R. & M. No. 3605

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MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

A Simulator Investigation of Rolling Requirements for Landing Approach

by A. G. BARNES

British Aircraft Corporation, Preston Division

LONDON: HER MAJESTY'S STATIONERY OFFICE
1969
PRICE £1 0s 0d [£1] NET

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Reports and Memoranda No. 3605*
August, 1967

Summary.

This Report describes a fixed-base simulator investigation of the rolling requirements for two types of aircraft on the landing approach. A small trainer/strike aircraft, and a large transport aircraft are simulated, and pilot opinion is obtained for differing values of damping in roll, and the maximum rolling acceleration for full aileron. The results are compared both with existing handling criteria, and also with known aircraft.

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1. *Introduction.*

The lateral handling qualities of an aircraft are primarily influenced by the roll control characteristics. In consequence, the requirements for satisfactory roll control have been extensively studied by various workers, both from theoretical and experimental viewpoints. Many factors influence such requirements, and explicit definition of the requirements for all flight circumstances is not yet possible.

The landing approach task is a particularly demanding one, requiring accurate positioning of the aircraft relative to the runway. Because the speed of the aircraft is low, the aerodynamic forces which are available for control are relatively low, and the provision of adequate control power can be a serious design problem. This problem is accentuated when high lift devices, which further reduce the approach speed, are incorporated in a design.

At the same time, the experimental evidence on which to determine a roll control criterion applicable to landing approach is strictly limited. Of course, existing aircraft provide a good source of data relating to satisfactory or marginally satisfactory characteristics, but flight evidence of marginally acceptable or dangerous characteristics is scarce. Moreover, it is not always possible to extrapolate from existing aircraft to new design projects, because of gross dis-similarities with respect to inertia distribution, wing-loading or dihedral effects.

The flight simulator affords a suitable means to investigate the roll control problem, and to produce the missing experimental data which is needed to formulate rolling requirements on the approach. To undertake such an investigation, and to obtain useful data, it is necessary to restrict as far as possible the variables in the experiment. Fortunately, the pure rolling mode of an aircraft is conveniently described by the two parameters $\dot{p}_M$, the rolling acceleration for full control, and τ_R the rolling mode time constant. Inter-action between the rolling mode and the other lateral modes does affect the handling in roll, but a formal investigation of such effects was not an aim of the work to be described. In consequence, aileron excitation of the dutch roll mode was made small. With the spiral and dutch roll modes held constant, a systematic study was made of the effects on handling of $\dot{p}_M$ and τ_R, for a landing approach task.

A further object of the investigation was to perform two similar experiments, each relating to a different type of aircraft at the same approach speed. The types chosen were (a) a military trainer/strike aircraft, and (b) a large transport aircraft. In this way, it was intended that the effect of aircraft size could be observed.

2. *Form of Investigation.*

The investigation was made on the fixed based simulator at Warton. The experiments relating to the small aircraft and the large aircraft were both conducted using the same cockpit, computers and display equipment: the only physical change was to replace the conventional fighter type control stick used for the 'small aircraft' tests by a two-handed airliner type control column for the 'large aircraft' tests and to adjust the feel forces. The same staff conducted the trials, and three of the assessment pilots took part in both experiments. A period of approximately six months divided the two experiments.

As stated previously, the two parameters varied were $\dot{p}_M$ and τ_R. It was originally intended to cover the same range of these parameters in both investigations: $0{\cdot}1 < \dot{p}_M < 3{\cdot}2$ rad/sec, and $0{\cdot}32 < \tau_R < 3{\cdot}2$ seconds. However, during the course of the first investigation it became apparent that, for the small aircraft, the lowest values of $\dot{p}_M$ and the highest values of τ_R were unacceptable. Rather than obtain a number of pilot ratings all of similar type, an intermediate value of $\dot{p}_M$ was introduced. This allows a more precise definition of the sought after pilot opinion boundaries to be made.

The reason that this change became necessary was simply that the pilots' task was different for each experiment. It is self-evident that the results of any tests of this nature are critically dependent on the task which the pilot is given. The basic task in both cases was to land the aircraft. The simulation was such as to give the pilot both visual flight, and instrument flight information, in order to perform this task. However, to obtain a pilot assessment of control power requirements, it is obvious that the bare statement 'perform a landing approach' is insufficient briefing for the pilot. In still air, using a straight-in approach, landings may be performed satisfactorily with very little lateral control. The effects of turbulence, crosswind and track or heading errors due to poor visual information will add to the complexity of the task. Each of these effects will make additional demands on the rolling stability and control requirements. Moreover, if these effects are not simulated, some pilots will try to extrapolate from the condition simulated, to the situation where such effects are present, and bias their assessment accordingly.

Thus, in order to get reasonably consistent, repeatable pilot ratings, a well defined task together with a well defined rating system is necessary. The original intention was to give the pilot the same task for both the trainer/strike aircraft and the transport aircraft investigations. Slight to moderate turbulence was simulated, and the assessment was to be made based on the difficulty of correcting a 300 feet error in track, at a range of 3000 feet from the runway threshold.

In the case of the trainer/strike aircraft, however, it was found that although this task could be performed with most of the combinations of $\dot{p}_M$ and τ_R, in fact, many configurations would nevertheless be quite unacceptable for this type of aircraft. Other tasks were cited by pilots which make greater demands on the control power requirements. Of these the main ones were (a) ability to do a 'tight circuit', (b) ability for the instructor to recover from a potentially dangerous situation caused by student error, and (c) collision evasion manoeuvres. Consequently the task was modified to that described in the next Section.

In the case of the transport aircraft, the need to simulate both instrument and visual flight rapidly became apparent. The outcome of early tests was to standardise on an ILS task, starting from a height of 1000 feet on instruments, breaking cloud at 300 feet with a 300 feet track error, and completing the approach visually.

Steady crosswinds were not simulated in either case. They are normally compensated in the approach phase by a shift in heading datum (drift approach), so that the adverse effects of a steady crosswind are most apparent during flare and touchdown. The simulation was not meant to be fully representative of the latter phase; pilot assessment was based only on the lateral handling during the approach phase.

The longitudinal dynamics which were simulated were representative of the two types of aircraft, in terms of short period stability and control response. In all cases, however, the speed was held constant at 135 knots. This allowed the pilot to concentrate on the lateral assessment, and also ensured that the kinematic flight path was not influenced by speed changes.

3. *Details of Simulation.*

3.1. *Representation of Aircraft.*

The small perturbation aircraft equations of motion and the associated kinematic relationships are listed in Appendix 1. Numerical values of the derivatives used to describe the two aircraft are also presented in this Appendix, together with the lateral and longitudinal stability parameters which normally are used to correlate with pilot opinion.

The equations were solved by conventional means on analogue computers, which were coupled to a fixed based cockpit. The cockpit contains conventional stick and rudder pedals; the stick may be removed, and an airliner control column put in its place. The stick force for full aileron control was 12 lbs in the case of the strike/trainer aircraft, and 25 lbs in the case of the control column. Maximum stick travel was 3 in. at the pilot's grip; the control column wheel had $\pm 25°$ travel.

The principal difference in the lateral stability characteristics of the two aircraft lies in the higher short period frequency and the higher roll/yaw ratio of the strike aircraft, compared to that of the transport aircraft. In both investigations, the spiral and Dutch roll roots were held constant as $\dot{p}_M$ and τ_R were varied. $\dot{p}_M$ was changed by varying l_ξ, and τ_R by varying l_p. The only significant correction term necessary to keep the spiral and Dutch roll roots constant was a corrective damping term n_β. $\dfrac{\omega\phi}{\omega d}$ was held constant by varying n_ξ in proportion to l_ξ.

3.2. *Pilots Display.*

The pilot's display consisted of both conventional flight instruments and a closed circuit television display which gives a pilot's view of the runway and surrounding countryside. The model is to a scale of 1000:1, and is mounted on a continuous belt, enabling a strip of country approximately 6 miles by 2 miles to be overflown. The pilot views the TV monitor directly. The TV system allows the cloud-base and visibility to be pre-set; the maximum visibility, which is determined by the model dimensions, is $2\frac{1}{2}$ nm. The height range is from 1000 feet to 10 feet; bank angles up to $\pm 90°$ and heading changes up to $\pm 50°$ may be used.

3.3. *Turbulence.*

The correct representation of the effects of turbulence during landing approach presents several difficulties. Firstly, the frequency content is a function of height above ground (presumably a measure of the increasing contribution of orographic effects as height decreases). Secondly, if the selected power spectrum of turbulence has significant low frequency content, the most severe gusts will occur infrequently. In consequence, during approaches of two or three minutes duration, on some occasions the turbulence will embarrass the pilot, and on others it will not, with the same nominal turbulence input.

These difficulties were circumvented by the use of a fixed level of turbulence—fully described in Appendix 2—throughout the experiment. A high-pass filter was used to avoid the second of the above difficulties, and the level of turbulence was set at an r.m.s of 3 ft/second. This represents light-to-moderate turbulence, and was mainly intended to ensure that some pilot correction was needed, even on a straight approach.

Uncorrelated turbulence was fed into the longitudinal and lateral equations of motion, by using two tracks of an Ampex 1300 tape deck. The turbulence on each track was pre-recorded, this method allows the use of a single noise generator to obtain independent turbulence signals, and ensures that repeatable random noise is available.

3.4. *Pilot's Task.*

The critical effect on results which the pilot's task will have, has already been discussed. The tasks appropriate to each aircraft were as follows.

3.4.1. *Aircraft A—Trainer Strike.* Pilots insisted on a task which made more demands on technique and control usage than the correction of a nominal localiser beam error during an ILS approach. Consequently, a standard manoeuvre was formulated which approximated to the final stages of a visual circuit, but could be performed within the physical limitations of the TV/model equipment. An easily recognised building was situated on the model, approximately 0·5 nm to the left of the runway centreline, and 2·0 nm from the runway threshold. Pilots were asked to over-fly this building on a heading parallel to the runway heading, and to initiate the landing approach manoeuvre after passing overhead. A nominal height of 500 feet was specified when approaching the landmark.

This task calls for a reasonably large heading change (20° to 40°), and allows the pilot some freedom in the choice of bank angle, turn rate, and kinematic flight path, when adequate lateral control power is available. The second leg of the S-manoeuvre simulates the final stages of a turning approach, in which the aircraft must roll out on the runway heading, and on the runway centreline.

Full flight instruments were available, but pilot assessments were made almost entirely on the visual task.

3.4.2. *Aircraft B—transport.* The aircraft was flown at a constant height of 1000 feet on instruments, until the ILS indicator directed the pilot onto a 3° glide slope, at a range of 19 000 feet. Pilots were informed that the cloud base was 300 feet, and to go visual at this height.

The TV picture was set to come out of cloud at 300 feet. Track errors were introduced so that the ILS indicator was off-set by 300 feet to either the right or the left of the runway centreline. The touchdown point was 1000 feet from the runway threshold, so that the pilot had approximately 23 seconds from seeing the track error to crossing the runway threshold.

For both aircraft A and aircraft B, the pilot was allowed a maximum of three approaches, before giving a pilot rating to the configuration. The configurations were presented to him in a random order and several practice configurations were given before ratings were recorded, to allow the pilot to become familiar with the simulation. The ratings were given in terms of the Cooper scale: all the pilots who took part had previous experience in the use of this rating scale.

4. *Results and Pilot Comments.*

The assessments of the trainer/strike aircraft rolling requirements were made by five B.A.C. pilots. Three of these pilots completed two sets of results. The ratings given are listed on Table 1, which also contains the mean of the 8 ratings.

For the ratings of the transport aircraft, three of the pilots who took part in the earlier tests were available. Initial assessments were made by a B.A.C. pilot from Weybridge, with experience of large aircraft; he validated the simulation. During the tests a pilot from R.A.E., Bedford contributed a complete set of ratings. The results are listed on Table 2.

The presentation of these results will be based on the mean ratings. The presumption in doing so may be assessed by reference to the Tables. Scatter about the mean is not larger than 2 points on the scale, and the main source of variability is inter-pilot.

Figure 1 contains cross-plots of the mean pilot ratings obtained for aircraft A, against $\dot{p}_M$ and τ_R. Figure 2 presents the same plots for aircraft B. These four plots allow values of $\dot{p}_M$ and τ_R to be read for selected values of pilot rating. In this way, it is possible to construct the pilot rating iso-opinion plots shown on Figures 3 and 4, for the trainer/strike and transport aircraft respectively. These two figures in which $\dot{p}_M$ and τ_R are ordinate and abcissa, summarise the results of the simulator investigation.

Before discussing the results, the following pilot comments must be noted. With 'good' values of $\dot{p}_M$ and τ_R, aircraft A was considered to be a good aircraft generally. Aircraft B was thought to be more difficult to fly longitudinally than a typical large aircraft, particularly during the flare. However, it was satisfactory for the purposes of the experiment. The relatively low Dutch roll damping of aircraft B did not receive adverse comment. In neither case did the turbulence inputs produce more than a slightly increased workload on the pilot. The lack of occasional large gusts was the main pilot criticism of the turbulence simulation.

5. *Discussion of Results.*

Figures 3 and 4 show that well defined boundaries of a familiar pattern emerge. The iso-opinion lines appear to be asymptotic to a constant rate of roll line, for the lower values of $\dot{p}_M$ and τ_R. In this region, therefore, pilot's opinion is primarily based on rate of roll, rather than on the initial rolling response, or any apparent lag before bank angles are achieved. These latter factors become more important as τ_R increases, and cause the boundaries to curve upwards.

Although the boundaries on figures 3 and 4 are of similar shape, the values of $\dot{p}_M$ and τ_R associated with each graph differ considerably. This difference must be attributed to the gross difference in the task on which each set of ratings is based. It could be argued, therefore, that the position of the pilot opinion boundaries obtained are mainly determined by the experimenter, through task specification. However, since the task in both parts of this experiment was modified as a result of pilot comment (for the strike aircraft assessment, the task was changed completely from that originally intended) confidence may be restored in the belief that these boundaries are a true reflection of desirable handling qualities for the two control situations.

In terms of absolute values, the trainer/strike aircraft results suggest that for low values of τ_R, satisfactory handling in roll is obtained with a steady rate of roll in excess of 28 deg/second. The 3·5 boundary is similarly defined for the transport aircraft by a rate of roll in excess of 10 deg/second. For purposes of comparison, Figure 5 shows the control power and damping necessary to achieve a specified bank angle in a specified time, without stopping—in other words, in response to a full aileron step input. Figure 6 is a similar plot for the bank and stop manoeuvre. A comparison of Figures 3 and 5 is made on Figure 10. This shows that the 3·5 boundary at low τ_R corresponds well to the bank to 20 deg in one second line. For the transport aircraft, an equivalent criterion would be a bank angle of approximately 8 deg in one second. (*See* Figure 11).

A criterion based on bank angle in one second is not a particularly practical one however. Firstly, the pilot cannot be expected to apply full aileron as a step input, and secondly, for power controlled aircraft, the power control response time will significantly affect the result. These difficulties may be overcome by applying a criterion which specifies a maximum time to roll to and stop at a large bank angle (Figure 6). For the transport aircraft 60 deg in 6 seconds gives a reasonable fit to the 3·5 boundary, for $\tau_R < 0{\cdot}6$ (Figure 11). The 6·5 boundary however does not fit well with this type of criterion; the pilots appear to want a minimum $\dot{p}_M$, whatever the value of τ_R.

In terms of maximum satisfactory rolling acceleration, only the transport aircraft results reveal a requirement. This may be artificial, since the results were obtained on a fixed base simulator. Also the pilot ratings were not based on difficulties of control so much as the comment that the passengers would find the motions of the aircraft uncomfortable. In spite of the double extrapolation, this factor is worthy of consideration.

One further point concerning the position of the complete 3·5 boundary on figure 4, the 'good' area (pilot rating > 3·5) represents a rather flat optimum. This may be confirmed from the basic rating data of Table 2. Ratings better than 3 are rare. Thus the contour of Figure 4 represents a rather flat headland. In consequence, minor manipulation to the basic data could change the position of the 3·5 boundary quite markedly, in comparison say to the result of a similar manipulation of the data which gives the 3·5 boundary of Figure 3.

The underlying reason for the reluctance of the pilots to rate the large aircraft in roll as better than 3 is not immediately apparent. Possibly this reflects the experience of this group of pilots on fighter aircraft. Perhaps the low Dutch roll damping is the cause. Alternatively, it could mean that there is room for improvement in the roll control of large aircraft over and above that which can be obtained by allowing the pilot to control roll rate through a first order lag. The use of a higher order control system (as obtained from a manoeuvre demand type of control system) is the obvious starting point, if this line of enquiry is pursued.

6. *Comparison with other Criteria.*

Consider first the long established 'helix angle' criterion which states that $\frac{pb}{2V}$ shall be greater than a certain value, depending on the role of the aircraft. It has the merit of simplicity, and is based on steady rate of roll for full aileron, which is obviously an inportant consideration. There is an implicit assumption in the criterion that as the wing span increases, or the speed decreases, so the need for roll response is reduced. For a land based fighter aircraft on the approach, the requirement is that $\frac{pb}{2V} \geqslant 0{\cdot}07$. Applying this to configuration A, the minimum steady rate of roll for full aileron is 51 deg/second. Our simulator results indicate that such a rate of roll would be satisfactory for values of $\tau_R < 0{\cdot}6$, but unsatisfactory for high values of τ_R. The criticism, then, of $\frac{pb}{2V}$ as a criterion is that in some cases it will be met, but the aircraft may be unsatisfactory, and in others, it will not be met and the aircraft may be satisfactory. This is particularly true for the more extreme values of wing-span and approach speed, as exemplified by aircraft like the C–5A and the F–104.

These criticisms are partly overcome by the use of the $\dot{p}_M$ *vs* τ_R carpet plot, which is the basis of this investigation. Reference 1 contains such a plot, relating to fighter aircraft in the combat role. These boundaries have been widely used as a criterion for up-and-away flight. They are presented on Figure 7.

The requirements for the rolling requirements of large aircraft are discussed by Bisgood in Reference 2. His study of the characteristics of many transport aircraft leads to the roll-response boundaries reproduced on Figure 8. The dotted boundaries are based on less conclusive evidence than the solid boundary; the upper limit on $\dot{p}_M$ is founded on the hypothesis that pilots are unwilling to make gain adjustments by a factor of more than 6, without complaining.

Reference 3 contains the $\dot{p}_M$ *vs* τ_R boundaries shown in Figure 9. These boundaries were obtained from a variable stability Navion aircraft, and relate to the requirements for a carrier approach task.

(a) *Trainer/strike aircraft requirements.*

A comparison of Figure 3 with Figures 7 (*see* Fig. 12) shows that lower values of rolling acceleration are required on the approach, than in combat conditions, as might be expected. However, the minimum acceptable damping on Figure 3 is higher than that of Figure 7, which is rather surprising. Before attributing this result to the lack of motion cues on the simulator, let us compare Figures 3, and 9 (*see* Fig. 13) In this case, the comparison is more meaningful, because both graphs relate to the landing approach configuration.

The rolling acceleration requirements of Figure 9 are higher than those of the trainer/strike aircraft; a result that may be attributed to the greater demands imposed by a carrier approach. The minimum acceptable damping is the same for both cases.

A further confirmation of our simulator results is obtained from Reference 4. This suggests that for small high performance aircraft on the approach, full aileron must give at least 20 deg bank in the first second. A comparison of the 3·5 boundary on Figure 3 and the 20° line on Figure 5 shows that this criterion is valid, for $\tau_R < 0{\cdot}5$.

(b) *Transport aircraft.*

Comparing the lower 3·5 boundaries on Figures 4 and 8, (*see* Fig. 14), it will be seen that the curves agree well for $\tau_R < 0{\cdot}5$, after which the simulator results give a more severe requirement. The lower 3·5 and 6·5 boundaries on Figure 8 coincide with lines which represent a 'bank to 60 deg and stop' manoeuvre. This manoeuvre takes 6·5 seconds for the 3·5 boundary and 10·5 seconds for the 6·5 boundary. For $0{\cdot}5 < \tau_R < 1{\cdot}0$, the 3·5 boundary of Figure 3 shows a better correlation with 'bank angle in one second', as shown on Figure 5. The 3·5 boundary approximates to a line representing 8 deg in one second.

Once again, this is confirmed by Reference 4, which quotes a minimum bank angle of 8 deg in one second, for satisfactory characteristics with this class of aircraft.

Before concluding that bank angle in one second, ϕ_1, is a better parameter to use than time to bank to 60° and stop, T_{60}, we must consider the relevant conclusions of Reference 5. Here, Ashkenas studies the open and closed loop characteristics of roll control, together with known aircraft characteristics and other experimental data. He dismisses bank angle in one second, and suggests 'time to bank 30 deg', t_{30}, as a criterion for transport aircraft on landing approach ($t_{30} < 3{\cdot}5$ seconds for satisfactory rating). This then restores confidence in T_{60}, since time to bank, and time to bank and stop, do not differ greatly if the specified bank angle is large, and τ_R is relatively small (say less than 1·0). Moreover, the practical difficulties of measuring ϕ_1, since full control cannot be applied instantaneously, restrict its use considerably.

At this point, it is worth remarking that neither ϕ_1, not T_{60}, nor t_{30} can be correlated with pilot opinion for values of $\tau_R > 1{\cdot}0$. It is obvious that stability rather than control aspects become dominant. In such circumstances, an easily applied, universal criterion which has physical significance is not apparent.

7. *Comparison with known Aircraft.*

One of the difficulties which arises in trying to substantiate the simulator results by comparison with known aircraft is that existing aircraft only cover a limited range of values of $\dot{p}_M$ and τ_R. Hence only a small part of the total iso-opinion plot may be compared.

Furthermore, we have seen that the boundaries obtained are primarily a function of task, or in more practical terms, the type of approach path which is flown. The span, wing loading, or operational role of the aircraft will have much less effect on the lateral control requirements than the type of approach which is used. On the other hand, wing loading and operational role may determine directly the type of approach. For example, a modern jet transport aircraft would be restricted to the type of approach path it currently uses, even if it had the rolling performance of a light trainer, by longitudinal dynamic and kinematic considerations.

Figures 3 and 4 represent pilot rating curves only for two specific tasks. If the task in the large aircraft investigation had been replaced by a straight approach without track error, the boundaries would undoubtedly have been more accommodating.

Table 3 contains the characteristics of various aircraft in the approach configuration. These aircraft are compared with the results of this investigation on Figures 15 and 16. To do so, each aircraft on Table 3 must be arbitrarily classified as a trainer/strike, or a transport aircraft. In most cases no argument can arise, although in the case of the high performance interceptor aircraft such as F–104, F–105 and Lightning, there is no doubt that the form of approach path used is more akin to that used by transport aircraft, than that used by trainer aircraft. They should therefore be assessed on a pilot-opinion plot somewhere between Figures 3 and 4. Nevertheless, these aircraft are plotted on Figure 15. None of the aircraft as plotted on Figure 15 are rated worse than 4·5; the small trainer aircraft are in the centre of the 'good' region. It is interesting to note that the Hunter is occasionally landed in 'manual', in which case the ailerons are moved solely by the forces applied on the stick by the pilot. The stick force per rate of roll is then extremely high. A generous estimate of the maximum control power available, based on how much force a pilot can apply with one hand, would indicate that $\dot{p}_M$ is down by a factor of 10, from the value quoted in Table 3. Figure 15 would then indicate that the aircraft cannot be landed. This simply means that it cannot be landed *using the approach path on which this assessment is based.* A long straight approach, with no crosswind or turbulence, is quite a different matter.

Other examples of landings made with minimal lateral control could be quoted—all serving to illustrate that the form of approach is the critical factor. The addition of underwing stores rarely degrades the pilot rating of the roll control of the fighter aircraft on the approach. Possibly the reduced sensitivity to gusts compensates for the reduction in control effectiveness. Also, the type of approach in use is not so severe as to be limited by the rolling control characteristics.

Some of the transport aircraft plotted on Figure 16 lie in the 3·5 to 5·0 region. Aircraft 8, 6 and 13 were subject to considerable pilot criticism for poor rate of roll on the approach; aircraft 3 and 7 were not rated as well as 1 and 2 (*see* Reference 6). The Britannia point is rather mysterious; perhaps the presence of servo-tabs on the ailerons improves the rolling characteristics over those which would be present without them. A $\dot{p}_M$ *vs* τ_R criterion does not allow the effects of control system dynamics to be taken into account. These effects can easily cause control difficulties (high forces for full control, power control lag, or rate limiting are obvious sources of trouble). In some circumstances, however, the control system characteristics can be arranged to improve the handling of the aircraft.

Although the 3·5 boundary of Figure 16 does not embrace all the aircraft which are known to be satisfactory, none of these aircraft would be rated worse than 4·5 on this criterion. In view of the rather flat optimum discussed previously, which makes the position of the 3·5 boundary sensitive to data manipulation, Figure 4 is a useful criterion to apply to large aircraft. It may be rather severe; on the other hand it could be argued that the bottom right hand corner of the Bisgood criterion (Fig. 8) is rather lenient.

The question of a suitable lateral control criterion for large aircraft is of growing importance. Modern approach facilities are allowing much more accurate approaches to be made; category 2 and category 3 operation make increasingly severe demands on lateral control qualities. At the same time, the provision of adequate lateral control power becomes more difficult with increasing aircraft size. Reference 7 contains experimental results on a variable stability aircraft pertaining to the C–5A. Unfortunately, these results are not suitable for comparison with our simulator results (they are considerably influenced by a simulated control lag of 0·6 seconds), but they do demonstrate the potential difficulties of lateral control for very large aircraft. Large control lags, and low control rate limits may well be unavoidable. Under these circumstances, it may be necessary to resort to a command augmentation system, or to a non-linear control system, to obtain suitable rolling control characteristics.

8. *Conclusions.*

1. Tests have been made on a flight simulator to determine the relationship between pilot opinion and the rolling characteristics of an aircraft on the landing approach. Two different types of aircraft have been investigated—a trainer/strike aircraft and a transport aircraft. Every effort was made to make the results of both investigations directly comparable.

2. The results are presented in the form of plots of pilot opinion *versus* maximum rolling acceleration, $\dot{p}_M$, and rolling mode time constant, τ_R. The shapes of the resulting boundaries are largely influenced by the form of the approach task given to the pilots. Pilots did not consider the '300 ft offset at 300 ft height' task, which was used to assess the transport aircraft, to be a suitable task on which to judge a trainer/strike aircraft. In consequence the plots for the two types of aircraft differ considerably.

3. Both plots have been discussed relative to existing criteria, and to known aircraft. Each plot appears to provide a suitable basis on which to judge the likely handling characteristics of a projected aircraft, if tempered with a little optimism.

4. Several other factors, not considered in this investigation, will influence pilot opinion of roll control on the approach. These include the responsiveness of the aircraft to turbulence, the aircraft's Dutch roll characteristics, the crosswind landing characteristics, the stick force and stick travel necessary to achieve full control, and the dynamic characteristics of the control system. These factors, together with the form of approach, determine the control requirements, rather than aircraft size.

5. Because several factors are involved, no single criterion on which to judge the handling qualities in roll is likely to be found. Fortunately, an aircraft which is bad in one respect, is not likely to be troublesome in another—for example low wing loading and wing sweep rarely occur in the same design. Similarly, large aircraft are not required to do carrier landings. In consequence, a single criterion for a given class of transport is not unrealistic.

6. The pilot opinion boundaries obtained are useful to quantify the relationship between kinematic approach path, and control requirements. Further understanding of this relationship should be sought. Existing criteria based on other factors should also be studied, in order to produce a set of rolling requirements of general applicability.

7. The provision of good roll control for very large aircraft appears to be difficult and may involve the use of more elaborate control systems than previously employed in transport aircraft.

LIST OF SYMBOLS

R	Resistance
s	Laplace operator
T_{60}	Time to bank to 60 deg, and stop
t_{30}	Time to bank through 30 deg
V	Aircraft velocity
y_v	Side Force due to side velocity derivative
y_v	Side force due to side velocity derivative
z_w	Normal force due to vertical velocity derivative
z_η	Normal force due to elevator derivative
α	Incidence
α_T	Incremental incidence due to turbulence
β	Sideslip
β_T	Incremental sideslip due to turbulence
γ	Flight path angle
ε	Azimuth direction of velocity vector
ζ_d	Dutch roll damping
ζ_n	Longitudinal short period damping
ζ	Rudder angle
η	Elevator angle
λ	Turbulence wavelength
ρ	Air density
τ	Aerodynamic time $= \dfrac{m}{S_p V}$
τ_R	Rolling mode time constant
ϕ	Bank angle
ϕ_1	Bank angle in one second
ψ	Heading
Ω	Spatial frequency
ω_ϕ	Aileron-to-bank transfer-function numerator natural frequency
ω_d	Dutch roll undamped natural frequency
ω_n	Longitudinal short-period natural frequency
a_y	Side acceleration at c.g.
a_z	Normal acceleration at c.g.

LIST OF SYMBOLS (contd.)

b	Wing span
C	Capacitance
g	Gravitational acceleration
h	Height
i_a	Rolling-inertia coefficient
i_c	Yawing-inertia coefficient
i_e	Product of inertia coefficient
L	Turbulence scale length
L_α	Lift parameter $\left(\simeq \frac{z_w}{\tau}\right)$
l	Tail arm
l_v	Rolling moment due to side-velocity derivative
l_r	Rolling moment due to yaw-rate derivative
l_p	Rolling moment due to roll-rate derivative
l_ξ	Rolling moment due to aileron derivative
l_ξ	Rolling moment due to rudder derivative
m	Mass of aircraft
m_w	Pitching moment due to vertical-velocity derivative
m_q	Pitching moment due to pitch-rate derivative
m_η	Pitching moment due to elevator derivative
$m_{\dot{w}}$	Pitching moment due to vertical-acceleration derivative
n_v	Yawing moment due to side-velocity derivative
n_r	Yawing moment due to yaw-rate derivative
n_p	Yawing moment due to roll-rate derivative
n_ξ	Yawing moment due to aileron derivative
n_ζ	Yawing moment due to rudder derivative
$\dot{p}_m$	Rolling acceleration due to full aileron
p	Rate of roll
q	Rate of pitch
r	Rate of yaw

REFERENCE

No.	Author(s)	Title, etc.
1	Green Stewart .. .. .. Merrick and Drinkwater	A pilot opinion study of lateral control requirements for fighter type aircraft. NASA Memo. 1–29–59A (1959).
2	P. L. Bisgood	A review of recent handling qualities research, and its application to the handling problems of large aircraft. A.R.C. R. & M. 3458 (1964).
3	E. Seckel, G. E. Miller and W. B. Nixon ..	Lateral directional flying qualities for power approach. Princeton University Report 727. (1965).
4	G. A. Patterson and .. .. W. Spangenberg	The Provision of adequate lateral control power for landing approach conditions. AGARD Report 419 (1963).
5	I. L. Ashkenas	A study of conventional airplane handling qualities requirements. AFFDL–TR–65–138 Part 1. (1965).
6	D. M. Perry, W. G. A. Port .. and J. C. Morrall	A flight study of the sidestep manoeuvre during landing. A.R.C. R. & M. 3347 (1961).
7	R. A. Mabli, J. W. Carlson .. and R. O. Sickeler	Results of handling qualities research for the C–5A. AIAA Paper No. 65–740. (1965).

APPENDIX 1

Aircraft Equations of Motion—R. & M. 1801 Notation.

Dynamic

Incidence $\dot{\alpha} = \dfrac{z_\omega}{\tau}(\alpha+\alpha_t)+q+\dfrac{z_\eta}{\tau}\eta\,.$

Pitch $\quad \dot{q} = \dfrac{m_{\dot{\omega}}}{\tau_{i_B}}\dot{\alpha}+\dfrac{Vm_\omega}{\tau_{i_B}l}(\alpha+\alpha_t)+\dfrac{m_q}{\tau_{i_B}}q+\dfrac{Vm_\eta}{\tau_{i_B}l}\eta\,.$

Sideslip $\dot{\beta} = \dfrac{y_v}{\tau}(\beta+\beta_t)-r+\dfrac{g}{V}\sin\phi+\dfrac{y_\zeta}{\tau}\zeta\,.$

Roll $\quad \dot{p} = \dfrac{2V}{b\tau_{i_a}}l_v(\beta+\beta_t)+\dfrac{l_p}{\tau_{i_a}}p+\dfrac{l_r}{\tau_{i_a}}r+\dfrac{i_\varepsilon}{i_a}\dot{r}+\dfrac{2V}{b\tau_{i_a}}l_\xi\xi+\dfrac{2V}{b\tau_{i_a}}l_\zeta\zeta\,.$

Yaw $\quad \dot{r} = \dfrac{2V}{b\tau_{i_c}}n_v(\beta+\beta_t)+\dfrac{n_p}{\tau_{i_c}}p+\dfrac{n_r}{\tau_{i_c}}r+\dfrac{i_\varepsilon}{i_c}\dot{p}+\dfrac{2V}{b\tau_{i_c}}n_\xi\xi+\dfrac{2V}{b\tau_{i_c}}n_\zeta\zeta\,.$

Kinematic

Normal acceleration at c.g. $a_z = 1-\dfrac{V}{g}\left[\dfrac{z_\omega}{\tau}(\alpha+\alpha_t)+\dfrac{z_\eta}{\tau}\eta\right].$

Side acceleration at c.g., $a_y = -\dfrac{V}{g}\left[\dfrac{y_v}{\tau}(\beta+\beta_t)+\dfrac{y_\zeta}{\tau}\zeta\right].$

In space-fixed axes, $a_{z_{s.a}} = a_z\cos\phi-a_y\sin\phi-1$

$$a_{y_{s.a}} = a_z\sin\phi+a_y\cos\phi\,.$$

Rate of turn of velocity vector in azimuth, $\varepsilon = \dfrac{a_{y_{s.a}}}{V}.$

Rate of turn of velocity vector in elevation $\dot{\gamma} = \dfrac{a_{z_{s.a}}}{V}.$

$$\alpha_{s.a} = \alpha\cos\phi-\beta\sin\phi\,.$$

$$\beta_{s.a} = \alpha\sin\phi+\beta\cos\phi\,.$$

Orientation in space

$$\theta_{s.a} = \gamma + \alpha_{s.a}$$

$$\psi_{s.a} = \varepsilon + \beta_{s.a}.$$

Velocity in space

$$\dot{h} = V\gamma$$

$$\dot{y} = V\varepsilon$$

Suffices: $s.a$ = space axes

t = turbulence

others as in R. & M. 1801.

Numerical Values (basic)

A = Trainer/strike aircraft B = Transport aircraft

	$V_{\text{app.}}$ (*kts*)	i_a	i_b	i_c	i_e	b	l	τ
A	135	·073	·33	·39	−·037	36	18	3·80
B	135	·054	·26	·24	−·034	140	62	3·97

Lateral derivatives

	y_v	y_ζ	l_v	l_p	l_r	l_ξ	l_ζ	n_v	n_p	n_r	n_ξ	n_ζ
A	−·49	·16	−·17	−·15	·14	−·12	·010	·20	·06	−·37	0	−·09
B	−·38	·12	−·17	−·39	·28	−·22	·026	·12	−·09	−·122	0	−·075

Longitudinal derivatives

	z_ω	z_η	$\mu_1 m_{\dot{\omega}}$	m_ω	m_q	m_η
A	−2·28	−·20	−·150	−·150	−·24	−·480
B	−2·48	−·175	−·064	−·206	−·45	−·187

Lateral parameters

	ω_d	ζ_d	τ_s	ϕ/β	ϕ/v_e	$\omega\phi/\omega d$
A	2·1	·13	12	3·2	·82	0·9
B	·82	·05	43	1·8	·46	0·9

Longitudinal parameters

	L_α	ω_n	ζ_n	n/g	SF/g
A	·60	1·21	·38	8°	15 lbs
B	·63	·82	·55	22°	45 lbs

Parameters investigated

$$\dot{p}_M = \frac{2V}{b\tau_{i_a}} l_\xi \xi$$

$$\tau_R = \frac{\tau_{i_a}}{l_p} \quad \text{(approx)}$$

Max. steady state of roll $= \dot{p}_M . \tau_R$.

APPENDIX 2

Definition of Turbulence Spectrum used in Simulation.

The widely accepted formula for the representation of turbulence (the Dryden spectra) is

$$\phi(\omega) = \sigma^2 \frac{L}{2\pi V} \frac{1+3(L\Omega)^2}{[1+(L\Omega)^2]^2}$$

where σ = r.m.s. of turbulence intensity (ft/sec)

L = scale length of turbulence (ft) for $h < 1000$ feet, $L_\omega \leqslant h$

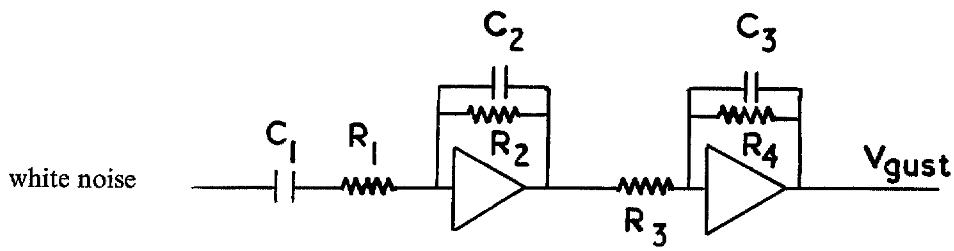
Ω = spatial frequency, rad/ft $= \dfrac{\omega}{V} = \dfrac{2\pi}{\lambda}$

ω = frequency, rad/sec

λ = turbulence wavelength, feet.

For practical reasons, variation of L_ω with height could not be simulated, and so a fixed scale length of 200 feet was chosen. Also, it was desirable to reduce the power at the lowest frequencies, so as to ensure that a similar level of excitation occurred during each approach. Otherwise, the relatively short time taken for each approach meant that the probability of encountering severe gusts on each approach was low. Consequently a high pass filter was necessary.

A simple and reasonably good fit to the above requirements is obtained by the circuit shown below



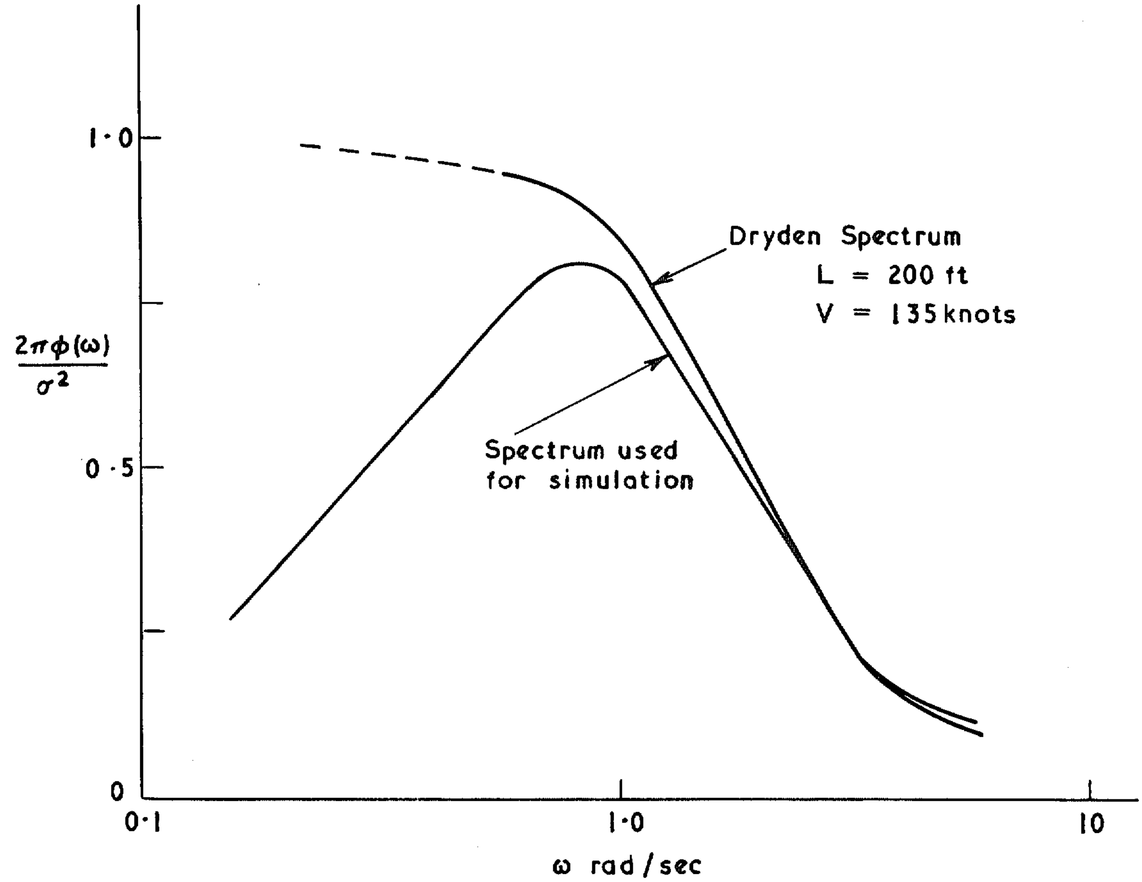
This circuit corresponds to a filter of the following type

$$\frac{0}{i} = \frac{R_2 C_1 S}{(1+R_2C_2S)(1+R_1C_1S)} \cdot \frac{R_2}{R_3} \cdot \frac{1}{(1+R_4C_3S)}$$

Component values used were

$$R_1 = 2M, R_2 = 10M, R_3 = 5M, R_4 = 5M, C_1 = 0{\cdot}5\mu F, C_2 = 0{\cdot}1\mu F, C_3 = 0{\cdot}1\mu F$$

giving a filter of the form $\dfrac{\cdot 5S}{1+5S} \cdot \dfrac{10}{(1+S)^2}$



The comparison of the power spectrum used with the Dryden Spectrum is shown above. Excitation of the aircraft's lateral and longitudinal short period modes is approximately correct. The level of excitation was adjusted to given r.m.s. of 3 feet/second (light-moderate turbulence).

TABLE 1

Pilot Ratings—Trainer/Strike Aircraft

$\dot{p}_M$	τ_R	Pilot								Mean
		A	A	B	B	C	C	D	E	
3·2	0·32	2	2	2	$3\frac{1}{2}$	$3\frac{1}{2}$	$2\frac{1}{2}$	$2\frac{1}{2}$	1	2·4
2·0	0·32	$2\frac{1}{2}$	2	$2\frac{1}{2}$	$2\frac{1}{2}$	$4\frac{1}{2}$	5	$2\frac{1}{2}$	2	2·9
1·0	0·32	$3\frac{1}{2}$	$4\frac{1}{2}$	$5\frac{1}{2}$	5	$6\frac{1}{2}$	$6\frac{1}{2}$	$4\frac{1}{2}$	5	5·1
·32	0·32	7	7	$9\frac{1}{2}$	10	7	8	$8\frac{1}{2}$	$6\frac{1}{2}$	8·0
3·2	0·57	2	2	$4\frac{1}{2}$	3	2	$1\frac{1}{2}$	$3\frac{1}{2}$	$4\frac{1}{2}$	2·9
2·0	0·57	2	2	3	3	$3\frac{1}{2}$	$2\frac{1}{2}$	$2\frac{1}{2}$	2	2·6
1·0	0·57	$3\frac{1}{2}$	3	3	5	5	$6\frac{1}{2}$	$4\frac{1}{2}$	5	4·4
·32	0·57	$6\frac{1}{2}$	6	9	9	$6\frac{1}{2}$	$8\frac{1}{2}$	8	$5\frac{1}{2}$	7·4
3·2	1·0	$3\frac{1}{2}$	3	5	$4\frac{1}{2}$	$4\frac{1}{2}$	3	4	5	3·9
2·0	1·0	4	3	5	5	$4\frac{1}{2}$	3	5	3	4·1
1·0	1·0	$3\frac{1}{2}$	4	$2\frac{1}{2}$	3	7, $6\frac{1}{2}$	5	4	$5\frac{1}{2}$	4·6
·32	1·0	$5\frac{1}{2}$	6	7	9	$7\frac{1}{2}$	$8\frac{1}{2}$	7	$5\frac{1}{2}$	7·0
3·2	1·78	$4\frac{1}{2}$	5	7	7	$5\frac{1}{2}$	5	7	$5\frac{1}{2}$	5·8
2·0	1·78	4	$4\frac{1}{2}$	$6\frac{1}{2}$	6	6	4	6	$5\frac{1}{2}$	5·3
1·0	1·78	$3\frac{1}{2}$	6	$4\frac{1}{2}$	5	$5\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	6	4·9
·32	1·78	6	8	$8\frac{1}{2}$	9	8	8	8	7	7·8

TABLE 2

Pilot Ratings—Transport Aircraft

$\dot{p}_M$	τ_R	Pilot						Mean
		F	G	H	I	J	K	
3·2	0·32	$3\frac{1}{2}$	$3\frac{1}{2}$	$2\frac{1}{2}$		3	3	3·1
1·0	0·32	3	2	2			2	2·5
0·32	0·32	7	5	$4\frac{1}{2}$	$5\frac{1}{2}$		$5\frac{1}{2}$	5·5
0·10	0·32	9		7			9	8·3
3·2	0·57	3	2	4	$3\frac{1}{2}$		$4\frac{1}{2}$	3·4
1·0	0·57	2	3	2			2	2·3
0·32	0·57	6		$4\frac{1}{2}$		$3\frac{1}{2}$	$4\frac{1}{2}$	4·7
0·10	0·57	9		8			8	8·3
3·2	1·0	4	4	2	2	2	5	3·2
1·0	1·0	3	4	2	4	$3\frac{1}{2}$	2	3·1
0·32	1·0	4	7	5	7	4	$3\frac{1}{2}$	5·1
0·10	1·0	9		9			8	8·7
3·2	1·78	4		$3\frac{1}{2}$	$4\frac{1}{2}$		6	4·5
1·0	1·78	2	5	$2\frac{1}{2}$	$3\frac{1}{2}$		$4\frac{1}{2}$	3·5
0·32	1·78	5		$3\frac{1}{2}$		4	$3\frac{1}{2}$	4·0
0·10	1·78	9		$9\frac{1}{2}$			$7\frac{1}{2}$	8·7
3·2	3·20	6		5	6	5	$7\frac{1}{2}$	5·9
1·0	3·20	5		$3\frac{1}{2}$	1	$4\frac{1}{2}$	6	4·0
0·32	3·20	$4\frac{1}{2}$		3	5	$6\frac{1}{2}$	3	4·5
0·10	3·20	8		7	9	10	6	8·0

TABLE 3

Rolling Characteristics of Existing Aircraft on Landing Approach

Aircraft	Weight lbs × 10^{-3}	Span ft	Speed knots	$\dot{p}_M$ rad/sec^2	τ_R sec^{-1}	Source
1. Viking	30	89	110	·38	·74	Ref. 6
2. Viscount	60	94	120	·50	·64	Ref. 6
3. Ambassador	47	115	115	·49	·45	Ref. 6
4. Comet 4C	110	115	128	·51	·68	RAE TR 66244
5. Argonaut	68	117	120	·38	·63	Ref. 6
6. Lincoln	55	120	110	·21	·82	Ref. 6
7. Constellation	87	123	120	·38	·57	Ref. 6
8. Stratocruiser	110	141	130	·31	·64	Ref. 6
9. Britannia	130	142	115	·30	·70	ARC CP 833
10. Vanguard	125	118	127	·45	·70	ARC CP 833
11. Boeing 707	207	142	135	·59	1·0	NASA CR 239
12. VC 10	200	140	139	1·15	·54	B.A.C.
13. Vulcan 1	110	111	125	·25	1·0	ARC CP 833
14. Vulcan 2	110	111	125	·50	1·0	ARC CP 833
15. Canberra	28	64	115	1·20	·45	B.A.C.
16. Dove	7·7	57	90	2·4	·17	Cranfield
17. F-101	35	40	170	1·1	·85	Ref. 5
18. F-104G	17	25	180	1·8	0·8	Ref. 5
19. F-105	35	35	175	1·5	0·7	Ref. 5
20. T-38A	9	25	155	2·7	0·5	Ref. 5
21. Lightning	30	35	175	2·5	0·9	B.A.C.
22. Hunter	16	33·5	150	1·55	·65	RAE TN Aero 2753
23. Jet Provost	6	37	100	2·48	·47	B.A.C.
24. Meteor	14	38	130	·96	·50	RAE Bedford
25. Aero 707A	9·5	34	120	1·90	·45	RAE TR 65075
26. Aero Commander	7·5	50	90	·80	·80	NASA TN D3726
27. Breguet 941	39	76	60	·42	·82	NASA TN D2231
28. B.A.C. 1–11	68	88	125	·85	·62	B.A.C.

Values in $\dot{p}_M$ and τ_R are only approximate; the form of available data makes accurate values difficult to deduce in some cases.

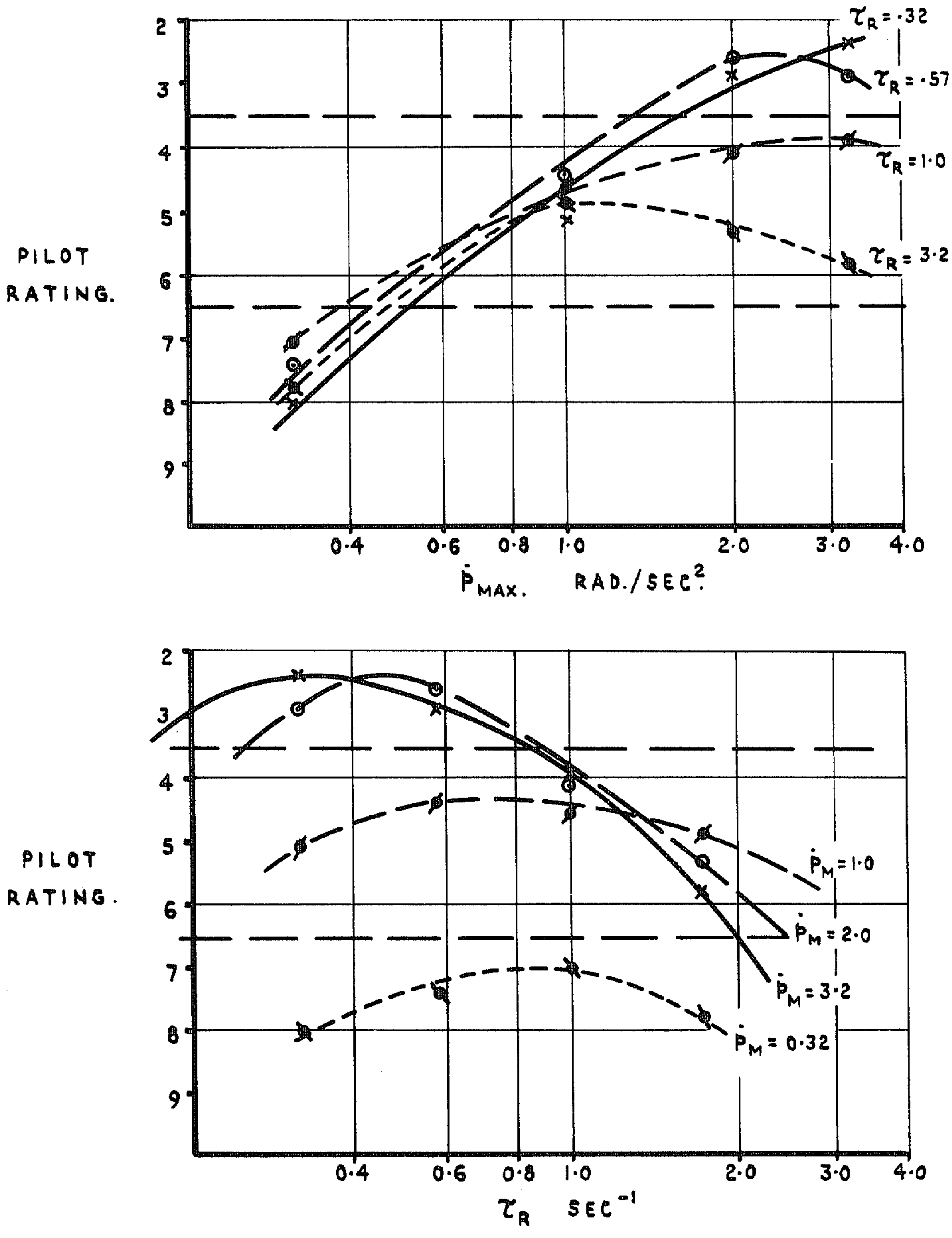


FIG. 1. Pilot rating *vs* τ_R and $\dot{p}_M$; trainer strike results.

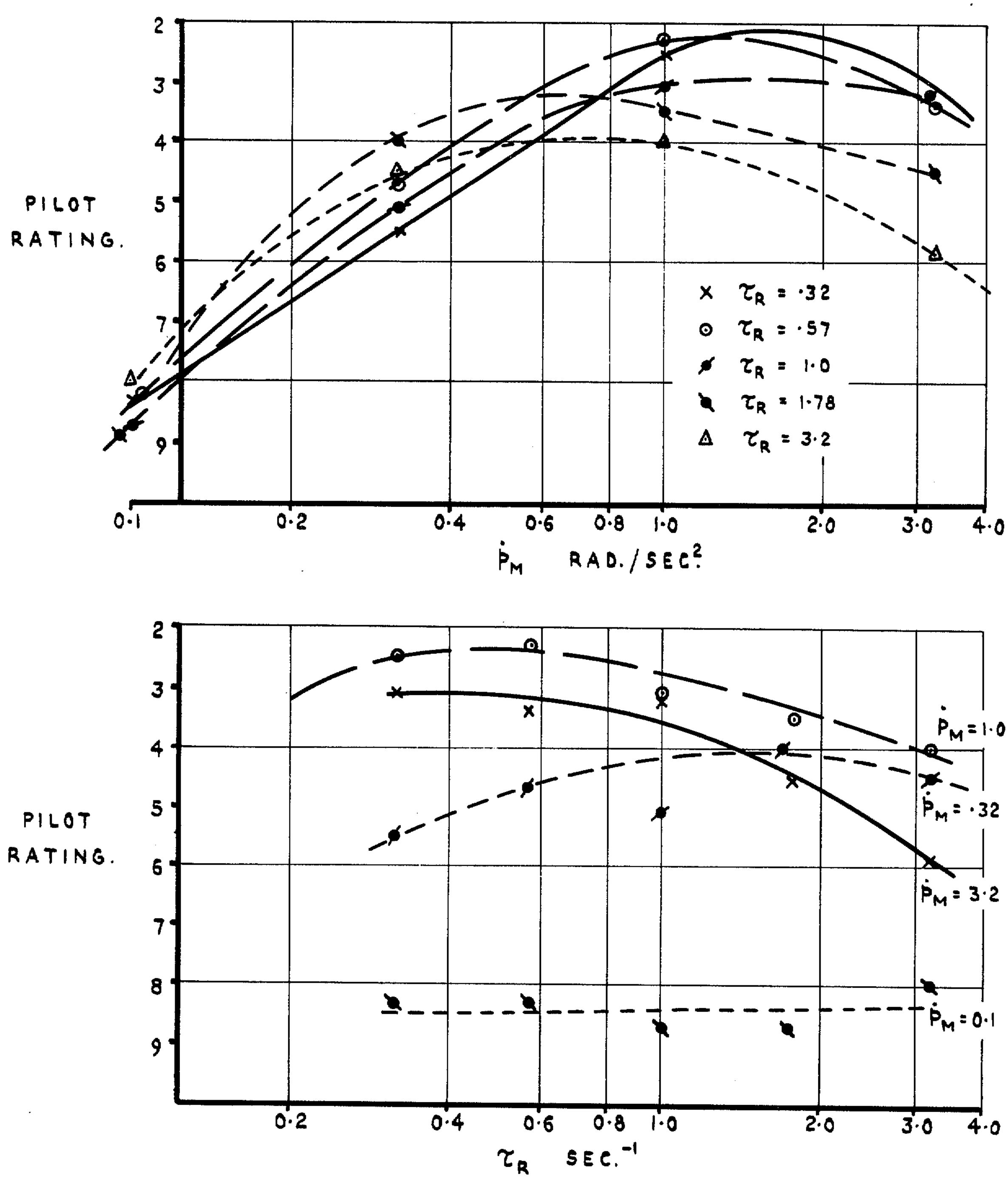


FIG. 2. Pilot rating *vs* τ_R and $\dot{p}_M$; transport aircraft results.

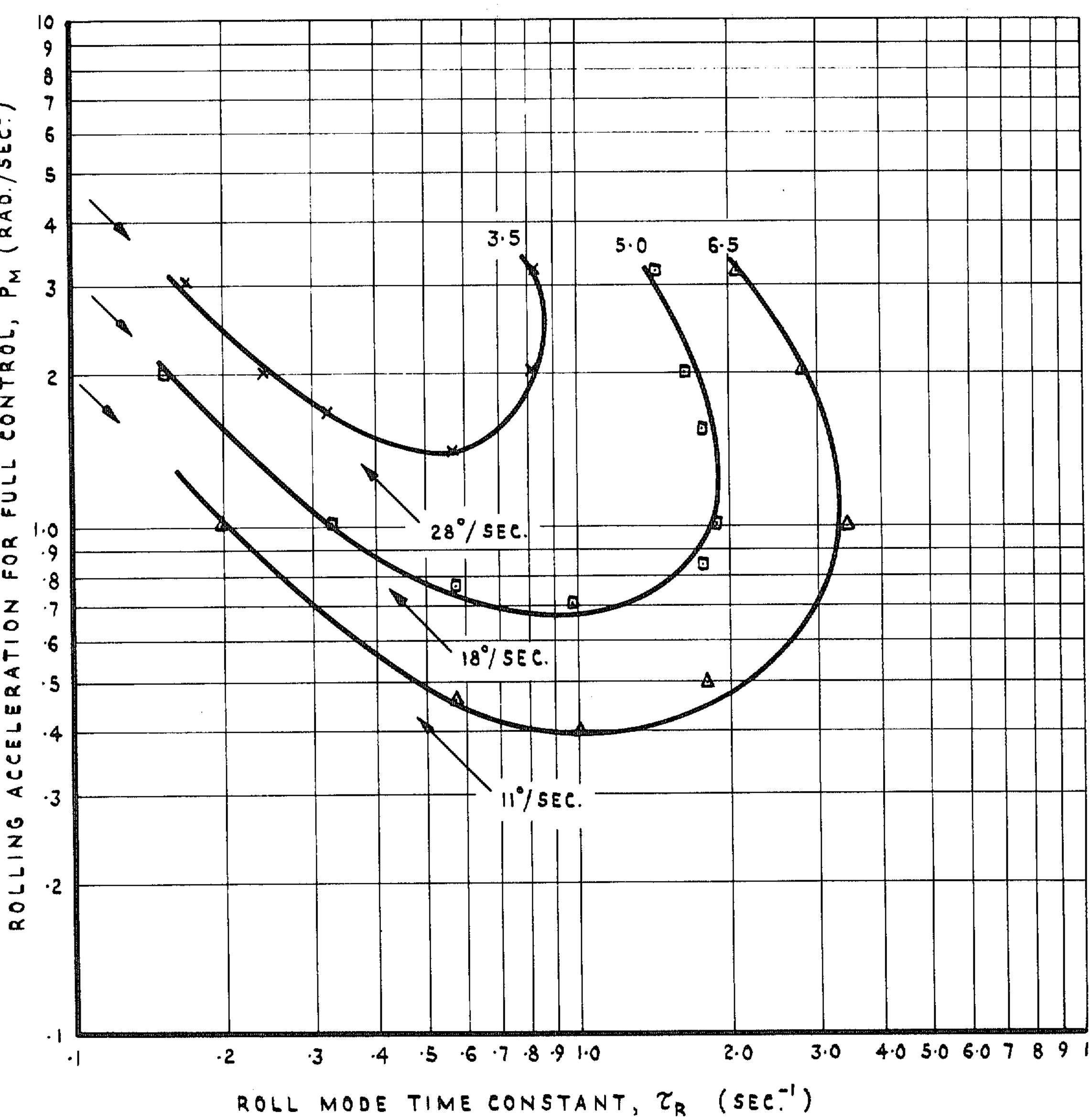


FIG. 3. Pilot opinion boundaries: trainer/strike aircraft.

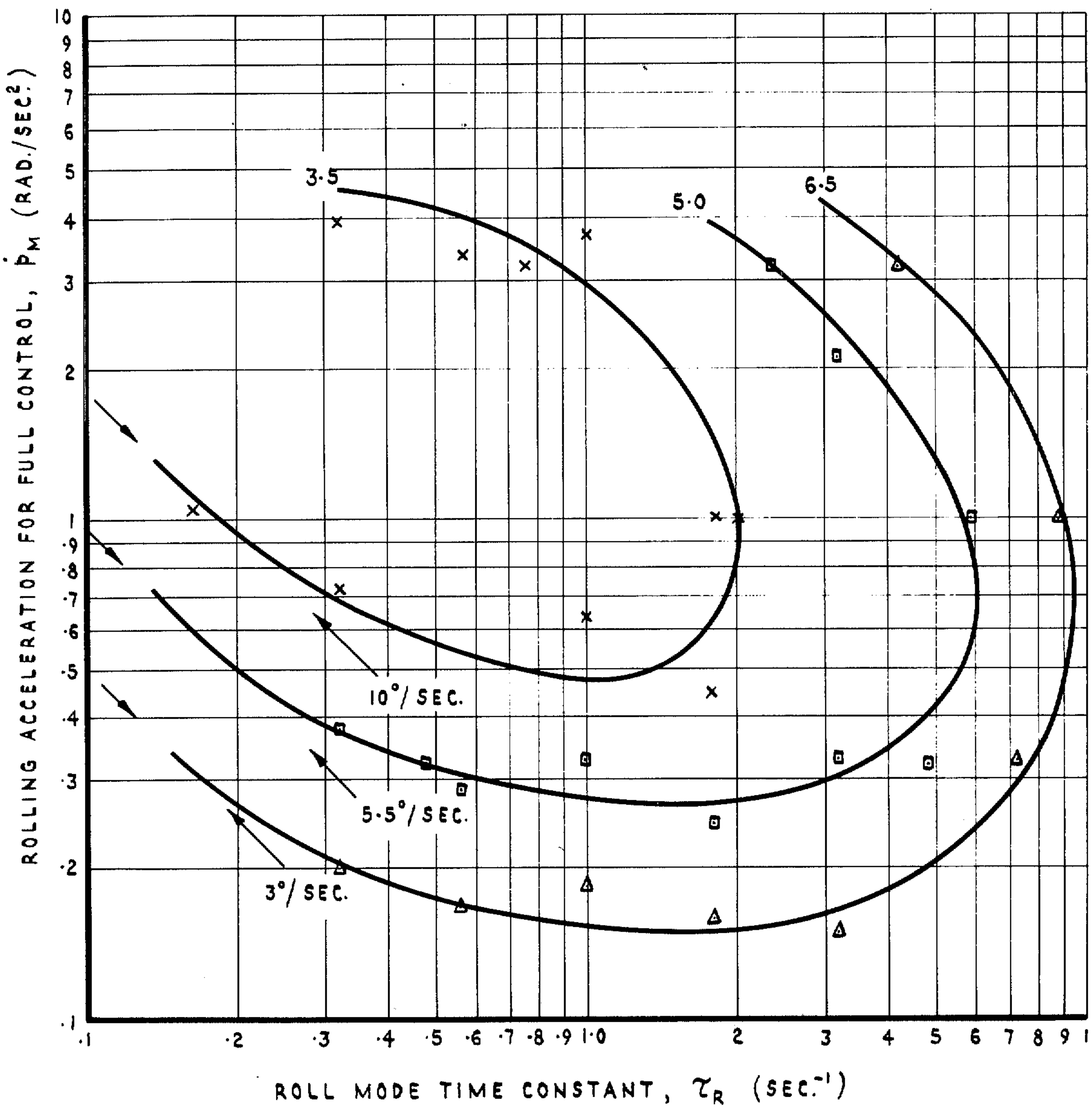


FIG. 4. Pilot opinion boundaries; transport aircraft.

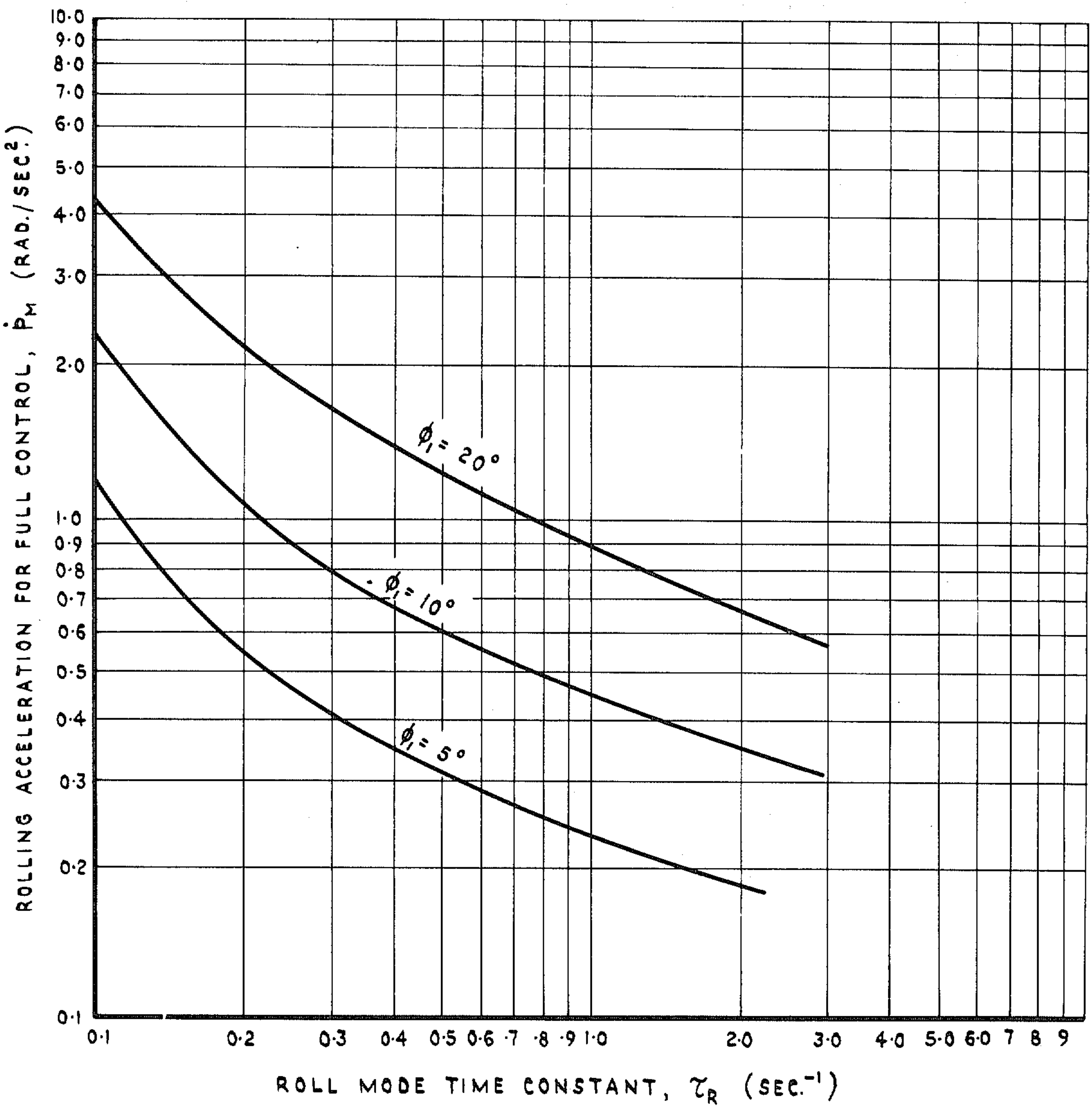


FIG. 5. Bank angle achieved in one second, ϕ_1, step input.

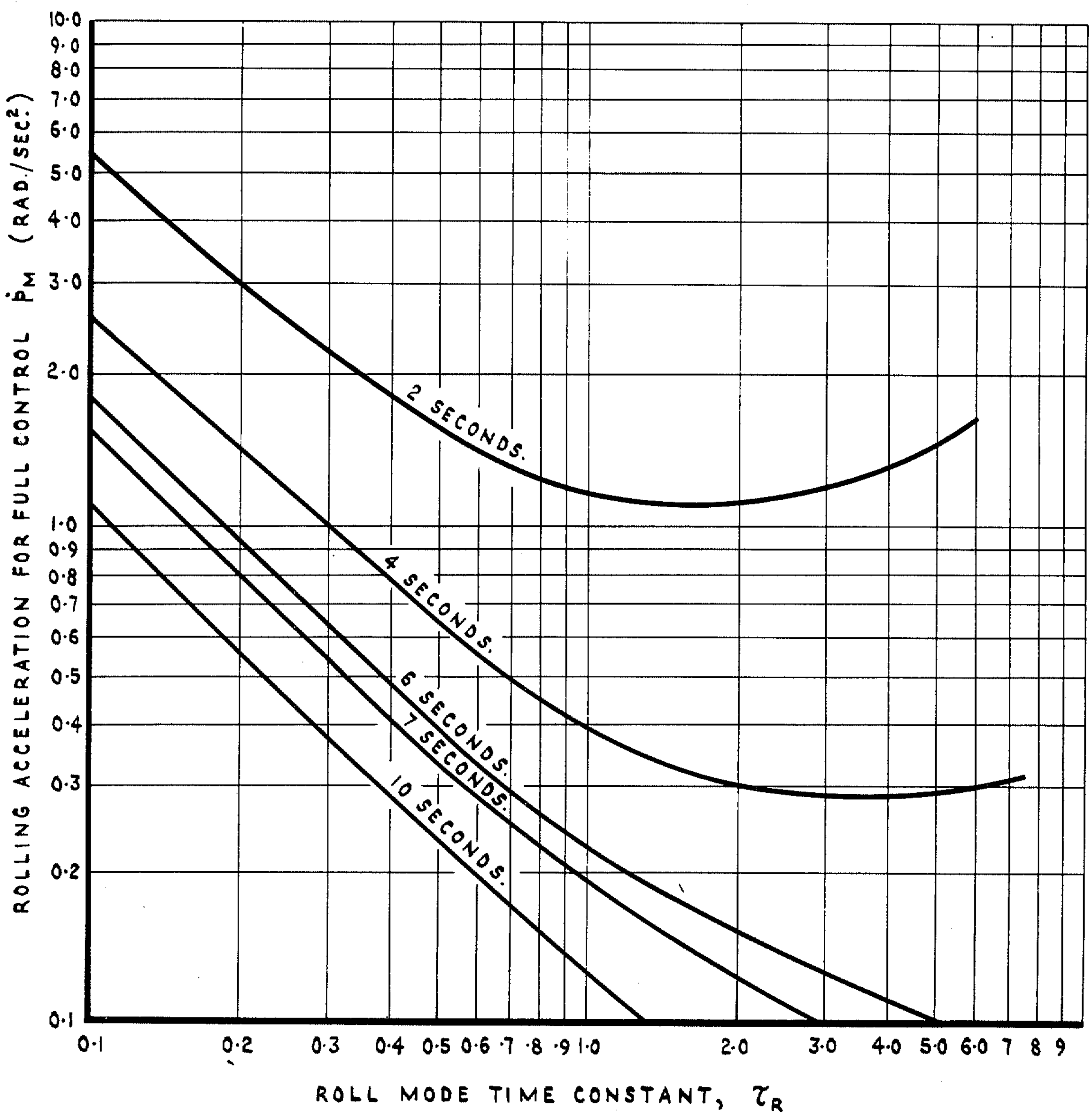


FIG. 6. Time to bank to 60° and stop, T_{60} step input.

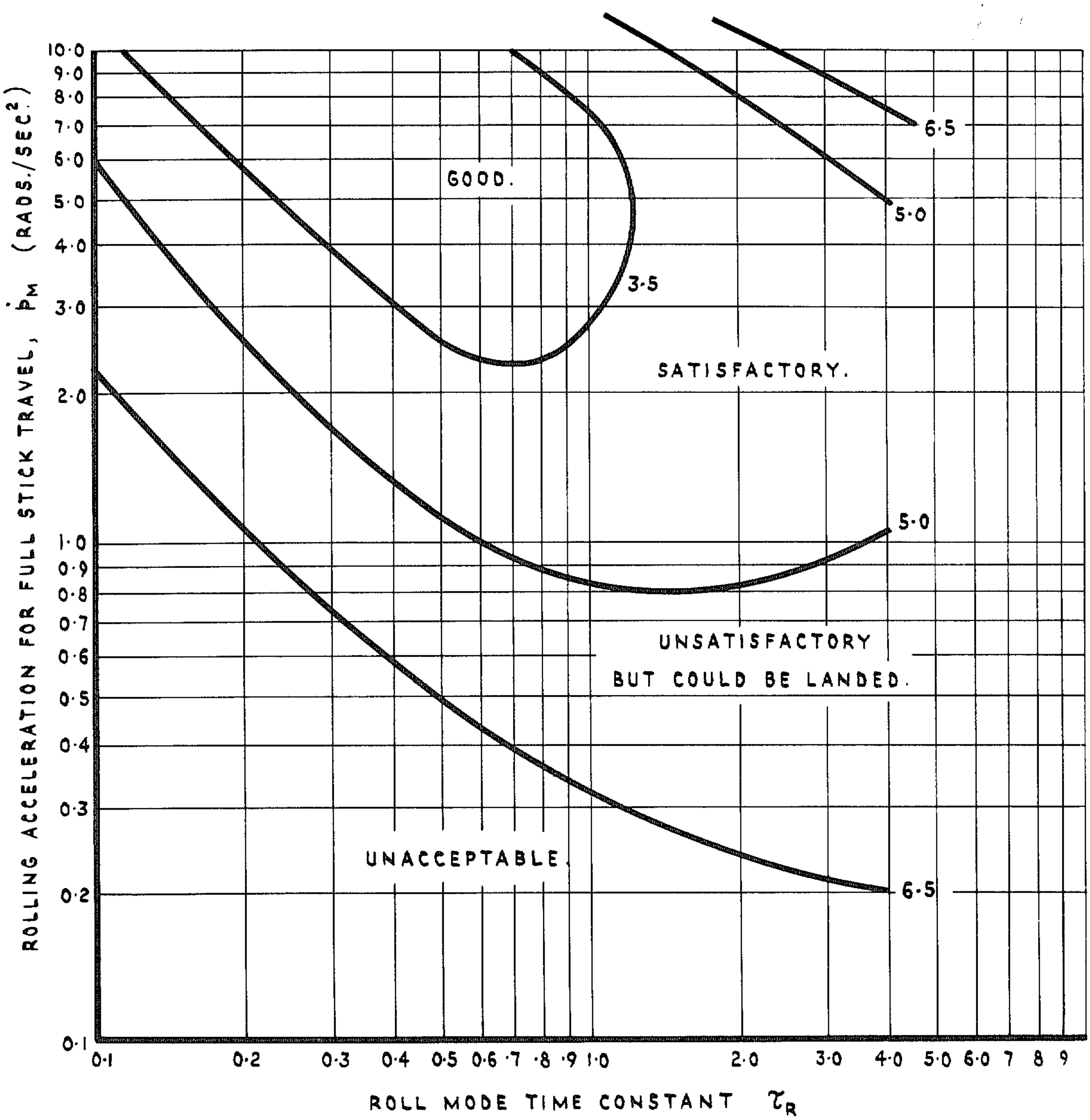


FIG. 7. Pilot rating of single degree of freedom rolling requirement for combat (from Reference 1).

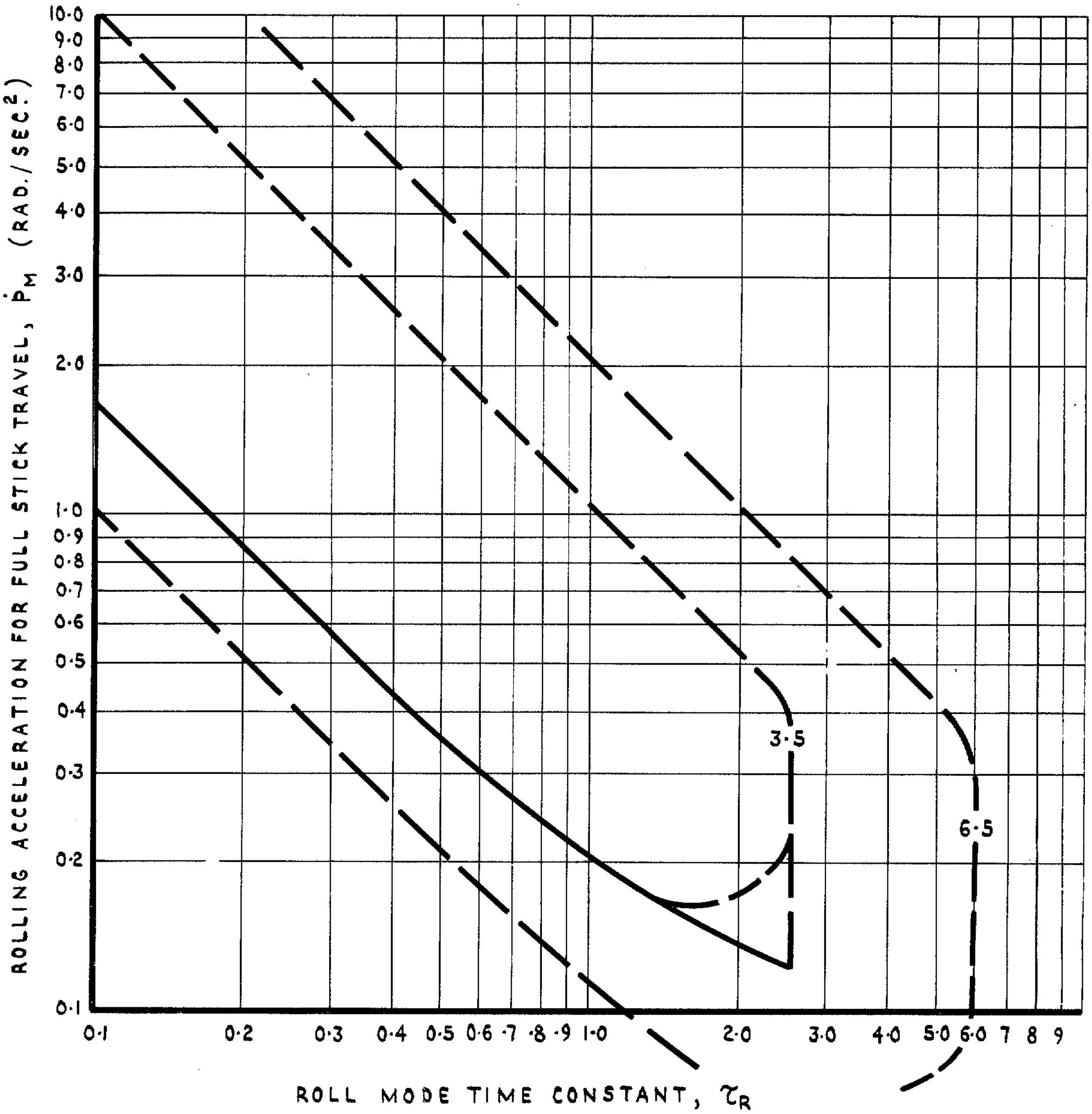


FIG. 8. Roll response boundaries for large aircraft (approach conditions)—from Reference 2.

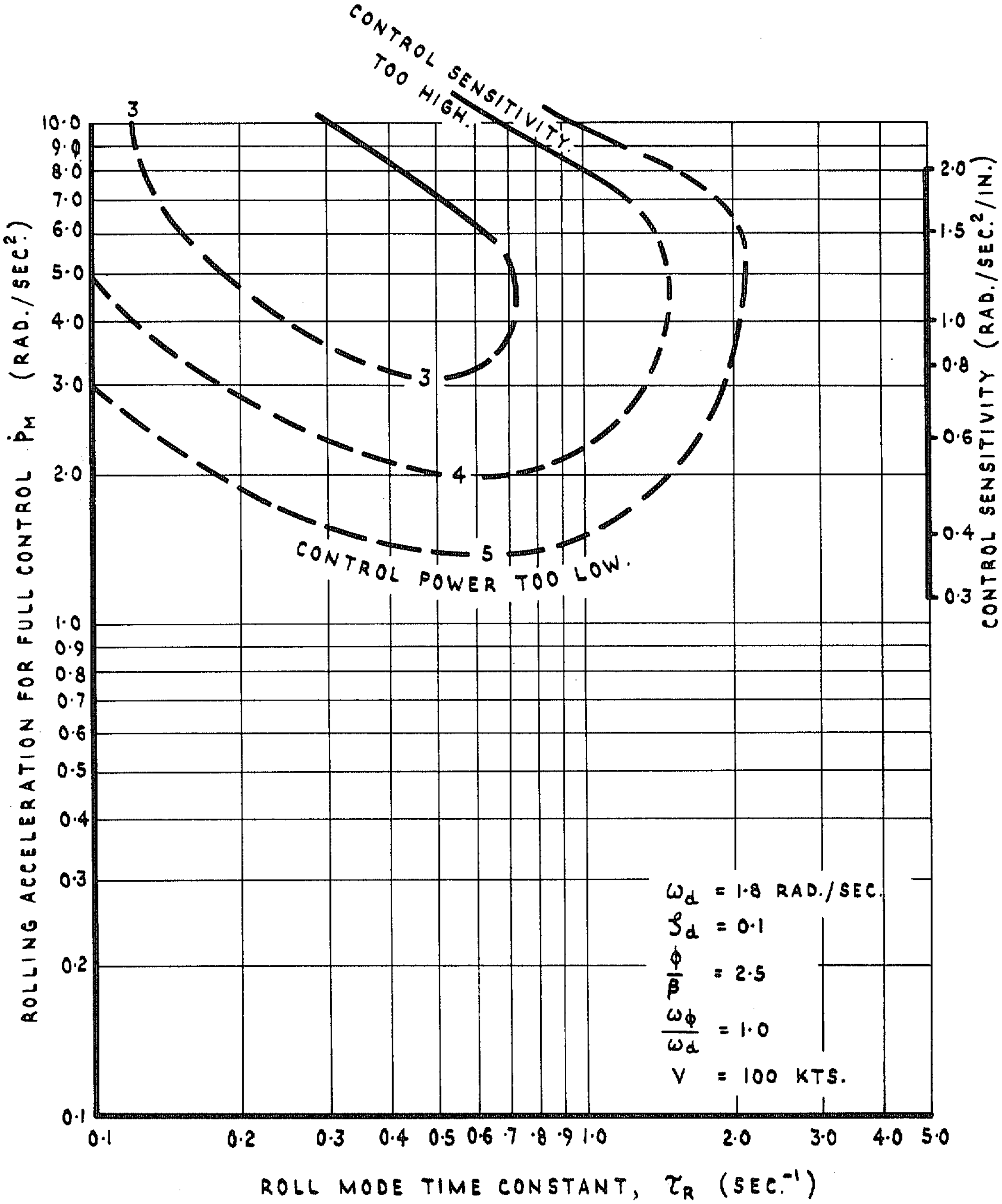


FIG. 9. Roll control requirements for carrier approach—from Reference 3.

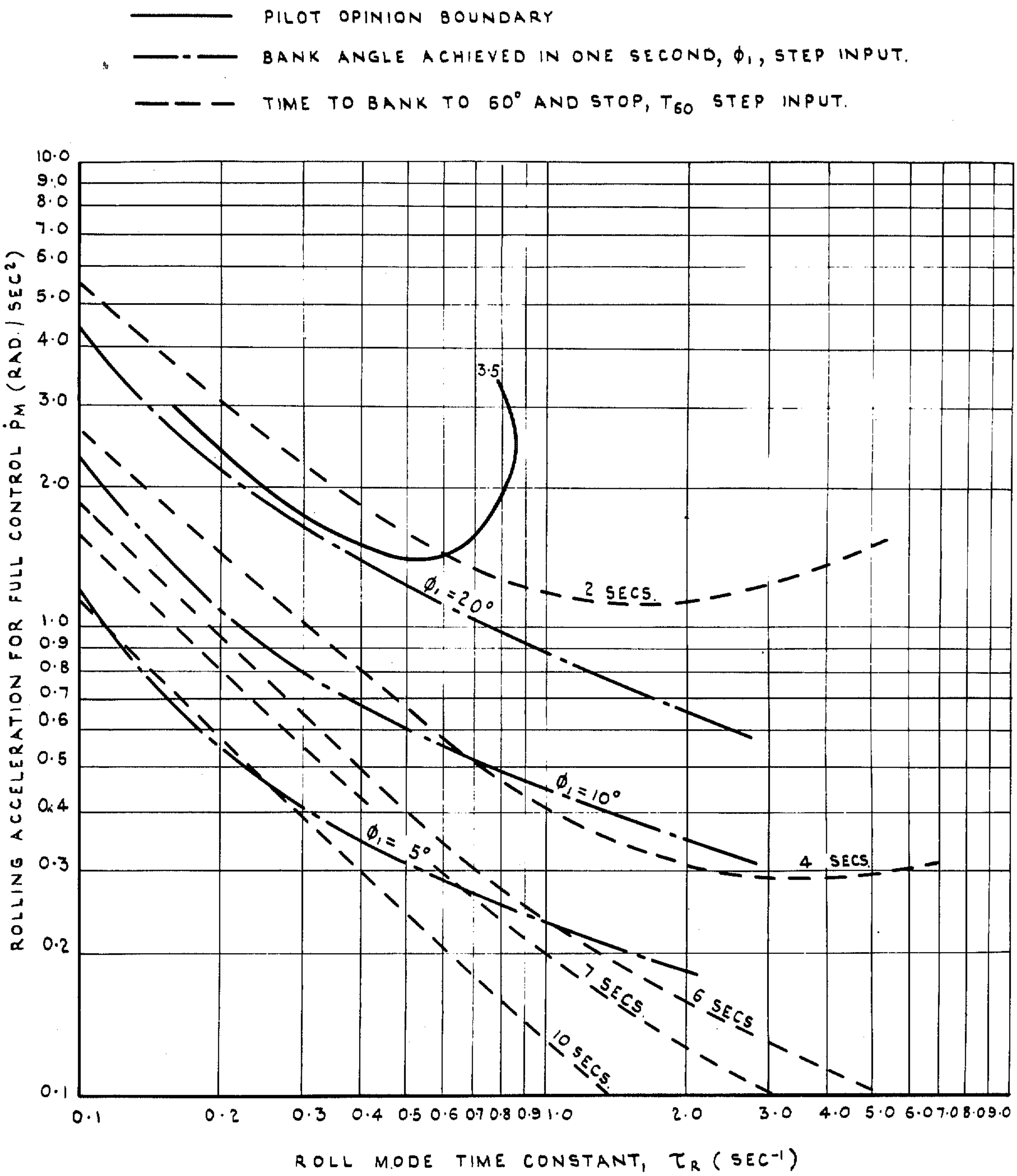


FIG. 10. Comparison of trainer/strike aircraft boundary.

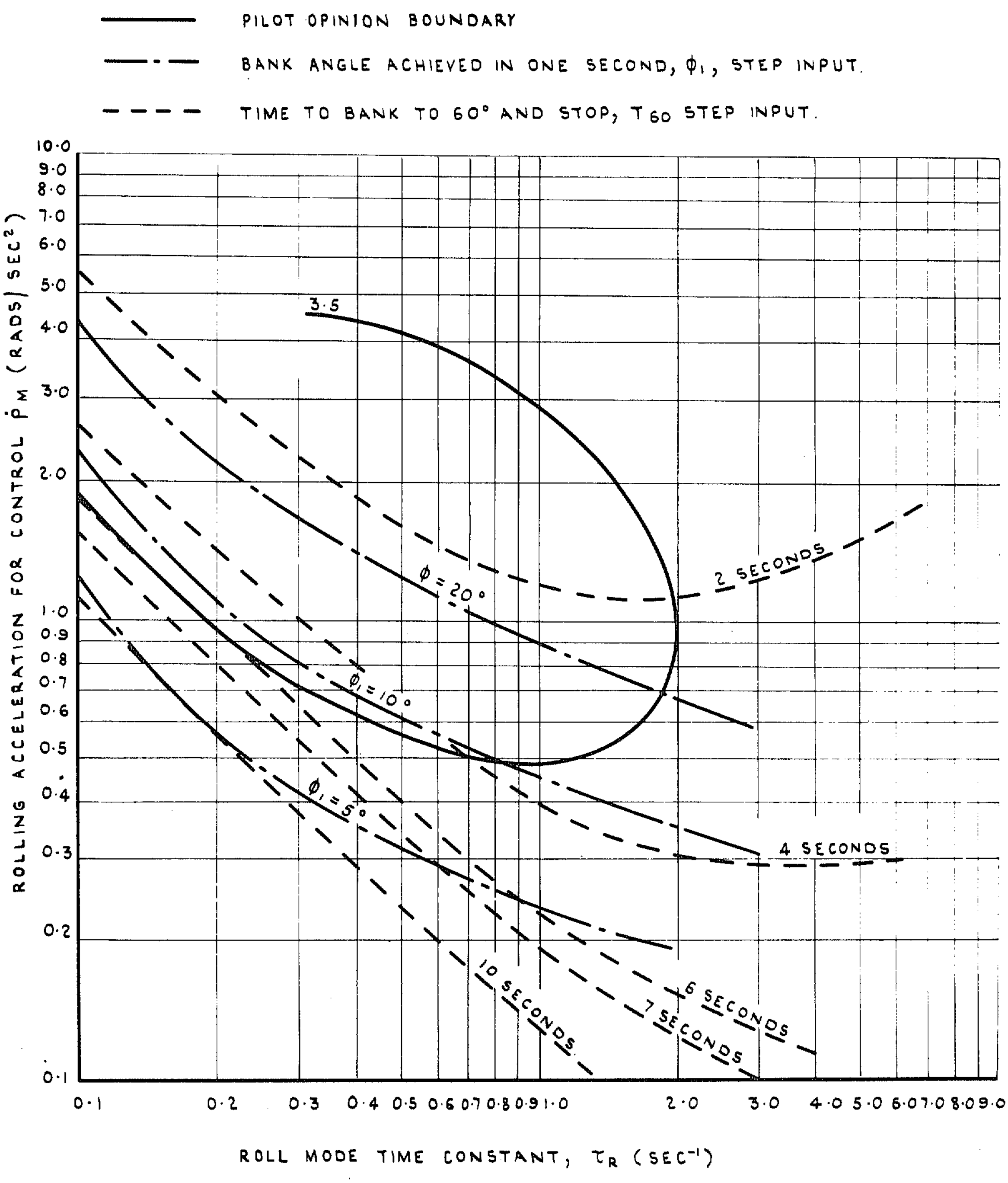


FIG. 11. Comparison of transport aircraft boundary.

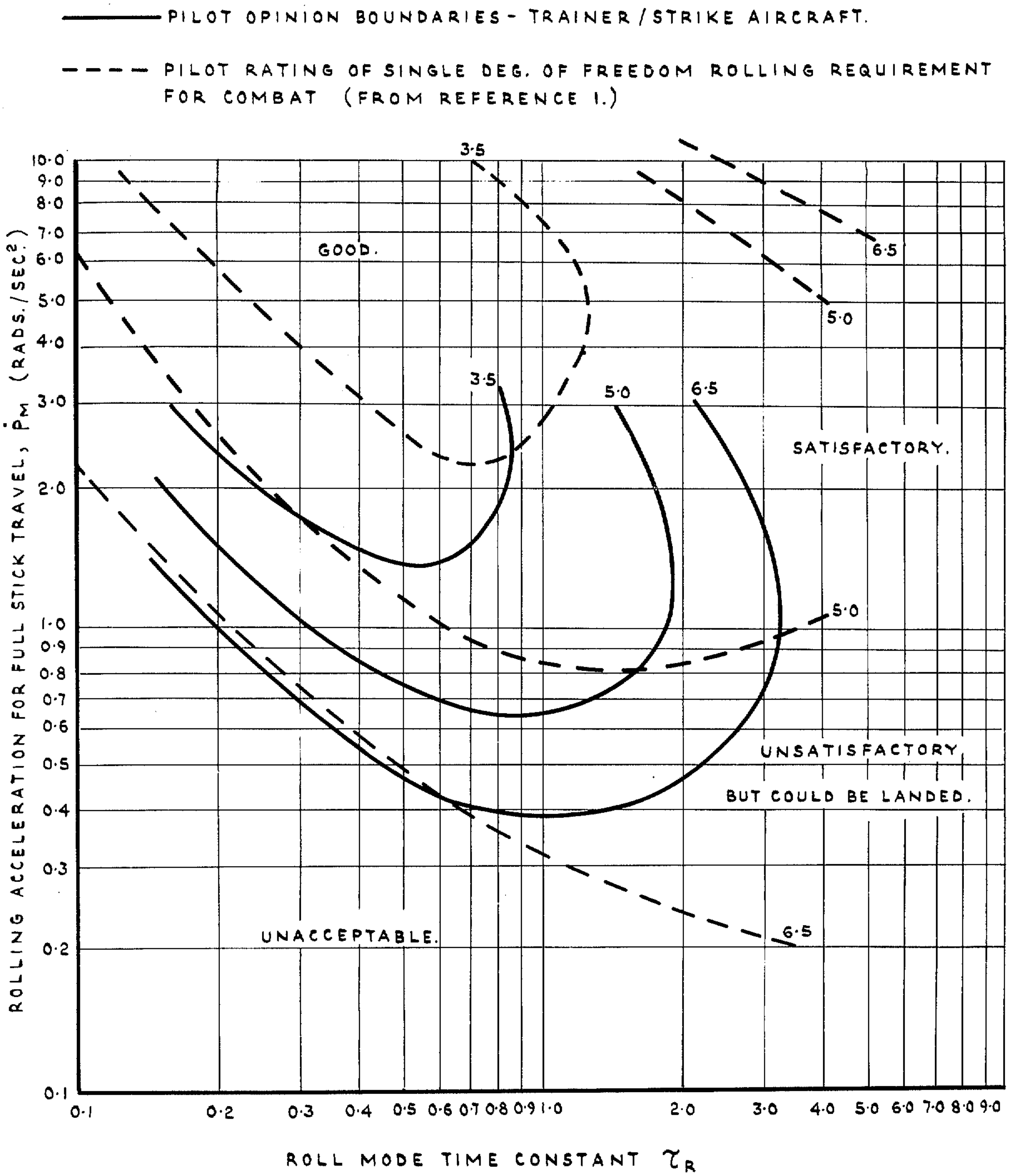


FIG. 12. Comparison of trainer/strike aircraft with combat aircraft.

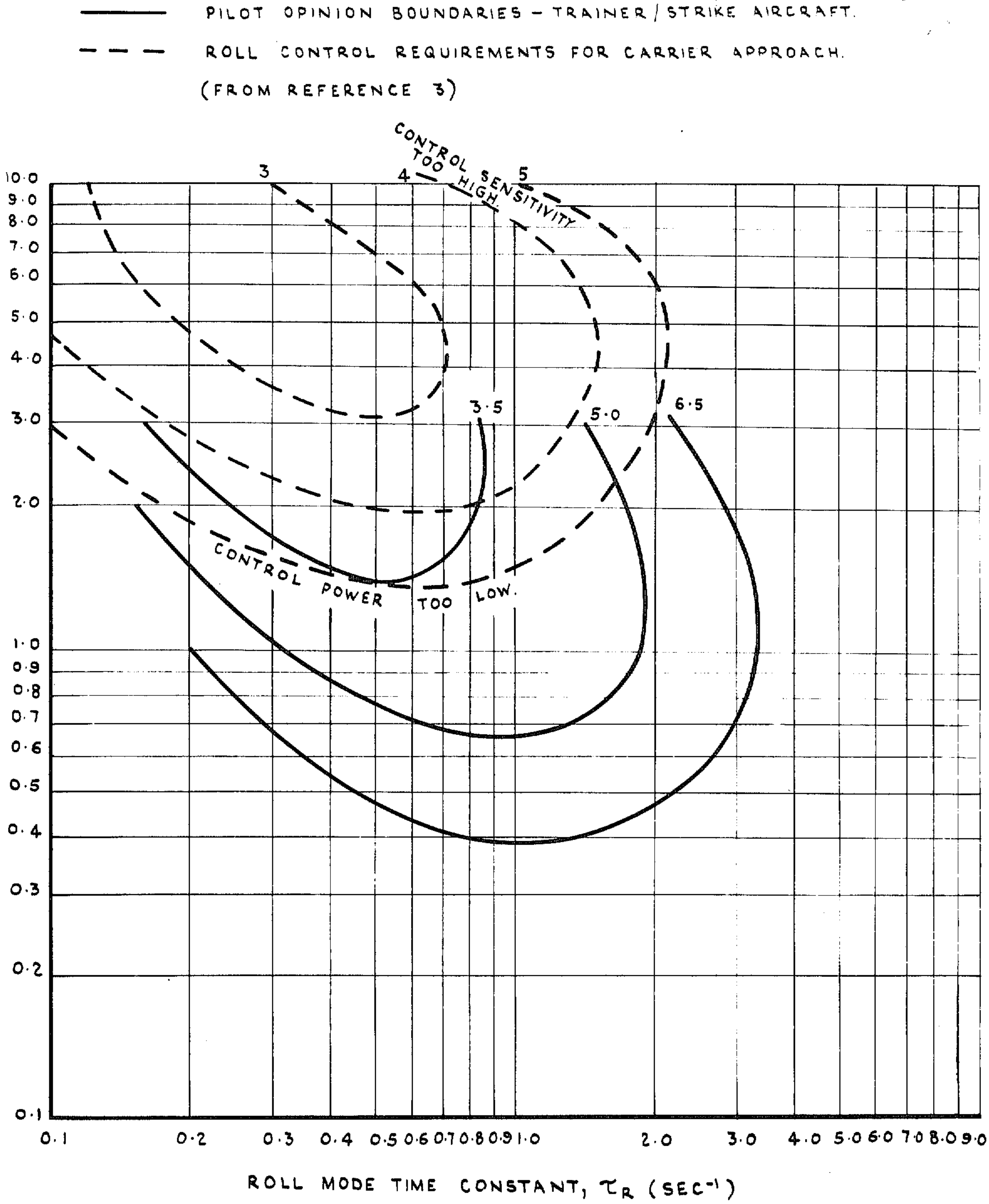


FIG. 13. Comparison of trainer/strike aircraft with aircraft on carrier approach.

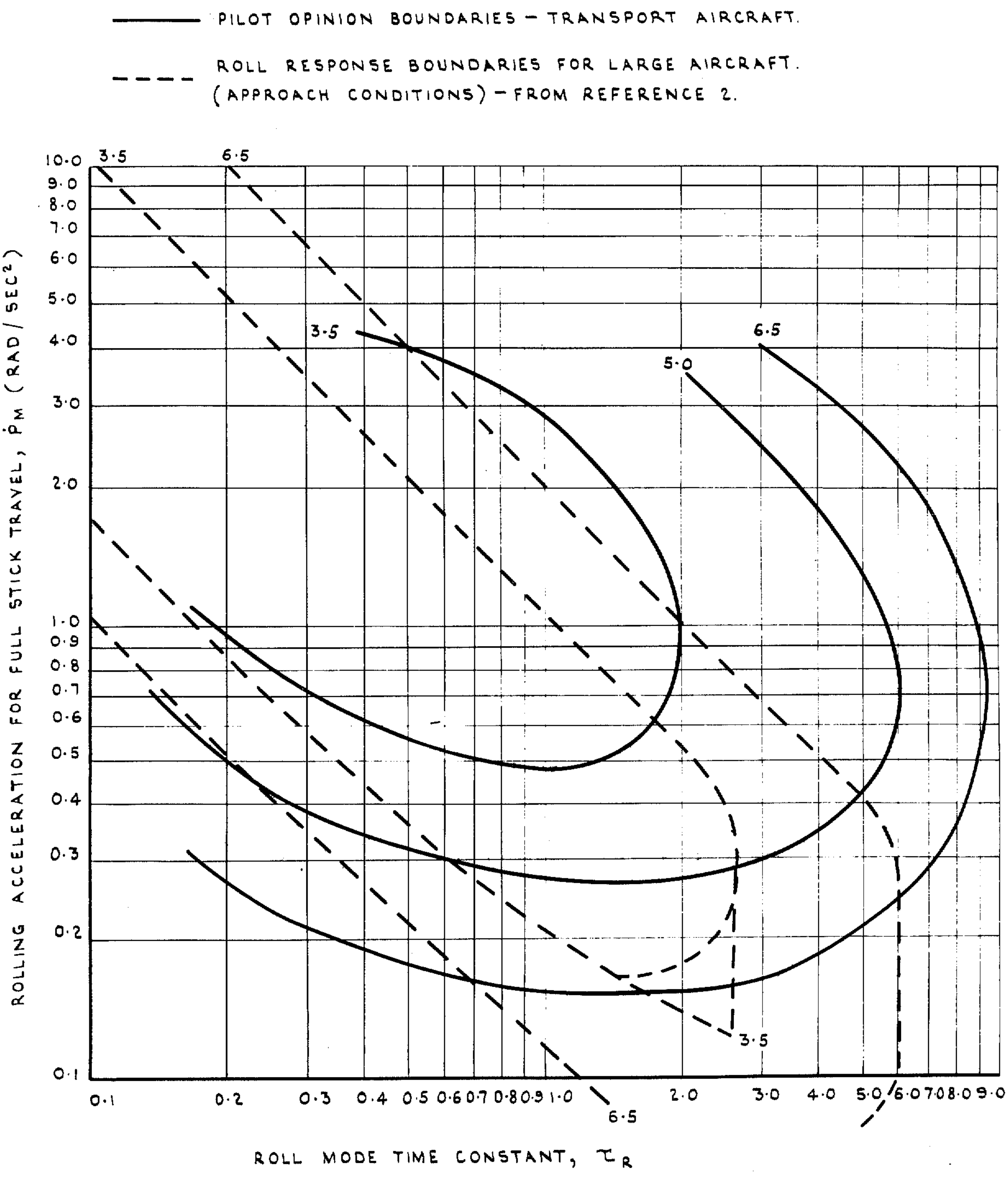


FIG. 14. Comparison of transport aircraft with large aircraft from Ref. 2.

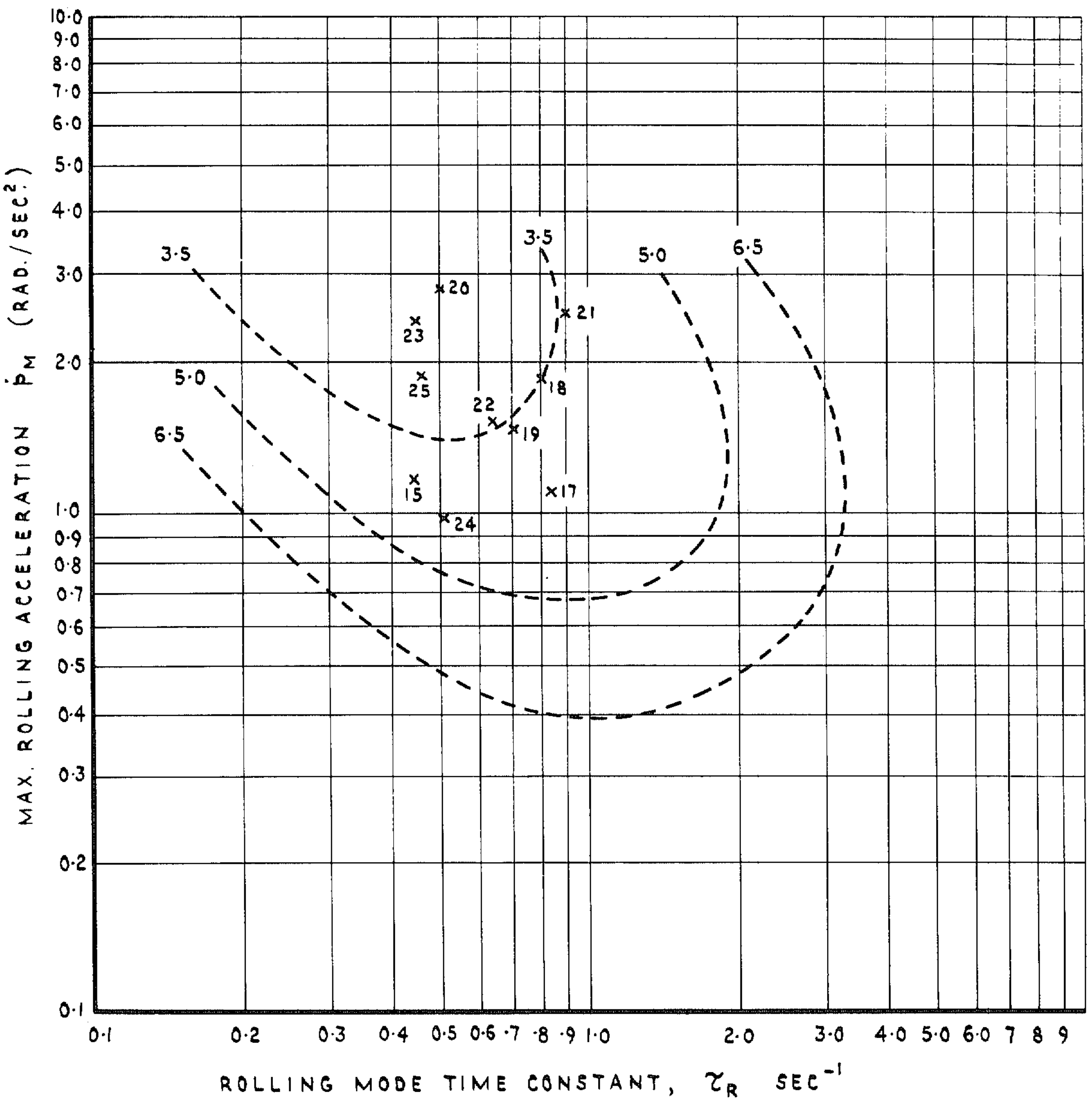


FIG. 15. Comparison of existing trainer/fighter aircraft on Table 3 with boundaries of Fig. 3.

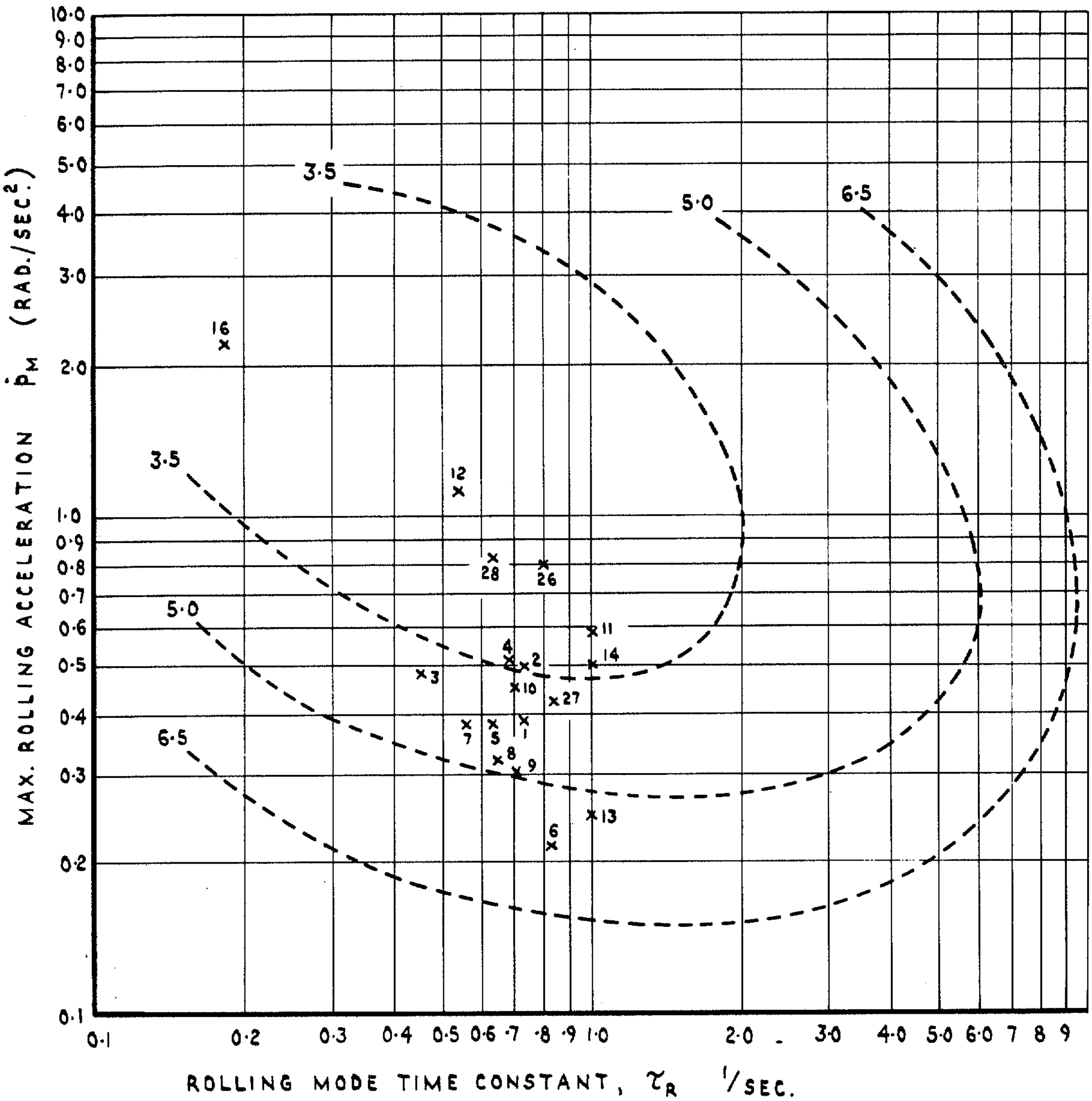


FIG. 16. Comparison of existing transport aircraft on Table 3 with boundaries of Fig. 4.

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Dd. 146916 K.5.