensional with a maximum value for each pilot of unity. The mean of the throttle and elevator scaled variances was defined as the total input, that of the speed and glide-path as the total output, and the mean of all four as the total measure. There is an implicit assumption that each parameter is of equal importance (in relation to its maximum variance) in determining the difficulty of the task. There is no defence for this assumption except the absence of an obviously better alternative. Statistical tests using scaled variances gave similar results to those obtained from the measured, dimensional, variances except in certain obvious cases; where, for example, the variances from one of the pilots were consistently larger than from the other pilots the increased scatter could reduce the level of significance, an effect eliminated by using scaled variances.

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*A 'configuration' is defined as a given cg position, glide-path control, and autothrottle law. Change in the gain of the autothrottle terms, i.e. a change in speed stability, does not change the configuration.

The scatter in results obtained under nominally constant conditions has required the use of statistical methods to determine the influence of the variables on the measurements. When two or more factors may be important the technique of 'analysis of variance' can be used to find out which, if any, of the factors is affecting the results. Thus, for example, it is possible to see whether a change in cg position is causing differences in the results of tests made over a range of speed stability, or alternatively, whether a change in glide-path control, or the addition of the $\partial T/\partial\alpha$ term, is important. If on the other hand, one wishes to compare any two levels of speed stability in otherwise identical conditions the 'Students t' test is appropriate. For example, in the configuration of aft cg, tight theodolite control and destabilising $\partial T/\partial V$, there are twelve measurements for each of the four parameters at each of nine levels of speed stability. The 'Students t' test can be used to compare the mean of one group of twelve measurements with the mean of any of the other eight groups, taking account of the spread of values about the means, to determine whether they are drawn from the same, or different, populations. If the populations are said to differ at the 5 per cent level of significance it is implied that there is a one-in-twenty chance that the observed difference is due to some unidentified random cause rather than a real difference due to the factor under consideration. A difference at the 1 per cent level is more significant than one at the 5 per cent level, there then being only a one-in-a-hundred chance of this result being accidental, i.e. the result is exposing what is very likely to be a genuine effect of the factor on the measurements.

Finally, the relation between both the throttle and elevator position and each of the errors in speed and glide-path can be determined by regression lines from which cross-correlations can be calculated. It is then possible to test whether any one pilot's control is used primarily for controlling any one of the outputs.

7.3. *The Pilots' Assessments.*

The four pilots participating in the initial approach tests, which have been analysed statistically, commented on the relative difficulty of the task at various levels of speed stability, the influence of the terms in the autothrottle, and the effect on performance of the method of glide-path control. In the later series of tests, with four different pilots, an attempt was made to define levels of pilot acceptability using a numerical rating scale, at the same time extending the speed stability range and accumulating more measurements of control usage and performance. The rating scale is given in Table 4 and is a slightly modified version, directed more towards the approach task, of the familiar NASA scale[12].

The descriptive wording of the rating table was discussed with and approved by the pilots prior to the start of the assessment but experience of its use indicated that the inclusion of 'average', with its various qualifications, was a mistake. Pilots' opinion of 'average' differed, so that the subsequent description could be incomparable with it; e.g. one pilot considered the average aeroplane of this type as pleasant to fly on the approach and should be rated 2, not 4, as demanded by Table 4. At an early stage it was decided, therefore, to ignore the 'average' descriptions and to rate on the basis of aircraft characteristics only. This illustrates the danger of redundant information in a rating scale.*

The pilots were asked to rate the aircraft solely on the conditions they experienced during the particular approach. They were not expected to extrapolate their impressions to a hypothetical aircraft in an operational environment taking account of their background experience.

8. *Approach Measurements and Analysis of Results.*

The approach measurements have been divided into two series: the initial series in which four pilots participated and on which statistical tests have been made, and the later series by four different pilots to greater levels of instability on which no statistical analysis was done.

Most of the measurements for the initial series were made with the aircraft at the aft cg position (0·287 $\bar{c}$) using artificial $\partial T/\partial V$ only and tight theodolite talkdown control. Each of the four pilots made three

*The rating scale used has a number of inconsistencies inherited from the NASA scale and has, subsequent to the tests described, been improved. But Table 4 presents the scale actually used by the pilots and must therefore be retained here.

approaches at each of eight different autothrottle gain settings in addition to six approaches in the basic aircraft condition. The same pilots then repeated the tests at the forward cg position (0·234 $\bar{c}$) but making only one approach at each gain setting. Two of these pilots also made one approach at each gain setting with the aircraft at the aft cg position and using a combination of artificial $\partial T/\partial V$ and $\partial T/\partial \alpha$. They then made some further approaches in the same aircraft configuration to investigate various talkdown techniques, viz. tight control, loose control and P.A.R. control.

The later series of tests was made in the aft cg position and covered both artificial $\partial T/\partial V$ and a combination of $\partial T/\partial V$ and $\partial T/\partial \alpha$, tight talkdown control and P.A.R. control, and the addition of engine lag. These tests were made primarily to obtain numerical pilot opinion ratings; measurements of performance were made and are presented but the number of approaches in each condition was variable, and particularly at the higher gain settings (i.e. the more unstable conditions) the mean results represent in many cases only one approach by one pilot. The trends shown in the figures are therefore only indicative and no statistical analysis of the results has been made; indeed no confidence could be placed on such an analysis. Further, as discussed in Appendix C, there is some doubt as to the actual level of speed instability obtained at the higher gain settings, due to the lag in the engine thrust response.

The statistical tests have been made on the basis of the variance of the measured results, i.e. throttle, elevator, speed and glide-path variance. However, the figures show the standard deviation of the parameters as this gives more comprehensible units.

8.1. *Aft cg Position, Artificial $\partial T/\partial V$ only, Tight Talkdown Control.*

We shall concentrate on tests in these conditions as they provide the most satisfactory statistical sample.

The basic aircraft was speed stable with a time to half amplitude of 59·5 seconds, or $1/T_{\frac{1}{2}} = 0{\cdot}0168$ second^{-1}. The most severe conditions of speed instability tested statistically simulated a time to double amplitude of 6·02 seconds, or $1/T_2 = 0{\cdot}166$ second^{-1}. The later series of tests included times to double amplitude, nominally as low as 2·22 seconds, or $1/T_2 = 0{\cdot}451$ second^{-1}.

As an indication of the need for statistical analysis the approach records of elevator angle and throttle position, and of speed error and glide-path elevation error, have been converted into histograms which show the proportion of time (i.e. number of half seconds) for which each quantity was at a given value. Some typical results are shown in Fig. 9 where the upper two rows are for the basic aircraft and the lower two rows for a time to double amplitude of 6·02 seconds. The 'best' and 'worst' approaches by one pilot are shown. 'Best' and 'worst' are not used in any precise sense but merely to draw a distinction between a set of histograms with pronounced peaks, indicating low values of the variance, and those which are spread out, giving high values of the variance. The problems of determining the difficulty of the task are apparent. For example, the output (speed and glide-path error) in the 'best' performance of the unstable aircraft, Fig. 9c has a lower variance (more peaky histogram) than the 'worst' performance of the stable aircraft, and indeed the glide-path results are little different for the 'worst' performance in the two cases, Fig. 9b and Fig. 9d.

Fig. 10 shows the standard deviations of the four measured quantities against speed stability. The scatter from the individual pilots (each point is itself the mean of three approaches) is considerable and it is difficult to see any obvious trend with speed stability. Statistical tests have therefore been made using the method of scaled variances discussed in Section 7.2.

Fig. 14 shows the mean scaled variances for this configuration. The throttle scaled variance Fig. 14a shows the most uniform change with speed stability. The elevator variance is erratic and causes a similar variation in the total input. However, the total output, Fig. 14b, is considerably smoother than either the speed or glide-path individually. The total measure, Fig. 14c, also shows a comparatively smooth variation with speed stability. Table 6A summarises the statistical tests. The rows are compared with the columns, a letter indicating that a given row is worse than a given column at the 5 per cent level of significance, or more. Thus, as an example of the use of this Table, the first column shows that the throttle variance was greater for all unstable speed conditions than it was for the basic aircraft; likewise, at levels of speed stability represented by $1/T_2$ of 0·122 second^{-1} and 0·166 second^{-1} by reading across the rows at these two values it is seen that the throttle variance was greater than for all speed stabilities given by $1/T_2$ up to and including the column headed 0·069 second^{-1}.

Certain general features are apparent from Table 6A. The throttle usage shows the most frequent significant differences. On no occasion is there a marked deterioration of speed or glide-path holding or in total output. Only rarely is there an important difference in the elevator usage, and rather more frequently in total input and total measure, the latter two being influenced of course by the throttle.

8.2. *Effect of cg Position.*

Fig. 11 compares the mean standard deviations calculated for all pilots and all approaches at the aft cg with those for the forward cg, in both cases with artificial $\partial T/\partial V$ only and tight talkdown control. The small differences in the curves for the aft cg from those of the previous figure are due to the inclusion of results from the second series of tests, which also provide measurements at much more severe levels of instability. Although no statistical tests were made at these higher levels of instability it is interesting to note the continued increase in throttle usage as the aircraft becomes more unstable and to compare this with the lack of any similar clear trend for elevator usage and speed holding.

The results of the statistical tests on the effect of cg position are shown in Table 5. Considering only the basic aircraft there is no large effect on the throttle usage, or speed and glide-path holding but the elevator usage is increased at more than the 1 per cent of significance with forward cg movement. The same result is obtained for throttle, elevator and glide-path when considering all comparable levels of speed stability (i.e. up to $1/T_2 \simeq 0{\cdot}17$) but the speed holding is now improved at the 5 per cent level. The fact that the elevator variance is roughly doubled by the forward cg movement is explained by the increase in static margin. This is, of course, not necessarily an indication of increased effort and reflects perhaps more a potential weakness of this parameter as an absolute criterion.

The statistical tests at various levels of speed instability for the forward cg are given in Table 6B; the much smaller number of approaches at this cg position should be remembered, However, the throttle is again clearly the important measure. The four occasions on which significant differences in speed variance occur are due to exceptionally good speed holding at $1/T_2 = 0{\cdot}022$ second^{-1} rather than poor speed holding at the four higher levels of instability. As for the aft cg, glide-path and total output do not feature in the Table; neither on this occasion do elevator or total measure.

8.3. *Effect of the Addition of Artificial $\partial T/\partial \alpha$.*

Fig. 11 compares artificial $\partial T/\partial V$ alone with artificial $\partial T/\partial V$ plus $\partial T/\partial \alpha$, both at the aft cg position, with tight talkdown control. The results in Table 5 show that the additional term causes a reduction in the speed and glide-path errors at the 1 per cent level of significance. The reduced speed and glide-path errors are to be expected due to the lower value of artificial $\partial T/\partial V$ at a given speed stability; the tendency, for example, to be both fast as well as high following a head gust, as discussed in Section 7.1, is reduced by the addition of artificial $\partial T/\partial \alpha$. While Table 5 shows no important effect of the addition of $\partial T/\partial \alpha$ on the elevator and throttle usage, Fig. 11 appears to indicate a relative decrease in throttle and increase in elevator usage at the higher levels of speed instability. Though plausible, this result must be treated with great caution as only one pilot made only one approach for each of the two autothrottle laws at each level of speed stability where $1/T_2 > 0{\cdot}25$ (nominal).

Table 6C shows the tests for the significance of speed stability. Apart from the appearance again of the throttle there are now a number of differences in total measure occurring in isolation. This may be indicative of a general deterioration in several of the parameters, none of which is individually important, but is more likely to be due to the nature of the statistical tests. In this case only two approaches were made at each gain setting so that in the tests for significance on the basic parameters (throttle, elevator, speed and glide-path) only two samples are available, requiring rather a large change to show a statistical difference, whereas on total measure there are eight samples (two from each of the basic parameters), with a consequent reduction in the size of the change required.

8.4. *Effect of Type of Talkdown Control.*

Fig. 12 shows the results with the three types of glide-path control for the aircraft in the aft cg position and with both artificial $\partial T/\partial V$ and $\partial T/\partial \alpha$. As shown in Table 5 there is no large difference between tight and loose glide-path control by the theodolite but with P.A.R. control the speed and glide-path holding show a large deterioration. The variances for these parameters differ at more than the 1 per cent level of significance, both when considered for the basic aircraft alone and for all levels of speed stability. Some of the glide-path variance is probably due to the imprecise nature of the control so that even had the pilot managed to follow instructions as perfectly as his interpretation of what was required allowed, there would still be a large variance. Pilots found P.A.R. control more difficult, mainly due to demands for heading corrections at times when the pilot was fully occupied with the longitudinal control problem. Lateral corrections under theodolite control were made visually, and consequently at any convenient time. The need to 'look out' for lateral guidance was also a contributory reason for the greater ease of theodolite control since additional visual information on glide-path, aircraft attitude, etc. was obtained. It is noteworthy, however, that the important throttle usage under P.A.R. control does not differ appreciably from that for the other types of control.

Table 6D shows the effects of speed stability on the variances when under P.A.R. control. Again the throttle is much in evidence, with occasional significant differences also in elevator, speed and total input. The total measure also appears quite frequently, occasionally in isolation; the same remarks as in Section 8.3 on the limited number of approaches apply also in this case.

8.5. *Effect of Engine Response.*

Only a few tests were made with additional lag incorporated in the engine control system. Fig. 13 therefore gives only a general indication of the effect of poorer response on the results and is a quite inadequate sample for drawing firm conclusions. There is, nevertheless, an indication of increased throttle usage and a deterioration in speed holding with the extra lag incorporated. Pilots were very disturbed by the poor engine response characteristics.

8.6. *Results of the Pilots' Assessments.*

The pilots engaged in the initial series of tests commented in general terms on the influence of speed stability in the various aircraft configurations and with various types of talkdown control but did not assign any 'ratings' as in the later tests. The cg position made no difference to the assessment of the influence of speed stability but the forward cg was less comfortable; this was due solely to an excessively aft position of the control stick in the trimmed state. The addition of artificial $\partial T/\partial\alpha$ also made no difference to pilots comments at corresponding levels of speed stability.

Pilots comments under tight talkdown control indicated that in calm air there was little increase in difficulty at lower values of instability but a sharp increase in difficulty at $1/T_2 \simeq 0{\cdot}1$ second^{-1} and thereafter a progressive increase in difficulty. Under moderately turbulent conditions increased difficulty was experienced at $1/T_2 \simeq 0{\cdot}04$ and under more turbulent conditions all levels of instability were more difficult than the basic aircraft, with $1/T_2 \simeq 0{\cdot}17$ requiring great concentration and $1/T_2 \simeq 0{\cdot}23$ being considered marginal for the approach.

Pilots claimed that loose talkdown control by the theodolite was easier than tight control, although the measurements show no difference. This, perhaps, is due to the reduced mental pressure on the pilots with less frequent demands for glide-path changes but with still sufficient information to give them a clear indication of their position.

P.A.R. control was the most difficult of the glide-path control systems. Time spent in heading changes left less time for longitudinal control, and inadvertent elevator movements occurred as a result of control stick inputs for lateral corrections. At speed stabilities given by $1/T_2 \geqslant 0{\cdot}17$ second^{-1} it was necessary to concentrate on glide-path control at the expense of azimuth control. The infrequent and imprecise glide-path information made large corrections necessary, which is highly undesirable in an unstable system.

Four different pilots in the later series of tests used the rating scale of Table 4 for assessing the approach. The cg was in the aft position throughout and both tight theodolites and P.A.R. control were rated.

Fig. 15* shows the individual ratings obtained, plotted against speed stability, and shows a separate graph for tight theodolite control and for P.A.R. control. Two speed stability scales are shown on the figure; that marked 'nominal' corresponds to instantaneous response to a demanded thrust change and that marked 'estimated effective speed stability' takes account of thrust lag as discussed in Appendix C. As stated in Section 7.3, pilots rated the aircraft according to their experience on the particular approach being assessed. Some of the scatter may be due to this, as the difficulty of a given approach clearly depends on a number of extraneous factors as well as on the speed stability. Pilots were, however, asked to assess the level of turbulence during each approach, but no consistent variation of rating with this factor could be discovered. Nor was there any consistent difference between pilots. Detailed comparisons in the figure indicate that P.A.R. control tends to be rated rather more difficult than tight theodolite control but by less than one point on the scale on average.

Fig. 16 shows the variation of rating with speed stability; the distinction between the types of glide-path control has here been ignored and mean ratings are given at those levels of speed stability where more than one rating is available. While such averaging assumes a linearity which the rating scale does not inherently possess, and could lead to false results where the ratings differ appreciably for any particular approach condition, Fig. 16 does nevertheless give a good general indication of the trend of rating variation with speed stability.

Fig. 16a confirms the earlier comments that the addition of $\partial T/\partial\alpha$ made no marked difference to the ratings. At $1/T_2 \simeq 0{\cdot}1$ second^{-1} the approach characteristics are such that they are becoming unacceptable for normal operation. However, not until a nominal $1/T_2 \simeq 0{\cdot}45$ second^{-1} do the characteristics become dangerous; this is a surprising result implying that in an emergency times to double amplitude of $2\frac{1}{4}$ seconds, or a time constant of $-3\frac{1}{4}$ seconds, could be tolerated. However, at these nominal levels of speed instability the lag in the thrust response to speed changes reduces the actual instability although even with the estimated effective value a time to double amplitude of only $2\frac{3}{4}$ second is obtained. An additional factor is that under these conditions the autothrottle gain setting was so high that occasionally the limits of throttle movement were reached. The destabilising terms were not then effective and a potentially uncontrollable situation may have been avoided. Finally, Fig. 15 shows that at these higher levels of speed instability there are few rating points and that almost as high ratings are obtained at very much lower levels of instability. It would therefore be rash in the extreme to draw any firm conclusion on dangerous levels of speed instability from the limited data here available. Suffice it to say that greater instability does seem to be tolerable in an emergency than had hitherto been supposed, provided that the other aircraft characteristics are reasonable.

Fig. 16b shows the effect of the additional engine response lag on the ratings. Even small amounts of instability are now unacceptable for normal operation and dangerous conditions are reached at $1/T_2 \simeq 0{\cdot}15$ second^{-1}, or $\tau = -10$ seconds.

9. *General Discussion.*

The results show that variations in speed or angular displacement from the glide-path are not a sufficiently sensitive measure of the difficulty of the task since harder work by the pilot produces similar results at all levels of speed stability which have been analysed. The only measured quantities which could be expected to show a meaningful correlation with pilot effort in the present tests were the inputs to the elevator and throttle controls. Movement of the elevator due to general pilot 'noise' and the instinctive correction of aircraft attitude changes due to atmospheric turbulence effectively masked any deliberate movements for the correction of speed or glide-path errors. However, the work load as measured by throttle variance during the approach does show marked changes with change in speed stability, and these changes are consistent with pilots' assessment of the difficulty of the approach task.

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*Here, and in Fig. 16, the annotations to the right refer to the main sub-divisions (left-hand column) of Table 4. But (*see* footnote, Section 7.3) it should be noted, for example, than an 'unsatisfactory' rating can also be 'unacceptable' under normal circumstances.

The use of mean scaled variances proved quite successful in adding together the individual variances to give meaningful parameters showing better correlation with task difficulty than any one of the individual variances. Thus the total pilot effort as indicated by the total input (throttle plus elevator), and the overall task assessment, pilot effort plus approach performance, as indicated by the total measure (sum of throttle, elevator, speed and glide-path) gave additional information. This was particularly so when only a few approaches were available for analysis at each level of speed stability, as shown for example in Tables 6C and 6D. Of the four individual parameters measured in the present experiment, however, throttle usage provided the most sensitive measure of pilot effort and therefore presumably of task difficulty.

Table 6A shows that, compared with the basic aircraft, $1/T_2 = -0{\cdot}017$ second^{-1}, any speed instability causes a marked increase in pilot workload as measured by the throttle usage. Thus the throttle assumes more the characteristics of a primary control rather than a simple trimmer and the workload on the pilot is increased. However, it is not until a level of speed instability represented by $1/T_2$ between 0·091 second^{-1} and 0·122 second^{-1} that there is a marked increase in throttle usage compared not only with the basic aircraft but also with lower levels of speed instability. This marked increase in workload corresponds very well with the pilot ratings of Fig. 16a which show that at $1/T_2 \simeq 0{\cdot}1$ the aircraft is becoming unacceptable for normal operation. These results therefore indicate that, on this class of aircraft and with this type of glide-path control, a value of speed stability given by $T_2 = 10$ seconds, or time constant $\tau = -14{\cdot}5$ seconds could be accepted for normal operation, *provided* no particular difficulties are encountered from other aircraft characteristics. In this connection it should be noted that the thrust response was satisfactory, Fig. 8; the control thrust available, $\dfrac{\Delta T}{W} \simeq 0{\cdot}14$, at the nominal approach speed of 120 knots, was greater than the suggested minimum[3,4] of $\dfrac{\Delta T}{W} = 0{\cdot}12$; also, the lateral characteristics were generally satisfactory. The lateral oscillation had a period of 3·6 seconds with a time to half amplitude of 2·6 seconds and the spiral mode was mildly convergent ($T_{\frac{1}{2}} = 36$ seconds). The response to sudden aileron application was oscillatory but the roll rate remained of the desired sign.

The value of speed stability determined above as a minimum can be applied strictly only to the aircraft of these tests, or to one of similar type and characteristics. The effects on the approach difficulty of deterioration in lateral characteristics, very small or negative static margins, changes in elevator response, etc., required further investigation. Also, the influence of aircraft size on acceptable speed stability may be important, particularly perhaps where it leads to the movement of the aircraft throttles by a pilot different from the one flying the approach. It should further be noted that the value of speed stability determined here is very much lower than the minimum suggested by Lean and Eaton[2], their parameter giving values of the time constant $\tau = +64$ seconds for instrument approaches on the aircraft of the present tests, $\tau = -64$ seconds for ordinary visual airfield approaches, and $\tau = -22$ seconds for aircraft carrier approaches. It is, of course, debatable whether 'selected' or even 'minimum comfortable' airspeed on the approach, on which the analysis of Ref. 2 is based, is the same as the 'minimum acceptable for normal operation', bearing in mind that this corresponds to a pilot rating, ($4\frac{1}{2}$) in Table 4, which is nevertheless 'unsatisfactory'. Further, while a number of the aircraft considered in Ref. 2 were stated to be limited by drag effects in the determination of approach speed, it is not known to what extent a general deterioration in other characteristics influenced the difficulty of the approach task. On the other hand, it is probable that, in the present tests, additional information was obtained by the pilot, from the change in engine noise (*see* Section 7.1) resulting from the operation of the automatic throttle; but it is not obvious how important this cue was in the presence of the continuous 'talkdown' from the theodolite ground controller, although pilots admitted to being aware of it. It was also possible for the pilot to see the movement of the aircraft throttle, but it was well out of his normal visual field. In fact, unless continuously monitored to hold it in a fixed position, the aircraft throttle would be of little help since it would lag behind information available from the airspeed indicator.

The effects of the type of glide-path control on the difficulty of the approach are of some interest. The precision approach radar control, P.A.R., gave a large increase, compared with other types of control, in speed and glide-path deviations but no significant change in the amount of throttle movement. Nevertheless, the change in throttle variance with speed stability followed a similar pattern to that under other types of control. It would appear that, where throttle variance is used as a measure of the difficulty of an approach, the type of glide-path control is not important for comparative assessments, although it should be noted that only 'talkdown' types of control have been investigated. The use of visual approach guidance, e.g. Instrument Landing System, zero reader, deck landing projector sight or visual glide-path indicator, might result in a different conclusion. Also, pilots commented that the need for lateral corrections with P.A.R. control, often at times when they were busy with the longitudinal control task, made the latter more difficult. This was not evident from the throttle usage results although pilot ratings did indicate a slight increase in difficulty. Further evidence is therefore required as to whether throttle variance is a sufficient measure of difficulty in the case where lateral characteristics are changed at a given level of speed stability. The large deterioration in speed holding ability under P.A.R. control is due to the larger corrections required as a consequence of the imprecise glide-path control.

The manner in which a pilot uses the controls to maintain a constant speed and glide-path is frequently under discussion. To provide some information on this the cross correlations were made between throttle position and elevator angle and also between each of these and speed error and glide-path deviation. These showed that the throttle position was strongly dependent on the speed error, as also was the elevator angle. Similarly, both throttle position and elevator angle were strongly dependent on glide-path error. Thus, no one pilot's control was exclusively used for the elimination of any one type of error, and whether pilots claim to use the throttle for speed control and the elevator for glide-path control, or *vice-versa*, the evidence is that on this particular aircraft at least they used both together. In statistical terms, the cross correlations are highly significant, being greater than the 1 per cent level. The fact that, in the absence of a change of trim with thrust, pilots co-ordinate their control movements extremely well, does not mean that the need to co-ordinate has no effect on the difficulty of the approach task. Some pilots at least think in terms of throttle for speed control, and thus a small nose down change of trim with increasing thrust, producing a change of speed with little effect on the glide-path angle, might be desirable. On the other hand, a nose up change of trim with increasing thrust, producing a change of glide-path angle with relatively little effect on the speed might be preferred by pilots thinking in terms of throttle for glide-path control.

The increasingly wide adoption of automatic throttle control for aircraft on which the speed stability characteristics might present problems, and even on those where no such difficulties are anticipated—for use in automatic landing for example—might lead to the conclusion that the natural speed stability of an aircraft is no longer of real significance. While the use of automatic throttles has undoubtedly alleviated potentially critical speed stability characteristics, and suggests an experiment to determine the optimum speed stability rather than the level of instability which can just be tolerated, it is nevertheless still of considerable importance to determine the acceptability to the pilot of various levels of speed instability. The required reliability, and hence the degree of redundancy, of the automatic throttle system will be influenced by the characteristics of the aircraft in the event of failure. Cases can be envisioned in which the complication and expense of fitting an automatic throttle may be in dispute.

The present Report provides information only on a small, single engined, aircraft with a rather special type of glide-path control. For the more general case work is required particularly on large aircraft using conventional civil aviation landing aids. The pilot's willingness to operate the throttles of a multiengined aircraft at the same frequency as in the case of a single throttle may be doubted. The type of operation in which one pilot flies the approach and a second pilot moves the throttles in response to requests from the first pilot represents a different form of control. The case where the pilot on the throttles moves them, on his own initiative, in response to airspeed changes represents yet another form of control; in this instance the correlation between throttle movement and elevator or glide-path changes is clearly destroyed.

Experiments to investigate these different types of operational control, and the effect of speed stability on them, have still to be done.

10. *Conclusions.*

Tests have been made on an Avro 707A research aircraft to investigate the effect of speed stability on the difficulty of the landing approach task. The speed stability was varied at a nominally constant approach speed by changing engine thrust in response to speed errors, or incidence changes, using an automatic throttle control operating in the 'reversed' sense.

The flight measurements showed that the throttle variance, or mean square movement, is the best single guide as to difficulty of the approach. No important changes in elevator usage, or speed and glide-path holding were apparent as speed stability was altered. On the other hand, change from a tight talkdown form of glide-path control by theodolite to P.A.R. control, showed significant increases in speed and glide-path deviations, but not in the throttle variance, suggesting that where the throttle is used as a measure, the type of talkdown control is not important.

At all levels of speed instability the throttle usage was significantly greater than for the basic, speed stable aircraft. Further, at a level of speed instability given by a time to double amplitude of about 10 seconds, the throttle usage differed significantly from that at all less unstable speed conditions, and this level corresponds to that at which pilots' ratings indicate that the approach characteristics were just unacceptable for normal operation. This minimum level of acceptable speed stability is considerably lower than that previously determined and further investigation is required, particularly to consider the effect of aircraft lateral characteristics, and perhaps also the effect of 'split control' on large, or multi-engined, aircraft where the throttles are moved by a pilot different from the one flying the approach.

The incorporation of a rather large deterioration in thrust response to pilots throttle movement caused a considerable decrease in the maximum tolerable instability so that a condition of doubling amplitude in 50 seconds became unacceptable for normal operation.

Measurements of the aircraft longitudinal characteristics in the landing configuration showed a marked change of behaviour due to adding the artificial stability terms only in the phugoid oscillation. The period of the oscillation was little affected but the damping deteriorated from a time to half amplitude of under 30 seconds for the basic aircraft to a time to double amplitude of about 4 seconds in the most severe condition of speed instability investigated.

LIST OF SYMBOLS

		Units
$a = \dfrac{\partial C_L}{\partial \alpha}$	Lift-curve slope	—
B	Moment of inertia in pitch	slugs ft^2
$C_D = \dfrac{D}{qS}$	Drag coefficient	—
$C_L = \dfrac{L}{qS}$	Lift coefficient	—
C_{L_t}	Trimmed lift coefficient	—
$C_p = \dfrac{p-p_0}{q}$	Pressure coefficient	—
$\bar{c}$	Mean aerodynamic chord	ft
D	Drag	lb
g	Gravitational acceleration	ft/s^2
H_m	Manoeuvre margin, stick fixed	$\bar{c}$
h	Centre of gravity position	$\bar{c}$
$i_B = \dfrac{B}{\dfrac{W}{g}\bar{c}^2}$	Non-dimensional pitching moment of inertia coefficient	—
$J = \dfrac{2\pi\hat{t}}{P}$	Non-dimensional frequency	—
L	Lift	lb
$m_q = \frac{1}{2}\dfrac{\partial Cm}{\partial\left(\dfrac{q\bar{c}}{V}\right)}$	Pitching-moment derivative due to rate of pitch	—
$m_w = \frac{1}{2}\dfrac{\partial C_m}{\partial \alpha}$	Pitching-moment derivative due to change of incidence	—
$m_{\dot{w}} = \frac{1}{2}\dfrac{\partial C_m}{\partial \dot{\alpha}}$	Pitching-moment derivative due to rate of change of incidence	—
$m_\eta = \frac{1}{2}\dfrac{\partial C_m}{\partial \eta}$	Pitching-moment derivative due to change of elevator angle	—
$m_{\dot{\theta}} = m_q + m_{\dot{w}}$	Complete pitching rotary-damping derivative	
P	Period	seconds
p	Vent hole static pressure	lb/ft^2
p_0	Atmospheric pressure	lb/ft^2
$q = \frac{1}{2}\rho V^2$	Dynamic pressure head, or rate of pitch	lb/ft^2 rad/s

LIST OF SYMBOLS—*continued*

		Units
$R = \dfrac{0{\cdot}693\,\hat{t}}{T_{\frac{1}{2}}}$	Non-dimensional damping factor	—
S	Wing area	ft^2
T	Thrust	lb
$T_{\frac{1}{2}}$	Time to half amplitude	s
T_2	Time to double amplitude	s
$\hat{t} = \dfrac{W}{g\rho SV}$	Unit of aerodynamic time	air s
u	Change in aircraft speed	ft/s
V	True airspeed	ft/s
V_R	Rectified airspeed	knots
W	Aircraft weight	lb
$\dot{x} = \dfrac{u}{\bar{c}}$	Change in aircraft speed	$\bar{c}$/s
z_w	z-force derivative due to change of incidence	—
α	Angle of incidence	rad
γ	Angle of climb	rad
ε_D	Damping angle	deg
η	Elevator angle	rad, deg
θ	Pitch attitude	rad
$\mu = \dfrac{W}{g\rho S\bar{c}}$	Aircraft relative density	—
ρ	Air density	$slugs/ft^3$
σ	Standard deviation	various
τ	Time constant of speed stability	s
ω	Circular frequency of oscillation	s

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APPENDIX A

Aircraft Longitudinal Aerodynamic Characteristics.

A.1. *Introduction.*

As part of the speed stability investigation detailed measurements were made of the lift, drag and longitudinal stability of the Avro 707A. The results have been quoted as necessary in the main text but are presented here in full so as to define accurately the pertinent characteristics of the aircraft and to permit comparison with other aircraft used for similar investigations. All tests were made in the landing configuration of undercarriage down, trim flaps fully up, and airbrakes fully extended.

A.2. *Lift and Drag.*

The lift and drag were measured in the landing configuration at the mid cg position (0·265 $\bar{c}$) by the partial glide technique. Glides were made at flight idling power over a speed range 100 to 170 knots and altitude range 7000 to 5000 feet. Aircraft attitude was determined from a pendulum level and angle of glide from rate of change of altitude.

Fig. 17 shows the measured variation of trimmed lift coefficient with incidence. The considerable effect of cg position on the lift-curve slope is shown in Fig. 18 where the lift contribution of the elevator has been taken as $dC_L/d\eta = 0{\cdot}573$ per radian, from tunnel tests[7]. A curve is also shown of the variation of lift coefficient with incidence, elevator fixed*, with a lift-curve slope, $dC_L/d\alpha = 2{\cdot}66$ per radian; this is the derivative required for the analysis of short-period pitching and phugoid oscillations.

The drag measurements are shown in Fig. 19. The linear portion, $C_{L_t} < 0{\cdot}5$, can be represented by:

$$C_D = 0{\cdot}054 + 0{\cdot}16\, C_{L_t}^2$$

where C_{L_t} is trimmed lift coefficient.

Some of the drag is due to the deflected elevator required to trim. Estimates[8] have been made of elevator drag assuming equivalence to a trailing edge plain flap and a corresponding drag equation deduced for the forward (0·234 $\bar{c}$) and aft (0·287 $\bar{c}$) cg positions. It was then also possible to deduce the relation between drag and incidence, elevator fixed (required for the stability analyses), giving:

$$\frac{dC_D}{d\alpha} = 0{\cdot}774\, C_{L_t}.$$

These results are summarized in Table 2.

A.3. *Static Stability.*

The aircraft was trimmed, in the landing configuration, at 7000 feet with engine thrust for level flight at the forward, mid and aft cg positions and with flight idling thrust at the mid cg position. The speed range was 100 to 170 knots.

Curves of elevator angle to trim against trimmed lift coefficient are shown in Fig. 20 from which it is apparent that the effect of thrust is negligible. Fig. 21 shows a similar plot with the lift coefficient corrected to constant, zero, elevator angle and is indicative of the static stability of the aircraft at the three cg positions. Fig. 22 is a cross plot of Fig. 21 of elevator angle to trim against cg position for various values

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*A down elevator angle, $\eta = 3{\cdot}0°$, has been chosen as this is the trimmed condition for all cg positions at zero lift coefficient (*see* Fig. 20).

of lift coefficient. The slope of the tangent to these lines at any point gives the elevator power since (*see* Appendix B):

$$\frac{dC_m}{d\eta} = -\frac{dh}{d\eta}C_{L_t}$$

where h is cg position and η elevator angle.

Elevator power is given in Fig. 23. Conversion to pitching moment coefficient, C_m, of the elevator angle to trim of Fig. 21 allows the determination of the stability parameter dC_m/dC_L, which is shown in Fig. 24. Fig. 25 shows the conventional stability derivative, m_w, the displacement of the curves with varying cg position being entirely due to the increase in up elevator, and hence increase in incidence, for a given C_{L_t} as the cg is moved forward.

A.4. *Short Period Pitching Oscillation and Elevator Response.*

Tests on the pitching oscillation were made at 120 knots with various autothrottle gain settings ($\partial T/\partial V$ only). The oscillations were initiated by short, up or down, pulses of the elevator. The mean trimmed lift coefficients were 0·481, 0·460, 0·491 at the forward, mid and aft cg respectively. Fig. 25 shows that the condition investigated, chosen because it was the approach target speed, was one of rapidly changing aircraft static stability so that the analysis, based on fixed coefficients in the linearised stability equations, is not strictly valid. This, combined with inevitable variations in trimmed lift coefficient on different test runs, could account for the scatter in the results below.

Fig. 26 shows the period and damping of the oscillation at various autothrottle gain settings. Mean values are indicated for each cg position as there is no clear trend with gain setting. The oscillation was sufficiently heavily damped to have ceased before any appreciable speed change had occurred; the high damping made it difficult to measure accurately its value, and that of the period, from the trace records.

The full rotary damping derivative, $m_{\dot{\theta}}$, can be calculated from[9]:

$$m_{\dot{\theta}} = m_q + m_{\dot{w}} = -i_B\left(2R - \frac{a}{2}\right)$$

where a is the lift curve slope, i_B is the non-dimensional inertia in pitch and R the non-dimensional damping factor.

The manoeuvre margin, H_m, can be obtained from:

$$H_m = \frac{i_B}{\mu}\frac{2}{a}(R^2 + J^2)$$

where μ is the aircraft relative density and J the non-dimensional frequency of the oscillation.

Finally, if m_q or $m_{\dot{w}}$ can be estimated or deduced, the aircraft static-stability derivative is given by:

$$m_w = -\frac{a}{2}\left(H_m + \frac{m_q}{\mu}\right).$$

Alternatively, if the static value of m_w (Fig. 25), is assumed to hold in the oscillatory case then a value of m_q can be obtained by substituting for H_m and rearranging:

$$m_q = -\frac{2}{a}[\mu m_w + i_B(R^2 + J^2)].$$

However, the accuracy is poor in that, for example, a 10 per cent increase in m_w about halves the value of m_q deduced from the above formula, for this aircraft.

The derivatives have been calculated from mean values of C_L, $T_{\frac{1}{2}}$, P with values for m_q and $m_{\dot{w}}$ derived from estimates[10] and the above formula but adjusted so that their sum gives the flight value of $m_{\dot{\theta}}$. Ground measurements were made of the aircraft pitching moment of inertia, from which i_B was derived, on a rig similar to that used for the Avro 707B[6]. The pitching oscillation results are summarised in Table 3.

The theoretical response to a step elevator input, assuming the speed to remain constant and neglecting the gravity component, is given by[11]:

$$\frac{q}{q_{\text{steady}}} = 1 + \frac{\lambda_2 (\lambda_1 + z_w) e^{-\lambda_1 \tau} - \lambda_1 (\lambda_2 + z_w) e^{-\lambda_2 \tau}}{(\lambda_1 - \lambda_2) z_w}$$

where $-\lambda_1$, $-\lambda_2$ are the roots of:

$$\lambda^2 - \lambda \left(z_w + \frac{m_q + m_{\dot{w}}}{i_B} \right) + \frac{z_w m_q - \mu m_w}{i_B} = 0$$

and q_{steady}, the final, constant, rate of pitch after the transient has damped out, is given by:

$$q_{\text{steady}} = \frac{z_w \mu m_\eta \Delta\eta}{\hat{t} (\mu m_w - m_q z_w)}$$

where $\Delta\eta$ is the magnitude of the elevator step.

Fig. 27a compares the calculated response with the flight measurements for the forward cg position. The ratio q/q_{steady} has been computed from the measured rate of pitch and a value of q_{steady} from the above formula. The effect of the speed change and entry into the phugoid oscillation is shown by the divergence of the flight results from the theoretical curve after the first two seconds. This is more marked at the higher autothrottle gain setting.

Fig. 27b shows a similar comparison at aft cg and gives an additional curve with $\partial T/\partial \alpha$ included as an autothrottle term. The larger effect of this term is due to the rapid incidence change, demanding immediate thrust changes, compared with $\partial T/\partial V$ alone, when no thrust change is demanded until the speed has changed due to the basic aircraft motion.

A.5. *Phugoid Oscillation.*

Phugoid oscillations were induced by increasing speed, using elevator alone, from trimmed level flight at 120 knots and about 6000 feet. Measurements were made at all three cg positions with artificial $\partial T/\partial V$ and at the forward cg with both $\partial T/\partial V$ and $\partial T/\partial \alpha$. Mean values of the damping were obtained from continuous records of pitch attitude and airspeed, and of the period from pitch attitude, airspeed, throttle position and jet pipe pressure. Phase angles between attitude, speed and engine thrust were also measured.

The measured period and damping of the oscillation for the forward and aft cg positions are shown in Fig. 28. Fig. 28b also shows some estimated curves of damping, derived as discussed below, and these are well supported by the flight results.

The measured phase angle between thrust and airspeed, an indication of the autothrottle system response, with artificial $\partial T/\partial V$ gave scattered values between 35° and 15° with some indication of a reduction at the higher gain settings. The reduction could be attributed to a more rapid increase with speed change in signal strength at the higher gain settings, thus causing earlier closing of the relays operating the throttle servo-motor. If this is so then the phase lag would also depend on the rate of change of speed or, in other words, on the amplitude of the speed excursion during the oscillation. Some of the thrust/airspeed phase angle scatter, which will also be reflected in the measured results of period and damping, can be attributed to these causes, and some to the difficulty of accurately determining the phase angle from the records. For the later calculations a constant phase angle of 25° has been taken for all gain settings. With artificial $\partial T/\partial \alpha$ added to $\partial T/\partial V$ the thrust changes occur in response to both speed and incidence changes, and as these variables are not in phase it is not possible to measure the phase angle between thrust and incidence directly. A lag of 25 deg, as in the thrust/speed case, has therefore been assumed. The two cases must give identical phase angles if all the lag occurs after the two pressure transducers as the system is then common to both (Fig. 3), and in fact the lag in the pressure piping to the transducers, which are themselves nominally identical, is negligible.

Autothrottle gains giving $\partial T/\partial V$ as high as 100 lb ft^{-1} s^{-1} were used during the approach investigation but could not be used for the phugoid tests owing to the rapid divergence of the oscillation, which resulted in the throttle reaching the limits of its travels before records long enough for analysis had been obtained. Estimates were therefore made using vector diagrams; typical examples at moderate gain settings are shown in Figs. 29 a and b. The effect of the phase lag between thrust response and speed or incidence changes is shown by the orientation of the artificial $\partial T/\partial V$ vector, for example, relative to the C_D vector in the tangential forces diagram. In this diagram the damping angle, ε_D, is related to the time to half amplitude, $T_{\frac{1}{2}}$, by the relation:

$$T_{\frac{1}{2}} = \frac{0{\cdot}11P}{\tan \varepsilon_D}.$$

The diagrams also show, very small, contributions of articicial $\partial L/\partial V$ and $\partial L/\partial \alpha$ from the autothrottle; these are due to the inclination of the thrust line to the flight path. The phasing diagrams indicate that the excursions in incidence, α, are very small compared with the speed excursions so that the destabilising effect of $\partial T/\partial \alpha$ on the phugoid is relatively small compared with $\partial T/\partial V$. The advantages of the use of $\partial T/\partial \alpha$ for artificially producing speed instability are discussed in Section 7.1 of the main text; the vector diagrams show that it would also have given a more normal damping of the phugoid motion.

The vector diagrams gave estimates of the period in the forward cg position of 33 seconds for the basic aircraft, rising to about 36 seconds at a $\partial T/\partial V$ of 100 lb ft^{-1} s^{-1}. Addition of $\partial T/\partial \alpha$ to $\partial T/\partial V$ gave an increase in period of less than $\frac{1}{2}$ second throughout the range, and aft movement of the cg also increased the period, but by less than one second. These calculations are supported in a general way by the flight results of Fig. 28a. The estimated damping of the oscillation is shown in Fig. 30 which shows the effect of both cg position and the addition of $\partial T/\partial \alpha$.

A.6. *Elevator Control System.*

Finally, Fig. 31 shows the position and force characteristics of the elevator-stick control system at the nominal approach speed of 120 knots. There is an appreciable breakout force from the trimmed position but relatively little backlash in the control movement.

APPENDIX B

Analysis of Static Longitudinal Stability and Elevator Power.

For linearised stability theory, $m_w = \frac{1}{2}\frac{dC_m}{d\alpha}$ on a tailless aircraft with controls fixed.

For flight tests at several cg positions the elevator angle to trim is measured at various values of trimmed C_L.

Assuming conventional superposition of forces so that the force due to the wing depends on the incidence, α, and that due to the elevator on elevator deflection, η, and let h be the distance of the wing aerodynamic centre from the cg, and x the distance of the elevator centre of lift from the cg.

Then

$$C_{L_t} = C_{L_{wing}} + \frac{dC_L}{d\eta}\eta\,. \tag{B.1}$$

Moments about cg:

$$\frac{dC_L}{d\eta}\eta\, x + h\, C_{L_{wing}} = 0 \text{ in trimmed flight}\,. \tag{B.2}$$

Moments about new cg, moved Δh, at same incidence α:

$$\frac{dC_L}{d\eta}(\eta+\Delta\eta)(x+\Delta h)+(h+\Delta h)\, C_{L_{wing}} = 0 \tag{B.3}$$

(B.3) − (B.2):

$$\frac{dC_L}{d\eta}[\Delta\eta\, x + \Delta h\,(\eta+\Delta\eta)] + \Delta h\, C_{L_{wing}} = 0$$

or

$$\frac{dC_L}{d\eta}\Delta\eta\, x = -\left[\Delta h\, C_{L_{wing}} + \frac{dC_L}{d\eta}\Delta h\,(\eta+\Delta\eta)\right]$$

and as Δh, $\Delta\eta \to 0$

$$\frac{dC_m}{d\eta\ (\alpha = \text{const})} = -\frac{dh}{d\eta}C_{L_t} \quad \text{from (B.1)}$$

and then:

$$m_w = \tfrac{1}{2}\frac{dC_m}{d\alpha} = \tfrac{1}{2}\frac{dC_m}{d\alpha}\,\frac{d\eta}{dC_l\ (\eta = \text{const})}\cdot\frac{dC_L}{d\alpha\ (\eta = \text{const})}\,.$$

APPENDIX C

Estimates of the Effective Speed Stability.

Since it was impracticable to measure directly the speed-stability time constants achieved with the various autothrottle gains, estimates have been made on the basis of the known thrust characteristics of the engine and the aircraft drag. In the main text this has been done on the assumption that the dynamic lags between a demanded thrust changes and those actually obtained are negligible and the resulting time constants are therefore quoted as 'nominal' values. As shown in Fig. 8 for the example of a sudden 1000 lb thrust demand the engine response is subject to considerable lag and this should be taken into account when attempting to estimate the effective speed stability time constant.

Unfortunately the engine plus throttle system response is highly non-linear. This is illustrated by the responses to step demands shown in Fig. 32. For this investigation we are interested in the responses to step inputs in speed (or incidence) and from Fig. 3 it is clear that a step input to the airspeed capsule, representing a sharp edged gust, is identical to a step input to the auxiliary throttle. Accordingly the responses are plotted for step inputs of auxiliary throttle and an attempt has been made to fit a second order lag to these responses, as illustrated in Fig. 32. Estimates of the speed-stability time constant for these two demands are shown in Fig. 33 where the 'effective' time constant is plotted against the 'nominal' time constant obtained by ignoring the lag. Because of the non-linear character of the thrust response at differing demanded values, the time constant obtained is such that for small speed disturbances, and/or low autothrottle gains, the effective instability is approximated closely by the nominal values, whereas for large thrust demands the effect of the autothrottle is much reduced and the aircraft is less unstable than would be obtained ignoring the dynamic lag. This is made clearer by the specific example in the following paragraph.

Considering a nominal speed instability represented by $\frac{1}{T_2} = 0{\cdot}2$, Fig. 6 shows that this represents an autothrottle gain giving $\partial T/\partial V \approx 46$ lb ft^{-1} s^{-1} and that therefore a demanded thrust change of 300 lb would be obtained from a $6\frac{1}{2}$ ft/s sharp edged gust, whereas a demand for 1000 lb would require a sharp edged gust of almost 22 ft/s, a value unlikely to be met in the meteorological conditions of the tests. Obviously at lower values of $\frac{1}{T_2}$ even larger gusts would be required for a given thrust demand and *vice versa* at higher values of $\frac{1}{T_2}$. Thus at the lower levels of speed instability the $\Delta T = 300$ lb curve is more representative of approximate true speed instability, which tends towards the $\Delta T = 1000$ lb curve at higher levels of instability.

Fortunately, this is still an unduly pessimistic indication of the effect of engine lag on the simulated speed stability. The thrust demands so far considered have been step changes representing an instantaneous speed change. Speed changes, whether due to pilot action or gusts, take a finite time to occur*. The engine lag in the present tests is made up of two parts; that inherent in the engine due to inertia, fuel flow etc., and that due to the finite rate at which autothrottle system drives the main aircraft throttle. Because of this latter component, and also because of the incorporation of additional engine lag for some of the tests (which was in effect a further rate limit on the main throttle, *see* Section 3.2) the measured response of the engine to two different ramp inputs is available as shown in Fig. 34. The full line represents an almost step demand for thrust whereas the dotted lines in the upper half of the figure can be considered to represent the thrust demands from ramp gusts. The lower half of the figure, showing the amount by which the thrust lags behind that demanded, indicates the considerable benefit from assuming a gradual rather than instantaneous speed change.

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*On a truly speed-unstable aircraft penetration of a gust, even if sharp edged, would also not be instantaneous, but the time taken for the drag to change is not long enough to be significant in the present context.

A non-linear system of this type is not amenable to precise analysis in a general sense. Apart from the need to define a representative gust 'length' for each different intensity of gust, it is also necessary to know the frequency of occurrence of gusts of varying intensity. We also need to know the manner in which the pilot responds, whether as a continuous controller or discreetly. Accordingly a guess as to the effective speed stability has been made and is shown by the chain dotted line in Fig. 33. This line takes account of the infrequent occurrence of large gusts and assumes a longer time to full intensity compared with small gusts.

While no precision can be attached to the curve of estimated effective speed stability it is evident that any difference from the nominal speed stability is trivial for values of $\frac{1}{T_2}$ up to 0·23, the highest value covered by the statistical analysis of results in the main text. As speed instability increases further the results become less reliable and, as has been emphasised in the main text, should be treated with caution.

TABLE 1

AVRO 707A—Geometric Details.

Wings	
Gross area, ft^2	408
Span, ft	34·167
Aspect ratio	2·86
Geometric mean chord, ft	11·94
Aerodynamic mean chord, ft	14·537
Chord at centreline, ft	21·825
Chord at tip, ft	2·225
Sweepback, leading edge	49·9°
Sweepback, root to 29·8% semispan, trailing edge	0°
Sweepback, outboard of 29·8% semispan, trailing edge	3·54°
Wing-body setting	2·5°
Wing section, 29·8% semispan	NACA 0010
Wing section, tip	RAE 101
Elevators	
Area aft of hinge, each, ft^2	12·865
Span along hinge line, ft	6·248
Spanwise extent, % semispan	29·8 to 64·7
Mean chord, aft of hinge, ft	2·072
Hinge line sweepback	11·5°
Neutral setting to wing chord line	0°
Range	8° down to 20° up
Trim (drive recovery) flaps	
Area aft of hinge, each, ft^2	6·05
Span, ft	2·93
Spanwise extent, % semispan	12·7 to 29·8
Chord aft of hinge, ft	2·06
Hinge line sweep	0°
Neutral setting to wing chord line	2° up
Range	2° to 16·5° up
Air brakes (fully extended)	
Gross projecting frontal area (including mechanism) ft^2 upper, each	1·414
lower, each	1·9
Net frontal area (plate only) ft^2 upper, each	1·153
lower, each	1·671
Span ft, upper and lower, each	2·396
Spanwise extent, % semispan, upper and lower	14·3 to 28·35
Chord (plate) ft, upper	0·5
lower	0·72
Mean distance from wing trailing edge, ft, upper and lower	11·5

TABLE 1—*continued*

Miscellaneous

All up weight, full fuel, 180 lb pilot, cg at 0·237 $\bar{c}$, lb	10 440
All up weight, full fuel, 180 lb pilot, cg at 0·265 $\bar{c}$, lb	10 330
All up weight, full fuel, 180 lb pilot, cg at 0·286 $\bar{c}$, lb	10 660
Fuel capacity, gallons	196
Engine	Derwent Mk. 8
Engine thrust line to aircraft datum	0°
Nominal maximum thrust, lb	3600

TABLE 2

Summary of Lift and Drag Results.

cg position	0·234 $\bar{c}$	0·265 $\bar{c}$	0·287 $\bar{c}$
$\frac{dC_L}{d\alpha}$	2·66		
$\frac{dC_{L_t}}{d\alpha}$	1·91	2·19	2·37
C_D	$0{\cdot}0542 + 0{\cdot}1732\, C_{L_t}^2$	$0{\cdot}0540 + 0{\cdot}1600\, C_{L_t}^2$	$0{\cdot}0539 + 0{\cdot}1522\, C_{L_t}^2$
$\frac{dC_D}{d\alpha}$	$0{\cdot}774\, C_{L_t}$		

TABLE 3

Summary of Short-Period Pitching-Oscillation Results.

cg position	0·234 $\bar{c}$	0·265 $\bar{c}$	0·287 $\bar{c}$
C_{L_t} (mean)	0·481	0·460	0·491
P (mean), seconds	2·72	3·05	3·76
$T_{\frac{1}{2}}$ (mean), seconds	1·12	1·14	1·08
m_θ	−0·234	−0·177	−0·259
H_m	0·140	0·100	0·073
m_q	−0·417	−0·395	−0·363
$m_{\dot{w}}$	0·183	0·214	0·104

TABLE 4

The Pilot Rating Scale.

Satisfactory	1 2 3	Excellent Good Satisfactory	One of the easiest of its type. Well above average, pleasant to fly on approach. Above average, mildly unpleasant only.
Unsatisfactory	4 5 6	Acceptable Poor Very poor	Average, some unpleasant characteristics. Below average, unacceptable for normal operation. Well below average, acceptable for emergency only.
Unacceptable	7 8 9	Dangerous Very dangerous Barely controllable	May have to overshoot. Probably have to overshoot (on more than 50% occasions). Likely to break something no matter how many overshoots.
	10	Catastrophic	Certain to break something.

TABLE 5

Statistical Tests on the Effect of cg Position, the Addition of $\partial T/\partial\alpha$, and Type of Glide-Path Control on the Variances.

1 cg movement and the addition of $\partial T/\partial\alpha$ are compared with the aft cg, $\partial T/\partial V$ only, and tight theodolite control condition.

2 The loose theodolite and P.A.R. control are compared with the aft cg, $\partial T/\partial V$ and $\partial T/\partial\alpha$, tight theodolite control condition.

Effect of:	Tests on basic aircraft	Test at all levels of speed stability
[1]Forward movement of cg	Elevator greater at 1% level	Elevator greater at 1% level, speed less at 5% level.
[1]Addition of $\partial T/\partial\alpha$	Not applicable	Speed and glide-path less at 1% level
[2]Loose control	No significant effect	No significant effect
[2]P.A.R. control	Speed and glide-path greater at 1% level	Speed and glide-path greater at 1% level

TABLE 6

Significance of the Scaled Variances.

t, T = throttle; e, E = elevator; v, V = speed; i, I = total input;
m, M = total measure

The autothrottle gain settings producing the speed stabilities listed vertically give significantly worse results than those listed horizontally at the levels indicated by the letter case.

A blank space indicates no difference at the 5% level.

Lower case is significance level between 5% and 2%.

Upper case is significance level better than 2%.

A cg 0·287 $\bar{c}$, artificial $\partial T/\partial V$ only, tight control

$\frac{1}{T_2}$	−0·017	0·020	0·029	0·038	0·051	0·069	0·091	0·122	0·166
−0·017									
0·020	T								
0·029	t								
0·038	t								
0·051	t								
0·069	T		i						
0·091	T		t i		t				
0·122	T I M	t m	T E I M	T E I M	T E I M	t			
0·166	T	T m	T I M	T I M	T I M	T			

B cg 0·234 $\bar{c}$, artificial $\partial T/\partial V$ only, tight control

$\frac{1}{T_2}$	−0·015	0·022	0·031	0·040	0·053	0·071	0·094	0·125	0·170
−0·015									
0·022									
0·031		V							
0·040	T	V							
0·053	t	v							
0·071									
0·094	T	t	t						
0·125	T i	T i V	T i	t	t i	t	t i		
0·170	T	T	T	t	T	t	T		

TABLE 6—*continued*

C cg 0·287 $\bar{c}$, artificial $\partial T/\partial V$ and $\partial T/\partial \alpha$, tight control

$\frac{1}{T_2}$	−0·017	0·032	0·045	0·057	0·074	0·099	0·129	0·170	0·231
−0·017									
0·032									
0·045									
0·057									
0·074									
0·099									
0·129	t								
0·170	T m	m	T m	T		m	M		
0·231	T m	m	T v m	T		m	M		

D cg 0·287 $\bar{c}$, artificial $\partial T/\partial V$ and $\partial T/\partial \alpha$, P.A.R. control

$\frac{1}{T_2}$	−0·017	0·032	0·045	0·057	0·074	0·099	0·129	0·170	0·231
−0·017									
0·032	T								
0·045	T								
0·057	t								
0·074	T								
0·099	T								
0·129	t			M					
0·170	T I M	t m	e	t e I M	M	m	e M		
0·231	T I M	t		I V M	t				

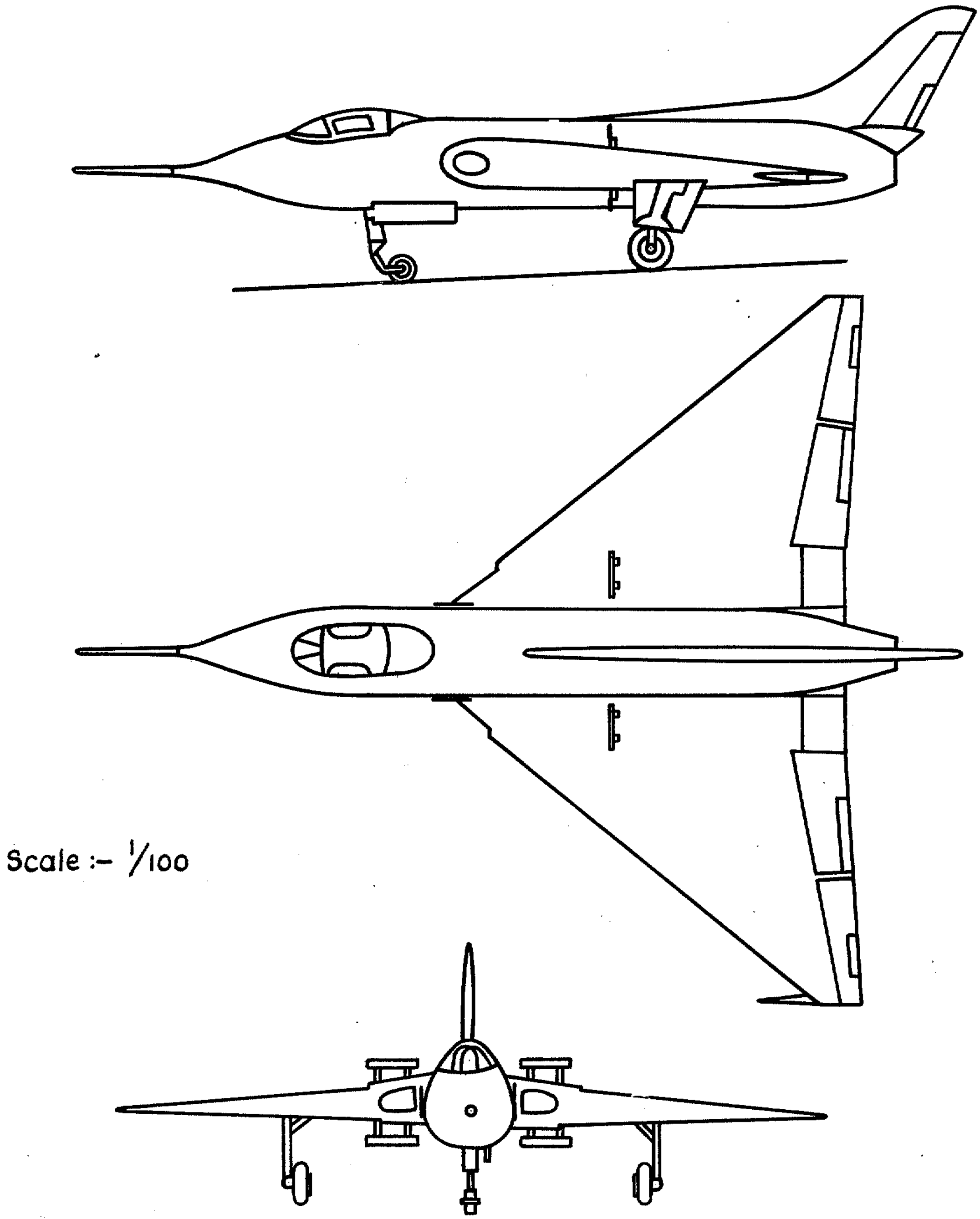


FIG. 1. Avro 707A WZ 736.
General arrangement—landing configuration.

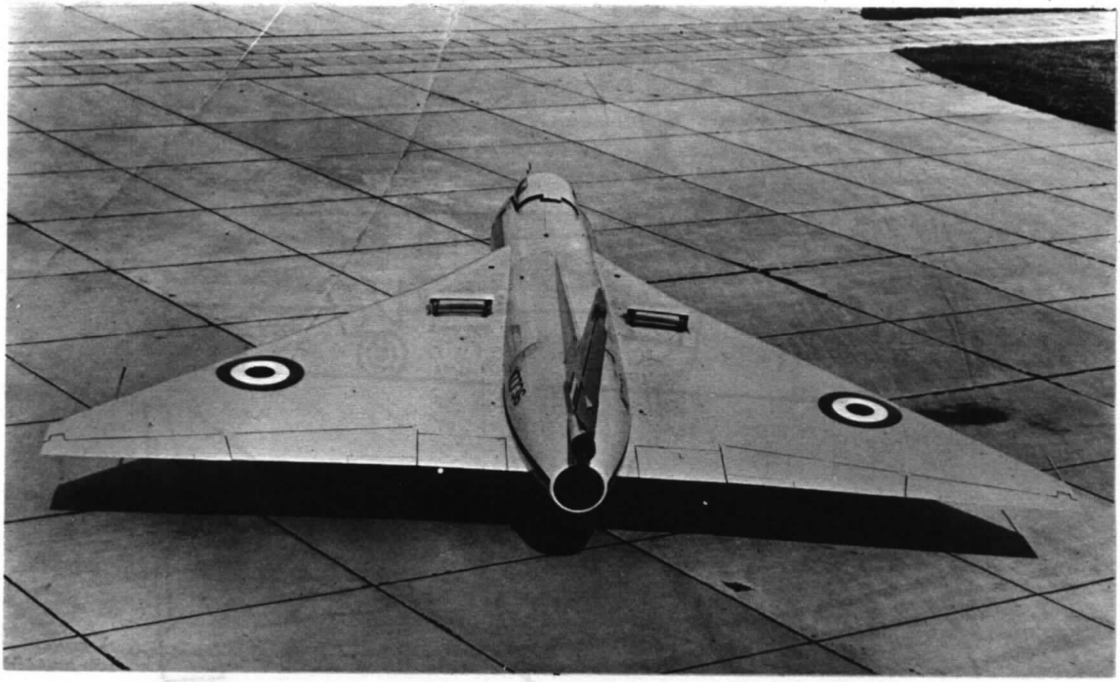


FIG. 2. Avro 707A.

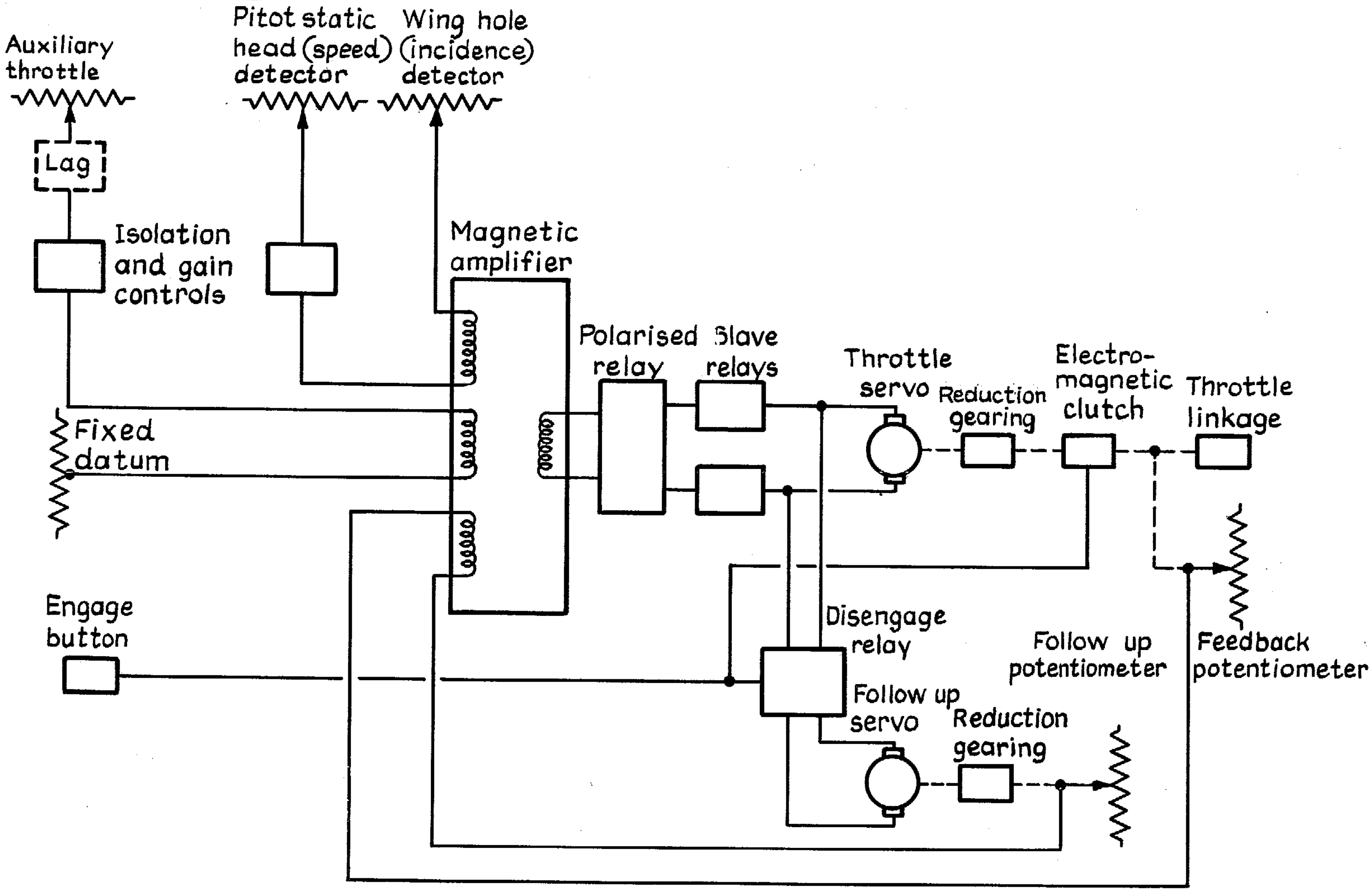


FIG. 3. Block diagram of the automatic throttle system.

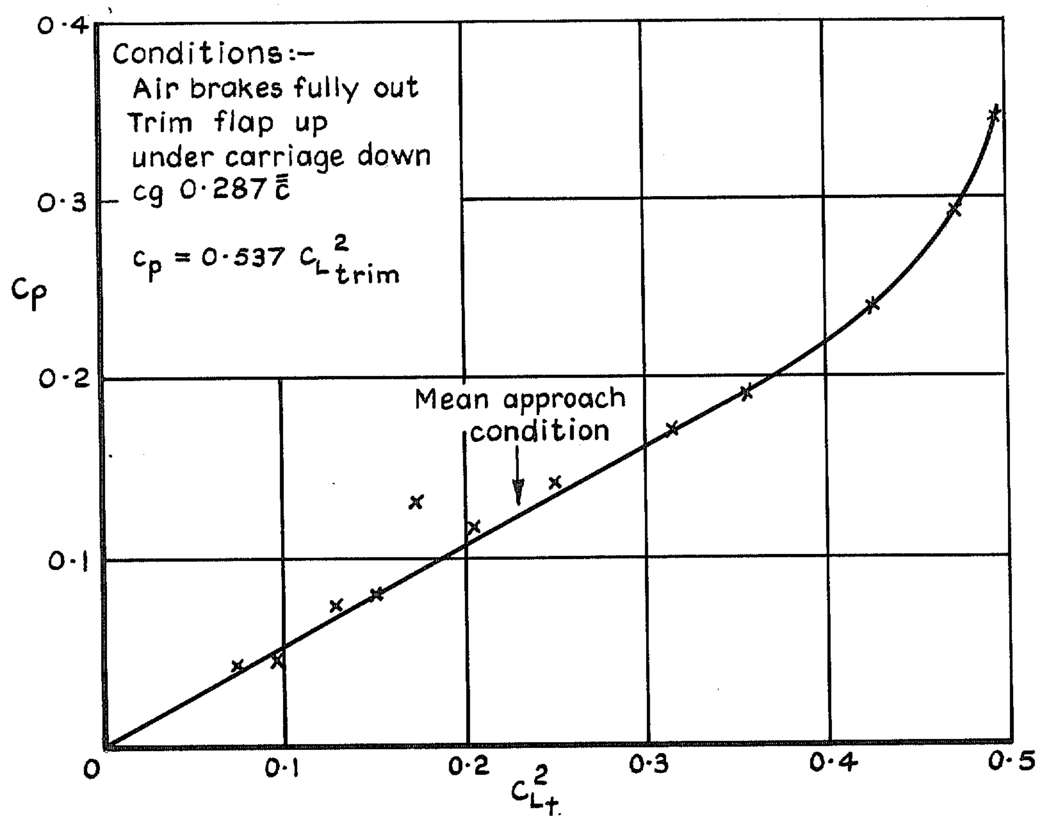


FIG 4. Calibration of wing hole pressure source against trimmed lift coefficient.

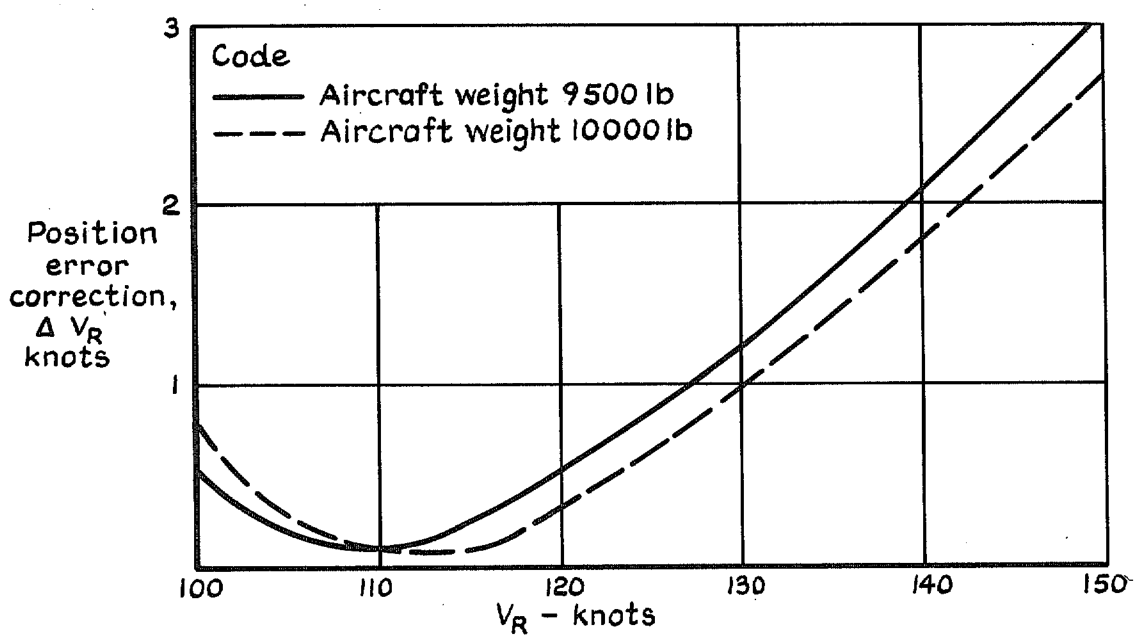


FIG. 5. Sea level position error correction.

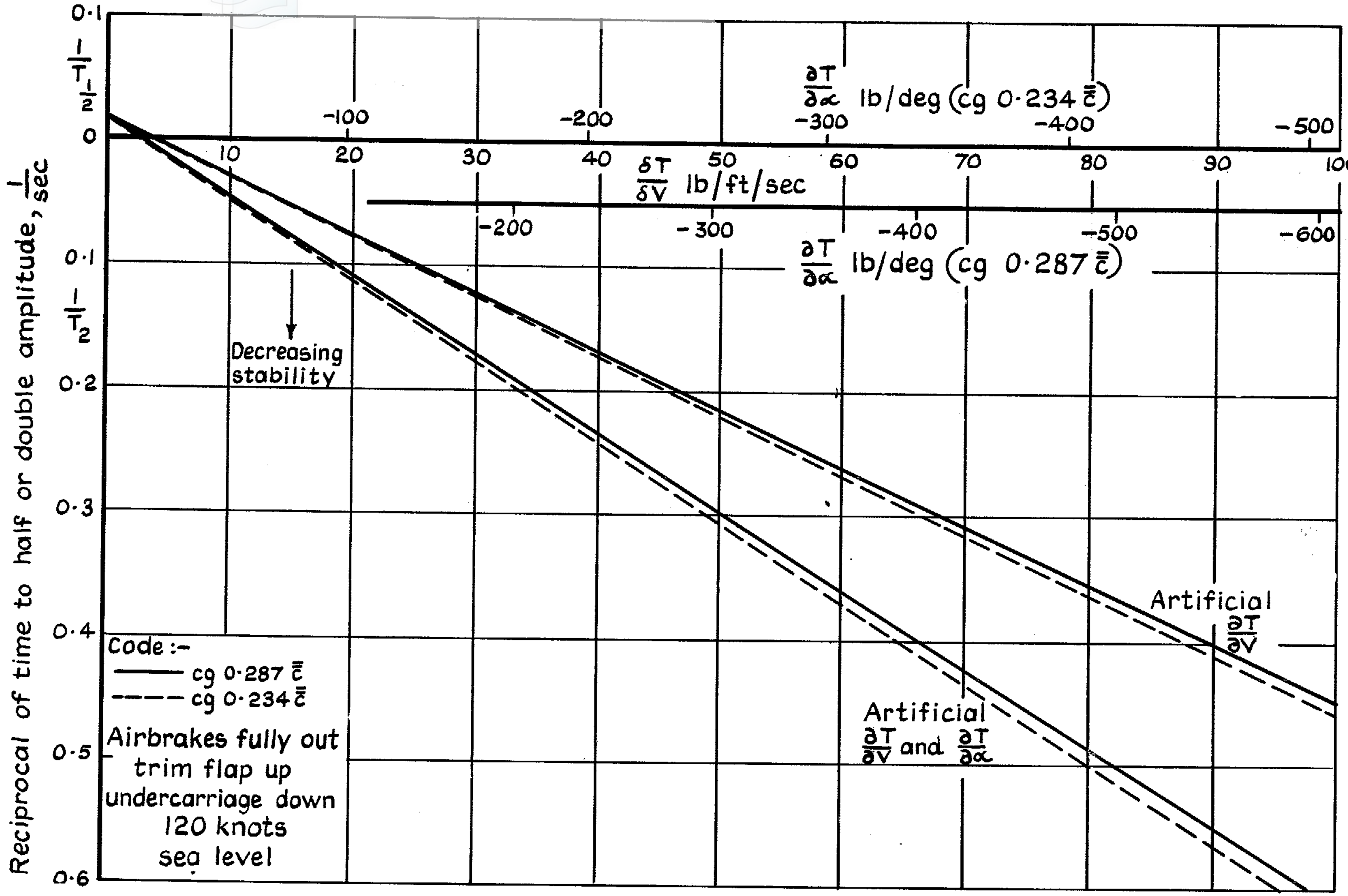
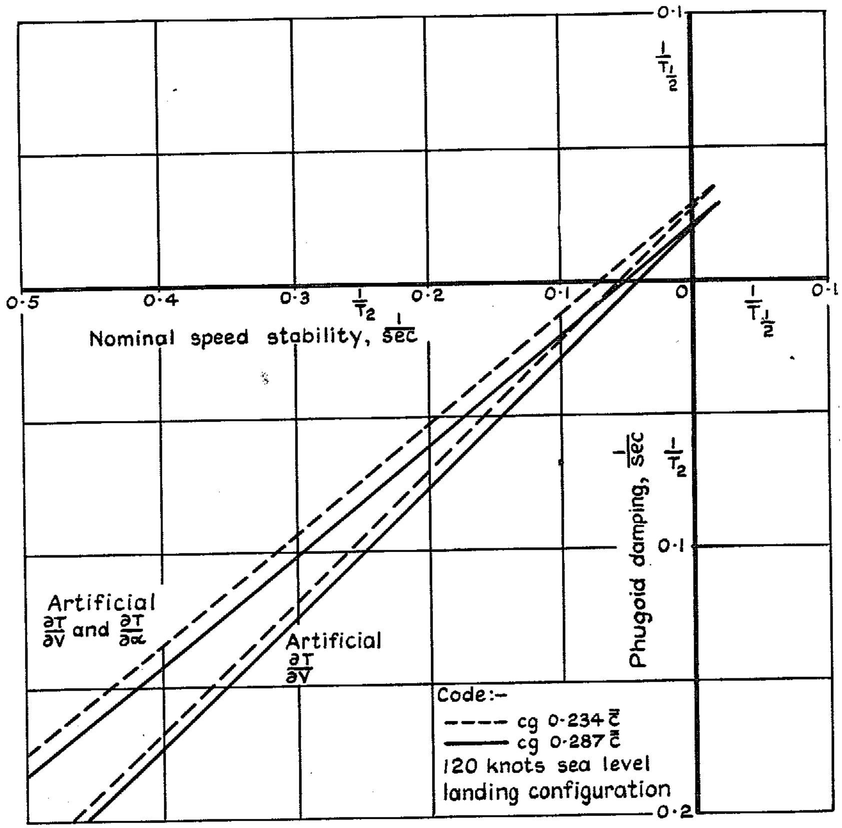


FIG. 6. The nominal speed stability calculated from autothrottle calibrations.



With artificial $\frac{\partial T}{\partial \alpha}$ added the ratio $\frac{\partial T}{\partial V} : \frac{\partial T}{\partial \alpha}$ remains constant at the following values :–

cg 0·234 $\bar{c}$: For unit lb thrust change per ft/sec there is 5·2 lb thrust change per degree incidence

cg 0·287 $\bar{c}$: For unit lb thrust change per ft/sec there is 6·1 lb thrust change per degree incidence

FIG. 7. The speed stability—phugoid damping relationship.

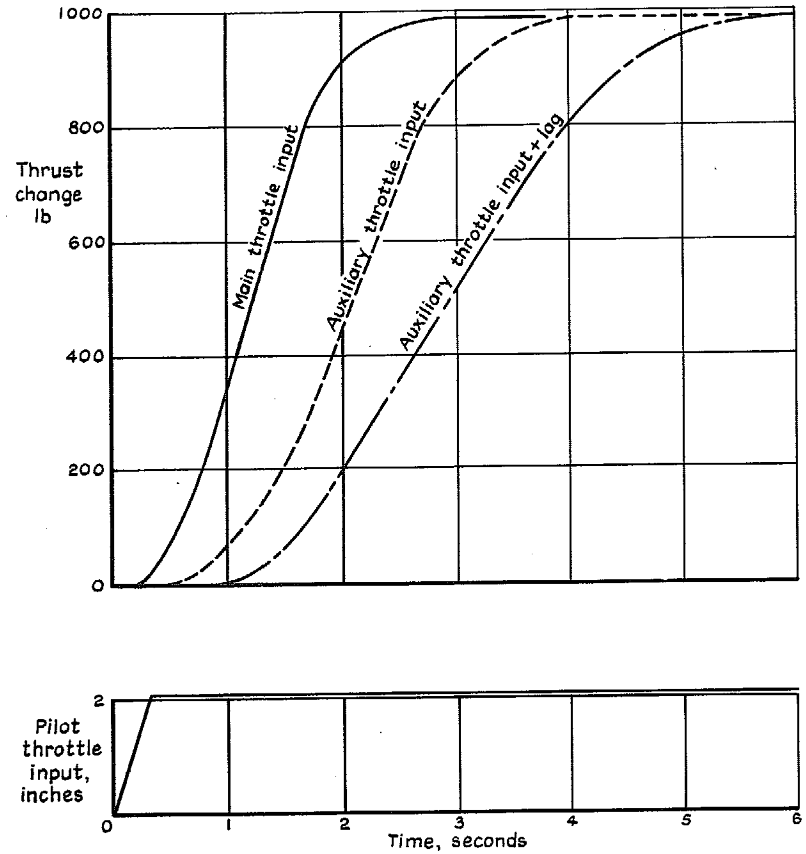


FIG. 8. Engine response to aircraft and auxiliary throttles.

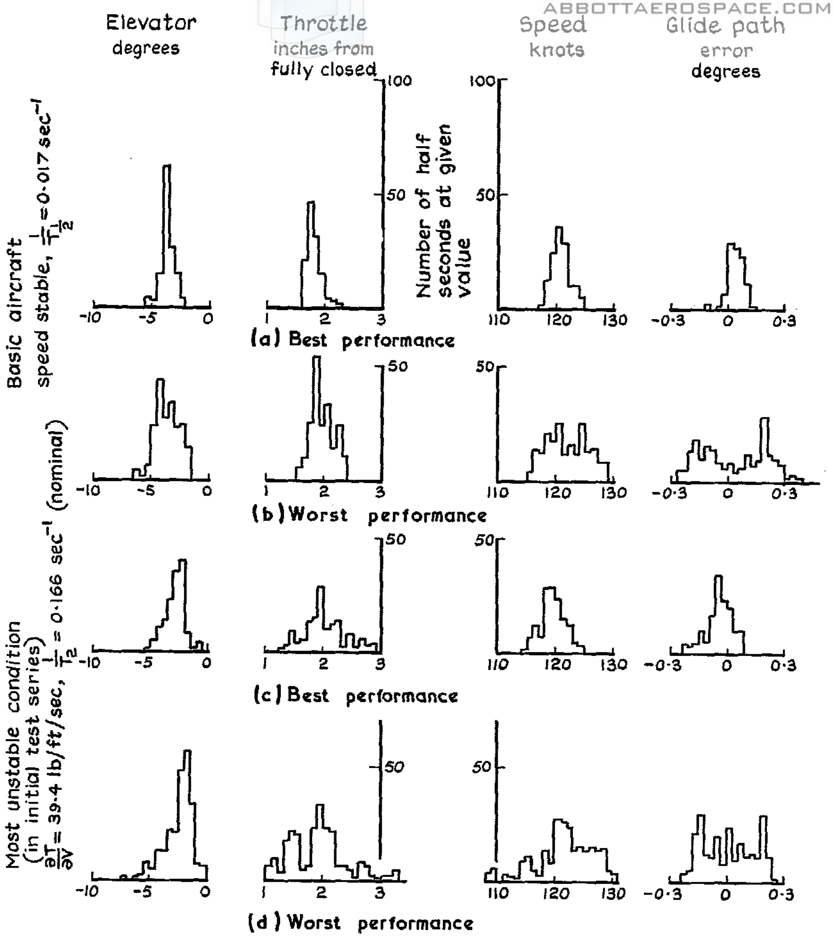


FIG. 9 a to d. Examples of histograms from recorded control positions and approach performance for the basic aircraft and speed unstable configurations respectively.

(aft cg, artificial $\frac{\partial T}{\partial V}$ only, tight theodolite control).

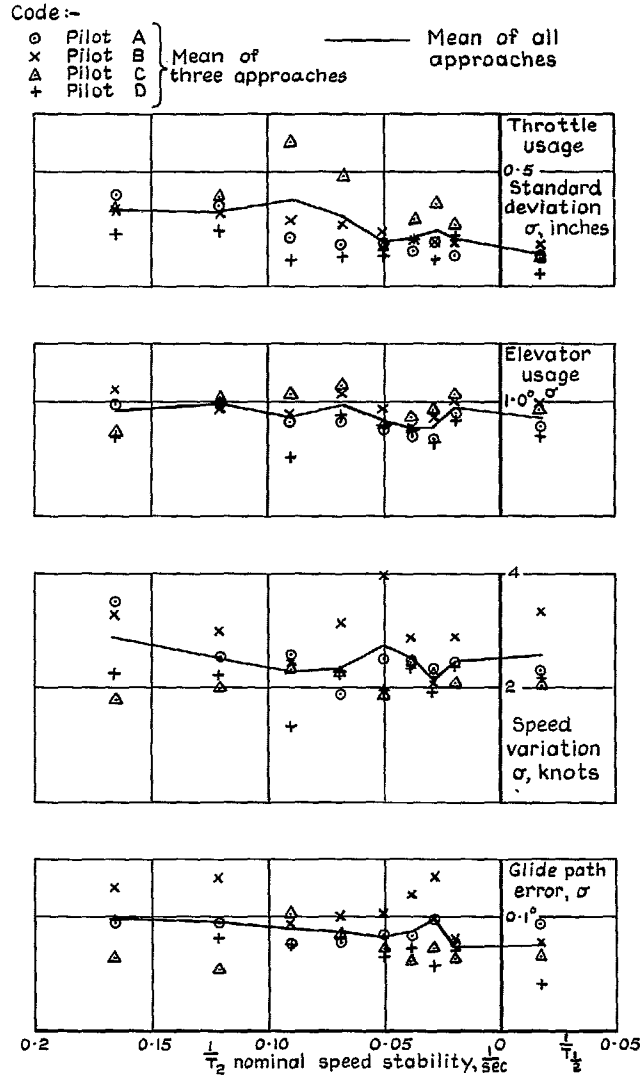


FIG. 10. Effect of speed stability on individual pilots and overall mean results.

(aft cg, tight theodolite control, $\frac{\partial T}{\partial V}$ only).

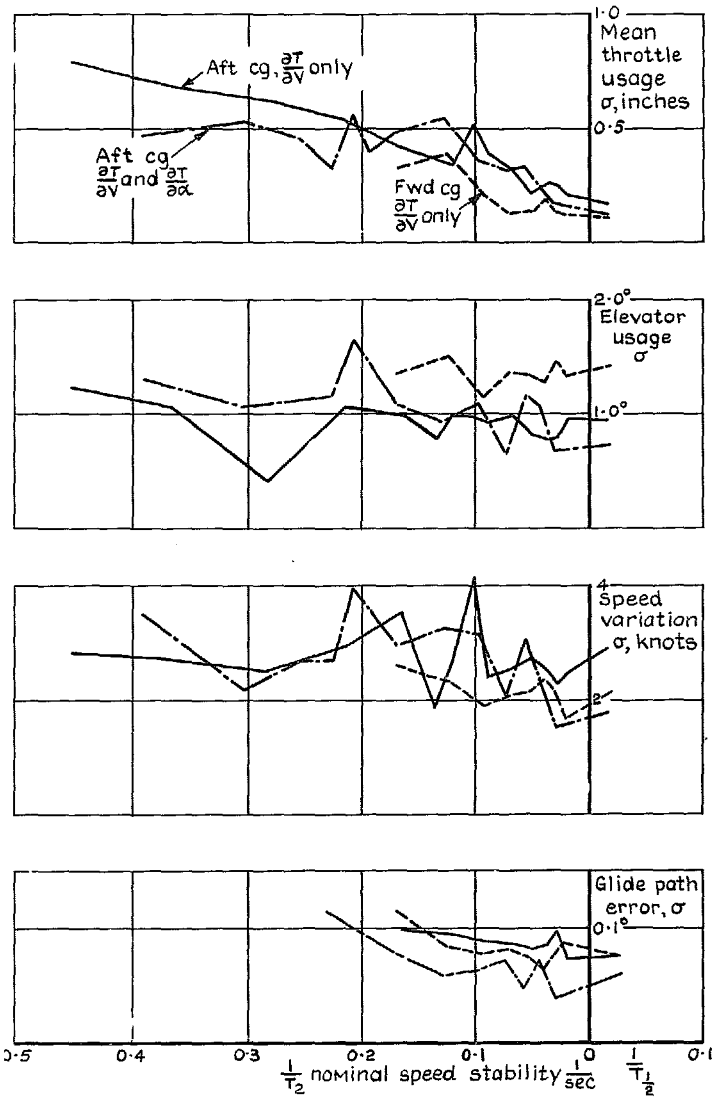


FIG. 11. Effect of cg position and destabilising terms on overall mean results of all pilots (tight theodolite control).

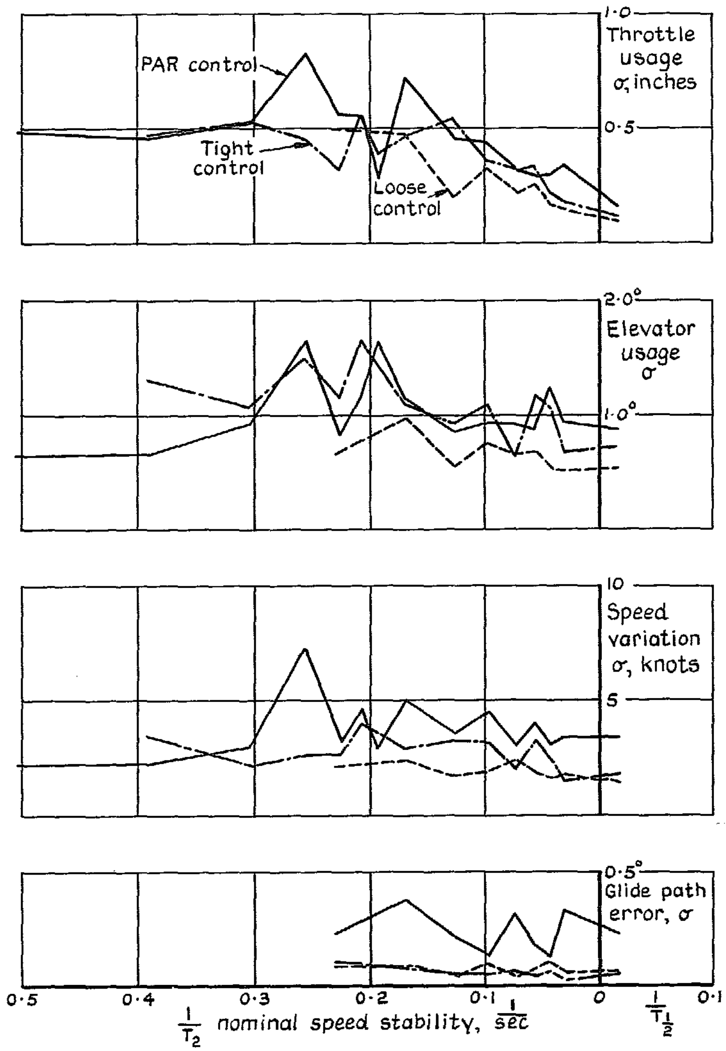


FIG. 12. Effect of type of glide path control on overall mean results of all pilots.

$$\left(\text{aft cg}, \frac{\partial T}{\partial V} \text{ and } \frac{\partial T}{\partial \alpha}\right)$$

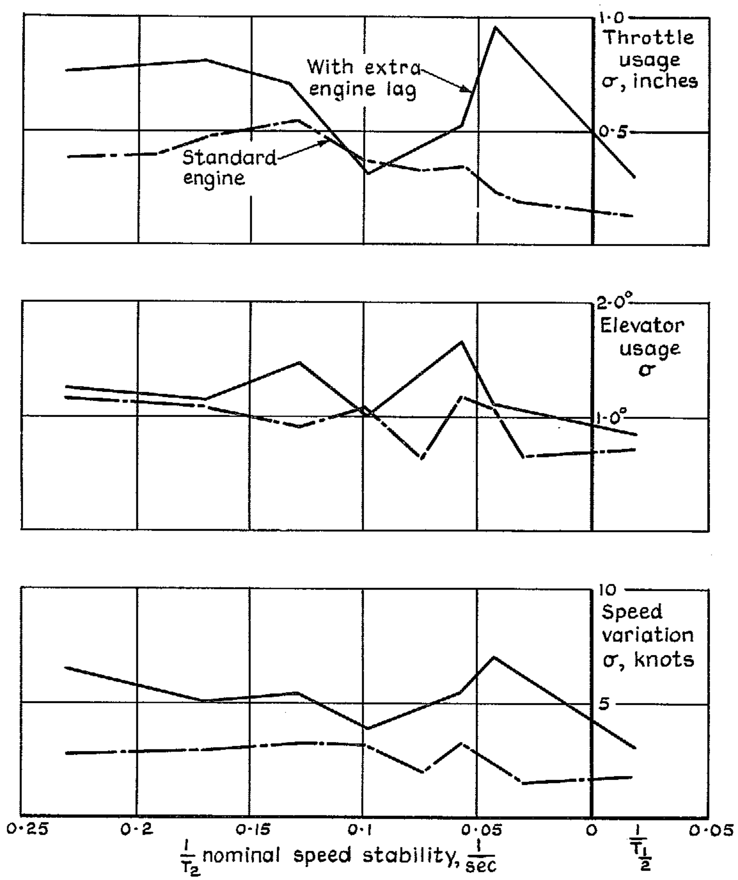


FIG. 13. Effect of engine lag on overall mean results.
$\left(\text{aft cg, } \frac{\partial T}{\partial V} \text{ and } \frac{\partial T}{\partial \alpha}\text{, tight theodolite control}\right)$.

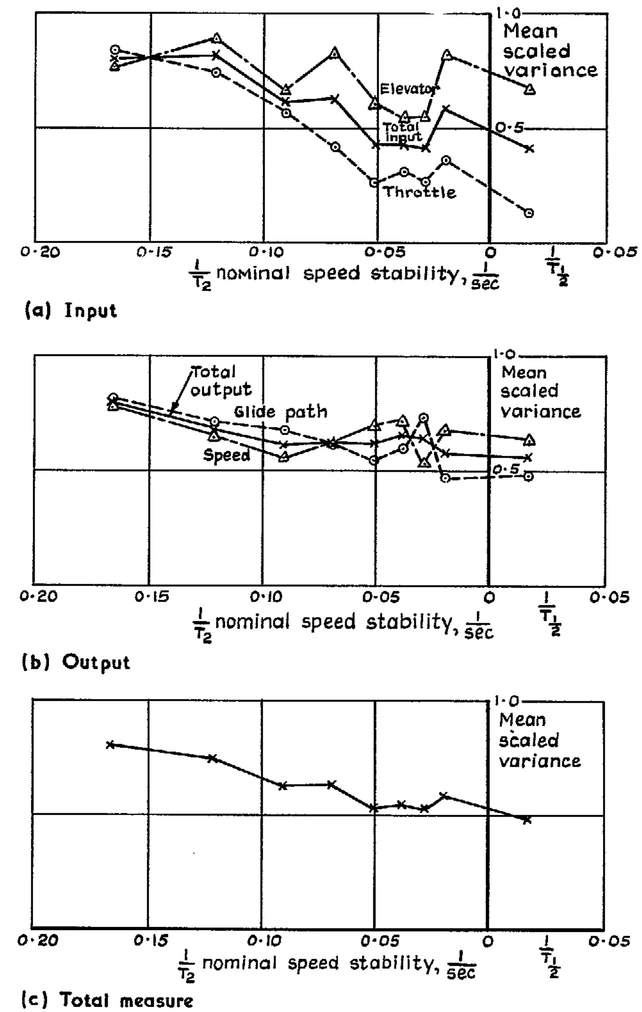


FIG. 14 a to c. Dependence of mean scaled variance on speed stability.
$\left(\text{aft cg, } \frac{\partial T}{\partial V} \text{ only, tight theodolite control}\right)$.

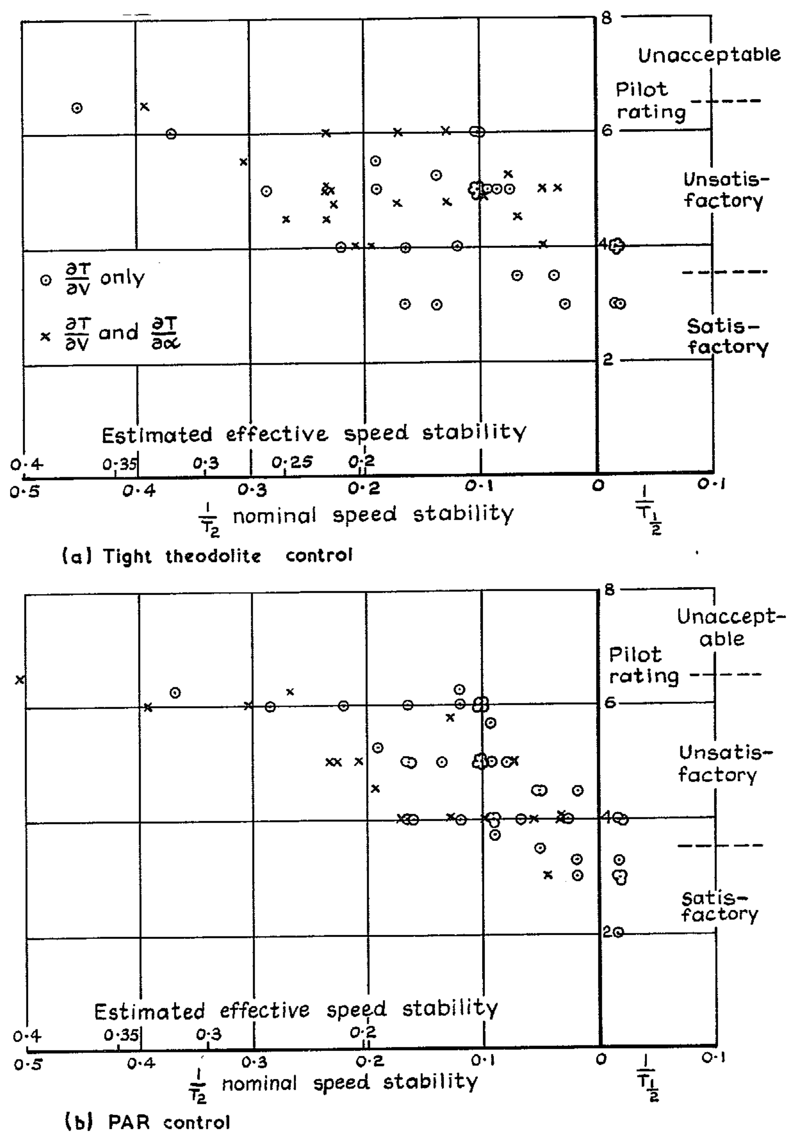


FIG. 15 a & b. Comparison of pilot rating under tight theodolite P.A.R. control.

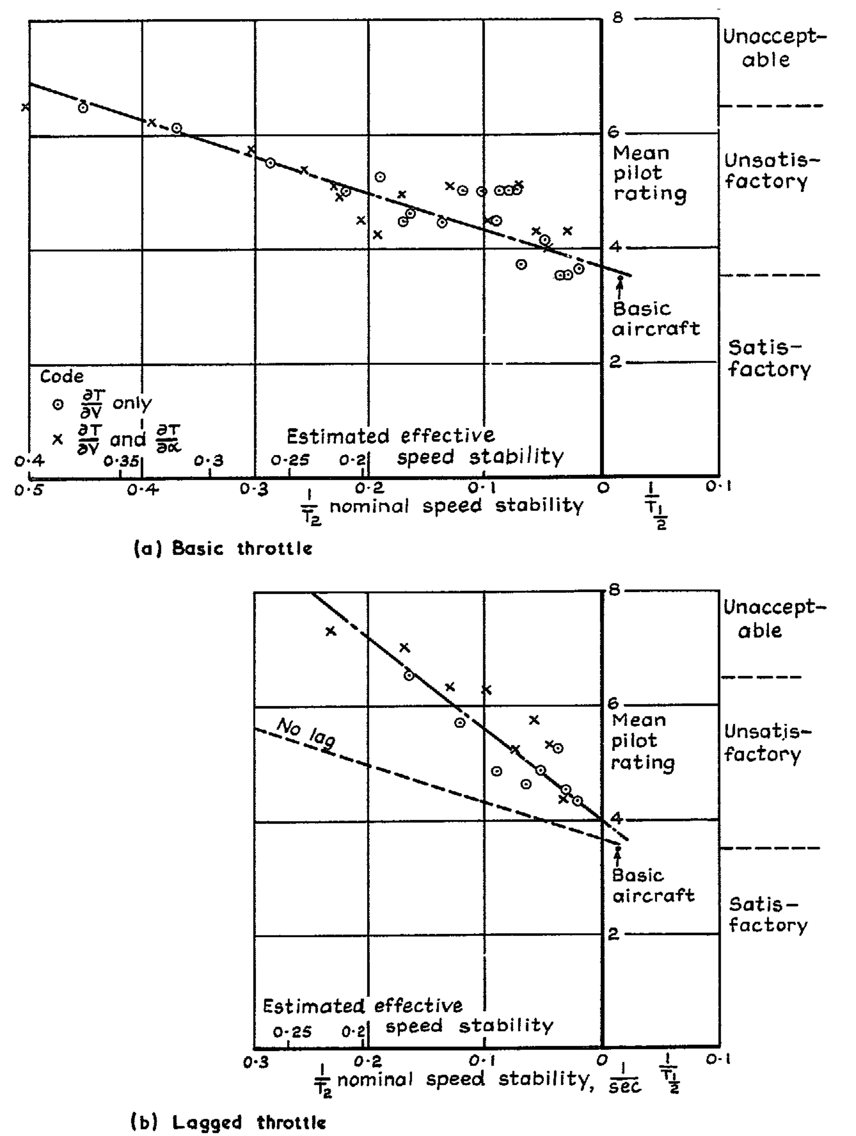


FIG. 16 a & b. Variation of pilot rating with speed stability, cg 0·287 $\bar{c}$.

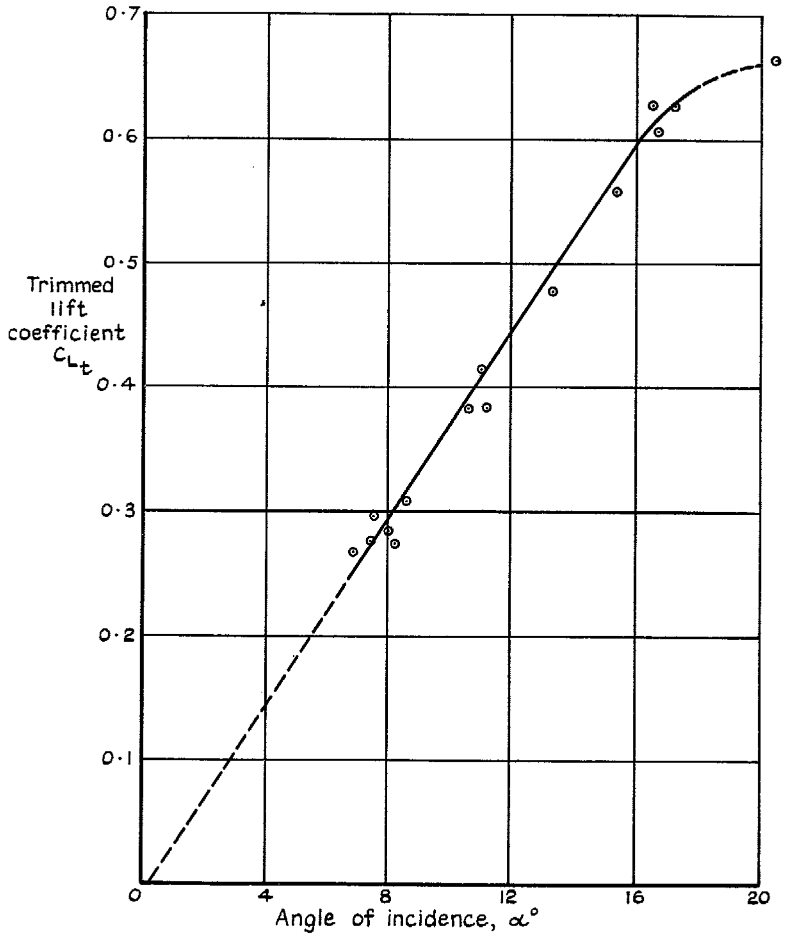


FIG. 17. Trimmed lift coefficient against incidence, cg 0·265 $\bar{c}$, landing configuration.

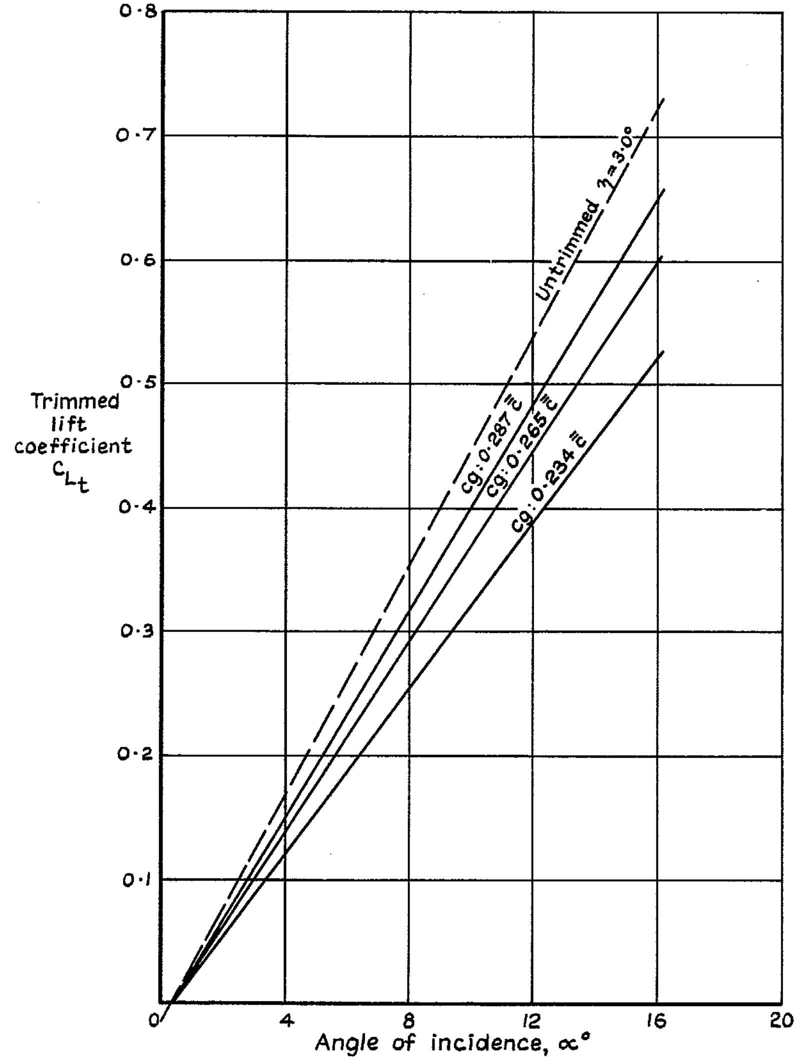


FIG. 18. Lift coefficient against incidence for various cg positions, and at constant elevator angle, landing configuration.

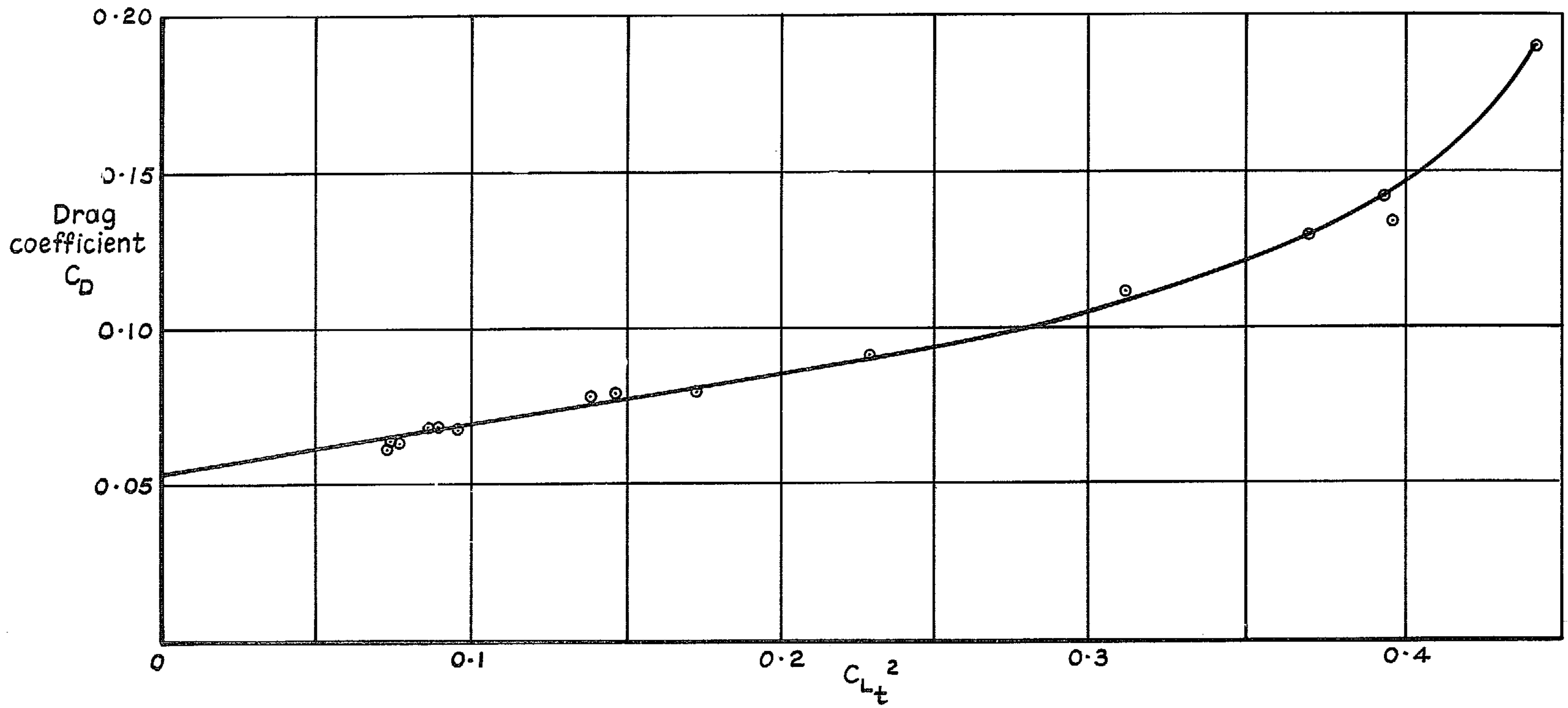


FIG. 19. Drag coefficient in landing configuration. cg 0·265 $\bar{\bar{c}}$.

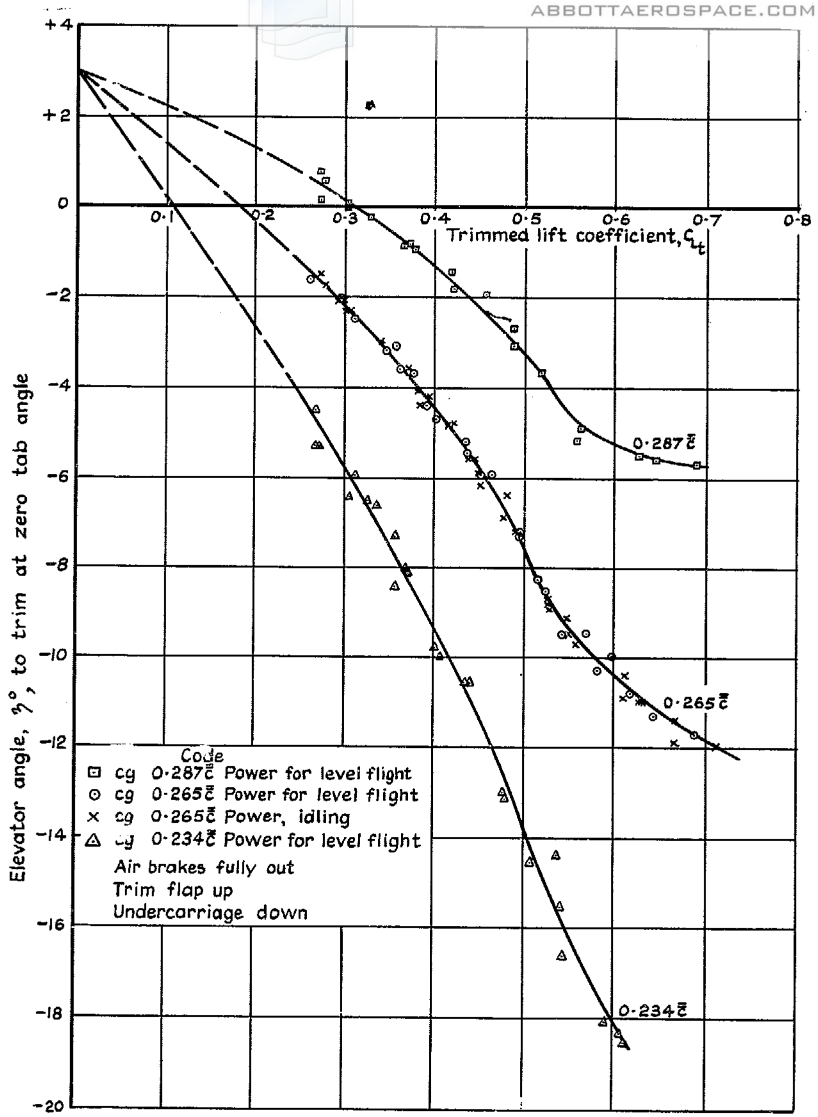


FIG. 20. Elevator angle to trim against trimmed lift coefficient at three cg positions.

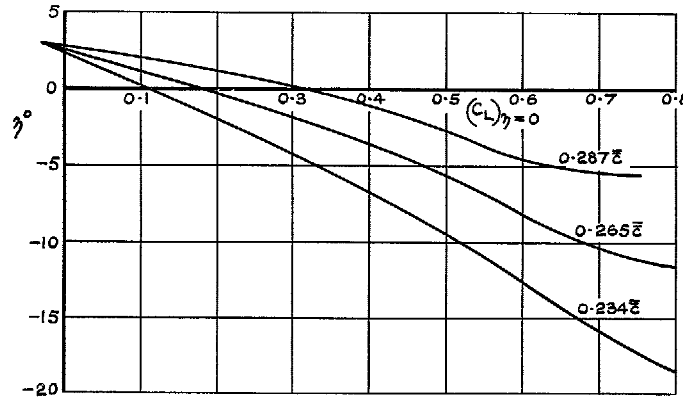


FIG. 21. Elevator angle to trim against lift coefficient, correct to zero elevator angle.

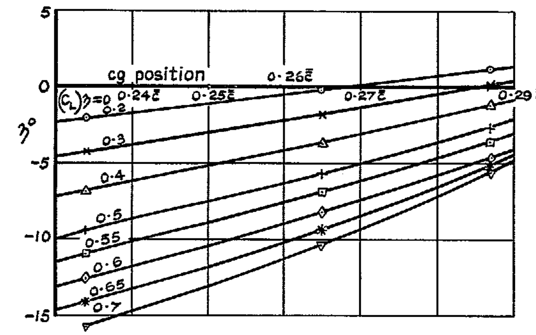


FIG. 22. Cross plot of elevator angle to trim against cg position at various values of $(C_L)_{\eta=0}$.

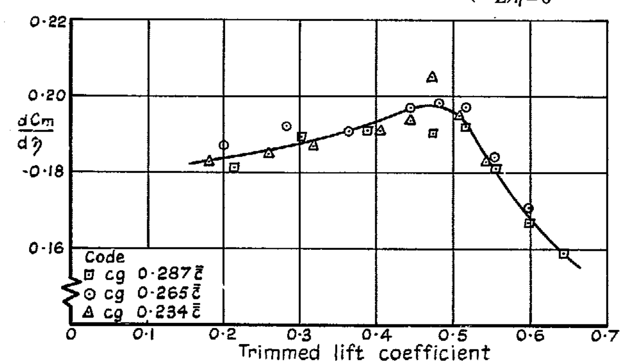


FIG. 23. Elevator power, landing configuration.

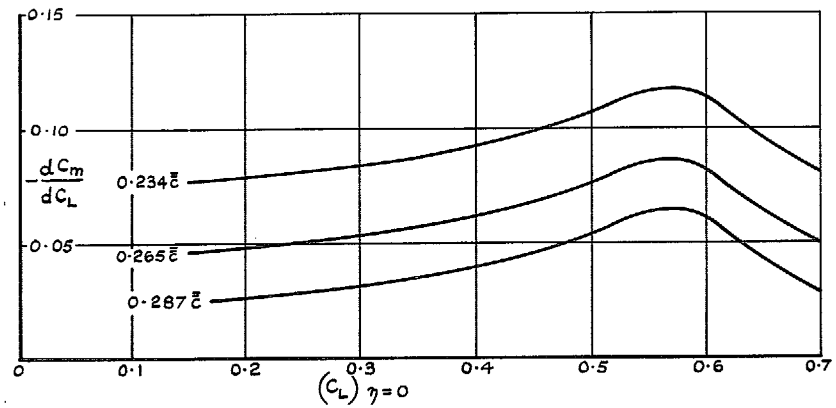


FIG. 24. Static stability against $(C_L)_{\eta=0}$, landing configuration.

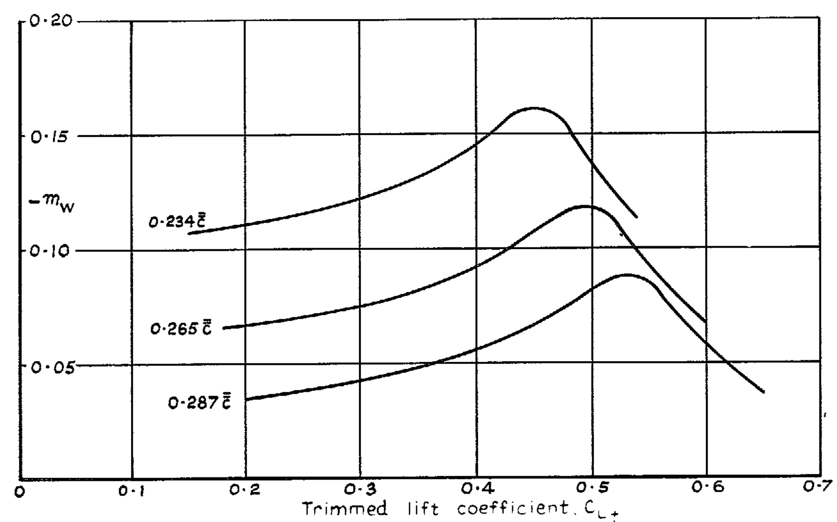


FIG. 25. Stability derivative, m_w, against trimmed lift coefficient.

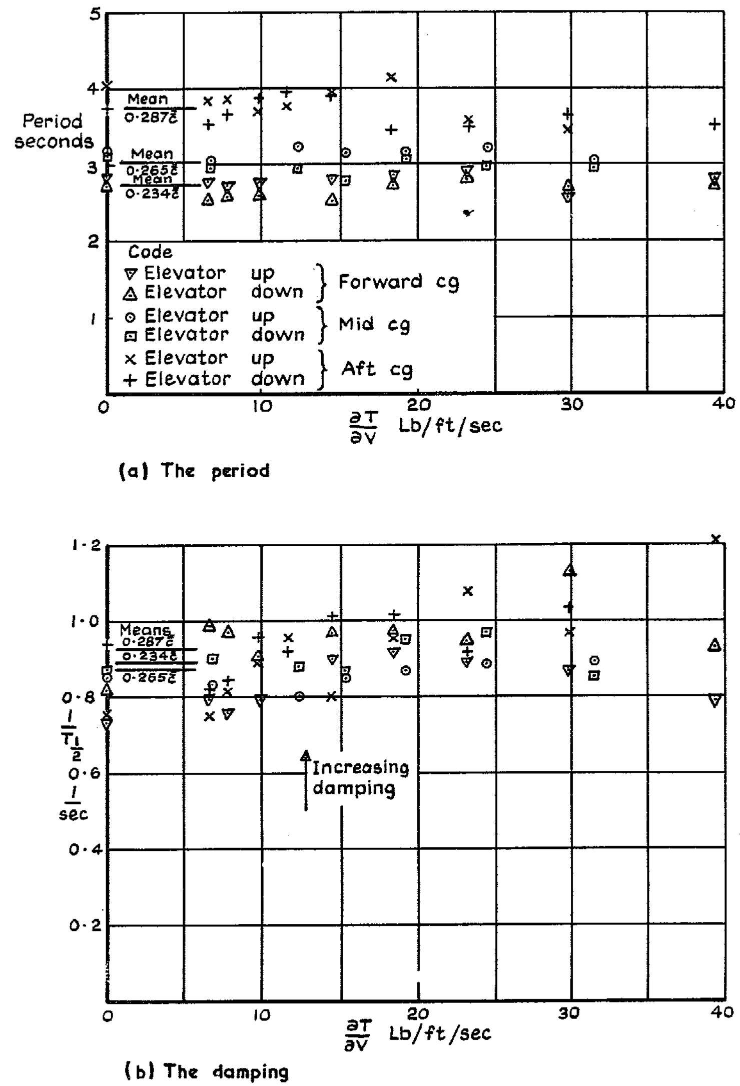


FIG. 26 a & b. Characteristics of the pitching oscillation landing configuration.

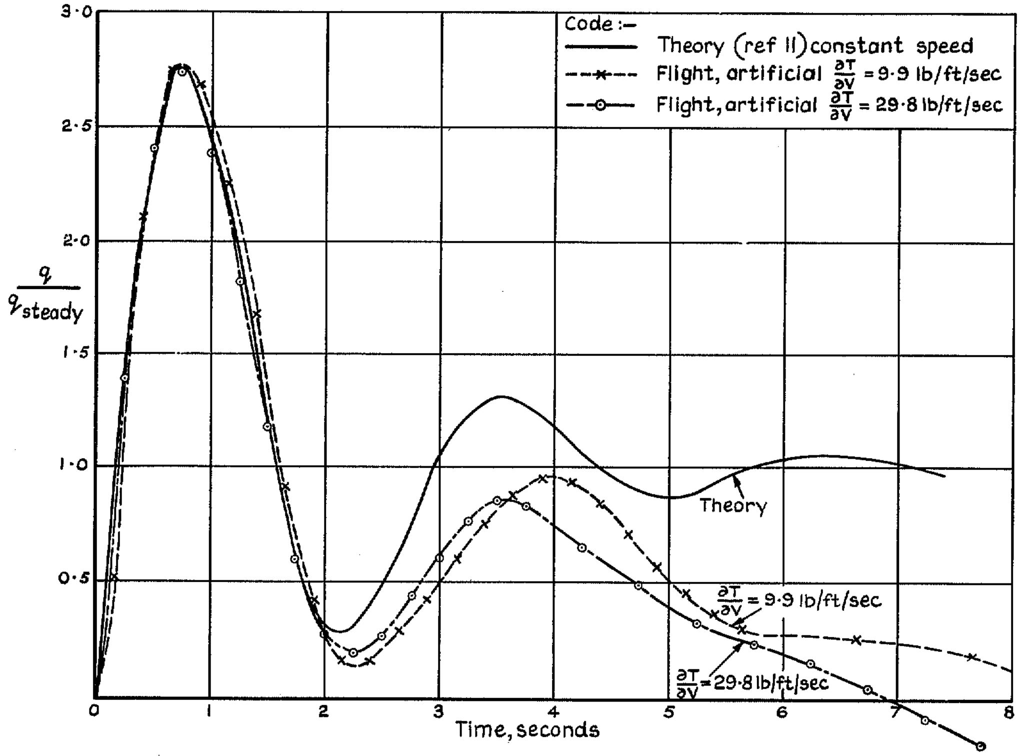


FIG. 27a. The response to a step elevator input, forward cg.

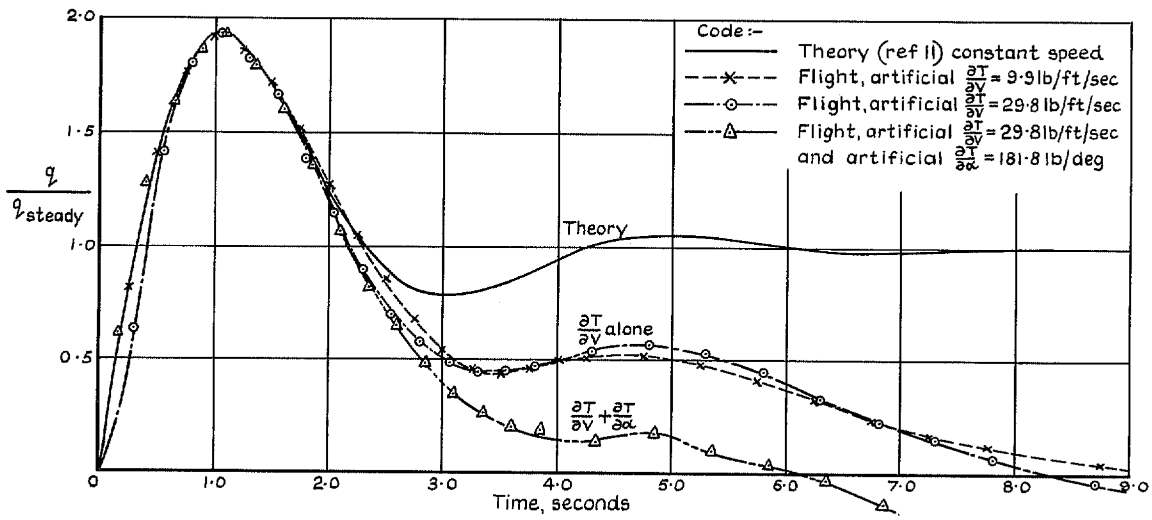
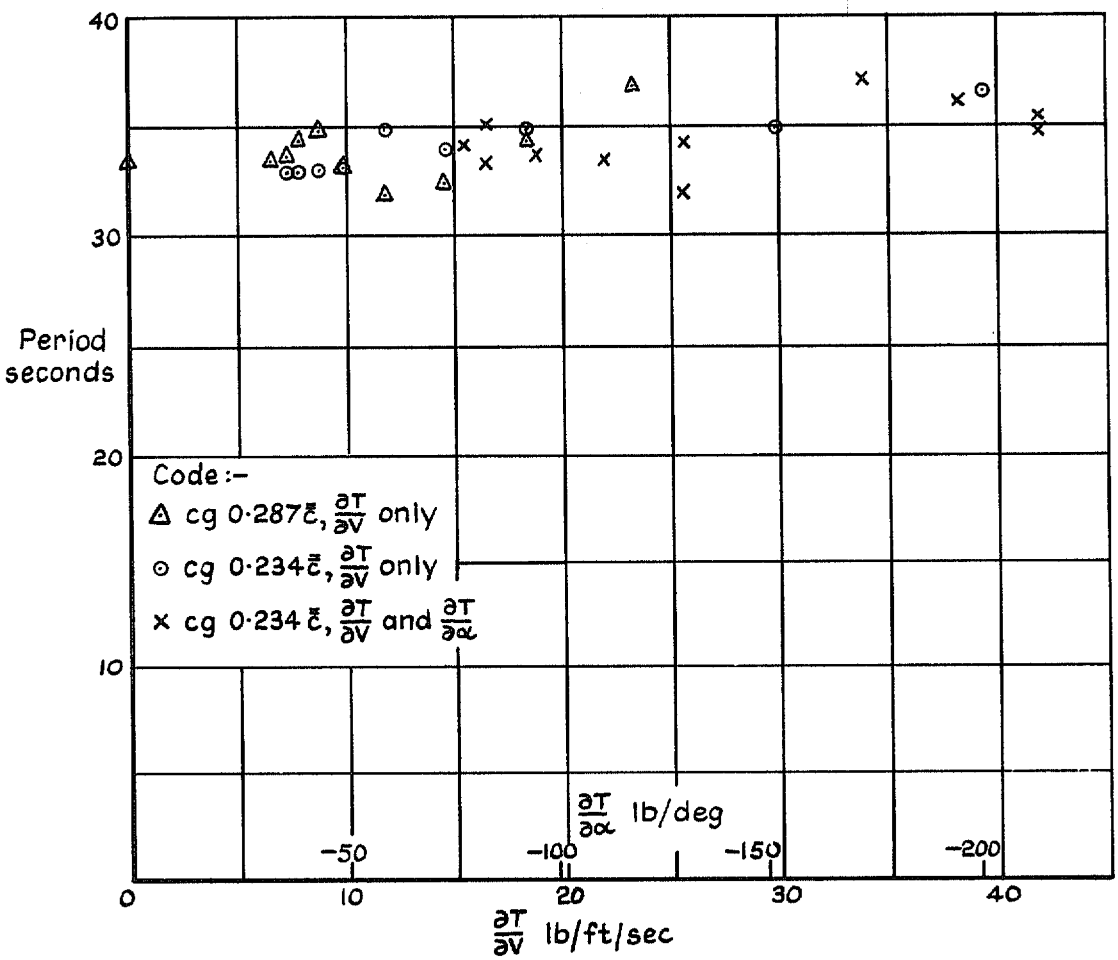
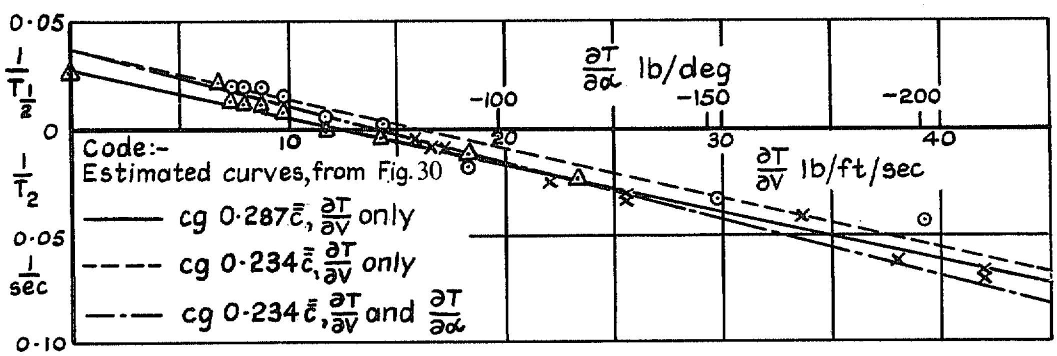


FIG. 27b. Time response to a step elevator input, aft cg.



(a) The period



(b) The damping

FIG. 28 a & b. Flight measured characteristics of the phugoid oscillation, landing configuration.

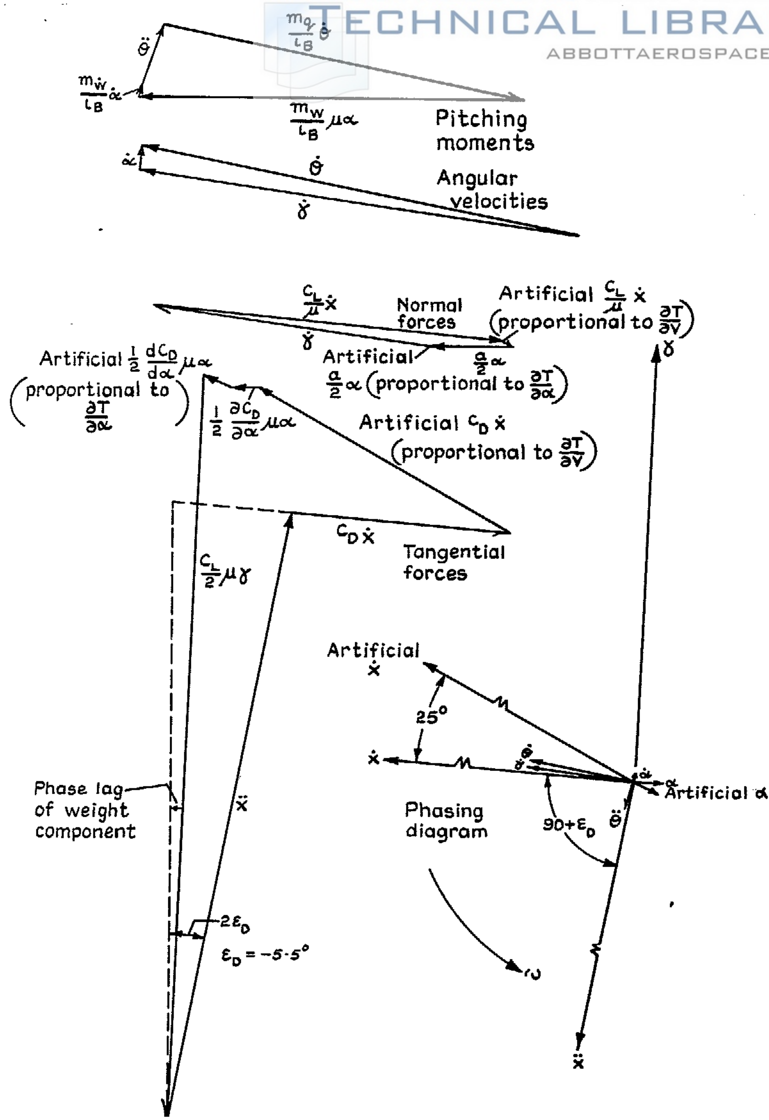


FIG. 29a. Vector diagram of the phugoid oscillation sea level 120 knots. cg 0·287 $\bar{c}$ period 34·5 seconds.

artificial $\frac{\partial T}{\partial V}$ = 23·2 lb/ft/sec.

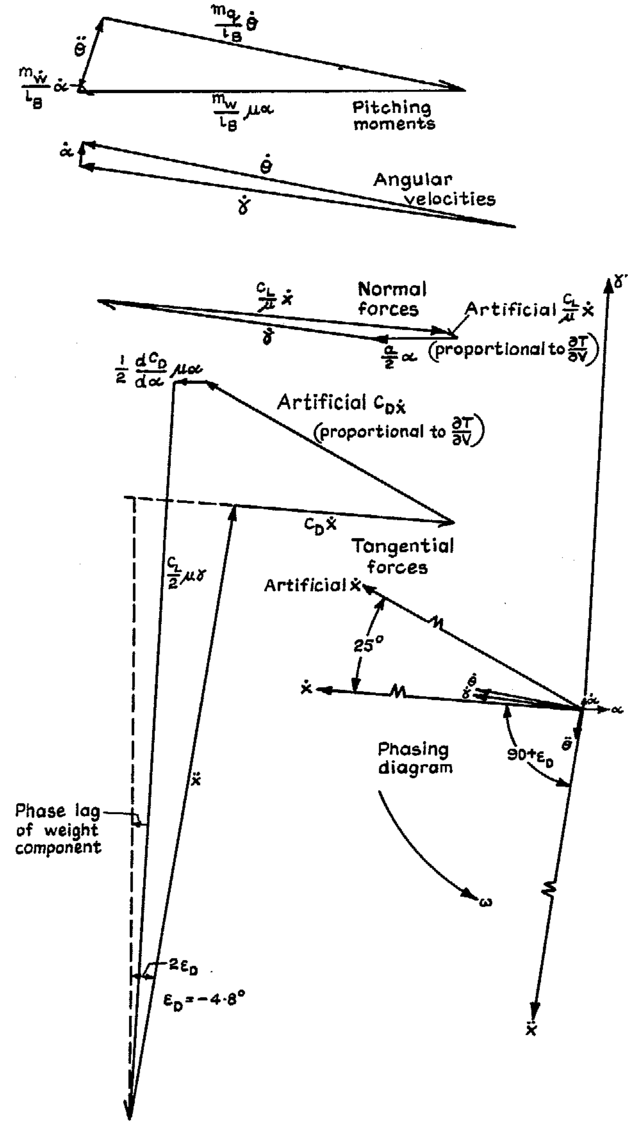


FIG. 29b. Vector diagram of phugoid oscillation sea level 120 knots. cg 0·287 $\bar{c}$ period 34·5 seconds.

artificial $\frac{\partial T}{\partial V}$ = 23·2 lb/ft/sec   artificial $\frac{\partial T}{\partial \alpha}$ = − 141·7 lb/degree.

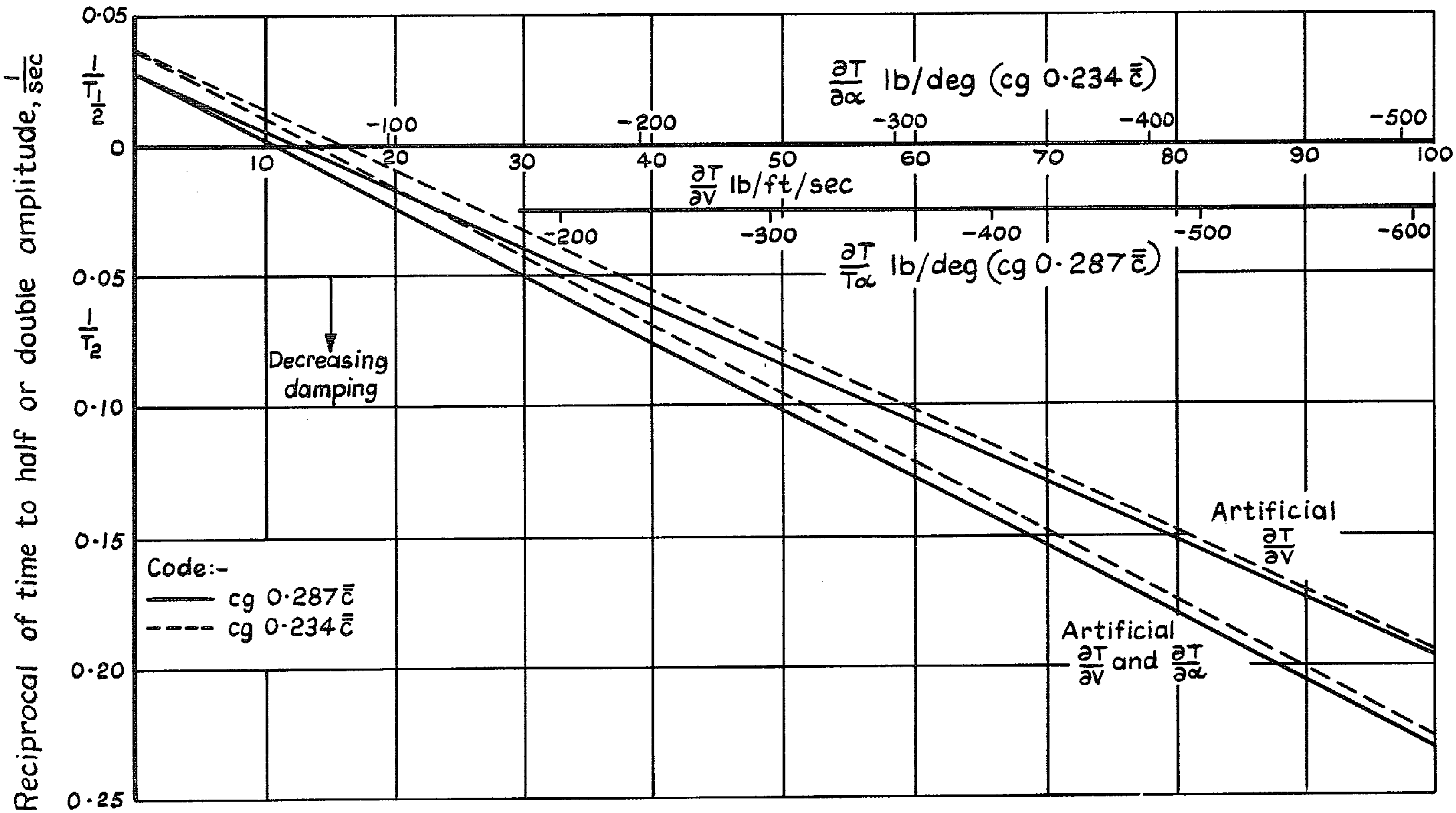


FIG. 30. Estimated damping of the phugoid oscillation from vector diagrams landing configuration.

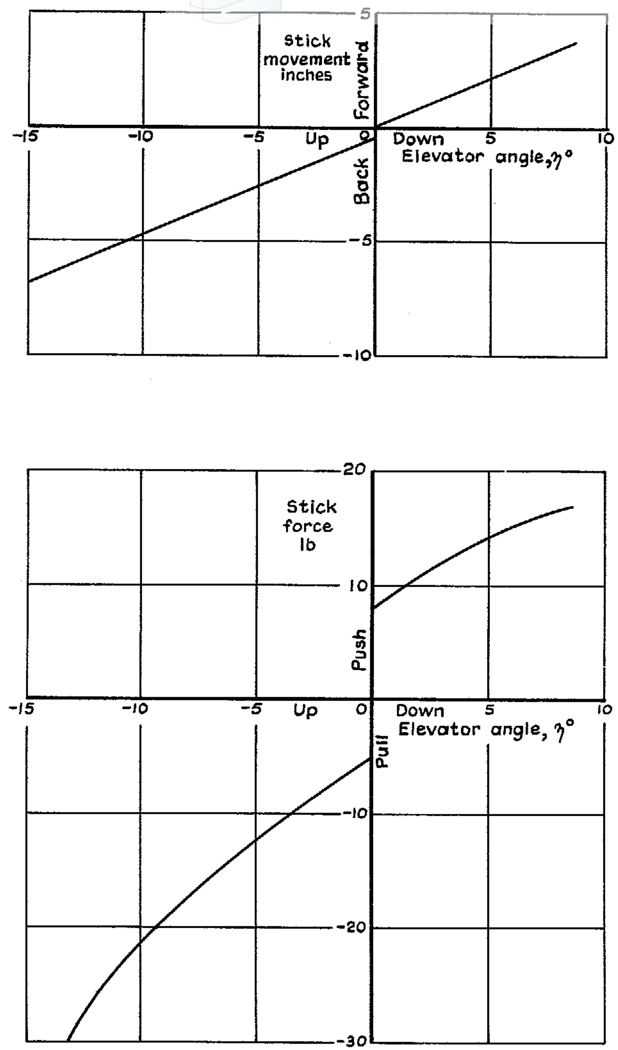


FIG. 31. Elevator-stick, deflection and force characteristics 120 knots FAS.

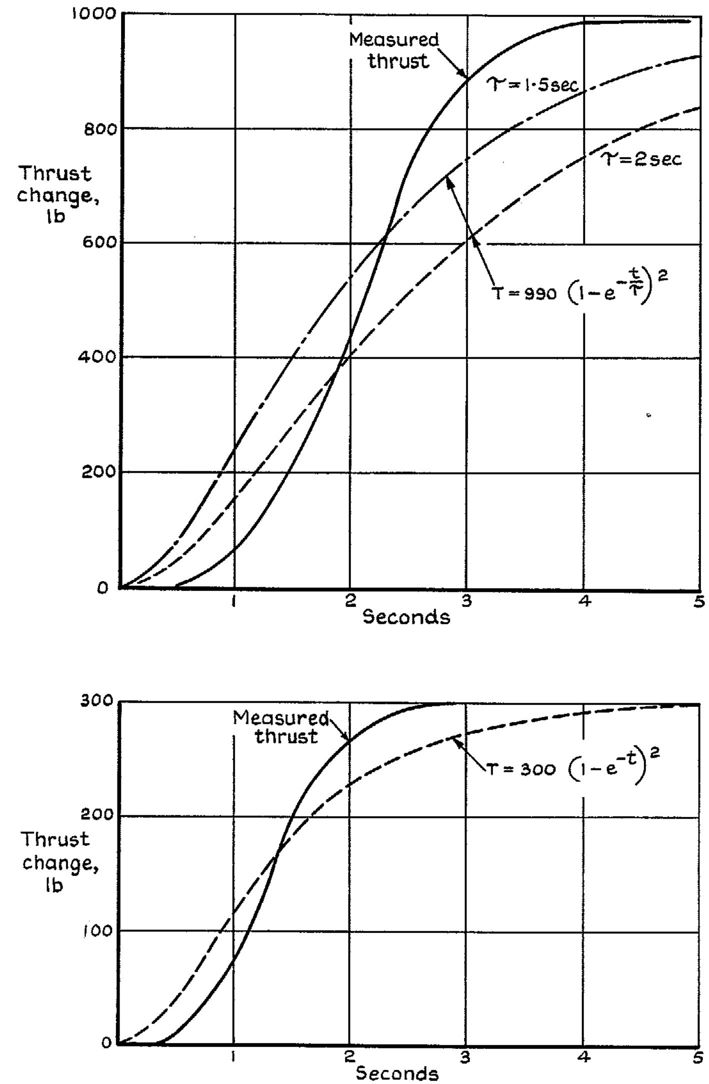


FIG. 32. Approximations to actual engine lag, step input.

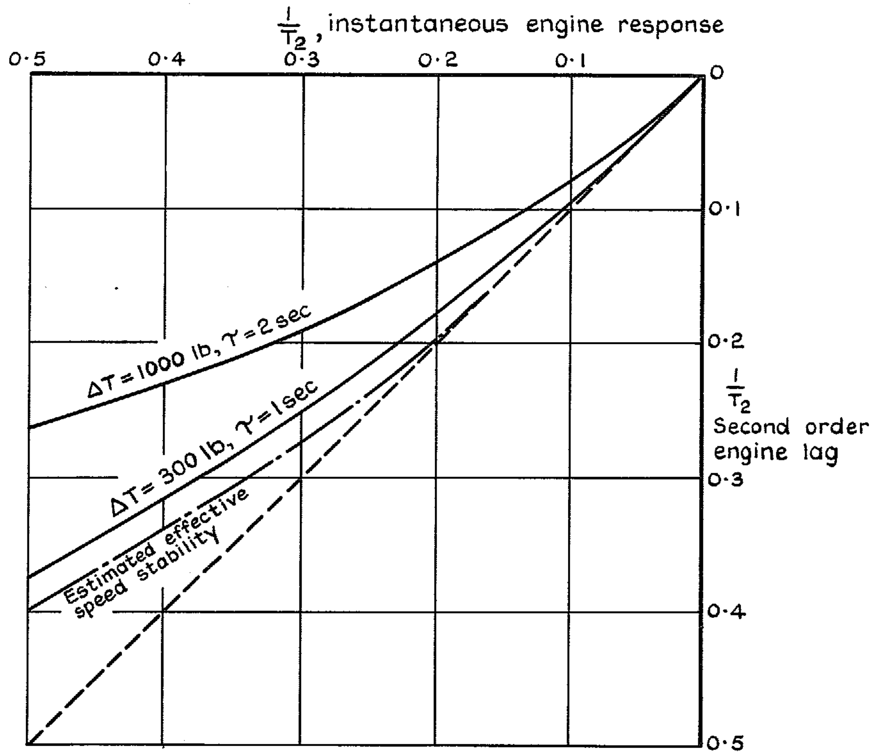


FIG. 33. The effect of engine lag on nominal speed instability.

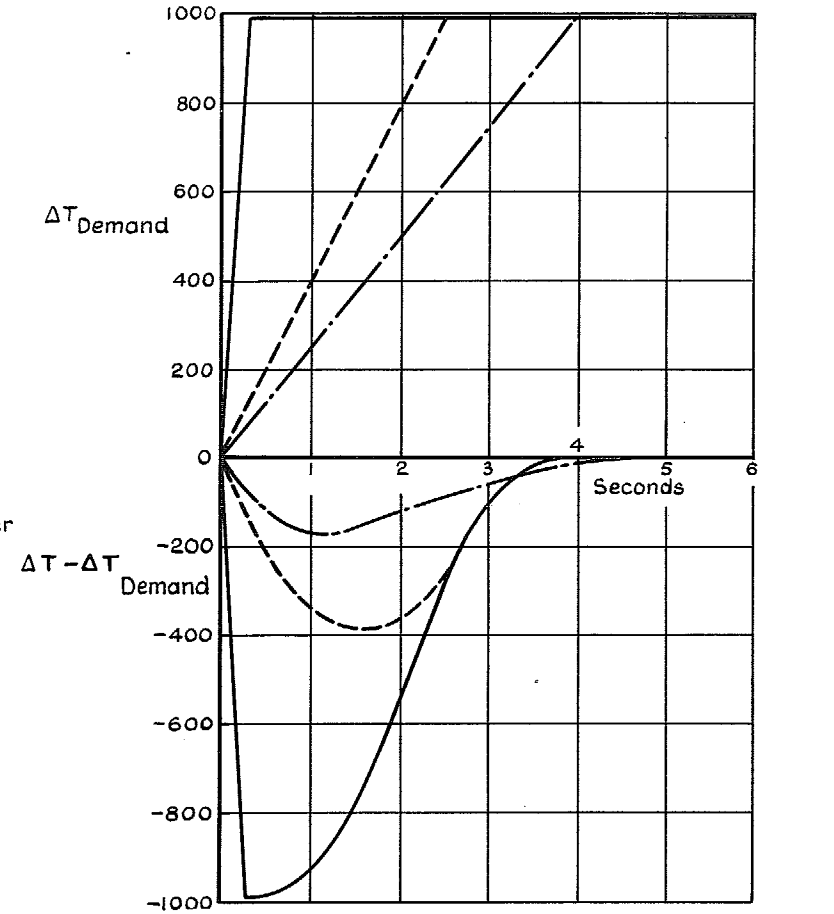


FIG. 34. Effect of ramp inputs on engine thrust response.

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