R. & M. No. 3606

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

A Review of Recent Research on Handling Qualities, and its Application to the Handling Problems of Large Aircraft

Part III. Longitudinal handling

by P. L. BISGOOD
Aerodynamics Dept., R.A.E., Bedford

LONDON: HER MAJESTY'S STATIONERY OFFICE
1970
PRICE £1 16*s* 6*d* [£1·82$\frac{1}{2}$] NET

A Review of Recent Research on Handling Qualities, and its Application to the Handling Problems of Large Aircraft

Part III. Longitudinal handling

by P. L. BISGOOD
Aerodynamics Dept., R.A.E., Bedford

Reports and Memoranda No. 3606*
January, 1968

Summary.

Recent research into longitudinal handling problems, based mainly on work with fighter-type aircraft, is reviewed and the results discussed with a view to formulating handling criteria. Using these results as a basis, together with *ad hoc* data, an attempt is made to synthesise handling criteria applicable to large aircraft. Separate criteria are advanced for the 'operational zone' and the landing approach. Because our knowledge of the factors involved remains rather rudimentary, the criteria proposed are incomplete and, in some areas, speculative.

LIST OF CONTENTS

Section

---

* Replaces RAE Technical Report 68022—A.R.C.30 600

1. *Introduction.*

Although we shall continue to follow the usual practice of treating the lateral and longitudinal motions separately, the reader's attention should be drawn to the reservations regarding this practice expressed at the beginning of Part II of Ref. 1. Recapitulating briefly, these are concerned with the fact that, even when there is little physical coupling between the longitudinal and lateral modes, the difficulty experienced by a pilot in controlling a particular mode (and hence his assessment of it) will be influenced by the demands made on him at the same time to control the other freedoms of the aircraft. Thus the longitudinal (or lateral) handling criteria derived from a particular investigation may be strictly applicable only when all the remaining significant characteristics are similar to those of the test vehicle. A device frequently adopted by workers in this field is to optimise all the aircraft characteristics other than those under study (i.e. they are adjusted to standards that in isolation would be considered as 'satisfactory'* or 'good') so that their results apply strictly only to an aircraft which is 'satisfactory' in all other respects.

Somewhat similar difficulties arise within the field treated as longitudinal handling where, normally, two distinct modes of motion are usually considered in isolation although they may interact very strongly under some conditions.

---

* In general the terms 'satisfactory' and 'acceptable for normal operation' are used in the sense of the original Cooper[4] rating scale, shown in Table 2: where exceptions occur they are noted in the text. It should be pointed out that the subject of pilot rating scales has been under discussion for some time with the objective of producing a revised formulation that would be less imprecise and would achieve wider acceptance and more uniform usage.

The natural modes of longitudinal motion which occur most frequently in practice are the familiar 'phugoid' and 'short-period oscillation' of classical stability theory. The complex roots normally associated with either or both of these modes can become real (e.g. with negative stability margins), which results in a combination of subsident and divergent motions. In some circumstances the roots may re-group in a manner resulting in the so-called 'third oscillation', which involves speed and incidence changes. When the inclination of the flight-path to the horizontal is constrained by pilot's elevator control, the classical phugoid degenerates into a simple subsidence or divergence in airspeed: the practical importance of this special case, for example its significance during the landing approach, will be obvious.

The pilot is concerned with the behaviour of the aircraft in response to his control demands and to external disturbances, and this is determined by the stability of the aircraft (i.e. the stability characteristics of the longitudinal modes) and by parameters describing the control characteristics and gust sensitivity. The practice, usual in handling research, of treating the longitudinal modes largely as distinct entities implies that each mode is assumed to correlate uniquely with a particular flying problem. This assumption is a reasonable one when the 'characteristic times' of the two modes are well-separated—a situation which prevails over much of the flight range, provided that the aircraft has adequate static stability; reducing the static stability decreases this separation, however, and can easily be carried to the point where the problems confronting the pilot can no longer be attributed to one mode or the other, but represent in some sense the 'resultant' of effects which normally are separable. Somewhat similar difficulties may occur at very low speeds (e.g. on the approach, particularly in the case of S.T.O.L. aircraft) even in aircraft having adequate static stability. Thus, while we shall follow the usual practice of treating the longitudinal modes as separate entities, and deal with them in separate sections of this report, the reader should appreciate that this division can become highly artificial in certain conditions and, therefore, that some topics may appear in more than one Section. A similar observation applies to the Section on control characteristics.

In each of the major Sections of Part III (dealing with long- and short-period motions and control systems, respectively) we shall consider first such systematic research work as is available and then (since little, if any, of this is applicable directly to large aircraft) attempt to use this information, together with data from general test sources, as guidance in formulating handling criteria for large aircraft. Where appropriate, different flight conditions (e.g. cruise and approach) are treated in separate sub-sections.

2. *Modes having a Long Period (or Time Constant)*

2.1. *The Phugoid*

The classical phugoid is a lightly-damped low-frequency oscillation in which changes of airspeed and height occur at substantially constant incidence. This picture of the motion is, of course, an approximate one but is reasonably accurate provided that the pitching derivative due to speed changes is small ($m_u \doteqdot 0$) and the static stability is large; in these circumstances (which occur quite frequently in practice) the phugoid period is proportional to true airspeed (a common approximation is $P_p = V/5$ sec, where V is in mile/h) and the damping ratio is inversely proportional to the lift-drag ratio. In the more general case, however, the motion involves changes of incidence also and the approximations for the phugoid period and damping must be modified to take account of this; however, the effects on the period usually are small and the motion remains essentially a long-period one, for example, in cruising flight the periods of typical transport aircraft range from one to two minutes.

Because of its low frequency, the pilot has generally little or no difficulty in controlling the phugoid mode, though low phugoid damping makes it difficult to establish an accurate trim and so influences the extent to which the pilot must monitor the situation in order to maintain a desired flight condition with sufficient accuracy. That is to say, the significance of the mode from a handling point of view lies mainly in the degree to which it may distract pilots' attention from more important tasks. This view is confirmed both by general practical experience and by the systematic investigations described below.

Refs. 2 and 3 describe a series of systematic tests, made by Cornell Aeronautical Laboratory in a variable-stability B–26 aircraft, to determine the influence of phugoid damping on pilots' assessments of the handling qualities and on their 'performance' in certain tasks. In these tests the damping was varied and the period maintained substantially constant (at about 50 seconds) by introducing incremental pitching derivatives ΔC_{m_u} and $\Delta C_{m_{\dot{u}}}$, by means of a small auxiliary aerofoil mounted on the side of the fuselage.

Under visual flight conditions, a change in phugoid damping ratio (ζ_p) from 0·32 to −0·12 produced no significant changes in task performance (height holding, etc.) or in the pilots' assessment of the flying qualities[2]. The effects of various levels of phugoid damping were then examined under simulated instrument flight conditions during which the pilot was responsible also for navigation tasks and radio operation, and was required to follow an 'airways' type flight pattern. Flight durations ranged from about 30 minutes[2] to one hour[3] per configuration. Task performance was now found to be influenced strongly by phugoid damping, for example, the power spectral density of height-holding errors at the phugoid frequency (0·02 cps) decreased from about $1{\cdot}5 \times 10^5$ ft^2/cps at $\zeta_p = -0{\cdot}2$, to about 2×10^4 ft^2/cps at $\zeta_p = 0{\cdot}3$. Pilots' assessments of the flying qualities also correlated with the phugoid damping, as illustrated in Fig. 1*; it should be noted, however, that imperfections in the artificial stability system used in these experiments appear to have introduced certain objectionable handling features, particularly at high damping ratios, so that the boundary of Fig. 1 may be distorted by these extraneous effects, especially in the area of high damping ratios. The general nature of the pilot comment indicates that in relatively undemanding situations, such as 'cruise' or 'holding', the pilot is content to exercise only rather loose control over speed and height and his opinion is influenced mainly by the frequency with which he must sample these quantities to achieve a satisfactory result. For this reason Leyman[5] has suggested that pilot opinion should be related to a parameter such as the time to halve or double amplitude, rather than damping ratio, and the curves of Ref. 3 are shown plotted on this basis in Fig. 2. As the Cornell tests were made at a fixed frequency, their results cannot be used to distinguish between these two hypotheses.

The damping times of several contemporary large aircraft under 'cruise' conditions have been included in Fig. 2. No formal assessments of the phugoid qualities of these aircraft are available but in view of their history of reasonably satisfactory service we have assumed, perhaps rashly, that they would most probably be rated not worse than 'acceptable—poor', as indicated by the vertical lines in Fig. 2. On this basis, it would appear that the damping—pilot rating relationship of Ref. 3 may be somewhat too demanding and that a more reasonable lower limit for 'satisfactory' operation (Cooper rating = 3·5) may perhaps correspond to about zero damping: there is very little evidence on which to base a limit of 'acceptability for normal operation' (Cooper rating = 5), but what there is suggests that the time for the phugoid to double amplitude (T_2) should be not less than about 4 seconds.

On the basis of pilot-airframe system analyses, Ashkenas and McRuer[6] have indicated that the interaction between the phugoid and short-period motions will not introduce significant handling problems provided that the ratio of the short period and phugoid frequencies (ω_n/ω_p) is greater than about 20. When this condition is not met, handling difficulties can arise—for example, the increasingly unfavourable assessments associated with decreasing (short-period) frequency that have been reported in some so-called short-period handling studies may arise, in part, from the increasing proximity of the short-period and phugoid frequencies.

The presence of certain adverse qualities (notably, excessive friction and backlash) in the longitudinal control or trimming systems can present the pilot with handling difficulties which appear similar to those associated with a divergent phugoid and may, in fact, mask any effects the phugoid might otherwise have on pilots' assessments of the handling qualities. We mention the point here simply to illustrate the complex inter-relationships which exist between 'stability' on the one hand and 'control' on the other. Control system qualities are discussed in more detail in a later Section.

---

* The scale of pilot ratings shown in Figs. 1 and 2 was devised by C.A.L. and used extensively by them in the earlier phases of their handling research, including the work under discussion. It is detailed in Table 1. While it differs significantly from the Cooper[4] scale (Table 2) in many respects it seems that ratings of 'acceptable' and 'acceptable—poor' correspond reasonably closely in definition to ratings of 3·5 and 5, respectively, on the Cooper scale.

2.2 *The 'Tuck' Mode*

There are many circumstances which can lead to the replacement of the normal phugoid oscillation by a divergence having a long time constant. One which occurs quite commonly in practice is engendered by the changes in m_u associated with the transition from sub- to supersonic conditions: these changes invariably are in the destabilising sense and, if sufficiently large, can lead to a nose-down divergence with increasing Mach number, known as the 'tuck' mode.

In general pilots have little difficulty in controlling the 'tuck' mode satisfactorily, since its time constant generally is relatively long. Such control does, however, demand a considerable degree of attention, and pilot opinion of the overall handling qualities suffers in consequence. Partly for this reason and partly because failure to control the 'tuck' would lead to undesirable and perhaps dangerous situations, a common design solution is to suppress the mode by automatically applying compensating pitching moments as a function of Mach number. Devices of this type are fitted to most of the present generation of large jet-aircraft designed for high subsonic speeds, and are often described as 'Mach trimmers' or 'Mach compensators'. It seems certain that whenever the 'tuck' mode appears as a real or potential source of trouble it will be automated out of existence by a Mach trimmer or similar device. There is, therefore, little point in discussing it further.

It should be noted, however, that when the static stability is low quite small (negative) values of m_u suffice to convert the conventional phugoid into a divergence, and it seems possible that this may have occurred in some short-period studies and given rise to additional difficulties (and hence to more unfavourable assessments) at low short-period frequencies.

2.3 *Stability under Constraint*

2.3.1 *General.* Another circumstance in which the phugoid is replaced by an aperiodic mode occurs when the aircraft is constrained, by use of the pitch control, to follow a rectilinear flight path[7]. The motion resulting from this suppression of one degree of freedom, following a disturbance (u_o) in airspeed, is of the form

$$u = u_0\, e^{-t/t_1}$$

where the time constant of the motion, t_1, is given by

$$t_1 = \frac{W}{g\left(\dfrac{\partial D}{\partial V} - \dfrac{\partial T}{\partial V}\right)} \left(\doteqdot \frac{V}{2g\left(\dfrac{C_D}{C_L} - \dfrac{dC_D}{dC_L}\right)}, \text{ at constant thrust, } T \right)$$

Clearly an initial speed error will decay if $\left(\dfrac{C_D}{C_L} - \dfrac{dC_D}{dC_L}\right)$ is positive and increase if it is negative or, to put it another way, will decay if the trimmed speed (V) is above the speed for minimum drag, and *vice versa*. The characteristic time of this mode can be said to describe the 'speed stability' of an aircraft.

The mode has little practical significance over much of the flight envelope because (a) the pilot does not often exercise sufficiently 'tight' control to create the degree of constraint needed for its existence, and (b) most aircraft operate normally at speeds well above the minimum drag speed, and here the mode is heavily damped even if it should be brought into play. Conversely, the speed stability may become highly significant when the pilot attempts to maintain a precise rectilinear flight path at speeds in the region of, and below, the minimum drag speed. The commonest and most important flight situation in which these conditions are likely to be satisfied occurs during the landing approach, and it is here that the level of speed stability has a profound effect on the difficulty of the piloting task—in an extreme case it may set a lower limit to the acceptable approach speed. Recent design trends have led, in the main, to aircraft whose useful low-speed regimes extend well below their minimum drag speeds, and so have enhanced the importance of these problems. The influence of speed stability on the problems of handling on the approach is discussed below.

2.3.2. *Speed stability on the approach.* Let us consider first those investigations in which systematic efforts were made to isolate and assess the influence of speed stability on the approach.

The test vehicle used by Staples[8] was a small, tailless, delta-winged aircraft (Avro 707A) fitted with a variable-gain auto-throttle which could be set to respond either to changes in speed alone (variable X_u) or to a combination of speed and incidence changes (variable X_u and X_w). In its basic condition the aircraft was speed stable at the approach speed of 120 kt, having a time to half-amplitude ($T_{\frac{1}{2}}$) of about 60 seconds; the longitudinal short-period mode had a natural frequency (ω_n) of 1·8 rad/sec and a damping ratio (ζ_n) of 0·36, and there was no change of trim with variation of engine thrust; this combination of longitudinal characteristics was rated as marginally 'satisfactory' and the lateral characteristics were also 'satisfactory'. In the tests, the aircraft was flown level to intercept the glide path at a range of 4 to 5 miles; thereafter the pilots attempted to maintain a constant approach speed and glide path. Information on glide-path errors was transmitted to the pilot by a ground controller in intervals of about 0·03 deg; this degree of sensitivity permitted very 'tight' control of the flight path and gave also some indication of rate of change of error. The pilots used visual references to detect azimuth errors.

The aircraft was assessed by four pilots over a range of destabilising gains applied to the auto-throttle system, and similar tests were made with a constant artificial lag in the thrust response to pilots' throttle lever inputs. Throughout these tests, all other handling parameters remained unchanged at the 'basic' aircraft levels. Atmospheric conditions during the test programme varied from 'smooth air' to 'moderate turbulence'.

The results of these tests are shown in Figs. 3a and 3b, for the 'normal' and 'lagged' thrust response respectively, in the form of mean pilot ratings plotted against the reciprocal of the time to double (T_2) or halve ($T_{\frac{1}{2}}$) an initial speed error. ($T_{2,\frac{1}{2}} = 0{\cdot}693|t_1|$). It will be seen that pilot ratings worsened in both cases roughly linearly with increasing $1/T_2$, and the adverse effect of the lagged engine response is evident from the increased gradient. It will be seen from Fig. 3 that the method used to vary the speed stability (i.e. by varying X_u alone, or by varying both X_u and X_w) seems to have had little influence on the results. The level of atmospheric turbulence also appears to have had little significant effect on the results, somewhat surprisingly, and a still more surprising result is evident in the very high levels of speed instability that the pilots were prepared to accept in this experiment—where, for example, the value of T_2 corresponding to the limit of 'acceptability for normal operation' lies between 5 and 10 seconds. Apart from the effects of 'learning', two factors may have contributed to this high tolerance: firstly, the pilots may have obtained 'advanced' information of impending speed changes from the changes in engine noise from operation of the auto-throttle (though they were not conscious of using such information); secondly, the information supplied by the ground controller may have made the task of flight-path control artificially easy and so enabled the pilot to devote more attention to speed control.

Ref. 9 describes a complementary simulator study of the speed stability problem. The simulator was set up to represent the aircraft used in the flight work of Ref. 8 and the experimental methods were generally similar except that it was not possible, in the simulator, to provide sufficiently good visual information and the participants had to make approaches using I.L.S. The results, in terms of pilot ratings, are shown in Fig. 4 for three levels of atmospheric turbulence (0, 3 and 6 ft/sec rms gust velocity). It will be seen that, at the milder levels of turbulence, the pilots' assessments agree quite well with those obtained in the flight experiment, particularly at the less extreme levels of speed instability. The results show a significant trend, not exhibited in the flight experiment, towards a worsening of pilot opinion with increasing turbulence; this may arise partly from the greater difficulty of the simulator task, which presented no motion cues.

It should be noted, however, that for each level of turbulence the pilots' ratings deteriorated with increasing speed instability at a slightly higher rate than that found in the flight experiments.

A flight investigation by C.A.L. is described in Ref. 10. In this, the variable-stability T.33 was used, fitted with secondary air brakes which were controlled, through a variable gain, by signals from an incidence vane (variable X_w). The main purpose of the investigation was to evaluate the influence of the short-period dynamics on the approach, and the way in which this was modified by the level of speed stability. The evaluation was made by a single pilot who assigned ratings on the basis of the revised Cornell scale shown in Table 3. Each test run comprised; (i) a let-down and initial approach (to 600 ft and 2 miles out) under simulated I/F conditions,* (ii) a final approach, using a visual glide slope indicator; (iii) an overshoot and visual circuit; (iv) a second approach using the visual glide slope indicator; (v) overshoot and climb away. The target speed for the entire pattern was 160 kt.

The results of Ref. 10 can be used to examine the influence of speed stability on pilot assessment provided, of course, that some account is taken of the variations in short-period characteristics. The results indicate that at any combination of speed stability and short-period frequency (ω_n), pilot opinion improves rapidly as the short-period damping ratio (ζ_n) is increased, up to values in the region of 0·4 and thereafter changes little with further increases in ζ_n. Data relating to this 'opinion plateau' are shown plotted against speed stability in Fig. 5a,** subdivided into three arbitrary ranges of short-period frequency. Fig. 5b shows a similar plot for somewhat lower short-period damping. Fig. 5 first shows the effect of the short-period characteristics on pilot rating, which is a topic to be discussed in detail later. What is of interest here is the fact that the deterioration of pilot rating with speed instability (i.e. the slope of the lines drawn in Fig. 5) is generally independent of the short-period characteristics, so that the two effects could be treated as virtually additive. In view of the scatter of the basic data this conclusion may be somewhat hasty, but comparing the trend with that obtained in Ref. 8 it would appear that the pilots participating in the experiment reported in Ref. 10 were more sensitive to and less tolerant of decrease in speed stability. The rather large scatter evident throughout Fig. 5 can be attributed in part to the fact that each set of data points covers a fairly wide range of short-period characteristics. No really consistent effects of turbulence are distinguishable, perhaps due to this cause.

The short-period characteristics of the test vehicle of Ref. 8 were comparable with those applicable to part of the Ref. 10 data ($\zeta_n \geqslant 0{\cdot}37$; $1{\cdot}6 < \omega_n < 2{\cdot}2$), and the curve of Ref. 8 has therefore been included in Fig. 5a for comparison. It will be seen that, while there is some measure of agreement between the two sources for speed stabilities near neutral, the Ref. 10 results show a much more rapid deterioration in pilot rating with increasing speed instability. In the present writer's opinion the main reasons for this lie partly in differences in the rating systems employed and partly in differences between the evaluation procedures used in these experiments and in the information sources available to the pilots; summarising the latter briefly—

(a) In the tests of Ref. 8 each trial run demanded a single change of flight path (and hence power). The approach phase lasted about 2 minutes, was made wholly under visual flight conditions, and during it the pilot was supplied aurally with glide path information of high accuracy and resolution. Whereas,

(b) In the tests of Ref. 10 each trial run was made partly on instruments and partly under visual conditions. The initial let-down demanded three changes in flight path to predetermined rates of descent (followed by a fourth as the pilot went visual) and the approach aids available during it seem to have been minimal: this stage lasted about 6 minutes. On 'going visual' the pilot had to correct any lateral offset developed during the let-down, acquire the glide path,† and follow it down to the overshoot height (25 to 100 ft): this phase lasted about 1 minute. The information derivable from the visual glide slope indicator was probably rather less accurate than the aural information supplied in the tests reported in Ref. 8, at least in the earlier parts of the approach.

In short, the evaluations of Ref. 10 covered a wider and more demanding range of manoeuvres than those of Ref. 8 and were made under generally more adverse conditions, indeed the aids used during

---

* This phase commenced with the aircraft in level flight at 5000 ft and 12 miles range. Power was reduced to give a rate of descent of about 2300 ft/min down to 1600 ft and was then readjusted to reduce the rate of descent to 600 ft/min; this condition was maintained down to 600 ft (range then about 4·5 miles), where a further power adjustment was made to achieve and maintain level flight in to a range of 2 miles.

** The data shown here and in Fig. 5b relate to the flaps-up case only (about 90 per cent of all approaches were made in this condition). Lowering the flaps changed the approach attitude, and hence the pilot's view, such that approach judgment became rather more difficult.

†Set at 3·6° compared with 3° in Ref. 8. From the comments in Ref. 10 the pilot seems to have been unaccustomed, initially at any rate, to so steep an approach path.

the let-down phase were inferior to those in current use. On balance it is thought that the evaluation manoeuvres of Ref. 10 and the conditions under which they were made were more demanding than those of contemporary practice and the results therefore present a somewhat pessimistic picture: conversely, the tests of Ref. 8 were made under favourable conditions and probably gave optimistic results.

Ref. 11 contains, *inter alia*, a description of some fixed-base simulator tests made to assess the approach handling characteristics of a large supersonic transport aircraft, including the effects of varying the speed stability. The evaluation manoeuvre comprised acquisition of the correct approach path (at 7 miles range, and 1500 ft) and a 'straight-in' instrument approach using I.L.S. down to a range of about 1 mile, followed by a 'visual' final approach (using a television display of the runway lighting system—DALTO). The lateral handling qualities were 'satisfactory', and 'mild' turbulence was fed into the computer. A current jet transport was also simulated and its characteristics were used as a yardstick against which to assess the SST. The influence of speed stability on pilot opinion as found in this work is shown in Fig. 4 for two levels of short-period dynamics. Very similar results were found in the simulator study of Ref. 12.

Bearing in mind the large differences existing between the aircraft simulated, there is a surprising measure of agreement between the results of Refs. 9, 11 and 12.

The landing approach is a situation wherein, perhaps more than any other, a large number of handling parameters interact to influence the pilots' assessment. We have insufficient knowledge of these interactions at present to be able to formulate criteria of wide applicability. The evidence which has been considered does, however, enable us to suggest approximate speed stability criteria for a restricted class of aircraft—those whose handling qualities would otherwise be rated as 'satisfactory' or 'good'—when making instrument approaches under conditions of moderate turbulence and using an approach aid not inferior to I.L.S. The proposed criteria are:

(i) For 'satisfactory' operation ($PR < 3{\cdot}5$) the aircraft should be speed stable, having a time constant (t_1) not greater than 50 sec (i.e. $T_{\frac{1}{2}} \not> 35$ sec approximately).

(ii) For 'acceptable' operation ($3{\cdot}5 < PR < 5$) the aircraft may be speed unstable, but if it is the time constant (t_1) should not be less than 25 sec (i.e. $T_2 \not< 17$ sec approximately).

(iii) In an emergency (e.g. a failed auto-throttle*) a higher degree of speed instability may be tolerable (provided the operating conditions do not deteriorate at the same time), but in no circumstances should t_1 fall below 10 sec (i.e. $T_2 \not< 7$ sec approximately).

These proposals are shown graphically in Fig. 6 where they are compared with the criteria put forward by Leyman[5]. Also shown in Fig. 6 are values of t_1 for several aircraft which are known to be at least 'acceptable' for visual and instrument approaches respectively: although data on the latter are rather sparse, they tend to confirm the criteria. Note also that the proposal relating to 'satisfactory' operation is broadly in agreement with the limit ($T_{\frac{1}{2}} \not> 50$ sec) proposed by Lean and Eaton[15] for instrument approaches.

There is no experimental evidence on the acceptable level of speed stability following sudden failure of an auto-throttle during the approach, but we may expect that less instability could be tolerated in this case than the level specified in (iii) above, which relates to a failure to which the pilot has had time to adjust.

It should be noted that the above criteria assume that a satisfactory thrust margin is available (Ref. 13 suggests a minimum value for $\frac{\Delta T}{W}$ should be 0·12) and that the thrust response is satisfactory.

Before leaving the topic of speed stability it is interesting to note that if an auto-throttle is used in an aircraft having the thrust line offset below the cg this will reduce the aircraft's static stability and so might cause the pilot to downgrade his assessment if the auto-throttle gain is too high.

---

* Assuming that the failure occurred prior to starting the approach.

3. *The Short-Period Oscillation.*

3.1. *General*

The longitudinal mode known generally as the 'short-period oscillation'* is essentially a motion in which the incidence oscillates while the airspeed remains substantially constant; to a good approximation, the aircraft motion can be resolved simply into pitching and plunging (i.e. vertical translation) components. The characteristics of the mode (i.e. its frequency and damping), together with parameters describing the control power, the response, and the gust sensitivity, define the short-term response to control inputs and to gusts and there can influence profoundly a pilot's assessment of the handling qualities of an aircraft.

The undamped natural frequency (ω_n) of the oscillation is, of course, related to the aerodynamic stiffness in pitch (i.e. to the manoeuvre margin, H_m) and the pitching inertia (B); neglecting airspeed changes and assuming $L_{\dot{\alpha}} = L_q = 0$, an approximate relationship can be written,

$$\omega_n^2 = -\frac{1}{B}\left(M_\alpha + M_q \frac{L_\alpha}{mV}\right) = \tfrac{1}{2}\rho\, V^2\, S\, \bar{c}\, \frac{aH_m}{B} \quad (\text{rad}^n/\text{sec})^2$$

where $M_i = \dfrac{\partial M}{\partial i}$, $i = \alpha, q, \dot{\alpha}$, etc.

$L_i = \dfrac{\partial L}{\partial i}$, $i = \alpha, q, \dot{\alpha}$, etc.

$a = \dfrac{\partial C_L}{\partial \alpha}$, and m = aircraft mass.

For aircraft having acceptable manoeuvre margins, H_m, ω_n may range from over 10 rad/sec to under 1 rad/sec, depending on the manoeuvre margin itself and on such additional factors as size, airspeed, height, etc. For negative manoeuvre margins, the motion degenerates into a divergence. This may be accompanied by a change in the character of the long-period motion (from the classical phugoid to an oscillation involving changes in both airspeed and incidence) which, however, does not appear to have a significant influence on pilot opinion.

Contributions to the damping arise from the pitching and plunging components of the motion. Neglecting airspeed changes, the total damping ($\zeta_n\, \omega_n$) is given approximately by,

$$2\zeta_n\, \omega_n = \frac{L_\alpha}{mV} - \frac{M_q + M_{\dot{\alpha}}}{B} = \tfrac{1}{2}\rho\, V^2\, S\left[\frac{a}{mV} - \frac{\bar{c}^2}{2BV}(m_q + m_{\dot{\alpha}})\right]$$

$$\text{where } m_q = \frac{\partial C_m}{\partial\left(\dfrac{q\bar{c}}{2V}\right)}, \text{ and } m_{\dot{\alpha}} = \frac{\partial C_m}{\partial\left(\dfrac{\dot{\alpha}\bar{c}}{2V}\right)}$$

The short-period oscillation is usually well-damped, and in some cases the damping ratio may be above critical ($\zeta_n > 1$) when the motion will degenerate into a subsidence. Under transonic conditions the damping generally tends to fall, particularly in the case of tailless aircraft where it may reach very low values ($\zeta_n \doteqdot 0$).

---

* The name is somewhat misleading since the period is not necessarily 'short'. A more evocative term would be 'the incidence oscillation' but it seems unlikely that any change from the present usage would be accepted generally.

The aircraft response to control inputs can be written conveniently in the form of transfer functions. With the same assumptions as before, the transfer functions with respect to control surface displacement are:

$$TF_{\alpha\eta}(s) = \frac{\alpha(s)}{\eta(s)} = \frac{K_\alpha(T_\alpha s+1)}{s^2+2\zeta_n\omega_n s+\omega_n^2}$$

$$TF_{\theta\eta}(s) = \frac{\theta(s)}{\eta(s)} = \frac{K_{\dot\theta}(T_\theta s+1)}{s(s^2+2\zeta_n\omega_n s+\omega_n^2)}$$

and, since $\gamma = \theta - \alpha$, and $n_z = \frac{V}{g}(\dot\theta-\dot\alpha)$

$$TF_{\gamma\eta}(s) = \frac{\gamma(s)}{\eta(s)} = \frac{K_{\dot\theta}(T_{n1} s+1)(T_{n2} s+1)}{s(s^2+2\zeta_n\omega_n s+\omega_n^2)}$$

$$TF_{n\eta}(s) = \frac{n_z(s)}{\eta(s)} = \frac{K_{nz}(T_{n1} s+1)(T_{n2} s+1)}{s^2+2\zeta_n\omega_n s+\omega_n^2}$$

where s is the Laplace operator, and

$$K_\alpha = \frac{1}{B}\left(M_\eta + \frac{M_q L_\eta}{mV}\right)$$

$$K_{\dot\theta} = \frac{1}{BmV}\left(M_\eta L_\alpha - M_\alpha L_\eta\right)$$

$$K_{nz} = \frac{V}{g}K_{\dot\theta}$$

$$T_\alpha = -\frac{B L_\eta}{mV\,M_\eta + M_q L_\eta}\,: \qquad T_\theta = \frac{m V M_\eta - M_{\dot\alpha} L_\eta}{M_\eta L_\alpha - M_\alpha L_\eta}$$

$$T_{n_1} T_{n_2} = -\frac{K_\alpha}{K_{\dot\theta}} T_\alpha = \frac{B L_\eta}{M_\eta L_\alpha - M_\alpha L_\eta}$$

$$T_{n_1} + T_{n_2} = T_\theta - \frac{K_\alpha}{K_{\dot\theta}} = -\frac{L_\eta(M_q + M_{\dot\alpha})}{M_\eta L_\alpha - M_\alpha L_\eta}$$

The lift due to control surface deflection (L_η) usually has a significant effect only on the response of tailless and very large aircraft, and here the complete expressions given above should be used. For conventional, tailed aircraft, however, L_η generally can be neglected, giving the simpler relationships

$$K_\alpha \doteqdot \frac{M_\eta}{B};\; K_{\dot\theta} \doteqdot \frac{M_\eta L_\alpha}{B\,m\,V};\; T_\theta \doteqdot \frac{mV}{L_\alpha}$$

and

$$T_\alpha = T_{n_1} = T_{n_2} = 0.$$

T_θ is a measure of the amount by which normal acceleration (or flight path) changes will lag behind changes in pitch attitude—the larger T_θ is, the slower will be the flight path response following an attitude change. For this reason we may anticipate that T_θ will prove a significant variable in the handling 'equation'. However, its influence on the normal acceleration response as perceived by the pilot, will be modified by extraneous factors, such as changes in the cockpit—cg distance, and may prove somewhat elusive.

The aircraft transfer functions become more meaningful from a handling viewpoint if they are related to stick movement or stick force rather than to control surface displacement, and this can be done simply by multiplying by the control-surface/stick-displacement or control-surface/stick-force transfer functions as appropriate, e.g.

$$TF_{\theta x}(s) = \frac{\theta(s)}{X_s(s)} = TF_{\theta\eta}(s)\, TF_{\eta x}(s)$$

$$TF_{\theta F}(s) = \frac{\theta(s)}{F(s)} = TF_{\theta\eta}(s)\, TF_{\eta F}(s) = TF_{\theta\eta}(s)\, TF_{\eta x}(s)\, TF_{xF}(s)\text{, etc.}$$

In the case of a perfect servo combined with a linear spring feel system, $TF_{\eta x}(s)$ becomes simply the surface-to-stick gear ratio, $\Delta\eta/\Delta X_s$ while $TF_{XF}(s)$ is the control feel gradient, $\Delta X_s/\Delta F$. Many control systems can be described adequately, from a handling point of view, by these simple 'gearings' and the overall gains can then be specified completely by quantities such as the stick-force or stick-movement per g. In general, however, it may be necessary to retain at least a simplified description of the frequency response of the control system $\left(\text{e.g. to approximate it by a first-order lag, } \frac{K_c}{1+T_c s}\right)$ if a proper understanding is to be obtained, though, of course, the static gains (e.g. the stick force per g) remain highly significant handling parameters.

Among the many factors which condition pilot acceptance of a particular set of handling qualities perhaps the most important are the flight task and the aircraft size. In considering the short-period data (as in other facets of handling) it will be necessary, therefore, to consider different regimes separately, and in the subsequent discussion we shall concentrate on two flight regimes of basic importance, namely,

(a) the operational zone, in which the aircraft performs those tasks associated with its primary function, and

(b) the approach and landing phase.

This omits much of the flight envelope, which has not, as yet, been the subject of systematic study.

Within the operational zone, further divisions will be made on the basis of size and function (the two are, to some extent, interrelated in this regime); the crude distinctions made in the present Report are between small, fighter-type aircraft, medium sized, attack aircraft, and large bomber or transport aircraft respectively. There seems to be no *a priori* reason why similar divisions should be needed for the approach case, though the possibility will be examined.

The systematic work, which is dealt with first in each division, relates only to small and medium-sized aircraft.

3.2. *Handling in the 'Operational Zone'.*

3.2.1. *Systematic investigations.* So far as the writer is aware, the first systematic investigation of short-period characteristics as handling parameters was made at Cornell, whose pioneer work in this field, using variable-stability aircraft[2,16], did much to set the pattern of later investigations. Since that time many more experimental studies of these problems have been made using either variable-stability aircraft[2,16,17,20,21] or ground-based simulators [22-27]; so many, in fact, that they cannot all be discussed in detail here.

It was felt that the relevant details of these tests were best presented in a table (Table 4) to allow the reader quick reference to all the important information that is relevant to a better understanding of the corresponding results, which are given in the usual form of iso-opinion contours in Figs. 7 to 19. Table 4 lists the type of vehicle used and the flight conditions covered; it describes briefly the tests on which the assessment was based and the number of pilots involved; and it gives critical comments on the tests and the results, notes any suspected shortcomings in the experiment, and suggests the areas to which the results may be especially applicable. For convenience a brief summary of the main features of the various tests and the results presented in Figs. 7 to 19 is given below.

As one must expect in work of this nature, there is generally considerable scatter in the basic results of a single experiment and the drawing of iso-opinion contours leaves the investigator with a good deal of latitude; this is especially so when the 'grid' of test points is relatively open. With the benefit of hindsight one feels compelled to modify the interpretations made by some of the original authors so as to get a more unified picture, within the limits of the original data, and this has been done where it appeared justifiable.

Fig. 7 shows results from early tests on variable-stability aircraft, (a) on a medium bomber[2], and (b) on a fighter aircraft[16]. The control servos used to vary the aircraft's stability had limitations which gave rise to difficulties when attempting to produce high 'natural' frequencies. In this area, therefore, the assessing pilot may have been influenced by side-effects arising from this feature, and the results must be regarded as dubious.

Fig. 8 shows later results obtained with improved control servos[17]. Note that the upper limiting frequencies of the iso-opinion areas have been raised compared with those of Fig. 7b. Some deficiencies remained in the servos which, it is thought, may have been responsible for the closure of the 'best tested' area at high frequencies. Note also the divergence of opinion shown by one of the three participating pilots regarding the lower limit of acceptable damping.

Fig. 9 gives the author's re-interpretation of the data of Ref. 17, which leads to less optimistic contours than the original, and also attempts to take some account of the uncertainties surrounding the higher frequencies.

Fig. 10 shows the results of tests on another variable-stability fighter aircraft,[20]. High damping ratios (above 1) were not examined. Note here that the 'satisfactory' boundary was shifted into regions of lower damping when the control system time-constant (T_c) was optimised. The nominal optimum time-constants selected by the pilots are shown in Fig. 11 as functions of ζ_n and ω_n.

Fig. 12 shows the boundaries obtained in Ref. 20 for unstable configurations, and includes data obtained in Ref. 17 for low static stability and low or negative damping. There appears to be reasonable agreement between the two sources in this area of marginal handling.

Fig. 13 shows the iso-opinion contours obtained with a variable-stability medium bomber, using improved control servos[21]. Note that as a result of this improvement the iso-opinion boundaries are extended to higher frequencies than those shown in Fig. 7a, which relate to the same aircraft. The $PR = 5$ contour was interpolated by the present author on the basis of the data given in Ref. 21. High damping ratios (above 0·7) were not examined.

Figs. 14 and 15 show the iso-opinion contours obtained in early tests in fixed-base simulators (Refs. 22 and 23 respectively). The coverage was somewhat sparse in the experiment reported in Ref. 22 and only 2 degrees of longitudinal freedom were simulated, though lateral dynamics were included. Few details are available of the work reported in Ref. 23.

Fig. 16 shows the results obtained using (a) a moving cockpit simulator having freedom in pitch[24], and (b) a moving-cockpit simulator based on a centrifuge[25]. The results of Ref. 25 probably are applicable only to re-entry vehicles in view of the high datum acceleration ($7g$) at which the tests were conducted. Two degrees of longitudinal freedom only were simulated.

Figs. 17 and 18 show the iso-opinion contours obtained in a moving-cockpit simulator based on the same centrifuge[26]. Only 2 degrees of longitudinal freedom were set up on the computer, and the tests were conducted at a mean normal acceleration of $3g$ to minimise spurious angular acceleration cues. The basic characteristics of the simulated aircraft were closely similar to those of the aircraft employed in the flight tests reported in Ref. 20 and the results of Ref. 20 are included in Fig. 17 for comparison.

Because the grid of experimental points was rather 'open' one cannot exclude the possibility that the 'acceptable' area may extend to unusually low values of damping at low frequencies (Fig. 17).

Fig. 19 shows the iso-opinion contours obtained with a moving-cockpit simulator having (limited) freedom in vertical translation. The task was essentially one of low-level terrain following and the coverage was rather sparse. The computation included only two degrees of longitudinal freedom, but the roll and spiral modes were included.

A brief study of Figs. 7 to 19 shows that there are considerable quantitative differences between the results of the various experiments. It is evident that some of these differences may be attributed to imperfections in the experimental equipment or to uncertainties in the assessments. Further causes are to be found in the variety of tasks on which the assessments were based; this variety results, of course, from the diverse operational roles studied. Apart from these areas of uncertainty it is to be expected (as was pointed out in the Introduction) that the assessments were influenced by aircraft parameters other than those treated as experimental variables: that, in fact, the acceptability of the short-period pitching motion is not uniquely defined by the two parameters ω_n and ζ_n alone. Quite apart from such extraneous influences as the stability and controllability of other aircraft modes, longitudinal short-term control will be affected more directly by the characteristics of the feel and control systems, and also by secondary features (which cannot be taken account of here) such as view and cockpit environment.

Despite the quantitative differences, referred to above, the results of all the investigations considered exhibit certain common features of a qualitative nature. In each case the results delineate areas in the ω_n—ζ_n plane (or in the ω_n^2—$(2\zeta_n\,\omega_n)$ plane), as for instance in Fig. 9, such that a similar aircraft whose short-period characteristics fell within these areas would satisfy certain qualitative handling standards. There is, in general, an inner area within which an aircraft would be considered 'satisfactory', a somewhat larger area in which the handling deficiences would still be 'acceptable', and a region outside this in which an aircraft would be 'unacceptable'. In most of the work the region of high natural frequencies has not been sufficiently well mapped to establish with certainty the upper bounds of these regions, or indeed if such upper bounds exist at all. In Fig. 9, for example, this is indicated by the dashed portions of the iso-opinion contours.

In addition to giving a general appraisal of the acceptability or otherwise of particular combinations of frequency and damping, pilots frequently specify their objections in more detail describing one combination as 'sluggish', another as 'over-sensitive', and so on: it is clear that while the same rating may be given in different regions of the ω_n—ζ_n plane the nature of the underlying criticisms may be quite different and may be concealed if only the overall rating is given. To obtain a proper grasp of the problem one must take account of the criticisms giving rise to a particular rating, and in attempting to formulate handling criteria compatible with the experimental iso-opinion contours it will be necessary to consider separately those segments (as opposed to the whole contour) which correspond broadly to regions where the handling problems encountered are predominantly of a single kind.

A study of the pilots' criticisms enables us to distinguish three such regions of the 'unacceptable' area in the ω_n—ζ_n plane namely—

(i) High damping combined with moderate to high frequencies gives rise mainly to complaints that the response is 'sluggish'*.

(ii) Low damping combined with moderate to high frequencies gives rise mainly to complaints that the response is oscillatory, over-sensitive and abrupt, and may lead to pilot induced oscillations.

(iii) At low frequencies the response may be criticised for its oscillatory nature, or its sluggishness, or both, depending on the damping, but there is uniform criticism which seems to be directed at a lack of static stability (e.g. 'difficulty in trimming' is a common complaint).

---

* Complaints of 'tuck-up' or 'tuck under' tendencies (e.g. *see* Fig. 7b) are quite consistent with a sluggish basic response and indicate merely that the pilot attempts to quicken the response by over-controlling initially.

Similar though less severe criticisms are made of the corresponding regions of the 'unsatisfactory but acceptable' area.

The significance of these distinct parts of the iso-opinion contours will be examined in detail in the Sections that follow, but before doing this let us consider briefly some of the possible pitfalls that may lie ahead. First, we shall find it necessary to relate our criteria to one particular aspect of the pilots' criticisms in each of the three main regions; this will be adequate provided that, in each region, we succeed in identifying the dominant source of complaint and provided this does not change significantly throughout the region—if it does, then we must subdivide the region and this, we shall see, proves necessary when dealing with the low-damping region ((ii) above). Where sources of complaint can be reduced to a common denominator the selection of the dominant source becomes less critical—for example, 'abruptness of response' may be related in a fairly uniform way to 'tendency to overshoot load factor' for aircraft of broadly similar design, with a corresponding relationship between criteria descriptive of these two qualities: one must exercise caution when applying such criteria to aircraft that lie outside the range for which such relationships exist. Second, the data with which we have to work often are incomplete—for example, the atmospheric conditions may not be described adequately (or, indeed, at all), so that the results and the criteria derived therefrom may, in some cases, relate to calm conditions only; if this were so, other and perhaps more demanding criteria related to the response in turbulence might take precedence in more general conditions. The latter point should be borne in mind particularly when we come to consider the lower limits of damping.

(a) *Upper limits of damping*

We have noted that when the damping becomes 'too high' at moderate or higher frequencies the available pilot comment is unanimous in criticising the sluggishness of the response, and it is evident that this sluggishness is the main reason for unfavourable assessments in this area.

It is possible to suggest many simple quantitative criteria by which the pilot might assess this property of sluggishness. He might, for example, base his assessment on the time taken to reach some fraction of the final steady response to a rapid control input; alternatively he might be concerned with the response to inputs at a moderate frequency (such as might be used for dynamic control), comparing these with the response to steady inputs of the same amplitude. Specific criteria based on features of the normal acceleration response to an idealised step input of stick force (but including the effect of control system lag) are shown in Fig. 20, where they are compared with the iso-opinion contours of Fig. 9: it will be seen that the agreement is good at damping ratios greater than about 0·9, and that the quantitative limits implied by these trial solutions appear intuitively to be reasonable. It should be added that criteria based on the response to continuous excitation or on response features other than normal acceleration can be formulated which fit the data equally well. Indeed the multiplicity of possible criteria creates a dilemma which cannot be resolved on the basis of data obtained under a single set of conditions (as in Ref. 17—the only considerable body of flight assessments at high damping ratios) but would require the systematic variation of other parameters, notably T_θ and V, in addition to the short-period characteristics. Since systematic flight data are not available we must look elsewhere for clues to help in our choice of criteria.

In the moving-cockpit simulator experiments reported in Ref. 27 the influence of short-period dynamics on handling was assessed under simulated low-level, high speed flight conditions. The 'satisfactory' boundary agrees moderately well in the high damping region with that of Ref. 17, bearing in mind the differences in task between the two sources (*see* Fig. 19). Because the values of T_θ (which affects the pitch response directly, but not the normal acceleration response) differed by a factor of about 2 between the Ref. 17 and 27 tests, this agreement tends to support the view that the pilot is concerned less with pitching than with normal acceleration response in this region of short-period dynamics: further supporting evidence can be found in the simulator tests reported in Ref. 28 (which also indicate that when n_{z_α} is low, as on the approach, the pilot may transfer his concern to the pitching response). The results of Ref. 27 indicated also that the boundary was only slightly affected by variations in the static stick force per g over the range 4 to 10 lb/g in the high-damping region. We shall, therefore, base our criteria on features of the normal acceleration response.

In the experiments reported in Ref. 18 the 'equivalent first-order time constant' (T_c) of the control system was among the parameters varied at constant short-period dynamics, and the optimum and the maximum and minimum 'acceptable' values of T_c were established for a range of SF/g and breakout forces. The maximum control lags rated as 'acceptable' were surprisingly large and, if valid, would be quite incompatible with criteria of sluggishness based on the response to a step input. However, the optimum T_c's of Ref. 18 are much higher than those established in a later study[20] made under similar conditions in the same aircraft, and it would seem unwise, in view of this discrepancy, to place too much weight on the evidence relating to maximum 'acceptable' time constants. It should be added that the frequency-response data for the control system of Ref. 18 (for nominal T_c's of 0·5, 1 and 2 sec) suggest that the effective values of T_c were in fact about 75 to 80 per cent of the nominal values, and it seems likely that a similar relationship would apply to the (virtually identical) control system used in the Ref. 20 experiments: if this is so, then the optimum T_c's established in Ref. 20 are not incompatible with criteria of sluggishness based on the response to a step input.

Taken together, the evidence suggests that handling criteria in this region of short-period dynamics can be related to features of the normal acceleration response to a step input of stick force, which set limits to the quality of 'sluggishness'. It is proposed that, for 'satisfactory' operation of fighter-type aircraft the time taken to reach 90 per cent of the final steady normal acceleration following a step input in stick force should not exceed 1 sec. For 'acceptable' behaviour, this time should not exceed 1·5 sec. These criteria* fit the experimental boundaries of both Refs. 17 and 27 reasonably well.

There is insufficient systematic data to enable us to determine how these criteria should be modified to take account of aircraft size and function but what there is indicates, as might be expected from past experience, that pilots will accept a more sluggish response in larger aircraft (probably this is associated with flight tasks which place less emphasis on high manoeuvrability, rather than an effect of size *per se*). Until more positive evidence becomes available it seems reasonable to suggest that limiting times about twice those for fighters should be used—that is to say 2 sec for 'satisfactory' and 3 sec for 'acceptable' behaviour.

(b) *Lower limits of frequency*

We have noted earlier that the 'sluggishness' criteria do not fit the iso-opinion boundaries in the vicinity of the minimum acceptable or satisfactory frequencies where, for a given level of damping, it is seen that pilots demand much higher natural frequencies than would have been expected on the basis of aircraft response characteristics alone. It should be noted also that the minimum frequencies of the iso-opinion contours derived from the simulator studies were consistently lower than those obtained in flight and, in a general sense, were fairly consistent with the 'sluggishness' criteria; however, so far as can be ascertained, the third degree of longitudinal freedom was omitted in these studies, and it is suggested therefore that the differences between flight and simulator in this region might derive from this omission**. At frequencies near the 'acceptable' minimum, combined with moderately high damping, the pilots' comments available from flight studies[2,16,17,21] were critical not only of the sluggish response but also of the low static stability or of some feature allied to it (e.g. 'difficulty in trimming' was a common complaint). It may be significant that the minimum frequencies for 'acceptability for normal operation' found in the flight studies of Refs. 17, 20 and 21 all correspond to static margins of about 3 per cent; at the same time it will be appreciated that quite small (negative) values of m_u would have sufficed to convert the normal phugoid into a divergence at these low static margins (and it seems not unlikely that this may have occurred in the cases of Refs. 17 and 20, at the Mach numbers involved) and that the pilots' assessments may have been influenced by effects of this kind rather than a simple lack of static stability.

---

*Note that these correspond to families of curves having the control system time constant, T_c, as a parameter.

**In this connection it may be observed that a simulator experiment in which the freedom in speed is suppressed can give, in a sense, a 'pure' picture of the influence of the short-period characteristics; this cannot be obtained from a flight experiment, where many other effects may interact to complicate matters.

In the medium-sized aircraft of Ref. 21, however, the phugoid period was maintained constant (at about 50 sec) so that the above considerations would not have applied in these experiments.

Although the above evidence suggests that the minimum frequencies are related in some way to the static margin, it is not sufficient to establish this relationship quantitatively. The relationship clearly cannot be a simple proportionality because the frequency minima would then vary more markedly with airspeed than experience indicates to be the case. It seems probable also that other factors must enter into the relationship.

In the absence of systematic studies to define the factors determining minimum satisfactory or acceptable frequencies it seems that simple statements of these minima must suffice. (It must be remembered, however, that such statements are tentative and may be valid only for aircraft that are similar in layout to the test vehicles considered). For fighter-type aircraft, frequency minima for 'satisfactory' and 'acceptable' handling in the operational zone of 0·5 and 0·35 cps respectively appear to offer the best compromise fit to the test data. For attack or light bomber aircraft of medium size the corresponding minima are about 0·3 and 0·24 cps for 'satisfactory' and 'acceptable' handling respectively; while for large transport or bomber aircraft it is suggested that limits of 0·25 and 0·18 cps respectively may be appropriate. The last named limits are speculative, and should be treated with some reserve. It is interesting to note here that, at the 'acceptable' limit, the pitch control begins to present the appearance to the pilot of commanding pitching-acceleration—a feature which seems likely to give rise to some difficulty.

(c) *Lower limits of damping*

Changes in the characteristics of the control and feel systems can be expected to modify the pilots' assessments of any combination of short-period dynamics. Quantitative data on these effects are rather scanty, but suggest that they are particularly significant when the damping is low (e.g. *see* Fig. 10, illustrating the effects of optimising the control-system time-constant, T_c). Because of this sensitivity and because the system characteristics often are not described in sufficient detail in the literature, any conclusions drawn from an examination of the various iso-opinion contours in the low-damping region must be speculative, and this should be borne in mind during the discussion which follows.

When the damping ratio is reduced at low to moderate frequencies pilots become increasingly critical of the oscillatory nature of the response and the adverse effect this has on tracking. Further reductions in ζ_n result in complaints of 'pilot-induced oscillations'. It seems clear that when a sufficiently low level of damping is reached the pilot attempts to augment the natural damping by control action, and that the increasing demand made on his 'pitch damping' abilities by further decreases in ζ_n leads first to critical assessment and ultimately to instability* of the pilot-aircraft system.

In this region of low frequency and low damping the iso-opinion contours bear some resemblance to lines of constant total damping, $\zeta_n \omega_n$. If we hypothesise that, to merit 'satisfactory' ratings, an aircraft must have sufficient damping for augmentation by the pilot to be unnecessary, then we might expect that variations in the control system characteristics (within normal limits) would have relatively minor effects on the 'satisfactory' boundary, which would then correspond approximately to a single value of $\zeta_n \omega_n$. This seems to be the case for a number of experimental results** in which the 'satisfactory' con-

---

* Although it may seem surprising at first that the pilot should experience difficulty in acting as a 'pitch damper' at the lower frequencies, it may be that his attempts to force a more rapid response from a rather 'sluggish' aircraft conflict with the requirements of his 'pitch' damping' activities; moreover, as the frequency decreases it will become increasingly difficult to predict from the initial response what the final response will be.

** Including the following

Ref. No.	Test	SF/g (lb)	X_s/g (in)	T_c (sec)	Breakout (lb)
17	Flight	4·8—6	0·09—0·2	0·08	0·25
20	„	10	1·0	0·15	0
26	Simulator	8	0·8	0·1	
27	..	5	0·2		1·2

tours in this region can be approximated by lines of constant damping lying between $T_{\frac{1}{2}} = 0{\cdot}4$ sec and $T_{\frac{1}{2}} = 0{\cdot}55$ sec (Fig. 21a). It is suggested, that the limiting condition for 'satisfactory' behaviour for fighter type aircraft can be specified by $T_{\frac{1}{2}} \ngtr 0{\cdot}5$ sec (a value which fits the flight data of Refs. 17 and 20 quite well) provided the control system characteristics are representative of good current practice. If the latter condition is not satisfied—for example, if the stick force per g is unusually low (*see* boundary of Ref. 27 for 1 lb/g, (Fig. 19)), or if there is a substantial response lag (*see* boundary of Ref. 20 for 'optimum' T_c, Fig. 10b)—this approximate criterion cannot be applied successfully, and it is evident that some allowance for control system characteristics should be made; we do not have sufficient information at this time to be able to formulate a more general criterion of this kind.

In the low-frequency, low-damping region the 'satisfactory' boundary of Ref. 21 conforms quite closely to a constant $T_{\frac{1}{2}}$ of 0·9 sec. Thus the total damping needed for 'satisfactory' behaviour in this medium-sized aircraft was of the order of one-half that required in small, fighter-type aircraft. This difference may originate in the differences in aircraft size and function, and may be influenced by the much greater SF/g of the larger aircraft (40 lb).

As the damping decreases towards the limit of 'acceptability for normal operation' at the lower frequencies, the pilot appears to become increasingly concerned to augment the natural damping and to avoid causing 'pilot induced oscillations'. We might expect, therefore, that the 'acceptable' contours would be more strongly influenced by the control system characteristics. This seems to be borne out by the experimental evidence, the 'acceptable boundary of Ref. 17 ($T_c = 0{\cdot}08$ sec: $SF/g = 5$–6 lb) corresponding to a $T_{\frac{1}{2}}$ of about 0·8 sec, while that of Ref. 20 ($T_c = 0{\cdot}15$ sec: $SF/g = 10$ lb) corresponds to a $T_{\frac{1}{2}}$ of about 1·3 sec (*see* Fig. 21b). It is clear that in formulating damping criteria for 'acceptable' handling fighter type aircraft we should attempt to take into account the control-system characteristics, and although the data does not permit a concise formulation it suggests that, as a rough guide, we should associate a more demanding damping requirement with low SF/g and *vice versa*. We suggest therefore that, for fighter-type aircraft having control system time constants of about 0·1 second the time to half amplitude should be not more than 0·9 second when the stick force per g is 5 lb (or less), and not more than 1·2 seconds when the SF/g is 10 lb (or more).

Although there are some grounds for believing that a pilot rating of 5 on the Cornell scale used in Ref. 21 may correspond to a slightly 'better' aircraft than does the limit of 'acceptability for normal operation' (PR = 5) on the Cooper scale, we shall treat them here as being approximately compatible. On this basis the limit of 'acceptability for normal operation' for the medium-sized aircraft of Ref. 21 can be represented in the low frequency, low-damping region by $T_{\frac{1}{2}} \ngtr 1{\cdot}2$ sec.

At the higher frequencies the lower limits of damping which give 'satisfactory' or 'acceptable' handling tend to increase with increasing frequency (the only exception to this occurs in the simulator study of Ref. 27 and is regarded with some doubt), and it is in this region also that they show the greatest sensitivity to variations in the control system characteristics[20]. With a 'conventional' control system the pilots' comments[2,16,17,21] regarding 'unsatisfactory' configurations usually are critical of the rapidity, abruptness and over-sensitivity of the response to control inputs* and become increasingly critical of the oscillatory nature of the response as the damping is further reduced. The 'acceptable' boundaries tend to be ill-defined in the main flight investigations.

The results of Ref. 20 show that the damping needed for 'satisfactory' handling at moderate or high frequencies can be reduced if the response of the control system is optimised (*see* Fig. 10b). In Ref. 20 the control system dynamics could be approximated by a first-order lag and were described by the 'equivalent first-order time constant', T_c. It was found that as ζ_n was reduced at a given frequency the value of T_c required for optimum overall handling first increased, reaching a maximum at a level of damping close to, though slightly greater than, the new limit for 'satisfactory' handling at that frequency

---

* But note that these criticisms may have been generated in part by the 'system instabilities' present at the highest frequencies of some tests in variable-stability aircraft (e.g. Ref. 16 and, to a lesser degree, Ref. 17). The apparent rate of increase of damping with frequency in these cases may have been exaggerated by such features.

(*see* Fig. 11); with further reductions in ζ_n, the optimum value of T_c started to fall. Within the limits covered by this data (i.e. up to about 1 cps) the optimum T_c for a given level of damping increased with increasing frequency (though clearly one could not expect this process to continue without limit). The lower limit of damping for 'satisfactory' handling (with optimum T_c) was equivalent to a $T_{\frac{1}{2}}$ not greater than 0·7 sec, approximately (Fig. 11). It seems reasonable to infer from all this that, provided the damping was adequate (i.e. $T_{\frac{1}{2}} \ngtr 0{\cdot}7$ sec in this case), the pilot selected values of T_c which slowed the response to a 'satisfactory' level or attenuated the response to 'high' frequency inputs in a similar way and this implies that his assessments were based on criteria related to the 'abruptness' or 'sensitivity' of the response. (It should be noted that the rather large values of T_c selected as optima seem to imply that the criteria of 'abruptness' cannot be related to such response features as the rise time following a step input of stick force because such large time constants would result in rise times much too slow to be credible as being the fastest that the pilot could tolerate.) When the damping was less than adequate (i.e. less than that corresponding to the 'satisfactory' boundary) the pilot appears to have become increasingly concerned to augment the damping himself and accepted lower values of T_c in order to do this more readily, even though this compromised the response in manoeuvres.

There is insufficient evidence from systematic tests to indicate clearly which of the many possible criteria may be most appropriate to this region of short-period dynamics (even when those based on 'rise times' are eliminated for the reasons mentioned above) and further experimental work is needed to clarify the situation. It follows that any criterion put forward will, of necessity, be in the nature of an hypothesis and this should be borne in mind during the discussion that follows.

One feels intuitively that this quality of 'abruptness' of response may be related to some high-order derivative of the motion, such as the angular acceleration in pitch ($\ddot{\theta}$), or the rate of change of normal acceleration ($\dot{n}_z$) for example. Examination has shown that there are, in fact, several forms of criteria based on quantities of this sort, which fit the experimental data reasonably well; however, the limited range of frequency covered in the main flight experiments[17,20] and the uncertain nature of the data obtained at the highest frequencies (*see* footnote, p. 17) makes it impossible to select one of these forms on the grounds that it fits the data slightly better than the rest. In these circumstances it seems permissible that our choice should be influenced by considerations of convenience (e.g. ease of calculation), and it is on these grounds that we shall prefer criteria based on the response to sinusoidal excitation.

Consider the amplitude of the rate of change of normal acceleration, $|\dot{n}_z|$, in response to a sinusoidal input of stick force of amplitude $|F|$. It is readily shown that this will vary as the input frequency varies and will reach a maximum at some specific frequency (which depends on T_c but is usually close to ω_n). If, therefore, we specify upper limits to the maximum value of the ratio of these amplitudes, $|\dot{n}_z/F|_{\max}$, we shall, in a sense, have limited the possible 'abruptness' of the response. Limits of this kind are compared with the iso-opinion contours of Refs. 17 and 20 (for constant T_c) in Figs. 22a and b respectively, the numerical values being so chosen that the limits demand about the same level of damping as the experimental contours, over the frequency range 0·7 to 1 cps. The curves representing the limits are shaped differently from the experimental contours and there is an increasing divergence between the two sets of curves as frequency increases above 1 cps. (It is pertinent to add here that all the other criteria examined showed similar divergences.) The 'control system instabilities' present at high frequency in the tests of Ref. 17 may well have given rise to the divergence in this case, the pilot demanding higher aircraft damping to offset the deteriorating control quality at the higher frequencies. Because control system 'state of the art' was similar for the equipment used in the Ref. 20 experiments, it may be that the divergence can be explained in a similar manner in this case also.

It will be seen from Fig. 22a and b that the limiting values of $|\dot{n}_z/F|_{\max}$ for 'satisfactory' operation are approximately 1·0 g/sec/lb and 0·65 g/sec/lb for the Ref. 17 and the Ref. 20 (constant T_c) data respectively. These values are roughly inversely proportional to the respective static stick-force/g so that, if we were to relate our limits to the increment in stick-force (F_1) needed to maintain unit excess g, a single value of $F_1|\dot{n}_z/F|_{\max}$ would serve to specify the 'satisfactory' boundaries of both Ref. 17 and Ref. 20 in this region of short-period dynamics. It seems reasonable to suppose that a pilot may adjust his 'gain' to accommodate changes in static stick-force/g, so that a formulation in these terms does not seem implausible. The upper limit in $F_1|\dot{n}_z/F|_{\max}$ proposed for 'satisfactory' operation is 6 g/sec: the boundaries corresponding to this limit are shown in Figs. 22a and b for the appropriate values of T_c, and they can be seen to be in fair agreement with the experimental results.

The 'acceptable' boundaries are poorly defined in this area of short-period dynamics due to the scarcity of data* and the scatter of pilot ratings, so that no firm conclusions can be drawn. We may note, however, that the limiting values of $|\dot{n}_z/F|_{\max}$ corresponding to the 'acceptable' boundaries of Refs. 17 and 20 are very nearly the same (1·64 and 1·5 g/sec/lb respectively), which could be interpreted as evidence of an 'absolute' limit of abruptness. Against this we may observe that an upper limit of $F_1|\dot{n}_z/F|_{\max}$ of 12 g/sec would be in reasonable conformity with the actual data points. The question of the form to be taken by criteria of 'acceptability' cannot be resolved on the basis of this information.

The data of Ref. 20 for 'optimum' T_c provide a test case for our tentative criterion of 'abruptness', which we will now examine. Using the values of ω_n and T_c corresponding to selected points lying on the 'satisfactory' boundary of Ref. 20 (i.e. to the intersections of the lines of constant T_c with the 'satisfactory' boundary in Fig. 11) we have calculated the values of ζ_n which would limit $F_1|\dot{n}_z/F|_{\max}$ to 6 g/sec, and these** are compared with the experimental 'satisfactory' boundary in Fig. 22c. Bearing in mind that the experimental boundary is not well-established at frequencies near and above 1 cps the agreement is very fair. The fact that such a wide range of control system characteristics can be accommodated in this way is most encouraging. However, it must be stressed that although these criteria of abruptness are compatible with the experimental evidence, the data are incomplete. For example, the conditions under which the tests of Ref. 20 were made are not known in sufficient detail and it is possible, therefore, that the tests may have been confined to substantially 'calm air': if this were so, the criteria adduced would be relevant to the problems of controllability in calm air while, in more general conditions, other and perhaps more demanding criteria related to the response in turbulence might take precedence.

The experimental boundaries for the medium-sized aircraft of Ref. 21 for the high-frequency, low-damping region are compared with limits of $|\dot{n}_z/F|_{\max}$ in Fig. 22d. A limit of 0·19 g/sec/lb is reasonably compatible with the 'satisfactory' boundary over the very limited frequency range in which comparison is possible. The value of 0·35 g/sec/lb put forward as an 'acceptable' limit is based on a tentative extrapolation of the experimental data and can be used only as a very rough guide.

Purely as speculation, let us suppose for the moment that the results of Refs. 17, 20 and 21 can usefully be compared, despite obvious differences in test conditions, tasks, etc: let us suppose further that the differences between these results can be attributed to the differences in static SF/g. We find then that the inverse limit, $|F/\dot{n}_z|_{\min}$, for 'satisfactory' ratings is linearly related to the static SF/g, F_1, by the expression

$$\left|\frac{F}{\dot{n}_z}\right|_{\min} = 0{\cdot}3 + 0{\cdot}125\,F_1$$

while for 'acceptable' ratings the relationship

$$\left|\frac{F}{\dot{n}_z}\right|_{\min} = 0{\cdot}15 + 0{\cdot}0625\,F_1$$

affords a reasonable approximation to the proposed limits. Taken at their face value these relationships imply that the iso-opinion contours in this region of short-period dynamics are influenced by both the control system time constant and the static stick force per g. They imply also that, even if zero stick force per g was tolerable, it would be necessary to provide a stick force proportional to rate of stick movement in order to achieve an 'acceptable' or 'satisfactory' aircraft. The result of this rather rash

---

* Ref. 17 shows only three configurations having $\zeta_n \leqslant 0{\cdot}4$ and $f_n \geqslant 0{\cdot}9$: Ref. 20 shows only one configuration having $\zeta_n \leqslant 0{\cdot}4$ and $f_n \geqslant 1$.

**In Fig. 22c the dampings corresponding to two values of T_c (0·7 and 0·8 sec) are shown at the frequency of 0·98 cps. This is because the maximum T_c selected as optimum was shown as 0·8 sec in Fig. 11 of Ref. 20, whereas in the text it was quoted as 0·7 sec. In practice this makes little difference to the results.

extrapolation accords with experience in that the handling qualities of aircraft having very low stick force per g have been improved by the addition of stick dampers. However, the relationships hinted at by these speculations need further study by systematic experiment before they can be incorporated in handling criteria.

3.2.2. *Criteria based on the systematic work.* From our study of systematic researches on fighter-type aircraft in the operational zone we have formulated certain handling criteria which are reasonably compatible with the data. These are summarised below:

(i) For 'satisfactory' operation the time to first reach 90 per cent of the final steady normal acceleration following a step input in stick force should not exceed 1 sec. For 'acceptable' operation this time should not exceed 1·5 sec.

(ii) For 'satisfactory' operation the undamped frequency of the short-period mode should not be less than 0·5 cps. For 'acceptable' operation it should not be less than 0·35 cps.

(iii) For 'satisfactory' operation the time to damp to half amplitude in the short-period mode should not be greater than 0·5 sec. For 'acceptable' operation, $T_{\frac{1}{2}}$ should not be greater than 0·9 sec when the SF/g is 5 lb (or less, and not greater than 1·2 sec when the SF/g is 10 lb (or more).

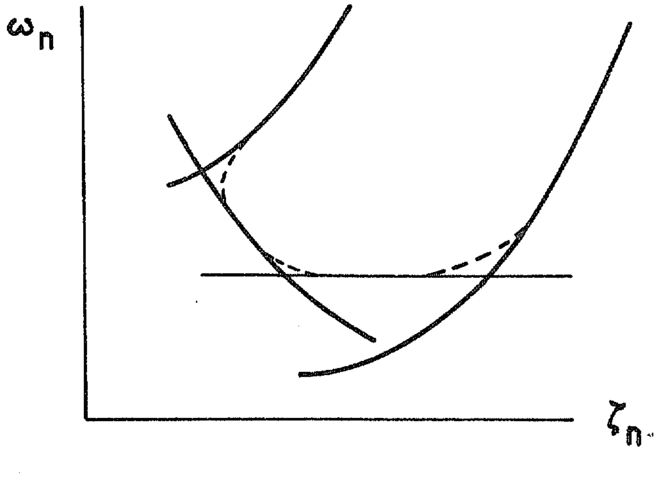
(iv) For 'satisfactory' operation the maximum rate of change of normal acceleration in response to a sinusoidal variation of stick force, the amplitude of which is equal to the static stick force per g, (i.e. $F_1|\dot{n}_z/F|_{\max}$) should not exceed 6 g/sec.

For 'acceptable' operation $F_1|\dot{n}_z/F|_{\max}$ should not exceed 12 g/sec as a tentative limit.

Both these limits may in fact vary with stick force per g, and we shall examine this possibility further in the next Section.

If we specify the control system characteristics these criteria can be presented graphically as functions of the short-period frequency and damping. Fig. 23 shows such a presentation based on the assumption that the control system can be represented adequately by a single lag having $T_c = 0{\cdot}1$ sec.

Clearly where two segments of these boundaries intersect, the pilot will be subject to a combination of two adverse features of the aircraft's response and his assessment of the combination is likely to be more adverse than his assessment of either feature on its own. It follows that the iso-opinion contours are likely to lie well inside either of the separate boundaries in the region of their intersections; in other words the sharp corners will be 'rounded off', as shown in the sketch. At present we have no means of specifying this.



There is insufficient data to establish the way in which the limiting values of $|\dot{n}_z/F|_{\max}$ may vary with static stick force per g for medium and large aircraft, and it is proposed therefore that the limits established in Ref. 21 for a stick force per g of 40 lb be used as approximate guides in these cases until further data becomes available. The remaining criteria proposed for 'satisfactory' and 'acceptable' handling respectively in large bomber or transport aircraft are—

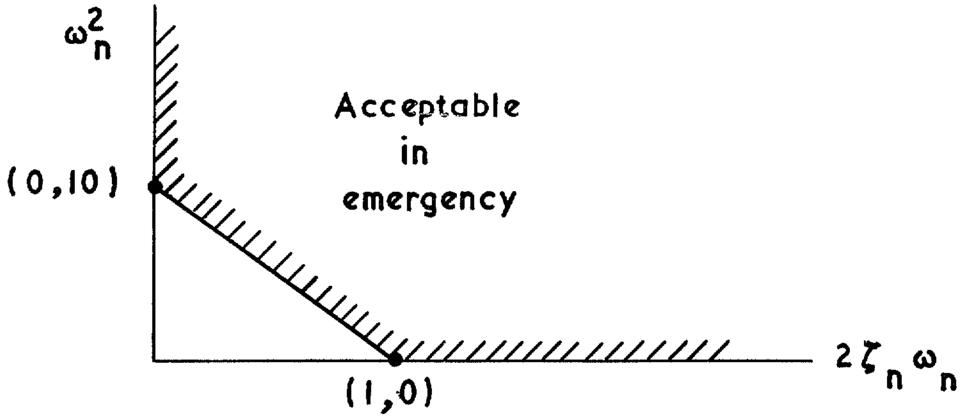
(a) Times to half amplitude not greater than 1 and 1·5 seconds.

(b) Minimum natural frequencies of 0·25 and 0·18 cps.

(c) The times to first reach 90 per cent of the final steady normal acceleration, following a step input in stick force, should not exceed 2 and 3 seconds, respectively.

These criteria are illustrated in Fig. 26 for an assumed control system time constant (T_c) of 0·2 sec.

Little has been said of the limits acceptable in an emergency. These seem likely to vary widely in response to the other demands that may be made on the pilots' skill and concentration, and with the flight task, atmospheric conditions and so forth, and no very precise definition should be sought. A study of the available data indicates that a fighter-type aircraft is likely to prove acceptable in an emergency provided its short-period characteristics lie within the positive quadrant of the $2\zeta_m \omega_n - \omega_n^2$ plane, excluding the triangular area near the origin bounded by the axes and the line joining the points (0, 10) and (1, 0) (*see* sketch): since tests show that a negative manoeuvre margin can be tolerated (provided the 'damping' term remains positive and is not too small), this limit probably is conservative. In the absence of any systematic evidence relating to large bomber or transport aircraft it is suggested that the 'fighter' limits be applied.



3.2.3. *Results from flight experience on individual fighter-type aircraft.* Information on the short-period characteristics of a number of fighter-type aircraft is available from routine tests (Refs. 29 to 40 and unpublished data) together with some indication of the aircrafts' operational suitability. This information, which covers a wide range of flight conditions, has been summarised graphically in Fig. 24, where different symbols have been used to distinguish between two classes of aircraft (fighter and strike aircraft, sub-divided further into conventional, and tailless delta) and three levels of pilot comment, *viz.*—

(a) favourable comment, or no adverse comment—presumed to correspond to a 'satisfactory' rating.

(b) mild to moderate adverse comment—aircraft presumed to be 'acceptable for normal operation' but less than 'satisfactory'.

(c) severe adverse comment—aircraft presumed to be 'unacceptable for normal operation' (i.e. for the relevant tasks).

It will be appreciated that these divisions are less than precise, furthermore the available comment often is not specific so that the assignment of an aircraft to a particular category then depends heavily on personal interpretation.

Boundaries based on the criteria summarised in Section 3.2.2. for fighter-type aircraft have been included in Fig. 24 for comparison purposes. Where the boundary is affected by the control system time-constant, T_c, we have assumed a value of 0·1 sec, as being representative of current fighter control-systems.

In several cases it has not proved possible to extract frequency and damping from the flight test results when ζ_n was high (e.g. with a pitch-damper operating) so that there is little data with which to compare the 'sluggishness' boundary. It will be seen from Fig. 24 that the short-period characteristics of the North-American A–5A (Ref. 39) lie partly outside this boundary, but since the aircraft was assessed as being near the 'satisfactory' limit (Cooper ratings of 3 to 3·5), is a strike aircraft, and is considerably larger than a typical fighter this violation is not thought to represent a particularly significant failure of the criterion.

Although there is a fair amount of scatter and the data is rather sparse in some areas, the remaining segments of the iso-opinion boundaries are, in the main, successful in outlining areas which correspond to the three levels of pilot rating considered here (bearing in mind our assumption of a 'typical' T_c of 0·1 sec), and tend to be slightly conservative. Two apparent exceptions to this are worth a more detailed examination—the aircraft identified as 'A' and 'B' in Fig. 24. In its original form, aircraft 'A' was subject to severe pilot-induced oscillations which rendered it quite unacceptable, as it is denoted in Fig. 24; however, the original control system had certain undesirable features (notably a lightly damped oscillatory mode close to the short-period mode in frequency[38]) which gave rise to a peak value of $F_1|\dot{n}_z/F|_{\max}$ of about 25 g/sec (estimated); successive modifications lowered this peak to about 12 g/sec (which compares closely with the limit of 'acceptability' proposed in Section 3.2.2.) and the tendency to pilot-induced oscillations was reduced to an 'acceptable' level, though it was not wholly eliminated. Aircraft 'B' was assessed as being on or over the border of 'acceptability' at high frequencies (and airspeeds) in its original form[40], where the stick force gradient was low for small increments of g (about 2 lb/g); an increase in gradient (to about 6 to 7 lb/g) combined with an increase in T_c rendered the aircraft marginally 'satisfactory' (i.e. P.R. $\doteqdot$ 3·5): this result indicates that the proposed criteria may be over-optimistic when applied to aircraft having low static stick force/g (i.e. significantly below 5 lb/g) and tends to confirm our view that the criteria should be related to stick force/g in some way, at least for aircraft having high natural frequency and low damping.

In an attempt to throw some further light on the influence of control force characteristics we have separated the data into groups covering four ranges of stick force/g, and these are compared with the proposed criteria of Section 3.2.2. in Figs. 25a, b, c and d. It appears from a study of these figures that, in those areas where the criteria are based on considerations of 'abruptness', there is a tendency for the criteria to under-estimate the damping required when the stick force per g is low, and to over-estimate it when the stick force/g is high. We have included in Fig. 25 boundaries based on the limiting values of $|F/\dot{n}_z|_{\min}$ discussed in Section 3.2.1(c), and it will be seen that these accommodate the data slightly better* than do the limits based on $F_1|\dot{n}_z/F|_{\max}$ and go some way to overcoming the above-mentioned disadvantage. However, the relatively slight improvement achieved by specifying limits of $|F/\dot{n}_z|_{\min}$ as linear functions of the stick force/g (F_1) (at least for stick forces/g greater than about 4 lb) and the tenuous evidence in favour of such a specification (*see* Section 3.2.1 (c)) leads us to retain the limits of $F_1|\dot{n}_z/F|_{\max}$ proposed in Section 3.2.2 for the present, noting that these are liable to prove misleading if applied to aircraft having a stick force/g less than about 4 lb.

The evidence of Fig. 25 tends to support the suggestion made earlier that the segment of the 'acceptable' boundary defined by total damping should be related to the stick force per g. It seems possible that a similar variation might exist for the 'satisfactory' boundary, though there is insufficient evidence to confirm this.

It will be noted that the opinion ratings for strike aircraft appear to imply a greater tolerance of low frequencies (and, to a lesser degree, low damping) than would be expected in a fighter. It is thought that this may arise mainly from the difference in function and associated tasks. This apparent discrepancy tends to confirm the suggestion made earlier that the frequency minima for strike aircraft should be somewhat lower than for fighters.

Unfortunately there is not sufficient evidence on the characteristics of delta-winged aircraft for us

---

* Note that aircraft 'C' (which had a SF/g ranging from about 3 lb/g at low f_n to 6 lb/g at high) which lies on or over the borderline of 'acceptability' for $T_c = 0{\cdot}1$, was in fact rated 'acceptable'. This aircraft was fitted with a device which effectively increased T_c, and the boundary probably should be shifted to the left to account for this; this would tend to improve the correspondence between predicted and actual ratings.

to draw firm conclusions regarding the applicability of the proposed criteria to this class of aircraft, and though the position of aircraft 'D' (a delta of near-slender class) in relation to the 'satisfactory' boundary of Fig. 24 indicates that the latter is too severe in this particular case, the remaining data seems to conform, though with some scatter. Until more evidence becomes available it is considered that the criteria should be applied only with caution to aircraft that differ grossly in shape from so-called 'conventional' aircraft (i.e. those having straight or swept wings and tailplanes).

Summarising, the criteria appear to fit the data reasonably well and probably can be used with some confidence as design guides for 'conventional' fighter-type aircraft, provided that the stick force per g is greater than 4 lb. Outside this class their applicability is more doubtful and further evidence on this point is needed.

3.2.4. *Results from flight experience on medium and large aircraft.* Although ultimately it may well prove necessary to differentiate between medium and large aircraft or between aircraft performing different functions, this does not seem feasible on the basis of the data available at the present time. Consequently we have treated medium and large aircraft (bombers, transports, etc.) as a single group and the flight-test data available on their short-period characteristics are summarised in Fig. 26; because this is rather scanty some estimated characteristics have been included. For comparison, boundaries based on the criteria proposed in Section 3.2.2 for large aircraft are also shown in Fig. 26; in constructing these it has been assumed that a T_c of 0·2 sec is a representative value for the class of aircraft considered.

It will be seen from Fig. 26 that although the data is rather scanty most of it conforms in a general way with the proposed boundaries. Of the exceptions to this perhaps the most important concern the relationships of aircraft 'A' and 'B' to the segments defined by considerations of 'abruptness' of the response. These suggest that the boundaries are pessimistic but, as noted earlier, this could arise from the possible inapplicability of these boundaries to tailless, delta-winged aircraft, though the existence of other differences between the test aircraft and the conditions to which the boundary refers makes this uncertain. In the absence of other test data in this region the 'sensitivity' boundary must still be regarded as speculative. The remaining segments of the boundaries have some support from the *ad hoc* evidence, but this is not sufficiently extensive at present to provide really firm backing. It is interesting to note that the strike aircraft of Ref. 39 conforms reasonably well with the 'large aircraft' criteria.

3.3. *Handling on the Approach.*

3.3.1. *Systematic investigations.* Until comparatively recently, surprisingly few systematic investigations of longitudinal handling qualities on the approach had been made. This situation has changed during the past two or three years and our knowledge of the significant parameters and their effects has increased in consequence, though it is still somewhat fragmentary and incomplete. During this time a considerable body of experimental evidence has accumulated (e.g. Refs. 52, 53, 54 and 55) which shows conclusively that approach handling criteria must include a parameter related to the aircraft's lift slope (in addition to the frequency and damping of the short-period oscillation), although further work is required before the detailed form of these criteria can be finalised. In the remainder of this Section we shall give a brief account of the experimental evidence available and attempt, from this, to formulate such partial criteria as we can.

Some early experiments in the approach handling field[50] were concerned to establish the limiting values of ω_n^2 and $2\zeta_n \omega_n$ under which an approach and landing could be made. The boundaries established in these tests are shown in Fig. 27 and represent conditions in which occasional overshoot action was necessary to avoid incident. The test conditions were quite favourable (mirror landing aid: no distractions e.g. due to radio management) which may explain the fact that the boundary conditions were considerably less demanding than those established in the later studies discussed below.

The tests of Ref. 10 have been described in some detail in connection with the effects of speed stability on the approach (Section 2.3.2). We need only add here (a) that the control system time constant, T_c, was about 0·3 sec, which is large for this class of aircraft, and (b) that the aircraft's lift slope in terms of L_α/mV ranged from about 1·0 to 1·2 depending on fuel state. It will be recalled that a range of short-period dynamics was studied at each of three levels of speed stability. For the purposes of this discussion it will be convenient first to consider together the data relating to positive and neutral speed stability, and this is shown plotted on the ω_n—ζ_n plane in Fig. 28a: it will be seen that although there is insufficient data to establish complete iso-opinion boundaries, the major areas of interest are covered. These results show that the dividing line between 'satisfactory' and 'acceptable' ratings over the frequency range 0·2 to 0·5 cps corresponds closely to a time to halve amplitude of about 1·1 seconds, while the dividing line between 'acceptable' and 'unacceptable' ratings,* though less well defined, corresponds roughly to a $T_{\frac{1}{2}}$ of 1·5 to 1·6 sec over the same range; these values are remarkably close to those arrived at for large aircraft in the operational zone. At frequencies below about 0·2 cps the pilot became increasingly critical of the sluggishness of the response and the consequent need to 'overcontrol', while at the single high-frequency point (0·65 cps) the complaint was of over-sensitive and abrupt response coupled with a high gust-sensitivity: these comments suggest that criteria broadly similar in principle to those evolved for the operational zone may be applicable to the approach case, though there is insufficient data to enable us to specify the form these criteria should take. In these circumstances we can only note that the lower limits of the 'satisfactory' and 'acceptable' areas of Fig. 28a can be approximated by lines of constant frequency (at 0·2 and 0·13 cps respectively), and suggest that this result may be applicable to other speed-stable aircraft having similar lift characteristics: in the region of 'abrupt response' we can only suggest that the boundaries may show trends of the kind indicated in Fig. 28a. The moderate degree of speed instability used in part of the Ref. 10 tests resulted in slightly more stringent requirements for 'acceptable' short-period characteristics, namely a time to halve amplitude not greater than 1·3 to 1·4 sec and a minimum frequency of about 0·16 cps (*see* Fig. 28b): only one 'satisfactory' rating was recorded in these tests (and that under very smooth atmospheric conditions) so that a region of 'satisfactory' short-period dynamics could not be defined.

We have noted earlier that the instrument approach aids used in the experiments of Ref. 10 were not good by current standards, and it follows that the results may be somewhat pessimistic when applied to a more normal approach environment. However, during the tests the pilot selected a control gearing for each configuration which he considered to be near-optimum** for approach work. It seems on balance that we might expect the boundaries of Ref. 10 to be conservative when applied to other speed-stable aircraft having lift characteristics similar to the test vehicle and control characteristics representative of good current practice.

Ref. 51 reports a fixed-base simulator study of instrument approaches in a large transport aircraft, in which pilot assessments were used to define a boundary between 'acceptable' and 'unacceptable' conditions. Uncertainties about the rating scale prevent us from making firm comparisons with other data, though we may note (from Fig. 29) that the boundaries are broadly similar to those established in Ref. 10. These boundaries are useful also in illustrating once again the importance of taking the control system characteristics into account in work of this nature.

The influence of the lift parameter on approach handling qualities is well illustrated by the work reported in Ref. 52, which relates to visual approaches made in a fixed-base simulator with T.V. display. The simulation covered a range of frequency and lift parameter at a single level of damping ($\zeta_n = 0{\cdot}5$) at each of two approach speeds (though the speed freedom itself was not simulated): stick force per g was held between 15 and 20 lb, both L_η and $M_{\dot\alpha}$ were zero, and the lateral handling characteristics were 'good'. It was not possible to distinguish between L_α/mV and $1/T_\theta$ in the circumstances of this experiment (since $L_\eta = 0$). The differences between the results obtained at the two approach speeds at a given frequency and L_α/mV were fairly small; it was inferred from this[52] that L_α/mV was a 'better' lift parameter than, for example, n_{z_α} ($= L_\alpha/W$), and accordingly the results were presented as iso-opinion contours in

---

* Note that this seems to be rather more demanding (i.e. requires a 'better' aircraft) on the revised Cornell scale than it does in the Cooper scale.

**At low frequencies the pilot selected high gearings to permit 'overdriving' the initial response, and accepted steady forces that were 'too light'. At moderate frequencies he was able to select gearings that gave both satisfactory initial response and steady forces. At high frequencies he selected low gearings to reduce the initial response, and accepted steady forces that were 'too heavy'.

the ω_n—L_α/mV plane—reproduced here in Fig. 30a. To the present writer this conclusion does not appear to be warranted since the rating data shows substantially the same level of scatter when plotted against either parameter (*see* Fig. 31), and we have therefore included, as Fig. 30b, iso-opinion contours in the ω_n—n_{z_α} plane. Although the data of Ref. 52 does not indicate which of several possible lift parameters may be the most appropriate, it does show decisively that some form of lift parameter is essential to a meaningful criterion—for example, the minimum 'satisfactory' frequency changes by a factor of about two over the range of lift parameter covered in these tests (*see* Fig. 30).

There is evidence (e.g. Ref. 10) to suggest that pilot ratings become insensitive to changes in the short-period damping when this lies between about 0·5 and 0·8. Accordingly Barnes[52] has compared the boundaries of Ref. 52 with data from other systematic tests in which the damping lay within these limits, and a slightly extended version of this comparison is shown in Fig. 32*. It will be seen that this data (Refs. 53, 54, 55 and part of Ref. 10) conforms reasonably well with the boundaries established in Ref. 52, and although the boundaries based on n_{z_α} appear to offer a somewhat better fit, the improvement is not really decisive. It is interesting to note that the ratings[55] relating to high L_α/mV ($= 1{\cdot}9$) at high frequencies appear compatible with a much-extended upper limb of the 'satisfactory' boundary of Ref. 52: at low frequency, however, the ratings seem to be at variance with any plausible extrapolation of the lower limb of that boundary; the reasons for this are not known. The aircraft employed in the various tests considered in this comparison differed very widely in size and layout; because there is a fair measure of agreement between the data from these sources, it would appear that aircraft size is not in itself a significant parameter in approach handling qualities.

It seems reasonable to conclude from this discussion that the boundaries of Fig. 30 can be used to predict the handling qualities of speed-stable, tailed, aircraft (i.e. L_η small), approaching at speeds in the 120—180 kt band, and having damping ratios between 0·5 and 0·8, 'good' feel characteristics and 'good' lateral handling qualities.

Attempts have been made (e.g. in Ref. 55) to formulate approach handling criteria that would have general applicability, but it seems to the writer that such attempts are premature at present since we lack sufficient systematic data. The need for further research is evident and pressing.

Although we have noted earlier that aircraft size *per se* does not appear to be a significant handling parameter, it should be added that increasing size does, in general, lead to reductions in the short-period frequency which may well have a most adverse effect on handling. Indeed, it seems likely that the so-called 'jumbo-jets' may be nearing the upper limit of size (or, more correctly, the lower limit of frequency) that can be controlled adequately by conventional methods, and that further increases in size may well require novel forms of approach control, such as 'direct lift control'. The handling requirements associated with 'direct-lift' control systems are beyond the scope of the present Report and at present only a few preliminary studies of these systems have been made. It is not unlikely that 'direct-lift' control may offer worthwhile advantages to a much wider range of aircraft than just the ultra-large, and it seems likely, therefore, to offer a fruitful subject for further investigation.

3.3.2. *Data from other sources.* The short-period characteristics of a number of current aircraft in the approach configuration have been obtained from flight-test data and from estimates. The aircraft considered covered a wide range of size and a variety of planforms, including the tailless delta, and most of them possessed natural or artificial speed stability. In the majority of cases, the handling qualities of these aircraft had not been assigned ratings on any of the familiar rating scales; however, since all these aircraft have seen considerable (and successful) service we can be confident that they merit Cooper ratings no worse than 5, indeed from the general absence of adverse comment it seems highly probable that most would be rated as 'satisfactory' (i.e. a Cooper rating of 3·5 or better).

Few of the current aircraft for which we have data had lift parameters comparable with that of the Ref. 10 test vehicle, but these few were found to have short-period characteristics that lay within the

---

* The two ratings given in Fig. 32 for the data of Ref. 54 relate to the 'best' and 'worst' combinations of stick force and movement per g tested. For the points denoted as 'Flight, Ref. 55', the ratings obtained in flight are shown at the right of each point; the ratings on the left were obtained in a fixed-base simulator.

'satisfactory' region established in Ref. 10 and shown in Fig. 28a. Since it is likely that these aircraft were, in fact, 'satisfactory' this result is encouraging so far as it goes.

We have noted earlier that although the iso-opinion contours of Ref. 52 were obtained at a single value of the damping ratio the evidence from other systematic tests suggests that they are, in fact, applicable over a range of damping ratios (from about 0·5 to 0·9). In attempting to correlate the characteristics of current aircraft with the boundaries of Ref. 52, therefore, we have considered only those aircraft whose damping ratios lay within a similar range (in the interests of obtaining a larger sample, the range was extended slightly to include aircraft whose damping ratios lay between about 0·4 and 1·0); the characteristics of these aircraft in terms of natural frequency and lift parameter are shown in Figs. 33 (lift parameter $= L_\alpha/mV$) and 34 (lift parameter $= n_{z_\alpha}$) where they are compared with the 'satisfactory' boundaries of Ref. 52. It will be seen that nearly all the data fall within the 'satisfactory' areas, while the two or three points which fall outside them lie close to the 'satisfactory' boundaries; this result confirms our expectations and, in a broad sense, provides further evidence to support the Ref. 52 boundaries.

In the comparisons of Figs. 33 and 34 there are several points of detail that merit some discussion. In the first place, if the lift parameter L_α/mV is replaced by $1/T_\theta$, Fig. 33 remains virtually unchanged except that the points relating to tailless aircraft (i.e. these having significant L_η) are shifted to the left; in the cases of aircraft 'A' and 'B' (*see* Fig. 33) it can be seen that this change improves the conformity since 'A', which is rated as 'good', is moved towards the centre of the 'satisfactory' area by it, while 'B', which is 'marginally satisfactory', is moved towards the periphery: this tends to support the view (held for other reasons) that $1/T_\theta$ is likely to be a 'better' parameter than L_α/mV.

It is the writer's opinion that, at its aft cg limit, a typical glider is likely to be rated 'marginally satisfactory' (i.e. P.R. $\sim$ 3·5) on the approach. If this is both correct and relevant, then comparing the points representing a 'typical glider' in relation to the boundaries of Figs. 33 and 34 would suggest that $1/T_\theta$ is a 'better' parameter than n_{z_α}. However, we should treat this suggestion with some reserve since the rating quoted may have been influenced by the problems of stick force and sensitivity that often arise with a manual control system at aft cg. It should be noted also that aircraft 'A' lies somewhat closer to the centre of the 'satisfactory' area in the ω_n—n_{z_α} plane* than it does in the ω_n—$1/T_\theta$ plane (compare Figs. 33 and 34) which accords more closely with the rating actually assigned to it but does not support a preference for $1/T_\theta$.

These arguments are all rather tenuous and inconclusive. On balance it does not seem justifiable at present to select one of the proposed lift parameters in preference to the other; further systematic work will be needed before this question can be resolved.

4. *Control Systems.*

As defined in this Report, 'handling' is concerned primarily with the basic stability and response characteristics of aircraft and control systems, and the ways in which these influence the pilot. We have seen in earlier sections some instances of the profound influence that the control system characteristics can have on pilots' assessments of a particular set of stability characteristics. Equally profound influences operate in the reverse direction and, in general, most statements about 'control' characteristics need a qualifying statement about 'stability' (and vice versa). This should be borne in mind during the subsequent discussion of control systems.

From a handling point of view the major features of any control system are (a) the stick forces and movements required to operate the cockpit controls, (b) the response of the control surfaces to these

---

* It seems reasonable to suppose that n_{z_α} will become more meaningful as a handling parameter if it is defined as the normal acceleration increment per unit change of incidence in a controlled pull-up, i.e. if L_η terms are included. In this case

$$n_{z_\alpha} \doteq \frac{L_\alpha}{W}\,\frac{1-\dfrac{M_\alpha}{M_\eta}\,\dfrac{L_\eta}{L_\alpha}}{1+\dfrac{M_q}{M_\eta}\,\dfrac{L_\eta}{mV}}.$$

inputs, (c) the response of the aircraft to control surface movement, and (d) the trimming system. Features (b) and (c) have been discussed in earlier Sections, but it should be added here that the study of control response influences has not yet been pursued very far and that it ought to be the subject of further experiment—for example, on control systems whose adequate description requires lags of higher order than the first.

In discussing feel systems, etc. we shall generally assume an irreversible, power-operated control system. This will simplify the discussion by excluding the difficulties that often arise when aerodynamic hinge-moments are fed back to the stick (e.g. differences between stick-fixed and stick-free behaviour, unusual transients, etc.) and can be justified on the grounds that control systems of this kind are now very widely used.

4.1. *Feel Relationships.*

Under theoretically ideal conditions the stick force per g in an aircraft having a direct mechanical link between stick and control surface is independent of airspeed at a given height and cg position: in practice, of course, the intervention of compressibility and aero-elasticity modify this relationship markedly. The advent of power-operated controls and associated artificial feel systems made it practical to consider feel relationships other than the classical, and these have been the subject of several studies. In Ref. 57, for example, twelve pilots selected 'optimum' stick forces per g at each of three speeds; the results showed that, for the very restricted speed range covered (150—250 kt), the forces selected varied nearly as the inverse of the speed, suggesting that the pilots were in fact aiming at roughly constant stick force per unit rate of pitch. (It is interesting to note also that pilots having a 'fighter' background consistently selected lower forces than did the 'bomber' pilots.) Results have been obtained in other studies over rather larger speed ranges (e.g. in Ref. 56) which have shown that pilots find a constant stick force per rate of pitch satisfactory despite the reduction in stick force per g at high airspeeds. Unfortunately we have no information on how acceptable such a system might be over really large airspeed ranges (say 10 to 1, or higher) though it seems likely that some form of acceleration-limiting device might then be required.

In principle it is a simple matter to employ a 'q-feel' system (i.e. one in which the stick force per unit control displacement varies as the dynamic pressure, $\bar{q}$) and in a subsonic aircraft this will provide a constant stick force per g throughout the speed range, provided aero-elastic effects are small: a similar result can be achieved in supersonic aircraft at the expense of some additional complication. Q-feel forms an essential part of practically all current power-operated longitudinal control systems, and it is mainly with these that we shall be concerned in the remainder of this Section. Before this, however, it is worth considering some of the alternative systems that are currently under development or in actual use.

The type of cockpit control provided obviously influences the overall force levels of the feel system. Normally the input system has taken the form of a centrally-mounted stick in fighter-type aircraft and a wheel or variant thereof in large aircraft. The advent of power-operated controls and non-mechanical forms of signalling makes it possible to dispense with the mechanical advantage offered by a conventional stick or wheel and to replace these traditional forms by miniature controllers operable by finger or wrist movements and situated on a suitable arm-rest. There is a growing body of opinion in favour of such a change, provided, of course, that the integrity of the signalling system can be assured, and various forms of side-located miniature controllers have been tested in simulators and in flight in fighter-type aircraft (e.g. in Ref. 56) where they have been well linked. No such extensive experience is available of the application to large aircraft, but the potential advantages suggest that a trial installation should be examined.

Many other interesting possibilities flow from the use of power-operated controls and non-mechanical signalling systems, since the limitations imposed by an effectively direct gearing between the stick and the control surfaces can be eliminated, making it possible to employ control laws that may offer improved handling. In the so-called 'manoeuvre demand' systems, for example, inputs to the stick command proportional responses which may be in rate of pitch, normal acceleration, or some other selected parameter; with zero stick input such a system functions as a powerful autostabiliser or an autopilot and it can also be engineered to act as an acceleration limiter. Systems of this kind have been studied extensively experimentally (e.g. *see* Ref. 56) and it has been found that pilots quickly adapt to and accept the novel forms of response introduced; perhaps the most successful systems have been those based on pitch-rate demand, for which pilots have shown a preference after very short periods of adaptation.

The most sophisticated recent development of control system engineering is that known as the 'adaptive control' or 'self-adaptive autopilot'. In effect these systems might be described as 'variable-stability in reverse', that is to say they involve motion sensors whose output is used to modify the position of the control surface servos in such a way that the aircraft response conforms to some pre-determined pattern that remains constant for all conditions of flight. To achieve this throughout the flight envelope the system gains must, of course, be varied and this is achieved, not by programmed changes, but by comparing the actual response with the pre-selected 'ideal' and changing the gain in the direction to minimise any difference. Although various experimental systems have been tested it appears that adaptive controls are still some way from general practical application, and we return to more mundane affairs in the following Section.

4.2. *Manoeuvring Stick-Forces.*

4.2.1. *In the 'operational zone'.* Ref. 16 reports some experiments made on a fighter-type aircraft in the 'operational zone' in which various combinations of stick force and stick movement per g were assessed by one pilot, who assigned ratings on the basis of the original Cornell scale (Table 1). The tests were conducted with nominally constant short-period dynamics which were described as 'good' on that scale (on the basis of our criteria they would lie near the minimum frequency of the 'satisfactory' region). The results were presented as iso-opinion contours in the stick-movement/stick-force plane and are reproduced in Fig. 35. It should be noted that the boundaries are not well defined in some areas and in particular the lower limit in X_s/n_z of the 'good' region may be set rather too high; a possible alternative is indicated by the dashed line in Fig. 35.

The short-period investigation of Ref. 17 included some assessment of desirable stick force characteristics in fighter-type aircraft. The values selected as being the best compromise over the wide range of short-period dynamics tested are indicated in Fig. 35, and it will be seen that they fall outside the 'good' area of Ref. 16, though not by a large margin. It was observed in Ref. 17 that the preferred stick force per g tended to increase as ζ_n was reduced—this is a corollary of the suggestion, made in an earlier section, that an increase in stick force per g makes lower damping more acceptable to the pilot—unfortunately no quantitative details were given in Ref. 17.

The above results, in conjunction with data from routine tests, lead us to suggest that for a fighter-type aircraft having good short-period dynamics and a control system representative of good current practice, a steady stick force per g between about 5 lb and 10 lb is likely to prove 'satisfactory' in the operational zone. 'Acceptable' values may range from about 3 lb/g to 15 lb/g. Steady stick forces per g below 3 lb may be made 'acceptable' but this usually seems to involve adjusting the control system dynamics to reduce the response to high frequency inputs. As the short-period damping diminishes it is probable that the lower limits of 'satisfactory' and 'acceptable' stick force per g will be raised and possible that the upper limits may be raised also.

The maximum and minimum stick-force gradients laid down in American military requirements (U.S. Military Specification MIL–F–8785 (ASG)) are based on the proof load factor (n_1). For a typical fighter with $n_1 = 7$ these become 9·1 lb/g and 3·5 lb/g respectively, which agree fairly well with the 'satisfactory' range proposed above. The British requirements also are related to n_1 and, taking the same value as an example, the maximum and minimum gradients become 14·9 lb/g and 1·9 lb/g respectively, which approximate to the proposed 'acceptable' range, though the minimum seems too permissive a lower limit and likely to cause handling difficulties unless special precautions are taken.

It seems reasonable to suppose that the upper limits of stick force per g stem from the need to apply normal accelerations regarded as adequate for combat, without having to apply excessive stick forces, or to retrim. One might argue further that when the normal acceleration available is less than usual (for example, due to limited control power supersonically), proportionately higher stick forces per g might be rated more favourably. Flight experience tends to support this view in that several supersonic fighters that are control-power limited have stick forces per g in the region of 15 lb, without attracting adverse comment.

Because large aircraft usually have low limiting load factors it is often argued that the stick force per *g* should be sufficiently high to deter the pilot from over-stressing the structure. This view is reflected in the design requirements of many countries, which permit high or very high maximum stick force gradients in low load-factor aircraft, and by the fact that some designers appear to aim for these maxima. It is fair to say then that the manoeuvring forces of large aircraft are strongly influenced by structural considerations. Possibly for this reason, there has been virtually no systematic investigation of the forces that are desirable from a handling point of view and it seems that our ignorance in this respect should be remedied. Even if one accepts the thesis that high stick forces act as a structural safeguard (and the writer does not), more positive forms of load factor limitation, such as *g*-restrictors, are becoming practicable and are certainly to be preferred; such devices would make it possible to select stick forces on the basis of suitability for handling, if these were known.

To judge from comments in routine handling reports the maximum stick force gradients currently permitted by Av.P.970 are objectionably high—for example, with a proof load factor of 2·5 this maximum is 123 lb/*g* for a wheel-type control and, in practice, manoeuvring forces of this order are criticised as being 'very heavy'. The maximum gradient permitted by American military requirements in a similar case is 80 lb/*g*; this seems a more reasonable figure, though pilot comment indicates that it probably is much higher than desirable from handling considerations.

The uncertainty that surrounds the question of desirable manoeuvring forces for large aircraft can be illustrated by two examples from comparatively recent history. In one case the aircraft had a stick force per *g* which, at 12 lb/*g* was well below the Av.P.970 minimum; pilot comment acknowledged this but added that 'any increase in elevator forces would have a deleterious effect on the handling characteristics'. In the other case the SF/*g* was about 40 lb/*g* (well above the permitted minimum), yet the longitudinal control was described as '. . . erring in the sense of being rather too light and sensitive . . . ' Instances of these kinds could be multiplied and the variability they illustrate may arise partly from differences in the aircraft's stability characteristics and partly from the personal preferences of the assessing pilots (including the degree to which they accept the tradition of high forces for large aircraft). The need for further investigation of desirable force levels for large aircraft and, in particular, the need to establish the interactions between 'stability' and 'control' (i.e. stick force) characteristics with and without effective load factor limiters will be obvious.

4.2.2. *On the approach.* The only systematic data available is that contained in Ref. 10, which relates to a fighter type aircraft in which both the short-period characteristics and the speed stability were varied. In these experiments the stick force per unit stick displacement was held nominally constant and the pilot selected a stick-to-surface gearing for each configuration which, in his view, was optimum for approach work. As noted earlier these optima often were compromises between desirable transient and steady forces, usually weighted in favour of the former; it seems likely that this weighting may have been influenced by the rather long control-system time constant which appears to have been used in these tests (0·33 sec).

The results of this investigation are summarised in Fig. 36 where the control gearings selected for each configuration are shown on the ω_n—ζ_n plane in terms of the steady incidence change per unit stick displacement. The lines of constant α/X_s shown in Fig. 36 are those put forward in Ref. 10 as best fitting the data, on the assumption that a relationship of the second degree in ω_n and ζ_n was the least complicated that would give an adequate fit. It will be observed that the data exhibits considerable scatter, and because of this it is difficult to distinguish any systematic variation between gains selected under differing conditions of speed stability. There is, however, a broad trend towards low gains at high frequency and low damping, and high gains at low frequency and high damping. The gains in terms of α/X_s can be converted approximately to steady stick forces per *g* in this case using the relationship

$$\frac{F}{n_z} \doteqdot 47 \frac{X_s}{\alpha}$$

It will be seen that the gains selected correspond to stick forces per *g* ranging from about 40 lb/*g* at $\omega_n = 3$, $\zeta_n = 0{\cdot}1$ to about 9 lb/*g* at $\omega_n = 1{\cdot}0$, $\zeta_n = 1{\cdot}0$. At short period frequencies around 2 rad/sec it was possible to select gearings that were 'satisfactory' both from the viewpoint of the initial response and the steady forces, and here the selected stick forces per g ranged from about 23 lb/g at $\zeta_n = 0{\cdot}1$ to about 13 lb/g at $\zeta_n = 1{\cdot}0$; the corresponding stick movements per g were roughly 3 in/g and 1·5 in/g respectively. These optima were much higher than those obtained from studies made in the 'operational zone' (e.g. Ref. 16), but comparisons made on the basis of the stick force per unit steady rate of pitch gave close agreement between assessments in the approach (Ref. 10) and 'operational zone' (Ref. 16); this may be yet another coincidence or it may indicate again a preference for constant stick force per unit pitch rate.

In Ref. 10 the pilot-selected gains in α/X_s were translated approximately into terms of longitudinal control sensitivity. The results were derived from the α/X_s curves shown in Fig. 36 and are reproduced here in terms of control power per inch of stick movement and per pound of stick force in Fig. 37; it is probable that this chart is applicable to aircraft of similar class and having similar control system characteristics.

The landing approach is a vital phase of flight, and there is a clear need to expand our understanding of the handling qualities and control characteristics that influence it: in particular our 'knowledge' of the feel characteristics desirable for large aircraft rests almost wholly on past usage and this should be rationalised by systematic research of the kind reported in Ref. 10.

4.2.3. *Friction, backlash and breakout forces.* It can be stated as a general rule that friction and backlash in the control system should be as low as possible, since if either is large it will present the pilot with control difficulties similar to those associated with a divergent phugoid (*see* Section 2.1 above).

A modest level of breakout force is not objectionable, and indeed is desirable since it provides positive centring and prevents disturbance by small, inadvertent force inputs. However, breakout forces should be small in comparison with normal manoeuvring forces (e.g. with the stick forces per g), though when the latter are low some compromise may be needed if inadvertent control inputs are to be avoided. The American military requirements give lower and upper limits to the permissible breakout forces (including friction); for a stick-controlled fighter these are 0·5 lb and 3 lb, and for a wheel-controlled transport they are 0·5 lb and 7 lb respectively. These limits appear to give satisfactory results in practice, though if the level of stick force per g for transport aircraft were to be reduced the relevant upper limit of breakout force probably would have to be reduced also. British requirements specify only the upper limits of breakout force (including friction) which are quoted as 4 lb for a fighter type aircraft and 10 lb for a transport; these limits seem slightly too high and the requirement ignores the desirability of providing for a minimum breakout force.

4.3. *Trimming Systems.*

It is not possible here to give detailed guidance on desirable trim system characteristics since these are conditioned by the trim changes and operating conditions peculiar to particular types of aircraft. However, some comments on general principles may be of interest and these are offered below.

Perhaps the most important point (and the most obvious) to be made regarding the trimming system is that it is intended to relieve the pilot of the steady control forces that result from changes in configuration, power, airspeed, etc. and should not normally be used as a primary means of control in manoeuvres*. Among other disadvantages, such usage introduces some objectionable handling features such as loss of feel, loss of the original datum (to which the pilot may wish to revert), unusual stick movements, and so on. It follows that the authority and rate of the trimming system should be the minimum compatible with a satisfactory ability to trim out long term changes.

When artificial feel is employed, trimming usually is accomplished either by repositioning the feel spring datum or by changing the length of an extensible link between the feel spring and the control jack. In the former system retrimming changes the position of the stick whereas in the latter the no-load stick position is constant. Trimming by extensible link eliminates one of the handling cues (changing

---

* In passing we may note that when the manoeuvring forces are high there is a greater temptation to use the trimmer as a primary control, to which some pilots are likely to succumb. When the trimmer is used in this way it becomes relatively easy for the pilot to overstress the aircraft, and so the 'structural protection' which the high forces were supposed to provide is largely negated.

trimmed stick position with airspeed), and also conceals from the pilot the amount of control still available, which could have serious consequences in certain circumstances. For these reasons, datum shift appears to be the preferable method, but it is only fair to note that both systems have been used successfully in practice and both have their adherents.

It is not uncommon to find in the design of aircraft (especially large ones) that relatively little pitch control power is needed to enable the satisfactory performance of all normal flight tasks, but that large pitching moments may be needed to accommodate extreme conditions—for example, near the extremities of a wide cg range. A possible design solution to this problem is to equip the aircraft with relatively small elevators for primary control and to provide a trimmable tailplane of sufficient authority to bring the total pitching power up to the requisite level. If, for example, such an aircraft were capable of high subsonic speeds (where the ratio of elevator to tailplane effectiveness decreases) there would be the danger that a tailplane mis-set by malfunction or mistake could overpower the elevator, and perhaps lead to disaster. Solutions of this type have been employed and have given rise to serious difficulties. It appears that in no circumstances should the authority of the trimming system exceed that of the primary control, even when the integrity of the former is comparable to that of the latter.

5. *Conclusions*

An attempt has been made to review longitudinal handling problems in the light of systematic studies and recent practice, with a view to deriving handling criteria. While some positive results have been obtained, the review has served mainly to illustrate the considerable gaps that still remain in our appreciation of handling problems, and particularly those of large aircraft. The division into separate sections relating to long and short-period motions and to control systems, respectively, follows the classical pattern, but it must be reiterated that these divisions are made mainly for convenience and that the interactions of one mode with another, or of 'control' with either, may make them unreal from a handling viewpoint.

The lack of a coherent, unified and wide-ranging body of systematic data makes the task of formulating handling criteria a difficult and uncertain process containing a large element of speculation. Some at least of the criteria put forward in this Report suffer in this respect and must be regarded as tentative and subject to revision. There is little doubt that other, no less plausible, criteria could be put forward which would fit the existing evidence equally well.

The longitudinal handling criteria can be summarised as follows*:

(i) A conventional phugoid mode has minor nuisance value and does not normally constitute a handling problem, though the mode should not be undamped if the aircraft's behaviour is to be 'satisfactory'. A tentative limit for 'acceptable' behaviour appears to be a time to double amplitude (T_2) not less than about 40 seconds.

Handling difficulties may arise if for any reason the phugoid frequency should approach that of the short-period motion. It is suggested, however, that no significant effect is likely provided the ratio of the short-period and phugoid frequencies (ω_n/ω_p) is greater than about 20.

(ii) When the aircraft is constrained to follow a rectilinear flight path its normal phugoid mode is replaced by a simple subsidence or divergence in airspeed. The stability of this mode is of particular significance during the approach, and the limits suggested for this phase are:

(a) for 'satisfactory' behaviour the aircraft should be speed stable and the time constant (t_1) of the subsidence not greater than 50 seconds,

(b) for 'acceptable' behaviour the aircraft may be speed unstable, but if it is the time constant should not be less than 25 seconds,

(c) a higher degree of instability may be tolerable in an emergency (e.g. due to a failed auto-throttle) but in no circumstances should the time constant fall below 10 seconds.

(iii) In considering the characteristics of the short-period oscillation it has seemed necessary to treat separately the approach phase and what we have termed the 'operational zone' in which the aircraft

---

* The term 'acceptable' used without qualification means acceptable for normal operation.

performs those tasks associated with its primary function. Within the latter, further distinctions have been made on the basis of aircraft size, though it seems not unlikely that these distinctions might more properly be related to function (there is, for example, a greater emphasis on tracking tasks in fighter-type aircraft, which usually are 'small'). The evidence of systematic tests supports the commonsense expectation that the acceptability of a particular set of short-period characteristics is influenced by the characteristics of the control system; in addition, the combined effect appears to be expressible in terms of features of the response to control inputs, as outlined below.

(iv) For fighter-type aircraft in the operational zone the following short-period criteria fit the systematic experimental data reasonably well:

(a) for 'satisfactory' handling the time to first reach 90 per cent of the final steady normal acceleration following a step input in stick force should not exceed 1 sec. For 'acceptable' behaviour this time should not exceed 1·5 sec.

(b) for 'satisfactory' handling the short-period frequency should be not less than 0·5 cps, and for 'acceptable' handling should be not less than 0·35 cps,

(c) for 'satisfactory' handling the time to half amplitude of the S.P.O. should not exceed about 0·5 sec. For 'acceptable' handling it is suggested that $T_{\frac{1}{2}}$ should be not more than about 0·9 sec when the static SF/g is 5 lb or less, and that $T_{\frac{1}{2}}$ should be not more than about 1·2 sec when the static SF/g is 10 lb or more,

(d) for 'satisfactory' handling the maximum rate of change of normal acceleration in response to a sinusoidal variation of stick force, the amplitude of which is equal to the static stick force per g (i.e. $F_1|\dot{n}_z/F|_{\max}$) should not exceed 6 g/sec. For 'acceptable' handling this limit should not exceed 12 g/sec. These limits may not be applicable to aircraft whose stick force per g is less than 4 lb.

These criteria are reasonably successful when applied to current conventional fighter-type aircraft having stick forces per g not less than 4 lb and probably can be used to assess the handling qualities of aircraft in this category. The criteria are illustrated in Fig. 23, assuming a control-system time-constant of 0·1 sec. Their applicability to unconventional configurations (e.g. tailless delta) or control systems (e.g. adaptive systems) is not established and may be questionable.

The evidence, from some systematic tests, in favour of relatively low upper limits of 'satisfactory' or 'acceptable' short-period frequency appears to be a by-product of imperfections in the experimental equipment and is at variance with evidence from routine flight tests. While upper limits of frequency may well exist we are not, at the moment, able to define them.

(v) For 'large' aircraft in the operational zone the evidence on which the short-period criteria depend is much more slender and the criteria are more tentative in consequence. The proposed criteria, which are similar in principle to those established for fighter type aircraft, are illustrated in Fig. 26 for an assumed control system time-constant of 0·2 sec. Although there is some support for these criteria from the body of *ad hoc* data available, the latter is not as extensive as might be wished and the criteria therefore are not well-substantiated in some areas and are speculative in others.

(vi) The evidence available from systematic investigations of approach handling is too fragmentary to enable us to formulate generally applicable handling criteria, but it does show conclusively that, to be applicable to this task, any criterion must take account of the aircraft lift characteristics, in addition to the short-period frequency and damping. The evidence is not sufficient to establish the most suitable form for the lift parameter to take, but at present the choice appears to lie between $1/T_\theta$ and n_{z_α} (where the latter is related to controlled manoeuvres, and therefore includes effects arising from the lift due to control movement).

For aircraft having damping ratios between about 0·4 and 1·0 and satisfactory control characteristics the iso-opinion contours of Fig. 30a or Fig. 30b can be used to predict handling qualities on the approach.

For aircraft having values of $1/T_\theta$ between about 1·0 and 1·2 and satisfactory control characteristics, the iso-opinion contours of Fig. 28a can be used to predict handling qualities on the approach.

(vii) Friction and backlash in the control system should be as small as possible and, while positive self-centring is desirable, the breakout forces should be small relative to the stick force per g. The limiting breakout forces given in American military requirements appear to give satisfactory results in practice.

(viii) For a fighter-type aircraft having good short-period dynamics the stick force per *g* should lie between about 5 and 10 lb for 'satisfactory' handling in the operational zone, and between about 3 lb and 15 lb for 'acceptable' handling. Lower manoeuvring forces can be made acceptable if the control system dynamics are suitably optimised. The 'optimum' force depends on the aircraft's short-period dynamics; for example it tends to increase as damping decreases to low values.

(ix) There is no conclusive evidence on the manoeuvring forces that are desirable from handling considerations in large aircraft and experiments to establish these levels should be made. There is, however, a good deal of evidence to show that the currently-permitted maxima are far too large to give satisfactory handling.

(x) For fighter-type aircraft, the optimum manoeuvring forces (SF/g) were generally much higher on the approach than in the operational zone, and varied markedly with the aircraft's short-period dynamics. The chart showing pitch control sensitivity as a function of the short-period characteristics (Fig. 33) probably can be used as a design guide for aircraft of similar class.

TABLE 1

The Cornell Rating Scale (from Ref. 17 *Part II)*
Used, with Minor Variations, in Refs. 2, 3, 16, 17 *and* 19

Rating	Definition
Optimum	This configuration is the best all round. It combines best precision of control with most comfortable control.
Acceptable good	Noticeably better than acceptable but still could be improved. For example, very comfortable to fly but not best control precision.
Acceptable	In this configuration the airplane's mission could be accomplished reasonably well, but with considerable pilot effort or attention required directly for flying the airplane.
Acceptable poor	Airplane safe to fly, but pilot effort or attention required is such as to reduce seriously the effectiveness of the airplane in accomplishing its mission.
Unacceptable	Pilot effort or attention required to the extent that the airplane's ability to accomplish its mission is doubtful. Or, airplane would be unsafe to fly if pilot's attention is required for navigation, radio, combat, etc.

The pilot was permitted to attach a plus or minus to the ratings given above if he felt a finer breakdown was necessary.
To establish 'minimum flyable' boundaries the 'unacceptable' area was sub-divided and extended as shown below.

Unacceptable	One or more unacceptable flight characteristics
Unacceptable 1	Magnification of unacceptable
Unacceptable 2	Difficult flyability, but safe
Unacceptable 3	Marginal safety and flyability
Unacceptable 4	Unflyable or unsafe

Again, a plus or minus sign could be attached to these ratings if a finer breakdown was thought to be necessary.

TABLE 2

The NASA 'Cooper' Scale (*Ref.* 4)

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable—dangerous	No	No
		9	Unacceptable—uncontrollable	No	No
	Unprintable	10	Motions possibly violent enough to prevent pilot escape	No	No

* Failure of a stability augmenter

TABLE 3

The Revised Cornell Rating Scale (Refs. 10, 21)

Category	*Adjective*	*Rating number*
Acceptable and satisfactory	Excellent	1
	Good	2
	Fair	3
Acceptable but unsatisfactory	Fair	4
	Poor	5
	Bad	6
Unacceptable*	Bad	7
	Very bad	8
	Dangerous	9
Unflyable		10

* Expanded definitions of unacceptable category

7. Unacceptable, bad:	The airplane is controllable but it requires a major portion of pilot's attention.
8. Unacceptable, very bad:	The airplane is controllable, but only with a minimum of cockpit duties.
9. Unacceptable, dangerous	The airplane is just controllable with complete attention and no cockpit duties.

TABLE 4

Summary of Longitudinal Short-Period Handling Investigations

Ref. No.	*Test conditions*	*Tests made*	*Results*	*Comments*
2	Variable-stability *B–26*. m_w and $m_{\dot{w}}$ varied to give— $1{\cdot}8 < \omega_n < 3{\cdot}5$ rad/sec $0{\cdot}15 < \zeta_n < 1{\cdot}35$ Eas = 200 miles/h: height = 10 000 ft Stick-force per g kept at about 66 lb/g.	Assessed by 1 pilot using Cornell rating scale (Table 1) on basis of trimmability: response to step inputs: slow and rapid turn entries: tracking a ground target.	Iso-opinion contours as functions of ω_n and ζ_n, *see* Fig. 7a.	Results are strictly applicable to light attack bomber only, but probably are valid for most medium-sized aircraft. Low natural frequency of the variable-stability servos render results at high frequencies rather dubious (Ref. 21).
16	Variable-stability *F–94*. m_w and $m_{\dot{w}}$ varied to give— $1{\cdot}25 < \omega_n < 5$ rad/sec $0{\cdot}2 < \zeta_n < 1{\cdot}5$ Eas = 300 kt: height = 20 000 ft Stick-force and -movement per g kept roughly constant $7{\cdot}7 < SF/g < 10{\cdot}2$ lb/g: $0{\cdot}18 < X_s/g < 0{\cdot}24$ in/g	Assessed by 1 pilot, using Cornell rating scale. Manoeuvres similar to Ref.2.	Iso-opinion contours as functions of ω_n and ζ_n, Fig. 7b.	Results are applicable to fighter-type aircraft only. Results not obtained above ω_n = 5 rad/sec because of 'system instabilities'. This may have influenced assessments at somewhat lower frequencies, making results rather dubious in this region.
17	Variable-stability *F–94*. m_w $m_{\dot{w}}$ varied to give— $0{\cdot}8 < \omega_n < 8$ rad/sec $0{\cdot}8 < \zeta_n < 1{\cdot}7$ Eas = 350 kt: height = 15 000 ft Pilot SF/g(lb/g) X$_s$/g(in/g) Part I A 6 0·2 B 6 0·1 Part II C 4·8 0·09 $T_c = 0{\cdot}08$ sec (*see* Ref. 20).	Assessed by 3 pilots, using Cornell rating scale. Manoeuvres similar to Ref. 2.	Iso-opinion contours as functions of ω_n and ζ_n, *see* Fig. 8. Modified contours shown in Fig. 9	Results are applicable to fighter-type aircraft only. Improved servo response enabled investigation of higher frequencies than in Ref. 16. Results probably reliable up to about 7 rad/sec: higher frequencies may be suspect owing to remaining 'system instabilities': the closure of the 'best tested' area at high frequencies is dubious. Scarcity of data in the region $\zeta < 0{\cdot}4$ and $f_n > 0{\cdot}9$ renders 'acceptable' boundary dubious.

TABLE 4 (*Contd.*)

Ref.	*Test conditions*	*Tests made*	*Results*	*Comments*
Part III	Some data obtained with low or negative stability or damping. Constant η/SF (= 0·21 /lb) for unstable configurations. SF/g = 6 lb/g for stable configurations.	Assessed by 1 pilot (A) using extended Cornell rating scale. (Table 1). Straight and level flight: turn entries and recoveries: general flying with random noise input to elevator servo (simulated turbulence).	Iso-opinion contours as functions of coefficients of characteristic equation, ω_n^2 and $2\zeta_n\omega_n$.	
20	Variable-stability YF–86D.m_w and m_q varied to give— (i) $1{\cdot}5 < \omega_n < 7{\cdot}5$ rad/sec $-0{\cdot}2 < \zeta_n < 0{\cdot}8$, with (a) Minimum control system constant, $T_c = 0{\cdot}15$ sec. (b) Pilot-selected optimum T_c (negative ζ_n's not investigated) SF/g = 10 lb/g. (ii) $-17 < \omega_n^2 < 12$ (rad/sec)^2 $0 < 2\zeta_n\omega_n < 4$ rad/sec $T_c = 0{\cdot}15$ sec. η/S.F. = 0·15°/lb Mach No. = 0·8: height = 35 000 ft throughout.	Assessed by one pilot using Cooper rating scale (Table 2). A limited number of check assessments were made by a second pilot. Assessment manoeuvres not reported in detail but included turn entries and exits, step and pulse inputs.	Iso-opinion contours as functions of ω_n and ζ_n, *see* Figs. 10a and b. Optimum control system time constants as functions of ω_n and ζ_n, *see* Fig. 11. Iso-opinion contours as functions of ω_n^2 and $2\zeta_n\omega_n$ (for unstable configurations), *see* Fig. 12.	Results are applicable to fighter-type aircraft only. Contours not well established at high frequencies, but show influence of T_c on short-period assessment.
21	Variable-stability B–26.m_w and $m_{\dot{w}}$ varied to give $1{\cdot}25 < w_n < 5$ rad/sec $0{\cdot}1 < \zeta_n < 0{\cdot}8$ Eas = 200 miles/h (range 180–230 miles/h) Height = 8000 ft Stick force per g = 40 lb Phugoid maintained at P_p = 50 sec: $\zeta_p = 0{\cdot}05$ $T_c = 0{\cdot}05$ sec.	Assessed by 15 pilots with evaluation time limited to 5–7 minutes, and by 3 pilots allowed unlimited evaluation time. All used revised Cornell rating scale (Table 3). Manoeuvres similar to Ref. 2.	Iso-opinion contours as functions of ω_n and ζ_n based on the 'long-look' assessments. *See* Fig. 13.	Results probably are valid for most medium-sized aircraft. The upper limit of the frequency range covered was prescribed by 'limitations of the variable-stability equipment'.

22	Fixed base simulator $0{\cdot}6 < \omega_n < 6{\cdot}3$ rad/sec $0{\cdot}2 \leqslant \zeta_n \leqslant 1$ 2-degrees of longitudinal freedom only. Lateral dynamics included	Tracking tasks with random-appearing forcing functions. Assessed by 2 pilots.	Iso-opinion contours as functions of ω_n and ζ_n. *See* Fig. 14.	Rather sparse coverage. Contours are tentative.
23	Fixed base simulator No other details available		Iso-opinion contours as functions of ω_n and ζ_n. *See* Fig. 15.	
24	Moving cockpit simulator ('pitch chair')		Iso-opinion contours as functions of ω_n and ζ_n. *See* Fig. 16.	
24	Moving cockpit simulator (centrifuge) 2 degrees of longitudinal freedom only	Assessed on Cooper scale (Table 2), using miniature side-located stick. Tracking task.	Iso-opinion contours as functions of ω_n and ζ_n. *See* Fig. 16.	Results probably applicable only to re-entry vehicles in view of very high datum n_z ($7g$). Spurious angular acceleration cues present may have influenced assessments.
26	Moving cockpit simulator (centrifuge) 2 degrees of longitudinal freedom only. No lateral dynamics (i) $1 \leqslant \omega_n \leqslant 6$ rad/sec $-0{\cdot}1 < \zeta_n < 1{\cdot}25$ $SF/g = 8$ lb: $T_c = 0{\cdot}1$ sec. (ii) $-1 < \omega_n^2 < -10$ $0{\cdot}5 < 2\zeta_n\,\omega_n < 8$ $\eta/SF = 0{\cdot}14°/\text{lb}$: $T = 0{\cdot}1$ sec.	Assessed by 6 pilots on Cooper scale. Tasks included familiarisation, abrupt θ and n changes, and tracking in simulated turbulence. Also assessed a miniature side-located stick.	Iso-opinion contours as functions of (i) ω_n and ζ_n, (*see* Fig. 17), (ii) ω_n^2 and $2\zeta_n\,\omega_n$, (*see* Fig. 18).	The purpose of these tests was to provide a comparison with the flight study of Ref. 20. To minimise spurious motion cues in other axes the tests were made at a mean n_z of $3g$. The residual spurious cues and the bias in n_z may have influenced assessments. Rather sparse coverage of ω_n—ζ_n plane means boundaries are tentative.
27	Moving cockpit simulator (G-seat) 2 degrees of longitudinal freedom only. Roll and spiral lateral modes included $0{\cdot}5 \leqslant f_n \leqslant 2$ cps $0{\cdot}2 \leqslant \zeta_n \leqslant 1{\cdot}5$ Range of constant SF/g and X_s/g: 1 to 10 lb/g and 0·1 to 1·0 in/g respectively. Breakout force = 1·2 lb	Assessed by 11 pilots, using Cooper rating scale. Tests concentrated on low-level terrain following tasks, but included other assessment manoeuvres.	Iso-opinion contours (P.R. = 3·5) as functions of ω_n and ζ_n for SF/g of 1, 5 and 10 lb/g. *See* Fig. 19.	Rather sparse coverage of ω_n—ζ_n plane. Contours are somewhat tentative and relate to specialised low-level task.

LIST OF SYMBOLS

a	$= \dfrac{\partial C_L}{\partial \alpha}$ Lift slope	
B	Moment of inertia in pitch	(slugs-ft^2)
C_D	$= \dfrac{D}{\frac{1}{2}\rho V^2 S}$ Drag coefficient	
C_L	$= \dfrac{L}{\frac{1}{2}\rho V^2 S}$ Lift coefficient	
C_m	$= \dfrac{M}{\frac{1}{2}\rho V^2 S\bar{c}}$ pitching-moment coefficient	
$\bar{c}$	Wing mean chord	(ft)
D	Drag force	(lb)
F	Stick force	(lb)
F_1	Steady stick force to maintain one excess g	(lb)
f_n	Undamped natural frequency of short period oscillation	(cps)
g	Acceleration due to gravity	(32·2 ft/sec^2)
H_m	Manoeuvre margin	
K_m	Static margin	
L	Lift force	(lb)
L_i	$\dfrac{\partial L}{\partial i}$, $i = \alpha, q, \dot{\alpha}, \eta$, etc.	
M	Pitching moment	(lb-ft)
M_i	$= \dfrac{\partial M}{\partial i}$, $i = \alpha, q, \dot{\alpha}, \eta$, etc.	
m	Aircraft mass	(slugs)
n_z	Normal acceleration	(g units)
P_p	Phugoid period	(sec)
q	Rate of pitch	(rad/sec)
$\bar{q}$	$= \frac{1}{2}\rho V^2$, Dynamic pressure	(lb/ft^2)
S	Wing area	(ft^2)
s	Laplace operator	
$T_{\frac{1}{2},2}$	Time to halve or double amplitude	(sec)
T_c	Equivalent first-order time constant of control system	(sec)
$TF_{ab}(s)$	Transfer function of a with respect to b in Laplace notation	(sec)
t	Time	
t_1	Time constant of speed subsidence or divergence	(sec)
u	Disturbance velocity along flight path	(ft/sec)
u_0	Initial value of u	
V	True airspeed	(ft/sec, except where no
W	Aircraft weight	(lb)
X_s	Stick displacement	(inches)
α	Incidence	(deg or rad)
γ	Inclination of flight path to horizontal	(deg or rad)
η	Displacement of pitch control surface	(deg or rad)
ζ_n	Damping rate of short-period oscillation	
ζ_p	Damping ratio of phugoid	
θ	Inclination of aircraft longitudinal axis to horizontal	(deg or rad)
ω_n	Undamped natural frequency of short-period oscillation	(rad/sec)
ω_p	Undamped natural frequency of phugoid	(rad/sec)

REFERENCES

No.	*Author(s)*	*Title, etc.*
1	P. L. Bisgood	A review of recent research on handling qualities, and its application to the handling problems of large aircraft. Parts I and II A.R.C. & R & M 3458 (1964).
2	F. Newell and G. Campbell	Flight evaluation of variable short-period and phugoid characteristics in a B.26. Cornell Aero Lab. Inc. WADC TR54–594. P 7723 (1954).
3	F. Newell and D. W. Rhoads	Flight evaluations of the effect of variable phugoid damping in a JTB–26B airplane. Cornell Aero. Lab. Inc. WADC TR56–223 (1956).
4	G. E. Cooper	Understanding and interpreting pilot opinion. *Aero. Eng. Review*. Vol. 16 Nos. 3 (1957).
5	C. Leyman and E. R. Nuttall	A survey of aircraft handling criteria. A.R.C. C.P. 833 (1964).
6	D. T. McRuer, I. L. Ashkenas and C. L. Guerre	A systems analysis view of longitudinal flying qualities. WADC TR60–43 (1960).
7	S. Neumark	Problems of longitudinal stability below minimum drag speed, and theory of stability under constraint. A.R.C. R & M 2983 (1953).
8	K. J. Staples	Flight measurements of the influence of speed stability on the landing approach. AGARD Report 420.
9	D. H. Perry	Flight simulators and the study of aircraft handling characteristics. Symposium on aircraft take-off and landing problems. TOLS/7 R.A.E. (1962).
10	C. R. Chalk	Flight evaluations of various short-period dynamics at four drag configurations for the landing approach task. Cornell Aero. Lab. Inc. FDL–TDR–64–60 (1964).
11	M. D. White, M. Sadoff, R. S. Bray and G. E. Cooper	Assessment of critical problem areas of the supersonic transport by means of piloted simulators. I.A.S. Paper No. 62–20 (1962).
12	R. S. Bray	A piloted simulator study of longitudinal handling qualities of supersonic transports in the landing manoeuvre. NASA TN D–2251 (1964).
13	F. J. Drinkwater and G. E. Cooper	A flight evaluation of the factors which influence the selection of landing approach speeds. NASA Memo 10–6058A (1958).

REFERENCES (contd.)

No.	*Author(s)*	*Title, etc.*
14	M. D. White, F. J. Drinkwater and B. A. Schlaff	A comparison of flight measured carrier-approach speeds with values predicted by several different criteria for 41 fighter-type airplane configurations. NACA RN A57L11 (1958).
15	D. Lean and R. Eaton	The influence of drag characteristics on the choice of landing approach speeds. AGARD Report 122 (1957).
16	R. P. Harper	Flight evaluations of various longitudinal handling qualities in a variable-stability jet fighter. Cornell Aero. Lab. Inc. WADC TR 55–299. P 57724 (1955).
17	C. R. Chalk	Additional flight evaluations of various longitudinal handling qualities in a variable-stability jet fighter. Cornell Aero. Lab. Inc. WADC TR 57–719 Part I March 1958, Part II 1958.
18	M. Sadoff	The effects of longitudinal control system dynamics on pilot opinion and response characteristics as determined from flight tests and from ground simulator studies. NASA Memo 10–1–58A (A.R.C. 21045) (1958).
19	G. Bull	Minimum flyable longitudinal handling qualities of airplanes. Cornell Aero. Lab. Inc. Report TB–1313–F–1 (1959).
20	N. M. McFadden, R. F. Vomaske and D. R. Heinle	Flight investigation using variable-stability airplanes of minimum stability requirements for high speed, high-altitude vehicles. NASA TN D–779 (1961)
21	E. A. Kidd and G. Bull	Handling qualities requirements as influenced by pilot evaluation time and sample size. Cornell Aero. Lab. Inc. Report TB–1444–F–1 (1963).
22	I. A. M. Hall	Effects of controlled element on the human pilot. W.A.D.C. TR 57–709 Princeton University (1958).
23	G. A. Rathert, B. Y. Creer and J. G. Douvillier	Use of flight simulators for pilot-control problems. NASA Memo 3–6–59A (A.R.C. 21046) (1959).
24	B. Y. Creer, D. R. Heinle and R. C. Wingrove	Study of stability and control characteristics of atmosphere-entry type aircraft through use of piloted flight simulators. Inst. Aero. Sciences. Paper No. 59–129 (1959).
25	B. Y. Creer, H. A. Smedal and R. C. Wingrove	Centrifuge study of pilot tolerance to acceleration and the effects of acceleration on pilot performance. NASA TND–337 (1960).

REFERENCES (contd.)

No.	*Author*(*s*)	*Title, etc.*
26	M. Sadoff, N. M. McFadden and D. R. Heinle	A study of longitudinal control problems at low and negative damping and stability with emphasis on the effects of motion cues. NASA TN D–348 (1961).
27	R. C. A'Harrah	Low-altitude, high-speed handling and riding qualities. A.I.A.A. Paper No. 63–229 (1963).
28	C. R. Chalk	Fixed-base simulator investigation of the effects of L_α and true speed on pilot opinion of longitudinal flying qualities. Technical Documentary Report ASD–TDR–63–399 (1963).
29	R. G. Hoey and M. T. Apt	F–100V Phase IV stability and control test. AFFTC–TR–56–25. P2226 (1956) (and Addendum 1956).
30	D. C. Leisy and H. P. Hunewadel	F–100D Category II performance, stability and control tests. P 73348. AFFTC–TR–58–27 (1958).
31	C. H. Wolowicz	Dynamic longitudinal stability characteristics of a swept-wing fighter-type airplane at Mach numbers between 0·36 and 1·45. NASA/TIL/6588 (NACA RM H56H03) (1957).
32	R. G. Hoey and I. C. Kincheloe	F–104A. Stability and control tests. AFFTC–TR–58–14 (1958) (and Addendum 1 1959).
33	W. H. Andrews, T. R. Sisk and R. W. Darville	Longitudinal stability characteristics of the Convair YF–102 airplane determined from flight tests. NASA/TIL/6682 (NACA RM H56I17) (1956).
		AFFTC–TR–59–13. P 78134 (1959).
		AFFTC–TR–56–36. P 64719A.
34	—	Phase 1. Navy preliminary evaluation of the Model F8U–3 airplane. NATC Report PTR AC–27101.1.
35	—	Limited preview on second development aircraft (Gnat). 1st Part of A. and AEE Report 926.
36	J. D. McDaniel	A summary of the flying characteristics of the Avro Arrow. A. V. Roe (Canada) Report.
37	T. H. Kerr and J. Clark	Flight test measurements at high Mach numbers of the longitudinal short-period oscillation of a 45° swept tailless delta (BP111A) having taper ratios of 0·01, 0·14 and 0·27. R.A.E. Tech. Memo Aero 491 (A.R.C. 19001) (1956).

38	O. A. Levi and W. E. Nelson	An analytical and flight test approach to the reduction of pilot-induced oscillation susceptibility. *Journal of Aircraft*. Vol. 1 No. 4 (July–Aug. 1964).
39	J. D. Richardson and R. C. A'Harrah	Application of flight simulators to the development of the A–5A Vigilante. *Journal of Aircraft*. Vol. 1 No. 4 (July–Aug. 1964).
40	R. C. Adams	Investigation of low-level high-speed flight problems. SETP Symposium (1964).
41	A. D. Phillips and G. M. Townsend	B.52A Phase II performance and stability tests. AFFTC TR–55–27 (1955).
42	C. C. Crawford and J. P. Seigler	KC–135A Stability and control test. AFFTC TR–58–18. P 72608 (1958).
43	W. A. Lusby and R. S. Martin	Model CL–329 Air Force flight evaluation. AFFTC TR–58–25. P 72857 (1958).
44	A. De Anda and R. L. Fetty	B–57B Limited phase IV performance and stability. AFFTC TR–17. P 61288 (1956).
45	—	Valiant B. Mk. 1. 1st Part of A and AEE Report 882.
46	—	Comet C. Mk. 2. 3rd Part of A and AEE Report 924.
47	M. D. White and R. C. Innis	Flight investigation of the low-speed handling qualities of a tailless delta-wing fighter airplane. NASA Memo 4–15–59A. TIL 6541 (1958).
48	H. C. Quigley, S. B. Anderson and R. C. Innis	Flight investigation of the low-speed characteristics of a 45° swept wing fighter-type airplane with blowing boundary-layer control applied to the trailing-edge flaps. NACA RM A58E05. TIL 6098 (1958).
49	H. C. Quigley, S. B. Anderson and R. C. Innis	Flight investigation of the low-speed characteristics of a 45° swept wing fighter-type airplane with blowing boundary-layer control applied to the leading- and trailing-edge flaps. NASA TN D–321 (1960).
50	G. Bull	Minimum flyable longitudinal handling qualities of airplanes. Cornell Aero. Lab. Report TB–1313–F–1 (1959).
51	D. K. Mandella	The investigation of aircraft stability in the landing configuration. De Havilland Aero Dept Report 3107 (1961).

52 A. G. Barnes .. .. .. A simulator investigation of the effects of ω_n and L_α on the landing approach task.
BAC Report Ae, 266 (1966).

53 W. T. Kehrer .. .. .. Longitudinal stability and control of large supersonic aircraft at low speeds.
ICAS Paper No. 64–586 (1964).

54 A. R. Mabli, J. W. Carlson and R. O. Sickeler .. .. .. Results of handling qualities research for the C–5A.
A.I.A.A. Paper 65–740 (1965).

55 H. A. Shomber and W. M. Gersten .. .. Longitudinal handling qualities criteria: an evaluation.
A.I.A.A. Paper 65–780 (1965).

56 S. A. Sjoberg, W. R. Russell and W. L. Alford .. .. .. Flight investigation of a small side-located control stick used with electronic control systems in a fighter airplane.
NACA RM L56L28a. TIL 5459.

57 F. Newell and G. Campbell .. .. .. Evaluations of elevator force gradients and types of force feel in a B-26.
W.A.D.C. TR 54–442. P 62346.

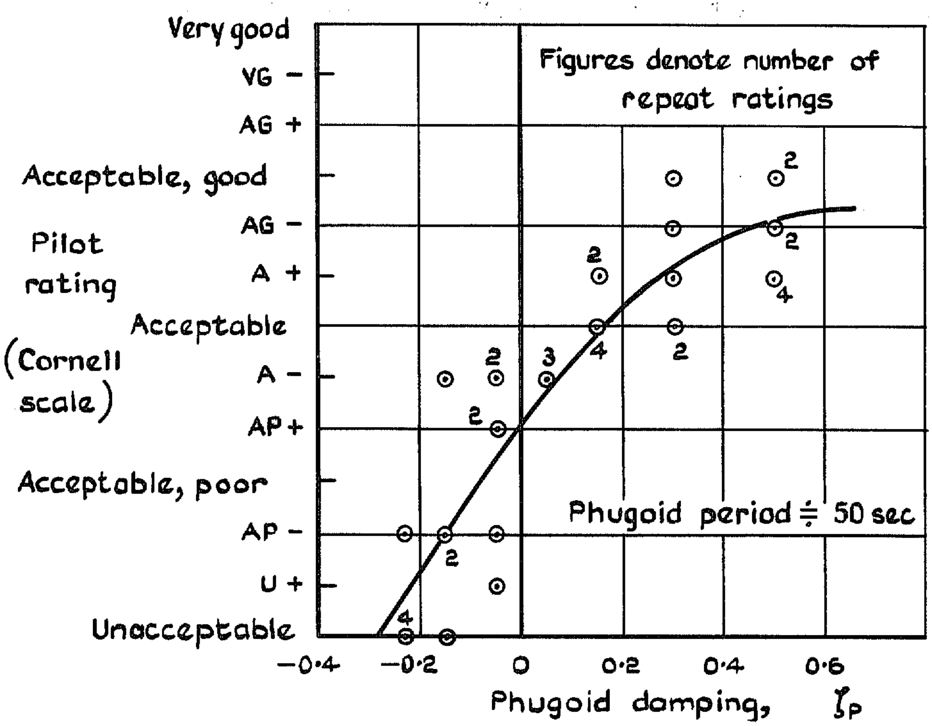


FIG. 1. Effect of Phugoid damping on pilot rating (data of Ref. 3).

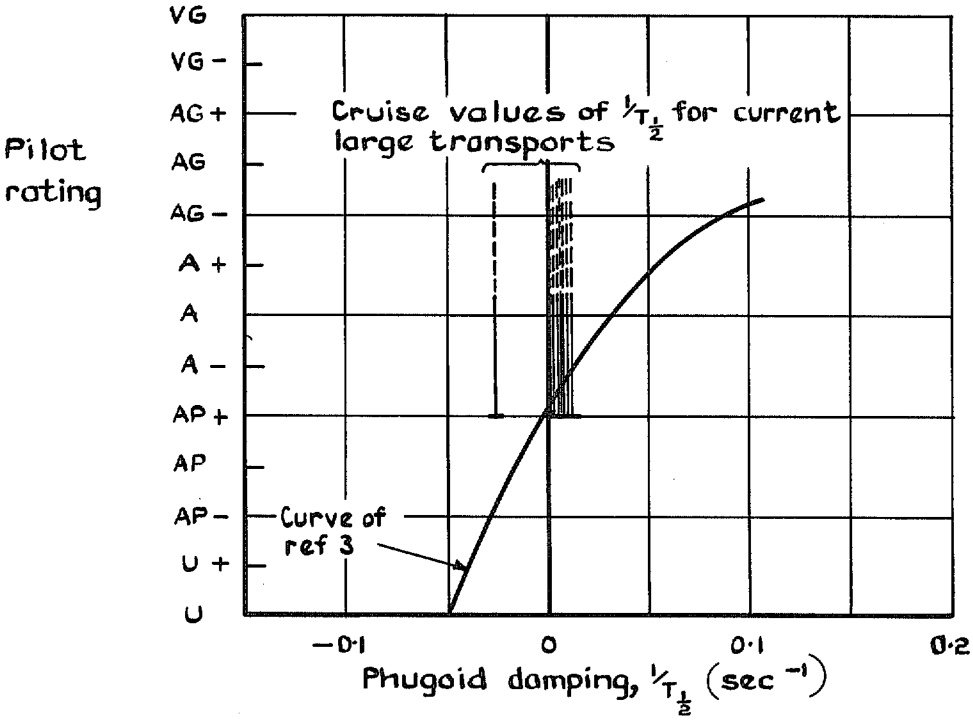
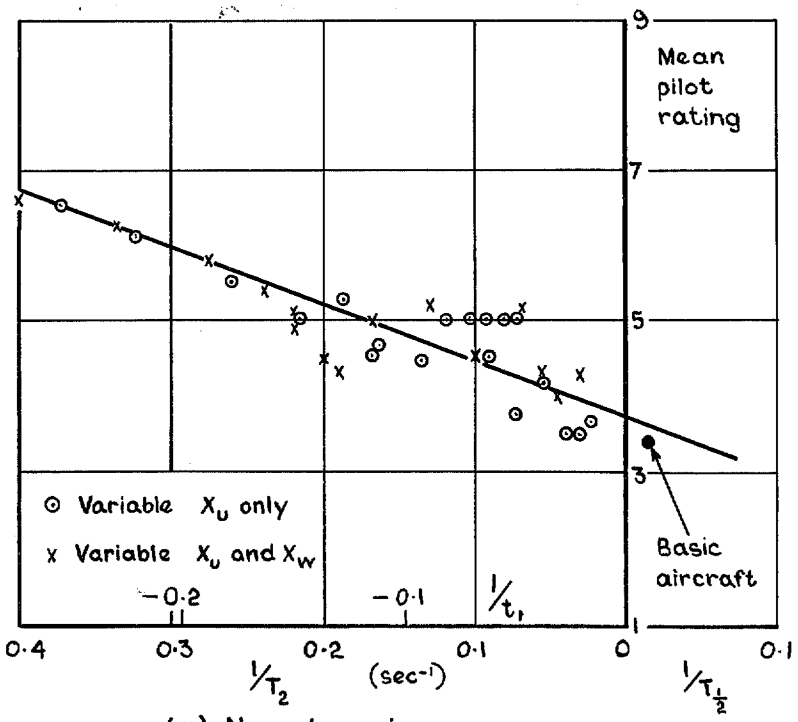
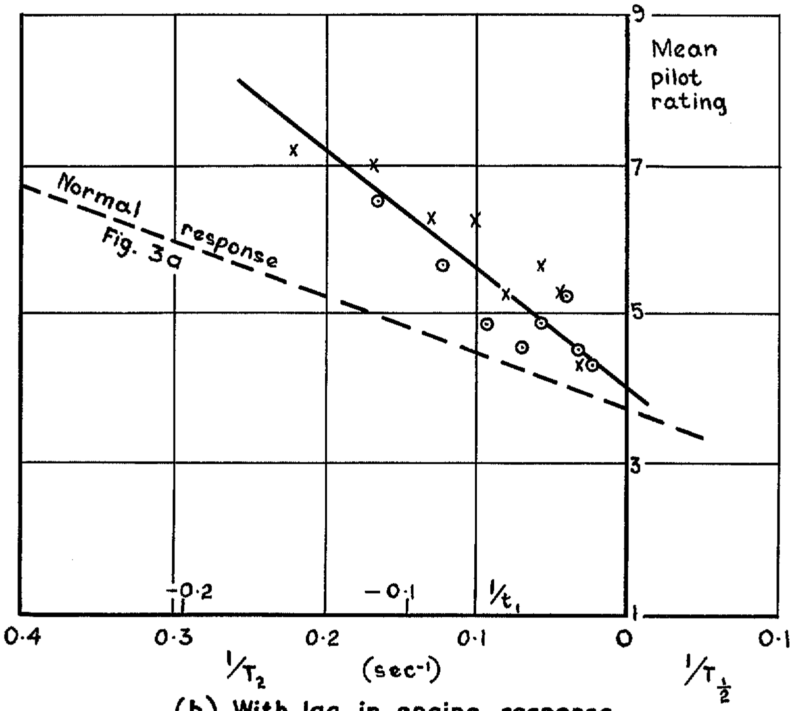


FIG. 2. Effect of Phugoid damping.



(a) Normal engine response



(b) With lag in engine response

FIG. 3a & b. Variation of pilot rating with speed stability (Ref. 8).

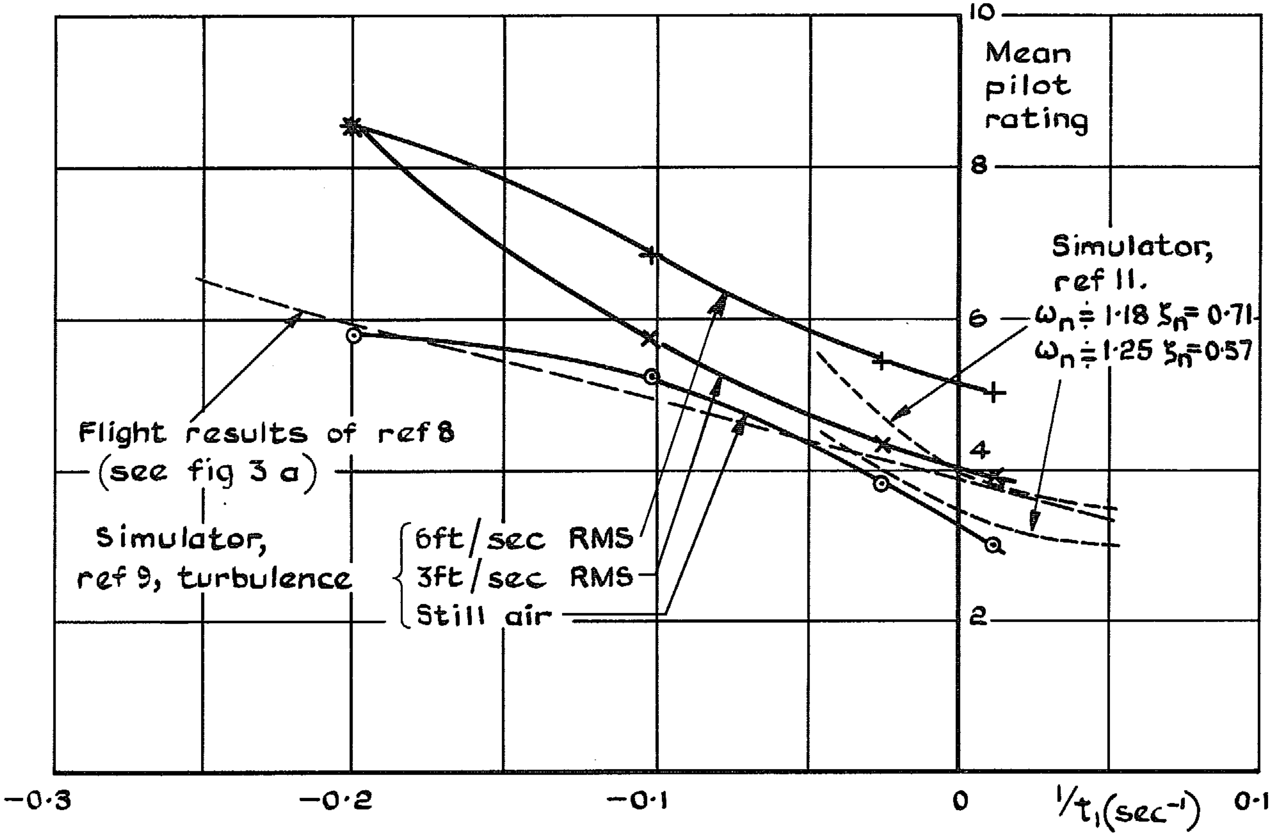
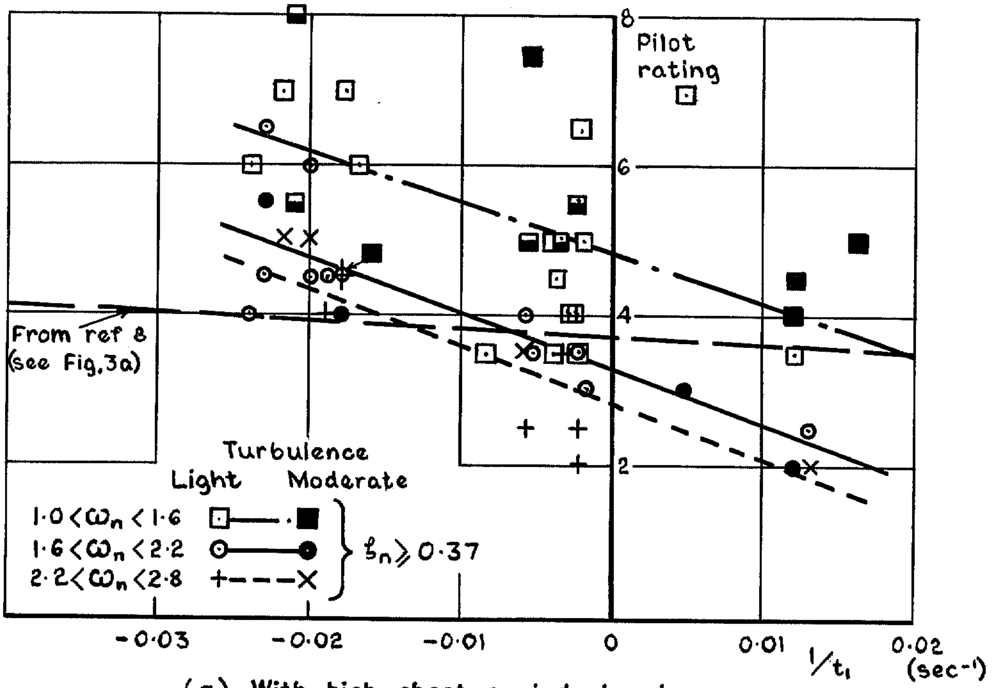
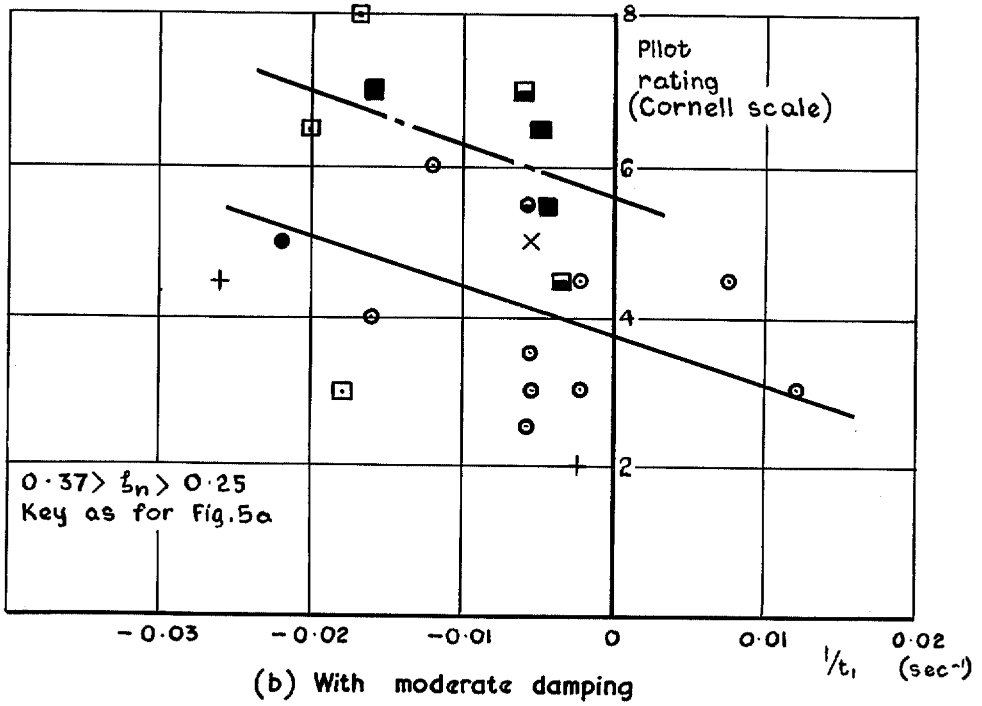


FIG. 4. Variation of pilot rating with speed stability (Ref. 9 & 11).



(a) With high short-period damping



(b) With moderate damping

FIG. 5a & b. Variation of pilot rating with speed stability (data of Ref. 10).

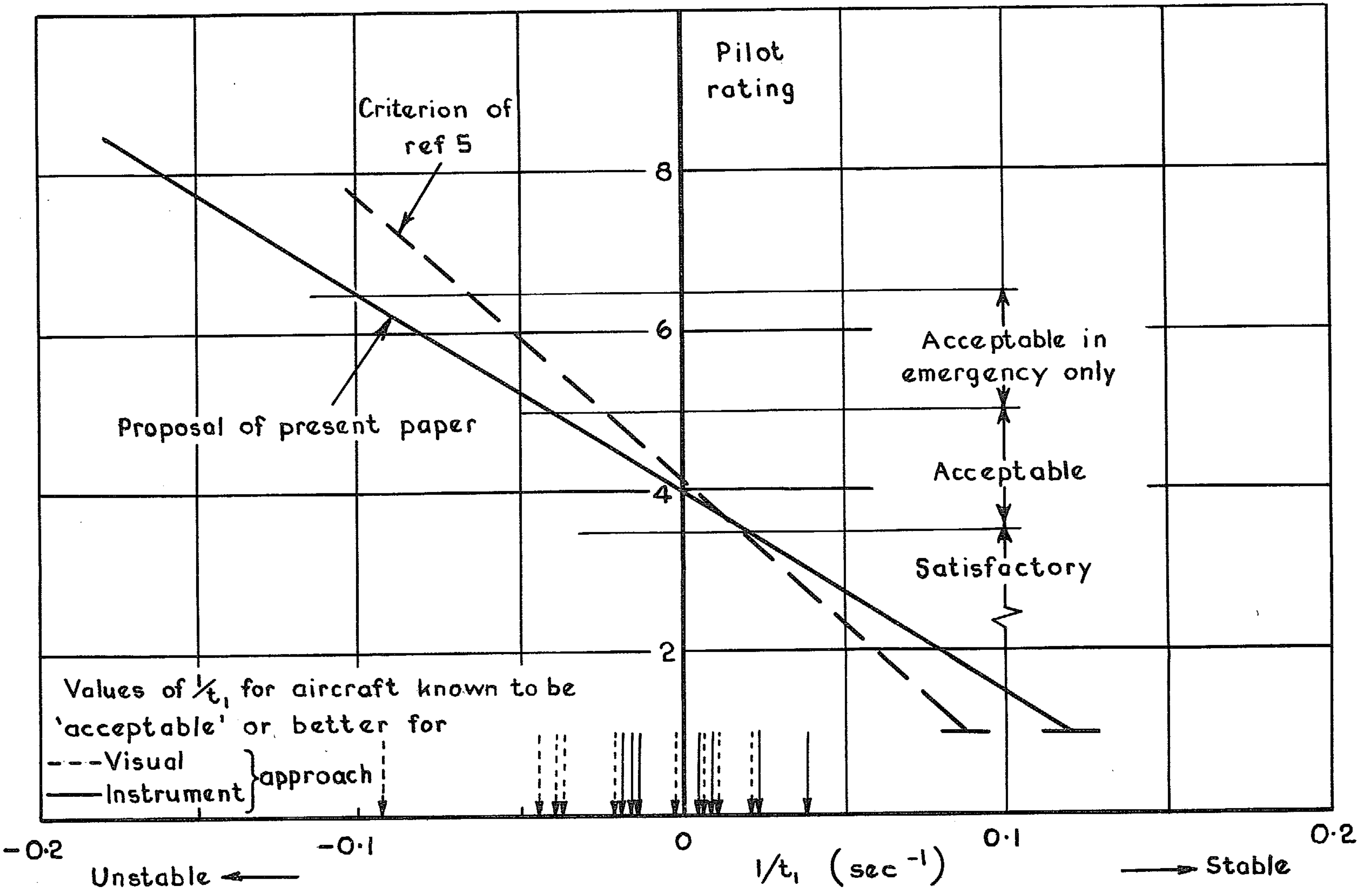


FIG. 6. Proposed speed stability criteria.

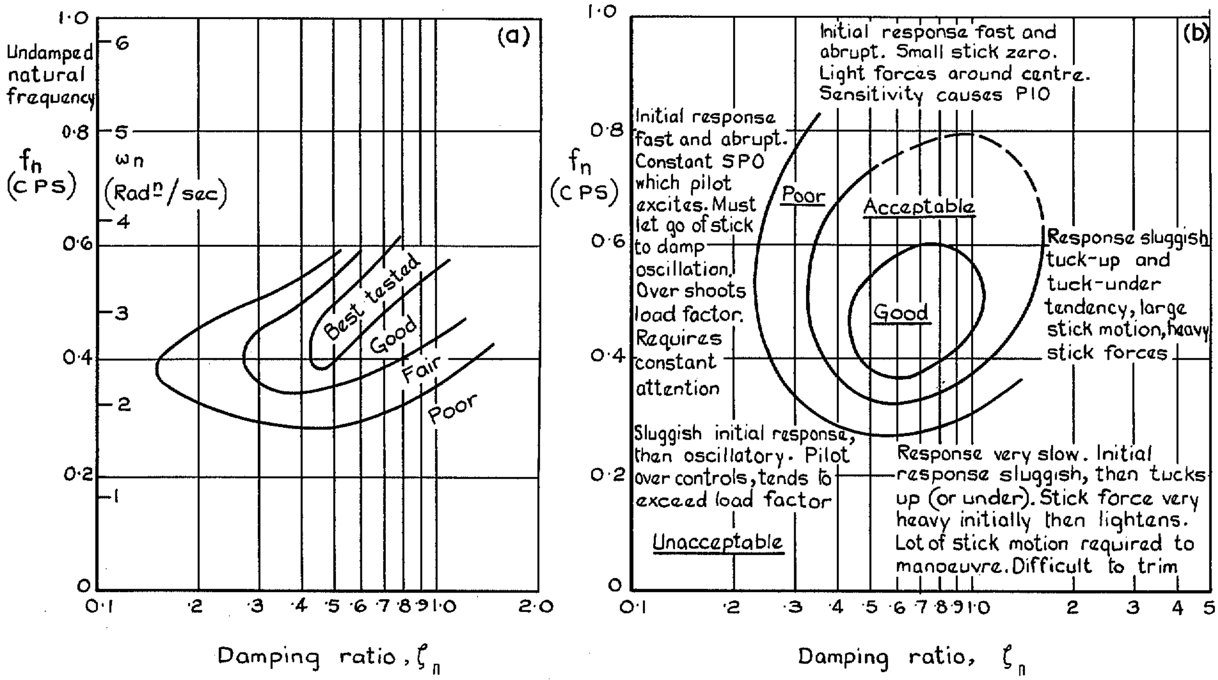


FIG. 7. Longitudinal SPO. Iso-opinion contours.
(a) Variable-stability B–26 (Ref. 12).
(b) Variable-stability F–94 (Ref. 16).

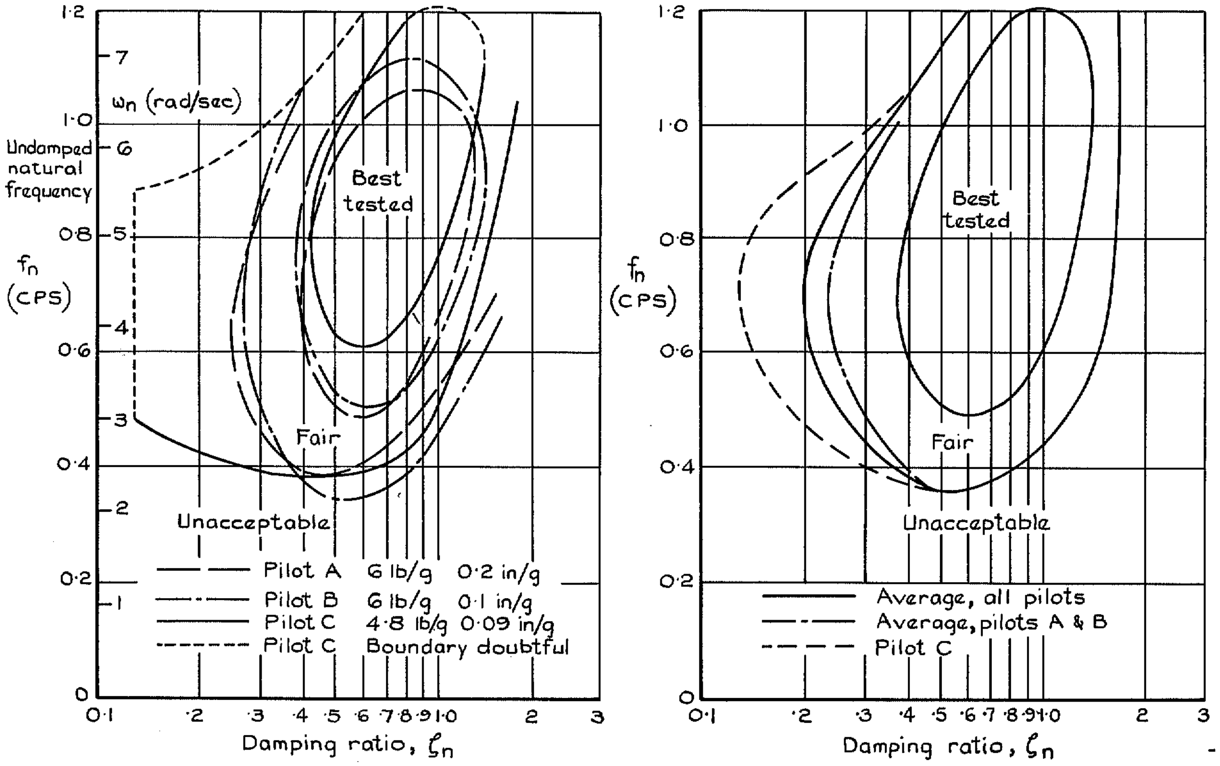


FIG. 8. Longitudinal SPO. Variable-stability F–94 (Ref. 17).

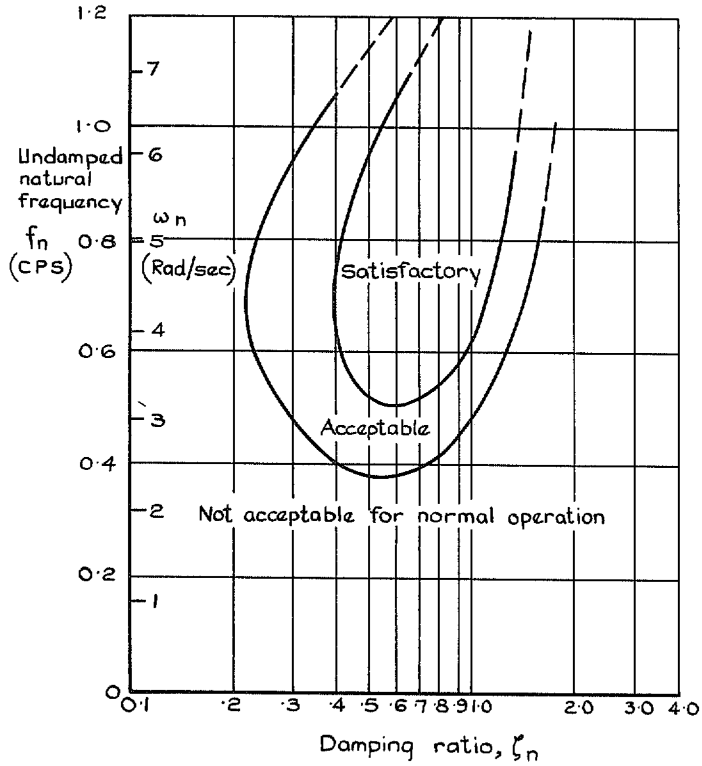
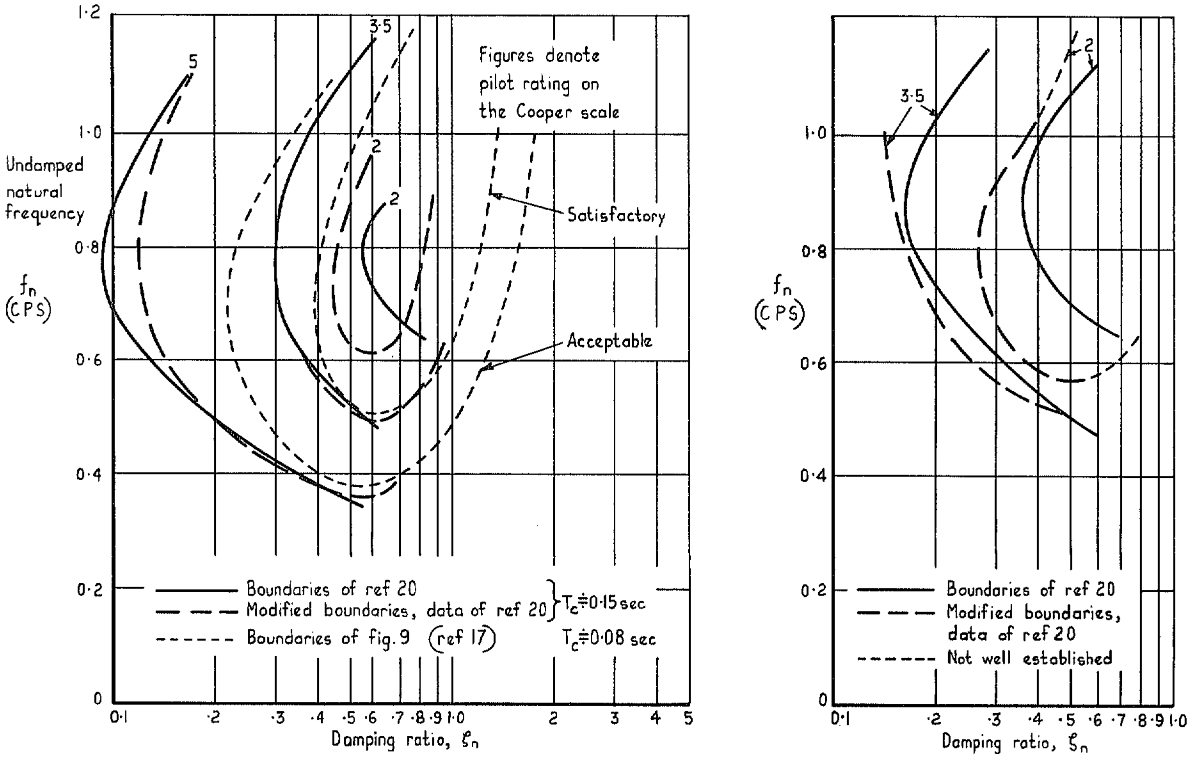


FIG. 9. Longitudinal SPO. Alternative iso-opinion contours based on data of Ref. 17.



(a) With constant T_c

(b) With optimum T_c

FIG. 10a & b. Longitudinal SPO. Iso-opinion contours. Variable-stability F–86 (Ref. 20).

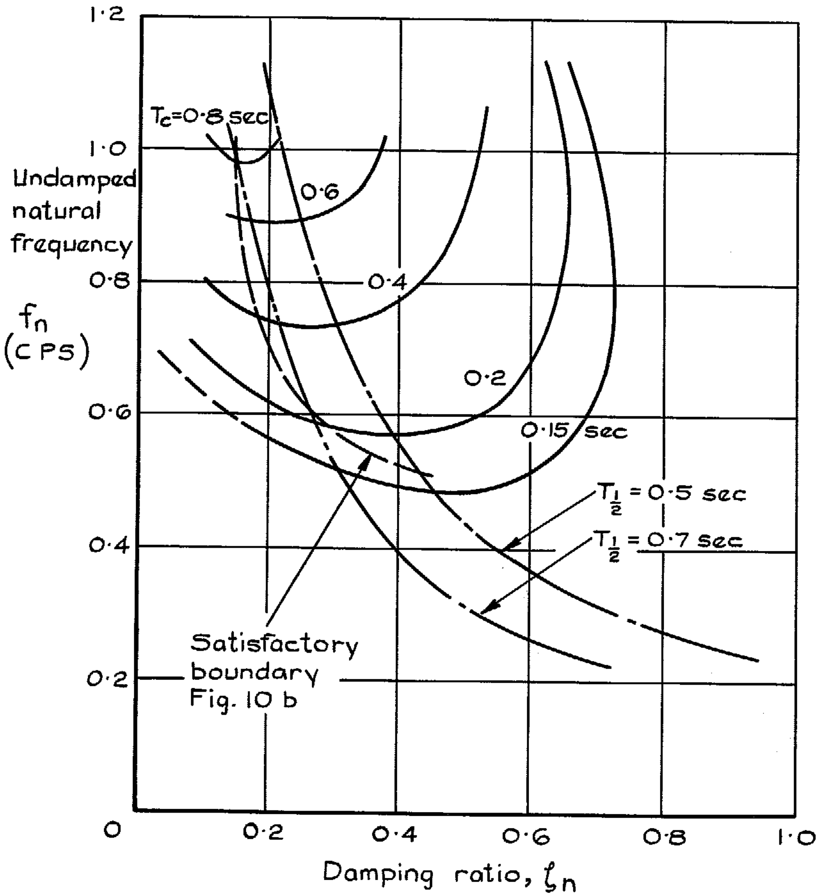


FIG. 11. Control system time constants selected as optimum. Variable-stability F–86 (Ref. 20).

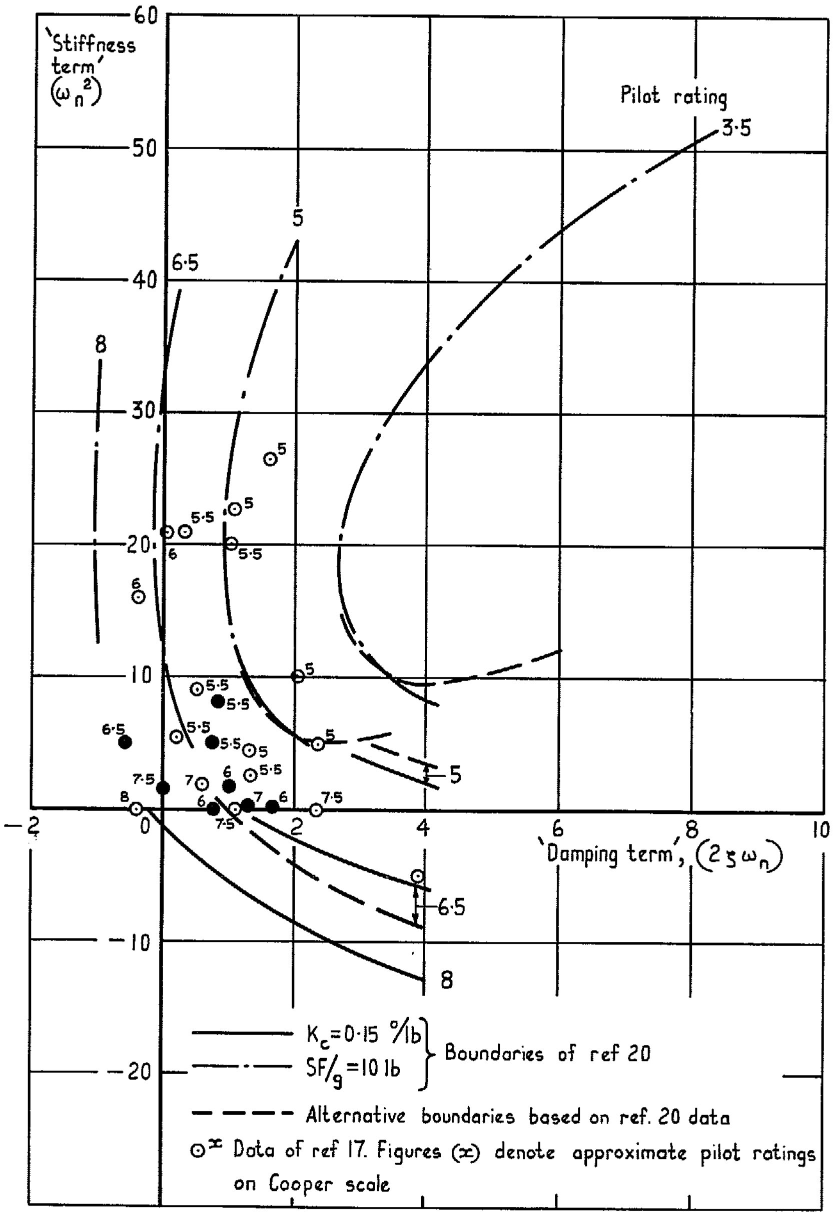


FIG. 12. Longitudinal SPO. Iso-opinion contours of Ref. 20 and data of Ref. 17.

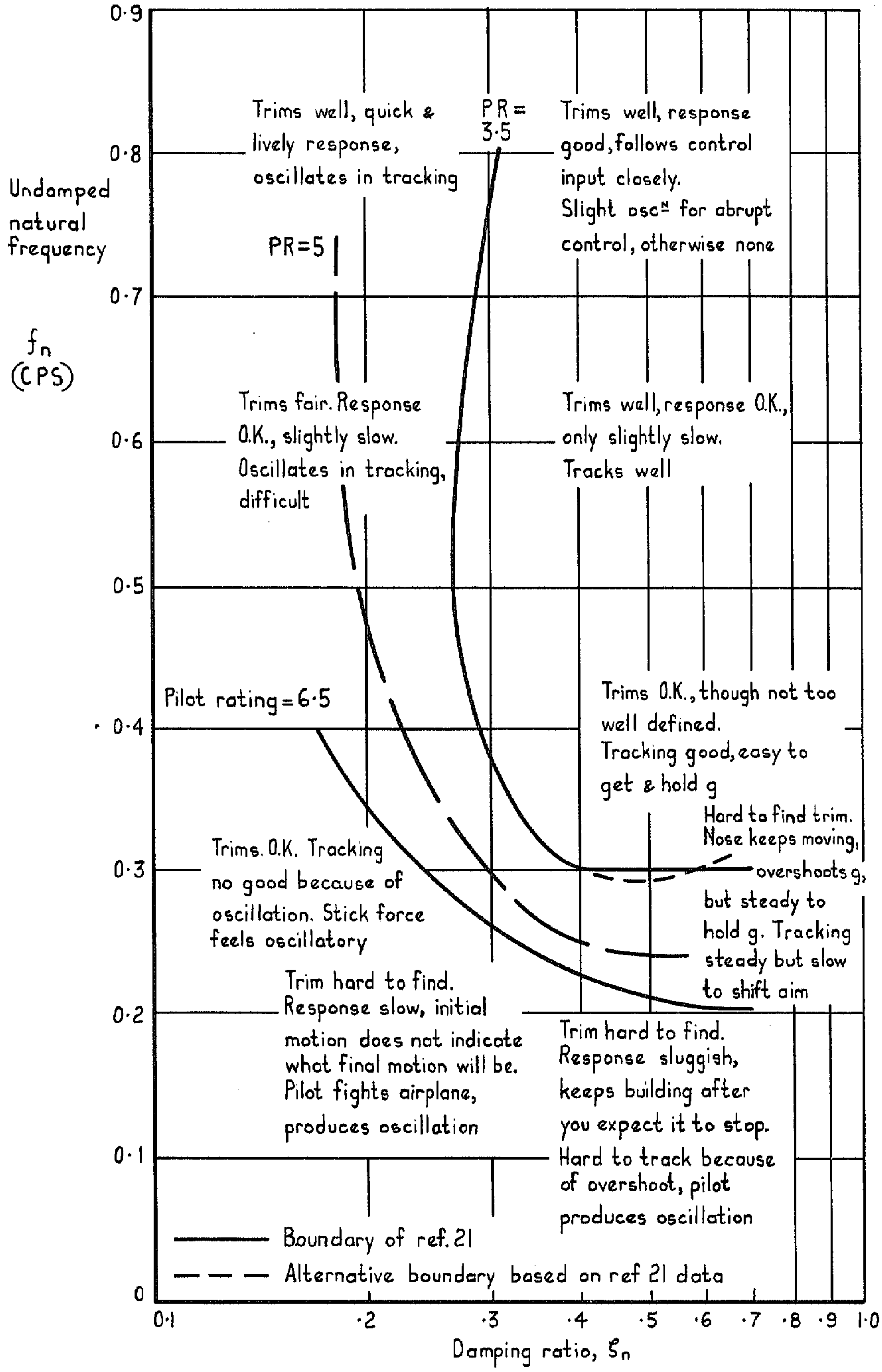
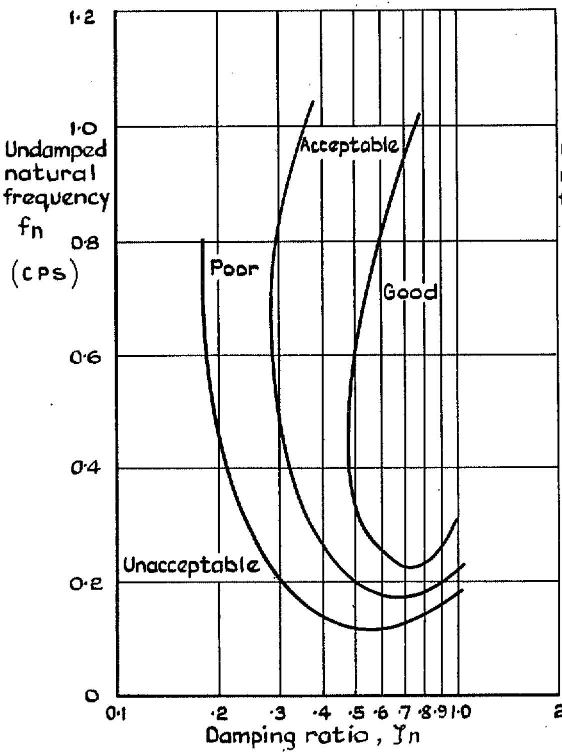
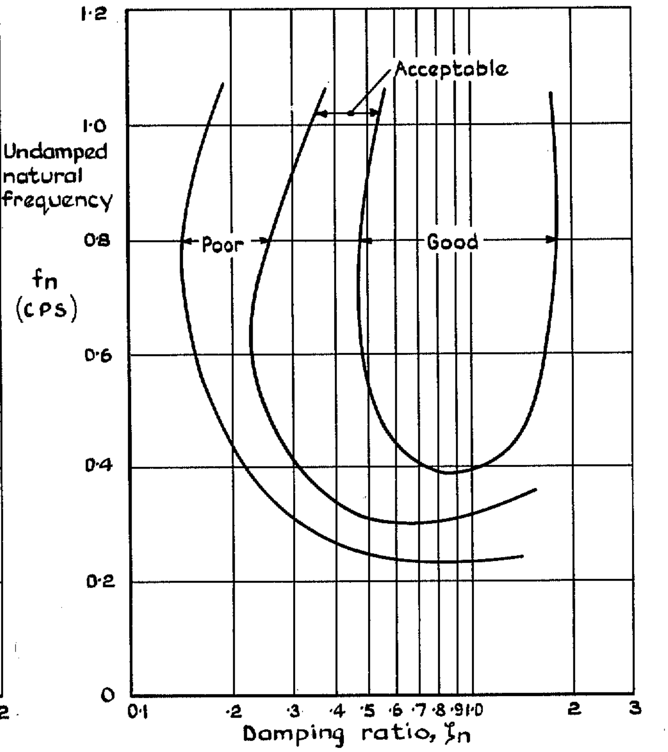


FIG. 13. Longitudinal SPO. Iso-opinion contours. Variable-stability B–26 (Ref. 21).

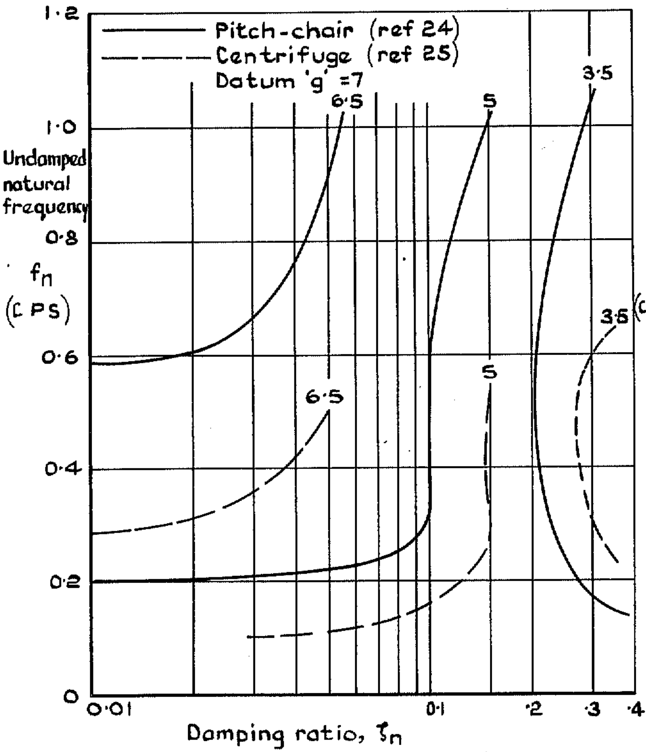


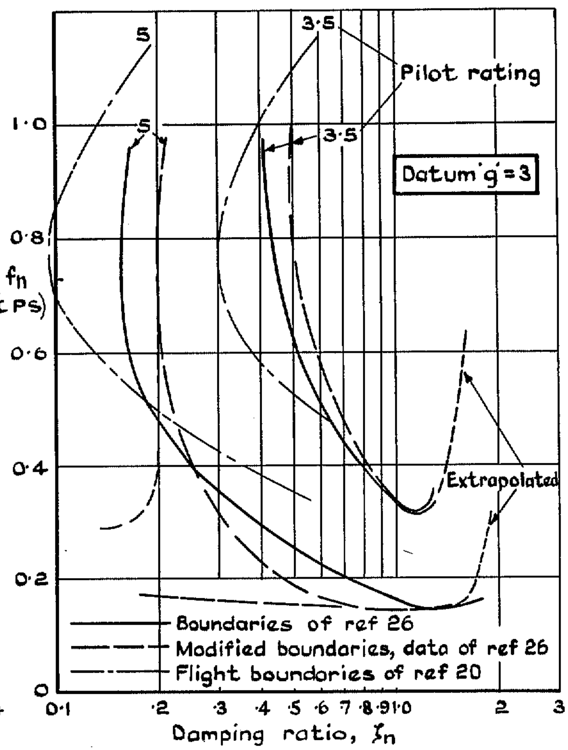


Longitudinal SPO. Iso-opinion contours.

FIG. 14. Fixed-base simulator (Ref. 22).

FIG. 15. Simulator (Ref. 23).





Longitudinal SPO. Iso-opinion contours.

FIG. 16. Pitch-chair (Ref. 24) and centrifuge (Ref. 25).

FIG. 17. Centrifuge tests (Ref. 26).

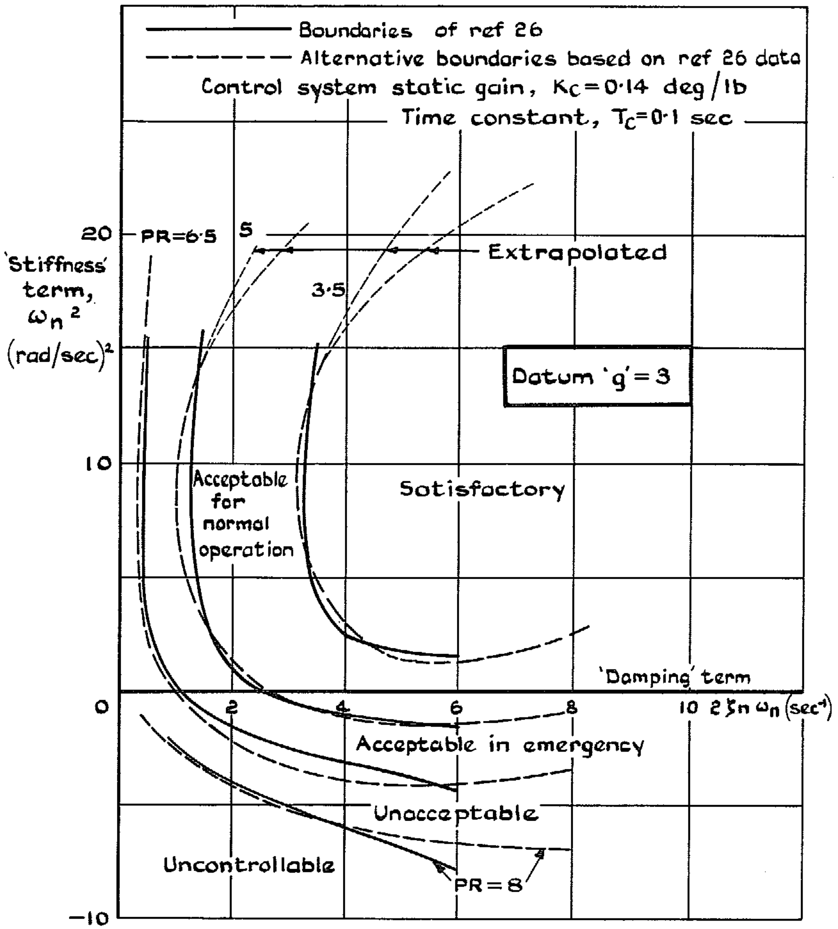


FIG. 18. Longitudinal SPO.
Evaluation of unstable dynamics in centrifuge
(Ref. 26).

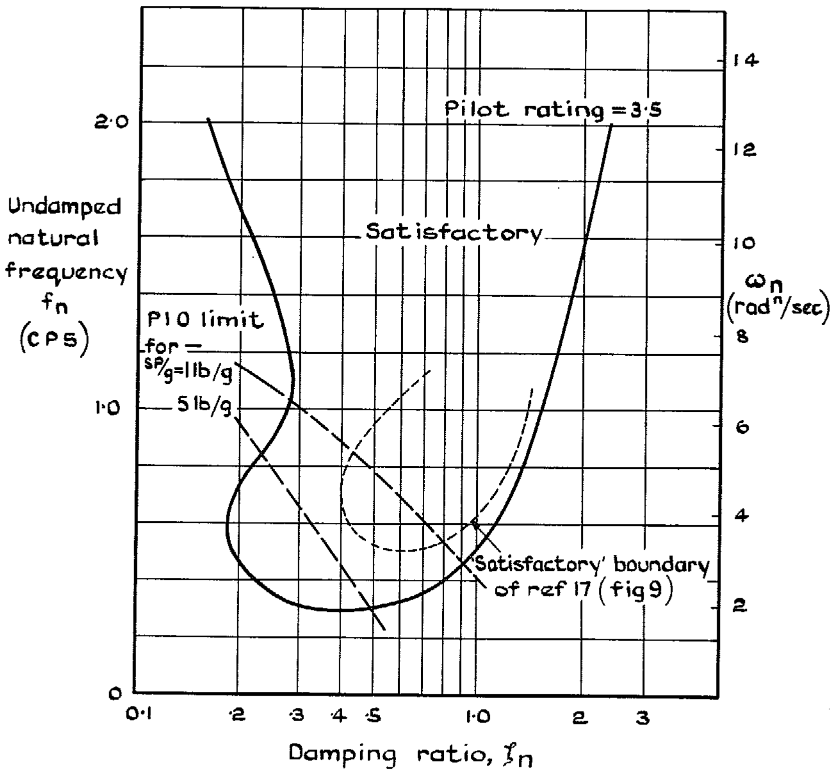


FIG. 19. Longitudinal SPO.
Iso-opinion contours in 'G-seat' tests (Ref. 27).

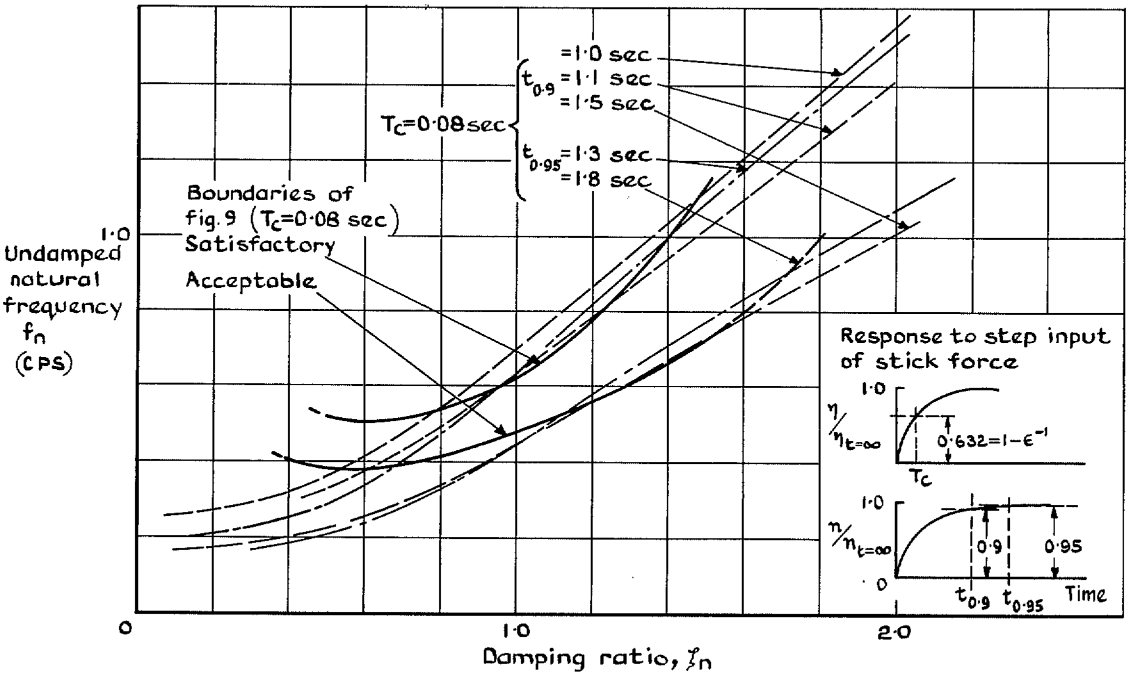


FIG. 20. Criteria based on response to step input compared with boundaries of Ref. 17.

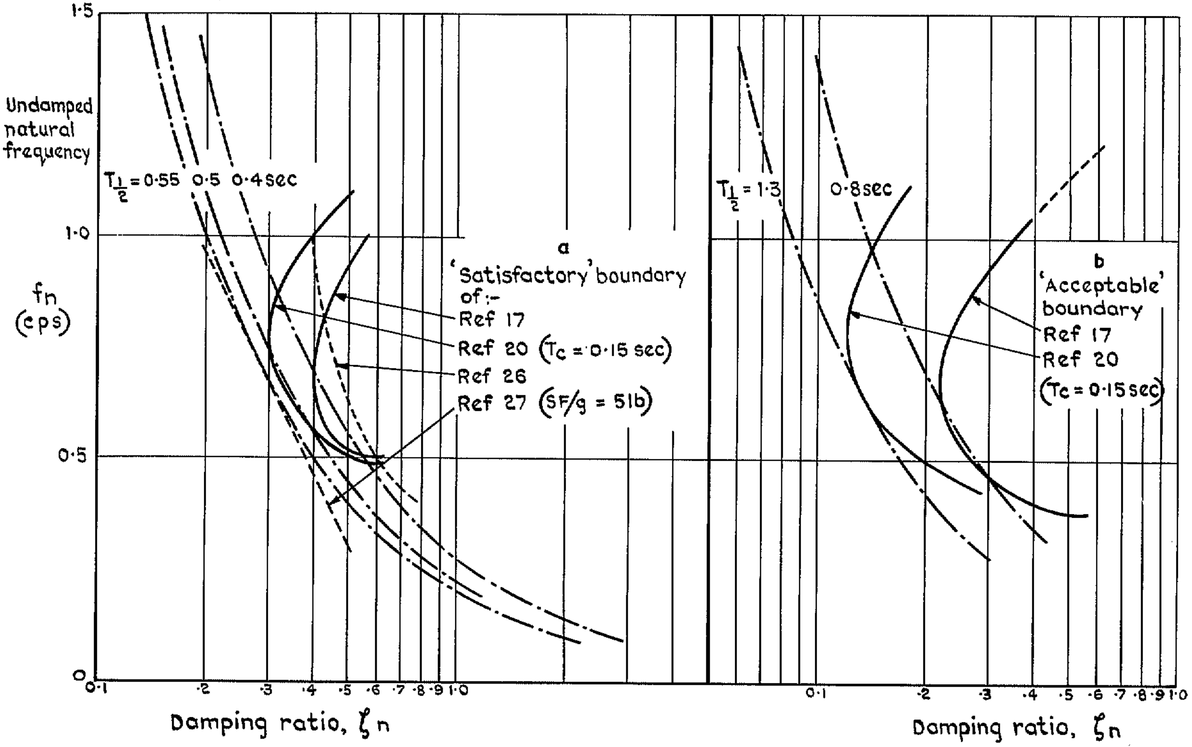
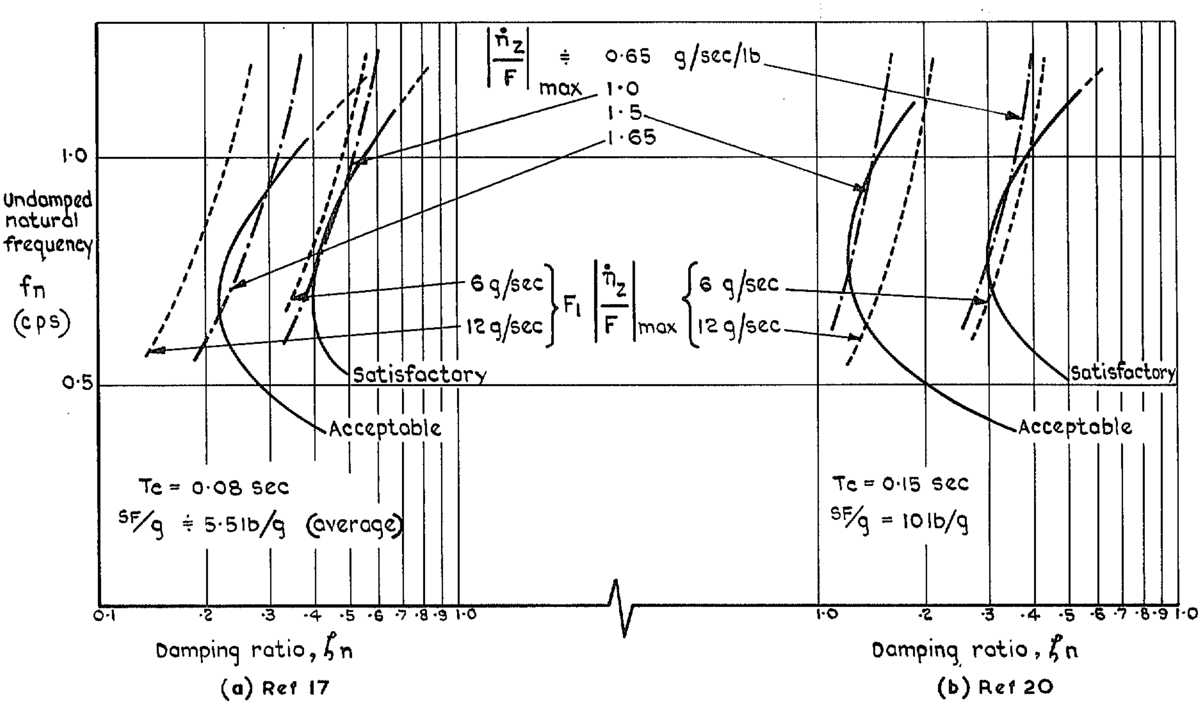


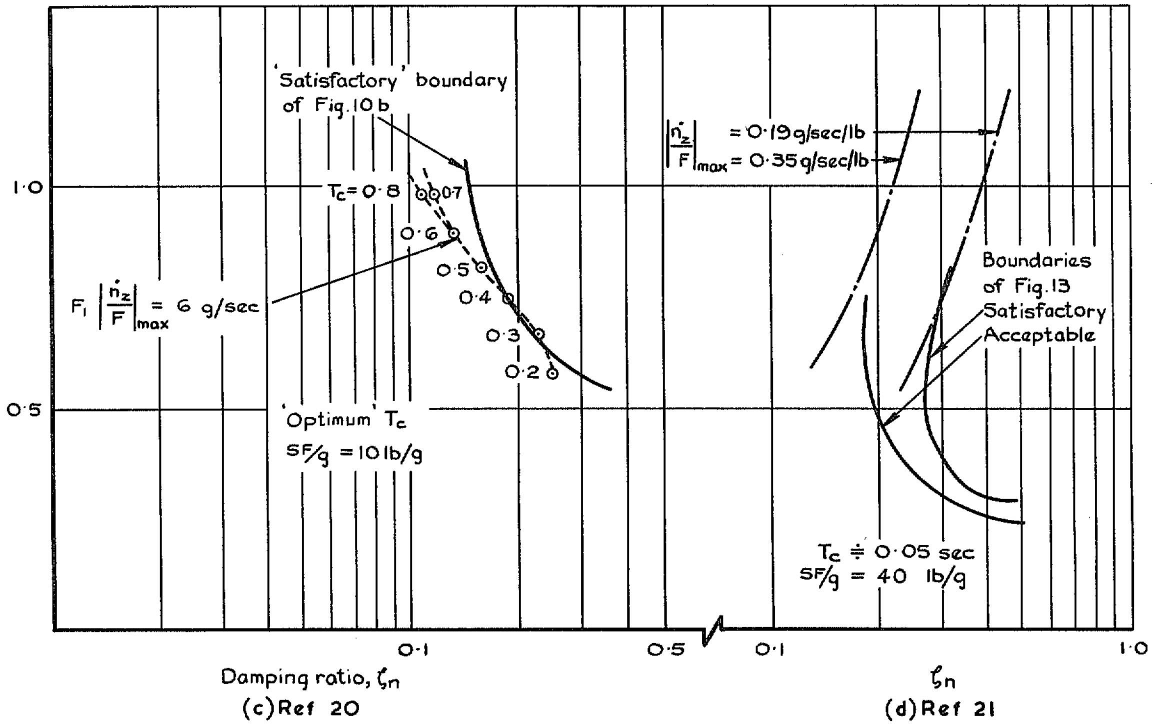
FIG. 21a & b. Comparison of experimental boundaries with lines of constant total damping.



(a) Ref 17

(b) Ref 20

FIG. 22a & b. Comparison of criteria of 'abruptness' with flight test data of (a) Ref. 17, and (b) Ref. 20.



(c) Ref 20

(d) Ref 21

FIG. 22c & d. Comparison of criteria of 'abruptness' with flight test data of (c) Ref. 20, and (d) Ref. 21.

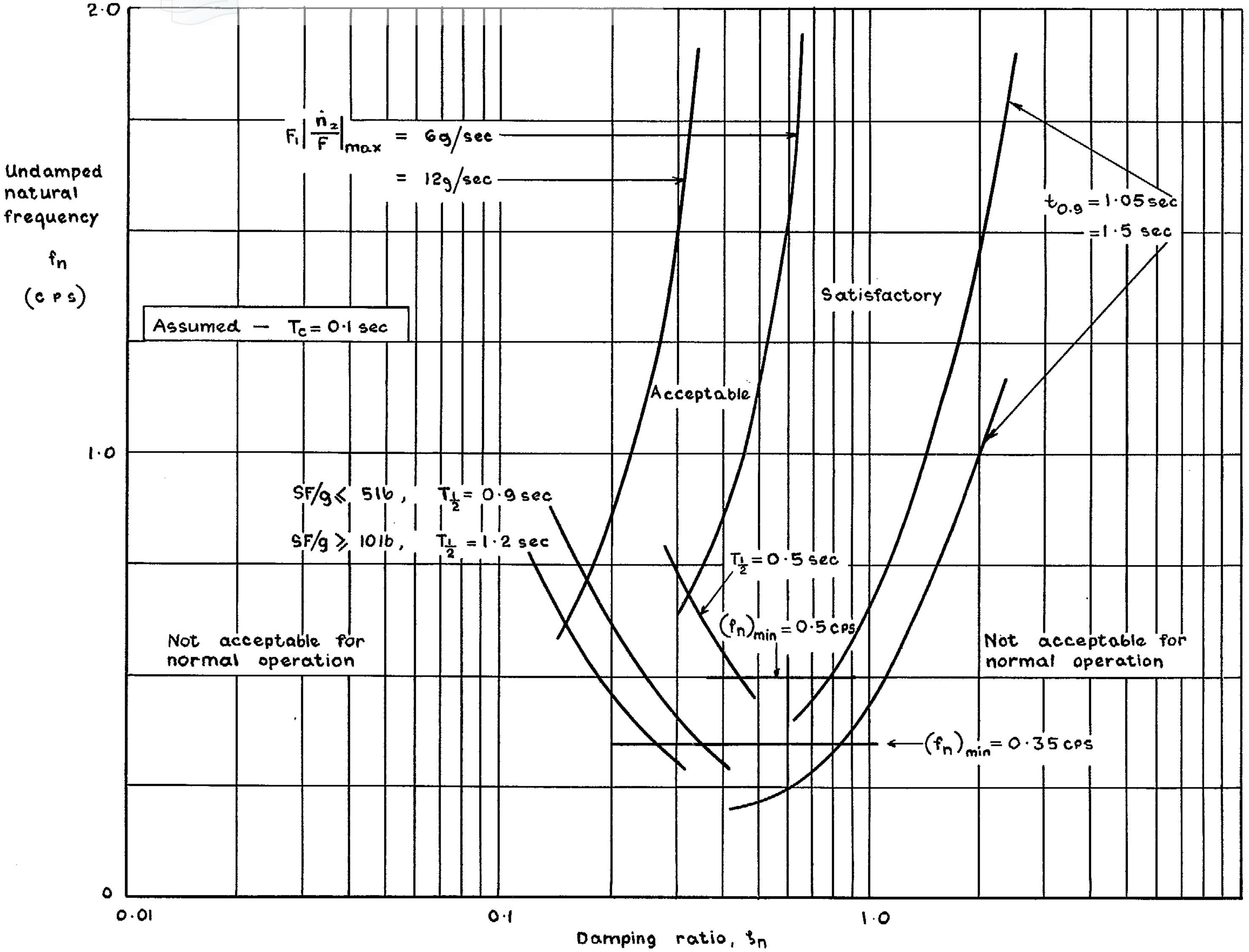


FIG. 23. Short-period criteria proposed for fighter-type aircraft.

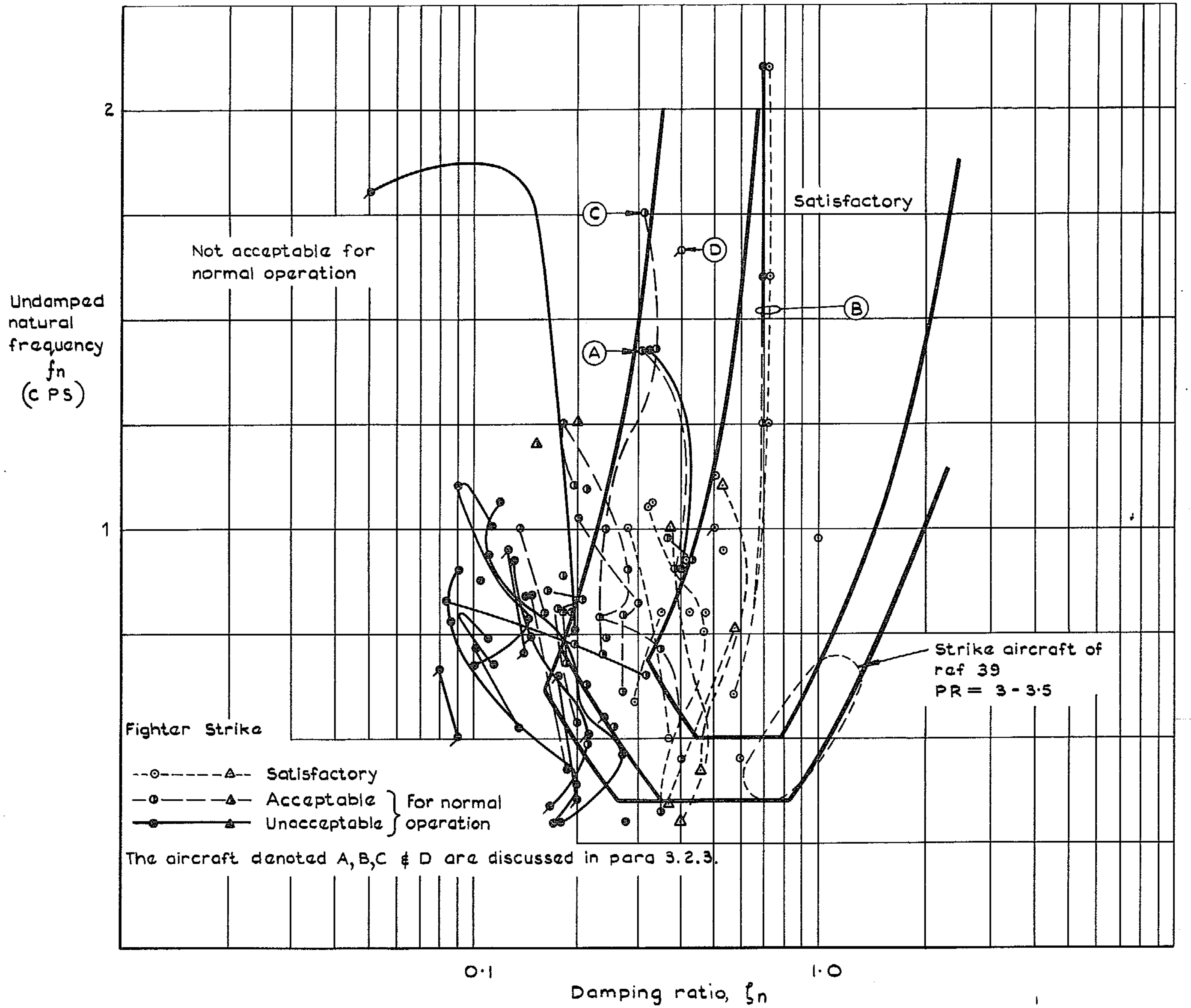
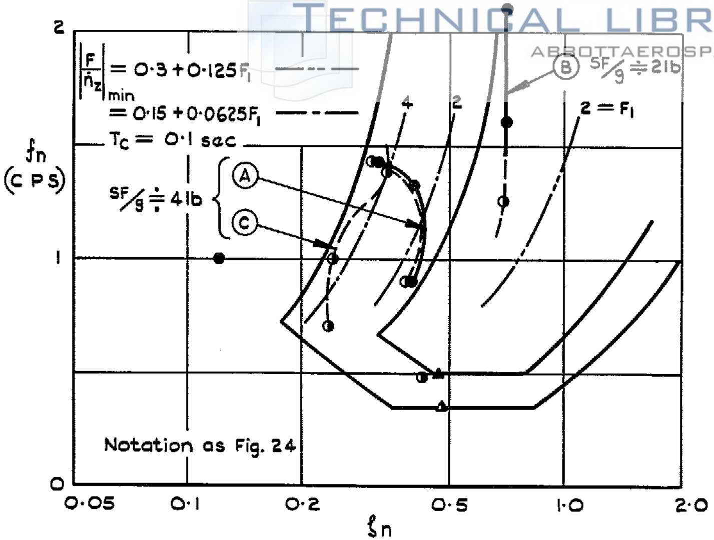
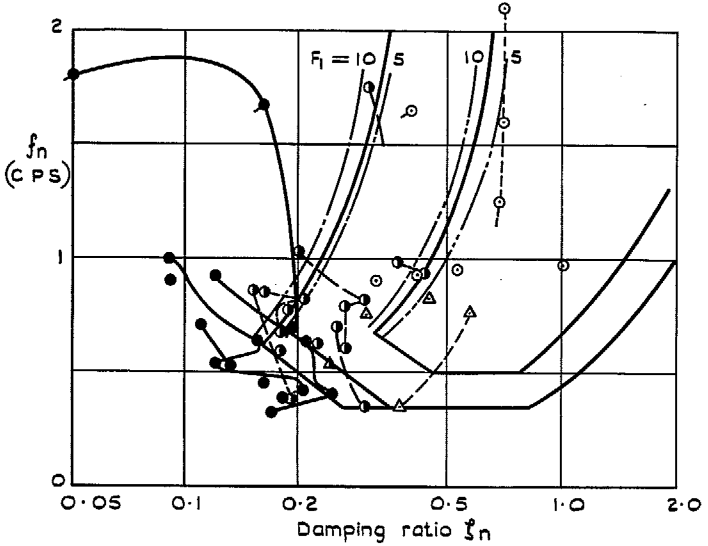


FIG. 24. Comparison of proposed short-period criteria for fighter-type aircraft with flight-test results.

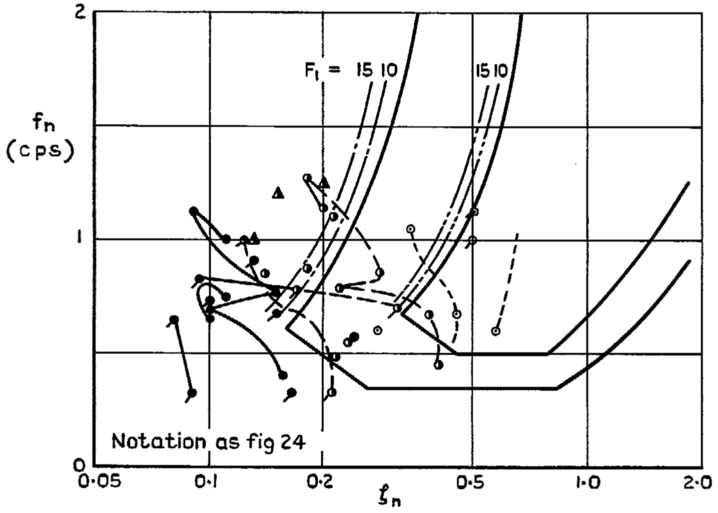


(a) SF/g < 5 lb

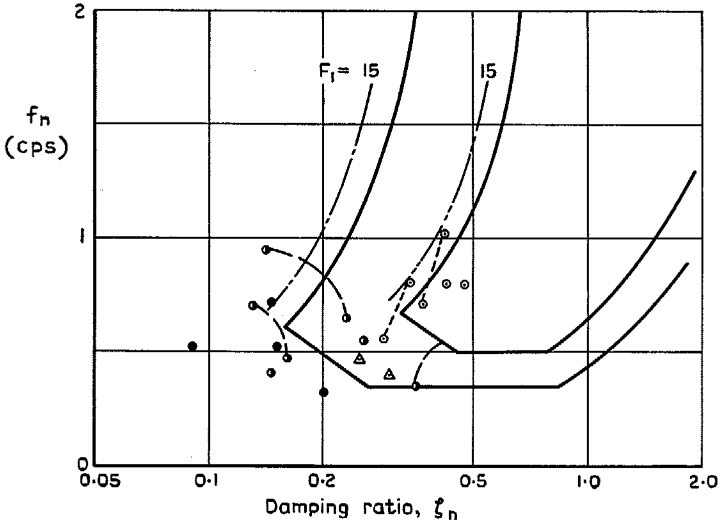


(b) 5 < SF/g < 10 lb

FIG. 25a & b. Comparison of short-period criteria with flight-test results for fighter-type aircraft.



(c) 10 < SF/g < 15 lb



(d) SF/g > 15 lb

FIG. 25c & d. Comparison of short-period criteria with flight-test results for fighter-type aircraft.

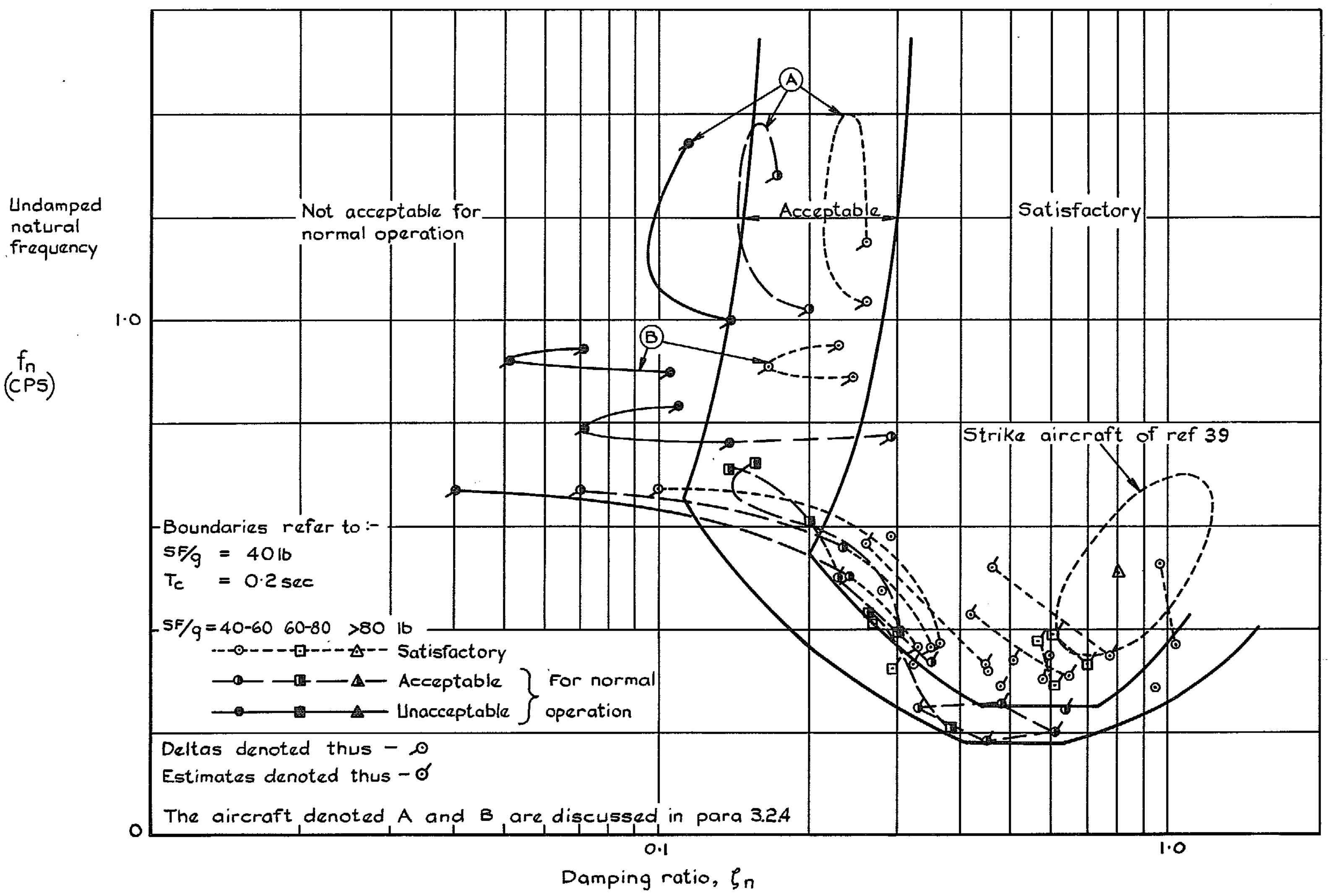


FIG. 26. Comparison of proposed short-period criteria for large aircraft with flight-test results.

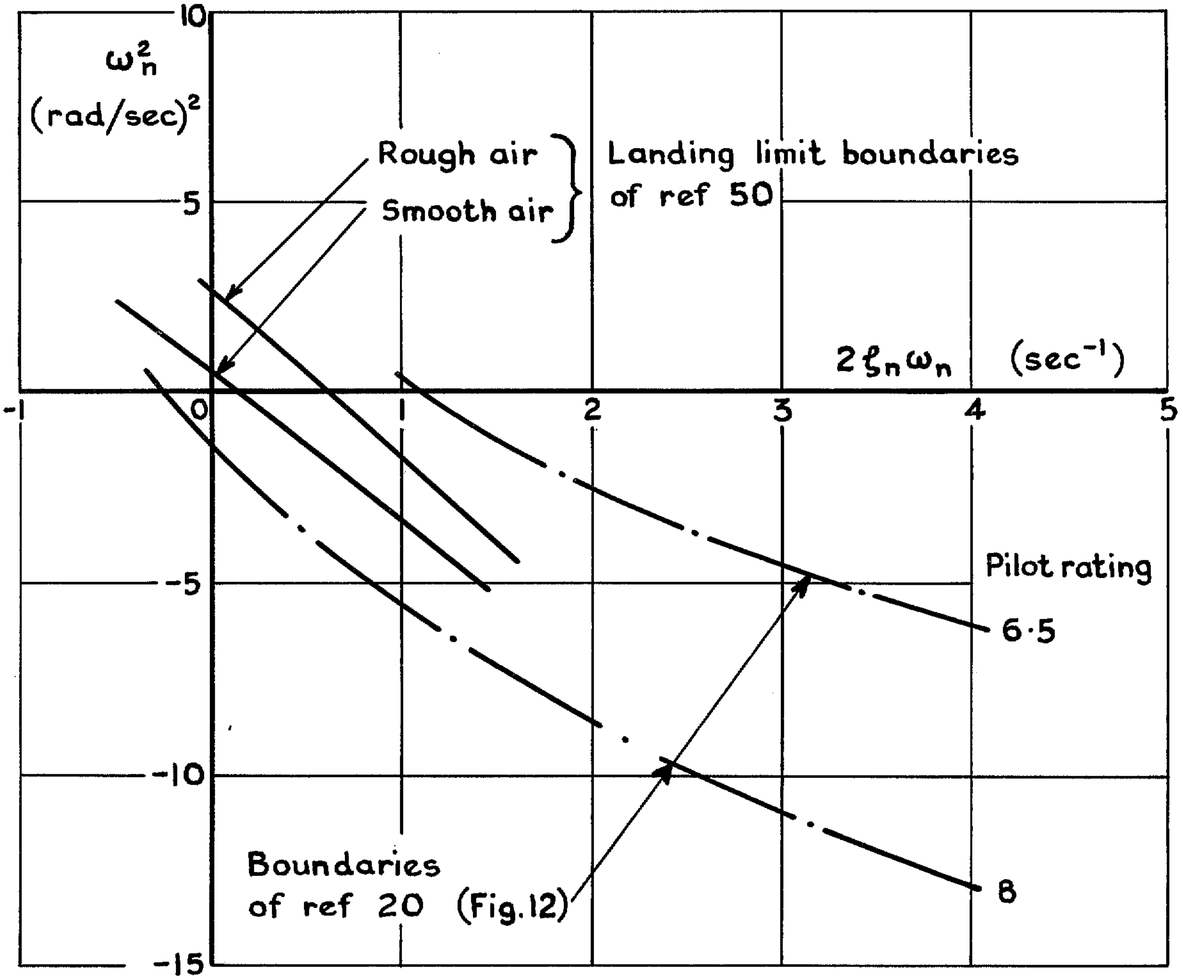


FIG. 27. Comparison of 'landing limit' boundaries of Ref. 50 with iso-opinion contours of Ref. 20.

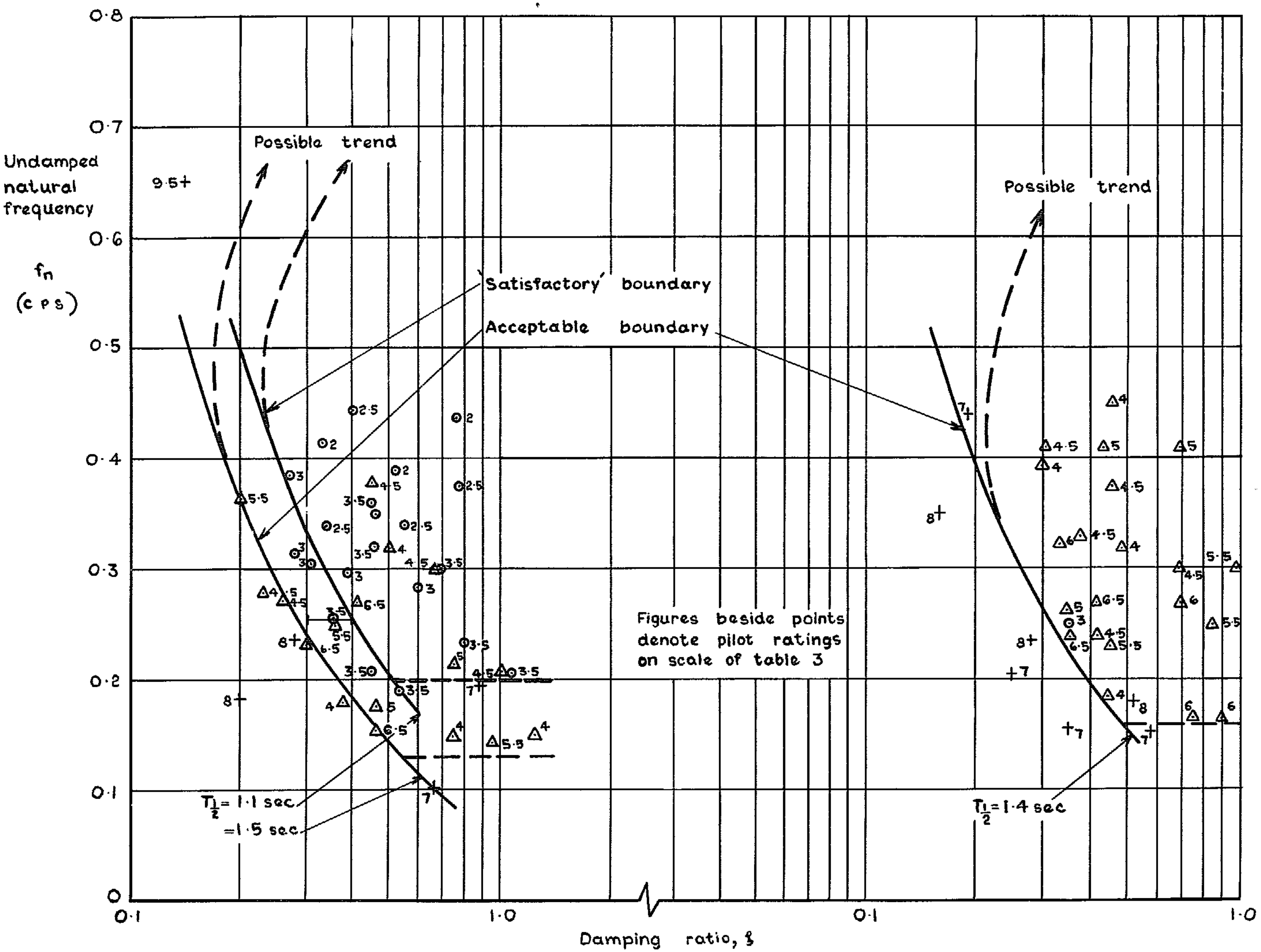


FIG. 28a & b. Longitudinal SPO on the approach. Variable-stability T–33. Data of Ref. 10.

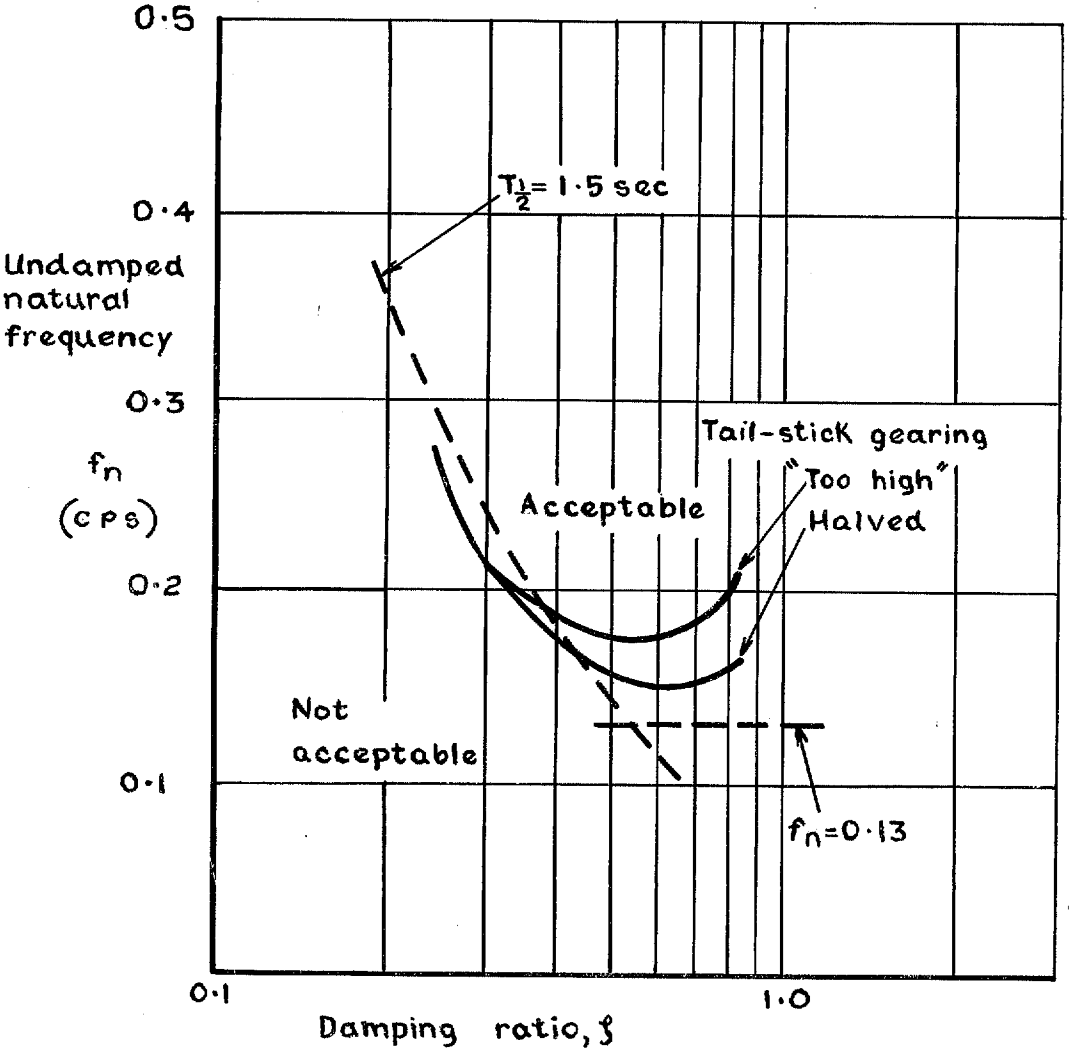


FIG. 29. Longitudinal SPO on the approach. Fixed-base simulator tests of Ref. 51.

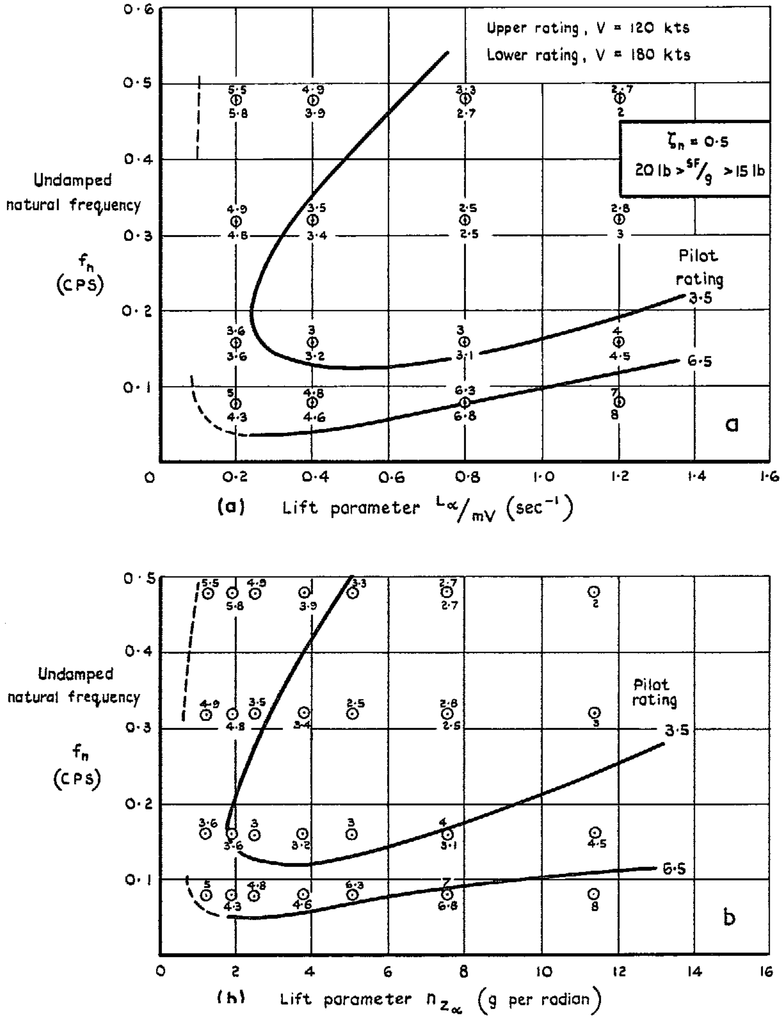


FIG. 30. Longitudinal SPO on the approach. Fixed-base simulator tests of Ref. 52. Iso-opinion contours as functions of (a) f_n and L_α/mV; (b) f_n and n_{z_α}.

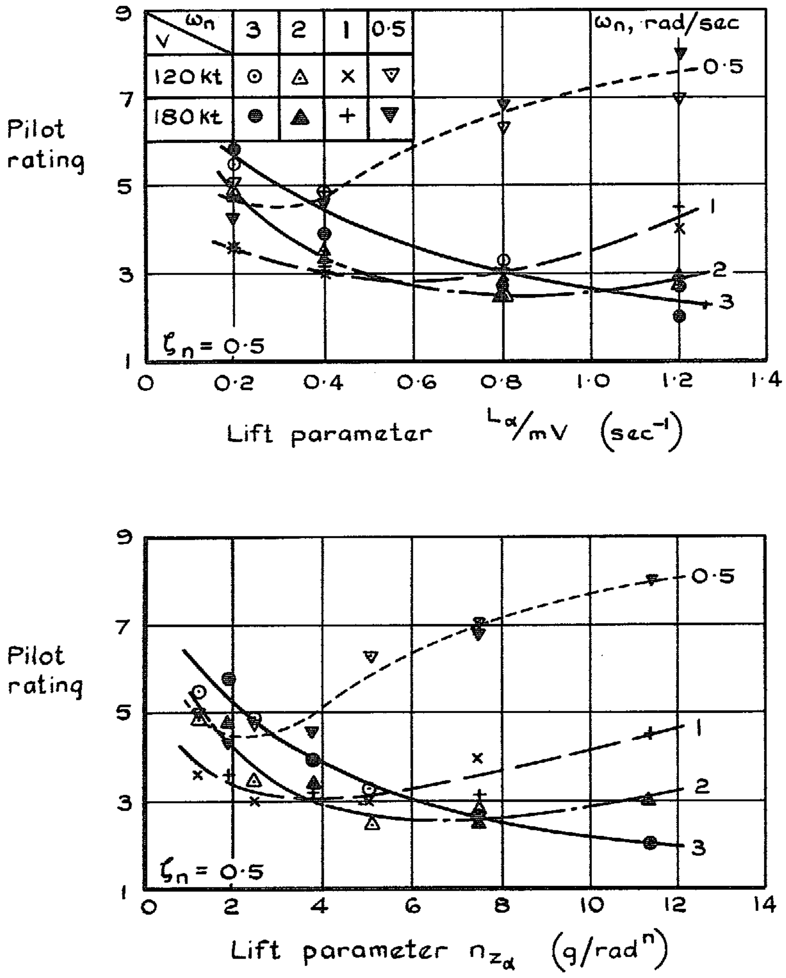


FIG. 31. Variation of pilot rating with lift parameter at various constant frequencies (data of Ref. 52).

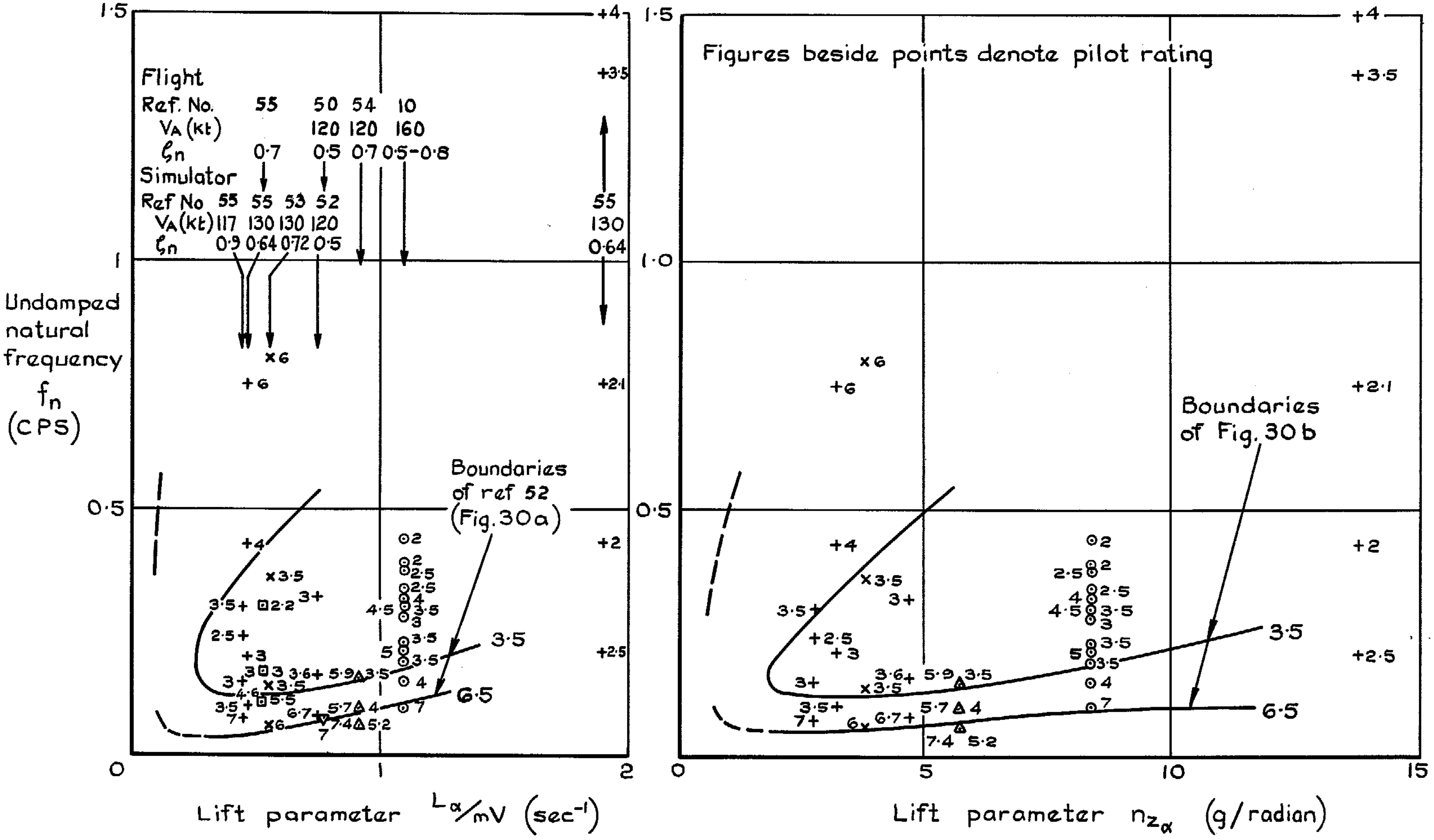


FIG. 32. Iso-opinion contours of Ref. 52 compared with data from other systematic tests (Refs. 10, 53, 54 & 55).

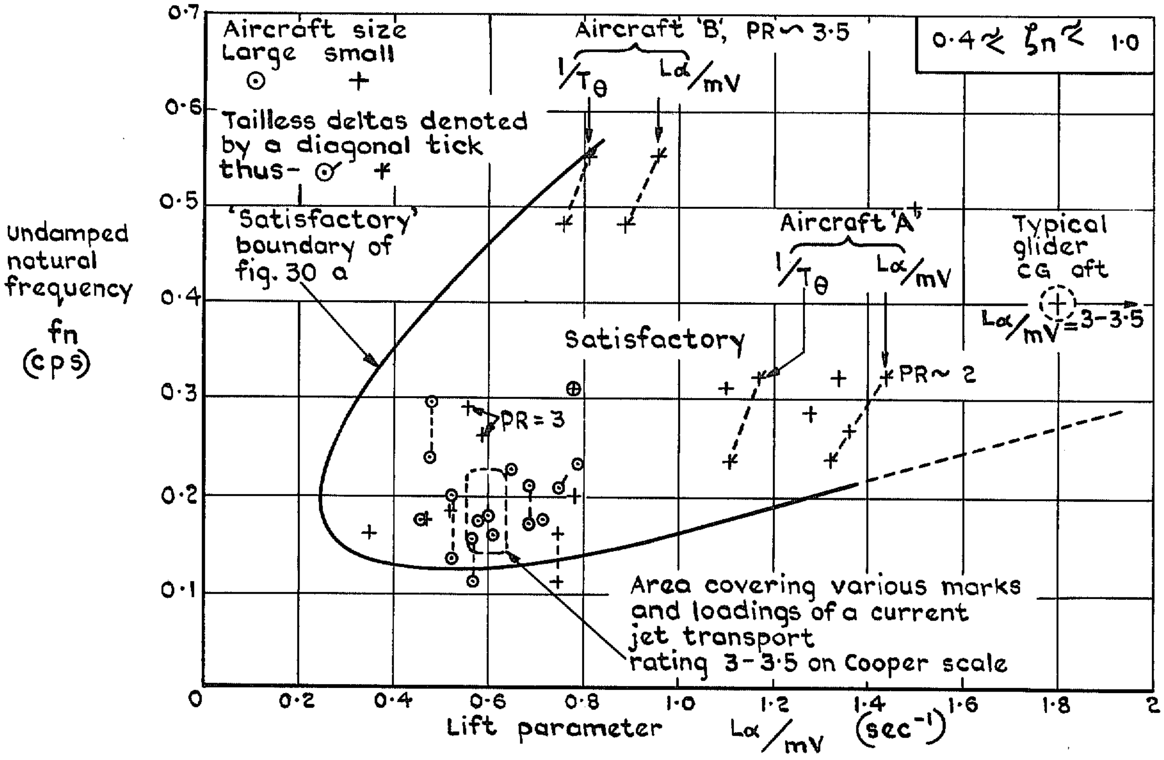


FIG. 33. Characteristics of current aircraft compared with the criterion of Fig. 30a.

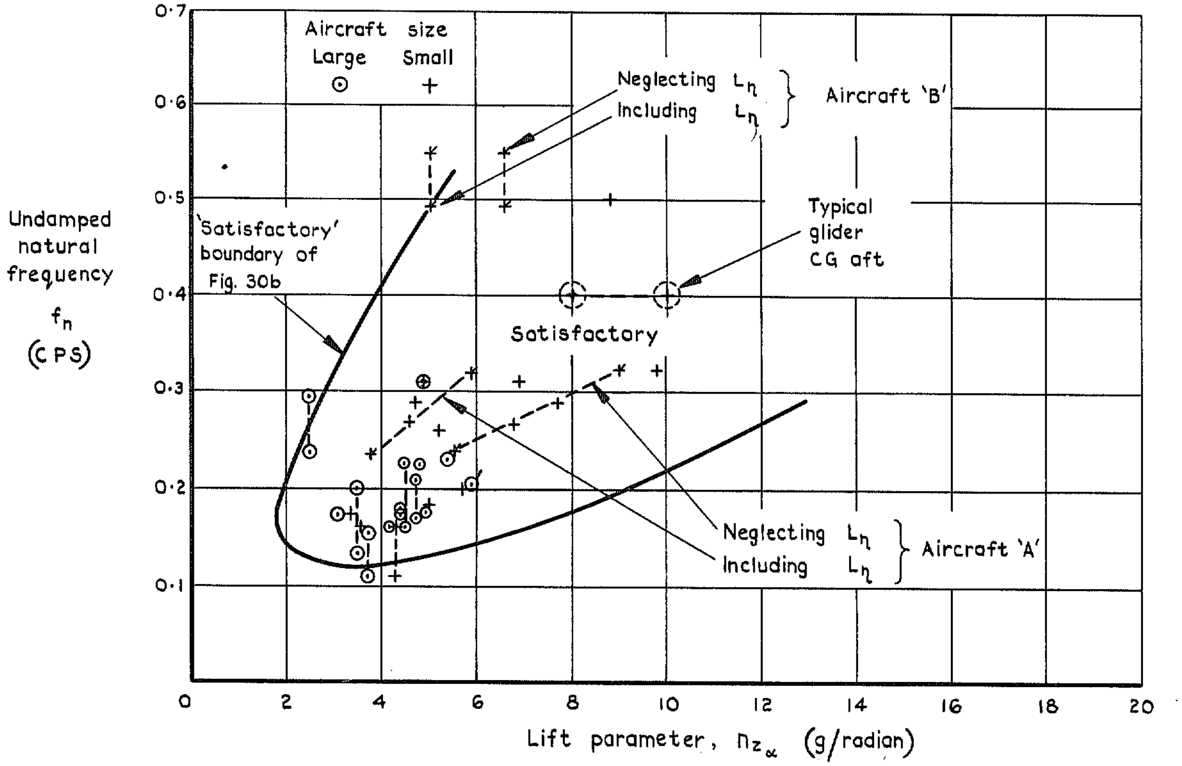


FIG. 34. Characteristics of current aircraft compared with the criterion of Fig. 30b.

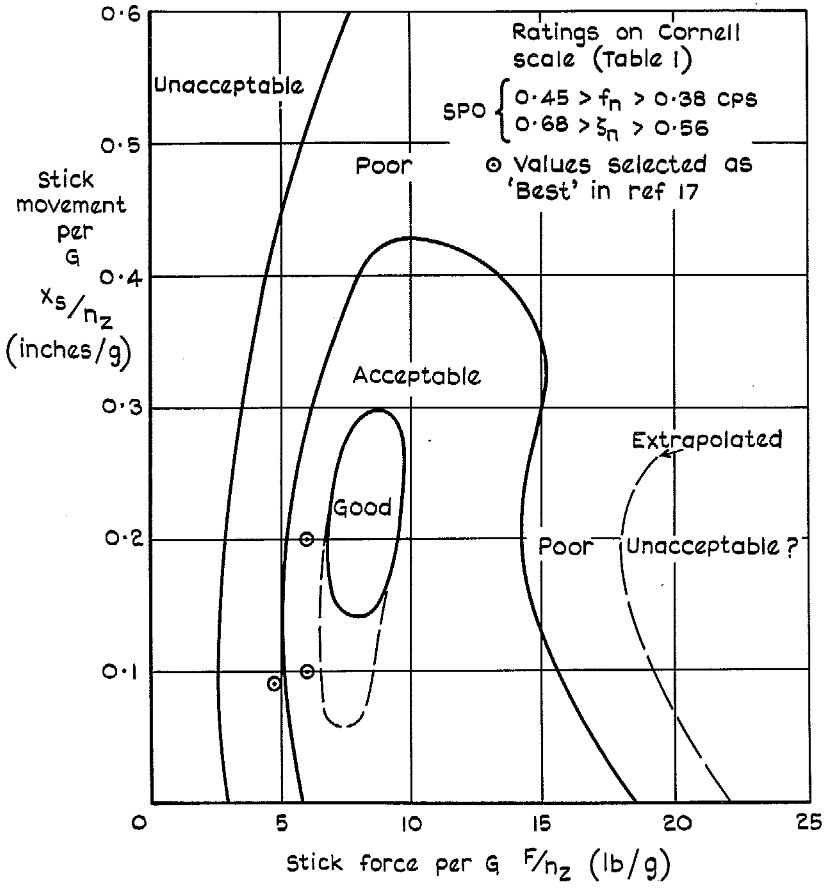


FIG. 35. Effect of stick-force and stick movement on pilot rating. Fighter-type aircraft (Ref. 16).

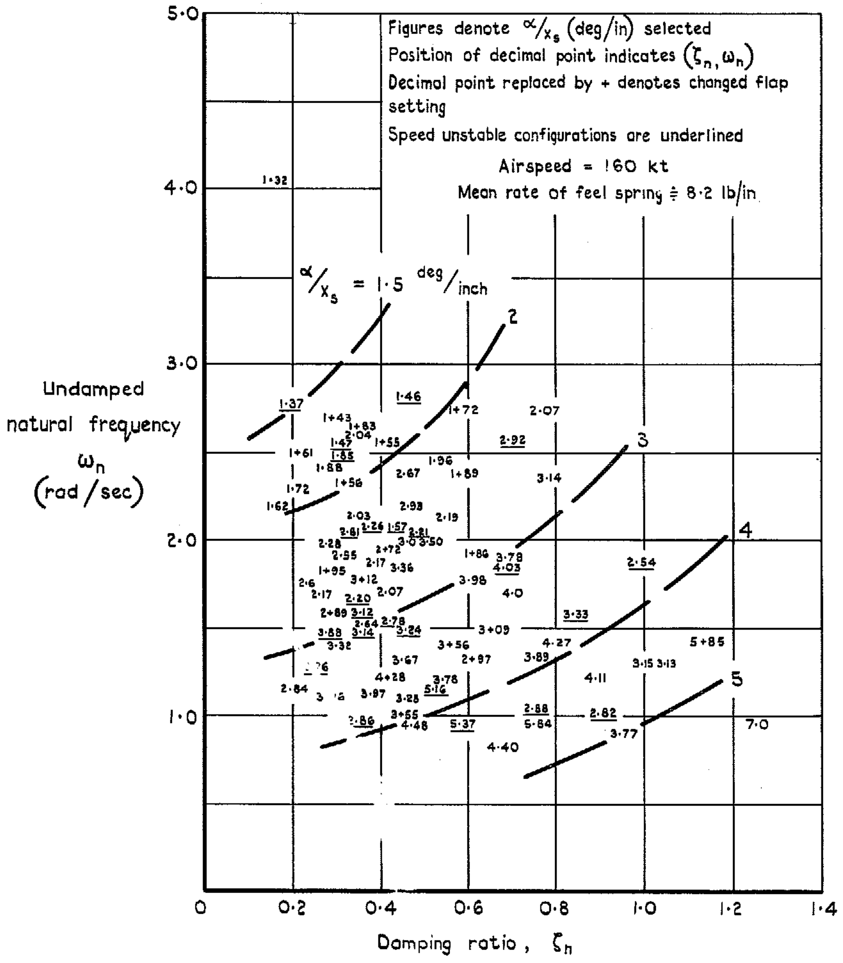


FIG. 36. Control gearings selected on the approach (Ref. 10).

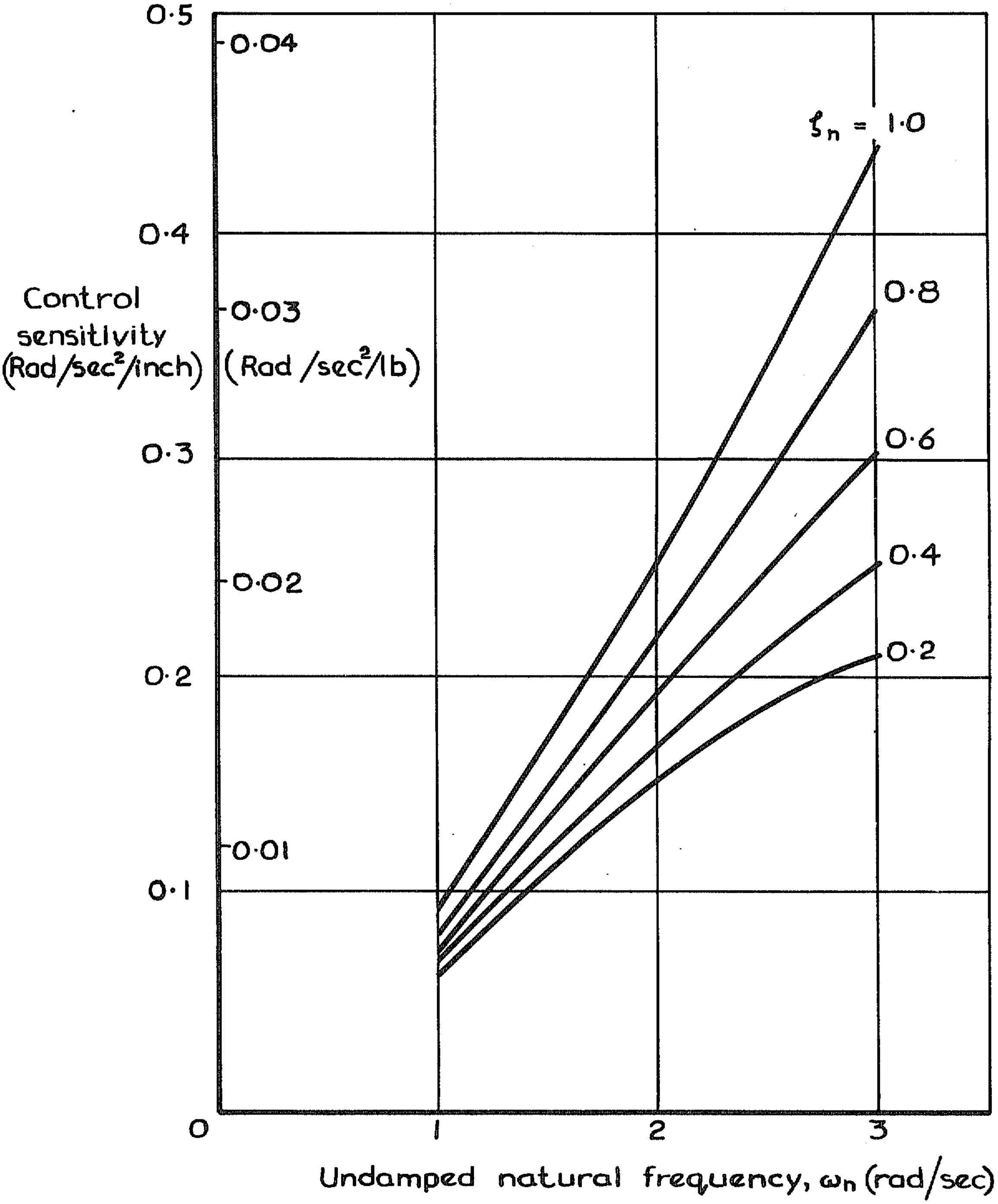


FIG. 37. Control sensitivity selected on the approach (Ref. 10).

Printed in Wales for Her Majesty's Stationery Office by Allens Printers (Wales) Limited
Dd.146916 K5.

R. & M. No. 3

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London WC1
13a Castle Street, Edinburgh EH2 3AR
109 St Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
50 Fairfax Street, Bristol BS1 3DE
258 Broad Street, Birmingham 1
7 Linenhall Street, Belfast BT2 8AY
or through any bookseller

R. & M. No. 3

SBN 11 47024