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

## Part I.—Observations on Handling Problems and their Study
## Part II.—Lateral-Directional Handling

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

By P. L. BISGOOD

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## Part I.—Observations on Handling Problems and their Study

*Summary.*

Part I contains a general discussion of handling research, the methods currently employed therein, and some of the difficulties encountered.

### LIST OF CONTENTS

*Section*

### 1. *Introduction.*

The changes in aircraft design and performance that have occurred since the second World War have introduced new stability and control problems, and have shifted the emphasis in others. These changes have had a profound effect on the flying qualities of aircraft, and in consequence there has been a marked increase, particularly during the past decade, in the attention and effort devoted to the study

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*Replaces R.A.E. Report No. Aero 2688. A.R.C. 26509.

of handling problems. Of particular importance in this work has been the development of variable-stability aircraft and ground-based simulators, which has made it possible to systematise the study of handling problems, and has added considerably to our knowledge of the factors that affect the ease with which an aircraft can be controlled (although that knowledge is still very far from complete). It should be noted, however, that the majority of the work done so far relates to the control of fighter-type aircraft and very little systematic evidence is available which applies directly to the handling of large aircraft.

In view of the considerable volume of published work on handling topics, the present review has been broken down into several parts, Parts I and II being contained in the present paper. In Part I we discuss some of the problems and developments of handling research in general. Part II deals with lateral-directional handling problems: in it an attempt is made to review the present state of our knowledge, to collect together the lateral handling criteria which have been established and to discuss possible further developments.

Part II is concerned also with the formulation of handling criteria for 'large' aircraft, i.e. roughly, aircraft having weights above 80,000 lb, and wing spans in excess of 85 ft. Unfortunately, practically all the systematic handling investigations made to date have related to small aircraft of the fighter type, and clearly the handling criteria based on this work cannot be expected to apply, without modification, to aircraft which differ substantially from this class in size or in function; for example, the period of the lateral oscillation of a 'large' aircraft will be roughly 1·5 – 2 times that of a fighter operating in similar conditions, which should ease the pilots' task of controlling this mode; in addition it is notable that the pilot of a 'large' aircraft will accept a lower standard of manoeuvrability than will the pilot of a 'fighter' (though there seems no obvious *a priori* reason why this should be so). For these reasons we attempt to modify the criteria obtained from systematic tests by allowing for the reduced manoeuvre requirements of the larger aircraft, and by taking into account all the available flight test data for large aircraft*.

Large aircraft spend much of their flight time under automatic control, manual control being largely restricted to the approach and landing and the takeoff and climb out phases. For this reason, and also because the above-mentioned phases tend to be more critical from a handling point of view, we shall concentrate mainly on developing handling criteria applicable to these phases.

## 2. *What does 'Handling' Involve?*

Although the physical characteristics of an aircraft such as its dynamic response, its control feel, etc., can be defined completely and rigorously in quantitative terms, the sum total of those features presenting themselves to the pilot as 'the handling characteristics' of an aircraft do not lend themselves to such a straightforward description. The handling characteristics are, however, an overall measure of the vehicle's acceptability and suitability for safe and efficient control by the pilot and, ultimately, they are assessed by the pilot in a wholly subjective manner. In these circumstances, perhaps the best way of 'defining' handling is to say that an aircraft will be regarded as having 'good' handling qualities when its characteristics are such that they allow the pilot to complete those manoeuvres (in the broadest sense of the term) or maintain those conditions of flight which are necessary or desirable, with little mental or physical effort; conversely, the pilot will be able to achieve these ends only with great effort or concentration, if at all, in the case of an aircraft having 'bad' handling characteristics: the assessment of 'goodness' or 'badness' will be essentially a matter of pilot's judgement in any given case, and this point will be discussed in greater detail below.

It is evident that the above definition would include in the category of handling qualities *all* those features capable of influencing a pilot's opinion of an aircraft's suitability for safe and efficient control, and this formulation has been used to emphasise that 'handling qualities' in fact comprise many more variables than the current, more narrow usage of the term might suggest – for example, features such as view, instrument presentation, cockpit position, etc., can be regarded as handling qualities in this

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*These data relate to a class of aircraft having roughly 2·5 – 4 times the linear dimensions of typical fighter-type aircraft, on which the basic research was done, and having similar wing loadings.

sense, since they influence the flow of information to the pilot and can, therefore, have a marked effect on pilot performance. However, a comprehensive review of handling qualities, in this broad sense, would be prohibitively lengthy and difficult and will not be attempted here; instead we shall confine our attention to what might be termed the 'primary' handling qualities, that is to say, the basic stability and response characteristics of aircraft and control systems*. It must be borne in mind, however, that any particular handling investigation is carried out on a particular vehicle and that strictly the results obtained during such tests may not be applicable to aircraft which differ significantly from the test vehicle in their 'secondary' characteristics (e.g. view, instrument presentation, cockpit position and layout, etc.).

Even with the above restriction, the number of variables which may influence pilot opinion is large in all but the simplest cases, and, generally speaking, pilot opinion will reflect an integrated overall assessment of these numerous elements, even when in an experiment his attention has been directed primarily at some specific aspect of handling. It follows that although handling can be studied systematically only by breaking the problems down into manageable parts, these divisions are essentially artificial, and the assessment obtained of some particular set of aircraft characteristics may be valid only for aircraft similar to the test vehicle in all other important aspects of handling.

## 3. *A Scale for Assessing Handling Characteristics.*

It would appear that the least controversial and most 'scientific' way of assessing the acceptability of a given configuration for a particular task might be to measure the degree of success achieved by a pilot (or a number of pilots) in performing such a task. Numerous attempts have been made to use error scores (e.g. in tracking tasks) as a quantitative measure of success, and therefore as a measure of the acceptability of the configuration, but these have proved surprisingly disappointing. Generally it is found that overall piloting achievement, as measured by, say, r.m.s. error in a tracking task, varies little over a wide range of some particular control characteristic which one would expect intuitively directly to affect controllability. However if this characteristic is degraded beyond a certain point, performance then deteriorates dramatically. This appears to suggest that a very non-linear relationship exists between, say, aircraft stability on the one hand, and controllability by the pilot on the other. However it is commonly found that the corresponding comments by pilots become progressively more critical of a configuration long before the implied control difficulty begins to show up in a marked deterioration of performance. The deterioration in opinion is clearly a reflection of the increased effort needed to maintain a satisfactory level of performance. Repeated experiences of this nature have convinced research workers in this field that a suitably defined pilot rating scale may, in fact, be the more sensitive measure the true handling qualities of aircraft. Before we discuss pilot assessments and rating systems in more detail, however, mention should be made of an alternative approach.

It has been noted above that, as some particular control feature deteriorates, pilots maintain a substantially constant level of performance by 'working harder' – at least up to the point where they become 'saturated', i.e. when the abrupt deterioration in performance occurs. It follows that there may well be a close correlation between 'pilot effort' and aircraft acceptability. Attempts to find such correlations have in fact proved reasonably successful (notably in Staples' work on the effects of speed instability on the approach[42]), but as yet no very practical method has been devised which could readily be applied to many kinds of handling tests: the difficulty here is that there are too many possible ways of defining 'pilot effort' and some of the more promising are difficult to formulate in a way suitable for computation. Thus, although this type of approach has considerable promise it is not yet (and may never be) developed to a point where it can replace pilots' assessments as the basic yardstick of handling research.

One of the objectives of handling research is to establish correlations between qualitative ratings given by the pilot (pilot opinion rating) and the aircraft characteristics which affect his execution of a particular task. Ideally these correlations should establish quantitative limits to the relevant aircraft

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*The term 'handling qualities', without qualification, will be used in this sense hereafter.

characteristics, corresponding to certain critical points in the rating scale, so that these can be used as design criteria. Some of the factors which help to define the conditions necessary to achieve this objective are discussed below.

Probably the most consistent correlations will be obtained, other things being equal, when the primary task used in the evaluation is very restricted in scope and can be specified in detail, but such tasks may be rather artificial and produce results whose usefulness is strictly limited (as in some simulator tests, for example). Although many of the more complex handling tasks can advantageously be broken down into simpler components, there are limits beyond which this process cannot legitimately be carried.

Since they may have a decisive effect on the pilots' assessment, the conditions for which correlations are established should be reasonably uniform for any particular set of tests (and, one might add, should be adequately described), the sensitivity to test conditions should then be examined and, if necessary, further correlations established to cover a suitable range of test conditions – one example of this sort of influential 'condition' would be the level of atmospheric turbulence. Obviously this ideal approach would entail a prohibitive amount of work, and in practice some compromises are unavoidable.

In performing any primary task, the pilot is inevitably called on to perform auxiliary or secondary tasks* (e.g. in a task which is primarily one involving longitudinal control, the pilot will have, as a minimum, the secondary task of keeping the wings laterally level), and these may, particularly if they are difficult, modify his assessment of the characteristics associated with the primary task. This factor clearly makes it difficult to establish opinion – characteristic correlations solely on the basis of *ad hoc* data relating to a number of different aircraft whose auxiliary characteristics** may differ widely (though such data can, and indeed must, be used in a supporting role), and this, in turn, has lent impetus to the development of variable-stability equipment by which specific aircraft characteristics (relating to the primary task) can be varied over a wide range, while others (relating to auxiliary tasks) are kept substantially constant. Variable-stability devices have proved of immense and continuing value in handling research, and are discussed further in the next Section.

When several pilots assess a given set of handling characteristics, it is usual to find that their assessments differ (except, perhaps, when the condition rated is either 'very good' or 'very bad'). These differences may arise either from the normal variations in experience, skill, etc., that exist between pilots, or from differing interpretations of the rating system, or a combination of these. These differences will be reduced to some extent by the fact that test pilots are highly experienced and skilled, and will be reduced further if the pilots selected for a particular investigation have backgrounds appropriate to the class of aircraft and the task under study. Even in these circumstances residual differences of pilot rating will exist, and as a consequence, the results of handling investigations are usually presented as 'rating averages' taken among several pilots†. It should be noted, however, that the differences between the ratings given by several pilots are sometimes so large as to raise doubts as to the uniformity of the test conditions (e.g. turbulence levels, etc.) under which each pilot operated; if these doubts are well founded, the concept of 'rating averages' would seem largely devoid of meaning in these cases. If, on the other hand, large differences in rating persist despite uniform test conditions, the usual practice of using 'rating averages' to define marginal aircraft characteristics (e.g. to divide the 'acceptable' from the 'unacceptable') appears questionable, and an average biassed towards the less favourable ratings may prove more reliable as a design guide: at present we do not know how such weighting should be done.

It is evident that most handling research investigations will involve relatively large numbers of individual assessments, possibly several hundred per investigation, and the economic advantages of

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*In complex tasks the distinction between primary and secondary features may become rather arbitrary, the definition of a primary feature then being on the lines of 'the one we are investigating at present'.

**An auxiliary characteristic is one associated with an auxiliary task.

†For reasons of economy, the number of participants is usually kept as small as seems reasonable to the investigators, and is often limited to two or three pilots. This may be reasonable where these pilots are known to score consistently near the average of the group they represent.

keeping the time spent on each assessment to a minimum are obvious. For the few cases where an estimate can be made from the published data, the assessment times range from about half an hour (which seems reasonable), to about five minutes (which seems undesirably short). Since assessment times of this order probably are not sufficient for the pilot to become fully familiarised, his assessments, at least of less conventional configurations, may tend to be conservative compared with those of a 'fully-converted' pilot; on the other hand the assessment of emergency conditions may be somewhat optimistic if, in practice, the emergencies can last for much longer than the assessment time.

Broadly speaking, the handling qualities of an aircraft will be classified by pilots as being either (a) satisfactory, (b) unsatisfactory but acceptable, or (c) unacceptable. Somewhat finer gradations of assessment are necessary for research purposes, and these are provided by opinion 'rating scales', which attempt to define subdivisions of these major categories; the scale proposed by Cooper[1] and reproduced here in Table 1 is a good example. Since rating scales cannot be defined without ambiguity they tend to be most reliable when they can be used to express 'orders of merit' (e.g. in tests where some set of aircraft characteristics are varied systematically), though they remain useful in a more general sense *.

The Cooper rating scale[1] and most of its derivatives incorporate a rating of 'acceptable for emergency', and quote a failed auto-stabiliser or similar contingency as an example of the emergency considered. In systematic tests, the conditions are usually such that the ratings relate to time-invariant characteristics so that a rating of 'acceptable for emergency' relates essentially to conditions *after* the failure has occurred and the pilot has adapted to the new situation. There is some evidence[43] to show that a more critical condition can occur during the immediate post-failure period (i.e. before the pilot has adapted fully to the new situation), particularly if the failure occurs in conditions demanding precise control; these circumstances can lead to temporary instability of the pilot-airframe closed-loop, even though the failed condition may be rated as 'acceptable for emergency' when pilot-adaptation is complete. The need for more data on the transient effects of failures of this sort will be evident. In the meantime, predicted ratings of 'acceptable for emergency' based on 'steady-state', systematic tests, should be treated with some reserve.

## 4. *Variable-Stability Devices.*

The development of variable-stability devices has made it possible to adopt a systematic approach in experimental handling research and, at the same time, to extend the range of investigation into areas not covered by existing aircraft; this constitutes a major advance which has revolutionised the study of handling problems.

These variable-stability devices fall into two main groups, ground-based simulators and variable-stability aircraft. The quality of both these research tools has improved greatly during their period of existence, and increasing experience in the use of these devices has led to a better understanding of their limitations and shortcomings; these improvements have reduced the possibility of obtaining grossly misleading results (such as were obtained in some of the earlier work in this field), but a critical examination of each application remains necessary if more subtle pitfalls are to be avoided – some general observations on these lines are included in the following Sections, and some specific examples will be discussed in the Sections dealing with detailed handling criteria.

### 4.1. *Ground-Based Simulators.*

A necessary condition for these devices to function satisfactorily as handling research tools is that they should put the pilot into a situation representative of the postulated flying conditions. Clearly, the extent to which the simulator must reproduce the flight environment will vary with the conditions being investigated; for example, a non-moving simulator with appropriate cockpit presentation (i.e. flight

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*In this context we may note that the comparison of data from different sources would be made easier by the universal adoption of a single rating scale: the wide measure of acceptance already achieved by the Cooper scale makes it an obvious choice for this purpose, at least as the framework around which a more detailed system could be built.

instruments) will be adequate for studies of instrument flight conditions not involving significant motion inputs to the pilot, but for situations other than these the simulator may have to include some representation of the external visual field, possibly in combination with realistic and appropriate motion stimuli. Visual presentations giving a rather simplified view of the outside world, as in the so-called 'contact analogue' or by optical projection of a simple horizon and cloudscape, have proved adequate for investigating most forms of contact flying well away from the ground; but more sophisticated displays are required for manoeuvres such as the approach and landing (where the pilot makes use of redundancies in the visual field in forming his judgements), though the degree of sophistication necessary is still a matter for discussion and experiment. As might be expected, the non-moving simulator produces misleading results when applied to certain combinations of flight task and aircraft dynamics; for example, the non-moving simulator may fail to reveal the susceptibility to pilot-induced oscillations which occurs in flight with certain combinations of dynamics. On the other hand by denying phase-advanced information to the pilot, it may make other combinations of dynamics appear less tractable than they are in flight. It has been shown that these discrepancies can be reduced or eliminated by providing appropriate motion stimuli; since these stimuli cannot be wholly accurate in any practicable simulator, considerable research effort is still needed to establish the degree of realism needed to give satisfactory results in particular circumstances.

It is unlikely that the ground-based simulator will be able to reproduce in the pilots (except for the most imaginative) the psychological stress levels that they may experience in flight; the resulting discrepancy between flight and simulator is likely to be greatest in situations of marginal controllability and may cause simulator-derived opinions to be optimistic in these circumstances.

Provided their limitations are not exceeded, ground-based simulators are well adapted to the 'piecemeal' approach to handling research, since they readily permit the investigator to vary individual characteristics while maintaining others constant.

### 4.2. *Variable-Stability Aircraft.*

Variable-stability aircraft have become one of the most valuable and dependable tools of handling research. In certain areas, however, the results obtained by their use, or, more properly, the interpretation placed on those results, appear open to question. To consider a specific example, when studying the influence of the frequency of a short-period oscillatory mode on pilot opinion it is usual to vary this by artificially changing the 'stiffness' term (i.e. the static stability); it is likely that at the lower frequencies pilot opinion may be coloured adversely by the associated low static stabilities or some allied features (e.g. difficulty in trimming), and pilot comment, where available, supports this view; to attribute these criticisms to the low frequency alone is, therefore, somewhat misleading; an alternative method of varying frequency – by varying artificially the 'effective inertia' – seems likely to yield somewhat different results and might be preferable, though it would demand very advanced equipment and has not been attempted, so far as the writer is aware.

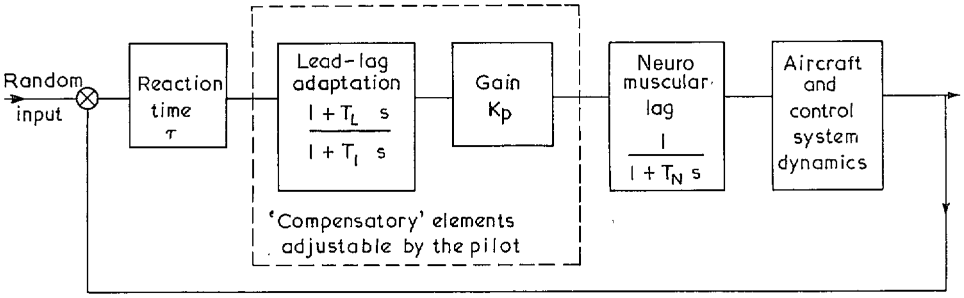
Another difficulty in variable-stability aircraft tests is that of ensuring that the level of atmospheric turbulence remains substantially the same throughout a given test programme. In the later and more sophisticated vehicles, this difficulty has been overcome, to some extent, by flying in 'calm' conditions and generating artificially some of the effects of turbulence by feeding random commands to the control servos.

## 5. *A Theoretical Approach.*

In recent years, considerable progress has been made in the development of a theory for the prediction of handling qualities. Ashkenas and McRuer and their associates[2,3,4] have applied the techniques of servo-mechanism analysis to the study of an important class of handling problems (tracking-like tasks with random disturbances) with considerable sucess. Detailed discussions of this theory and its application will be found in the referenced literature, but a brief outline of the main features is given below:

(i) The theory proceeds from the hypothesis that the pilot can be regarded as a linear system. Numerous experiments have shown that, in tracking-type tasks with random-seeming inputs, a major part of the pilot's output is in fact highly correlated with the input. This correlation can be analysed to determine an effective pilot transfer function or 'describing function'. It has been shown, moreover, that the 'remnant' (i.e. that part of the pilot's output which does not correlate with the input) forms only a small fraction of the total output (less than 20 per cent) for all but the more arduous tasks, so that the describing function is a fairly realistic representation of the pilot in many cases.

(ii) In tracking experiments at least, the pilot's response appears to be described adequately by a simple 'describing function', as indicated in the block diagram below



In this model the pilot is assumed to receive a simple stimulus, which, in the tracking case, would be the error between aiming point and target.

The stimulus is assumed to reach the pilot's decision-making centre *via* a reaction time delay, $\tau$, which is relatively unalterable for a given individual and situation. Also relatively constant for a given individual is the neuro-muscular time lag, $T_N$, which delays the application of control after the pilot has made his decision. The remaining elements in the loop (i.e. the pilot's gain, $K_p$, and the lead and/or lag time constants that he may generate, $T_L$, $T_I$) are variables meant to represent the pilot's ability to adapt his response to 'optimise' the overall system performance. Thus, when presented with an aircraft having certain dynamic characteristics the pilot is assumed to modify his 'compensatory' behaviour by a process of trial and error, presumably until he finds a mode of response which allows him the necessary closeness of control of the aircraft; the mechanism by which the pilot makes this adaptation is highly complex and is outside the scope of the theory.

(iii) The authors put forward criteria for the stability and performance of the closed-loop system which the pilot appears to aim for in simulator tests. Using servo-analysis theory they calculate those values of the describing function parameters which satisfy these criteria. They then postulate that there must be a relation between these parameters and the pilot's rating of the controlled system.

(iv) The experimental evidence supports, in a generalised sense, the hypothesis that pilot ratings are related to the required 'compensatory' characteristics of the describing function ($K_p$, $T_L$, $T_I$), though it is not yet sufficient to permit quantitative expression of these relationships. The conditions necessary for 'good' pilot ratings have been established, however, and can be used in conjunction with servo-analysis techniques, to establish limits for the relevant aircraft parameters. At the opposite extreme, conditions associated with incipient uncontrollability have also been established. The theory is capable of identifying some of the 'crucial' aircraft parameters, and of supplying a basis on which the handling qualities of configurations having unfamiliar dynamic characteristics can be assessed.

Although it has proved already to be a tool of some power, it will be appreciated that this synthesis is not yet fully developed and suffers from several shortcomings in consequence. For example, the experimental data referred to above were obtained in non-moving simulators and therefore related to purely visual stimuli, thus the present approach may need some modification to take account of the effects of motion stimuli; for a second example, the method has, so far, been established for essentially single-loop control problems and its extension to more realistic tasks involving multiple stimuli and multiple-loop control and co-ordination (e.g. the simultaneous control of pitch and bank attitudes) is likely to present serious difficulties. It seems probable, however, that most of these shortcomings can be resolved by further development and as more data are acquired, resulting in a research tool of the first importance.

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

By P. L. BISGOOD

## Part II.—Lateral-Directional Handling

*Summary.*

Part II is a review of recent research into lateral-directional handling problems and the results that this has achieved. From the basis of these results, together with *ad hoc* data, an attempt is made to synthesise some lateral handling criteria applicable to large aircraft, with particular reference to the handling at low speeds. Because our knowledge of the factors involved remains rather rudimentary (despite the considerable advances made in the last decade), the criteria proposed are somewhat tentative.

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LIST OF CONTENTS

*Section*

## LIST OF CONTENTS—*continued*

## LIST OF ILLUSTRATIONS.

*Figure*

## 1. *Introduction.*

Although we shall follow the usual practice in stability theory of treating the lateral and longitudinal motions separately, it must be realised that such an approach is not strictly permissible in a discussion of handling, even when there is in fact little physical coupling between the lateral and longitudinal modes, and even this is not always true with the modern aircraft. In assessing a particular aircraft mode the pilot will consider the degree of difficulty he has in keeping this mode under control. This will of course be influenced by the demands made on him at the same time to control the other freedoms of the aircraft*.

There is in fact evidence to show that a deterioration in longitudinal handling will cause pilots to downgrade their assessment of the lateral characteristics and *vice versa.* The few cases in which this interaction has been properly assessed are, however, totally inadequate to permit the formulation of generalised rules for the prediction of such cross-interference effects on handling criteria.

The best that can be done in this complex situation, and in fact what is generally done by workers in this field, is to optimise all the aircraft characteristics other than those under study, i.e. they are adjusted to a standard that in isolation would be considered as 'satisfactory' or 'good'.

The same difficulty arises of course within the field treated as lateral handling, where three distinct modes of motion have to be considered in isolation although an even stronger interaction is to be expected.

Apart from a few rare instances where a lateral 'phugoid' replaces the roll and spiral modes, the lateral motion of aircraft consists of three distinct modes, the dutch roll oscillation, the roll subsidence and the spiral subsidence or divergence.

Basically the pilot is not concerned with the character of these modes but with the behaviour of the aircraft to his control demands and to external disturbances. This behaviour is of course determined by the stability of the aircraft, i.e. by the stability characteristics of these modes and, in addition, by other parameters describing control and gust sensitivity.

Historically, lateral handling research has treated the three principal lateral modes largely as distinct entities, with the implied assumption that each correlates uniquely with a particular flying problem. Fortunately, for the majority of aircraft this was in fact a reasonable assumption to make, as the 'characteristic times' of the three modes were well-separated from one another. For a medium-sized aircraft for instance, the roll subsidence would have a time constant of less than 1 sec, the dutch roll a period of say 4–5 sec and the spiral a time constant of perhaps 40 sec. Also each of these modes was largely associated with a particular freedom of the aircraft motion without too much coupling into others.

Consequently, in such a case, the roll subsidence would describe the immediate response of the aircraft to a roll demand and would therefore be of interest to the pilot in his primary lateral control task, the control of bank angle.

The dutch roll on the other hand would determine the more long-term steadiness of flight and be of concern in particular in flight through turbulent air.

The spiral mode, finally, described the long term stability of the aircraft and affected the pilot's ability to achieve lateral trim in steady flight.

Clearly once the assumptions permitting this separation of the modes are invalidated, for instance when the dutch roll period and the roll subsidence time constant are close to each other, the simple correlations between a handling criterion and the stability parameters of a particular mode can no longer be expected to exist and perhaps an entirely different type of handling criterion should be established.

As all the generalised research on handling has been based on this concept of separate lateral modes, the results of the present review are accordingly limited to this situation and cannot necessarily be applied to configurations with unconventional lateral characteristics such as might be found on some slender wing aircraft in low speed flight, or indeed with VTOL aircraft.

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*A situation in which this complication does not arise could, for instance, be investigated in a simulator by freezing the remaining freedoms or, in the air, by flying under partial automatic control, but such situations are extremely artificial and do not resemble flight under manual control, which is the proper subject of this study.

The final sections deal with two specific handling problems, by a more speculative approach, control in turbulent air and during crosswind approaches.

## 2. *The Roll Response.*

The ideal lateral control from a handling point of view is one which commands a response in roll alone (i.e. one which excites only the roll mode), and it seems probable that the ideal form of this response is a steady rate of roll* achieved after the shortest practicable transient and proportional to control displacement. Quite close approximations to these ideals occur fairly frequently in practice and it is reasonable, therefore, to begin our investigation by considering the response involving the isolated roll mode.

The single-degree of freedom response of an aircraft in roll can be written in Laplace transform notation.

$$\Phi(s) = \frac{L'_\xi \, \xi(s)}{A' s(s+1/T_R)} \tag{1}$$

where $T_R$ = time constant of the roll mode $= -\dfrac{A'}{L'_p}$ (seconds).

This is defined completely by the roll time constant and the control power available (expressed in terms of the rolling acceleration it can generate, $\dfrac{L'_\xi \cdot \xi_{\max}}{A'}$); provided the control forces and the control system dynamics are satisfactory, pilot opinion should correlate with these two parameters alone.

There has been no systematic research into the lateral manoeuverability specifically of large aircraft, and therefore we shall consider first the results available for fighter-type aircraft; from these, in conjunction with the results obtained from *ad hoc* tests on large aircraft, we shall attempt to synthesise handling criteria applicable to large aircraft.

Reference 5 describes a programme of systematic, single degree of freedom, tests in which a moving-cockpit simulator having complete freedom in roll was used; the frequency response of the simulator system (which is considered excellent) is most unlikely to have had a distorting effect on the results, and the control-force gradient used throughout the tests is considered reasonable for a fighter; however, because the maximum stick deflection (and force) was kept constant it was not possible to distinguish between the effects of control power and control sensitivity in the analysis. The pilots who took part in these tests had extensive and up-to-date experience in current fighter aircraft, and they were asked to assess the various combinations of time constant and control power according to the Cooper scale[1] (quoted in Table 1). As a result of these tests, boundaries were established which divided the rolling power – time constant plane into areas classified as 'satisfactory', 'unsatisfactory but acceptable', and 'unacceptable' respectively; boundaries derived from Fig. 10 of Ref. 5 are reproduced in Fig. 1.

A comparison of ratings predicted on the basis of the simulator test results with the actual ratings assigned during corresponding flight tests of a number of aircraft is included in Ref. 5 and shows good agreement (differences not greater than one point on the Cooper rating scale, the predicted ratings erring on the side of optimism) between the two sources for 29 of the 32 aircraft configurations considered; the exceptions occurred in the case of aircraft in which the dutch-roll component of the total response to aileron was large and here, as might be expected, the simulator-derived ratings were optimistic. It is clear that the boundaries established in Ref. 5 are valid for those present generation fighter-type aircraft in which control coupling between the roll and dutch roll modes is not excessive.

Now it is reasonable to suppose that boundaries qualitatively similar, in at least some features, to those established for fighter-type aircraft will define the lateral manoeuverability required for larger aircraft, and some discussion of these features follows.

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*Control systems which command bank angle are technically feasible, but there is no evidence to to suggest that they would be superior or preferable to rate-command systems and they will not be considered here.

### 2.1. *Limiting Values of the Roll Time-Constant.*

The work of Ref. 5 shows that pilots will rate as unsatisfactory any fighter-type aircraft which has a roll time constant longer than about 1·5 seconds, regardless of the rolling power available (it is interesting to note that this result confirms the suggestions of Pinsker[6] and Zbrozek[7] that values of $T_R > 1$ second will render a fighter-type aircraft difficult to fly; a similar conclusion was reached by Ashkenas and McRuer[2]). It is thought that the limit for 'satisfactory' handling reflects the fact that, as the time constant of the roll mode increases in relation to some manoeuvre time ($t_m$), typical of the class of aircraft considered, the lateral control appears to the pilot to operate as an acceleration-command system to an increasing extent, and the consequent increase in the effort and concentration involved in making rapid, precise, adjustments to attitude causes pilot opinion to deteriorate. The value of $T_R/t_m$ beyond which a pilot would rate an aircraft as 'unsatisfactory' is thought to be characteristic of the human pilot and is therefore substantially independent of aircraft type or function. The 'satisfactory' limit established in Ref. 5 should be associated with a 'manoeuvre time' typical of fighter tactics (a representative figure would be about 2 seconds) and it is thought that a typical manoeuvre time for current bomber or transport aircraft will be between $1\frac{1}{2}$ times and twice this, as a consequence $T_R$ should not exceed about 2 to 3 seconds for 'satisfactory' lateral control of these classes of aircraft. In general the small amount of experimental evidence available from flight reports tends to confirm this suggestion, and indicates that pilot opinion starts to become unfavourable when $T_R$ is in the region of 2 seconds.

The trend shown by the Ref. 5 boundary suggests that there may be an upper limit to $T_R$ beyond which an aircraft would be rated as 'unacceptable for normal operation', though the tests did not cover sufficiently high values of $T_R$ to confirm this positively: extrapolation of the appropriate boundary in Fig. 1 suggests that this limit is reached when the time constant is of the order of 6-8 seconds. It seems highly unlikely than an upper limit of $T_R$ for 'acceptable' handling (if such exists) of large aircraft would be significantly greater than the value suggested for 'fighters', even when the response to aileron is confined to the roll mode, and it is suggested that the value of 6 seconds be assigned to this limit. It must be emphasised that there appears to be no flight experience with 'conventional' aircraft having time constants of this order and consequently this suggestion lacks experimental justification and must be treated as speculative*.

### 2.2. *Lower Limits of Rolling Power.*

The minimum requirements for rolling power to achieve a given pilot rating as shown in Fig. 1 vary as a function of the roll time-constant, $T_R$. In the region where the roll subsidence is well damped, say when $T_R < 0{\cdot}4$ sec, these boundaries correspond very closely to constant values of steady roll rate. For values of $T_R$ greater than this, increasingly larger rolling capability is demanded, although the demand in terms of rolling acceleration still decreases. Finally the influence of $T_R$ as a limitation in its own right becomes dominant. However, in the major portion of this regime, where in fact control power dominates the picture, it can be shown that the contours of the boundaries define limits to the capability of performing certain operational bank manoeuvres. Single degree of freedom responses were calculated for a range of aileron inputs and showed that it was, in fact, possible to select realistic bank-and-stop manoeuvres which correlated quite well with the experimental boundaries. The results of this exercise are illustrated in Fig. 2 and summarised in the Table below**:

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*Some experimental data relating to 'long' time constants is available from VTOL research. However, in view of the differences in flight task, etc., it seems that this information would have little relevance to the handling of conventional aircraft.

**These results refer to cases where full aileron is applied in 0·25 sec, a realistic value for a maximum effort manoeuvre in fighter-type aircraft.

| *Boundary* | *Bank-and-stop manoeuvre* | *Accuracy of the comparison* |
|---|---|---|
| Satisfactory | 1·5 radians in 2 sec | about $\pm 15\%$ over the range $0{\cdot}1 < T_R < 0{\cdot}7$ sec |
| Acceptable for normal operation | 2 radians in 4 sec | better than $\pm 10\%$ over the range $0{\cdot}1 < T_R < 2$ sec |
| Acceptable for emergency only | 1 radian in 5 sec | better than $\pm 10\%$ over the range $0{\cdot}1 < T_R < 4$ sec |

It is evident that the bank-and-stop manoeuvre provides a satisfactory criterion of roll manoeuvrability for values of $T_R$ not greater than those at which the rolling power demanded for a certain standard of acceptability has a minimum and it seems likely that pilots' assessments are in fact based on criteria of this sort: this may still be true at larger values of $T_R$, though the changes in pilot response which probably are necessary to achieve adequate closed-loop performance in these circumstances imply that it would no longer be sufficient to use manoeuvre capability as the prime criterion. A detailed analysis including the pilot response is beyond the scope of the present paper.

Now for large aircraft it is likely that the heaviest normal demand on roll manoeuvrability will occur during the approach, in particular, when correcting a lateral offset from the runway (e.g. which may appear on 'going visual' during the final approach phase). These corrections known as 'sidesteps'[11], involve a minimum of three consecutive bank-and-stop manoeuvres and it is not unlikely therefore, that such manoeuvres will again form the basis on which the pilot assesses the adequacy of roll performance; it was shown in the flight study of Ref. 11 that the maximum bank changes used in manoeuvres of this type were invariably less than 60 deg. (i.e. reversal of a bank less than 30 deg.).

In an attempt to establish quantitative criteria we have examined the rolling performance of a number of large aircraft in the approach configuration (Refs. 8-22, and unpublished data) and related this data to pilot's assessments of the roll manoeuvrability. The assessments were obtained mainly from routine handling reports and did not employ a common rating system, so that it has been possible to separate opinions into only three rather broad categories, namely:

'satisfactory' — adequate roll manoeuvrability

'marginal' — roll manoeuvrability is unsatisfactory and/or response is poor, though not to a dangerous extent

'unacceptable' — insufficient manoeuvrability to attempt an approach in anything less than ideal conditions.

These assessments are intended to refer solely to the lateral manoeuvrability and any associated adverse comments (e.g. of excessive control forces) have been ignored; however, it is not known to what extent the assessments may have been coloured, in some cases, by pilot opinion of the response and controllability in turbulence.

Wherever possible the values of rolling power and time constant of these aircraft were derived wholly from flight measurements made in rudder-fixed rolls; where the data available were not sufficient to permit this, a combination of flight results and wind-tunnel data or estimates has been used. Rolling performance data and pilots' assessments were available for twenty-one large aircraft of recent vintage; nineteen of these aircraft had spans in the range 89–142 ft, with the majority concentrated in the range 105–125 ft span, and the remaining two had spans of approximately 180 ft.

The results of this analysis are shown in Fig. 3. Where data were available for more than one speed of a given configuration the relevant points are shown linked together in the figure, different configurations of a given aircraft (e.g. different flap settings, or different amounts of available lateral control) are plotted separately. Included in Fig. 3 are theoretical curves defining the relationships between rolling power and roll time-constant which would enable 60 deg. bank-and-stop manoeuvres to be completed in various times (assuming full aileron to be applied in 0·5 sec*).

It will be seen from Fig. 3 that the dividing line between 'marginal' and 'satisfactory' characteristics conforms quite closely to the relationship defining the capacity to perform an idealised bank-and-stop manoeuvre of 60 deg. in about 6·5 seconds; in fact, if this criterion were applied to the data considered it will be seen that only one 'marginal' aircraft would pass and one 'satisfactory' aircraft fail, and in neither case is the discrepancy large. Probably some allowance should be made for the fact that, in practice, a pilot is unlikely to achieve the idealised input considered here, and it is thought that a practical criterion of 'satisfactory' roll manoeuvrability for large aircraft should specify that a 60 deg. bank-and-stop manoeuvre can be completed in not more than 6·5 seconds, with an accuracy of, say, ±10 per cent in bank angle. It must be emphasised that this criterion may prove satisfactory only within the range which has been covered fairly thoroughly in the present investigation (i.e. $T_R < 1{\cdot}8$ seconds); for example we can expect that further data at higher values of $T_R$ may show a demand for increasing rolling power, qualitatively similar to the trend shown in the case of fighter-type aircraft, though, as mentioned earlier, this effect may be associated with the increased difficulty of manoeuvring with large $T_R$ and may, therefore, be covered to some degree by the bank-and-stop criterion.

As was to be expected, very few cases of 'unacceptable' roll manoeuvrability were encountered in this analysis, and these occurred where only a part of the normal lateral control was used in the tests (e.g. a test using ailerons only in an aircraft in which both ailerons and spoilers would be available normally); there were insufficient data of this sort to establish a boundary between 'marginal' and 'unacceptable' characteristics and on the very limited evidence available (*see* Fig. 3) we can only suggest tentatively that this may correspond to the capacity to perform a bank-and-stop manoeuvre of 60 deg. in about 11 seconds.

### 2.3. *Upper Limits in Rolling Power.*

Although no current large aircraft have handling problems associated with excessive rolling power, this situation may not continue indefinitely; in particular, the current trend towards higher values of $l_v$ on the approach may, if continued, result in cases where the aileron power required is dictated by consideration of the approach in cross-winds and is considerably larger than that required for manoeuvring. In view of this, a brief discussion of the upper limits in rolling power is given below though, in the absence of any direct evidence relating to large aircraft, the discussion is necessarily speculative.

The comparison between fixed-and moving-cockpit simulator results in Ref. 5 shows that, when the maximum roll acceleration available is less than about 8 rad/sec$^2$ there is little difference between boundaries obtained from the two sources; above this value the two sets of boundaries diverge, relatively less rolling acceleration being tolerated in the moving simulator (e.g. at $T_R = 0{\cdot}2$ the upper limits to rolling acceleration for 'satisfactory' operation in the fixed and moving simulators are 36 and 20 rad/sec$^2$ respectively). This feature suggests that the pilots' assessment is strongly influenced by the physiological or psychological effects of rolling acceleration when this is high.

When acceleration effects are unimportant (i.e. in the fixed simulator) the upper boundary of the 'satisfactory' area of Ref. 5 corresponds closely to a constant maximum steady rate of roll, and this is approximately true also of the upper limit of 'acceptability for normal operation'.

The rolling accelerations available in current large aircraft are not sufficient to inconvenience the pilot and it seems most unlikely that this situation will change significantly in the immediate future; it is suggested therefore that the upper boundaries of the 'satisfactory' and 'acceptable' areas for large aircraft will be qualitatively similar (i.e. lines corresponding to constant roll rates) to those obtained in the fixed-base simulator.

It can be seen from Fig. 1 that at low values of $T_R$, the ratios between the steady rates of roll representing the upper and lower boundaries of the 'satisfactory' and 'acceptable' (for normal operation) areas of

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*Examination of a large number of flight records shows that this is a reasonable application time for maximum effort rolls in large aircraft.

Ref. 5 were roughly 6 and 20 respectively in the fixed-base simulator. Now it is probably fair to assume that these ratios represent the ranges over which the pilot can adjust his gain 'satisfactorily' or 'acceptably' (given constant stick force for full control movement) and that these ranges are likely to be independent of aircraft type as such, though there will probably be a tendency for the ranges to expand if two-handed operation is available (as it usually is in large aircraft); it is likely, therefore, that if the above ratios were applied to the lower $T_R$ – range of the boundaries established in Section 2.2 for large aircraft, the resulting upper limits would err on the side of safety. The upper limits so obtained are approximately 60 deg./sec and 120 deg./sec for 'satisfactory' and 'acceptable' operation respectively, and it is recommended that these values should be used as a guide until more positive evidence becomes available.

The rolling performance boundaries proposed for large aircraft on the approach are summarised in Fig. 4; the portions represented by dashed lines are somewhat speculative and should be used only as approximate guides.

### 2.4. *Control Movements and Forces.*

The evidence available from handling reports indicates that pilots dislike those systems in which full lateral control requires rotations exceeding 90 deg. of a wheel-type control input; this is particularly true when the rolling performance is near the lower limit. It appears that as a general rule the maximum wheel travel should not exceed 90 deg.

It has not been possible, on the evidence available, to establish upper limits to the control sensitivity, but it is clear that sensitivities at least as high as 0·5 deg/sec rate of roll/degree of wheel displacement are regarded as satisfactory (provided, of course, that the associated force levels are reasonable); this figure is less than, and therefore compatible with, the sensitivity (0·67 deg/sec/deg wheel displacement) associated with the suggested upper limit of 60 deg/sec for 'satisfactory' operation (Section 2.3 above) combined with a 90 deg wheel displacement.

A detailed discussion of the relative merits of various control and feel systems has been given by Lang and Dickinson in Ref. 23. So far as the lateral control of large aircraft is concerned, their main conclusions may be summarised as follows:

(a) Friction and backlash in the control system should be kept as low as possible,

(b) Positive self-centering should be provided, preferably with only a small break-out force,

(c) Simple spring feel it quite adequate from a handling point of view; on many aircraft this may necessitate some means of limiting the control angle available at high E.A.S. to avoid over-stressing the structure,

(d) The force required for full application of a wheel-type control should probably be about 40 lb.

With regard to (b), it is known that an aircraft with a break-out force of roughly 50 per cent of the force to apply full control *can* be flown, but is generally unpleasant to handle and lacks precision in control. As a guess it seems desirable that the break-out force should not exceed 10 per cent of the force for full control movement, or 5 lb, whichever is the smaller.

The evidence available on desirable levels of control force is too scanty to permit really firm conclusions to be drawn. It was noted, however, that when the control sensitivity on the approach was in the region of 0·2 deg/sec/lb or less the forces were rated as 'too heavy' or 'much too heavy' (*see*, for example, Refs. 15 and 21), whereas sensitivities in the region of 0·3 deg/sec/lb attracted no adverse comment; this leads one to suggest that a lower limit for 'satisfactory' control sensitivity on the approach should be in the region of 0·25 deg/sec/lb. At the other end of the scale, a number of large aircraft are known in which the control sensitivity lies in the range 1 to 1·5 deg/sec/lb and, in general, these are not criticised for 'over-sensitivity' – or at worst, the criticisms are mild; it seems reasonable, therefore, to suggest that an upper limit in the region of 1·5 deg/sec/lb* would prove 'satisfactory' on the approach. There is a tendency for the lower

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*It is interesting to note that the ratio of these upper and lower limits of sensitivity is the same as the ratio of the gains considered in Section 2.3.

limit of sensitivity to be associated with low rates of roll and vice versa, and it is likely that these limits are, to some extent a function of the rolling performance available, though we have insufficient data to establish the connection. It is by no means certain that the figure quoted as an upper limit derives solely from considerations of lateral control sensitivity – it is possible, for example, that more sensitive lateral control might lead to disharmony between lateral and longitudinal control forces.

Associating the upper limit of sensitivity with the upper boundary of Fig. 4, and the lower limit with the linear portion of the lower boundary shows that, in all aircraft having 'satisfactory' lateral manoeuvrability, a force of about 40 lb for full control should give 'satisfactory' feel – this agrees well with the figure suggested in (d) above.

There is a growing body of opinion against retaining the traditional wheel-type control in large aircraft, and a case can be made for its replacement by either a conventional central stick or a miniature side-located stick. Various types of side-located stick have been tested in simulators and in flight in fighter-type aircraft (e.g. Ref. 24), where they have been well-liked. However, no comparable tests have been made for large aircraft, so that the suitability of this form of cockpit control for transport aircraft remains a matter of speculation.

## 3. *The Spiral Mode.*

Spiral stability is a measure of an aircraft's ability to maintain a given course when trimmed. In a spirally unstable aircraft the pilot will have to make more or less frequent control movements to maintain a given heading and will have to 'hold off bank' in steady turns, whereas a spirally stable aircraft tends to resist heading changes and the pilot will need to 'hold on bank' to maintain a steady turn. Spiral stability is strongly influenced by flight path inclination to the horizontal (in addition to the aerodynamic derivatives), positive inclination (i.e. climb) being destabilising, and vice versa.

Pilots are generally unaware of the spiral mode, whether stable or unstable, provided its time constant ($T_s$) is sufficiently long, i.e. if it is a nearly neutrally stable motion. Consequently a small degree of instability is acceptable; for example, the American military requirements demand a divergent spiral should not double amplitude in less than 20 seconds in the cruise and approach conditions, and this limit is generally in agreement with flight evidence.

Cases of aircraft having a substantial degree of positive spiral stability do not appear to have occurred in practice – other than in steep dives, where no objections are recorded. Consequently no general flight evidence can be offered to delineate a possible region of excessive spiral stability. However, such a condition might well be objectionable, since it would restrict manoeuvrability in the horizontal plane.

Ashkenas and McRuer[2] have made a theoretical study of the spiral mode and its effect on pilots' control using the methods outlined in Part I, Section 2.4. The results of this analysis are rather sensitive to the characteristics assigned to the 'pilot analogue', consequently its conclusions must at this stage be interpreted with caution. Nevertheless, this investigation has revealed some entirely novel concepts which clearly will have to be considered in the appropriate cases.

First, Ref. 2 concludes that the spiral mode will not affect pilots control if it is nearly neutrally stable and that it may become unsatisfactory if it is either more stable or more unstable than defined by a time constant less than 10 to 20 secs, roughly. Further, Ref. 2 suggests that there exists an interaction between the control of the roll subsidence and the spiral mode and that for satisfactory handling these modes should be separated by a ratio (again independent of the sign of the spiral stability) of

$$|T_s|/T_R > 30.$$

Ref. 25 reports on a series of variable stability aircraft tests in which a wide range of spiral stability characteristics was covered. The results of this investigation appear to support Ashkenas and McRuer's first criterion. Broadly the following boundaries were established in these tests

Estimates indicate that, on the approach, a number of modern large aircraft have divergent spiral modes with time constants of the order of 20 sec and in several cases the ratio of $|T_s|/T_R$ lies between 20 and 30. The fact that in none of these cases adverse comments have been made which can be attributed to the spiral divergence, does at least not conflict with the criteria of Ref. 2.

On the basis of the relatively sparse evidence available it is recommended that, to avoid any significant deterioration of handling, the time constant of the spiral mode should be

$$|T_s| > 20 \text{ sec}$$

a value of roughly one half of this is likely to be accepted without serious objection.

Furthermore if the ratio of the spiral time-constant to that of the roll subsidence,

$$|T_s|/T_R < 30$$

minor handling difficulties might arise if the predictions of the theoretical approach of Ref. 2 are substantiated.

Spiral stability has a large effect on the maintenance of trimmed flight and thus a poor lateral trim system will present to a pilot difficulties often indistinguishable from those generated by a divergent spiral. A comprehensive study of lateral control of steady flight should take into account the additional contributions from both these causes, but no systematic work has been done to offer suitable guidance in this field.

## 4. *The Dutch Roll Mode.*

The so-called dutch roll mode is a short period oscillation having components in yaw, roll and sideslip. For most practical purposes it can be described adequately by three parameters, namely; the period, the damping, and a parameter, such as the amplitude ratio of bank to sideslip $|\phi/\beta|$, which defines the degree to which the principal freedoms are coupled in this motion.

As a result of recent developments in aircraft design and performance the dutch roll has become more prominent as a handling problem. This has led on the one hand to the development of artificial stability augmenters, and on the other to extensive research into the factors which govern pilot opinion of the dutch roll characteristics. This work has been done almost entirely in the U.S.A. So far as is known, no systematic work on large aircraft is available (the American programmes have all employed fighters converted to function as variable-stability aeroplanes) so that, once again, we shall have to attempt to synthesise handling criteria from a combination of the systematic results available for fighter-type aircraft with the results of *ad hoc* testing in large aircraft. A review of the systematic work will be given first.

Some early flight work by N.A.C.A.[27] suggested that pilot's assessment of the dutch roll characteristics was influenced by the amplitude ratio of the bank and sideslip angles occurring during the oscillation, in addition to the period and the damping of the motion. An investigation made at Cornell[28] covered rather lower values of $|\phi/\beta|$ than Ref. 27 and indicated that, within the range covered, pilot opinion was controlled mainly by damping and did not correlate significantly with either $|\phi/\beta|$ or period.

An extensive investigation[29] was then made by the N.A.C.A., using a rather more sophisticated variable-stability aeroplane. The results indicated that pilot rating was influenced by two main parameters, – the damping of the oscillation (in terms of the number of cycles to halve amplitude) and the amplitude ratio of bank angle to equivalent side-velocity $\left(\left|\frac{\phi}{v_e}\right| = \frac{57\cdot3}{V\sqrt{\sigma}}\left|\frac{\phi}{\beta}\right| \text{ deg/ft/sec}\right)$, and suggested that the dutch roll would be rated as unsatisfactory or intolerable if the latter parameter exceeded about 0·55 or 0·8 respectively, regardless of damping. At low values of $|\phi/v_e|$ satisfactory and tolerable handling demanded damping to half amplitude in 1 and 4 cycles respectively. No significant effect of period was observed in these tests. The subject report notes that certain of the configurations tested were subject to rolling velocity reversals during rudder-fixed rolls; in addition, though little stress was laid on this, a large number of configurations had excessive yaw response to aileron, and a close examination of the test data has shown that the limiting values of $|\phi/v_e|$ for satisfactory or tolerable handling were, in fact, obtained on configurations which suffered from this defect. It seems certain that these short-comings of the lateral control must have had an adverse effect on pilot opinion and, hence, on the general applicability of the results of this pioneer investigation.

The C.A.L. investigation, reported in Ref. 25, produced results which were basically similar to those of Ref. 29, though the damping required for a given rating did not increase as rapidly with increasing $|\phi/\beta|$, and rather more damping was demanded at low $|\phi/\beta|$ than was found necessary in Ref. 29. The latter feature may derive from the fact that the Cornell investigation placed rather more emphasis on gun-aiming. The tests of Ref. 25 were conducted at a single airspeed and height, so that it was not possible from these results to separate the parameters $|\phi/v_e|$ and $|\phi/\beta|$ and to resolve the controversy as to which of these two would correlate better with pilot rating.

Ref. 30 includes a review of the lateral oscillatory characteristics of a number of aircraft and suggests, as a result of this, that aircraft can be divided into two main categories from the viewpoint of general handling (i.e. excluding precision tasks such as gunnery and bombing – apparently the landing approach was excluded also):

(i) cases in which the roll/yaw ratio, $|p/r|$, was greater than 4, which were generally regarded as unsatisfactory regardless of the damping (this agrees broadly with the conclusions of Ref. 29),

(ii) cases in which $|p/r|$ was less than 4, where the pilot's assessments depended on a combination of the period and damping.

The quality of control in the aircraft considered is not mentioned, so that one cannot be certain that the first of these conclusions does not result from a combination of high roll/yaw ratio and poor lateral control rather than from the roll/yaw ratio alone; however, it is probably fair to say that, even if high roll/yaw ratio is not in itself a bar to satisfactory handling, it will make a satisfactory overall system (i.e. aircraft + control system) more difficult to obtain The dependence of pilot opinion on period and damping is a logical expectation and is borne out in practice: the data of Ref. 30 for roll/yaw ratios less than 4 can be interpreted in several ways, but it appears that if the time to half amplitude ($T_{\frac{1}{2}}$) is not greater than 2 seconds for periods ($P$) less than 2 (or, possibly 3) seconds, and is permitted to increase linearly with period up to $T_{\frac{1}{2}} = 10$ sec at $P = 6$ sec, this should produce 'tolerable' characteristics.

### 4.1. *Dutch Roll on the Approach.*

A recent report[31] issued by the N.A.S.A. gives details of a further flight investigation into the handling problems associated with the dutch roll. This investigation was concerned specifically with the approach condition and is by far the most comprehensive study available at present; it is, therefore, of particular interest and importance to the present review and will be discussed in some detail.

The test vehicle used was a variable-stability F–86E, in which the derivatives $l_v$, $l_p$ and $l_\xi$, $n_v$, $n_r$ and $n_\xi$ could be varied over wide ranges, and the system as a whole represented a considerable advance over those used in earlier investigations. In practice $l_\xi$ was maintained constant throughout the tests, while an optimum value of $n_\xi$ was selected, for each configuration, by the pilot; it is unlikely, therefore, that the pilots' assessments were significantly biassed by the presence of undesirable characteristics of the controls themselves. The longitudinal characteristics were constant and 'satisfactory' throughout the programme. The tests covered a wide range of period, damping and roll/yaw ratio (though rather sparsely in some areas) under simulated approach conditions at a nominally constant airspeed in smooth and rough air; as a result of these tests the seven pilots assigned ratings to each combination on the basis of the Cooper scale[1] (*see* Table 1). The data obtained can be separated into four natural groups as indicated below:

(i) a compact group concentrated around a mean period of about 2 sec (range 1·80–2·38 sec) and a mean $|\phi/v_e|$ of about 0·55 deg/ft/sec (range 0·45–0·63 deg/ft/sec) covering a range of damping (expressed in terms of $1/T_{\frac{1}{2}}$) from about 1·0 to 0·7 $\sec^{-1}$,

(ii) a compact group concentrated around a mean period of about 3·5 sec (range 2·75–4·15 sec) and a mean $|\phi/v_e|$ of about 0·57 deg/ft/sec (range 0·49–0·63 deg/ft/sec) covering a range of $1/T_{\frac{1}{2}}$ from about 0·7 to $-0{\cdot}5$ $\sec^{-1}$,

(iii) a group having the same mean period as (ii), covering the range of $|\phi/v_e|$ from 0·84 to 1·62 deg/ft/sec and a range of $1/T_{\frac{1}{2}}$ from about 0·5 to $-0{\cdot}3$,

(iv) an amorphous group in which the period ranged from 4·32 to 6·9 sec, $|\phi/v_e|$ ranged from 0·68 to 1·65 deg/ft/sec, and $1/T_{\frac{1}{2}}$ ranged from about 0·8 to 0.

In the analysis of Ref. 31 the data was divided into four groups containing equal numbers of data points and covering arbitrary ranges of $|\phi/v_e|$. It was shown that, within each of the groups so formed, the numerical ratings (P.R.) assigned by the pilots decreased (i.e. opinion improved) approximately linearly as the damping increased, until a level was reached where further increases in damping produced little further change in pilot opinion. The data of group (i) was also analysed as a separate entity in an attempt to isolate the effect of the shorter period, and showed the same trends. The damping corresponding to various levels of pilot opinion, obtained from the above mentioned plots, was then plotted against the mean value of $|\phi/v_e|$ for the relevant data-group and, in this way, boundaries dividing the $1/T_{\frac{1}{2}} - |\phi/v_e|$ plane into 'satisfactory', 'unsatisfactory but acceptable' and 'unacceptable' areas were obtained. Although there is good agreement as to the damping required for 'satisfactory' handling at low $|\phi/v_e|$, in all other respects, these boundaries are markedly different from those of Ref. 29; they show firstly, that the pilot will accept very low or negative damping in an emergency – this may well derive from the much more specific rating system employed in Ref. 31; secondly, the very steep rise in damping with $|\phi/v_e|$ shown in Ref. 29 is completely absent from the later boundaries – this may have arisen for several reasons, of which the more important possibilities are:

(a) A change in the climate of pilot opinion during the interval between the two investigations – high roll/yaw ratios were something of a rarity at the time of the earlier tests but have since become fairly commonplace; pilots would therefore be more accustomed to the phenomenon and more generally practiced in dealing with it.

(b) The absence, in the later investigation, of any important adverse control effects, such as were present in many configurations in the earlier tests (we shall return to this point later).

(c) The fact that data relating to widely different periods were considered together in the analysis; in particular, it seems that the inclusion of the data relating to longer periods in the general analysis of Ref. 31 may have produced a bias in the results tending to make high roll/yaw ratios appear less unfavourable.

To eliminate (c), the data of groups (ii) and (iii) only has been re-analysed, group (iii) being sub-divided arbitrarily to cover two ranges of $|\phi/v_e|$. The results, which are qualitatively similar to those of Ref. 31, are shown in Figs. 5b, c and d. The data of group (i) is shown in Fig. 5a. It will be seen that the scatter of pilot rating is strikingly small, particularly in Figs. 5a and b.

This change in emphasis in the analysis produces negligible changes in the boundaries defining acceptability (normal and emergency), but the 'satisfactory' boundary becomes undefined at high roll/yaw ratios ($|\phi/v_e| > 1{\cdot}5$, approximately) and one can no longer exclude the possibility of a rapid increase in the damping required in this region. The revised boundaries, which are shown in Fig. 6, refer to periods lying within the range 2·75 – 4·15 sec, with most of the data lying close to the mean period of about 3·5 sec. Also shown in Fig. 6 are the limits obtained from Fig. 5a for the data of group (i) (i.e. for a mean period of 2 sec) – it will be observed that these differ only slightly from the boundaries for 3·5 seconds period, though the difference is in the expected sense, i.e. less damping is required with the longer period.

The distribution of data in group (iv) makes it impossible to divide the material into sub-groups which are reasonably homogeneous in terms of period and roll/yaw ratio and, at the same time, cover the range of damping adequately: analysis of the group as a whole is rather unsatisfactory since the results represent some mean taken over a wide range of parameters and may not be particularly meaningful. It was clear, however, that with a mean period of 5·2 sec the damping ($1/T_{\frac{1}{2}}$) required for a 'satisfactory' rating at a mean $|\phi/v_e|$ of about 1·3 was less than 0·5*, which is appreciably below the level suggested by the (extrapolated) results for 3·5 seconds period; on the other hand, the damping required for 'satisfactory' and 'acceptable' ratings was rather higher (0·49 and 0·1 respectively) for the longer period at a mean $|\phi/v_e|$ of about 0·8. In short, the pilots in these tests did not show a clear-cut preference for longer periods – this may have been due to the way in which the test data was distributed but, since similar investigations have also yielded inconclusive results on the effect of period, it is possible that the method used to increase the period in all these variable-stability aircraft (i.e. by reducing the 'stiffness' term, $n_v$) produced side effects which were sufficiently objectionable to outweigh the advantages normally associated with longer periods. If this is so, then the technically much more difficult alternative of increasing the period, in a variable-stability aircraft, by artificially increasing the 'inertia' might prove more satisfactory in future investigations of this type. Another possible explanation for the absence of a decisive improvement in pilot opinion with increase in period may be that the experiments were made in 'small' aircraft (usually modified fighters) which, in their normal condition, would have relatively short periods; when the period was increased artificially, the aircraft would no longer 'fly like a fighter' and this may have distorted the pilots' opinions.

The strong influence of the aileron yawing moments on pilots' assessments of the dutch roll behaviour is noted in Ref. 31, though no details are given. It is known, however, that the pilot-selected optima for $n_\xi$ were such that the overall yaw response resulting from aileron application tended to be minimised. For the F–86E aircraft used in these tests the damping ($1/T_{\frac{1}{2}}$) required for a given level of pilot opinion increased by roughly 0·15 for each change of $\pm 0{\cdot}01$ from the optimum $n_\xi$**. It is reasonable to assume that the results of Ref. 29 were sensitive to $n_\xi$ to roughly the same extent, in which case the steep rise in damping with increasing $|\phi/v_e|$ shown in that Report can be attributed, at least partly, to unfavourable control characteristics rather than to high roll/yaw ratio by itself. The quantitative exchange rate between control quality and damping established in Ref. 31 should not be applied generally, and further research is needed before general numerical standards can be formulated. The question of roll-yaw coupling is discussed further in the next section.

It will be apparent from the above review that although the dutch-roll parameter $|\phi/v_e|$ has come to be accepted (particularly in America) as a major factor in determining pilot opinion, the published evidence in favour of its selection is by no means overwhelming and, in fact, consists of one series of tests[29] in which extraneous factors seem to have played a large part: further investigation may show some other parameter or group of parameters to correlate better with pilot opinion. For the present, however, we shall continue to use $|\phi/v_e|$. A good case can be made for this parameter as it indicates the sensitivity of the aircraft to side-gust disturbance, which must have a strong influence on pilot control.

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*The lower limit for 'satisfactory' handling could not be established precisely owing to the scarcity of data relating to low damping.

**Communicated privately.

### 4.2. *Large Aircraft on the Approach.*

We shall attempt now to establish handling criteria applicable to the lateral short-period mode of large aircraft in the approach condition. In general the period of the oscillation in these cases lies between 5 and 9 seconds approximately; a fairly typical average for the group is about 7 seconds, or roughly twice the mean period to which the boundaries of Fig. 6 refer. A difference of this magnitude by itself makes it virtually certain that these boundaries could not be applied to the present case without some modification.

The results of routine lateral-directional stability tests of a number of large aircraft in the approach (Refs. 9–11, 15–22, 32–34) have been analysed and correlated with pilots' assessments of the dutch roll mode, and are shown in Fig. 7. The 'long period' ($P > 4{\cdot}5$ sec) data of Ref. 31 has been included in Fig. 7, together with some routine test data relating to periods in the region of 4–4·5 sec; this supplied additional information in the range of medium and high $|\phi/v_e|$ and permitted better definition of the boundaries in these areas. It will be appreciated that the data included in Fig. 7 covers a range of period (and probably of control characteristics also) which may be undesirably wide, however, it is difficult to break the data down into a number of more homogeneous sub-groups, each containing a sufficiently large sample; it seemed better, therefore, to treat the group as a whole and to regard the results as representing a typical average for present-day large aircraft.

Examination of the data of Fig. 7 showed that, for values of $|\phi/v_e|$ below about 0·5, the boundary between 'satisfactory' and 'acceptable' handling could reasonably be represented by a line of constant damping ($1/T_{\frac{1}{2}}$), the damping required lying between 0·15 and 0·2; it is clear that we should err in favour of better handling and therefore the higher value ($1/T_{\frac{1}{2}} = 0{\cdot}2$) is proposed as the lower limit of 'satisfactory' qualities for aircraft in which the dutch roll period is about 7 seconds and $|\phi/v_e|$ is less than 0·5.

For the same conditions of $|\phi/v_e|$, the boundary between 'acceptable for normal operation' and 'acceptable for emergency only' was less well-defined; pilots' comments suggested that, under test conditions, divergent oscillations which doubled amplitude in about 20 seconds ($1/T_{\frac{1}{2}} = -0{\cdot}05$) were considered marginal, and it is likely that more damping would be required when the pilot has to cope with additional distractions (e.g. air traffic and radio procedures). For these reasons it is suggested that zero damping should form the lower limit of 'acceptability' for normal operation.

The data available for values of $|\phi/v_e|$ less than 0·5 did not extend to large negative values of damping and included no 'unacceptable' ratings. It was impossible, therefore, to establish the 'unacceptable' boundary in this region, though the data suggests that a time to double amplitude of less than 8 seconds may be acceptable in an emergency and the 'unacceptable' boundary should, therefore, be somewhat lower than this. It is shown in Ref. 31 that pilot opinion deteriorates at a roughly constant rate as the damping decreases below a certain value, and we shall assume a similar variation to exist for the present data; this leads us to postulate that the lower limit of damping for 'acceptability' in an emergency may be a time to double amplitude of 5 seconds for this range of $|\phi/v_e|$. It will be appreciated that the proposed limit is purely hypothetical and that further experimental evidence is required before its usefulness can be assessed realistically.

At values of $|\phi/v_e|$ greater than 0·5, the distribution of data makes it difficult to define pilot-opinion boundaries with any great precision. However, there is a clear tendency for the damping requirement to increase as $|\phi/v_e|$ increases, and the overall picture suggests that the rate of increase for all three boundaries is comparable to that of the 'unacceptable' boundary of Ref. 31; when boundaries having this slope were inserted in Fig. 7 they were found to fit the data reasonably well, bearing in mind that some of this data referred to relatively short periods. It is proposed that, for values of $|\phi/v_e|$ greater than 0·5 and periods of about 7 seconds, the damping ($1/T_{\frac{1}{2}}$) necessary to ensure a given level of pilot opinion should increase by 0·4 per unit $|\phi/v_e|$, from values of 0·2, 0 and $-0{\cdot}2$, for 'satisfactory', 'acceptable', and 'acceptable in emergency only' ratings respectively.

### 5. *Control Coupling Between the Modes.*

Before discussing the influence on pilot opinion of control-coupling between the normal lateral-directional modes we may mention briefly the case where the modes may differ from the classical pattern.

This may occur when the real roots normally associated with the spiral and roll modes combine to form a complex pair*; the associated mode being a lateral oscillation of fairly long period. So far as is known, no practical examples of this condition exist at the present time (though this situation may change in the future), but it is possible that the presence of such a mode would make the pilots' task more difficult, possibly to an extent where some form of artificial stabilisation** becomes essential, and would certainly attract serious adverse comment.

Except in special circumstances, movement of the ailerons will excite all three lateral modes in varying degrees, and the resulting 'coupling' of the modes must be expected to have a pronounced effect on pilot opinion.

We have discussed earlier the influence of roll-spiral mode control coupling on pilot opinion (Section 3).

It has been known for many years that control coupling between the roll and oscillatory modes can influence pilot opinion to an important extent, and various attempts have been made to formulate requirements which seek to restrict the degree of aileron excitation of the dutch roll (e.g. *see* Ref. 35, Sections 3.4 and 6.3). It is only comparatively recently, however, that a start has been made on the systematic study of the problems involved, and this is discussed below.

On the basis of the results of a non-moving simulator investigation, it is suggested in Ref. 37 that pilot opinion correlates with 'the ratio of the initial amplitude of the dutch roll component of the aircraft response to the steady roll rate', and upper limits for this ratio of 0·05, 0·10 and 0·20 (in round figures) are proposed, corresponding to pilot ratings of 'satisfactory', 'acceptable' and 'just flyable' respectively. However, the latter two limits are contradicted by general flight experience (for example, there are several aircraft in which the 'unflyable' limit of Ref. 37 is exceeded and which are assessed as 'acceptable') and by the results of the flight and simulator study of Ref. 39, and we conclude that the ratio $|p_1|/p_\infty$ is not, by itself, an adequate criterion for permissible dutch roll excitation.

Ashkenas and McRuer[2] have applied closed-loop servo-system analysis to the problem of manual aileron control of the lateral motion. Rudder was assumed fixed and any configuration in which a pilot would naturally prefer to use rudder, was thereby ignored. It was found that the principal parameters affecting pilots control are:

(i) $\zeta_d$, the damping ratio of the dutch roll.

(ii) $\omega_\phi/\omega_d$, a parameter in the airframe transfer function for which a good approximation is

$$\left(\frac{\omega_\phi}{\omega_d}\right)^2 \div 1-\frac{n'_\xi}{l'_\xi}\,\frac{l'_v}{n'_v}.$$

This parameter is a measure of the yaw-excitation generated by roll control. Normally it will be greater than 1 if the effective aileron yawing moment $n'_\xi = n_\xi+\frac{E}{A}\,l_\xi$ is negative, i.e. if it generates favourable yaw, and *vice versa*.

(iii) $\omega_d\,T_R$, the product of the undamped frequency of the dutch roll and the roll subsidence time constant.

Ashkenas and McRuer's results can be summarized as follows:

(a) When the basic damping of the dutch roll mode ($\zeta_d$) is low, the damping of the pilot-airframe closed-loop is increased relative to the basic damping when $\omega_\phi/\omega_d<1$ and conversely, is reduced if $\omega_\phi/\omega_d>1$. Depending on other aircraft parameters, a sufficiently large $\omega_\phi/\omega_d$ may make the closed-loop system unstable.

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*This can occur, for example, if $l_v$ is abnormally large and $l_p$ abnormally small.

**In the example quoted above, this would take the form of artificial damping in roll.

(b) Increasing damping of the dutch roll, $\zeta_d$, will moderate the influence of aileron-yaw coupling.

(c) The effect of aileron-yaw coupling will be amplified if $\omega_d \, T_R \doteqdot 1$. This effect has been demonstrated in simulator tests quoted in Ref. 4.

The analysis uses as the only criterion the ease of maintaining stable flight and does not consider the problem of deliberate control of bank.

It can be shown that values of $\omega_\phi/\omega_d$ of less than approximately 0·7 (although most favourable for closed-loop stability) are likely to promote rolling velocity reversals in response to a step aileron input and are certainly objectionable on these grounds. Ashkenas and McRuer suggest, therefore that the optimum value of $\omega_\phi/\omega_d$ is likely to be within the range $0{\cdot}75 < \omega_\phi/\omega_d < 1{\cdot}0$ in cases where the dutch roll damping is poor. For configurations with well damped dutch rolls, where according to (b) the stabilising influence of a small $\omega_\phi/\omega_d$ is less powerful, manoeuvring considerations may predominate and as a consequence the optimum $\omega_\phi/\omega_d$ may be nearer to 1.

Although this analysis must be considered as a major contribution to our understanding of the nature of the piloting problem in the control of such a complex motion, its authors warn that in its present state of development it may still be over-simplified and the results should not be generalized indiscriminately.

So far as is known, two series of systematic tests have been made to date to study the effect of aileron yaw on dutch roll handling. In the more comprehensive of these[38], $\omega_\phi/\omega_d$ was varied in various configurations having otherwise nominally constant dutch roll characteristics (frequency, damping and $|\phi/\beta|$). The tests were carried out by one pilot on a sophisticated variable-stability aircraft designed to study re-entry vehicle characteristics. The effects of artifically generated random disturbances about all three axes were also investigated during this experiment. The characteristics of the spiral mode, of the roll subsidence and the longitudinal stability were also maintained constant during the tests, at levels which, in isolation, would have resulted in 'good' ratings. In practice some of these parameters varied to an extent which made detailed analysis difficult in some cases. However, the broad conclusions can be summarised as follows:

(a) Optimum $\omega_\phi/\omega_d$ is close to unity in all conditions tested except where both dutch roll damping, $\zeta_d$, is poor and the dutch roll ratio $|\phi/\beta|$ is high.

In the latter cases, the sensitivity of pilot rating to changes in $\omega_\phi/\omega_d$ is generally much reduced and though the optimum is less well defined, it is shifted to values of $\omega_\phi/\omega_d < 1$.

(b) The effects of $\omega_\phi/\omega_d$ variation in either direction from the optimum on pilots rating are generally more powerful when $|\phi/\beta|$ is low.

It is noted in Ref. 38 that where the dutch roll ratio $|\phi/\beta|$ was low, the pilot used rudder as the principal means for suppressing the dutch roll.

However, in all cases the results confirm generally the theoretical predictions of Ref. 2, namely that pilots prefer $\omega_\phi/\omega_d = 1$ in well damped dutch rolls but choose a lower value of this ratio when the damping is low.

A special situation, which is not considered by Ashkenas and McRuer, arose during tests in which $|\phi/\beta|$ was very low; here pilot ratings deteriorated exceptionally rapidly with relatively small changes in $\omega_\phi/\omega_d$ from optimum, as shown in Fig. 8. Because of the small $l_v$ simulated to achieve the low $|\phi/\beta|$ ratio, very large values of $n_\xi$ were needed to make even small changes to $\omega_\phi/\omega_d$, and these $n_\xi$ values produced objectionably large sideslip angles and lateral accelerations in rolling manoeuvres.

Ref. 39 reports a combined flight and simulator investigation in which three pilots participated; it should be noted, however, that the flight assessments were made mainly by a single pilot and supported by limited checks made by a second pilot. The flight assessments were made in the same variable-stability aircraft as was used in the dutch-roll investigation of Ref. 31 and once again, the longitudinal handling was 'satisfactory'. The tests were conducted at nominally constant $\omega_d$, $|\phi/\beta|$ and $T_R$; covered a range of damping that included negative values; and covered a very wide range of $\omega_\phi/\omega_d$, though with rather large intervals.

The results show similar qualitative trends to those of Ref. 38, and a comparison of data from the two sources is shown in Fig. 9; the data was selected so that the parameters other than $\omega_\phi/\omega_d$ were most nearly identical. It will be seen that the variation of pilot rating with $\omega_\phi/\omega_d$ was much greater in the tests reported in Ref. 38, and this difference is believed to be due to the different tasks studied, and perhaps, the different rating scales used in the two experiments.

As shown in Fig. 10, the effect of reducing the damping at the moderate $|\phi/\beta|$ obtaining in these tests (2·9) was to shift the optimum $\omega_\phi/\omega_d$ to a value somewhat less than 1. This result lends further confirmation to the theoretical predictions of Ref. 2.

Pilot opinions[39] of the dutch-roll characteristics for near-optimum $\omega_\phi/\omega_d$ were in excellent agreement with predictions derived from the boundaries of Ref. 31 (Fig. 6) (it will be remembered that these also referred to optimum conditions).

In this series of tests pilot ratings were also obtained for variations in aileron power. The results of Ref. 38 for a single value of $T_R$, have been compared with the corresponding data from Ref. 5 in Fig. 11. It can be seen that the results from the two sources agree well within the range of low rolling power (i.e. in their assessment of minimum control required) if the dutch roll damping $\zeta_d$ was not less than about 0·1. However the two tests failed to establish agreement in the desired optimum and gave entirely different assessments of maximum tolerable rolling power. The agreement between Ref. 5 and Ref. 38 data was somewhat worse for $\zeta_d = 0{\cdot}01$, and practically non-existent for $\zeta_d = -0{\cdot}06$. Since the lower limits of rolling power established in Ref. 5 appear to remain valid even when $\zeta_d$ is low and $N'_\xi$ is very large and adverse, there seem to be some grounds for hoping that the minimum requirements for rolling power established for large aircraft (Fig. 3) may also be unaffected in similar circumstances, bearing in mind that the flight data covers a range of $\zeta_d$ and $N'_\xi$. Conversely, it seems highly probable that the corresponding upper limits proposed for large aircraft (Section 2.3; Fig. 4) may require drastic revision for cases where $N'_\xi$ is large and 'favourable', and/or $\zeta_d$ is low or negative. It is clear that more experimental evidence is needed before the influence of the '$\omega_\phi/\omega_d$ effects' on rolling power requirements can be established.

## 6. *Rudder Control.*

The response of an aircraft to rudder is dynamically perhaps even more complex than that to aileron and involves essentially all three lateral modes, even with a 'conventional' configuration. This might well have generated a great deal of study of the handling implications were it not for the fact that, as distinct from the ailerons, the rudder is not regarded by either the designer or the pilot as a primary means of control. Exceptions to this occur in a few special circumstances (e.g. following an engine failure, during a cross-wind landing, or in a spin recovery), but in all normal flight conditions the rudder is used solely to maintain sideslip at or near zero, e.g. to counteract changes of directional trim with speed or power, or in co-ordinating a turn or a turn entry. Pilots have always objected to aircraft in which 'excessive' use of the rudder is necessary to co-ordinate turn entries, etc., but the amount regarded as 'excessive' seems to have decreased during recent years, and the ideal now seems to be an aircraft requiring virtually no rudder co-ordination. It may be noted that when the parameter $(\omega_\phi/\omega_d)$ is equal to unity (the optimum value for control of the dutch roll in many cases), no rudder co-ordination is required for turn entry, though it may still be needed in a steady turn.

As implied above, the rudder has received virtually no attention in recent handling research programmes; in consequence, we can offer here only some rather general observations on a few facets of rudder control:

(a) It is highly desirable that the relationships between rudder angle and sideslip, and pedal force and sideslip should be essentially linear over a reasonable range of sideslip. Beyond this range, an increase in rudder angle should still produce an increase in sideslip, though the rate at which it does so may change; it is permissible for the rudder pedal force to decrease (but not to zero), though it is clearly preferable that the pedal force gradient should retain the same sign.

(b) The rudder should self-centre, but the breakout force should not be excessive (not greater than 10 lb, say).

(c) Because the fin and rudder have to be stressed for inadvertent applications of rudder at high airspeed, there is a strong incentive for the designer to provide only the minimum rudder power compatible with the engine-cut case. In consequence, a fairly common practice has been to 'limit' the rudder angle which can be applied, by making the pedal force gradients high (though acceptable for the engine-cut case); this has led frequently to pedal forces which are uncomfortably high for long-term tasks, such as turn co-ordination, and this may be at least a partial cause of pilots' objections to the need to use co-ordinating rudder movements. It seems possible that better overall solutions might be found in making the rudder stops variable with speed and optimising pedal force gradients for turn co-ordination. To determine such optimum gradients would require further research.

## 7. *The Effects of External Disturbances.*

In the era of straight-winged aircraft, control of external disturbances (turbulence) had little or no impact on the requirements for lateral control power, since control power adequate for manoeuvring would, in general, prove more than sufficient to deal with turbulence. The advent of swept wings has changed this situation somewhat, and more drastic changes can be expected as sweep-back becomes more extreme, since the control power required will then be dictated to an increasing extent by turbulence rather than by manoeuvring. In these circumstances there is (and has been for some time) an obvious need for a rational method of assessing the control power required to deal with turbulence. A theoretical basis of a possible method has been put forward in a recent paper[40] by Zbrozek. A means of calculating power spectra of the bank disturbances experienced by aircraft in random atmospheric turbulence is proposed, and the control requirements to maintain these excursions within certain limits are examined, assuming various simple 'pilot control laws'. Experiments aimed at checking the validity of the theory are in progress. The outcome of this research may lead eventually to a considerable advance on present methods of assessing control power requirements.

For the present, however, a rough idea of the problems involved can be obtained from an extension of a method put forward by Pinsker[44], as outlined below:

(i) The aircraft is assumed to be disturbed by a step side-gust, the strength of which is expressed in terms of the initial rolling acceleration ($\dot{p}_G$) that it imposes on the aircraft.

(ii) The aircraft's subsequent response is assumed to be confined to the roll subsidence mode (it has been shown[44] that this assumption, despite its crudity, provides a fair approximation to the earlier stages of the response).

(iii) When the pilot senses some feature of the gust response he is assumed to remain inactive for a period of duration $t_D$, at the end of which he applies a step input to the ailerons (producing an initial rolling acceleration of $\dot{p}_\xi$). For ease of computation this has been preferred to the more realistic 'pilot response' of an inactive period, followed by a period in which aileron angle is changed at constant rate, followed by a period in which constant aileron angle is maintained.

On the basis of the above assumptions, the maximum bank angles reached following a side-gust disturbance and counter control action have been calculated for a range of $\dot{p}_G$, $t_D$, $T_R$ and $\dot{p}_\xi$, and the results are shown in Fig. 12.

In Fig. 13a the rolling power required to limit the maximum bank angle to 2·5 deg. or 5 deg.* is shown as a function of the gust rolling power for three values of $T_R$ (1, 1·5 and 2) typical of large aircraft on the approach. In this case the pilot was assumed to sense rolling acceleration and the delay time was assumed to be 0·5 sec (this can be considered as the sum of the pilots reaction time delay – typically about 0·25 sec – and one-half the time taken to apply aileron – typically about 0·5 sec when not rate-limited).

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*These figures are approximately one- and two-thirds, respectively, of the ground clearance angles in bank of several current large aircraft.

Fig. 13b shows similar results for a 5 deg. maximum bank angle only. In this case the pilot was assumed to sense bank displacement with a threshold of perception of 0·5 deg. The overall delay time ($T_D$) was then the sum of the time taken to reach the threshold ($t_{\theta=0\cdot5}$), and the pilots' delay time, which was again assumed to be 0·5 sec.

Comparison of Figs. 13a and b will show the change in control power required to keep the bank within certain limits, brought about by a change in the pilots' mode of operation; it will be seen that, at low and moderate values of $\dot{p}_G$, the control power required by the 'bank-sensing' pilot is only slightly greater than that required by the 'acceleration-sensing' pilot, but that at high values of $\dot{p}_G$ (say, about 0·3) the former's requirement would be twice the latter's for $T_R = 1$, and four times the latter's for $T_R = 2$. In practice, however, it seems likely that the pilot will tend to sense and respond to roll acceleration more readily when this is high, provided of course that the information is not too heavily contaminated by other acceleration components of the response.

The number of large aircraft in which pilots have complained strongly of inadequate lateral control during approaches in turbulence is comparatively small, and it is difficult, therefore, to assess reliably what is implied by 'inadequacy' in this context. We may note that in a large delta-winged aircraft which was the subject of many complaints the pilot would, on the assumptions outlined above, have required 80–100 per cent aileron to limit the bank disturbance to 5 deg. following a 10 knot sidegust: the aileron power was later doubled and the complaints greatly decreased in severity and frequency. It is interesting to note also that a large swept-wing aircraft, described as 'somewhat marginal in rough air during the final phases of landing'[13] would require 30–40 per cent aileron (depending on the mode of pilot operation) to limit the bank to 5 deg. following a 10 knot sidegust. This leads us to suggest that, under approach conditions, a large aircraft will be classed as at least 'acceptable for normal operation' provided the bank following a 10 knot sidegust can be limited to 5 deg. by the use of not more than one-half aileron. It will be appreciated that this suggestion is put forward tentatively as a very rough design guide and that further research into the problem is required.

An interesting corollary of the above suggestion arises in connection with the so-called 'slender' planforms currently being considered for supersonic transport aircraft; for these aircraft on the approach, $T_R$ will be about 2 sec and $\dot{p}_G$, about 0·3 (for a 10 knot sidegust) so that the aileron power needed to limit the bank disturbance to 5 deg. would be 0·42 rad/sec$^2$, working on the favourable assumption that the pilot responds to rolling acceleration (Fig. 13a). If, as suggested above, this should be one-half of the aileron power available, then the total aileron power available will be very close to the upper limit of 'acceptability' for manoeuvring, proposed in Fig. 4. Thus, a conflict between the manoeuvring and gust response requirements appears quite possible for this class of aircraft.

## 8. *Approach and Landing in Cross-Winds.*

The piloting techniques employed in making a cross-wind approach and landing can be divided into two quite well-defined categories; these can be described as:

(a) The 'crabbed approach' technique. A wings-level, zero-sideslip approach in which the aircraft track is aligned with the runway axis and its heading is displaced into the cross-wind; the track-heading angle is adjusted to close the velocity vector-triangle. Immediately prior to touch-down the pilot 'kicks off drift' and aligns the aircraft with the runway (this is unnecessary in aircraft fitted with 'drift under-carriages' that can be prealigned – e.g. the Boeing B – 52 series).

(b) The 'sideslipping' or 'wing-down' technique. Here the aircraft's track and heading are aligned with the runway axis, and the approach is made in a straight steady sideslip. The side force generated by the sideslip is balanced by an appropriate bank, while the rolling and yawing moments due to sideslip are balanced by suitable deflection of the controls. Immediately prior to touch-down the pilot rolls the aircraft to a wings-level attitude.

Satisfactory performance using either of these techniques demands a fairly high level of judgement, precision and co-ordination in 'conventional' aircraft, and pilots appear to be fairly evenly divided on the relative merits of the two methods. The trend towards increased rolling moments due to sideslip on the approach, associated with large angles of wing sweepback, demands more precise co-ordination in case (a), where the pilot then has to make a relatively large and correctly phased movement of the ailerons during the 'kick off'; on the other hand, a similar amount of aileron has to be held on throughout the approach in case (b), and re-applied after the 'roll-out': for moderate angles of sweep there again seems to be no clear-cut preference for any one method. When $l_v$ is large at approach speeds (e.g. with extreme sweepback, as in the slender wing) the rolling power necessary to make a sideslipping approach, while retaining an adequate reserve to cope with turbulence and manoeuvring, may dictate the use of exceptionally large and powerful controls; from a design point of view the 'crabbed' approach may then seem preferable, even if the difficulties of making a satisfactory 'kick off' are such that the need for this manoeuvre has to be eliminated by providing a 'drift undercarriage'. At the present time we do not know the stage at which the 'kick-off' becomes 'too difficult' for the pilot, or even if such a stage exists. The need for further research is evident.

## 9. *Conclusions.*

The development, during the past decade, of variable-stability aircraft and simulators has made possible a systematic approach to the experimental study of handling problems, and has facilitated the identification of influential parameters and their correlation with pilot opinion. Despite the considerable advances that have been made in this field, it is evident, firstly, that in several important areas we are only now beginning to identify the parameters involved, and, secondly, that the lack (both in the U.S. and U.K.) of any systematic experimental study of the handling qualities of large aircraft has led to a situation where the formulation of handling criteria for this important class rests on an insecure foundation and tends to lag behind practice. There is an obvious need for a continuation of handling research and in particular for an extension to large aircraft.

The application of servomechanism theory to the study of the pilot-airframe system has already proved valuable and seems likely, with further development, to provide a powerful and much-needed method for studying the nature of handling problems.

The main results of the review of lateral handling qualities can be summarised as follows:

(i) When aileron excitation of the dutch roll is not excessive the requirements for roll control power appear to be a function of the roll-subsidence time-constant only, the iso-opinion contours taking the form shown in Fig. 1. From this and other considerations, and taking into account the *ad hoc* data, qualitatively similar boundaries have been derived for large aircraft on the approach; these are of a rather tentative nature, and are shown in Fig. 4.

It appears that the maximum travel of a wheel-type control should not exceed 90 deg. and that the force for full travel should be in the region of 40 lb. Control system friction and backlash should be minimised, and, although positive self-centering is desirable, this should not involve a break-out force of more than 5 lb (approximately).

(ii) The spiral mode need not be stable but it is suggested that if unstable the time constant $T_S$ should not be shorter than 20 sec and if stable not shorter than 10 sec for satisfactory handling. It is likely that the spiral mode would be accepted without serious objection if these figures are halved.

There is also some evidence that handling may suffer if the ratio of the spiral time constant to the time constant of the roll subsidence is such that $\frac{|T_S|}{T_R} < 30$.

(iii) For configurations in which aileron yawing moments do not complicate the control problem, pilot's assessments of the dutch roll behaviour on the approach[31] appear to be influenced only by the damping and a parameter describing the dutch roll ratio such as $|\phi/\beta|$ or $|\phi/v_e|$ – the latter is generally preferred. The iso-opinion contours obtained from systematic tests in fighter-type aircraft take the form shown in Fig. 6, and qualitatively similar contours for large aircraft on the approach have been derived, and are shown in Fig. 7.

(iv) More recent work has also indicated the extent to which coupling between the roll subsidence and the dutch roll affects lateral control. Theoretical and flight studies have shown that this effect is related to the parameter $(\omega_\phi/\omega_d)^2 \doteqdot 1 - \frac{n'_\xi}{l'_\xi}\,\frac{l'_v}{n'_v}$ which is a measure of the effective aileron yaw coupling. Favourable yaw, i.e. $\omega_\phi/\omega_d > 1$ has been shown to be deterimental to the achievement of stability in closed-loop control whereas unfavourable yaw ($\omega_\phi/\omega_d < 1$) while it improves closed-loop stability may, if excessive, adversely affect the roll manoeuvring capability of aircraft. The optimum value of $\omega_\phi/\omega_d$ for a given aircraft, and the sensitivity of the handling qualities to variation of this parameter from the optimum, depend on a number of factors, principally, dutch-roll damping, period and the dutch-roll ratio. The effect of $\omega_\phi/\omega_d$ is particularly strong when dutch-roll damping is poor. For more detailed analysis the references quoted in the text must be consulted.

(v) There is very little evidence on the influence of the '$\omega_\phi/\omega_d$ effects' on pilots requirements for rolling power. What evidence there is suggests that, provided $\zeta_d > 0{\cdot}05$ and $\omega_\phi/\omega_d \ngtr 1$, minimum requirements for aileron power corresponding to a given opinion-level depend only on the roll subsidence time-constant $T_R$, and do not change significantly from the single-degree-of-freedom results of Ref. 5: conversely, when $\omega_\phi/\omega_d > 1$, the upper limits of tolerable rolling power may be much less than those applicable to cases where there is little coupling between the roll and dutch-roll response. Here again there is a clear need for further investigation.

An approximate method is given for estimating the rolling power required for control in turbulence and it is suggested that, to avoid control difficulties, the rolling power required to 'control' the equivalent of a 10 knot 'side gust' should not exceed about one-half of the rolling power available.

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $A$ | Moment of inertia in roll | (slugs-ft$^2$) |
| $A' = A\left(1-\frac{E^2}{AC}\right)$ | 'Effective' moment of inertia in roll | (slugs-ft$^2$) |
| $b$ | Wing span | (ft) |
| $C$ | Moment of inertia in yaw | (slugs-ft$^2$) |
| $C' = C\left(1-\frac{E^2}{AC}\right)$ | 'Effective' moment of inertia in yaw | (slugs-ft$^2$) |
| $E$ | Product of inertia | (slugs-ft$^2$) |
| $L$ | Rolling moment | lb-ft |
| $L_i = \frac{\partial L}{\partial i}$ | $i = \beta, p, \xi$, etc. | |
| $L'_i = L_i\left(1+\frac{N_i}{L_i}\,\frac{E}{C}\right)$ | | |
| $l_v = \frac{\partial C_l}{\partial \beta}$ | $C_l = \frac{L}{\frac{1}{2}\rho\, V^2\, Sb}$ | |
| $l_p = \frac{\partial C_l}{\partial\left(\frac{pb}{2V}\right)}$ | | |
| $l_\xi = \frac{\partial C_l}{\partial \xi}$ | | |
| $N$ | Yawing moment | (lb-ft) |
| $N_i = \frac{\partial N}{\partial i}$ | $i = \beta, p, \xi$, etc. | |
| $N'_i = N_i\left(1+\frac{L_i}{N_i}\,\frac{E}{A}\right)$ | | |
| $n_v = \frac{\partial C_n}{\partial \beta}$ | $C_n = \frac{N}{\frac{1}{2}\rho\, V^2\, Sb}$ | |
| $n_p = \frac{\partial C_n}{\partial\left(\frac{pb}{2V}\right)}$ | | |
| $n_\xi = \frac{\partial C_n}{\partial \xi}$ | | |

## LIST OF SYMBOLS—(continued)

| | | |
|---|---|---|
| $P.R.$ | Pilot opinion rating | (Cooper scale) |
| $p$ | Rolling velocity | (rad/sec) |
| $r$ | Yawing velocity | (rad/sec) |
| $S$ | Wing area | (ft$^2$) |
| $s$ | Laplace operator | |
| $T_{\frac{1}{2}}$ $T_2$ | Time to half or double amplitude | $\left(=\frac{0 \cdot 693}{\zeta\omega}\right)$ (sec) |
| $T_R$ | Time constant of roll mode | (sec) |
| $T_s$ | Time constant of spiral mode | (sec) |
| $V$ | True airspeed | (ft/sec) |
| $v_e$ | Equivalent side velocity | (ft/sec) |
| $\beta$ | Sideslip angle | (rad) |
| $\zeta_d$ | Dutch roll damping ratio | |
| $\phi$ | Bank angle | (rad) |
| $\lvert\phi/\beta\rvert$ | Roll to sideslip ratio | at dutch roll frequency |
| $\lvert\phi/v_e\rvert = \frac{57 \cdot 3}{V\sqrt{\sigma}}\lvert\phi/\beta\rvert$ | Roll to equivalent side-velocity ratio (deg/ft/sec) | |
| $\omega_d$ | Dutch roll undamped natural frequency | (rad/sec) |

A dot above a symbol denotes differentiation with respect to time.

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TABLE 1

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

[1] Failure of a stability augmenter.

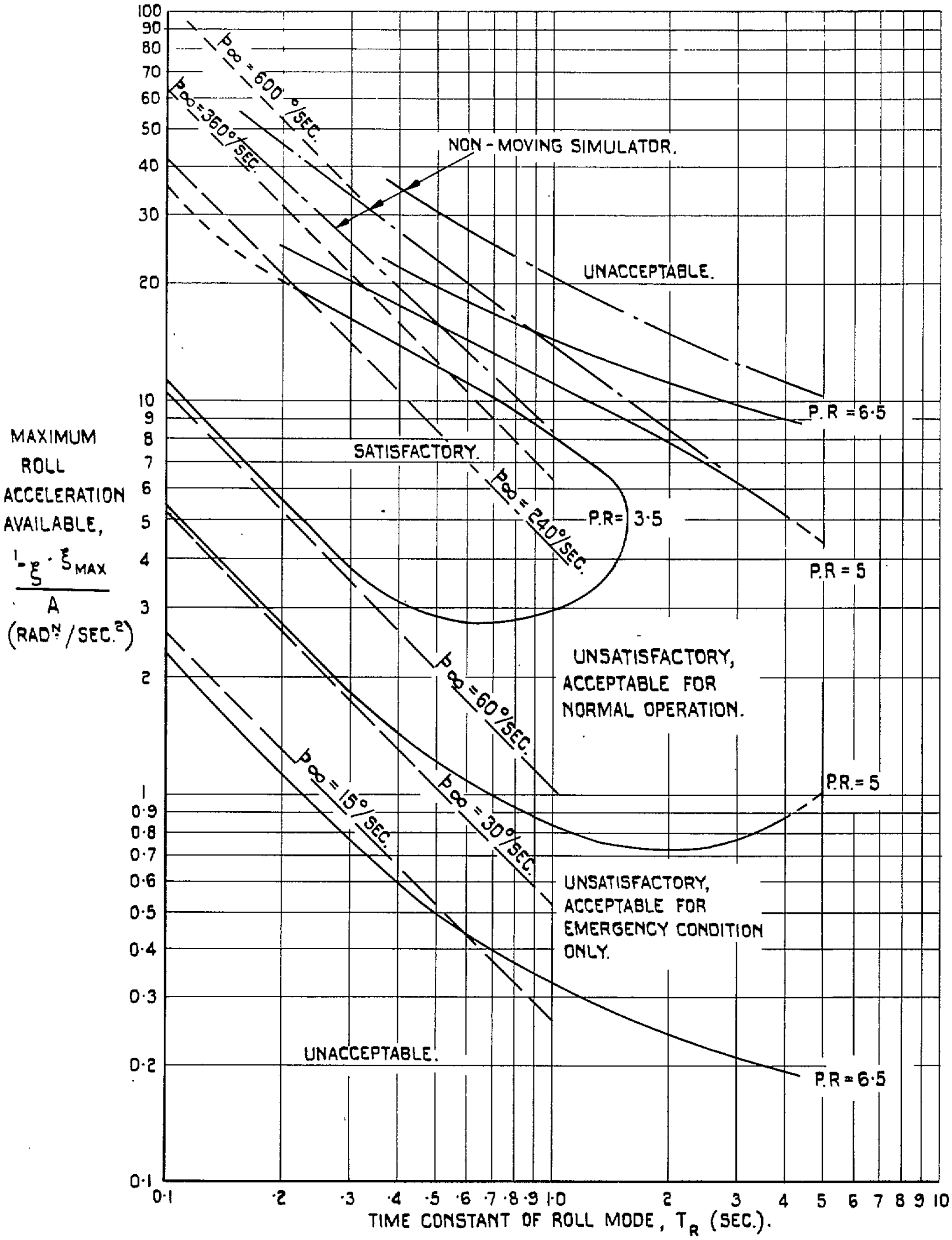

FIG. 1. Roll response. Pilot-opinion boundaries for fighter-type aircraft (Ref. 5).

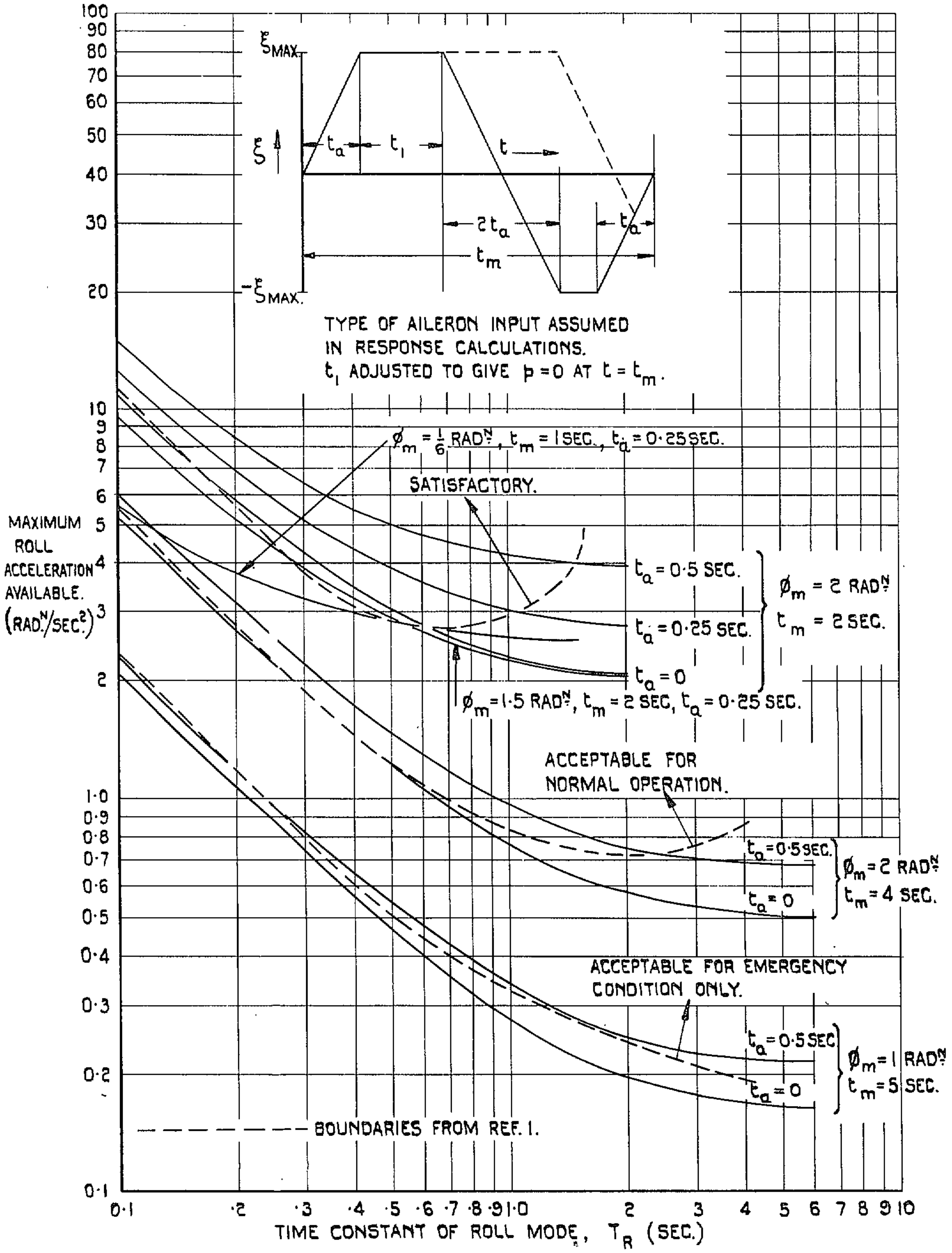

FIG. 2. Comparison of Ref. 5 boundaries with various bank-and-stop manoeuvres.

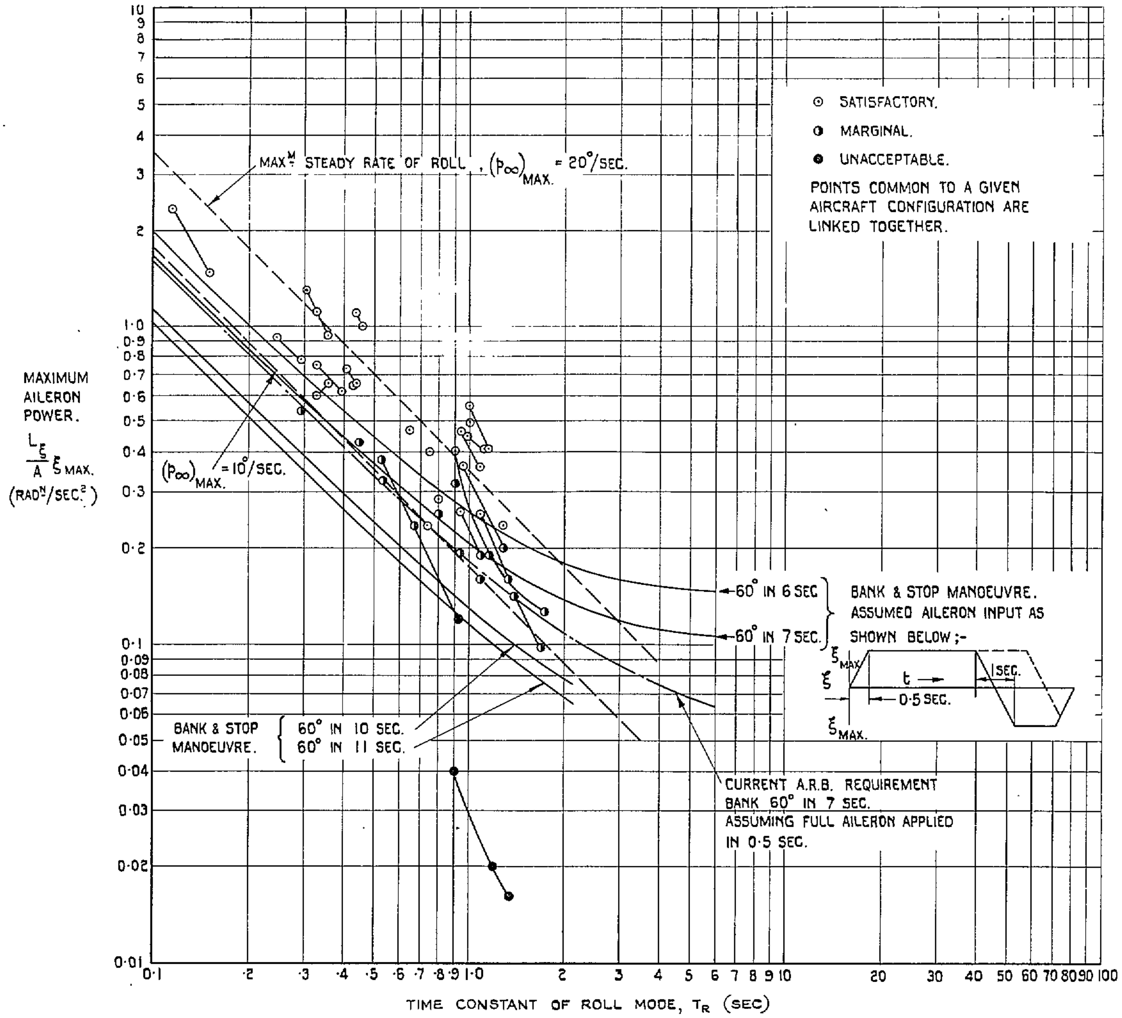

FIG. 3. Roll response. Large aircraft.

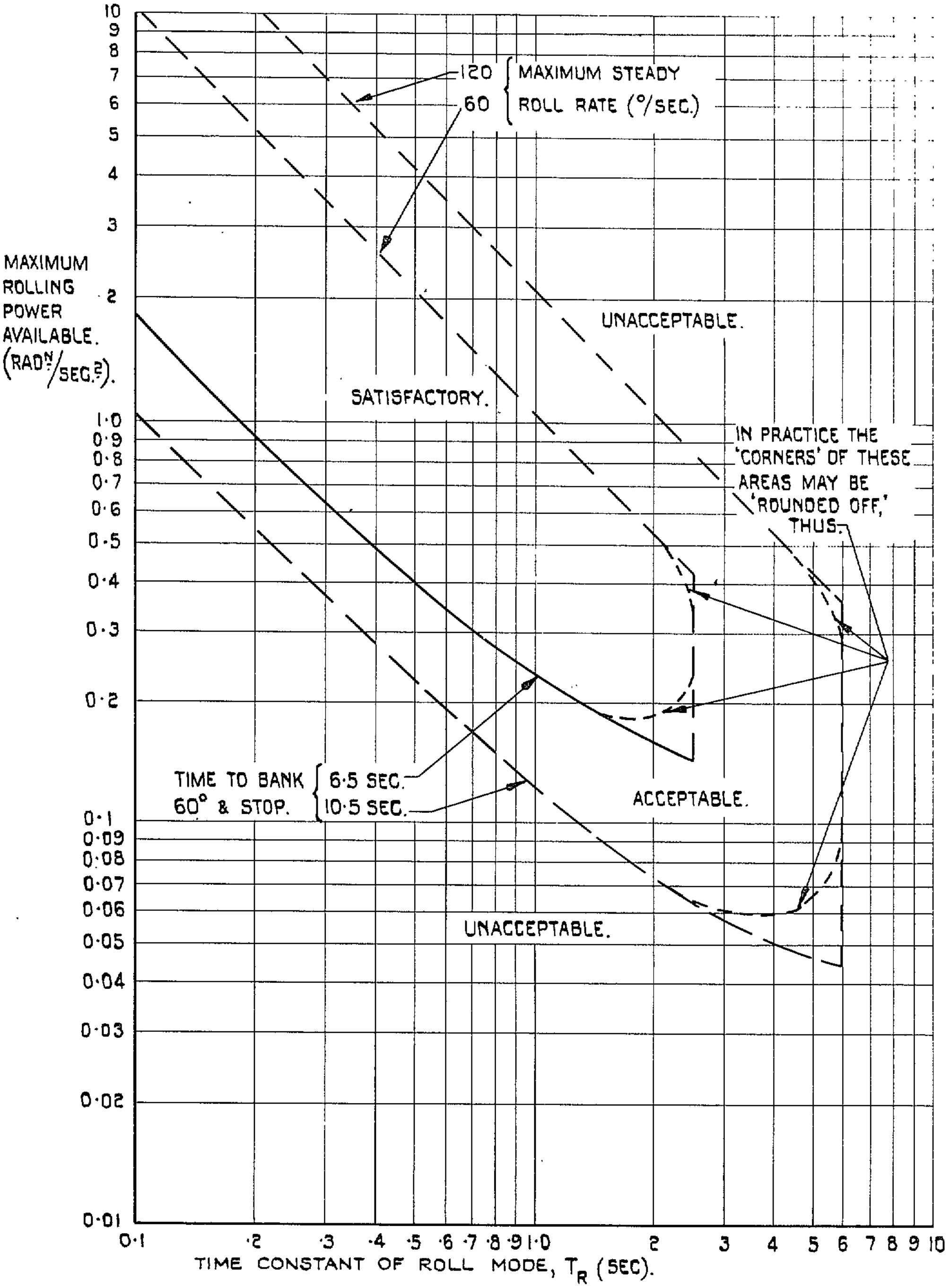

FIG. 4. Suggested roll-response boundaries for large aircraft. (Approach conditions).

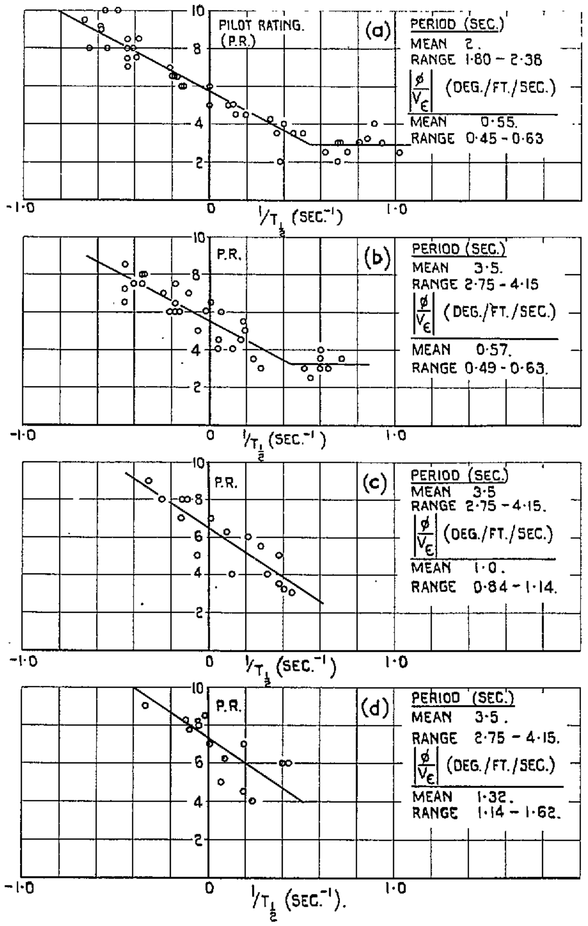

FIG. 5. Lateral S.P.O. – pilot-opinion as a function of damping. (Data of Ref. 31).

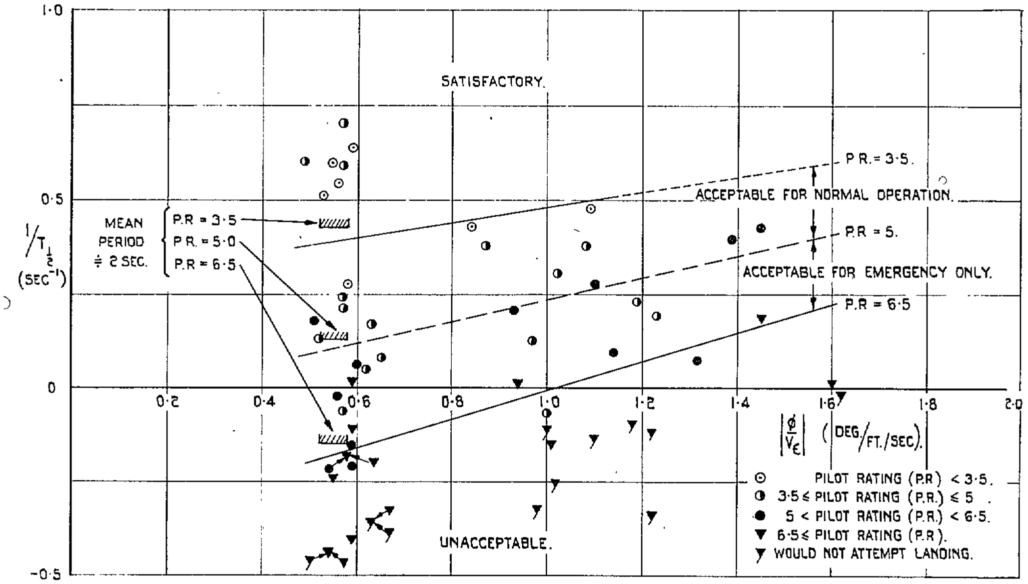

FIG. 6. Lateral S.P.O. – pilot-opinion boundaries, mean period ≑ 3·5 sec. (Data of Ref. 31).

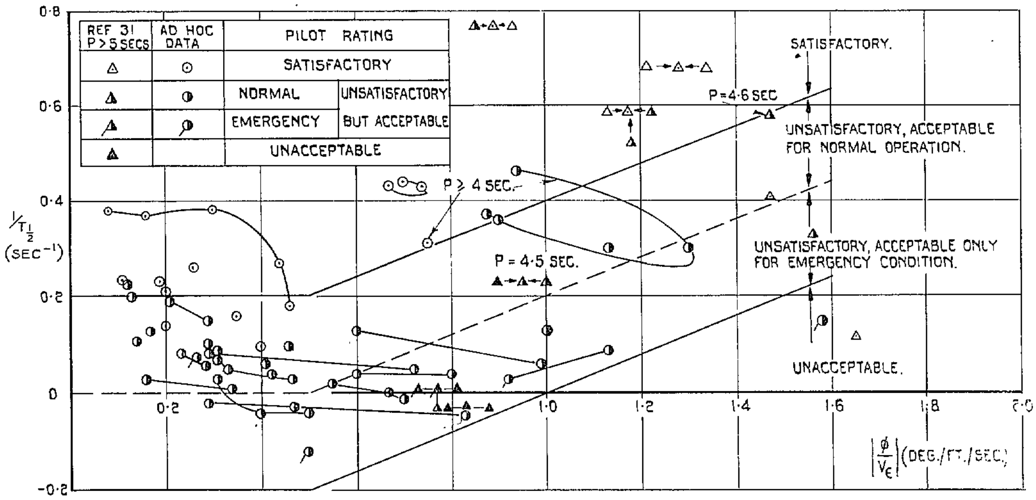

FIG. 7. Lateral S.P.O. – pilot-opinion data and proposed boundaries, mean period ≑ 7 secs.

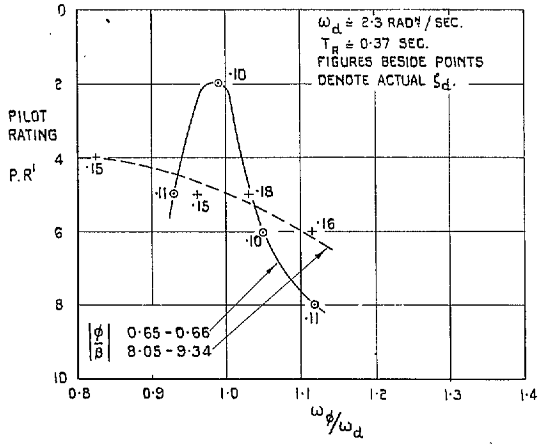

FIG. 8. Variation of pilot-opinion with $\omega_\phi/\omega_d$. (Data of Ref. 38).

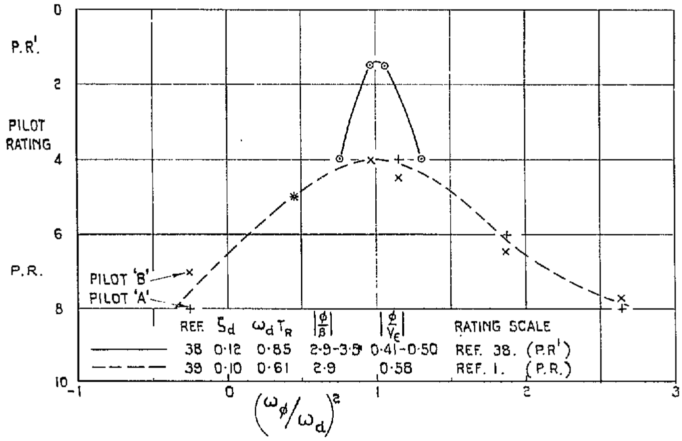

FIG. 9. Comparison of pilot-opinion. (Data of Refs. 38 and 39).

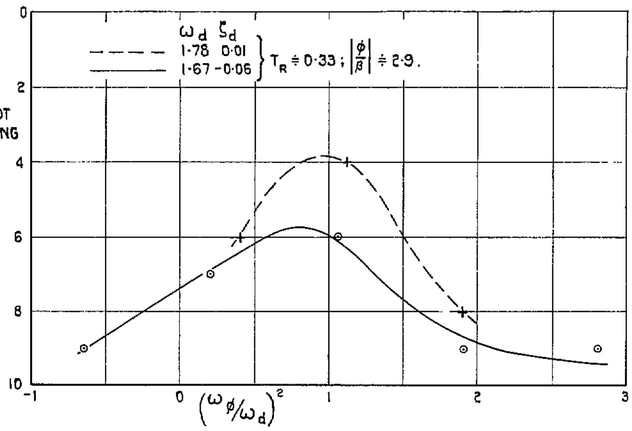

FIG. 10. Variation of pilot-opinion with $(\omega_\phi/\omega_d)^2$. (Data of Ref. 39).

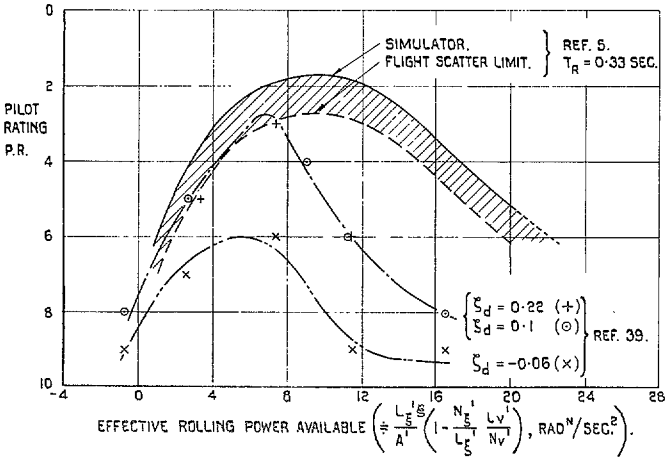

FIG. 11. Variation of pilot-opinion with rolling power available. (Comparison of Refs. 5 and 39).

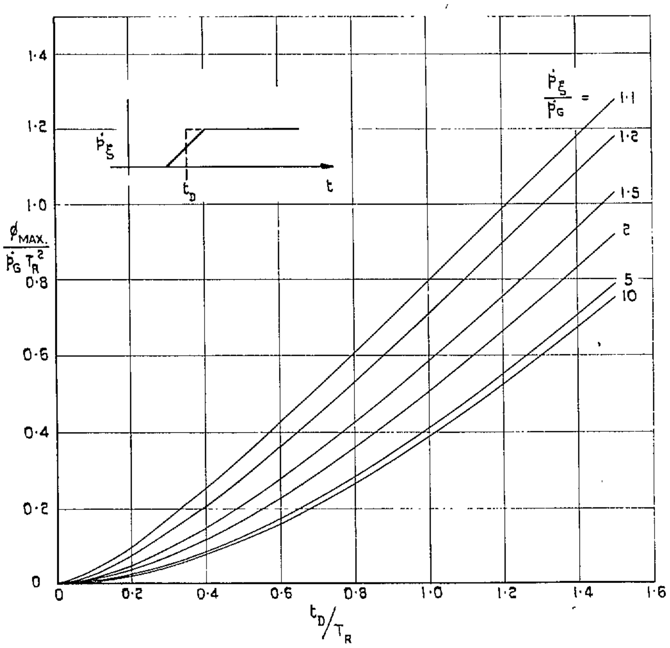

FIG. 12. The effect of pilot's control delay, aileron power, and aircraft roll response on maximum bank angle following a step sidegust. (Roll mode only).

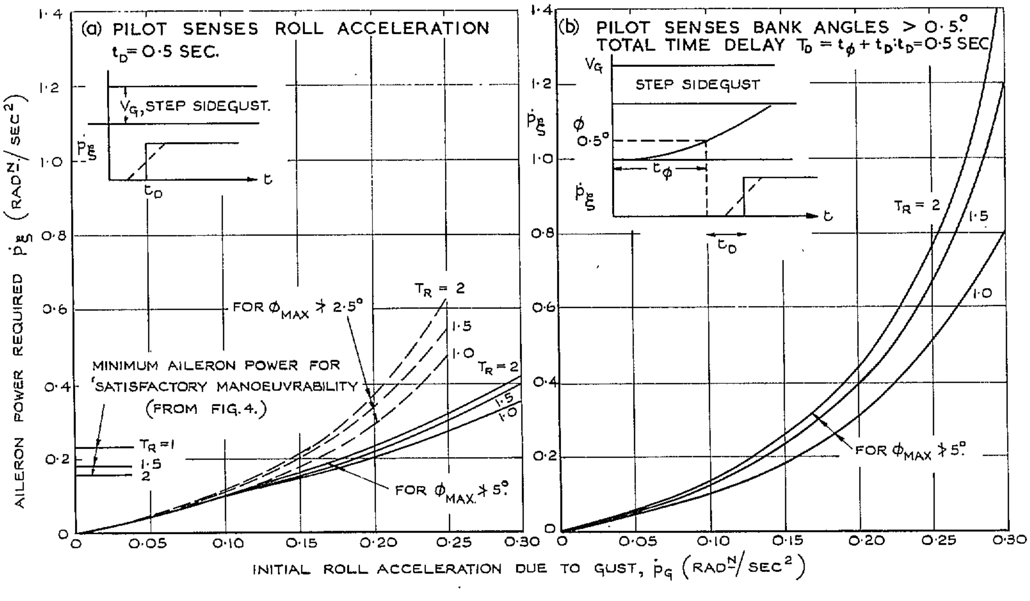

FIG. 13. Aileron power required to limit bank disturbance (to 2·5° or 5°) following a step sidegust, assuming two types of pilot response. (Roll mode only).

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