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A Survey of Aircraft Handling Criteria

By

C. Leyman and E. R. Nuttall

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A SURVEY OF AIRCRAFT HANDLING CRITERIA

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C. Leyman and E. R. Nuttall
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SUMMARY

This note discusses the requirements for satisfactory and minimum acceptable handling qualities of aircraft. Published criteria based on various sources, e.g. variable stability aircraft and flight simulators, are compared and some present day aircraft examined in the light of the criteria. It is shown that some modification of the published criteria is necessary when large aircraft are considered, and that the criteria must in any case be used with due regard to the flight condition and aircraft role under consideration.

Part I gives some background information on handling research and discusses pilot opinion rating scales. Parts II and III contain detailed surveys of longitudinal and lateral handling criteria respectively. Part IV discusses a theory of handling qualities based on a servo-analytical approach and Part V presents some broad conclusions.

The Appendix gives a summary of the contents of the more important published works on handling qualities.

PART I

SOME GENERAL NOTES

1.1 Background

The accepted techniques of assuring satisfactory, or at least acceptable handling qualities is to specify numerical values of certain fundamental aerodynamic parameters, e.g. the static margin. While this approach is still valid for 'conventional' aircraft, the advent of novel configurations for high speed flight has led to a continuing deterioration of flying qualities. This, coupled with the poor handling qualities of certain present day aircraft and the needs of military aviation led the American Aeronautical Research Agencies to investigate in detail the problems of aircraft handling.

A common and useful method of presenting the result of handling investigations is a set of contours of constant pilot opinion (isopinion lines) plotted as functions of parameters describing the particular quality under investigation. An example of this is the well known lateral oscillation criterion, a series of lines dividing the damping-roll/sideslip ratio plane into regions of acceptable and unacceptable qualities.

Tools and methods of handling research vary greatly. The first and simplest approach is to use the characteristics of existing operational aircraft as a basis of requirements for future aircraft. This approach is ably summarised in Ref. 1. It is essentially a slow but safe method in that requirements lag behind design.

The first major advance was the use of so called variable stability aircraft. The stability characteristics of these research aircraft can be varied by deflecting the control surfaces independently of the pilot's input as varying functions of the aircraft motion, e.g. elevator deflection proportional to incidence. This approach has given valuable results.

The development of analogue computing has enabled the investigator to study handling problems under laboratory conditions. Fixed and moving base simulators of varying complexity have been successfully used. The latest development is the use of servo-analytical techniques which consider the pilot-airframe combination as a closed loop servo-mechanism. This involves the use of a mathematical model of the human pilot, on the derivation of which considerable research effort has been expended. As yet this is only a qualitative tool.

All of these basic techniques have their place in the formulation of requirements. With so many available methods, each of which involves some measure of pilot opinion it is clearly necessary to have a common yardstick that indicates the various levels of opinion, and to appreciate the significance of these levels with regard to the operational role of the aircraft.

1.2 Pilot Opinion

The factors which affect the pilot opinion of a given condition may be broadly classified:

(i) pilot - airframe safety
(ii) pilot and passenger comfort
(iii) control forces and movements
(iv) manoeuvrability
(v) precision flying ability.

These factors will all be encountered during handling investigations and it was the practice of early investigators to assign opinion ratings to each such factor. This led to a considerable diversity of rating scales with such measures as "acceptable good minus" which only has a meaning relative to the actual investigation in hand. These anomalies persisted until the general adoption of the Cooper scale (Ref. 2). This considers the overall rating of an aircraft for a particular role, and broadly divides opinion into optimum (POR 1), satisfactory, unsatisfactory and unacceptable with an ultimate 'catastrophic' rating of 10. The main boundaries are given ratings of 3.5 and 6.5. A copy of this scale is attached (Table I).

It is considered that in its present form the scale is reasonably satisfactory for military aircraft and research vehicles except that the distinction between ratings 4 and 5 is rather imprecise. A direct extension to transport aircraft is not possible in view of the entirely different operational roles involved. In deriving a scale for civil aircraft it has been considered that the implications of ratings 3.5 and 6.5 are sufficiently well known to make it inconvenient to lose them. A suggested new scale is attached (Table II). The main features are the suppression of ratings beyond 8 - these can have no meaning for civil operation: the introduction of specific queries, e.g. can you maintain flight at this condition (i.e. continue cruise) and if not can you successfully transit to a safe condition? It is assumed that a safe condition does exist - 'condition' means a specific speed and altitude. The 'can be landed' query only applies where approach dynamics are under investigation.

This scale is meant to be used only to indicate the pilot's opinion of the flying qualities for a given set of conditions. It is not meant to imply a rating for the whole flight envelope.

PART II

LONGITUDINAL HANDLING CRITERIA

2.1 Longitudinal Handling Parameters

As stated in paragraph 1 above, pilot opinion is affected, amongst other things, by the stick forces and movements, the short term effect of control movements and gusts, and the ease with which the pilot can achieve and maintain any required steady state condition. The effects of stick forces and movements are discussed briefly in 2.5.

It is customary to formulate handling criteria in terms of the short period stability characteristics, but it must be explained that these criteria are based primarily on the pilots reaction to the aircraft response to gross control movements and not to its behaviour under small perturbations. (It should be noted that this simple relationship between response and stability characteristics only holds if there is no significant lift due to control deflection, z_η). The consequences of this are further discussed in 2.6.

For the majority of cases, the characteristic quartic equation of the longitudinal motion can be factorised into two quadratics:

$$(\lambda^2 + 2\zeta p w_p \lambda + w_p^2) \quad (\lambda^2 + 2\zeta n \; w_n \lambda + w_n^2) = 0$$

The quadratic involving w_n^2 and $2\zeta n \; w_n$ will normally give rise to a complex pair of roots describing the longitudinal short period motion. In this case w_n is the undamped natural frequency, and ζ the damping ratio of the oscillation. The remaining quadratic, representing the phugoid, will also be oscillatory for the majority of cases, although degeneration into a subsidence and a divergence is not uncommon.

For small stability margins, either or both quadratics can give rise to real roots. In some circumstances, one root from each quadratic can combine to form a third oscillation which involves speed, incidence and attitude changes. This oscillation is only lightly excited and does not normally affect pilot opinion.

Early investigations used ζ_n and w_n to define the characteristics of the vehicle, but when investigations into marginal conditions were started, it became more convenient to use $2\zeta_n \; w_n$ and w_n^2 as parameters.

For this purpose, it was convenient to define $2\zeta\eta w_n = -(\lambda_1 + \lambda_2)$ and $w_n^2 = \lambda_1\lambda_2$, where λ_1 and λ_2 are the roots of the short period oscillation, or, where the "third" oscillation is present, λ_1 and λ_2 are the remaining two roots (one from the "phugoid" and one from the "short period"). It is not possible to define precisely these parameters if four real roots are present.

Both $\zeta \sim w_n$ and $2\zeta w_n \sim w_n^2$ plots are used in this report as convenient.

To assist the interpretation of these criteria, Fig. 1 has been prepared. This shows constant values of various important motion parameters on a $w_n^2 \sim 2\zeta w_n$ plot. It can be seen that where the motion is oscillatory, lines of constant time to double or half amplitude are lines of constant $2\zeta w_n$. Other characteristics, e.g. lines of constant t_s and t_r from Fig. 21 could also be plotted if desired.

It has been found desirable to derive criteria which are to some extent functions of aircraft size. This is because a large aircraft is obviously slower in manoeuvre than, say a fighter, and pilots will be more tolerant of this sluggishness (manifested as a lower w_n) on a large aircraft.

Obviously this process cannot be precise, and for the purposes of this report three classes of aircraft are considered:

(a) Small aircraft and fighters
(b) Medium aircraft say up to 60,000 lb.
(c) Large Transport Aircraft.

The particular class of any given aircraft must be given due consideration.

2.2 Short Period Criteria - Cruise

A large amount of work has been carried out in the U.S.A. on the effects of various short period characteristics on pilot opinion. The major part of this information has been obtained by the use of variable stability aircraft (Refs. 3, 17, 18, 19, 20, 21 and 22) supplemented by centrifuge and simulator results (Refs. 4, 23 and 24). A short description of the test conditions and work carried out in each of these reports is included as an Appendix. The actual results are plotted on Figs. 2 to 12.

2.2.1. Small Aircraft and Fighters

Using the relevant results from those given above, it is possible to derive a single criterion for small aircraft for flight well away from ground. This is presented in Fig. 13. A direct comparison with a similar criterion produced by English Electric (Ref. 10) is shown on Fig. 14 as a $\zeta \sim w_n$ plot.

The ultimate judgement of any criterion must rest on its prediction of the characteristics of aircraft which were not included in its derivation. Fig. 15 shows the characteristics of three research aircraft against the criterion of Fig. 13. It will be noted that in both cases, some portion of the flight envelope gives characteristics which would be rated (POR > 6.5) as "unacceptable even for emergency condition". The Pilots opinion is that under these conditions, the aircraft are satisfactory as research vehicles.

One important difference is apparent between the three aircraft - in the region $2\zeta w_n = 1$ $w_n^2 = 40$, the tailed aircraft is known to be prone to pilot induced oscillations (the reason for the boundary near this condition) whilst the tailless aircraft are not.

There are two possible reasons for this:-

(a) The response of the tailless aircraft to elevator application could reasonably be expected to be more sluggish due to the "short coupled" control and a pronounced effect of $Z\eta$.

(b) The tailless aircraft use variable gearing between the stick and the control surface. Recent simulator tests have shown the stick movement /g to be a very potent factor in eliminating pilot induced oscillations.

The important conclusion to be drawn from this is that published criteria are reliable provided that <u>all</u> the characteristics of the aircraft under consideration are near to those of the test aircraft or simulated aircraft. If one or more characteristics can be expected to be significantly different e.g. stick force gradient or $Z\eta/M\eta$ ratio, then the criteria may be extremely misleading and must be used with great caution.

It is obvious that much more work remains to be done on this topic. However the main purpose of this survey was to derive criteria for transport aircraft, so that the matter was not pursued further.

There is no available direct evidence of the desirable landing characteristics of small aircraft. However it may be possible to use the criterion developed for medium and large aircraft in this case. This is discussed below.

2.2.2 Medium Aircraft

Information on this class of aircraft is given in only two reports - Ref. 20 and 21. The results of Ref. 20 are therefore accepted as criteria for aircraft of the B.26 class, or, in the civil transport field, for aircraft of the Herald class. The criterion given in Fig. 11 is that proposed for this class of aircraft for "away from ground" conditions.

The results of Ref. 21 are applicable to approach conditions, a topic which will be discussed later.

2.2.3 Large Aircraft

In the absence of any variable stability aircraft tests on large aircraft, recourse must be made to the original method of defining handling qualities i.e. the use of current aircraft characteristics.

The calculated cruise characteristics of several large present day aircraft are shown in Fig. 16, together with the results of recent simulator tests. The boundary for a pilot rating of 3.5 is that proposed in the ARB/STAe document TSS No.5. More recent simulator results suggest that although the damping boundary is reasonable, the lower bound should be a constant w_n of about 1.2 rad/sec.

Also shown is a proposed boundary for a POR of 6.5. This is in reasonable agreement with simulator results for cruise conditions.

2.2.4. Discussion on Cruise Criteria

The boundaries of a pilot opinion rating of 3.5 for small, medium and large aircraft derived from Figs. 5, 11 and 16 are shown on Fig. 17, together with various aerodynamic parameters in the form of response times.

The boundaries bear out the hypothesis that pilots expect, and will accept, lower values of w_n on a large aircraft. They also show that there are values of ζ for all classes of aircraft below which pilot opinion degenerates. A good mean value seems to be about 0.3. Study of Fig. 18 indicates that for nearly all w_n's associated with $\zeta < 0.4$, the word "oscillatory" appears in pilot comments. This is in line with the fact that for $\zeta < 0.4$ there is a significant overshoot in the response to a step control input. (For $\zeta = 0.4$ the value of g/g_{ss} at 1st peak, Fig. 17, is 1.25).

No particular significance is attached to the values of t_s shown on Fig. 17, since t_s is a unique function of w_n and ζ, and since it has been shown that w_n is not, of itself, an important parameter, it would probably be better to define this part of the boundary in terms of a constant ζ which would be independent of aircraft size. ζ is of course directly interchangeable with cycles to half amplitude - -. $\zeta = 0.4 \equiv C_{\frac{1}{2}} = 0.25$.

However, the values of t_r shown are probably important. t_r by definition, is the time taken to initially achieve 0.5 of the steady state response following a step elevator input. Other values, e.g. time to 0.95 of steady state have been tried but do not seem to give such good agreement with the opinion boundaries.

Again, study of the pilot comments on Fig. 18 reveal the underlying reason for the boundary. For large and medium aircraft, a value of $t_r < 0.4$ seconds would be regarded as too low, the aircraft response (both to elevator and gusts) being too rapid. A value of $t_r > 0.9$ seconds would apparently be regarded as giving a sluggish aircraft with large stick forces. This line to some extent matches the proposed A.R.B. requirement that the aircraft should achieve steady state "g" in 2 seconds. However it must be emphasised once again that Ref. 5 has shown that much lower w_n (and hence larger t_r) values are acceptable for a supersonic transport, and this is verified by the simulator results, shown on Fig. 15.

The upper limit of t_r is not known exactly, but certainly from the results of Ref. 5 it may be at least 1 second. Because of the lack of definitive information, it is felt that no value can be given to this limit at the present time.

2.3 Phugoid Criteria - Cruise

The phugoid mode is in roughly the same position in the longitudinal plane as the spiral mode occupies in the lateral - its importance lies mainly in its nuisance value. It defines the ability of the aircraft to remain in trim, and viewed in this light is independent of aircraft size. Ref. 38 suggests that the importance of the phugoid to the pilot lies in the amount of time that he must spend sampling or monitoring the trim of the aircraft. If this is true, then pilot "effort" must depend on the time to half or double amplitude of this mode, and whilst this seems reasonable, no clear evidence is available to say whether this is the correct parameter. The phugoid characteristics of several aircraft are summarised below.

Aircraft	Condition	Phugoid Period	Phugoid Damping Ratio	$T_{\frac{1}{2}}$ (seconds)
Britannia	Cruise	96 seconds	.0495	212
"	Approach	68 "	.0734	102
V.C.10	Approach	102 "	.0769	147
Boeing	Cruise	300 "	-64	-40
707	Approach	39 "	.06	73
Vanguard	Cruise	97 "	.0115	92
"	High Alt.	89 "	.0690	141
"	Approach	37 "	.0695	59
D.C. 8	Approach	38 "	.009	990
Viscount	Approach	30 "	.633	52
"	Cruise	70 "	.0654	118

Where the aircraft is restrained, either by the pilot or an autopilot, to maintain a steady flight path (either level flight or a steady descent), then the phugoid degenerates into a speed variation. In this case the important parameter would become time to halve or double a speed error. Since no oscillation can be present in this case, the use of $T_{\frac{1}{2}}$ or T_2 as a phugoid parameter seems more reasonable, as the pilots problem is of the same general nature.

The results of Ref. 20 plotted in Figs. 19 and 20 show that either $T_{\frac{1}{2}}$ or ζp could be used as a parameter. It is believed that $T_{\frac{1}{2}}$ is more reasonable, and a mean line through the points would indicate $T_{\frac{1}{2}} < 20$ seconds for a rating of 3.5. However none of the aircraft mentioned above would meet this, and it seems that a sufficient requirement would be that the phugoid should be at least lightly damped. For a rating of 6.5, it is suggested that T_2 should be more than 20 seconds and possibly more than 40 seconds.

2.4 Approach Cases

As mentioned earlier, no information is available on approach characteristics for small aircraft, and only one report (Ref. 21) dealing with medium aircraft, and marginal conditions. The results of this investigation are presented on Fig. 12. The calculated characteristics of several aircraft of varying size are shown on Fig. 21.

The fact that the extreme high and low values of w_n encountered are given by a medium and a small aircraft respectively, with the large aircraft scattered between these, leads to the supposition that a single criterion, independent of aircraft size, could be used for the approach case. For aircraft with comparable landing speeds (and hence comparable allowable manoeuvre times) this is probably reasonable.

Using the results of Figs. 12 and 21, a tentative composite criterion has been plotted on Fig. 21. However it should be borne in mind that the region of low w_n^2 is usually a region of near zero C.G. margin, and that in this case there is a possibility of the stability equation having four real roots, i.e. no precise definition of w_n^2 and $2\zeta\ w_n$ is possible. A further complication arising from this is that interaction between phugoid and short period modes in this region is marked, so that the validity of a criterion based only on the apparent "short period" characteristics must be doubted.

Indeed, the low C.G margins of this region will give rise to an aircraft which is difficult to keep in trim, and this also will adversely affect pilot opinion. The pilot comments on various regions of the $w_n^2 \sim 2\zeta w_n$ plane given in Ref. 21 support this view. Some of these are shown on Fig. 23.

Actually, for an approach condition, in which the flight path is, or should be, tightly controlled by the pilot, the discussion of phugoid stability should be replaced by one on speed stability. Assuming 'good' short period dynamics, the pilot rating can be considerably influenced by the speed stability.

The problem has been considered by Lean (Ref. 6), who suggests that for approaches made in moderate turbulence, the pilot first notices a deterioration in handling for speed instabilities with time constants of less than 40 seconds. This condition on the revised scale, has been given a rating of 5. However visual landings could be made with time constants as low as -9 seconds, although pilots complained of this condition. A reasonable aim for transport aircraft would be a condition in which full instrument approaches were still possible even in an emergency. Ref. 6 suggests a figure of $T = -15$ seconds for this case, which would receive a rating of 6.5.

It is considered that for an aircraft to be satisfactory, it should be speed stable, with a time constant less than 60 seconds. This would have a rating of 3.5. A convenient plot of pilot rating versus 1/time constant is shown on Fig. 24, which indicates that with the above assumptions, the relationship is linear, and that for an 'excellent' rating, a time constant of the order of 11 seconds is reasonable. This also is in broad agreement with Ref. 6.

2.5 Effect of Control System Characteristics

All of the criteria discussed above have been derived on the assumption that the control system gave optimum characteristics for the case under consideration. However it is known (Refs. 1, 12, 13, 14, 15, 16, and 23) that stick force characteristics can considerably modify the pilots rating of a given short period characteristic, and further than stick friction (friction range of trim) could completely mask the effect of variation in phugoid damping, although no published work on this aspect is available.

The results of the investigation reported in Ref. 17 are given in Fig. 3. Although this shows only a small region of 'good' characteristics, it is obvious that stick force/g can have quite a wide variation and still be satisfactory. In this respect it is probable that the requirements for American military aircraft, or their B.C.A.R. equivalent are quite adequate. These are given in Table II.

The effects of control friction (breakout force) have been examined in Ref. 13. These indicate that pilots do not object to breakout forces provided that they are not large in comparison with the stick force per g. Although airworthiness requirements will probably be framed in terms of the friction range of trim speeds, it is believed that the values given in Table III (derived from American military requirements Refs. 1 and 7) are reasonable design aims.

Refs. 3, 14 and 15 show that when the pilot/aircraft system is subject to pilot induced oscillations, they can be minimised if an appreciable lag is present between the application of stick motion and movement of the control surface. The optimum values of lag is obviously dependent on the particular aircraft characteristics, and this problem is one where a servo analysis technique could be usefully employed (Refs. 38 and 39).

Fig. 6 shows that as would be expected, the improvement in pilot rating with a time lag in the control system is confined to aircraft with moderate or large w_n. In this case an appreciably lower value of ζ can be tolerated before the pilot induced oscillations become serious. Fig. 8 shows that as w_n increases, the value of time lag required by the pilot for the best performance also increases. It would be expected that this would not be relevant to civil transports which normally have low values of w_n.

If the problem area is not one of excessive C.G. margin but of low manoeuvre margin, then the presence of an appreciable lag in the control system could make control of the aircraft extremely difficult or even impossible.

2.6 Effect of Control Lift Terms

As indicated in 2.2.1, it is believed that the criteria developed may not be valid in some regions if an appreciable lift force accompanies the generation of pitching moment, i.e. an appreciable $Z\eta$ term.

Obviously the result of such an effect depends on the conditions under consideration. One example where $Z\eta$ might be beneficial has already been mentioned (2.2.1), but obviously an appreciable $Z\eta$ can also be disadvantageous, as for example when attempting to maintain a given path on approach. In this case if the pilot applies up elevator in an effort to gain height, the immediate motion of the aircraft is a slight sinking, to which the pilot may react with more up elevator. This can lead in some cases to a pilot induced instability of moderate period. This forces the pilot to use an 'inching' technique when making flight path changes, and the resulting enforced 'sluggishness' will almost certainly lead to poor ratings.

The effects of $Z\eta$ have not yet been studied either theoretically or using simulators, but it is generally recognised that for future configurations it will probably be very important especially since its effect is magnified for configurations with low lift curve slopes.

It is considered therefore that if the aircraft under consideration complies with these conditions, then the criteria given herein should be used with caution.

PART III

LATERAL HANDLING CRITERIA

3.1 Lateral Dynamics

The stability quartic of the lateral dynamics may generally be factorised as

$$(\lambda + \frac{1}{\tau_S}) \quad (\lambda + \frac{1}{\tau_R}) \quad (\lambda^2 + 2\zeta w_n\lambda + w_n^2) = 0$$

where τ_S, τ_R are the time constants of the aperiodic spiral and rolling modes, and ζ, w_n are the damping ratio and undamped natural frequency of the lateral oscillation. These three modes can be demonstrated individually on configurations with unswept wings, but modern design trends, viz. increasing sweep and reduction of the roll/yaw inertia ratio have produced aircraft with considerable interaction between the modes.

3.2 The Spiral Mode

The spiral mode is generally the weakest of the lateral modes and can be rated on its nuisance value. For instance a spiral divergence of only 2 seconds to double amplitude is perfectly flyable (Ref. 26) yet absolutely intolerable since it provides a continuous distraction when attempting to control other motions.

Little has been published on the subject of spiral stability. The two reports of any consequence (Refs. 26 and 27) were concerned with variable stability aircraft flight tests, using a light bomber and a fighter. They agree that a time of 20 seconds to double amplitude represents a broad boundary between satisfactory and acceptable ratings (POR 3.5). Divergences of only 4 seconds to double amplitude were considered 'acceptable poor' (POR 4.5).

The official requirements (Ref. 7 - the U.S. Military Specification) requires minima of 4 seconds to double amplitude in all conditions except the cruise and the approach where 20 seconds is required. Ref. 1 comments that the approach requirement was arbitrarily made as stringent as the cruise in view of the general trend towards deterioration of other low speed handling qualities. Bisgood (Ref. 28) has commented favourably on these military requirements.

It is reasonable to suppose that any spiral stability requirement should be most stringent for conditions where the pilot is not giving his full attention to the control of attitude, e.g. the cruise condition. Although this would imply that the approach requirements would be considerably less stringent, the approach remains the most critical flight regime that is normally encountered and should merit some particular attention.

The approach condition is considered in the light of some estimated data for some present day aircraft - see Fig. 25. It is apparent that there are several aircraft with divergences of less than 20 seconds to double amplitude. These aircraft are quite conventional and the spiral instability is not considered unreasonable. This indicates that the arbitrarily adopted 20 seconds is too high: it should also be noted that pilots have difficulty in clearly distinguishing between slow divergences of differing rates.

It is therefore proposed that a time to double amplitude of 10 seconds be adopted as a minimum approach requirement. This is not entirely arbitrary since a theoretical study of the closed loop pilot-airframe system (Ref. 40) has shown that POR deteriorates for unstable time constants less than 10 seconds. This corresponds to a double amplitude time of about 7 seconds. A loose correlation of T_2 with POR is also indicated in Fig. 25.

The case of the large aircraft should not be any different to the fighter type, save that the pilot effort to recover from a disturbance may be greater. This may be resolved by relating control system design to the dynamic as well as static stability characteristics. Concerning large aircraft in cruise, some recent flight experience has shown that in spite of a relatively slow divergence, dangerous attitudes and rates can be encountered before corrective action has been made. It is possible that such experience may override the 20 seconds to double amplitude requirement and even call for spiral stability.

3.3 The Rolling Mode

The rolling mode is the dominant lateral controlling mode and on conventional aircraft is essentially a single degree of freedom mode. Although various methods of analysis exist the form of the requirements is still very flexible.

The first requirement to be adopted was a measure of the wing tip helix angle (pb/2V) and this has formed the nucleus of official requirements for some years. More recent work has shown the deficiencies of this parameter as a design criterion and has given rise to the consideration of roll displacements after a specified time interval from initial control application. Current studies of the mode have shown pilot opinion to be directly related to available roll-acceleration and the inherent roll damping. It may be shown that the isopinion lines derived in this connection are related to criteria for performing checked bank manoeuvres in specified times.

Before investigating in detail the recent work on the subject it is of interest to compare the various official requirements. These are presented in Table IV. The predominance of the tip helix angle is quite marked, although the B.C.A.R. requirement of 60° bank in 7 seconds is fairly realistic. The American requirements (Ref. 7) are also based on correlations of measured rolling characteristics and are supplemented with pilot opinion obtained from simulation. For low speed handling the critical requirement is the necessity to maintain wings level in turbulence: the best correlation gave an average $pb/2V = .05$ for the first 30° in bank for full pilot's control deflection.

Recent research investigations have been concerned with the relative interactions of available roll acceleration and roll damping. Ref. 29 systematically explored combinations of these, to be assessed for fighter type aircraft flying in their combat speed range. Both fixed and moving base simulators were used and the results were substantiated by flight test. The isopinion lines derived from this study are shown in Fig. 26. It is this parameter plane that shows the deficiency of (pb/2V) as a rolling parameter since for any given point on this plane there exists only one value of POR but an infinity of values of (pb/2V). Hence opinion is independent of (pb/2V). However in spite of this argument it is true that certain correlation may be obtained, particularly with the fighter aircraft of World War II.

Discussing Fig. 26 in detail, regions of large available accelerations are disliked because of the inability to control precisely during a rolling manoeuvre. Long time constants are disliked since the aileron becomes essentially a roll acceleration control rather than a rate control. A long time constant also implies a significantly larger checking action in performing a checked bank manoeuvre - this is demonstrated in Fig. 27. It is therefore felt that any new requirement would include a maximum permissible time constant of about one second (for fighter aircraft).

The rolling characteristics of large aircraft on the approach can be assessed by consideration of the ability to perform a specific manoeuvre rather than the consideration of accelerations and rates. Various types of manoeuvre may be considered - the sidestep and checked and unchecked rolling manoeuvres. An R.A.E. flight study (Ref. 31) of the sidestep manoeuvre considered 14 aircraft ranging from a research vehicle (Avro 707B) to a civil transport (Britannia). As part of the study, pilots made general comments on the ability of each aircraft to perform the set manoeuvres as well as commenting on particular rolling characteristics such as the available rate of roll.

An attempt has been made to assess these flight results on the basis of a single degree of freedom motion, but certain inconsistencies arise when such an analysis is made. However, opinion ratings have been assigned to the recorded comments of this study and also to the known opinions of the rolling characteristics of other aircraft. From these a set of opinion contours have been drawn on the acceleration-time constant plane shown in Fig. 28. These contours show similar trends to the fighter aircraft opinion contours of Fig. 26 although there is insufficient data to define a boundary for large time constants. Bisgood (Ref. 28) has suggested that an aircraft with a time constant greater than four seconds would prove unacceptable.

It is possible to draw lines on this parameter plane corresponding to the dynamic requirements for performing certain rolling manoeuvres. Flight experience has shown however that these single degree of freedom analyses are somewhat inaccurate, particularly concerning checked bank manoeuvres. It is therefore unrealistic to derive a rolling requirement based solely on analyses made on this parameter plane. It may however be used as a design guide.

There is no evidence to show that the present B.C.A.R. requirement of rolling through 60° in 7 seconds is inadequate for defining the minimum rolling performance of a civil aircraft.

A maximum limit on rolling performance is unlikely to be applicable to a large aircraft in the approach condition since full control is rarely used: any undue sensitivity can be alleviated by suitable design of the aileron feel system.

There is little foundation on which to build a requirement for the rolling characteristics of large aircraft in the cruise condition. The U.S. requirement (Ref. 7 and Table IV) is in the form of (pb/2V) specification but this is open to the argument previously made against this parameter. It is reasonable that there should be a maximum permissible time constant. Bisgood (Ref. 28) has suggested that 4 seconds is the <u>minimum</u> time constant that would render an aircraft unacceptable - this is in reasonable accordance with the family of contours of Fig. 26.

3.4 The Lateral Oscillation

The lateral oscillation is probably the most complex of all aircraft modes, and the various approaches to a full understanding of it is reflected in the varying forms of official requirements through the years.

Early work was primarily concerned with the damping of what was an essentially pure yawing motion. The effects of frequency were then included and several criteria were produced. Typical of these is the boundary of Ref. 9 which is drawn in Fig. 29. This is cyclic damping period plane divided into satisfactory and unsatisfactory regions. The boundary may be correlated with a POR of 4, and was derived from simulator studies together with some flight test results. From the characteristics of the several aircraft shown on this figure, it is clear that they are well classified according to type, i.e. research aircraft poor and civil transports generally good.

As aircraft design progressed, particularly with the advent of sweepback the lateral oscillation became a combined rolling and yawing motion rather than simple yawing. It was found that high roll/yaw ratios are disliked by pilots and more damping is required. A considerable amount of work has been done in order to determine a suitable form of roll/yaw ratio criterion.

The studies described in Refs. 26 and 33 both considered various measures of roll/yaw ratios, i.e. $|\phi/\beta|$, $|\phi/\psi|$, $|p/r|$. Somewhat more consistent correlations have been obtained with $|\phi/\beta|$. and it is this parameter, or at any rate a variant thereof, that has been generally adopted. Ref. 33 discusses the variants the $|\phi/\beta|$: it was found that criteria based on damping and $|\phi/\beta|$ gave consistent results at any individual flight condition but not between different flight conditions. When $|\phi/\beta|$ was converted to $|\phi/V|$ (V the actual side velocity), this particular inconsistency was resolved. It is also considered a more logical parameter since a gust occurs as a V-change rather than a β - change.

Some flight test work (Ref. 34) has noted that pilots experience an objectionable increase in rolling motion in rough air as the altitude is increased. If $|\phi/V|$ is divided by $\sqrt{\sigma}$ it becomes $|\phi/V_E|$ where V_E is equivalent side velocity. In general, $|\phi/V_E|$ increases with altitude. Now although this change of variable is strictly arbitrary, an analysis of gust intensity with altitude (Ref. 11) showed that effective gust velocity measured in E.A.S does not vary with altitude. Hence $|\phi/V_E|$ was adopted as a significant lateral handling parameter.

However more recent analyses of gust variation with altitude (Ref. 45) have not substantiated the findings of Ref. 11 and show that the velocity falls off with altitude. In view of the trend towards higher cruise altitudes it is felt that the use of the $|\phi/V_E|$ parameter is unnecessarily stringent and will give unduly pessimistic results when applied at high altitudes. It is therefore proposed that a parameter k x $|\phi/V_E|$ be adopted where k is derived from the B.C.A.R. gust specification (Section D3-2). This factor k is drawn against altitude in Fig. 32(a). Its application is discussed below (page 15).

Other fields of investigation were concerned with fighter tracking accuracy and this led to the derivation of various criteria which combined with the above studies led to the present U.S. requirement (Ref. 7) presented in Fig. 30. This is a cyclic damping ~ $|\phi/Ve|$ plane divided into regions of acceptability, acceptability in emergency conditions, and unacceptable, the boundaries varying according to normal or fighter/bombing configurations etc. The requirements apply to all military aircraft.

The most useful of recent investigations is the work described in Ref. 35 where the lateral characteristics of a variable stability aircraft were assessed under simulated approach conditions. Each pilot selected an optimum aileron-yaw effect (i.e. an optimum $w\phi/w_d$ - see paragraph 3.6). Analysis of the results showed that a POR of 3.5 correlated well with the 'A' curve (Fig. 30) of the military specification. However a lower boundary, corresponding to that between 'permissible in emergency' and 'unacceptable' (POR 6.5) was found to be considerably less stringent than the 'B' boundary of the military specification. This is to say that pilots can tolerate considerably less damping than was previously believed, even to the extent of mild instabilities provided that the roll/slip ratio is not large ($|\phi/V_e| \nless .4$). The effect of frequency was examined and at moderate values of $|\phi/V_e|$ appeared to be taken into account by the use of $T\frac{1}{2}$ rather than $C\frac{1}{2}$ as a damping measure. There is insufficient data from which to draw firm conclusions about the lateral oscillation period, but as the period increases the required damping decreases, consistent with Fig. 29 discussed earlier. On this basis if the boundaries determined for higher frequencies are used they become more stringent than apparently necessary at the lower frequencies. The original work embraced periods up to 7 seconds but it is reasonable to suppose that this may be extended to 10 seconds at the risk of some conservatism. When considering civil operation this is not unreasonable. Bisgood (Ref. 28) has revised the boundaries slightly, and it is the revised version that is drawn in Fig. 31. The main revision is the introduction of lines of minimum damping for low values of $|\phi/V_e|$ (<.45) - this is reasonable since there must be a minimum damping regardless of the relative amplitudes of the motion.

The current A.R.B. proposal (Ref. 32) is a revised form of that shown in Fig. 31, and is drawn in Fig. 32. The cruise characteristics of several aircraft are plotted on this figure with and without the use of the altitude factor k (Fig. 32a) and it is seen that the high altitude aircraft are shown in a much more favourable light when the altitude correction is adopted.

Several other investigations have been made and generally suffer from one of two faults. The first is the construction of boundaries with insufficient data, giving very artificial results. The second is the failure to appreciate the variation of other parameters associated with the variation of the parameter in question. Such an effect is clearly demonstrated in Refs. 1 and 30 where the influence of aileron yaw initially vitiated a lateral oscillation analysis. When this was taken into account the results were reasonably consistent.

The nature of the lateral oscillation is such that a given characteristic is probably as equally objectionable (or otherwise) in a large aircraft as in a fighter, though possibly for different reasons. The approach is the regime of accurate flying common to all aircraft types and none of the features encountered in recent studies are peculiar to the test facilities employed, apart from control forces. These may have an effect on the direct evaluation of the lateral oscillation but this will be small in comparison with their effects on other modes. The plotting of known (and estimated) characteristics of numerous aircraft on these various criteria does not indicate any material difference between the requirements for large and small aircraft.

It will be shown in section 3.6 that the interaction of the lateral oscillation with the rolling mode can significantly alter the overall impression of the modes as described here.

3.5 Roll-Spiral Coupling

The most complete form of roll-spiral coupling occurs when the modes combine to form an oscillation. This is generally a rolling oscillation with little attendant lateral motion. There is no reported flight experience of this phenomenon and no specific investigations have been made, but the theoretical work of Ashkenas and McRuer (Ref. 40) has examined some related effects of the two modes. The oscillatory coupling may be undesirable in view of the resulting unfamiliar dynamic characteristics.

Opinion varies with the proximity of the two roots, but the only distinct quantitative boundary is $|\tau_S/\tau_R| = 30$, above this level there will be negligible effect on opinion. Below this, opinion may deteriorate but this should not be serious.

3.6 Roll-Lateral Oscillation Coupling

The analysis of certain conflicting results from various studies of the lateral oscillation has indicated the existence of a fundamental opinion coupling between the rolling mode and the lateral oscillation, or at least the relative excitations of the modes in an aileron controlled manoeuvre. This coupling has a significant effect on the overall handling qualities of a given configuration. It is due in general to three effects:

(i) aileron yawing moment
(ii) a high l_v/n_v ratio
(iii) an inertially slender configuration at high incidence.

The first of these has received the most attention in view of the ease with which it can be varied during investigations, but the significant coupling parameter that has been evolved embraces all three effects.

A simulator study (Ref. 36) investigated the coupling by considering the roll rate response to aileron application. A parameter that expressed the "ratio of the amplitude of the oscillatory roll rate at first overshoot to the steady state roll rate" was used - this is depicted in Fig. 33. It was found that pilot opinion significantly deteriorated if this ratio was greater than .045 - this determines a 'minimum satisfactory level' (POR 3.5). A good agreement with this was made by a combined flight and simulator study (Ref.37) but beyond this boundary the results showed that for a given POR the magnitude of this parameter varied markedly with effective aileron yaw. Consequently the parameter is of little general use. The results of the two studies are compared on Fig. 33.

Theoretical work (Ref. 40) has derived a parameter $(w_\phi/w_d)^2$ that describes the form of the sideslip response to aileron. The parameter occurs in the transfer function between bank angle and aileron.

$$\frac{\phi}{\xi} = \frac{L_\xi (S^2 + 2\zeta_\phi w_\phi S + w_\phi^2)}{(S + 1/\tau_s)(S + 1/\tau_r)(S^2 + 2\zeta_d w_d S + w_d^2)}$$

where the bracketed terms of the denominator represent in order the spiral, rolling and lateral oscillation modes. The terms suffixed 'ϕ' are simply factors of the numerator coefficients. An approximation for the parameter is

$$\left(\frac{w_\phi}{w_d}\right)^2 = 1 - \frac{\left(\frac{n_\xi}{l_\xi} + \frac{l_E}{l_A}\right)\left(\frac{l_v}{n_v} + \frac{l_E}{l_c}\right)}{1 + \frac{l_E}{l_A}\frac{l_v}{n_v}} \quad \text{(Ref. 47)}$$

which is seen to contain elements representing each of the effects listed at the start of this section. In particular the n_ξ/l_ξ ratio is present and this can be varied without altering the lateral oscillation characteristics. For the purposes of this section, a particular lateral oscillation has been assumed and $(^w\phi/w_d)^2$ varied by altering n_ξ/l_ξ. For $n_\xi >> 0$ ('adverse' yaw) the parameter is less than unity, and for $n_\xi << 0$ ('proverse' yaw), is greater than unity.

The response in rates of yaw and roll and in sideslip angle to a step aileron input is shown in Fig. 35, for different values of $(^w\phi/w_d)^2$. For a value of unity, the response in sideslip is predominantly that due to the lateral gravity component associated with bank angle. For values less than unity, larger amounts of sideslip are developed, ultimately leading to rolling velocity reversal via the l_v effect. This can happen for $(^w\phi/w_d)^2 < 0.5$, depending on the lateral oscillation damping ratio. Values of the parameter greater than unity are associated with a sideslip response reducing from that due to gravity alone, causing the aircraft to slip in the opposite direction 'out' of the turn but yawing 'into' it. The gravity effect will generally overcome this after the initial transient.

The theoretical work considered a closed loop system consisting of the above open loop transfer function and the feedback of aileron application proportional to bank angle. It was found that system performance could vary significantly with $(^w\phi/w_d)^2$ if the lateral oscillation damping ratio was low - say less than 20% critical. Subject to other conditions, involving in particular the product $w_d\tau_R$, there was a general performance optimum for values of $(^w\phi/w_d)^2$ slightly less than unity.

Flight tests associated with this theoretical study are reported in Refs. 30 and 37. They tend to confirm the theoretical predictions. Typical opinion contours (Ref. 37) are presented in Fig. 34. An analysis of flight experience with the X-15 aircraft (Ref. 22) also confirms the preference for $(^w\phi/w_d)^2$ less than unity, although in this particular case increasingly 'favourable' aileron yaw is required. This is due to the positive l_v effect on this aircraft. Some evidence to the contrary does exist however, i.e. a preference for $(^w\phi/w_d)^2 > 1$. This was noted in Ref. 40 - a gunnery task showed a preference for unity, but 'normal' flight opinion ratings were improved for $(^w\phi/w_d)^2 < 1$. There is also a general impression from all of the flight tests that the relationship between opinion rating and $(^w\phi/w_d)^2$ depends on the task involved. Certainly extreme values are disliked.

The flight test work of Ref. 35 that has provided the basis of the proposed A.R.B. lateral oscillation requirement (see Figs. 30 and 31) specifically used the 'optimum' $(^w\phi/w_d)$. For non-optimum $(^w\phi/w_d)$ it may be expected that the lateral oscillation damping should be increased for the higher values of ϕ/V_E. A possible correction for this is indicated in Fig. 30, based on Barnes (Ref. 10) analysis of the various results. For some configurations - notably with high l_v

low n_v and adverse aileron yaw, w_ϕ becomes small or even negative. In this case the steady state aileron gain is reversed in sign. This would appear to be intolerable, yet it has been recently demonstrated both in flight and by simulation, that successful approaches can be made in this condition, since pilot's rudder application (to co-ordinate the turn) is instinctive. The importance of w_ϕ would appear to be strongly dependent on the pilots task; gunnery and complicated tracking tasks increasing its importance. There are several interdependent parameters concerned in a full analysis of the lateral motion - the oscillatory characteristics such as damping, frequency, roll-sideslip ratio, also the rolling mode time constant. The parameter $(w_\phi/w_d)^2$ measures effects that are in many ways sensitive to all of these parameters. It is not possible in the light of present knowledge to define general handling criteria based on $(w_\phi/w_d)^2$ or related parameters such as $(w_\phi - w_d)$ (Ref. 22). Let it suffice to say that handling difficulties may arise if $(w_\phi/w_d)^2$ significantly differs from unity.

3.7 Lateral Control System Characteristics

Lateral manoeuvring generally involves only the rolling mode so that POR may be expected to vary with the control force required to achieve a given roll response. There is little foundation on which to examine the effects of break-out force, etc., but Ref. 7 does specify some levels - these, with other official requirements are given in Table II.

For the simulator study of Ref. 29, both the maximum stick travel and the stick force per inch were kept constant. At a particular value of τR the variation of POR with steady state rolling velocity per applied stick force may be found - a mean line for values of $\tau R < 1$ second has been drawn in Fig. 36. The same parameter was also examined in the flight study of Ref. 30 and has produced a similar curve.

It is seen from Fig. 36 that there is an optimum value and that in either side of this opinion will deteriorate. At a reasonable opinion level, say 3, there is a fairly wide band of rate response per applied stick force so that opinion is not unduly sensitive to this parameter. Similar results have been obtained in the longitudinal plane (Ref. 41) - this is also depicted on Fig. 36.

PART IV

SERVO-TECHNIQUES

4.1 Introduction

The latest advance in handling research is the use of servo-analytical techniques in an attempt to explain some of the reasons for the various pilot-opinion boundaries. A considerable volume of work has been published (e.g. Refs. 4, 38, 39, 40, 41, 42, and 43) and is generally written in the somewhat specialised language of the systems engineer.

Perhaps the clearest synopses of the subject are given in Refs. 39, 42 and 43, the first of which describes the overall situation as it existed in early 1962. These may be amplified by the work reported in Refs. 38 and 40 which were detailed studies of the longitudinal and lateral dynamics.

The basis of this work is the concept of the complete pilot-airframe system and it is thus necessary to construct a mathematical model of the pilot. Again a considerable amount of work has been published on this subject; and numerous models have been suggested. The form of the model varies according to the nature of the task but some general results have been produced for relatively simple flying tasks.

4.2 The Pilot Transfer Function

Of the many models used and derived in Refs. 4, 41, 42, and 44 the most general is of the form

$$Y_p = K_p \frac{1 + T_L S}{1 + T_I S} \left[\frac{e^{-\tau S}}{1 + T_N S} \right]$$

where S = Laplace operator

K_p = pilot gain, e.g. inches stick movement per radian attitude change

T_L = lead time constant

T_I = lag time constant

T_N = neuromuscular lag time constant ($.12 < T_N < .18$ sec.)

τ = reaction time delay

Y_p = stick movement or force per unit attitude change.

The terms in square brackets are relatively unalterable for any physically fit human, but the remaining terms are varied as the pilot adapts his response to produce the best results.

The lag term $(1 + T_I S)^{-1}$ is needed when the pilot adopts a "wait-and-see" attitude, i.e. allows the response to develop before applying further control. A lead term $(1 + T_L S)$ is used when the pilot has to anticipate the future response, for instance when performing a checked bank manoeuvre a lead term is generated, the magnitude of which increases as the time constant of the roll mode is increased (paragraph 3.3). The lag and lead terms generated are referred to as the pilot's "equalisation" characteristics. K_p is a function of stick gearing and airframe response sensitivity.

The above transfer function is only useful so long as the pilot's output remains linearly correlated with visual stimuli. As explained in Ref. 42 this is roughly true for the majority of cases, but for marginal conditions a further output term appears - the so-called remnant - which is in no way correlated to input. For these conditions the method may be of restricted usefulness.

4.3 Relationship Between Pilot Transfer Function and Opinion Rating

It has been established (Refs. 38 and 41) that a definite correlation exists between the POR of a given configuration and the form of transfer function that he must adopt in order to achieve the best results. The general conclusions, taken from Ref. 39, are given below:

Necessary Conditions for "Good" Ratings

1. Pilot equalisation essentially nil.

2. Pilot gain adjusted to near-optimum values.

3. $w_1 < w_c$; and, in addition, for closed loop system requiring a third order approximation, ζ_{CL} must be > 0.35

   w_1 = effective input bandwidth (frequency)

   w_c = open loop gain crossover (zero db) frequency.

Lag Introduction - slight degradation in opinion

Lead Introduction - degradation in ratings which increases to maximum values as the required lead increases

Non-Optimum Gain - rating degradations which increase to maximum values as the gain varies on either side of optimum values.

4.4 Possible Uses of the Method

There is no doubt that this method is already of significant use in investigating the dynamics of novel configurations such as re-entry vehicles. In terms of formulating handling requirements it is at present useful for yielding qualitative rather than quantitative results. However it could be used to investigate the requirements for large aircraft under marginal conditions - a region in which the available flight test information is negligible. A further use seems to be the possibility of using the concept to study conditions following an autostabiliser failure. If the use of the unautostabilised aircraft dynamics with the pilot transfer function appropriate to the stabilised aircraft give rise to excessive loads in the period shortly after failure then the level of autostabilisation used is probably too high.

The complete theory of handling derived in this manner suggests various parameters which could become important for future configurations and help to explain some of the anomalies arising from current and previous work. Perhaps the most notable of these is the parameter $(W\phi/W_d)^2$ which was derived using this theory and has since been found to be very important. This has been discussed in paragraph 3.6.

PART V

CONCLUSIONS

This survey has shown the importance of relating aircraft handling characteristics to the aircraft operational role, and in particular has considered the case of the large civil aircraft. A new pilot opinion rating scale has been proposed and has the specific advantage of maintaining the now familiar ratings of 3.5 and 6.5 as boundaries between three broad classes of acceptability.

The individual longitudinal and lateral modes have each been investigated and the following detailed conclusions have been made:

5.1 Longitudinal

Criteria have been developed which allow the designer to assess the probable manoeuvring characteristics of any configuration. Criteria are given for three class of aircraft and for cruise and approach conditions. It is believed that these are realistic for conventional (tailed) configurations, but that care is needed when applying them to configurations in which a considerable lift force accompanies the generation of control pitching moment. All criteria are subject to the condition that the control system must provide a reasonable gearing with small friction levels.

For civil requirements, the use of complex graphical boundaries which depend on aircraft size may be too complicated. It is suggested therefore that a good approximation to the boundaries for continuous flight (i.e. not transient cases) could be made as follows.

(a) Short Period

(1) Boundary of 3.5 rating (10^0 and $10^{-3.5}$ probability levels).

Damping ratio $\zeta > 0.3$

Rise time $x < t_r < y$ seconds, where x and y are functions of aircraft size. For large tailed aircraft $x \simeq 0.4$ seconds and $y \simeq 0.9$ seconds. For other configurations x is probably unchanged.

The upper limit on y is not known, but there is evidence that it is at least 1.0 second. However because of the lack of clear evidence, an upper limit to t_r has not been proposed.

(2) Boundary of 6.5 rating (10^{-7} probability).

Damping ratio $\zeta > 0.11$ ($C\frac{1}{2} < 1.0$).

Natural frequency, Wn, should be at least 0.5 rad/sec.

(b) Long Period

The effect of phugoid and/or speed stability has been investigated, and reasonable values of times to halve and double amplitude defined as follows.

(1)	Cruise -	phugoid stability	Rating 3.5	At least lightly damped
			Rating 6.5	$T_2 > 20$ - 40 seconds
(2)	Approach -	speed stability	Rating 3.5	$T_{\frac{1}{2}} \nless 40$ seconds
			Rating 6.5	$T_2 \ngtr 10$ seconds

5.2 Lateral

(a) Spiral Mode

A minimum time of 10 seconds to double amplitude for the approach condition is proposed. This is less stringent than the current U.S. military requirement. There is a case for a re-appraisal of the cruise condition in the light of experience with large aircraft.

(b) Rolling Mode

The present B.C.A.R. approach requirement appears to be adequate in defining acceptable rolling characteristics. It is important that any new requirement that may be considered should not be based entirely on the fundamental assumption of single degree of freedom motion. The 'classic' single degree of freedom parameter plane does however serve as a design guide.

(c) Lateral Oscillations

The proposed A.R.B. requirement for the lateral oscillation is a logical development of some recent research. However, unduly pessimistic assessments may be obtained for high altitude aircraft due to the implicit assumption that gust E.A.S. (mean) is invariant with altitude. This may be resolved by the introduction of a gust factor, k, defined above, 25,000 feet by B.C.A.R., on the rollsideslip parameter $|\phi/V_E|$.

(d) Rolling Manoeuvres

A parameter $(w_\phi/w_d)^2$ provides a qualitative measure of the response to aileron. There is some correlation between opinion rating and this parameter, but is both complicated and dependent on the control task involved.

For the general case it is possible only to say that handling difficulties may be encountered if $(w_\phi/w_d)^2$ significantly differs from unity.

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TABLE I

THE COOPER SCALE FOR OPINION RATING

	Adjective Rating	Numerical Rating	Description	Primary Mission Accomplished	Can be Landed
Normal Operation	Satisfactory	1	Excellent	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
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

*Failure of an autostabiliser system.

Extracted from: "Understanding and Interpreting Pilot Opinion" by George E. Cooper (Aeronautical Engineering Review, Volume 16, No. 3, March 1957)

TABLE II

PROPOSED PILOT OPINION RATING SCALE FOR CIVIL TRANSPORT AIRCRAFT

Adjective Rating	Numerical Rating	Description	Completion of Flight Phase	Completion of Emergency Diversion	Can be Landed*
Satisfactory	1	Excellent - no comment	Yes	Yes	Yes
	2	Very good - pleasant to fly. No tricks or special techniques required.	Yes	Yes	Yes
	3	Good - pleasant to fly generally but with certain irritations which can be lived with but should be improved if possible.	Yes	Yes	Yes
Unsatisfactory	4	Acceptable though with characteristics that would always be mildly worrying and must be improved if possible.	Yes	Yes	Yes
Unacceptable	5	Flyable but with unpleasant characteristics requiring constant concentrations and/or tiring techniques.	Doubtful	Yes	Probable
	6	Unacceptable for continuous operation. Satisfactory in emergency.	No	Yes	Probable
	7	Unacceptable - doubtful even in emergency.	No	Doubtful	Improbable
Catastrophic	8	Completely unacceptable. Dangerous or completely unflyable.	No	No	No

*This column should only be used when applying the rating scale to the landing phase.

TABLE III

REQUIREMENTS FOR CONTROL FORCE CHARACTERISTICS

(a) Elevator Manoeuvring Force Gradients (lb. per 'g')

		Fighters and Small Aircraft		Transport Aircraft	
		Minimum	Maximum	Minimum	Maximum
MIL-F-8785	Stick	$\frac{21}{n_1-1}$	$\frac{56}{n_1-1}$	$\frac{45}{n_1-1}$	$\frac{120}{n_1-1}$
	Wheel	$\frac{21}{n_1-1}$	$\frac{56}{n_1-1}$	$\frac{45}{n_1-1}$	$\frac{120}{n_1-1}$
Av.P. 970	Stick	$\frac{1.6(14-n_1)}{n_1-1}$	$\frac{12.8(14-n_1)}{n_1-1}$	$\frac{1.6(14-n_1)}{n_1-1}$	$\frac{12.8(14-n_1)}{n_1-1}$
	Wheel	$\frac{2.0(14-n_1)}{n_1-1}$	$\frac{16(14-n_1)}{n_1-1}$	$\frac{2.0(14-n_1)}{n_1-1}$	$\frac{16(14-n_1)}{n_1-1}$
B.C.A.R.	Stick				
	Wheel	$\frac{70}{n_1-1}$		$\frac{70}{n_1-1}$	

(n_1 = proof 'g')

For aircraft with powered flying controls, forces are at the designer's discretion. There is evidence that pilots would prefer control forces considerably lower than those in current use, provided that aircraft safety is ensured by stops or other suitable means.

TABLE III (Continued)

REQUIREMENTS FOR CONTROL FORCE CHARACTERISTICS

(b) Allowable Breakout Forces

	Control		Static Forces on Control (lb)			
			Fighters and Small Aircraft		Transport Aircraft	
			Minimum	Maximum	Minimum	Maximum
MIL-F-8785	Elevator	Stick	½	3	½	5
		Wheel	½	4	½	7
	Aileron	Stick	½	2	½	4
		Wheel	½	3	½	6
	Rudder		1	7	1	14
B.C.A.R. and Av.P. 970	Elevator	Stick		4		10
		Wheel		4		10
	Aileron	Stick		2		8
		Wheel		2		8
	Rudder			6		10

TABLE IV

ROLLING REQUIREMENTS

	U.S. Military Specification – MIL-F-8785 ASG Amendment 4 (1959)			British Military Specification Av.P. 970		British Civil Airworthiness Requirements
	Power-on Clean Aircraft	Maximum Operational Speed or Mach Number	Power-on Approach	Clean Aircraft	Approach	Approach
Altitude	All Altitudes	Lowest altitude at which M_{DMAX} may be obtained.	Low	10,000'	Low	Low
Speed	Up to V_C	Up to V_D	Approach Speed	.85 V_D or 403.75 kts. Use the lower.	1.3 V_S	Threshold Speed
Primary trainers, observation and other light aircraft.	$\frac{pb}{2V}$ = .09 At speeds $\leqslant$ .8 V_C	$\frac{pb}{2V}$ = .03	$\frac{pb}{2V}$ = .09	$p = \frac{88}{S} V'_D \left(1 - \frac{.3}{\sqrt{1 - M^2}}\right)$ or 7°/second whichever is the higher To be measured at .85 V'_D $\left[V'_D = V_D \text{ or 475 kts. at 10,000' (whichever is the lower)}; M = \text{Mach Number appropriate to } V'_D \right]$		
Horizontal bombers, cargo, heavy attack and other large aircraft.	Where $V_C \leqslant$ 500 kts. $\frac{pb}{2V}$ = .07 up to speeds of .8 M_H or 300 kts., whichever is the lower. Where V_C 500 kts. $\frac{pb}{2V}$ = .07 up to .6 M_H = .05 at .8 M_H	$\frac{pb}{2V}$ = .015	$\frac{pb}{2}$ = 10 ft/sec		$\frac{pb}{2V}$ = .07	From 30° bank through 60° in 7 seconds landing gear and flaps, etc. extended.
Fighters, interceptors and general attack aircraft.	$\frac{pb}{2V}$ = .07 between 1.1 V_S and minimum combat speed At 7,500 ft. From minimum subsonic combat speed to M_C or M = .95 (whichever the lower) it shall achieve 90° bank in 1 sec. 20,000–40,000 ft. From minimum subsonic combat speed to M_C or M = .95, it shall achieve 90° in bank in 1 sec.	30° in bank in 1 second with linear variation between M_C* and M_{DMAX}. 60° bank in 1 second with linear variation between M_C* and M_{DMAX}. *or M.95, whichever is the lower	Average $\frac{pb}{2V}$ = .05 for 1st 30° of bank			

APPENDIX

SUMMARY OF HANDLING QUALITIES INVESTIGATIONS

TEST CONDITIONS	MEASUREMENTS	RESULTS
REFERENCE 3 NASA TN D-779 FLIGHT INVESTIGATION USING VARIABLE STABILITY AIRPLANES OF MINIMUM STABILITY REQUIREMENTS FOR HIGH SPEED, HIGH ALTITUDE VEHICLES (1961)		
Longitudinal: single jet fighter (YF86D) with variable stability and variable control system characteristics. M = 0.8, 35,000 feet. S.F./g = 10 lb. for stable aircraft. Constant stick/control gearing for statically unstable aircraft. $-0.22 < \zeta_{SP} < 1$. Frequency range: 8 rads/second to static divergence, $T_2 = \frac{1}{2}$, 0.15 < control system time constant < 4.0 seconds Lateral: single jet fighter (F-86E). Facilities as in Reference 36. M0.6 and 0.75. 25,000 feet.	Aircraft responses and control deflections. Also stick forces and movements. 2 pilots using Cooper Opinion Rating Scale (table I). Set manoeuvres: rapid turn entries, to stabilise in turns, to hold straight and level flight and to track distant targets. Tests commenced with control system time constant of .15 seconds, then various settings.	Minimum longitudinal controllability boundaries correspond to $T_2 = 1\frac{1}{2}$ seconds oscillatory 1/3 second (aperiodic). Similar boundaries for laterals. Considerable learning time influence. Opinion boundaries drawn in Figures 6, 7, 8 also 13. Results essentially limited to small aircraft because of motion cues and stick characteristics. Provides strong evidence that pilots can control aircraft with negative manoeuvre margins giving quite fierce divergences (at least in still air).
REFERENCE 4 NASA TN D-746 FLIGHT CONTROLLABILITY LIMITS AND RELATED HUMAN TRANSFER FUNCTIONS AS DETERMINED FROM SIMULATOR AND FLIGHT TESTS (1961)		
Fixed base simulator, two aircraft (Reference 3), centrifuge results from other work.	1 pilot - concerned with absolute controllability rather than gradated opinion. Deemed controllable if $\Delta\alpha$, $\Delta\beta$ can be maintained less than 2° and $\Delta\phi < 45°$ for a period of 30 seconds.	Controllability limits drawn in Figure 9. See also Figure 13. Useful work on human transfer functions. Gives some comparison of boundaries derived in flight and fixed base simulators.
REFERENCE 12 WADC TR 54-442 EVALUATIONS OF ELEVATOR FORCE GRADIENTS AND TYPES OF FORCE FEEL IN A B-26 (1954)		
Twin-propeller bomber (B-26) with variable elevator control system. 150, 200, 250 m.p.h. I.A.S. at 10,000 feet. $\zeta_{SP} = 0.7$, $w_{SP} = .45$ c/s at 200 m.p.h.	α, n(g), η, $\frac{d\alpha}{dt}$, stick deflection and stick force. 12 pilots, various rating scales, up to 7 points. No specific manoeuvres. Investigations into fixed and variable spring rates, also bob-weights.	Optimum stick force varied with airspeed, but was about 60 lb/g mean. Fighter pilots flying the B-26 consistently preferred lighter forces. Bob-weight disliked, also fixed springs. Results indicate that Fs/g can have a wide range of values and still be acceptable.
REFERENCE 13 WADC TR 57-155 EFFECTS OF BREAKOUT FORCE ON LONGITUDINAL HANDLING QUALITIES (1957)		
Twin-propeller bomber (B-26) with variable elevator control system. 200 m.p.h. I.A.S. $.35 < w_{SP} < .6$ c/s, $.3 < \zeta_{SP} < .7$ SF/g = 35 lb., 60 lb.	1 pilot, rating scale acceptable good, acceptable, acceptable poor and unacceptable with plus and minus interpolations on each, save the latter - hence 10 point scale. Set manoeuvres: trim straight and level, rapid pull-ups and bunts, entry to and exit from shallow and steep turns, fly with stick 20 lb. out of trim.	Control friction has important effect on opinion ratings and the effects vary with aircraft dynamics, stick forces per g and the task involved. Breakout force tends to be more important for aircraft with large w_n and low damping.

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SUMMARY OF HANDLING QUALITIES INVESTIGATIONS

TEST CONDITIONS	MEASUREMENTS	RESULTS
REFERENCE 16 NASA TN D-912 EFFECTS OF CONTROL FEEL CONFIGURATION ON AIRPLANE LONGITUDINAL CONTROL RESPONSE (1961)		
Transonic fighter aircraft (F11-F) with variable feel system - stick force could vary in response to n, $\ddot{\theta}$, $\dot{\theta}$, stick deflection and rate. M.85, 28,000 feet.	Stick force and movement, η, n(g), $\ddot{\theta}$, $\dot{\theta}$. More than 1 pilot. Manoeuvres: entries to turns and steady pull-ups.	The American military requirement "that the peak force per g encountered during abrupt pitching manoeuvres should not fall below the steady force per g" was found to be insufficiently stringent for lightly damped conditions. It is shown that normal acceleration feel has a strong tendency to destabilise the short period and must be balanced by another feel component, preferably pitch acceleration feel.
REFERENCE 17 WADC TR 55-299 FLIGHT EVALUATIONS OF VARIOUS LONGITUDINAL HANDLING QUALITIES IN A VARIABLE STABILITY JET FIGHTER (1955)		
Jet fighter (F94) with variable stability equipment. 300 knots I.S.A., 20,000 feet. $0.2 < \zeta_{SP} < 1.5$ $0.2 < w_{SP} < 0.8$ c/s $3 < S.F/g < 16$ lb.	1 pilot, five point scale - optimum, acceptable good, acceptable, acceptable poor, unacceptable, with plus or minus ratings if desired. Set manoeuvres: trim in level flight, abrupt pull-ups and bunts, slow and rapid entries to turns, sustained dive and recover.	Opinion contours as functions of w_{SP} and ζ_{SP} See Figures 2, 3, 13. Opinion contours are relative to fighter aircraft only and should not be used for large aircraft.
REFERENCES 18 and 20 WADC TR 57-719 ADDITIONAL FLIGHT EVALUATIONS OF VARIOUS LONGITUDINAL HANDLING QUALITIES IN A VARIABLE STABILITY JET FIGHTER (1958)		
Jet fighter (F94) with variable stability equipment. 350 knots I.A.S., 15,000 feet. $0.2 < \zeta_{SP} < 1.5$ $0.2 < w_{SP} < 1.15$ c/s.	3 pilots. Rating scale as Reference 18, also manoeuvres.	Opinion contours as functions of w_{SP} and ζ_{SP} Stick force per g only of significant effect for high w_{SP}, high ζ_{SP}. See Figures 4, 5, 13. Results can only be used in relation to small aircraft and fighters.
REFERENCE 20 WADC TR 54-594 FLIGHT EVALUATIONS OF VARIABLE SHORT PERIOD AND PHUGOID CHARACTERISTICS IN A B-26 (1954)		
Twin propeller bomber (B-26) with variable stability equipment - varies m_w and $m_{\dot{w}}$, also m_u and $m_{\dot{u}}$. 150 - 200 m.p.h., 10,000 feet. 66 lb/g, 1.83 in/g. stick characteristics constant.	α, n(g), $\dot{\alpha}$, $\dot{u}$, stick force and deflection. 1 pilot, 19 point rating scale ("acceptable poor plus" etc.).	Opinion contours as functions of w_{SP} and ζ_{SP}. See Figures 11 and 18. Phugoid rating is roughly proportional to damping. See Figure 21. Results strictly applicable to light attack bomber but are probably valid for all medium sized aircraft.

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TEST CONDITIONS	MEASUREMENTS	RESULTS
REFERENCE 21 Cornell TB-1313-F-1 MINIMUM FLYABLE LONGITUDINAL HANDLING QUALITIES OF AIRPLANES (1959)		
Twin propeller bomber (B-26). Variable stability (m_w and $m_{\dot{w}}$). Mirror landing approaches, 117 - 122 knots. Smooth and rough air.	3 pilots - 3 point rating scale - acceptable, acceptable poor and unacceptable - facility for using plus or minus as appropriate. Manoeuvre: mirror approach: if this can be done it is assumed that the aircraft can be landed successfully.	Minimum flyable boundaries for smooth and rough air in terms of sum and product of short period characteristic roots. See Figures 12 and 23. Results show that aircraft with small negative manoeuvre margins can be landed by experienced pilots even in rough air. Pilots comments on various responses are illuminative.
REFERENCE 24 NASA TN D-348 A STUDY OF LONGITUDINAL CONTROL PROBLEMS AT LOW AND NEGATIVE DAMPING AND STABILITY WITH EMPHASIS ON EFFECTS OF MOTION CUES (1960)		
Centrifuge, correlation with other flight tests - also use of side-arm controller. $-10 < w_n^2 < 36$ 8 lb/g stick force $-1 < 2\zeta w_n < 10$ when stable	6 pilots - Cooper Scale (table I). Set manoeuvres: rapid changes of pitch angle and 'g'. Simulated tracking in rough air. Comparisons of centrifuge, pitch chair and fixed base simulator results with flight tests.	Opinion boundaries in terms of sum and product of short period characteristic roots. See Figure 10. It is suggested that motion cues are important only for high frequency lightly damped systems or moderately damped statically unstable systems.
REFERENCE 26 Cornell TB-574-F-6 A FLIGHT INVESTIGATION OF ACCEPTABLE ROLL-YAW RATIO OF THE DUTCH ROLL AND ACCEPTABLE SPIRAL DIVERGENCE (1952)		
Single propeller fighter aircraft (F4U-5) n_v, l_v, n_r, l_r, n_p, l_p variable. 195 knots I.A.S., 10,000 feet. $0 < 1/C_{\frac{1}{2}} < 3.4$, $.15 < \lvert\phi/\beta\rvert < 4.5$ $6.5 < T_2 < 35$ seconds (spiral). Generally smooth air.	ϕ, p, r, β, P, $C_{\frac{1}{2}}$, T_2, various control deflections. 8 pilots, rating scale intolerable, tolerable, satisfactory, excellent. Manoeuvres: (a) Dutch Roll: steady sideslip suddenly released, tracking stationary and moving targets, entry into and exit from instrument turns and also steep turns. (b) Spiral: initiate gentle turn and release controls, maintain straight and level flight on instruments, 40° banked turns on instruments, hands-off flight during simulated navigation problem, simulated instrument approach at safe altitude.	Intolerable - satisfactory Dutch-roll boundary given as function of $1/C_{\frac{1}{2}}$ versus $\lvert\phi/v\rvert$, versus $\lvert\phi/\beta\rvert$ and versus $\lvert\phi/v_E\rvert$ For spiral: minimum tolerable T_2 = 12 seconds minimum satisfactory T_2 = 20 seconds Typical early work showing significance of $\lvert\phi/\beta\rvert$ etc. Formed part of basis for U.S. Military Specification (Reference 7).

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TEST CONDITIONS	MEASUREMENTS	RESULTS
REFERENCE 27 Cornell TB-1094-F-1 FLIGHT EVALUATIONS OF THE EFFECT OF VARIABLE SPIRAL DAMPING IN A JTB-26B AIRPLANE		
Two propeller light bomber (JTB-26B) $n\phi$ varied by ϕ-feedback to forward auxiliary surfaces. 130 - 175 knots I.A.S., 10,000 feet. 0 $1/T_{\frac{1}{2}}$ 0.2, 0 $1/T_2$ 0.2 Light to moderate turbulence.	ϕ, ψ, various control deflections, $T_{\frac{1}{2}}$, T_2. 2 pilots, rating scale unacceptable, acceptable poor, acceptable, acceptable good, very good. Data taken during simulated IFR straight and level flight, turns and approaches, and straight and level VFR flight and VFR turns.	All configurations considered 'acceptable' with gradations from acceptable poor to acceptable good as spiral damping increased.
REFERENCE 29 NASA Memo 1-29-59A A PILOT OPINION STUDY OF LATERAL CONTROL REQUIREMENTS FOR FIGHTER TYPE AIRCRAFT (1958)		
Fixed and rolling single degree of freedom simulators, limited flight on 7 fighter aircraft. Simulator transfer function $\frac{\phi}{\zeta} = \frac{\tau_R L_\zeta}{s(\tau_R s + 1)}$ $L\zeta$, τ_R varied. For flight tests, ζ max. varied on 2 aircraft. Stick force = 2 lb/inch constant for all simulator tests.	2 pilots, Cooper rating scale (table I). Set manoeuvres: included rapid rolling (and pulling g in flight tests) and roll-and-stop manoeuvres.	Opinion boundaries as function of $L_\xi\, \xi_{max}$. τ_R (drawn in Figure 26). Fixed and rolling simulator agree quite well except for conditions corresponding to high attainable steady state rolling velocities. Flight test points generally agree.
REFERENCE 30 IAS Paper 60-93 IN-FLIGHT SIMULATION OF RE-ENTRY VEHICLE HANDLING QUALITIES (1960)		
Jet trainer aircraft (T-33). Comprehensive variable-stability installation. w_d, ζ_d, $\lvert\phi/\beta\rvert$, w_ϕ, τ_R and aileron stick force varied. M = 0.6, 25,000 feet. Generally smooth air.	1 pilot, modified Cooper rating scale. Set manoeuvres: straight and level flight, turning flight - shallow and steeply banked, rolling flight (up to 180° and 360° where possible), and straight flight in presence of simultaneous pitch, roll and yaw disturbances.	Curves of opinion versus τ_R (roll time constant) and aileron stick force given for good Dutch roll configurations. At optimum values of these, lateral-directional qualities were investigated by symmetric variation of w_d, ζ_d, $\lvert\phi/\beta\rvert$ and w_ϕ. Opinion shown to vary with independent variation of ζ_d, $\lvert\phi/\beta\rvert$, w_ϕ/w_d and to a lesser extent with w_d. Tends to confirm theoretical work (Reference 41). Qualitative rather than quantitative results.

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SUMMARY OF HANDLING QUALITIES INVESTIGATIONS

<table>
<tr><th>TEST CONDITIONS</th><th>MEASUREMENTS</th><th>RESULTS</th></tr>
<tr><td colspan="3">REFERENCE 31 R.A.E. Report Aero 2654 A FLIGHT STUDY OF THE SIDESTEP MANOEUVRE DURING LANDING (1956 TESTS)</td></tr>
<tr><td>14 aircraft ranging from a delta wing research configuration to large transport aircraft.

Typical approach conditions for each aircraft.

Daylight, good visibility. Some checks made in poor visibility and at night.</td><td>ϕ, ψ, p, r, lateral g.
Also measured rolling characteristics (rates and accelerations for full and half aileron) and oscillatory characteristics at altitude - results were corrected to sea level.

Various airline and R.A.E. pilots (30 in all).

General comments on rolling characteristics, oscillatory characteristics and ability to perform the set manoeuvres.

No specific rating scale.

Sidesteps of up to 800' to be corrected on glide path of 3^{0} (400' for 4^{0}), starting at 300' altitude.</td><td>Aircraft with available rates of roll less than 12^{0}/second gave poor performance and a minimum or at least 15^{0}/second is desirable. Control forces and harmony shown to be of considerable importance.

Time needed to correct initial displacements:

Initial displacement: 150 ft. Time: 9 - 14 secs.
350 12 - 18
750 15 - 26
(this covers all the aircraft tested).</td></tr>
<tr><td colspan="3">REFERENCE 32 NACA RM A51E16 FLIGHT STUDY OF REQUIREMENTS FOR SATISFACTORY LATERAL OSCILLATORY CHARACTERISTICS OF FIGHTER AIRCRAFT (1951)</td></tr>
<tr><td>Single propeller fighter aircraft (F6F).
120 - 200 knots I.A.S., 7,000 feet.
l_v, n_v, n_r variable.
2 < period (seconds) < 7.4.</td><td>P, $C_{\frac{1}{2}}$, $\overline{\lvert\phi/\beta\rvert}$, $\lvert\phi/V_E\rvert$, ζ, $\overline{\xi}$

12 pilots using numerical rating scale:

(1), (2), (3) "good" (safe and) (desirable) (or) (pleasant)
(4), (5), (6) "tolerable" (not dangerous) (but undesir-) (able)
(7), (8), (9) "intolerable" (flyable but) (dangerous in) (normal fighter) (operation)</td><td>Pilot opinion as function of $1/C_{\frac{1}{2}}$ and $\lvert\phi/V_E\rvert$.
Tests occasionally encountered an unstable aperiodic mode, distinct from the spiral.
Minimum values of 2.6 and 3.4 seconds to double amplitude correspond to minimum tolerable and minimum satisfactory levels.</td></tr>
</table>

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SUMMARY OF HANDLING QUALITIES INVESTIGATIONS

TEST CONDITIONS	MEASUREMENTS	RESULTS
REFERENCE 35 NASA Memo 12-10-58A FLIGHT INVESTIGATION TO DETERMINE THE LATERAL OSCILLATORY DAMPING ACCEPTABLE FOR AN AIRPLANE IN THE LANDING APPROACH (1958)		
Single jet fighter (F-86E). 170 knots I.A.S., 10,000 feet. n_v, n_r, n_p, $n\xi$, l_v, l_p, $l\xi$ variable. $n\xi / l\xi > 0$ for all flights. $1.5 < p < 6.9$, $.5 < \lvert\phi/V_E\rvert < 1.65$ $-1.7 < 1/C_{\frac{1}{2}} < 4.65$. Smooth air and simulated rough air.	$1/C_{\frac{1}{2}}$, $1/T_{\frac{1}{2}}$, $\lvert\phi/V_E\rvert$. 7 pilots, Cooper scale (table I). Based on i) lateral oscillation, controls fixed ii) handling in smooth air iii) handling in rough air iv) overall control. Aileron yaw was preselected to optimum by each pilot.	Opinion boundaries as functions of $1/C_{\frac{1}{2}}$ versus $\lvert\phi/V_E\rvert$, and $1/T_{\frac{1}{2}}$ versus $\lvert\phi/V_E\rvert$. The latter was found to be preferable although slightly inconsistent with additional flight test data. Boundaries are drawn in Figure 31 with some slight modifications. Foundation of current thought on lateral damping. Note that optimum aileron-yaw was used.
REFERENCE 36 IAS Paper No. 60-18 DEVELOPMENT OF LATERAL-DIRECTIONAL FLYING QUALITIES CRITERIA FOR SUPERSONIC VEHICLES BASED ON A STATIONARY SIMULATOR STUDY (1960)		
Fixed simulator, six degree of freedom dynamics simulated, and control system lags.	11 pilots using five point scale: excellent, satisfactory, acceptable, emergency only and unflyable. Based on i) entry to and exit from 30^0 banked turn ii) control pulses iii) one 'g' 60^0-60^0 and 90^0-90^0 turns iv) rolling pull-outs.	Opinion boundaries for Dutch roll are functions of $KT_{\frac{1}{2}}$ and $\lvert\phi/V_E\rvert$, where $K = P$ for $P < 2.4$, $K = 2.4$ otherwise. Also derives manoeuvring criteria for amount of lateral oscillation allowable in rolling manoeuvres in terms of 1st peak overshoot to steady state. See Figure 33. In general, disagrees with most other lateral studies.
REFERENCE 37 NASA TN D-1141 THE EFFECT OF LATERAL-DIRECTIONAL CONTROL COUPLING ON PILOT CONTROL OF AN AIRPLANE AS DETERMINED IN FLIGHT AND IN A FIXED BASE SIMULATOR (1961)		
Single jet fighter aircraft (F-86E) 170 knots I.A.S., 10,000 feet. Variable stability equipment as in Reference 35. Parameter range - $.13 < \zeta_d < .22$ $1.5 < w_d < 2$ $\lvert\phi/V_E\rvert \simeq 0.6$	2 pilots, ratings on Cooper scale (table I) Test manoeuvres: i) abrupt 45^0-60^0 bank angle turn entries using rudder to minimise sideslip ii) abrupt aileron reversals to effect rolling oscillations iii) rolling through $\pm 360^0$ bank angle with and without rudder.	Opinion boundaries as functions of ζ_d and $(w_\phi/w_d)^2$ (as drawn in Figure 34). General qualitative conclusion that the optimum aileron induced yaw differed slightly from zero, and increase of ζ_d increased the range of acceptable aileron yaw. Suggests other parameters that may be useful for predicting lateral qualities in various circumstances.

ACKNOWLEDGEMENT

We acknowledge with thanks the co-operations of de Havilland Aircraft Limited and Vickers Aircraft Limited in supplying data for various aircraft.

IMPORTANT NOTE

Many of the dynamic characteristics of the various aircraft depicted on the following figures are based on estimates. They should not in any way be taken as the manufacturer's data, and not necessarily as flight test data.

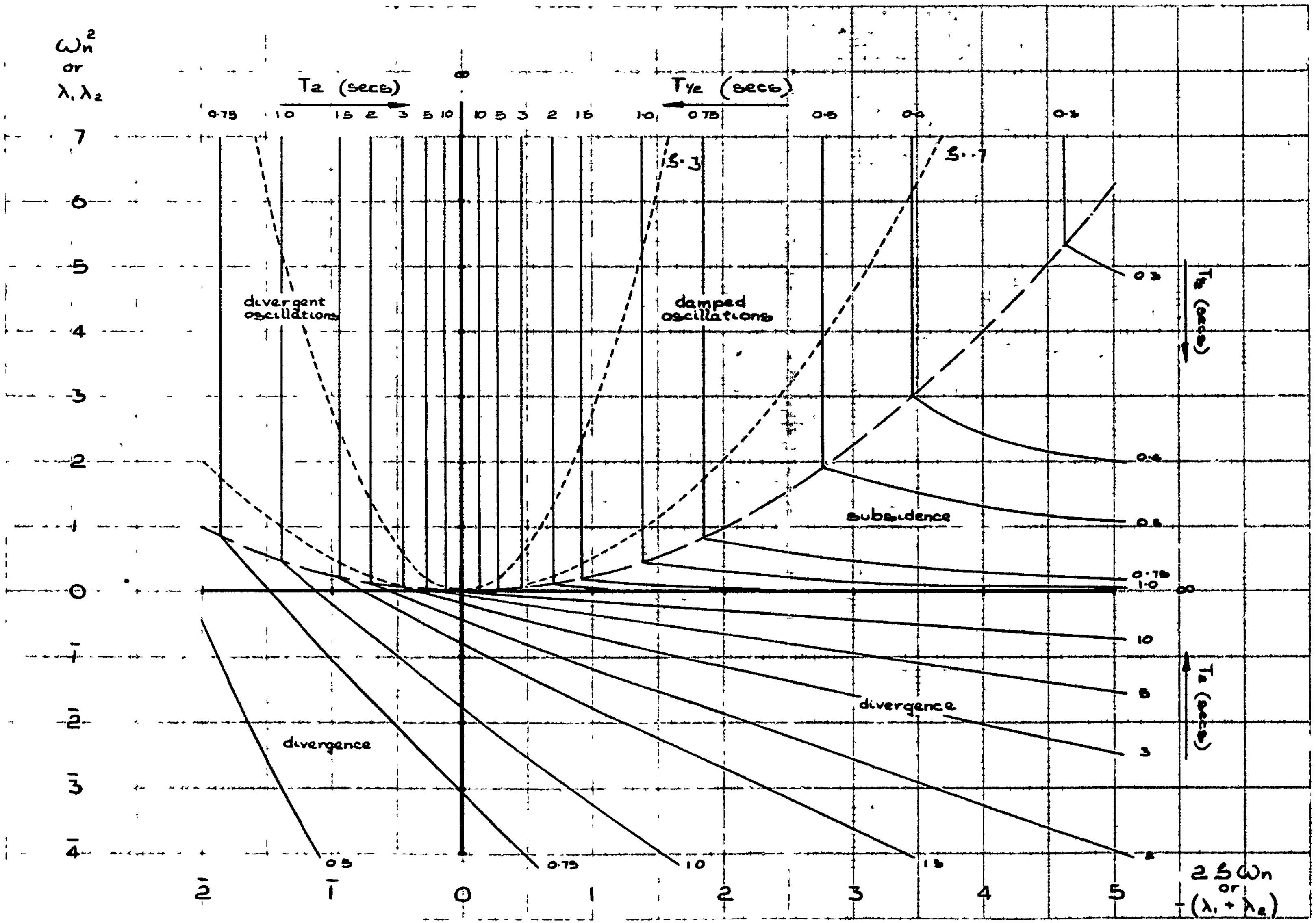
In particular the V.C. 10 and Bristol Type 188 information is derived from pre-flight estimates.

In spite of the above restrictions it is felt that the characteristics presented make a material contribution to the appreciation of the various criteria.

D 70357/1/125875 K.4 5/66 TB/CL

TIME TO HALF OR DOUBLE AMPLITUDE FOR THE NORMAL FAST MODE ~ DIFFERENTIAL EQUATION COEFFICIENTS

FIG. 1



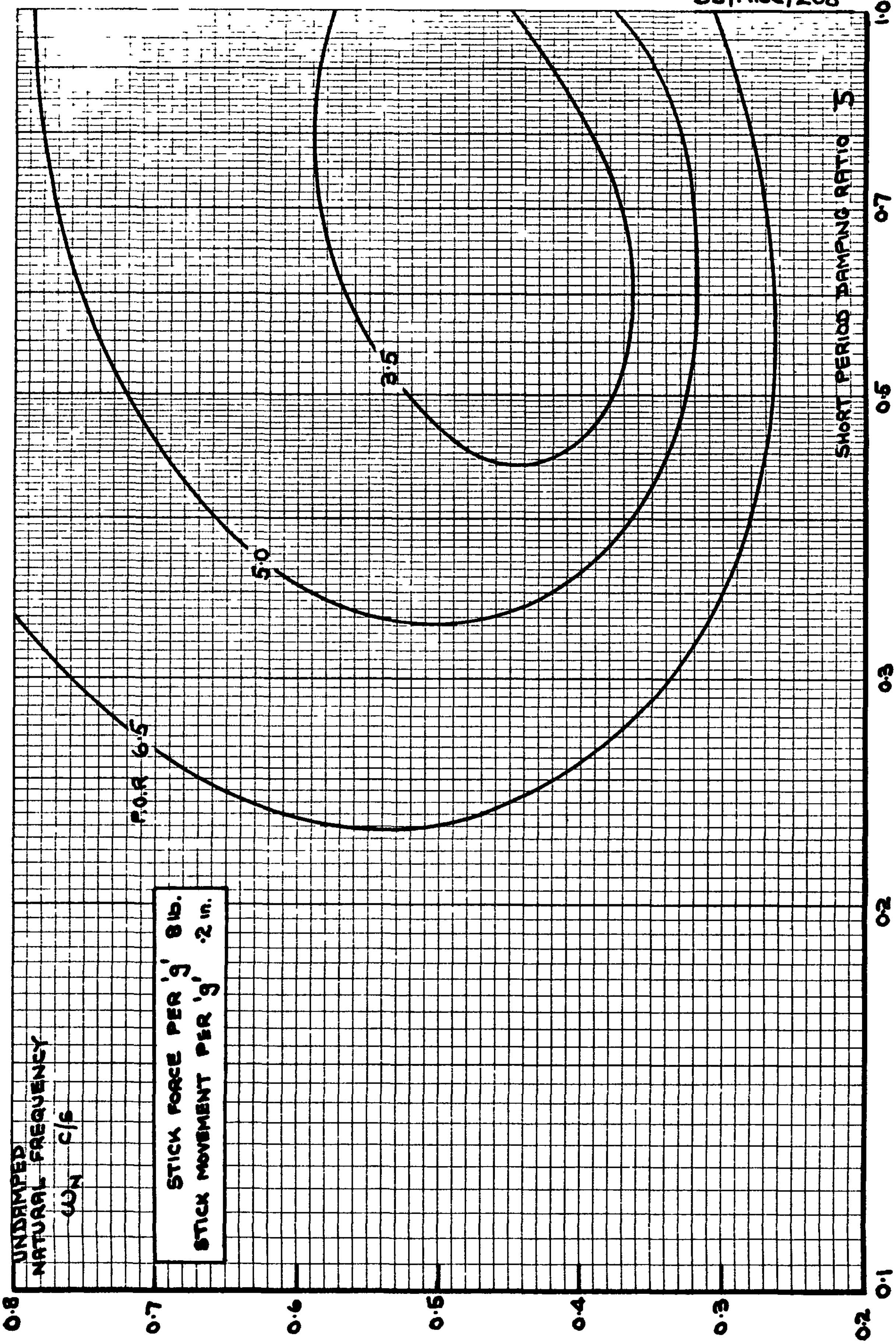
ACW 14 2 62

FIG. 2

FIGHTER LONGITUDINAL DYNAMICS — OPINION BOUNDARIES

WADC 55-299 (REF 18)

DS/MISC/208



EFFECT OF STICK FORCE AND STICK MOVEMENT PER 'g' ON PILOT OPINION — FIGHTER AIRCRAFT, STICK CONTROL

FIG. 3

W.A.D.C. TR 55-299 (REF. 18)

DS/MISC/209

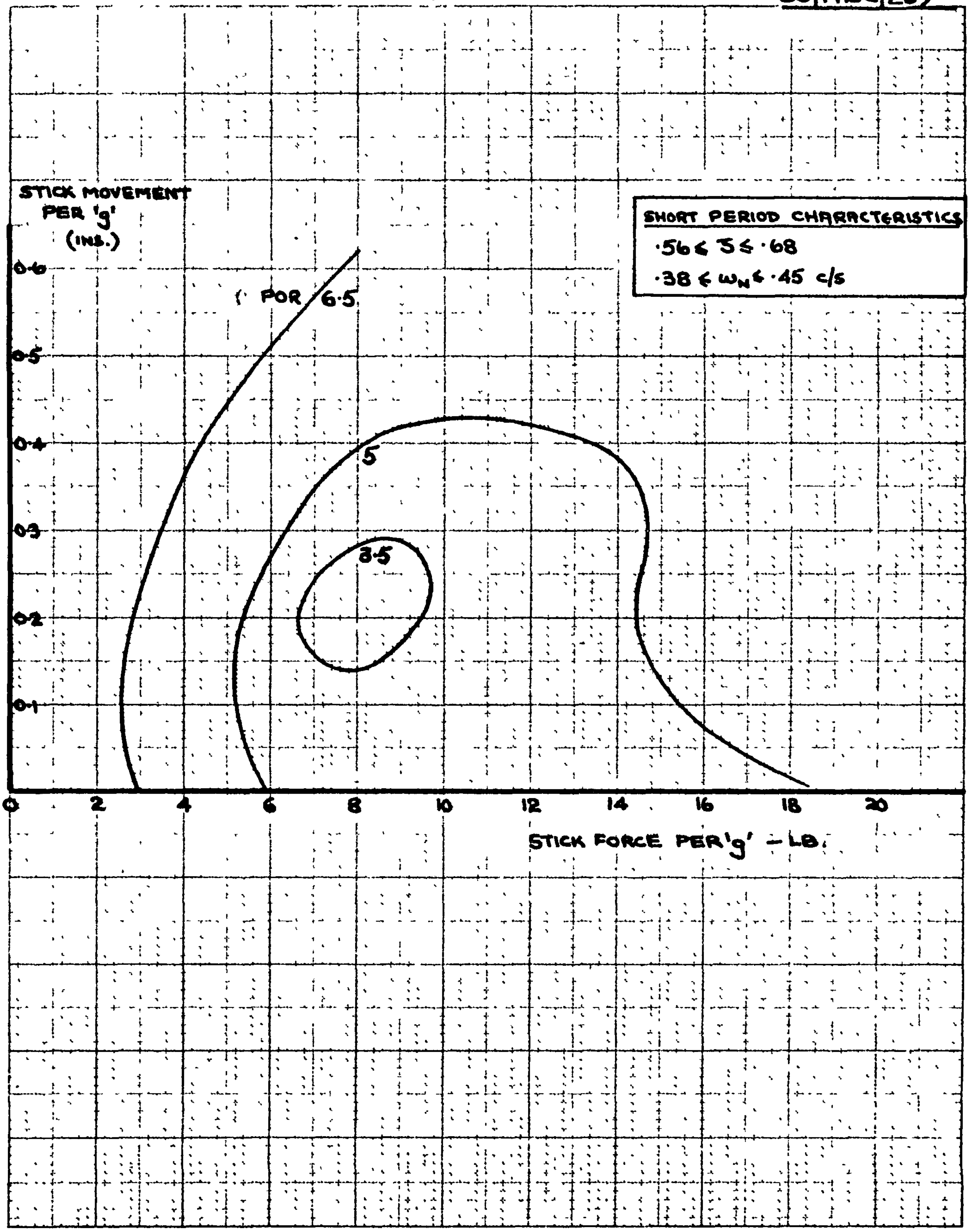


FIG. 4

FIGHTER LONGITUDINAL DYNAMICS - OPINION BOUNDARIES

W.A.D.C. 57-719 PART I (REF. 19) DS/MISC/210

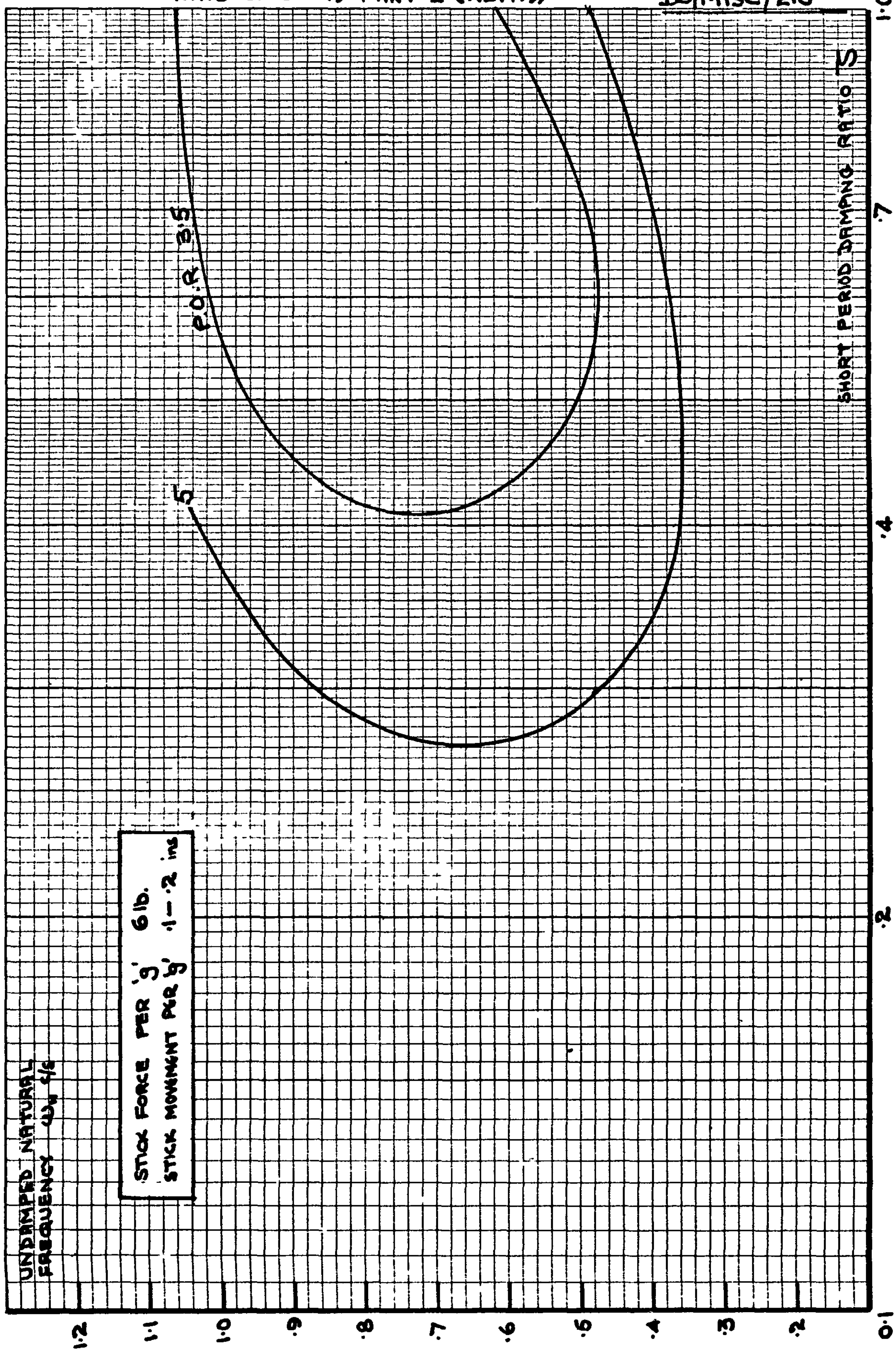
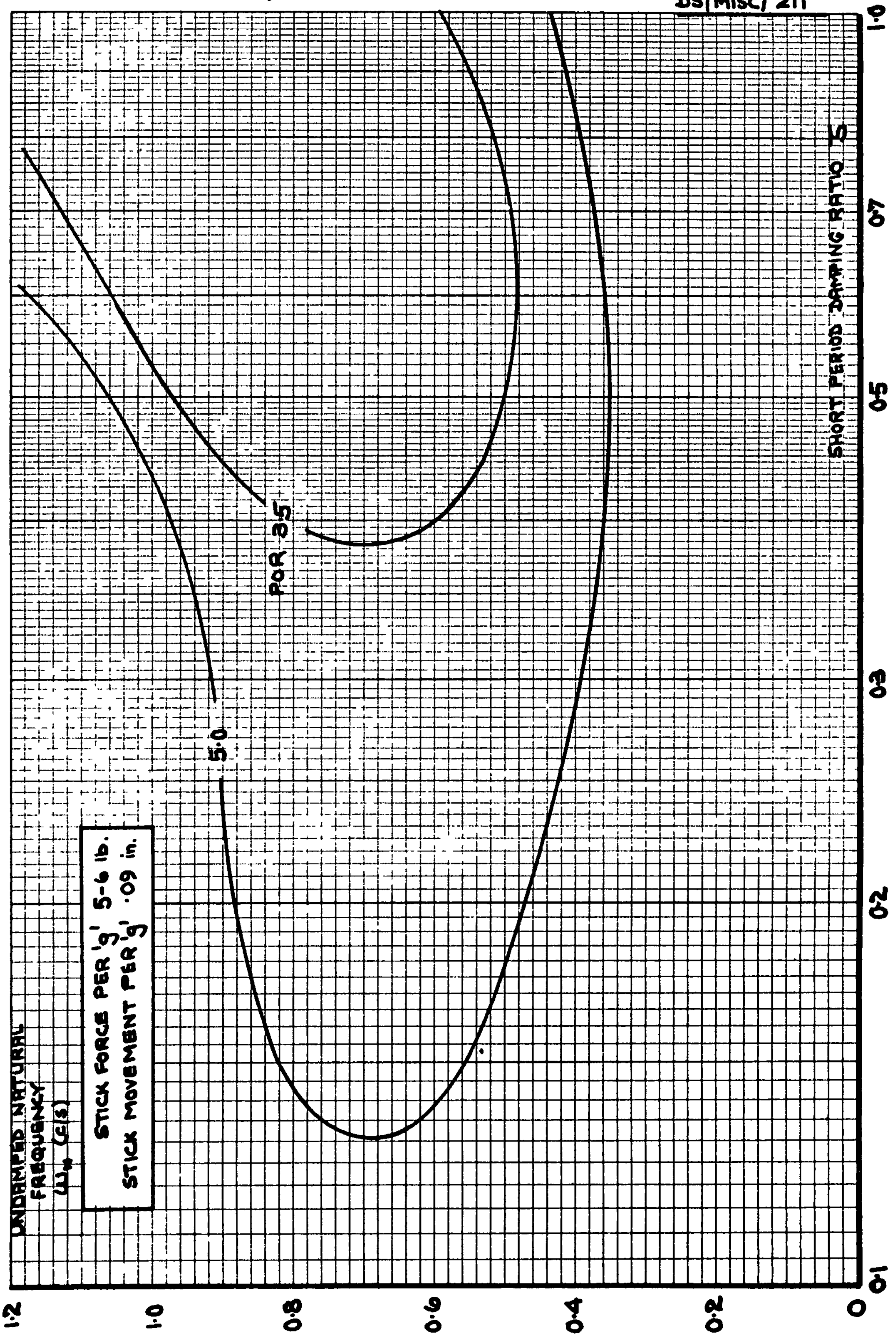


Fig. 5

FIGHTER LONGITUDINAL DYNAMICS - OPINION BOUNDARIES

WADC TR 57-719 PART II (REF. 20)

DS/MISC/211



FIGS 6,7

FIGHTER LONGITUDINAL DYNAMICS - OPINION BOUNDARIES

NASA TN D-779 (REF. 3)

DS/MISC/212

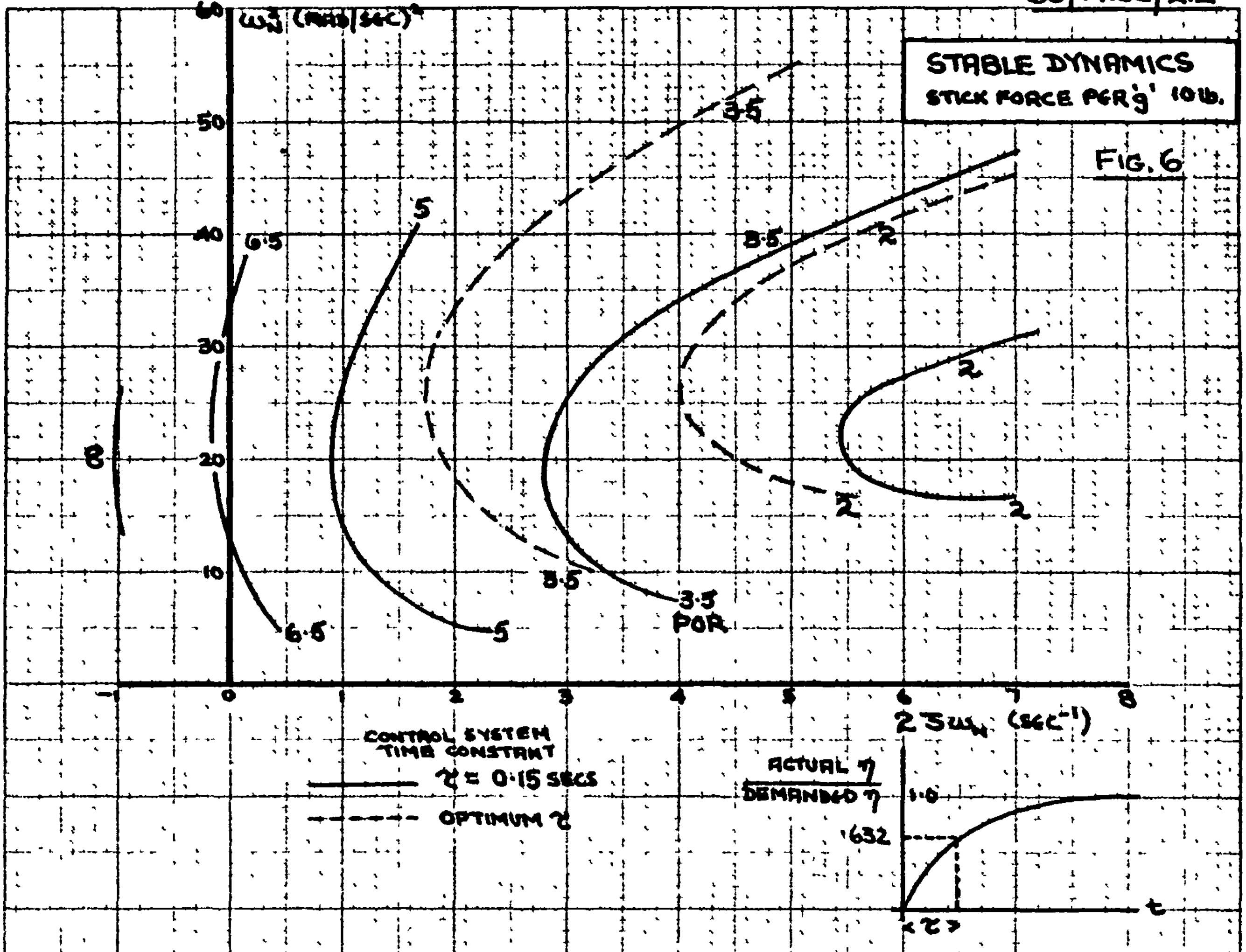


FIG. 6

FIG. 7

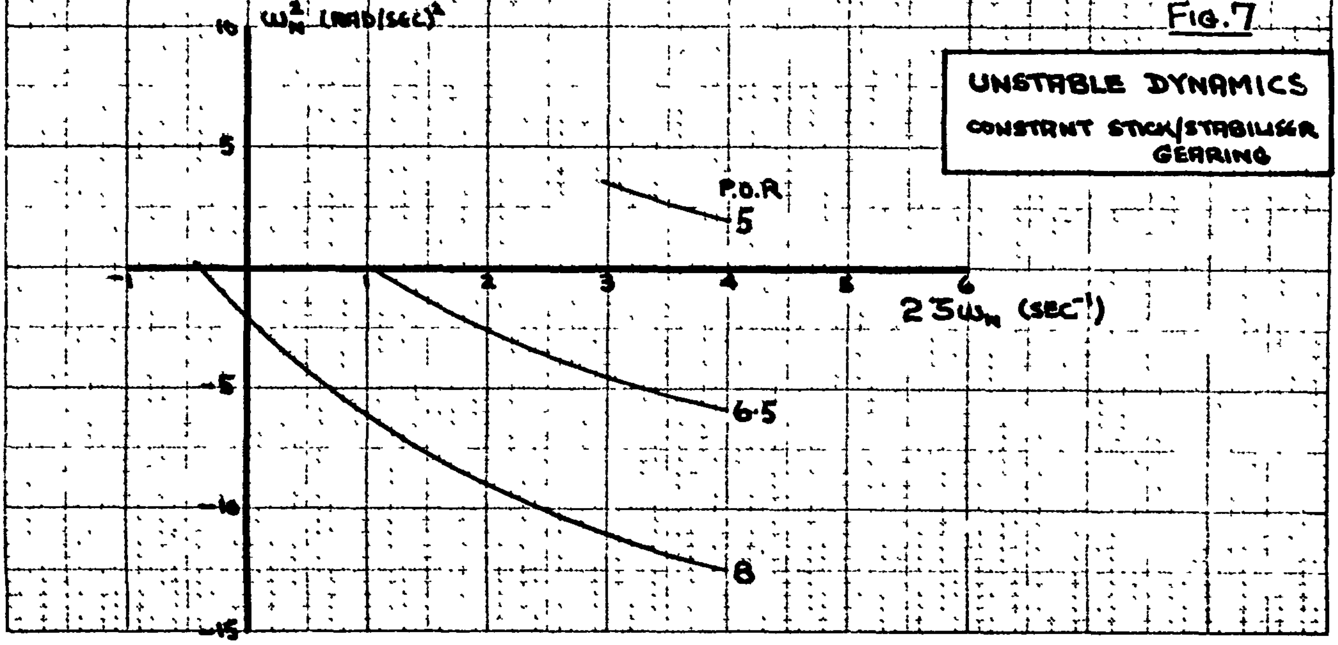


FIG. 8

FIGHTER LONGITUDINAL DYNAMICS - CONTROL SYSTEM TIME CONSTANTS SELECTED BY PILOT AS OPTIMUM

NASA TN D-719 (REF. 3)

DS/MISC/213

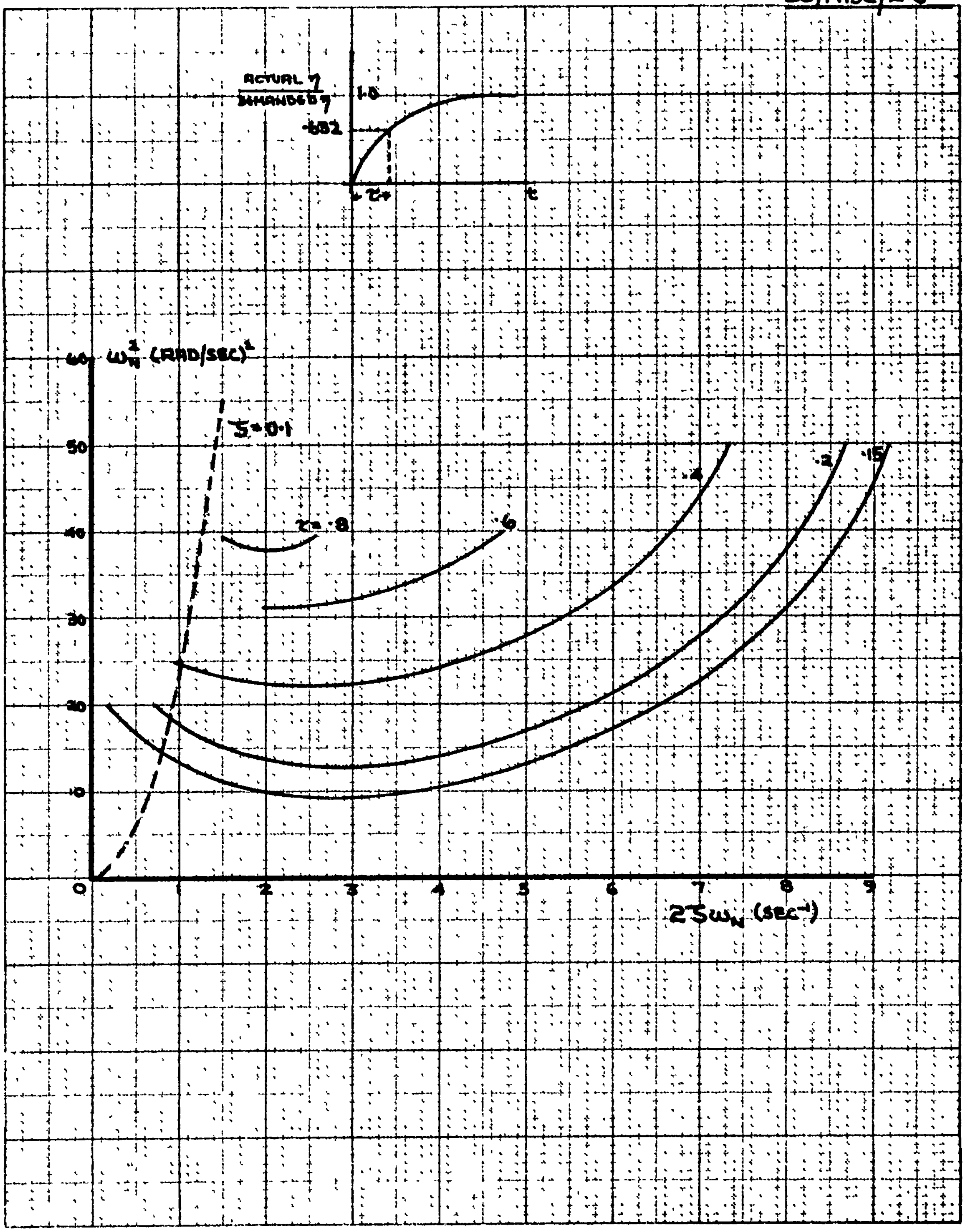


FIG. 9

EFFECT OF PILOT LEARNING AND OF DISTRACTION ON MINIMUM CONTROLLABLE LONGITUDINAL DYNAMICS

NASA TN-D-746 (REF. 4)

DS/MISC/214

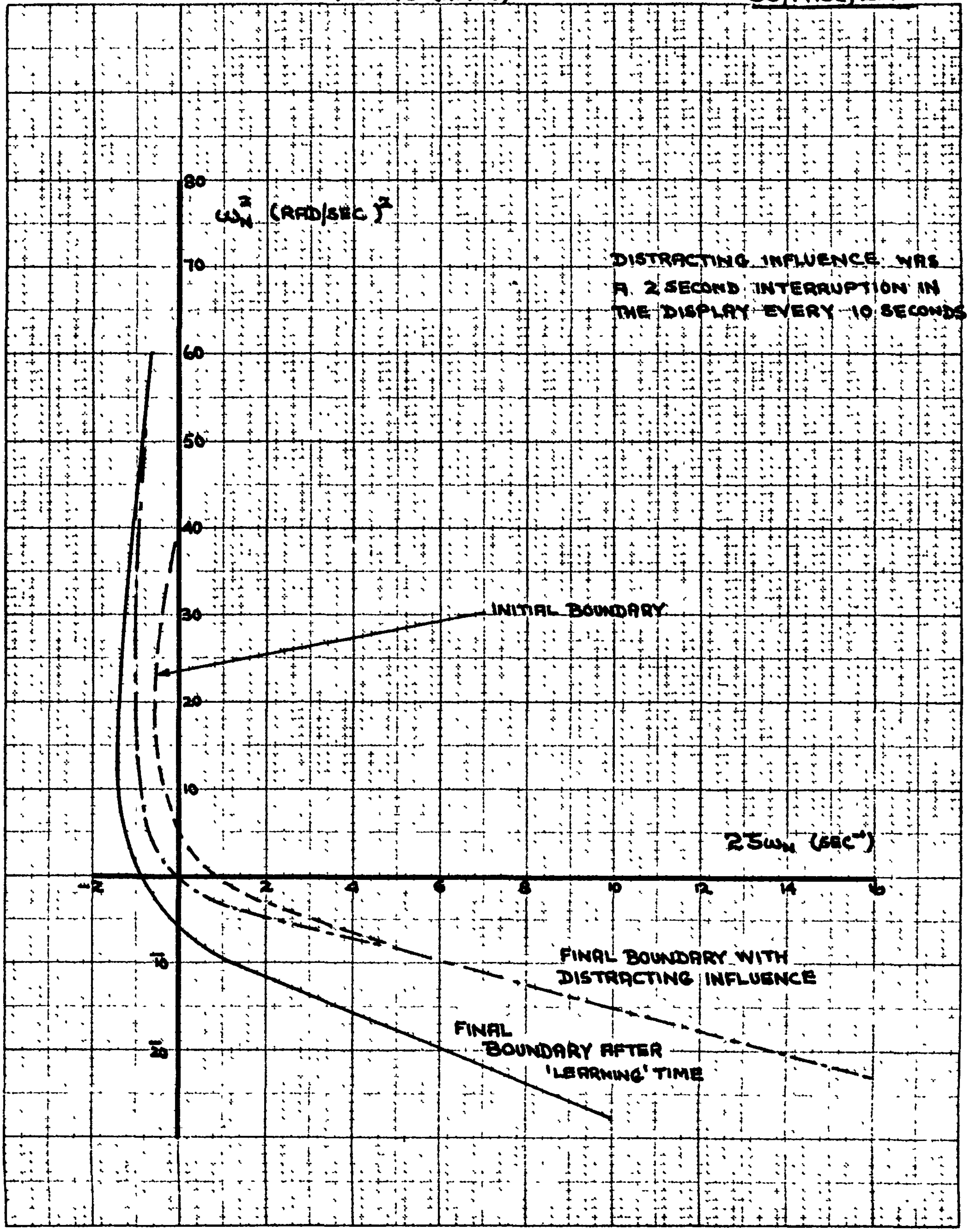
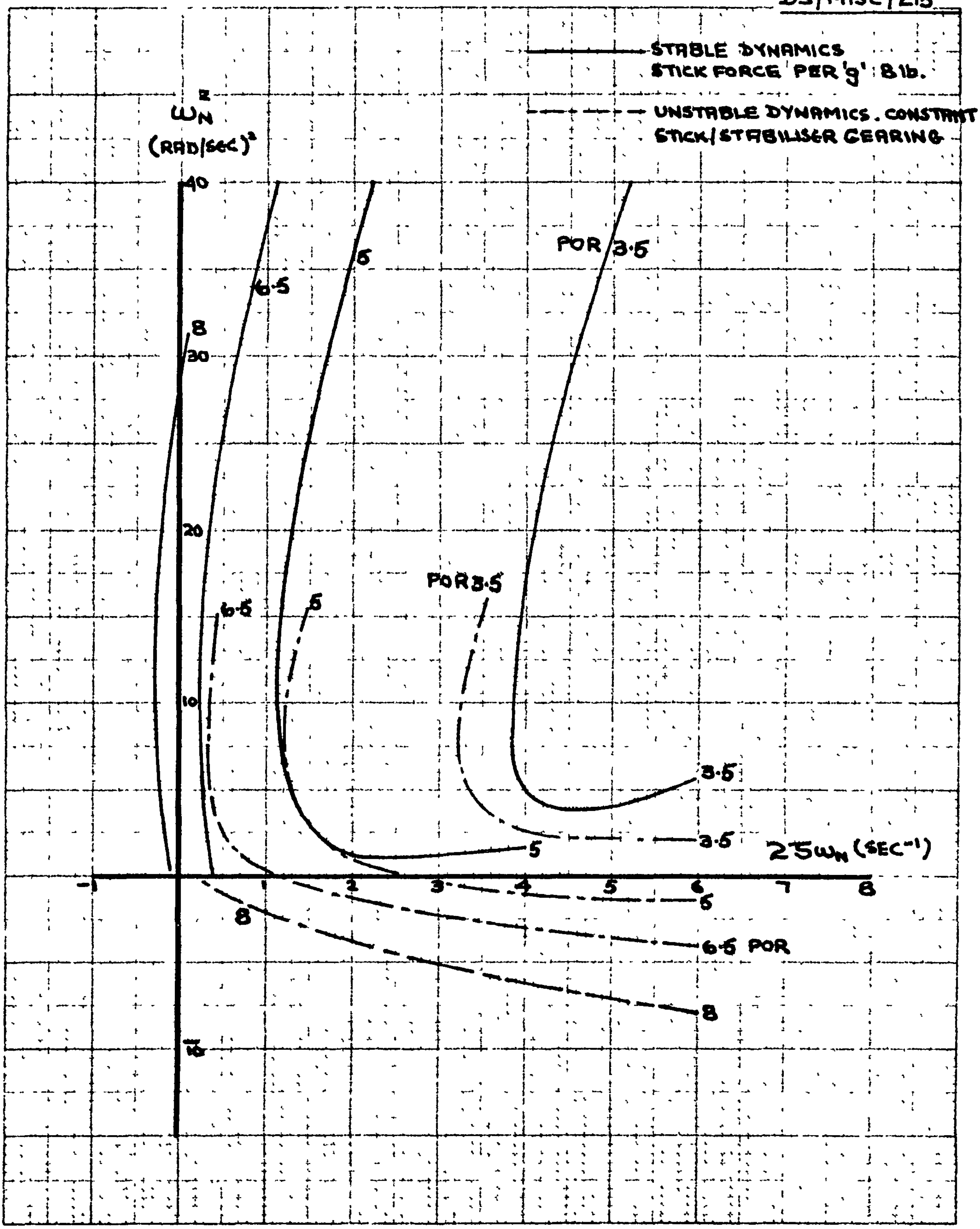


FIG. 10

FIGHTER LONGITUDINAL DYNAMICS — OPINION BOUNDARIES DETERMINED IN CENTRIFUGE

NASA TN-D-346 (REF. 25)

DS/MISC/215



LIGHT BOMBER LONGITUDINAL DYNAMICS – OPINION BOUNDARIES FIG. 11

W.A.D.C. TR 54-594 (REF. 21)

DS/MISC/216

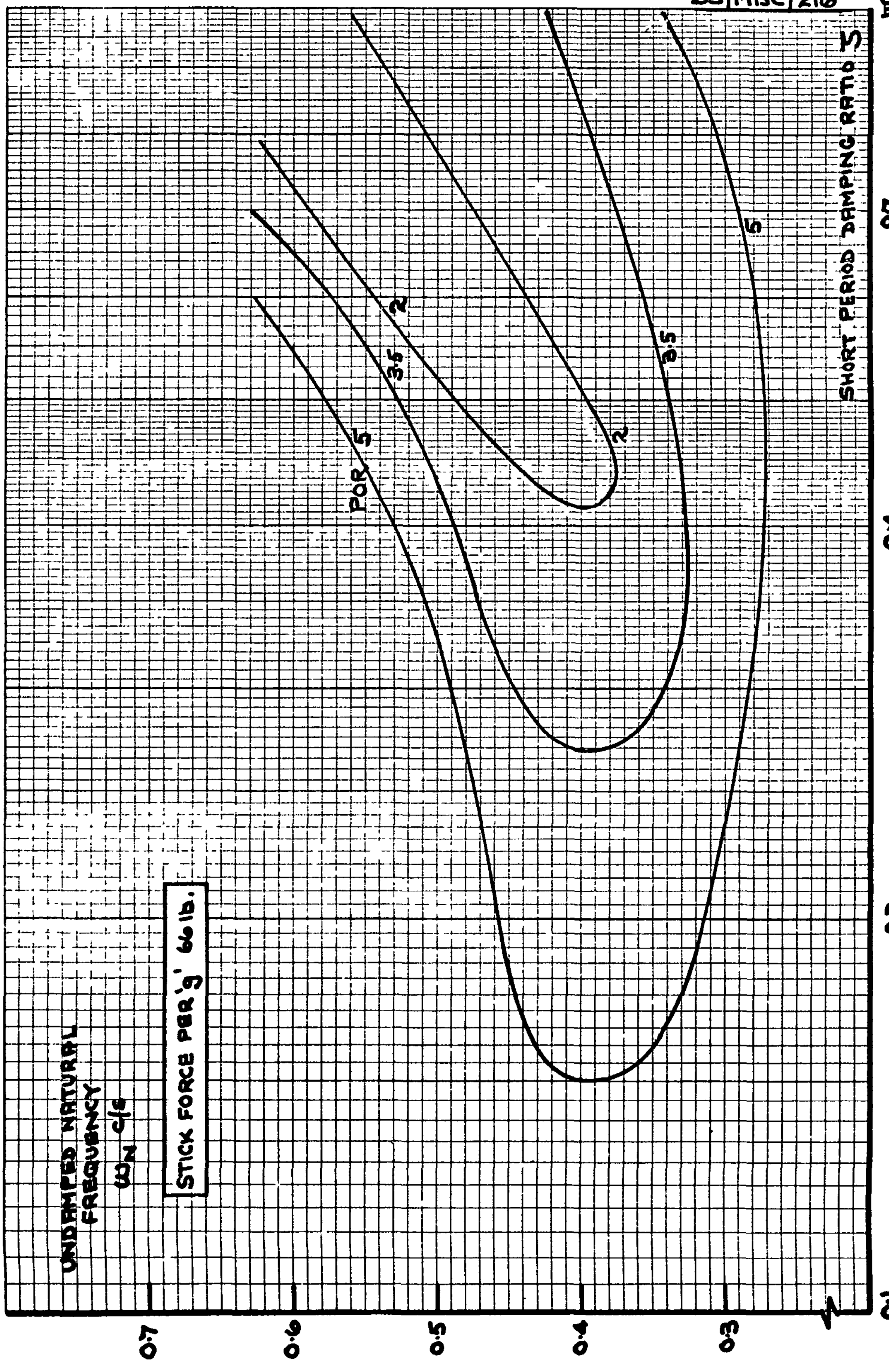


FIG. 12

LONGITUDINAL DYNAMICS – MINIMUM CONTROLLABLE BOUNDARIES

CORNELL AERO. LAB. TB-1313-F-1 (REF 22)

DS/MISC/217

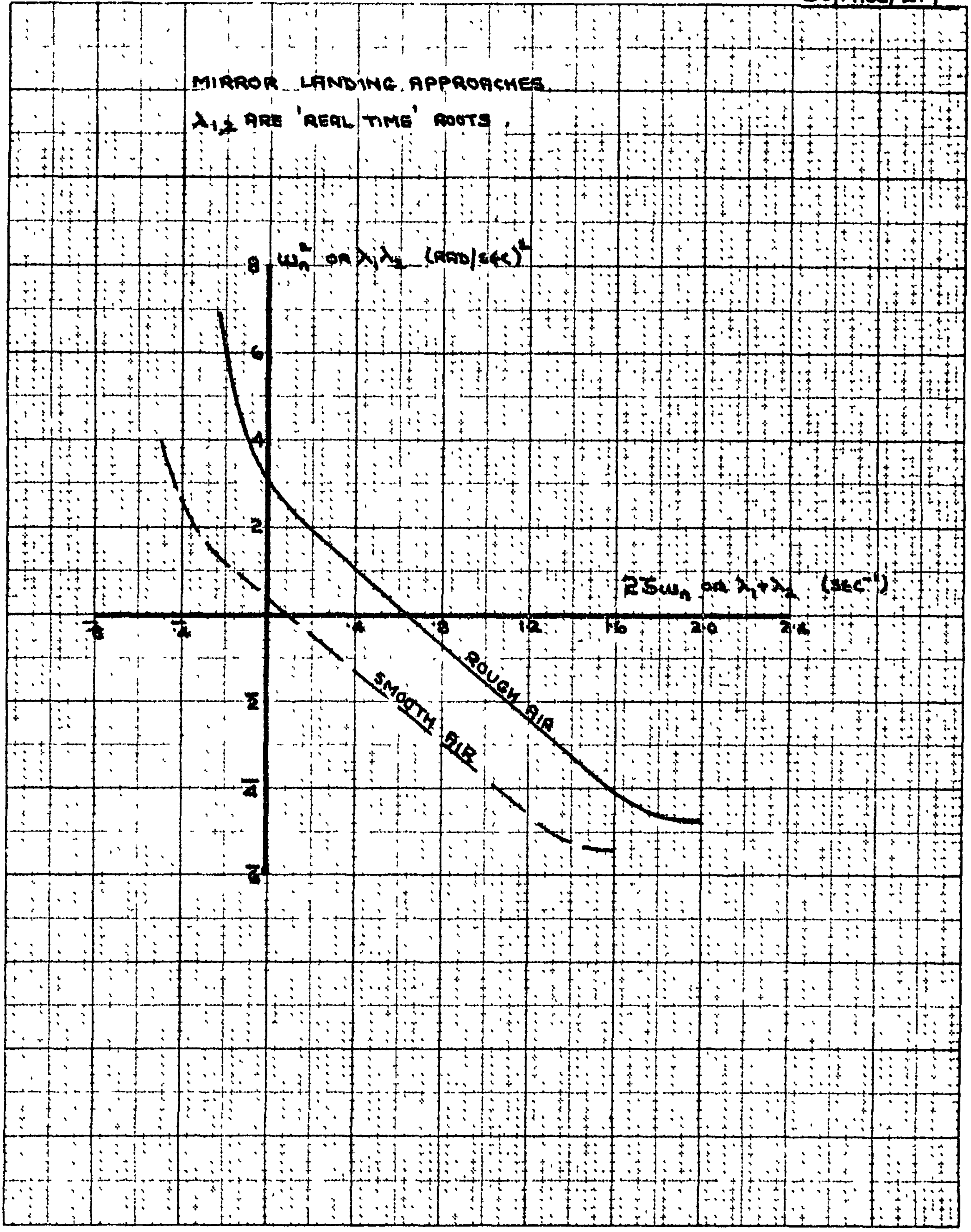


FIG. 13

FIGHTER LONGITUDINAL DYNAMICS - OPINION BOUNDARIES
FOR FLIGHT AWAY FROM GROUND

DS/MISC/218

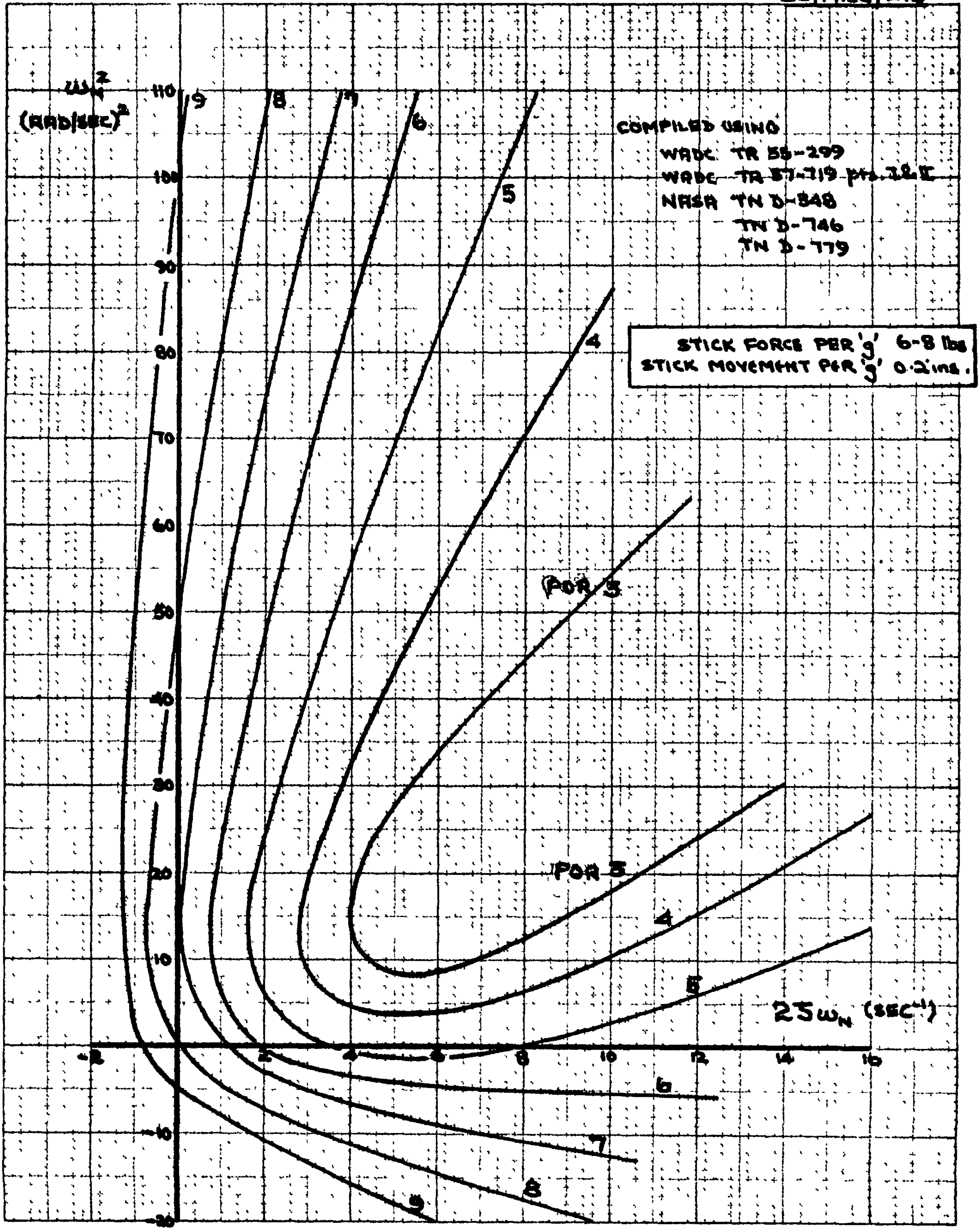


FIG. 14

FIGHTER LONGITUDINAL DYNAMICS – PILOT OPINION BOUNDARIES: COMPARISON WITH BARNES (REF. 10)

DS/MISC/219

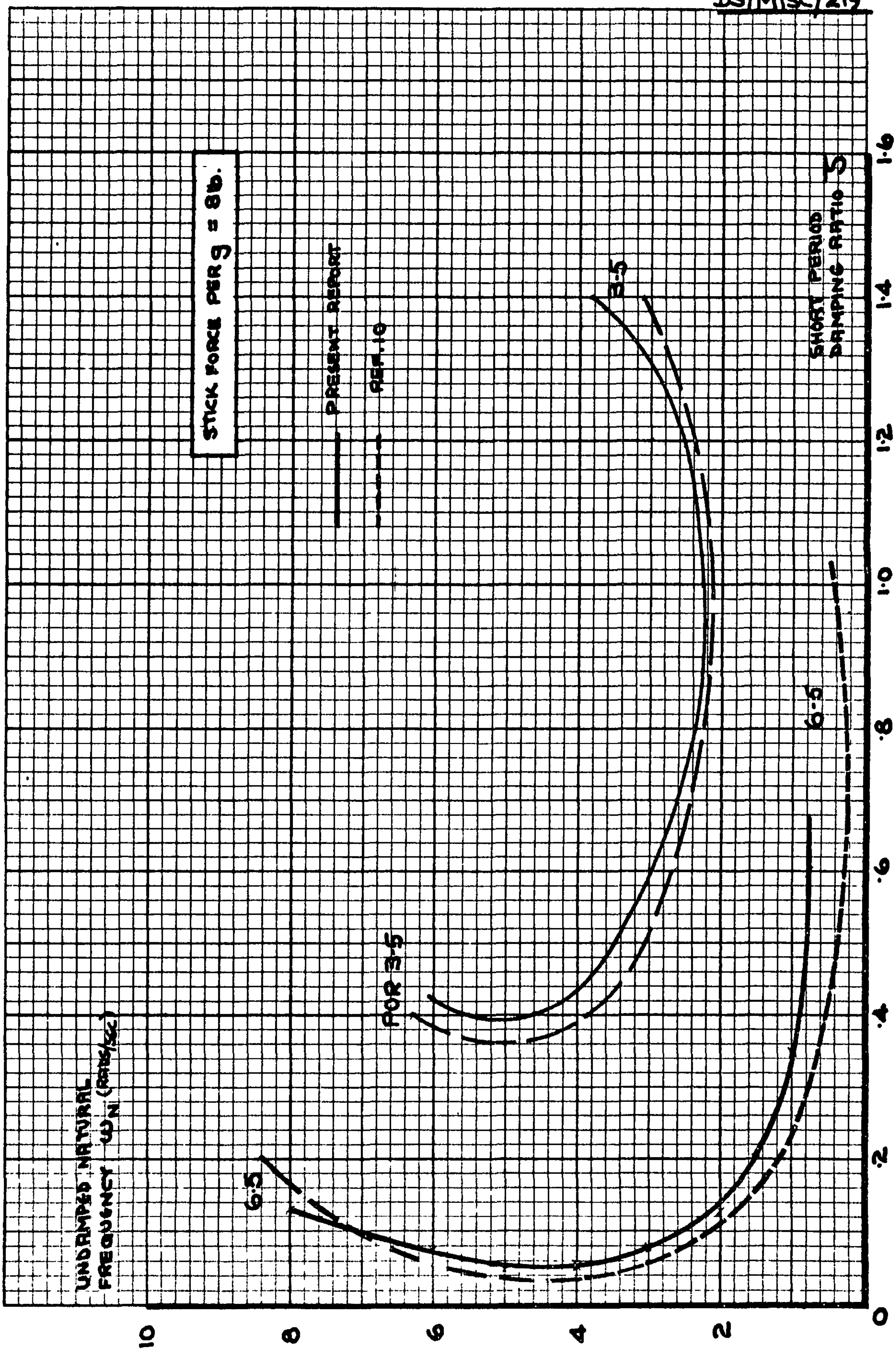
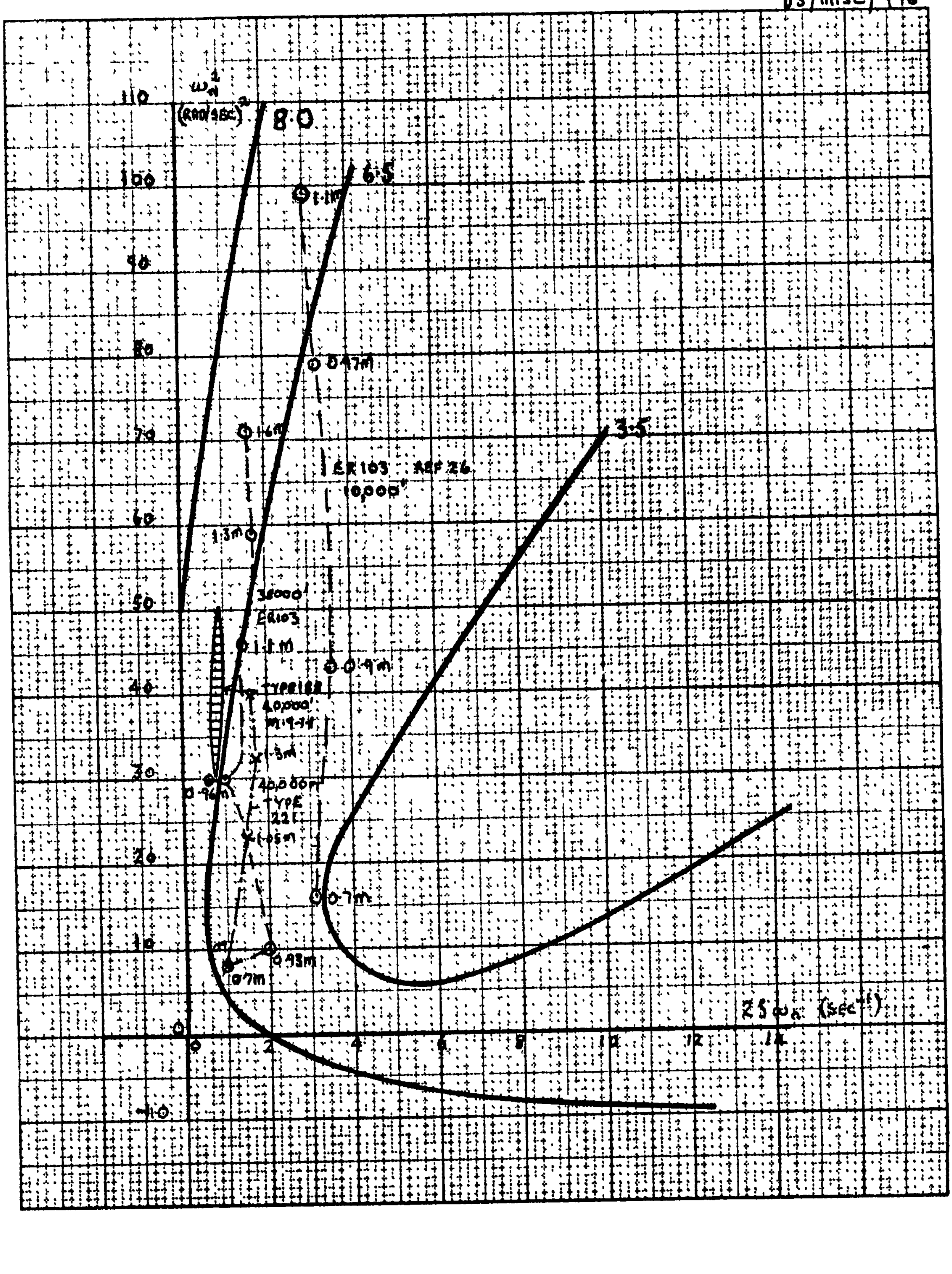


FIG 15

COMPARISON OF CHARACTERISTICS OF THREE SMALL AIRCRAFT WITH CRITERION GIVEN IN FIG 13

DS/misc/416

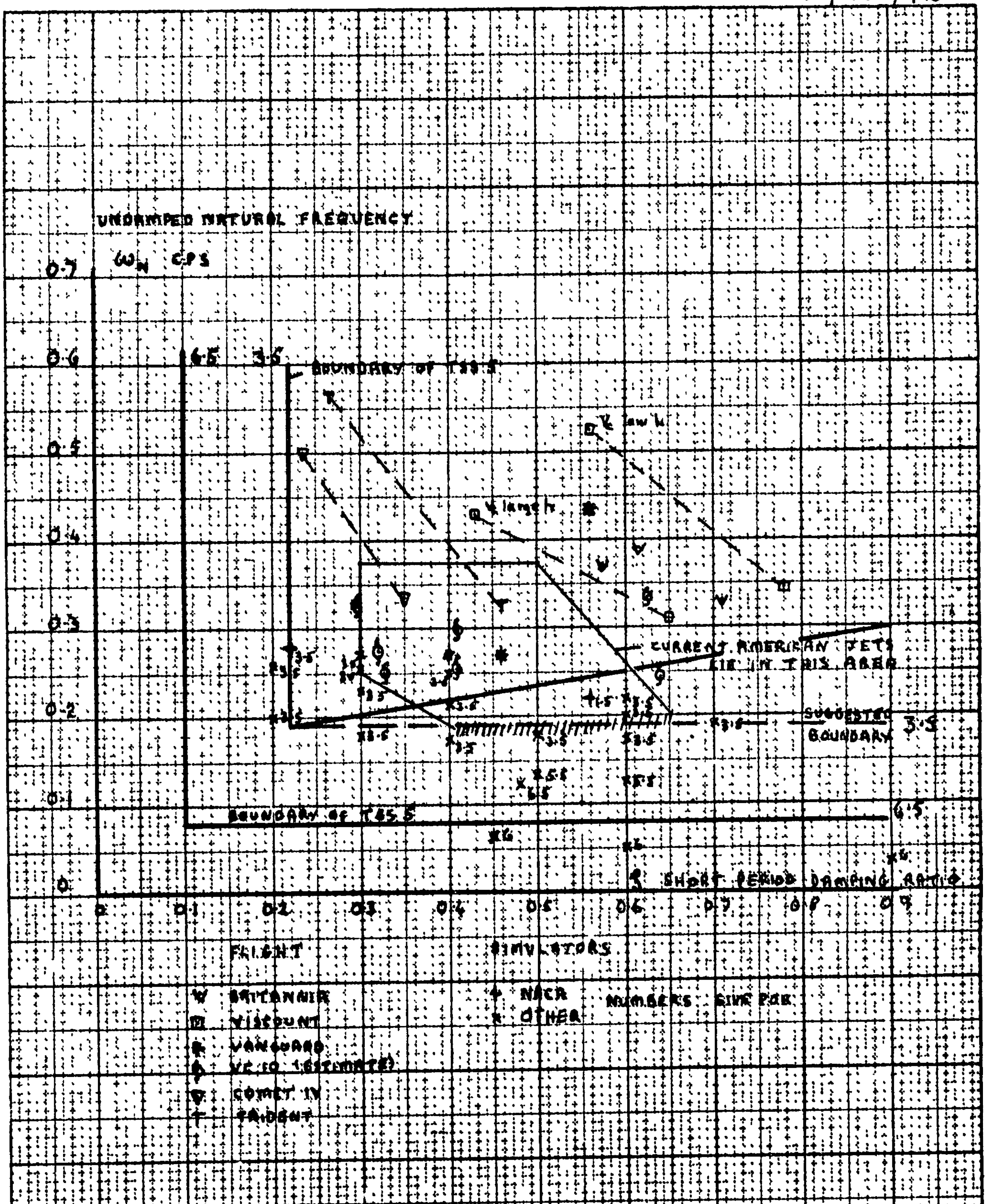


PILOT OPINION BOUNDARIES

LARGE AIRCRAFT IN CRUISE

FIG 16

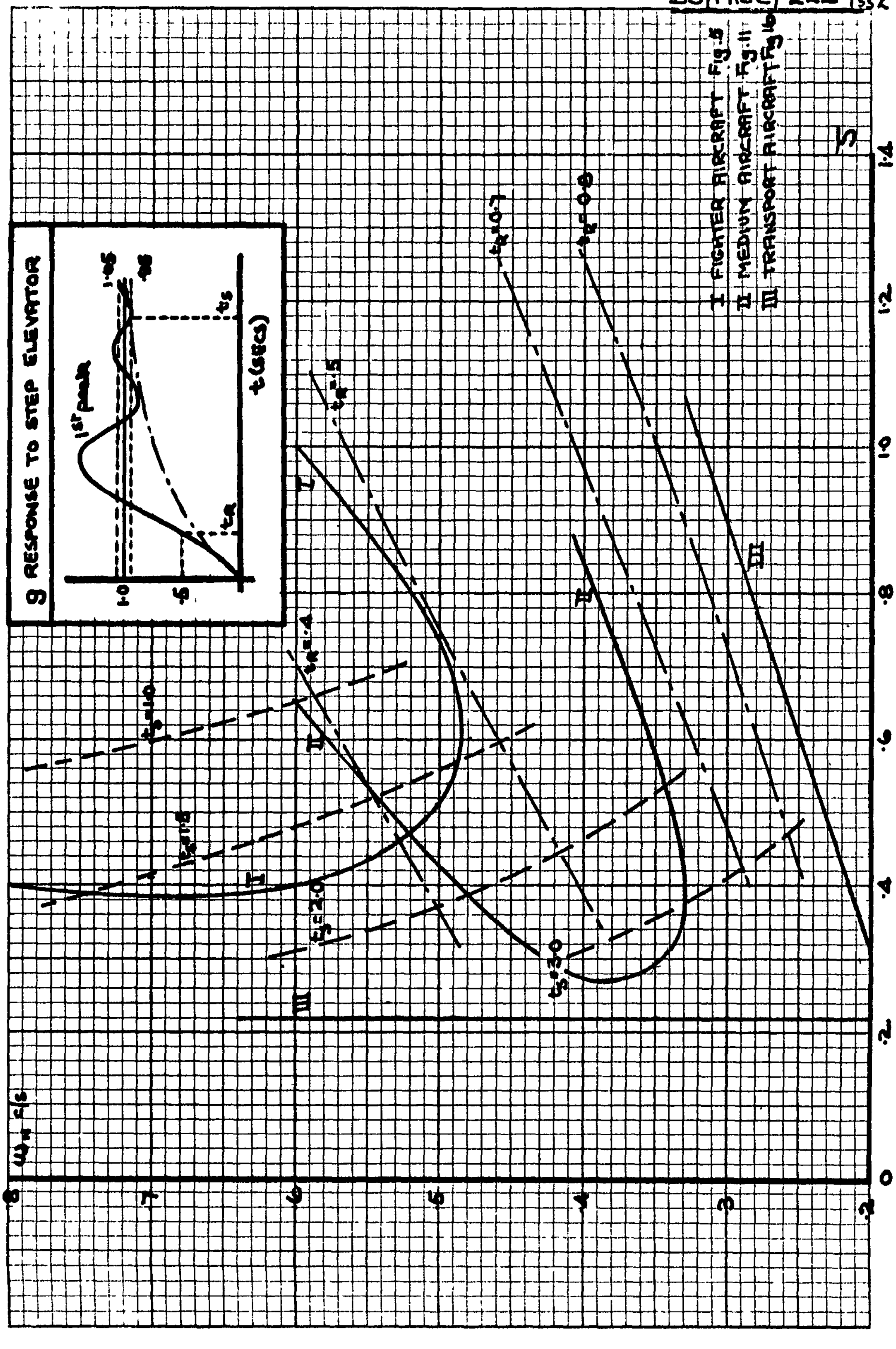
DS/MISC/415

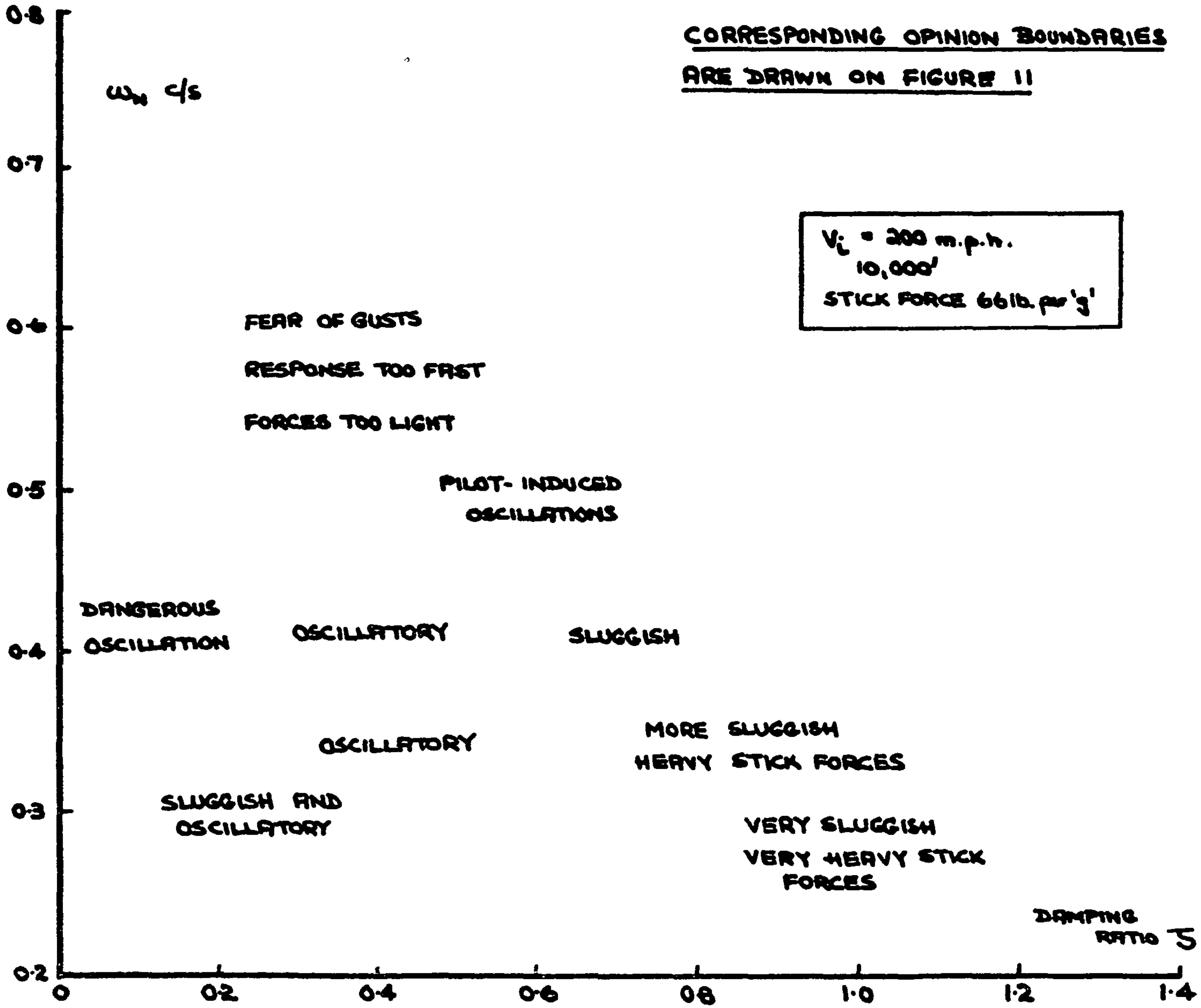


COMPARISON OF 'GOOD' BOUNDARIES (FOR ALL CLASSES OF AIRCRAFT) WITH VARIOUS SHORT PERIOD RESPONSE PARAMETERS

FIG. 17

DS/MISC/222 Iss 2





PILOT COMMENTS ON VARIOUS SHORT PERIOD DYNAMICS ON A LIGHT BOMBER (B-26) 'AWAY FROM GROUND' CONDITIONS

DS/MISC/223

FIG. 18

Fig. 19, 20

EFFECT OF PHUGOID CHARACTERISTICS ON OPINION

WADC TR 54-594 (REF. 21)

DS/MISC/224

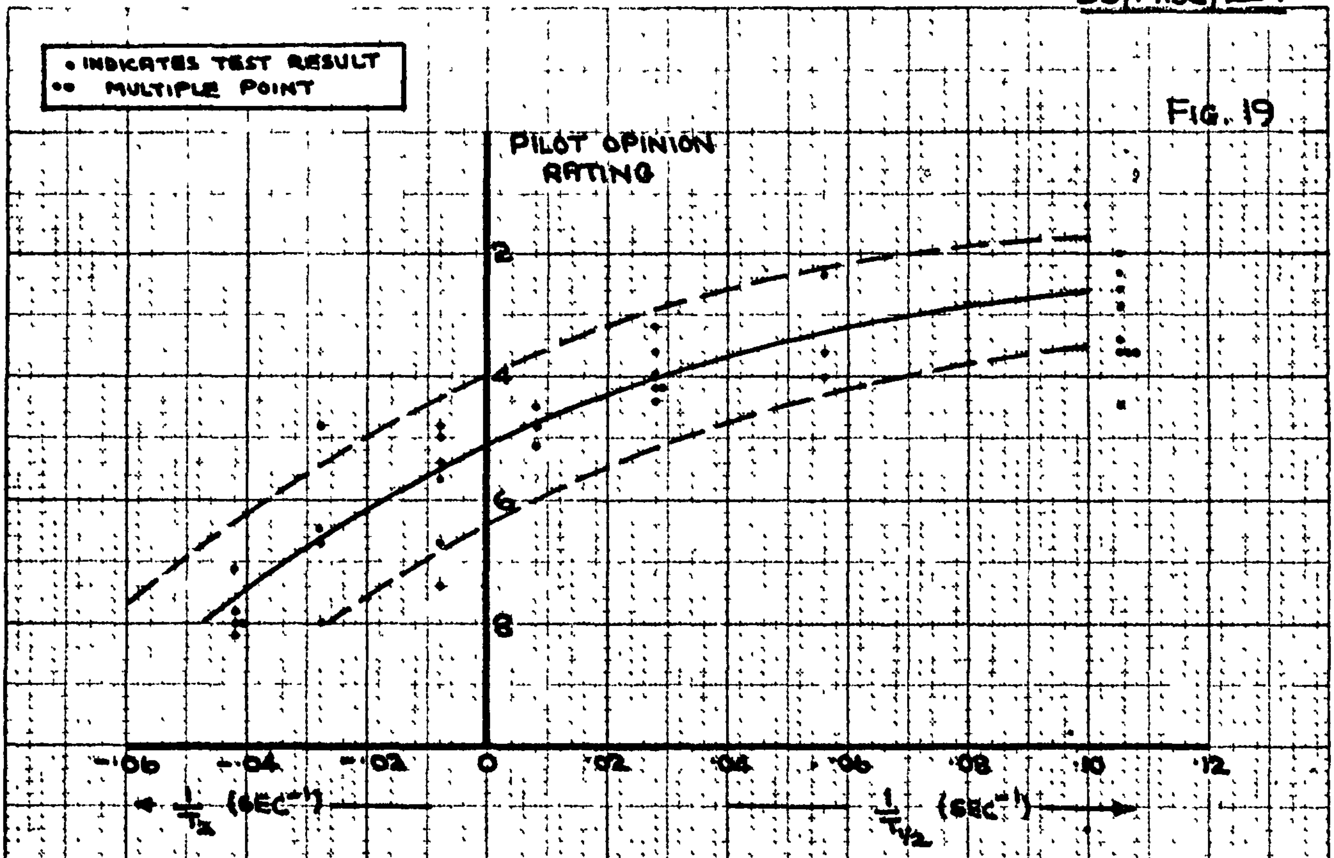


Fig. 19

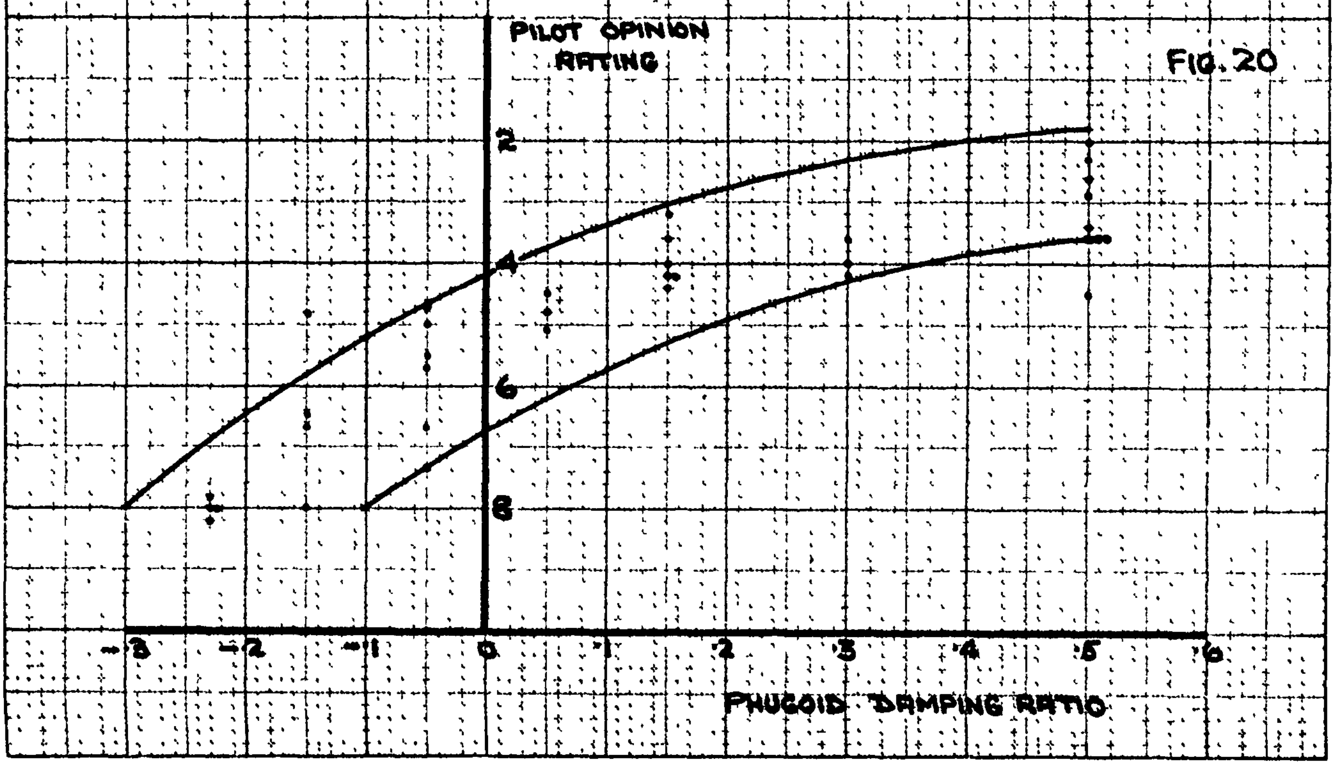


Fig. 20

APPROACH CHARACTERISTICS - LARGE AIRCRAFT

DS/MISC/225 Iss2

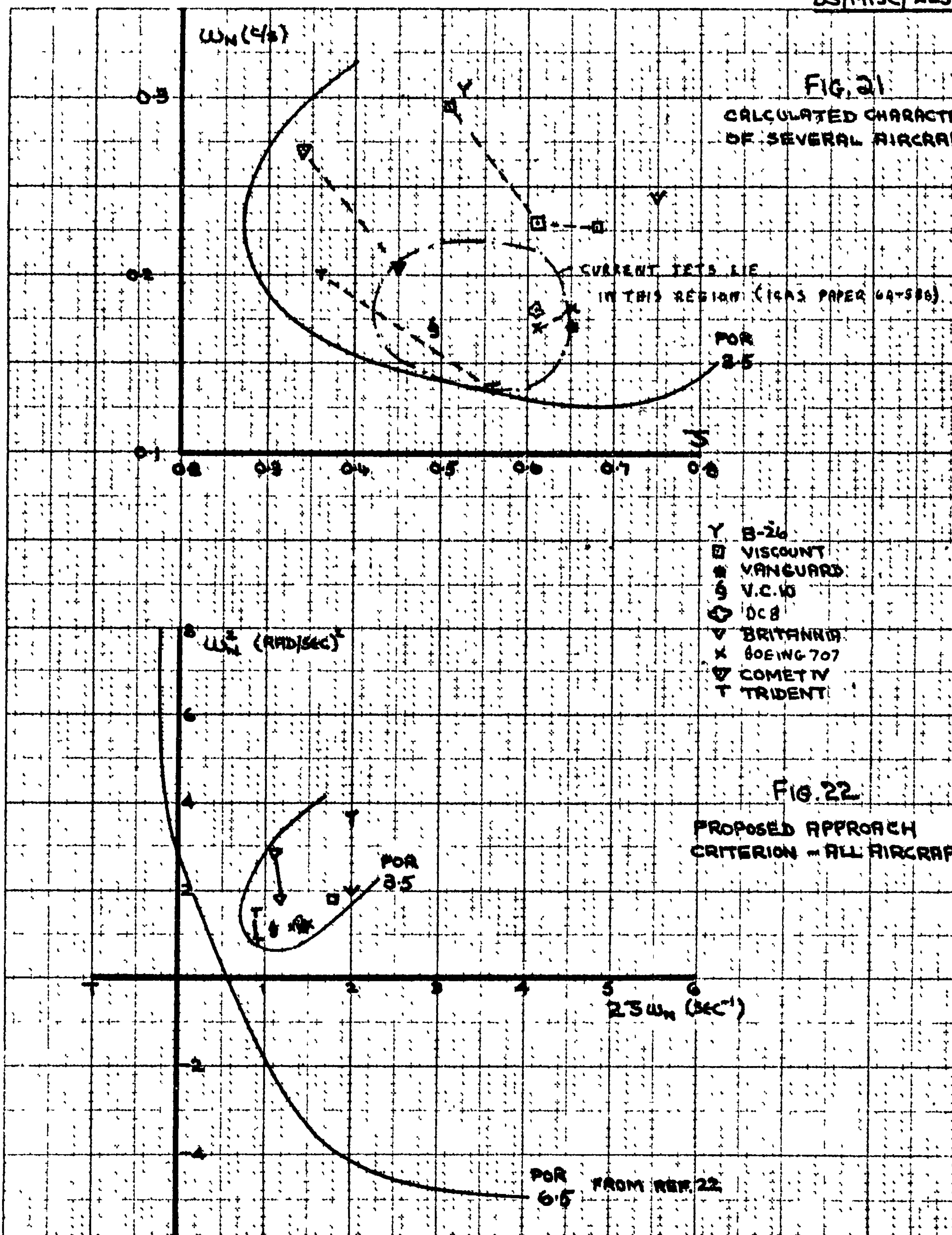


FIG. 21
CALCULATED CHARACTERISTICS OF SEVERAL AIRCRAFT.

FIG. 22
PROPOSED APPROACH CRITERION - ALL AIRCRAFT

FIG. 23

PILOT COMMENTS ON VARIOUS SHORT-PERIOD DYNAMICS ON A LIGHT BOMBER (B-26)
APPROACH CONDITIONS - MIRROR LANDING
CORNELL AERO. LAB. TB-1313-F-1 (REF. 22)

DS/MISC/226

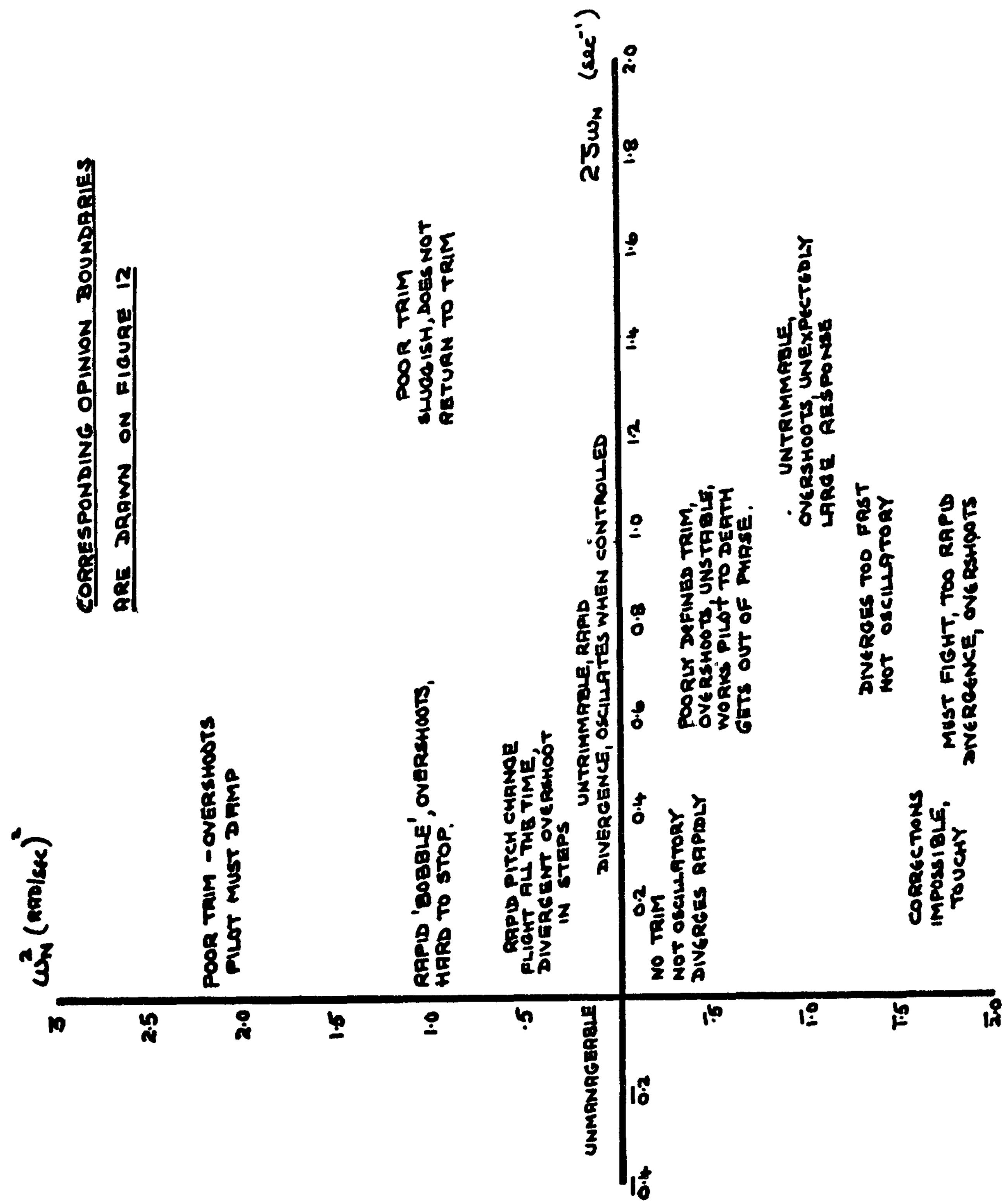
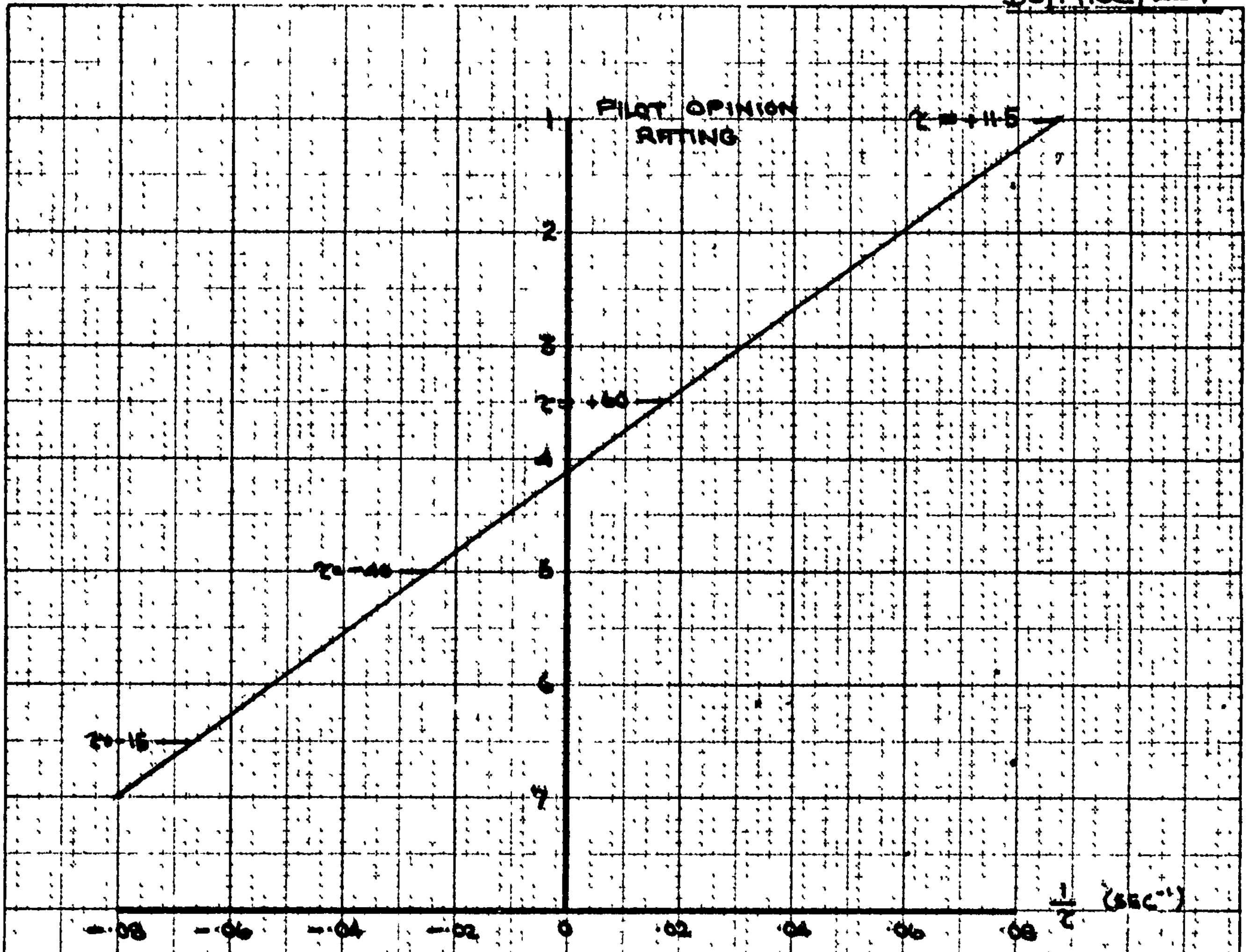


FIG. 24

LONGITUDINAL DYNAMICS - VARIATION OF OPINION WITH LEVEL OF SPEED STABILITY ON ELEVATOR CONTROLLED APPROACHES

DERIVED FROM REF. 6 (SPENCE & LEAN)

DS/MISC/227



τ = TIME CONSTANT OF SPEED SUBSIDENCE OR DIVERGENCE

$T_{1/2,2} = .693|\tau|$

FIG. 25

SPIRAL STABILITY CRITERIA

DS/MISC/228 Iss 2

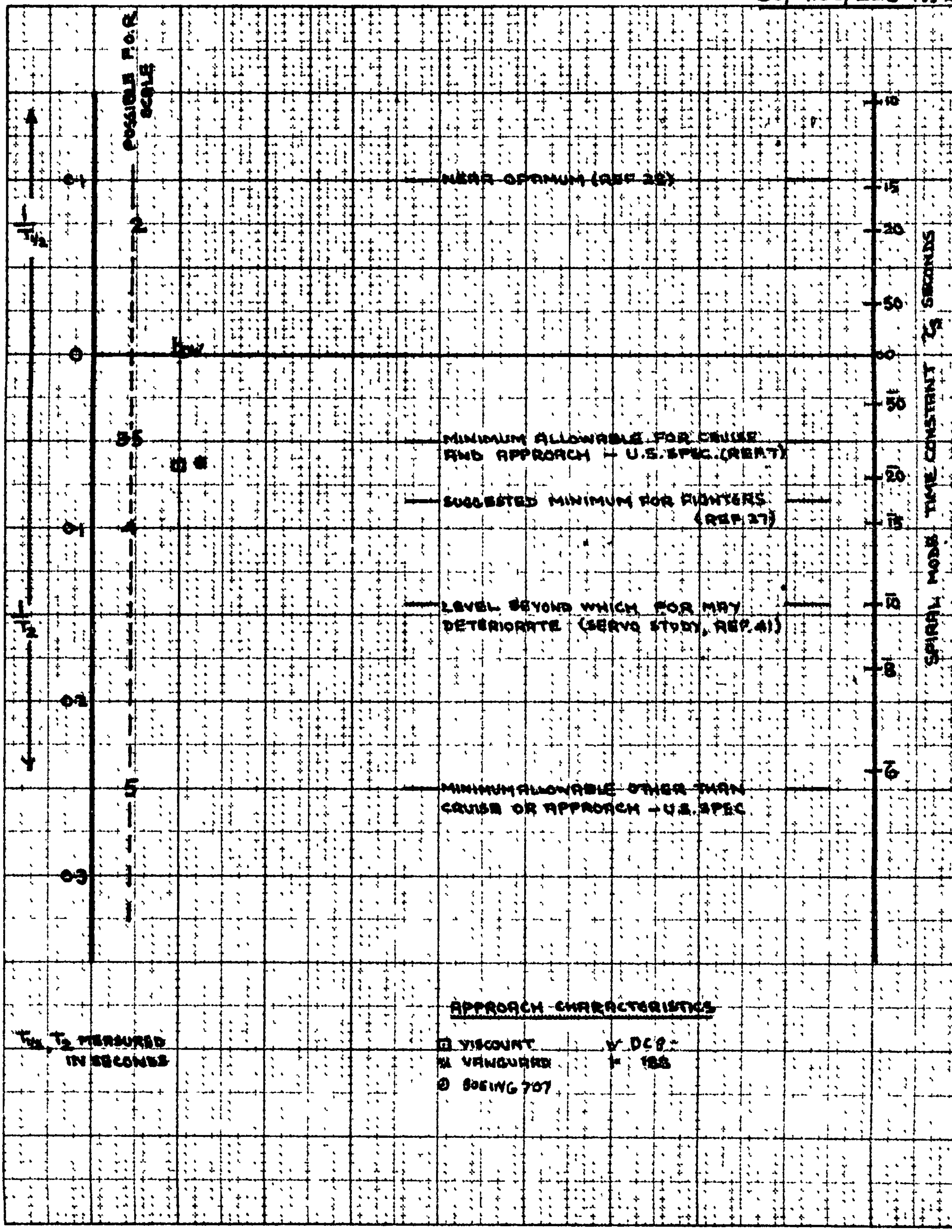
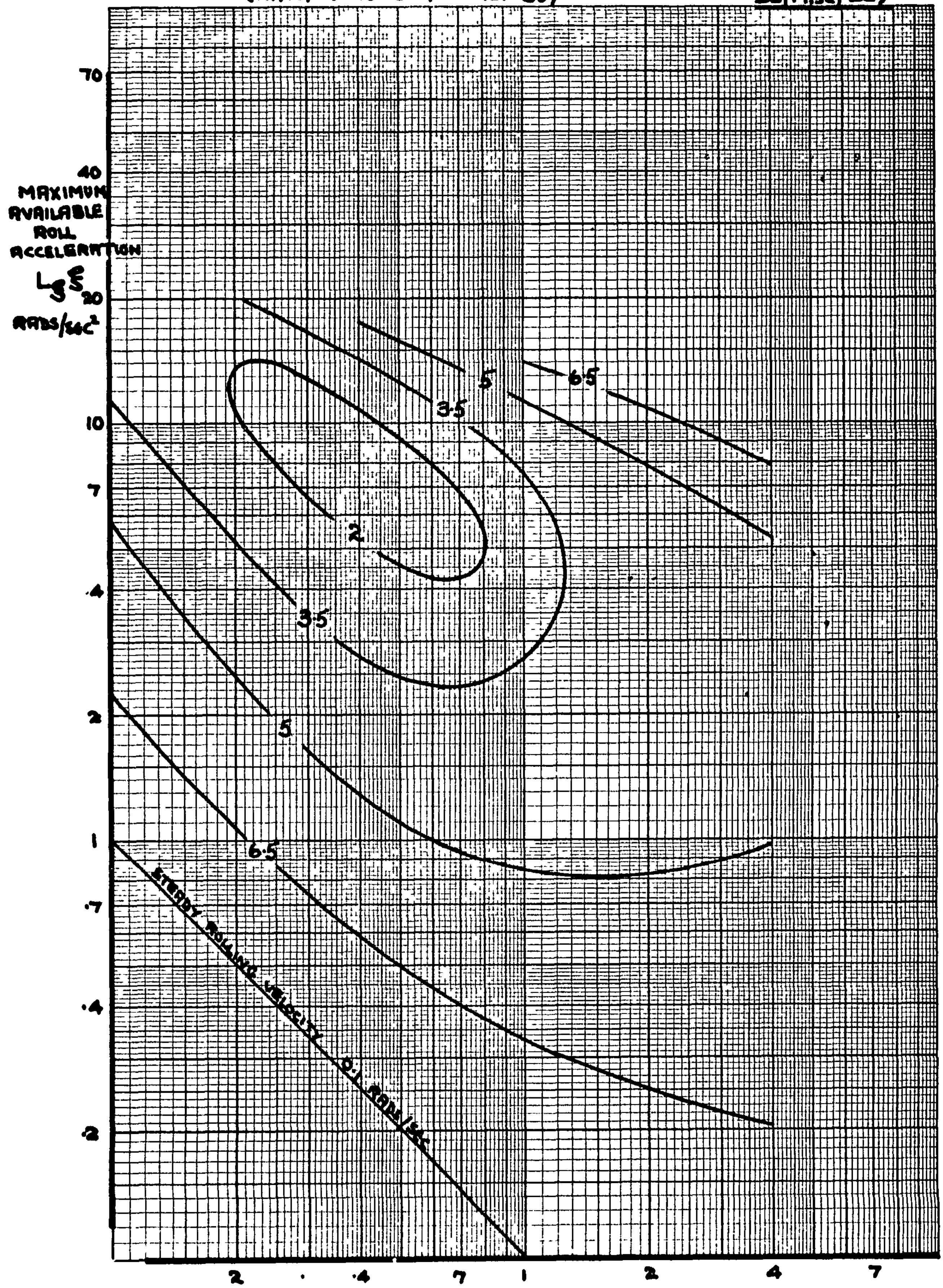


FIG. 26

ROLLING MODE OPINION CONTOURS, FIGHTER AIRCRAFT IN COMBAT CONDITIONS

(NASA 1-29-59A — REF 30)

DS/MISC/229



EFFECTS OF ROLLING MODE TIME CONSTANT

FIG. 27

DS/MISC/230

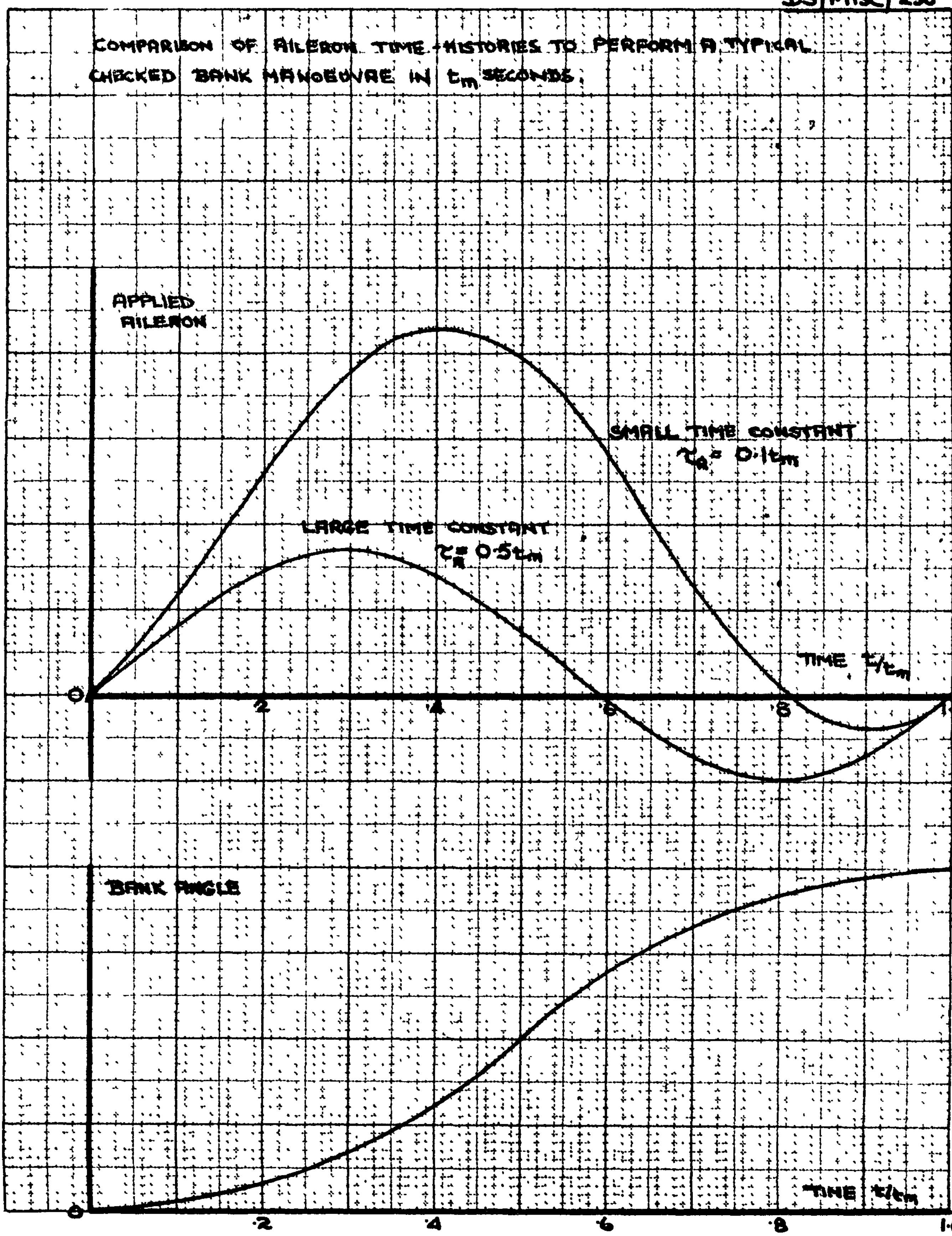
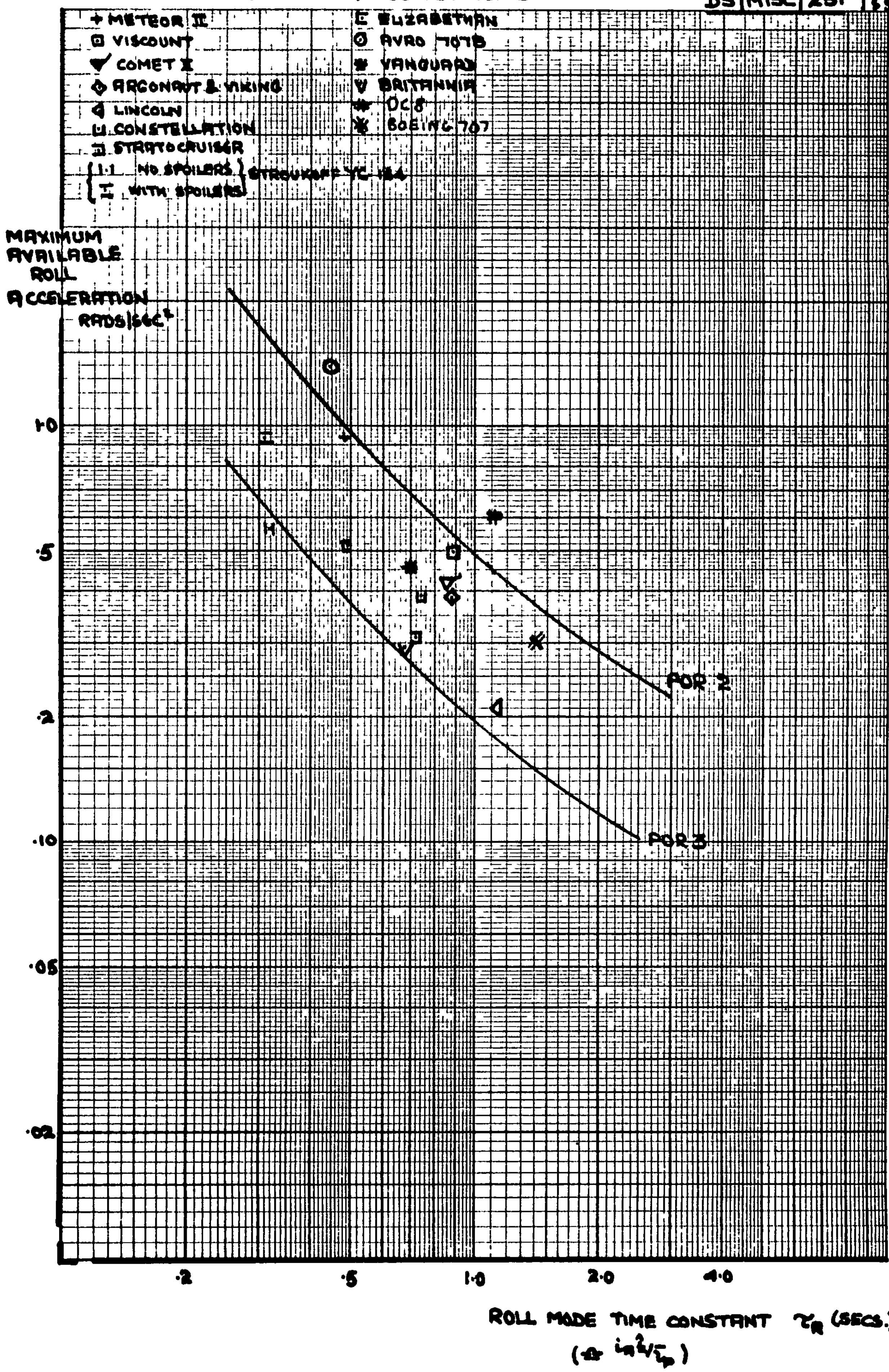


Fig. 28

SUGGESTED OPINION CONTOURS FOR ROLLING CHARACTERISTICS

APPROACH CONDITIONS

DS/MISC/281 Iss 2



LATERAL OSCILLATION REQUIREMENT

FOODY & MILLS (REF 9)

DS/misc/232/232

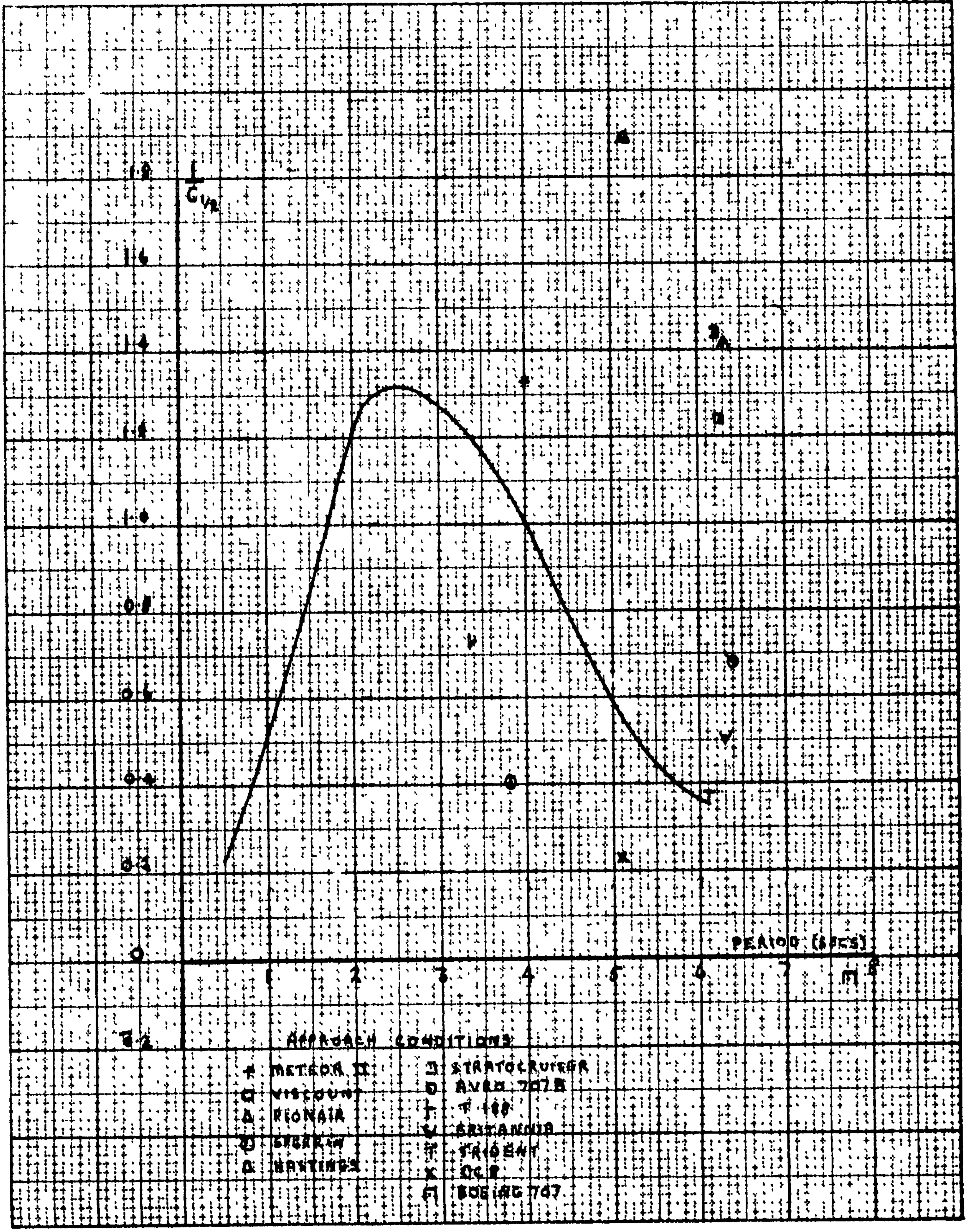


Fig. 30

REQUIREMENTS FOR THE LATERAL OSCILLATION

U.S. MILITARY SPECIFICATION (REF. 7)

DS/MISC/283 Iss2

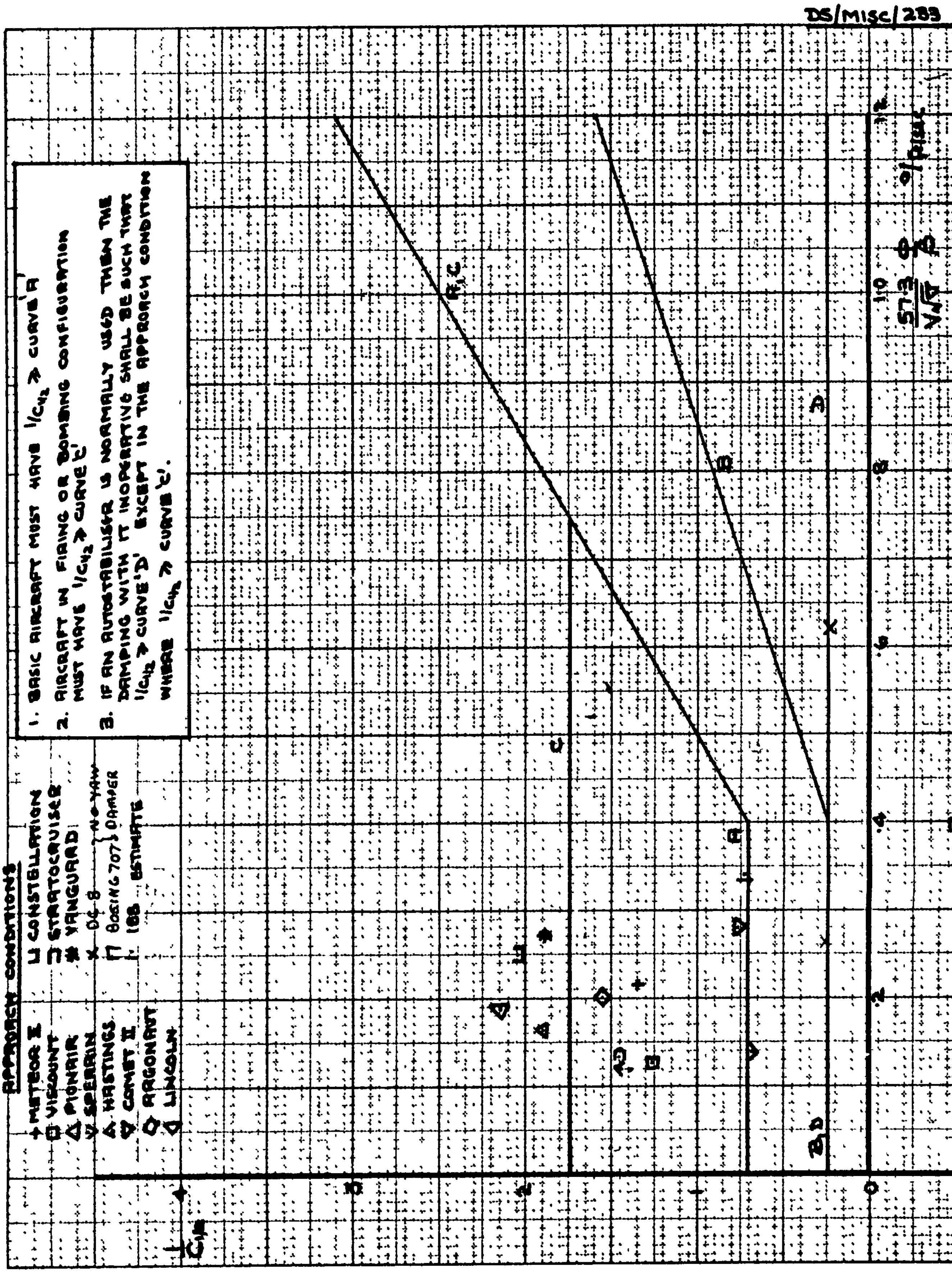
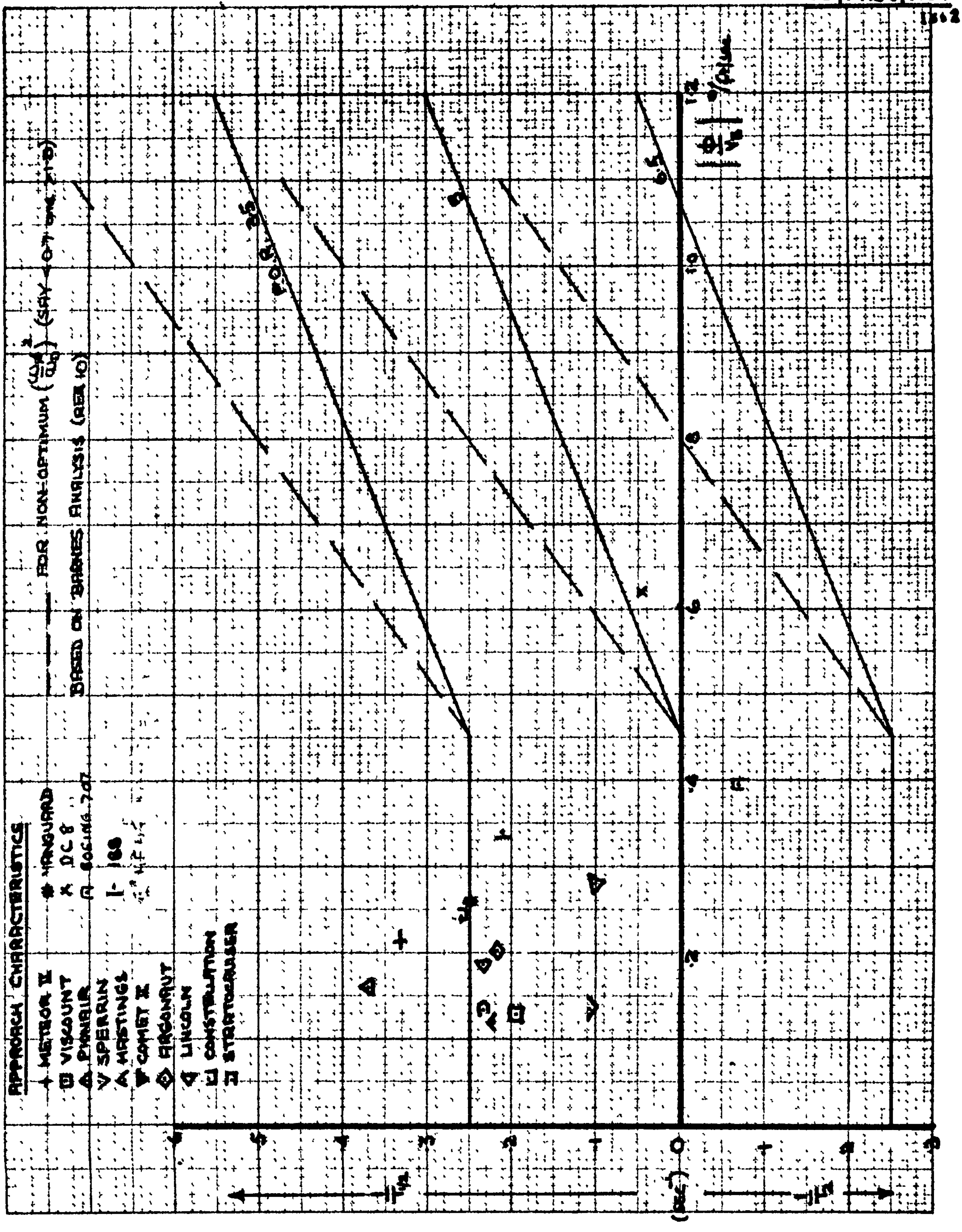


FIG. 31

LATERAL DYNAMICS — OSCILLATION OPINION BOUNDARIES

NASA MEMO 12-10-58A (REF. 36) WITH MODIFICATIONS (REF. 29)

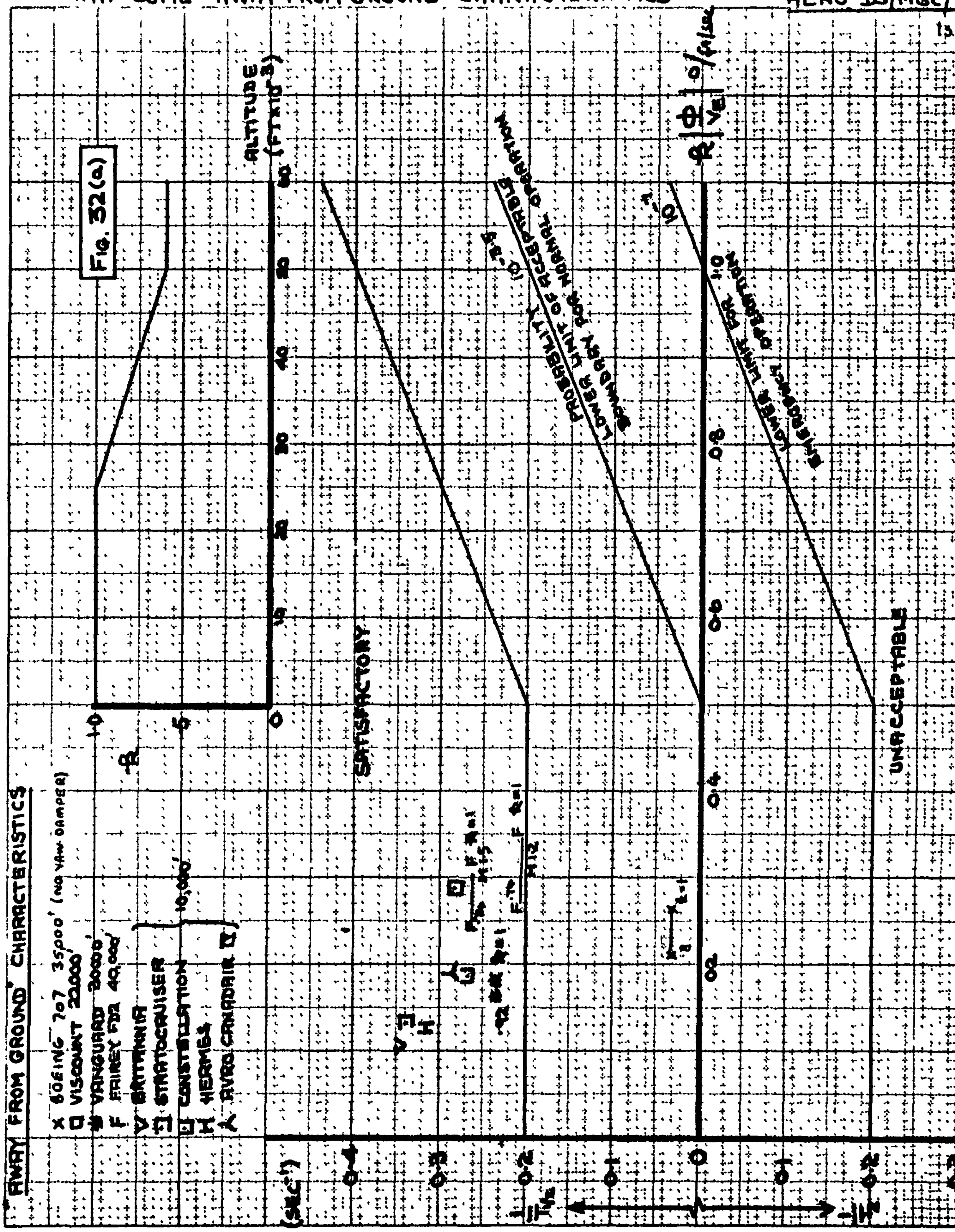
DS|MISC|284



LATERAL OSCILLATION REQUIREMENTS
A R.B CURRENT PROPOSAL WITH SUGGESTED
ALTITUDE CORRECTION FACTOR AND COMPARISON
WITH SOME 'AWAY FROM GROUND' CHARACTERISTICS

FIG. 32

AERO DS/MISC/235



VARIATION OF OPINION RATING WITH AMPLITUDE OF OSCILLATORY ROLL-RATE

FIG. 33

DS/MISC/236

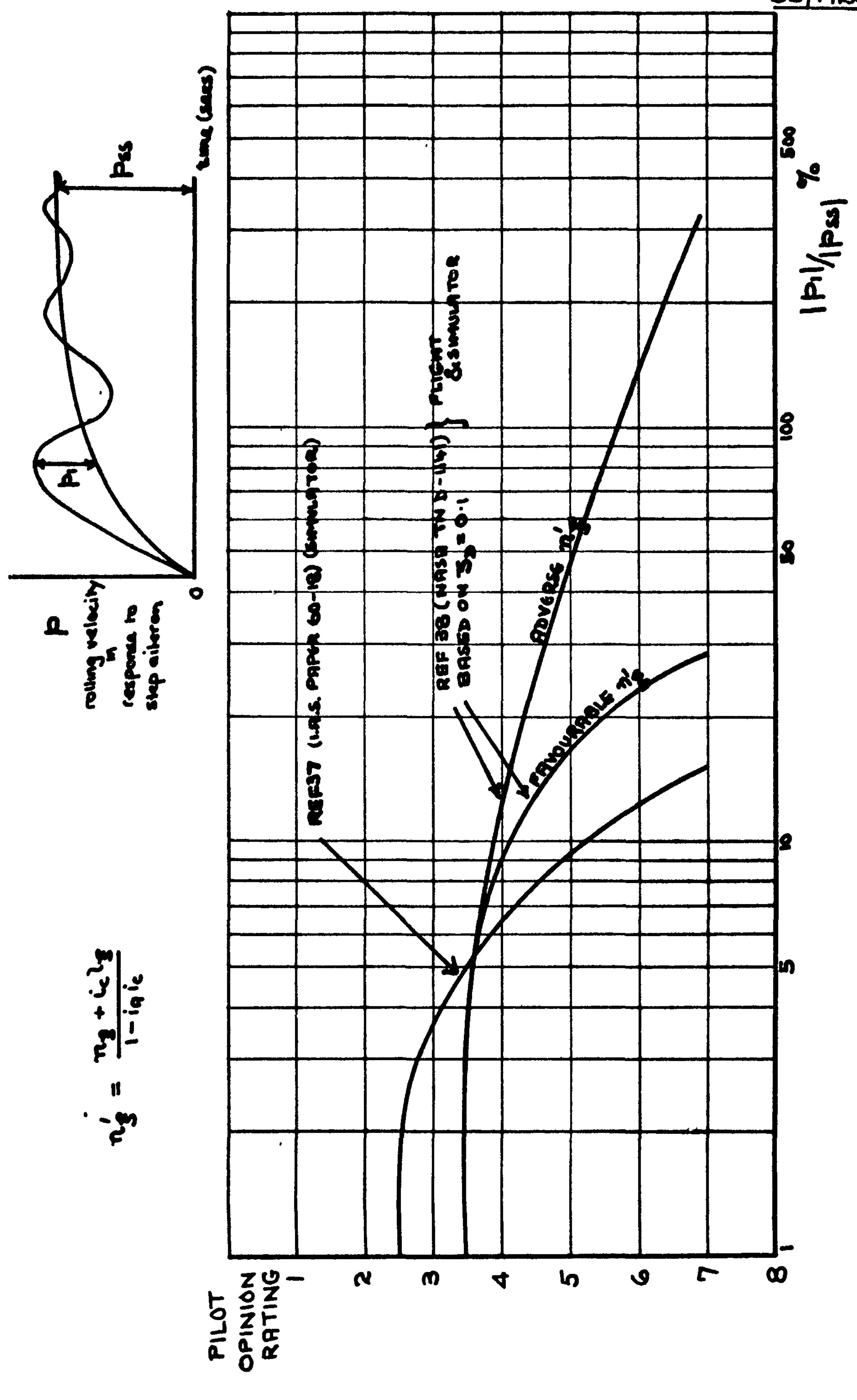


FIG. 34

OPINION CONTOURS AS FUNCTIONS OF LATERAL OSCILLATION DAMPING AND MODAL COUPLING PARAMETER $\left(\frac{\omega_\phi}{\omega_d}\right)^2$

NASA TN D-1141

DS/MISC/237

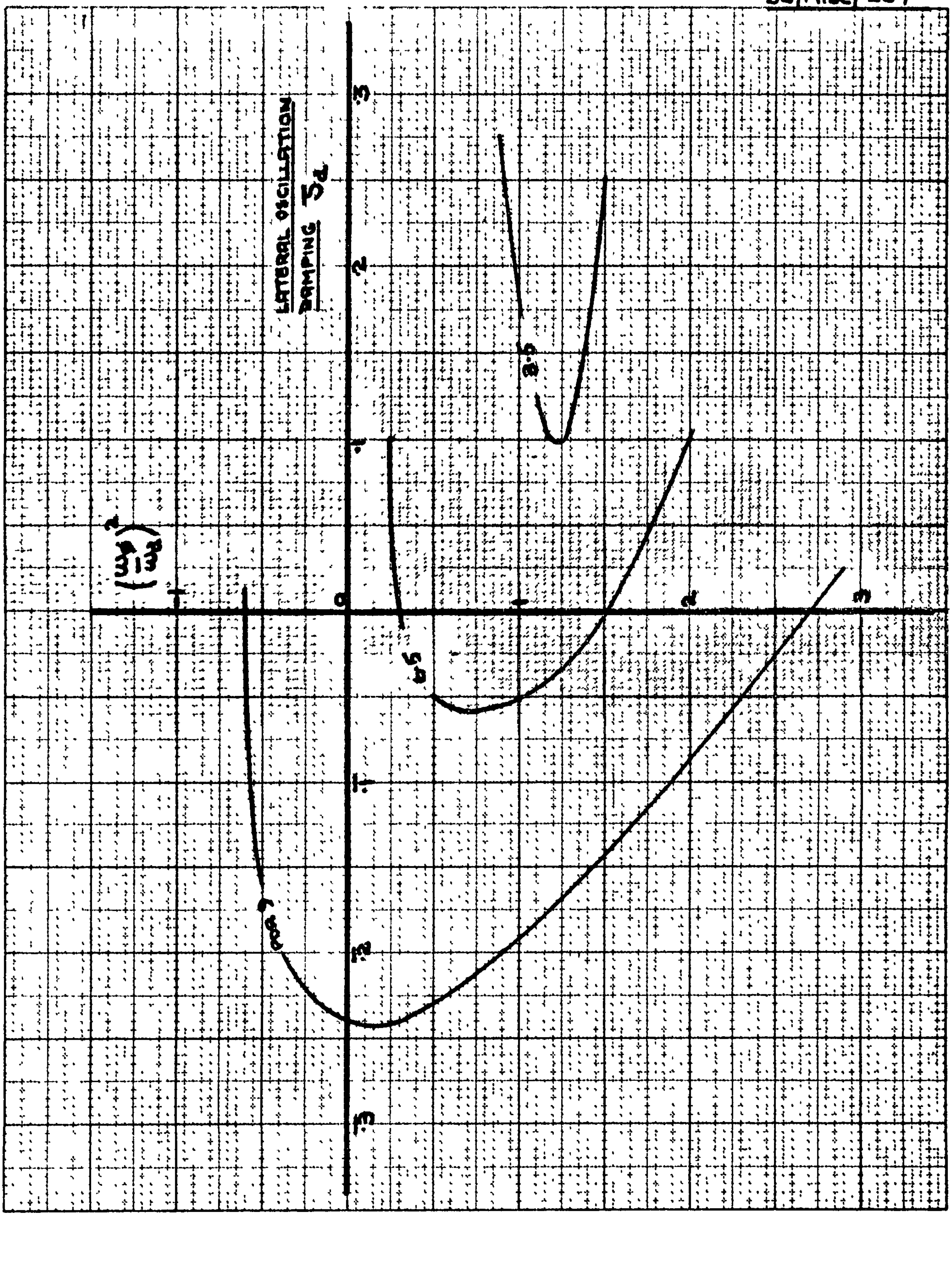
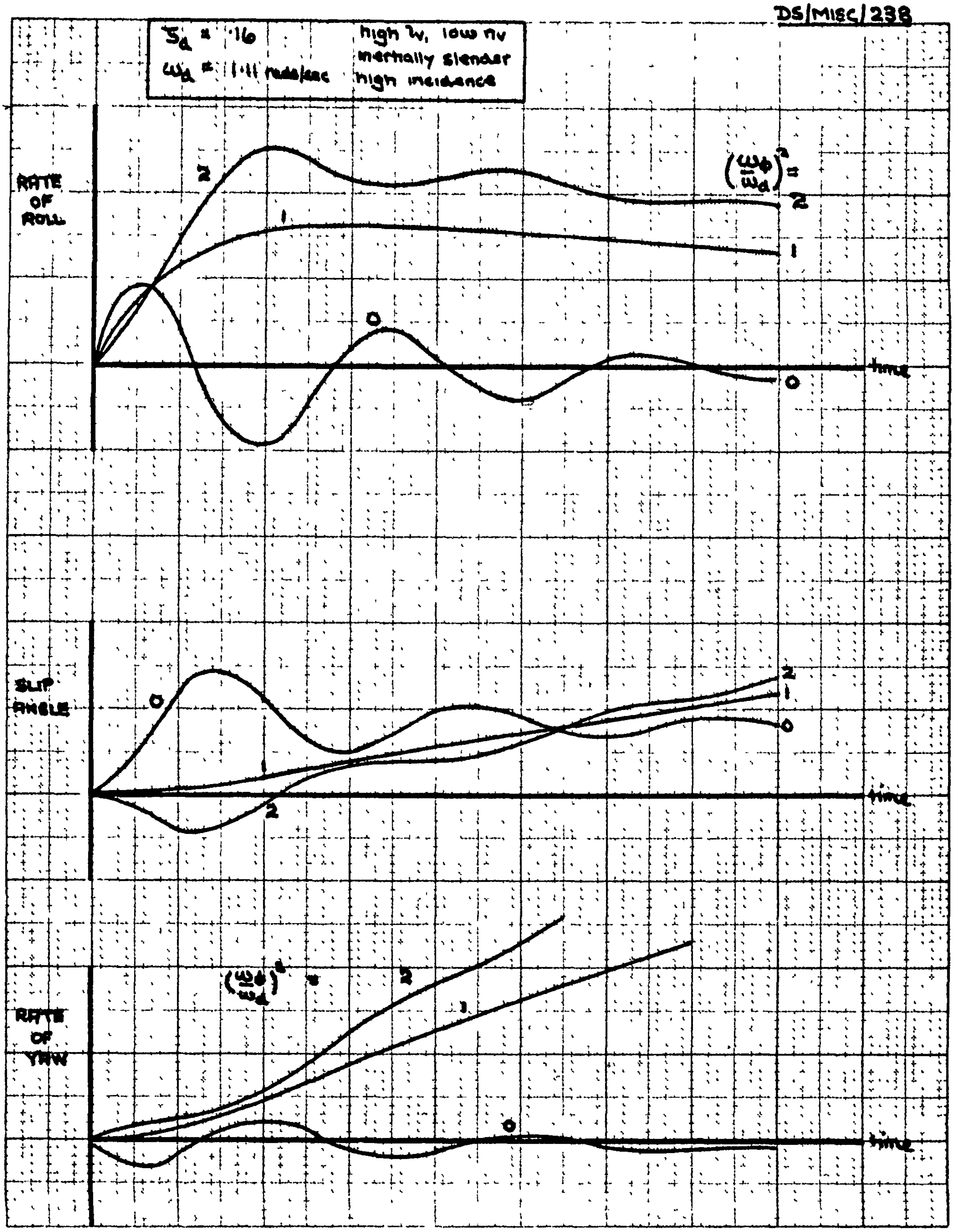


FIG. 35

EFFECT OF $\left(\frac{\omega_\phi}{\omega_d}\right)^2$ ON RESPONSE TO STEP AILERON

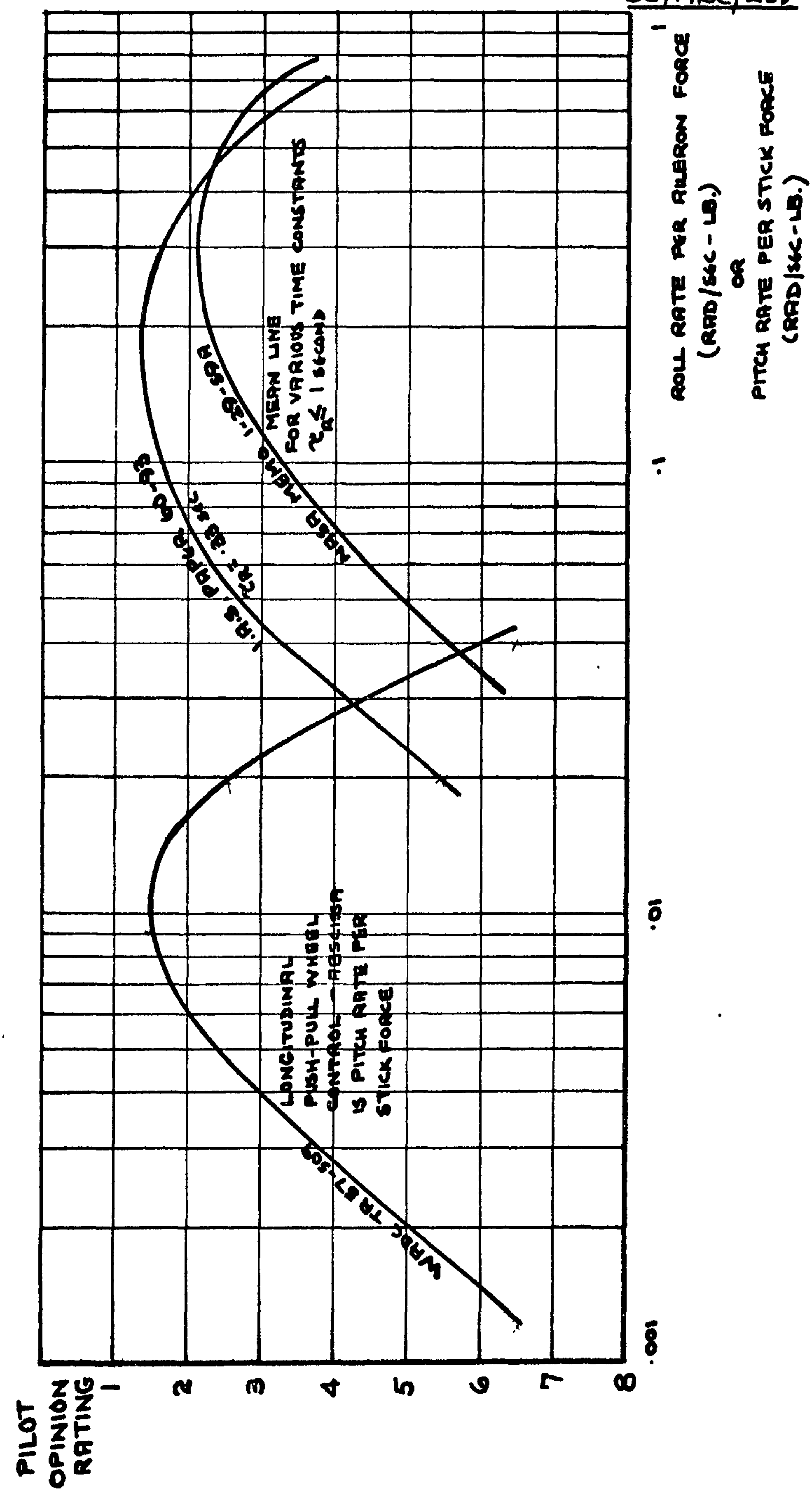
DS/MISC/238



VARIATION OF OPINION WITH AIRCRAFT RATE RESPONSE PER STICK FORCE

FIG. 36

DS/MISC/239



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