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MINISTRY OF DEFENCE (PROCUREMENT EXECUTIVE)

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

A Flight Simulator Investigation of the Effect of Turbulence on Rolling Requirements at Low Speed

By A. G. BARNES and N. A. PARSONS

Flight Simulation Section, British Aircraft Corporation, Ltd.

LONDON: HER MAJESTY'S STATIONERY OFFICE
1972

PRICE £1·55 NET

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Summary.

This report describes a moving base simulator investigation of the rolling requirements in turbulence of an aircraft on the landing approach. A typical swept fighter type aircraft was simulated and pilot opinions were obtained for differing values of the maximum rolling acceleration for full aileron and for differing levels of turbulence. Known aircraft were also simulated for comparison with the results of the parametric study.

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* Replaces A.R.C. 33046.

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1. Introduction.

Several factors influence the rolling requirements for aircraft at low speed. These include the control power necessary for specific manoeuvres, such as the correction of track error during landing approach, or kicking off drift during the flare. The control system itself is obviously important—power control characteristics, such as lags or rate limiting can cause control difficulties.

The landing approach task is a particularly demanding one which requires accurate positioning of the aircraft relative to the runway. Because the speed of the aircraft is low, the aerodynamic control forces are relatively low, and the provision of adequate control power can be a serious design problem. This problem is accentuated when the approach speed is reduced even more by the use of high lift devices.

One factor however, which is common to all aircraft is the properties of the air mass. Different aircraft respond to turbulence in different ways. Mathematical descriptions of turbulence exist, but doubts can be expressed about their validity in all circumstances. However, sufficient is known about turbulence and its effect on aircraft response to allow investigation of the influence on roll control requirements of turbulence.

Experimental evidence on which to determine a roll control criterion applicable to landing approach is strictly limited. Existing aircraft, undoubtedly provide a good source of data relating to satisfactory or marginally satisfactory characteristics, but data on marginally acceptable or dangerous characteristics is scarce. It is not always possible to extrapolate from existing aircraft to new aircraft projects because of large differences in inertia distribution, wing-loading or dihedral effects.

The ground based flight simulator affords a suitable means to investigate the roll control problem, and to produce the required experimental data needed to formulate rolling requirements in turbulence on the approach. Simulation allows the two major disadvantages of an in-flight investigation to be overcome: the high cost of such a venture and the difficulty of controlling the experimental conditions. Since the ability of the pilot to relate simulator flight to the actual flight environment is severely limited if the physical sensations associated with flight in turbulence are missing, a flight simulator with the best possible representation of the rolling motion of the aircraft must be used.

To obtain useful data from such an investigation it is necessary to restrict as much 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 can affect the handling in roll, if moderate coupling between modes exists. For this experiment, aileron excitation of the Dutch roll mode was made small. With the spiral and Dutch roll modes kept approximately constant, a systematic study of the effects of $\dot{p}$ max and levels of turbulence was made for a landing approach task.

The effects of two other aerodynamic derivatives, the rolling moment due to sideslip, L_β, and the rolling moment due to roll rate, L_p, were also studied.

2. Form of Investigation.

The investigation was made on the simulator, with roll motion, at Warton. Assessments of the experiment, in the form of pilot ratings, were made by eight B.A.C. and one R.A.E. (Bedford) pilots. A swept fighter type aircraft in the landing approach configuration at 120 knots was simulated.

The aircraft was assumed to have a well behaved Dutch-roll mode with stability parameters of $\omega d = 1{\cdot}5$ rad/sec and $\zeta_d = 0{\cdot}15$; just spirally stable with little or no yaw excitation with aileron. In order to keep the values ωd and ζ_d of the aircraft constant the derivatives N_β and N_β were varied as changes were made to L_β and L_p.

As previously stated, the parameters $\dot{p}$ max, the level of turbulence, the rolling moment due to sideslip L_β, and the damping in roll, L_p, were varied systematically. The values of $\dot{p}$ max were originally to be varied from 0·32 to 3·2 rad/sec^2 for full control, but were extended to cover a range 0·1 to 6·4 rad/sec^2 to include limiting boundaries of acceptable lateral control. The rudder control power was held constant throughout the experiment, at 1·5 rad/sec^2 for a pedal force of 100 lbs with full rudder. The levels of simulated turbulence were 2, 4, 6 and 8 feet/second RMS and were fed into the three lateral equations of motion, scaled in the appropriate manner. For the major part of the experiment, values of L_β of either $-6{\cdot}4$ or $-12{\cdot}8$ rad/sec^2/rad were used, with a value of L_p of $-1{\cdot}3$/sec. However, some cases were repeated with $L_p \times 2$, since the damping in roll has a major influence on roll control characteristics.

The longitudinal short period characteristics were held constant, with speed fixed, at $\omega n = 1{\cdot}5$ rad/second, $\zeta_n = 0{\cdot}7$, stick force/$g = 15$ lbs. The speed was held constant at 120 knots. This allowed the pilot to concentrate more on the lateral assessment, and also ensured that the kinematic flight path was not influenced by speed changes. However, to add realism to the simulation, turbulence was fed into the longitudinal equations of motion. This turbulence was uncorrelated to the lateral turbulence and its amplitude was varied according to the lateral turbulence level.

The longitudinal characteristics were not changed throughout the tests, even when the lateral characteristics of known aircraft were simulated.

The pilot's assessment was based on a straight-in visual approach from approximately two miles (*see* Appendix C). The pilots were asked to give a pilot rating to the lateral control characteristics on each approach. This rating was based on the new rating scale of Reference 1.

The experiment was divided into sets of cases, each set containing different values of turbulence level and maximum rolling acceleration, with fixed values of L_β and L_p. The cases were presented in a random order, and the pilots were not told which set was being assessed. Each set contained about sixteen cases, and took approximately an hour to complete.

To assist in the interpretation of the results, the variations in turbulence level and control power were also assessed relative to the stability characteristics of two aircraft with which the pilots were familiar.

3. Details of Simulation.

3.1. Representation of the Aircraft.

The small perturbation equations of motion and the associated kinematic relationships are listed in Appendix A. Numerical values of the lateral coefficients are presented in dimensional form on Table 1 for the aircraft which were simulated (Aircraft *R*, aircraft *L*, and aircraft *J*), and also for four well-known civil aircraft, each in a different weight classification.

In choosing an aircraft as a basis for the study, there is little merit in nominating a known aircraft, if the intended changes to the derivatives during the investigation make it unrecognisable to the pilots in most cases. Significant changes in the derivatives L_ξ, N_ξ, L_β, and L_p were made during these tests, and so it was preferable to refer to the simulated aircraft as the research aircraft, or aircraft *R*, even though the derivatives in the first column of Table 1 are close to those of an existing fighter aircraft. Aircraft *L* and *J* are fighter aircraft also familiar to the pilots taking part in the study. They thus provide a good basis for comparison.

Listed on Table 1 are the handling qualities parameters associated with the derivatives for each aircraft. These parameters are exact solutions, obtained from a digital computer programme.

The equations of motion in Appendix A were solved on a PACE 231R analogue computer, which was coupled to a moving base cockpit. The cockpit contains conventional stick and rudder pedals. The feel is produced by a hydraulic force-feedback feel system which while having at the time of the investigation, slight imperfections in pitch, operated smoothly in the aileron channel. Stick force for full aileron control was held constant throughout the investigation at 10 lbs; the maximum stick travel at the pilot's grip was ±3 inches.

3.2. Pilot's Display.

The pilot's display consisted of a directly viewed closed circuit television display, giving the pilot's view of a runway and surrounding countryside. The 625 line TV picture, in monochrome, comes from a GPS/Redifon visual flight attachment (VFA). The model, on a continuous belt, is to a scale of 1:1000, and an area of ground approximately 6 miles by 2 miles may be overflown. The maximum visibility, determined by the model scale, is $2\frac{1}{2}$ miles, and the height range is 10 to 1,000 feet. Bank angle limits are ±90 degrees, and heading limits are ±50 degrees.

Following one pilot's comments on the display, the picture was collimated, so that the image subtended true angles at the pilot's eye, by means of a Fresnel lens. (Before collimation, the picture subjected approximately half true angles.) Several cases were repeated to see if collimation influenced the pilot ratings.

At the time of the investigation, the primary head-down flight instruments were not operative, and use was made of a CRT display. The CRT presented the symbology of the TSR2 head-up display, and gave the pilot height, bank and pitch information. In addition the director dot was used to display, (i) as an azimuth error, the sideslip angle β, and (ii) as an elevation error, the rate of climb or descent, $\dot{h}$. (*See* Appendix C.)

3.3. Motion System.

The cockpit has motion in roll of particularly high fidelity obtained by the use of a high resolution drive system, with a considerable power margin over that normally provided on such devices. Figure 1 shows the frequency response of the moving cockpit with and without the bank washout filter.

The signals used to drive the cockpit were ϕ, the bank angle, and ay, the lateral acceleration. A washout filter was added to the ϕ signal and a small time lag to the ay signal. The drive signal in its final form was:

$$\phi_{\text{COCKPIT}} = k_1 \frac{2s}{1+2s} \cdot \phi_{\text{AIRCRAFT}} + \frac{k_2}{1+0{\cdot}5s} ay .$$

$$\text{where } k_1 = 0{\cdot}33$$

$$\text{and} \quad k_2 = 20^\circ/g .$$

The maximum value of ϕ_{COCKPIT} is ±30 degrees. These gains and filters are very similar to those used for landing approach simulations at RAE, Bedford. (At RAE a value of $k_1 = 0{\cdot}46$ was used.)

They were evolved at Bedford during tests to optimise the motion drive signals. The pilot preference for a lower k_1 at Warton is probably explained by the fact that the RAE simulation related to a transport aircraft.

4. Turbulence and Task.

4.1. Turbulence.

The correct representation of the effects of turbulence during landing approach presents several difficulties. The first difficulty is that the frequency content is a function of height above ground. The second, that if the power spectrum of turbulence has significant low frequency content, the most severe gusts will occur infrequently, and, therefore, on some of the runs the turbulence will embarrass the pilot and on others it will not, with the same nominal turbulence input.

These difficulties were overcome by the use of fixed levels of turbulence—fully described in Appendix B —throughout the experiment. A high by pass filter was used to avoid the second of the above difficulties, and the levels of turbulence were set at r.m.s. values of 2, 4, 6 and 8 ft/second. This represents a range of from light to severe turbulence and this meant that the pilot had to make from small to very large corrective inputs in order to perform the task. Also, a non-linearity (*see* Appendix B) was introduced into the turbulence simulation which produced occasional large gusts. They occurred about once every 30 seconds and generally added to the realism of the turbulence.

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.

4.2. Pilot's Task.

The investigation should show that turbulence is often the overriding consideration. For this to be observed, the task without turbulence inputs must not be so difficult as to dominate the pilot's choice of rating. In a previous investigation (Reference 2) it was found that the choice of task—in this case, the size of a lateral side-step manoeuvre, has as much influence on pilot rating as the rolling dynamics of the aircraft. The task without turbulence was therefore chosen as the simplest possible in a realistic situation. The pilots were asked to fly a straight-in approach from 1,000 feet on roughly a 3 degree glideslope judged visually on the visual display and the head-down electronic display. For some of the later tests, raw ILS on the head-down display, and a full set of flight instruments were included. Pilots were asked to minimise the bank angle deviation during the approach. The use of rudder was allowed if required. The approach was to be terminated by overshooting during the flare, since no touchdown or ground effects were simulated. Flying down the runway at minimum height was allowed if this assisted in the assessment. The assessment of the task was made on the ease of flying the approach and on judging whether a successful landing could be made or not. The pilot briefing sheet is presented as Appendix C.

5. Results and Pilot's Comments.

5.1. Results.

Eight BAC pilots and one RAE pilot took part in the assessment of handling qualities. The cases were given to the pilots in sets of 16. Although the pilot was told the flight condition (i.e. the parameters which were not varied during the assessments), the values of rolling acceleration and turbulence level were given to the pilot in a random order, without prior knowledge. The first six ratings from any pilot new to the simulation were discarded, since the likelihood of contamination by learning is high. To complete a set of sixteen cases took approximately an hour. Although pilots were permitted to do several landing approaches in any configuration, usually the pilot rating was given on the basis of one approach.

All the pilot ratings which were obtained are presented on Tables 2-5. Tables 2, 3 and 4 are the results for aircraft R; Table 5 shows the results for aircraft J and L. The tables contain approximately 500 pilot ratings. In general, the individual results show moderate scatter between pilots, and less scatter for repeat cases with the same pilot. It must be remembered that since the turbulence is itself pseudo-random (the chance of hitting a similar large gust at the same point of each approach is very unlikely) a degree of scatter will inevitably appear in the pilot rating's, additional to that normally encountered in this type of study.

The presentation of results will be based on the mean ratings. It is debatable whether an absolute level of pilot acceptance can be obtained from arithmetic means, although plausible trends must emerge. The use of mean rating is not a departure from previous practice however, and will only mislead the unwary. It provides perhaps the only convenient way of absorbing 'extreme' results (usually stemming from extraneous factors).

From the mean ratings on Tables 2-5, Figures 2-6 have been drawn. These are plots of pilot rating versus $\dot{p}_{\mathrm{MAX}}$ and turbulence level. Although the influence of each parameter on pilot rating may be seen on these figures their main purpose is to allow the construction to be made of the iso-opinion plots seen on Figures 7-11. The values of $\dot{p}_{MAX}$ and turbulence level for pilot ratings of 3·5, 5 and 6·5 on Figures 2-6 are used. By presenting the data in this manner, an easy comparison can be made of the influence of $\dot{p}_{MAX}$ and turbulence level and between the different configurations which were flown.

5.2. Pilot's comments on the Simulation.

The BAC pilots accepted the limitations of the simulation more readily than did the pilot from RAE. This is understandable, since the former are more familiar with the simulator, and had more opportunities to overcome any difficulties which they may have experienced when first given the overall control task. The pilots' comments are summarised below:

5.2.1. *The Visual Display.* The only adverse comment came from the RAE pilot, and concerned the use of a directly viewed monitor. He considered that because the outside world was not presented in true angles, height judgement was made more difficult. In consequence, his assessment of the lateral control was influenced by the associated difficulties in pitch control. This criticism was removed by introducing a Fresnel collimating lens between the display CRT and the pilot's eye. Some cases were repeated with another pilot, to see if a collimated display would influence the general trend of the ratings.

5.2.2. *Motion system.* The motion system was well received, both with respect to the quality of motion, and the signals with which it was driven. This was the first serious use of the new motion system at Warton. Two pilots, when asked what they thought of the motion system after their first set of cases, said that they were not consciously aware that the motion system was operating. This comment is a greater compliment than appears at first glance.

5.2.3. *Feel system.* The pitch feel was marred by a small amount of backlash (0·25 inches at the top of the stick); otherwise it was good. The aileron feel was also good, although with two rapid full deflection reversals it was possible to 'beat' the jack, with a consequent increase in stick force if the rapid movements continued. (The records of stick activity did not show any evidence of jack rate limiting during the assessments, even for the lowest control power cases.)

5.2.4. *Flight instruments.* The use of an electronic tube to present head-down instrument information was not entirely successful. One pilot severely criticised the presentation of vertical speed and sideslip as azimuth and elevation errors on the director dot. The response of the director dot to lateral turbulence, since it was not slugged (as is a slip ball), gave a misleading impression of sideslip. Towards the end of the programme, the important flight cases were re-assessed with the conventional flight instruments working, and the flight director giving raw ILS information.

5.2.5. *Turbulence.* Some pilots thought that the motion cues due to turbulence had softer edges than in real flight. Perhaps the explanation here lies in the fact that no structural modes were simulated. It is certainly true that the motions felt by either pilots or passengers in a transport aircraft in turbulence are predominantly the structural modes.

The fact that attenuation of turbulence as a function of height from the ground was not simulated was also queried by pilots. To do so would however make the presentation of results in a quantitative way very difficult, since r.m.s. turbulence level, which is one of the parameters varied, would no longer be independent of the other variables.

6. Discussion of Results.

Before discussing the results in detail, it is worthwhile to try to relate the quoted turbulence levels into a more familiar form. It is not unreasonable to assume that peak gusts are four times the r.m.s. value, and that peak gusts are about 50 per cent greater than the steady wind conditions. We could then say that 2 ft/sec r.m.s. gusts might be met in wind conditions of 10 knots, gusting to 15 knots, and 8 ft/sec r.m.s. gusts equate to wind conditions of 40 knots, gusting to 60 knots. The '35 knot crosswind landing', which often appears as a design requirement, is then represented by 7 ft/sec r.m.s. on our turbulence scale.

6.1. The Effect of Turbulence Level.

Figure 7, which relates to the higher value of L_β and the lower value of L_p, clearly shows that as the turbulence level is varied, so do the limits on satisfactory and acceptable values of the rolling acceleration for full control. As might be expected, the minimum acceptable value of $\dot{p}_M$ increases as the turbulence level increases. For an aircraft with these stability characteristics, if the turbulence increases from 2 ft/second r.m.s. to 8 ft/second r.m.s., the control power must be increased by a factor of between 2·5 and 3. This result is not unexpected, since as the turbulence level increases, so the pilot must increase his control activity. He then prefers to have more control power.

It will also be observed on Figure 7 that the maximum acceptable control power decreases as the turbulence level increases. The basis of the pilot ratings which produce the maximum acceptable boundary is the over-sensitive response to control inputs. Again it is logical to suppose that this oversensitivity is more apparent in turbulence, since more control action is called for.

The general pattern of Figure 7 is repeated in Figures 8, 9, 10 and 11.

6.2. The Effect of L_β.

The most striking fact to emerge from a comparison of Figures 7 and 8 is that if L_β is halved, the minimum control powers for ratings of 3·5, 5 and 6·5 at low levels of turbulence are also halved. This suggests that a strong correlation exists between the effects on handling qualities of L_β and $\dot{p}_M$, in conditions where the most of the excitation comes from the pilot. With such inputs, Dutch roll excitation is low, because we chose to use an optimum $\omega\phi/\omega d$. As the turbulence level increases, however, the control power for the same rating need not be increased as rapidly for the high L_β cases as for the low L_β cases.

The explanation may be as follows. The turbulence excites the Dutch roll oscillation. For high L_β, the oscillation is characterised by rolling rather than yawning motions, and the use of aileron will suppress the mode. For low L_β, the yawing component is more apparent, and the ailerons are a less effective control. Hence an increase in $\dot{p}_M$ will not bring the same increase in pilot rating as in the high L_β case.

Dutch roll excitation will also explain the third characteristic to emerge from a comparison of Figures 7 and 8. It will be seen that the optimum value of $\dot{p}_M$ is significantly less for the lower value of L_β.

If the above explanation for the ineffectiveness of increased roll control power with increasing turbulence at low L_β is true, then we may use the same argument to explain why the maximum satisfactory control power falls off more steeply on Figure 8. The high control power is not so effective in suppressing turbulence induced motions at low L_β as at high L_β. The optimum $\dot{p}_M$ may be considered as the intersection of the minimum satisfactory boundary and the maximum satisfactory boundary. The slope of each boundary and its origin (a values of $\dot{p}_M$ for zero turbulence) will determine this intersection.

It is probably a reasonable extrapolation to say that if $-L_\beta$ is reduced below 6·4, the rolling power which must be provided is likely to be set by factors other than the roll control in turbulence—for example, by manoeuvring requirements. On the other hand, it cannot be assumed that as $-L_\beta$ is increased, all that is needed is to increase the available roll control power. For values of $-L_\beta$ greatly in excess of 12·8, roll control oversensitivity will rapidly limit the benefit to be obtained in this way. Large bank angles are easily induced by turbulence; if the control power is low, the magnitude cannot be held to an acceptable level, and if the control power is high, overcontrolling is induced. Figure 11 showing the pilot rating boundaries for an aircraft with high L_β, illustrates this point.

6.3. The Effect of L_p.

Each pilot rating is based on several factors, all of which influence the pilot's ability to control the dynamic and kinematic modes of the aircraft. Previous work has shown the importance of the damping in roll, L_p, on lateral handling qualities. It might be anticipated, therefore, that in turbulence also, L_p is a critical parameter. That this is so may be seen in the comparison of Figures 8 and 9. When the damping in roll is doubled, much higher levels of turbulence are acceptable for a given level of roll control power.

Of particular interest is the fact that the minimum values of $\dot{p}_M$ for the 3·5 and the 5·0 boundaries on Figures 8 and 9 are the same, for a turbulence level of 2 ft/second r.m.s.; it is only for higher levels of turbulence that the full benefit of increased roll damping is realised.

In still air or mild turbulence, previous research on the $\dot{p}_M \, v \, \tau_R$ requirements has shown that as τ_R is decreased (L_p increased) so the minimum satisfactory value of $\dot{p}_M$ must increase, to maintain approximately the same steady rate of roll (Figure 13 illustrates this characteristic). This is quite understandable, if the pilot rating is based on the ability to perform a given task, in other words, to *manoeuvre* the aircraft. However, in turbulence, the rating may be based on the pilot's ability to stabilise the aircraft. In this case additional damping in roll is obviously desirable, since it helps to minimise the bank angle excursions due to turbulence, and so reduces the need for aileron control inputs. This is perhaps the most practical result to come out of this study—a roll rate autostabiliser is a great help in turbulence for aircraft with moderate to high L_β. In other words, if L_β is high, the control power requirements may be reduced by a roll autostabiliser.

6.4. Known Aircraft.

The results for two aircraft familiar to the pilots are shown on Figures 10 and 11. As might be expected, these results, although similar in character to previous figures, cannot be easily used to extrapolate the trends discussed above. Differences in stability and control parameters other than L_β, L_p, and $\dot{p}_M$ make such extrapolations invalid. They do however, confirm earlier suspicions.

For example, aircraft *L*, Figure 10, may be compared with aircraft *R*, Figure 7. Although aircraft *L* has a slightly higher L_β, and a lower $\omega\phi/\omega d$, the principal difference between the two aircraft is the Dutch roll frequency ω_d. This in turn means that ϕ/β for aircraft *L* is lower than ϕ/β for aircraft *R*, even though the L_βs are comparable. In consequence, for zero turbulence, aircraft *L* is rated more favourably than aircraft *R*. However, as the turbulence level is increased, and the pilot becomes aware of L_β because of the external disturbances, so the preference is reversed, and aircraft *R*, with the lower L_β receives slightly better ratings. It is also clear from Figure 10 that aileron power is not the limiting factor in a gusty crosswind landing. This confirms flight experience.

Figure 11, aircraft *J* does not easily compare with previous figures because of the high L_β. For low turbulence levels, the required minimum control powers for ratings of 3·5 and 5 are not too dis-similar from those of Figures 7 and 10 ($L_\beta = -12$ and -16). As the turbulence level increases, so the high L_β becomes more apparent to the pilot through the associated bank disturbances, with a consequent deterioration of pilot rating. The maximum crosswind for satisfactory handling qualities progressively decreases with increasing L_β in Figures 7, 10 and 11. Rather surprisingly, the lowest value of L_β (Fig. 8) does not conform to this pattern; the maximum crosswind for $L_\beta = -6{\cdot}4$ is less than for $L_\beta = -12{\cdot}8$ (Fig. 7). Although the excitation of roll by turbulence will be less for $L_\beta = -6{\cdot}4$, some other factor—perhaps the inability to control the yawing oscillations as discussed in Section 6.2—is causing a reversal in the trend of pilot opinion.

6.5. Effects of Collimation and Motion.

The small number of ratings obtained for cases with and without a collimated display, and the scatter to be expected because of the pseudo-random nature of the turbulence input, made it impossible to observe any influence on ratings due to collimation and so no distinction is made in the tables of pilot ratings. Certainly, there is no consistent trend to either better or worse ratings due to collimation, and the trace records taken of each approach do not reveal any change in control technique.

The effect of the cockpit motion system is slightly less obscure. The runs that were repeated with no input to the motion system are compared with the same pilot's results with motion in Table 2. Again, scatter confuses the situation, but there does seem to be a tendency to get a better rating without the motion system than with it. A study of the recorded aileron activity and aircraft response sheds light on the matter (Figure 12). The character of the records with and without motion differ greatly. With motion, both the amplitude and frequency of the pilot's stick inputs are greater, with a consequent improvement in the bank angle and sideslip excursions. The slightly poorer pilot rating with motion may reflect the greater work-load of the pilot, or may be due to the physical motions induced by turbulence, only felt by the pilot with "motion on".

6.6. General remarks.

An investigation of this type has many pitfalls—the description of the turbulence, the choice of aircraft, the need for a large number of pilot ratings, and so on. In fact, a flight investigation similar to this one is almost certainly excluded by the sheer magnitude of the task to get a sufficient number of landings, with a sufficient number of pilots, in the right atmospheric conditions. The emphasis here has been to get a reasonable number of ratings from different pilots at a given configuration, in order to be able to construct an iso-opinion plot. In consequence, only two or three configurations have been examined. Hence, the effects on handling qualities of the aerodynamic derivatives can only be seen in a very coarse sense, and many queries are unanswered. Confirmation of the beneficial effect of L_p at high L_β is desirable. Of even more significance would be a further investigation of the effects of turbulence at low L_β. It is likely that N_β will become a predominant factor, since this then represents the forcing function. It is possible, too, that the time to damp the Dutch roll, or $2_{\zeta_n\omega_n}$, is more significant than the relative damping ratio ζ_n. It is difficult to predict how the optimum $\dot{p}_M$ and L_p will vary with turbulence at low L_β.

7. Comparison with Other Results.

It has been difficult to find other data from experiments to isolate the effect of turbulence on lateral handling qualities. However, the following discussion highlights three previous studies which allow a limited comparison with the results of this investigation.

7.1. Comparison with Reference 2.

Pilot opinion boundaries as functions of $\dot{p}_M$ and τ_R are presented in Reference 2, for both a fighter/trainer aircraft, and for a transport aircraft. One conclusion of this study is that these boundaries are more dependent on the task than on the size of the aircraft. The task most like that of the present study is the one used in Reference 2 to establish the boundaries shown on Figure 13. These boundaries relate to a transport aircraft (VC.10), in light-to-moderate turbulence (3 ft/second r.m.s.). The difference in aerodynamic derivatives between the VC.10 and aircraft R, particularly L_β, will influence the pilot ratings. The allowance for L_β can be found by extrapolating the data of Figures 7 and 8 at a 3 ft/second turbulence level: this is shown on Figure 14. Also marked on Figure 14 are the values of $\dot{p}_M$ from Figure 13 for pilot ratings of 3·5, 5, and 6·5, with $\tau_R = 0{\cdot}71$ ($L_p = -1{\cdot}3$).

There is a good tie-up for the 5 and 6·5 boundaries. The 3·5 comparison is less impressive, probably due to the rather arbitrary position of the 3·5 boundary of Figure 13. Reference 2 points out that the 3·5 'peninsular' is very flat, for ratings better than 4, and so the 3·5 boundary cannot be positioned accurately.

7.2. Comparison with Reference 3.

Reference 3 describes a most comprehensive investigation of the lateral/directional flying qualities, made on a 'Navion' variable stability aircraft. The task was a carrier approach in moderate turbulence—perhaps comparable to our 4 ft/second r.m.s. level. Two figures have been extracted from this report and are seen as Figures 15 and 16.

Figure 15 shows iso-opinion boundaries as a function of ω_d and L_β. A direct comparison with our results is not possible, because of the high damping in roll ($\tau_R = {\cdot}25$), but the figure does give a useful insight into the reasons why pilots gave these boundaries. The figure confirms our suspicion that high values of L_β are satisfactory if L_p is also high. It also substantiates the point made in Section 6.2, that for low L_β (C and D), the pilots object to the predominantly yawing oscillation. It might be concluded from this figure that a large aircraft like the VC.10 ($L_\beta = -2{\cdot}5$, $\omega_d = 0{\cdot}96$) has poor handling qualities (rating 4·5) on the approach in moderate turbulence. However, it could equally be argued that here is an intrusion of task—the VC.10 is not called on to do carrier landings.

Figure 16 allows a closer comparison with the results of this experiment. The ratings for aircraft R (3 cases), aircraft L, and aircraft J, were obtained from Figures 2–6, using the optimum $\dot{p}_M$ and a turbulence level of 4 feet/second r.m.s. Although there are small differences in other parameters (ω_d, N_p), the tie up between this experiment and Reference 3 is very good. The implication is that at high L_β, the roll response in turbulence has been the basis of the rating in the Princeton study, since we have clearly established that turbulence level and rating are correlated.

7.3. Relationship to Other Aircraft.

Theoretical aspects of the rolling response in turbulence of various aircraft are discussed in Reference 4. Particular attention is given to the Hunter aircraft. Table 1 contains the assumed derivatives at 150 knots their similarity to aircraft R with $L_\beta = -12{\cdot}8$ should be noted.

Reference 4 considers the effect on roll response in turbulence of scaling up the size of an aircraft like the Hunter, without changing the shape, wing loading, or mass distribution. It is clear that such an aircraft is less responsive to turbulence (only the dimensional derivatives L_β, N_β, L_ξ and N_ξ are changed) but that less control power is available. Zbrozek concludes that these effects are more or less self-cancelling. From our study, it seems that scaling down the size (say a half scale Hunter) can result in a less satisfactory aircraft in turbulence.

A glance at Table 1 shows that small civil aircraft, such as the Dove or Navion, have rather high values of L_β, even though the roll to yaw ratio is less than corresponding values for the swept wing aircraft listed. In turbulence, L_β and N_β are themselves of more significance than the Dutch roll parameters, since they represent the forcing function. Since aircraft in this class are often "turbulence limited"—either by inadequate control power, or by ride comfort, an extension to the work described here is likely to have practical significance in the design of such aircraft.

8. Conclusions.

8.1. Flight simulation tests, using a cockpit which gave the pilot a good representation of rolling motions, have established certain relationships between the level of turbulence and the lateral stability and control characteristics of a fighter aircraft during landing approach. The results, in terms of pilot ratings, are subject to more scatter than often is achieved in tests of this type due to the random nature of the turbulence inputs. Nevertheless, distinct patterns appear.

8.2. Turbulence level, in terms of r.m.s. gust level, and the rolling acceleration for full aileron, $\dot{p}_M$ were the main variables in the experiment. It is clear that as the turbulence level is increased, so the requirements on roll control power become more severe. Several pilot rating boundaries between satisfactory/acceptable and acceptable/unsatisfactory have been established as functions of $\dot{p}_M$ and turbulence level, for fixed values of L_β and L_p.

8.3. An attempt has also been made to determine the effect of changes in the derivatives L_β and L_p on the pilot rating boundaries. As L_β is increased, so the minimum satisfactory control power is increased at a given level of turbulence. It would seem, however, that this effect can be easily offset by increasing the damping in roll L_p. Thus for an aircraft with a high L_β, a roll autostabiliser is likely to be beneficial in turbulence.

8.4. Two known aircraft were also simulated, to allow the results of the parametric study to be read across more easily to the real life situation. These results and pilot comment on the known aircraft do help to substantiate the results of the parametric study. There is also a good correlation between the results of this investigation at low turbulence levels, and the earlier work at Warton on roll control requirements, in which it was found that task is a critical parameter.

8.5. The requirement for satisfactory rolling characteristics cannot be simply stated. They are a function of many variables in addition to the ones considered in this study. Depending on the circumstances, one or several of these variables will determine the pilot's opinion of the handling qualities. Although this work goes some way to quantify the influence of turbulence, it is mainly applicable to fighter aircraft. Further investigation of the low L_β cases is recommended, since many transport aircraft come into this category. There is also a need to find under what circumstances the dimensional aerodynamic derivatives (L_β, L_p, N_β, etc.) correlate best with pilot rating, and under what circumstances the handling qualities parameters (ϕ/β, ζ_n, ω_ϕ/ω_d, etc.) correlate with pilot opinion.

LIST OF SYMBOLS

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	Tail arm
L_β	Rolling moment due to side-slip 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_ζ	Rolling moment due to rudder derivative
m	Mass of aircraft
M_α	Pitching moment due to incidence derivative
M_q	Pitching moment due to pitch-rate derivative
M_η	Pitching moment due to elevator derivative
$M_{\dot{\alpha}}$	Pitching moment due to change of incidence derivative
N_β	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
R	Resistance
s	Laplace operator
V	Aircraft velocity
Y_β	Side force due to side velocity derivative

LIST OF SYMBOLS—*continued*

Z_α	Normal force due to incidence 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_s	Spiral mode time constant
τ_R	Rolling mode time constant
ϕ	Bank angle
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.

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2	A. G. Barnes	A simulator investigation of rolling requirements for landing approach. A.R.C. R. & M. 3605 (1967).
3	G. E. Miller and J. R. Franklin	Lateral-directional flying qualities for power approach. Journal of Aircraft, Vol. 5, No. 6, pp. 125-134 (March/April 1968).
4	J. K. Zbrozek	Theoretical study of the rolling response of aircraft to turbulent air. R.A.E. TN Aero. 2753 (1961).

APPENDIX I

Aircraft Equations of Motion.

Dynamic

Incidence $\dot{\alpha}=Z_{\alpha}.(\alpha+\alpha_t)+q$.

Pitch $\dot{q}=M_{\alpha}(\alpha+\alpha_t)+Mq.q+M_{\eta}.\eta$.

Sideslip $\dot{\beta}=Y_{\beta}(\beta+\beta_t)-r+\alpha_0 p+\frac{g}{V}\sin\phi$.

Roll $\dot{p}=L_{\beta}(\beta+\beta_t)+Lp.p+Lr.r+L_{\zeta}.\xi$.

Yaw $\dot{r}=N_{\beta}(\beta+\beta_t)+Np.p+Nr.r+N_{\xi}.\xi+N_{\zeta}.\zeta+N_{\dot{\beta}}.\dot{\beta}$.

Kinematic

Normal acceleration at C.G. $a_z=1-\frac{V}{g}Z_{\alpha}.(\alpha+\alpha_t)$.

Side acceleration at C.G. $a_y=-\frac{V}{g}Y_{\beta}(\beta+\beta_t)$.

In space-fixed axes,

$$a_{z_{sa}}=a_z\cos\phi-a_y\sin\phi-1$$

and

$$a_{y_{sa}}=a_z\sin\phi+a_y\cos\phi\ .$$

Rate of turn of velocity vector in azimuth, $\bar{\varepsilon}=\frac{a_{y_{sa}}}{V}$,

Rate of turn of velocity vector in azimuth, $\dot{\gamma}=\frac{a_{z_{sa}}}{V}$.

$$\alpha_{sa}=\alpha\cos\phi-\beta\sin\phi$$

and

$$\beta_{sa}=\alpha\sin\phi+\beta\cos\phi\ .$$

Orientation in space

$$\theta_{sa}=\gamma+\alpha_{sa}$$

and

$$\psi_{sa}=\varepsilon-\beta_{sa}\ .$$

Velocity in space

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

and

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

Suffices

sa = space axes

t = turbulence.

Numerical Values for the Research Aircraft.

Lateral derivatives

	Y_β	α_0	L_β	L_p	Lr	N_β	N_p	Nr
1	$\bar{0}{\cdot}10$	3°	−12·8	−1·3	0·5	1·6	·05	−·4
2	$\bar{0}{\cdot}10$	3°	−6·4	−1·3	0·5	1·9	·05	−·4
3	$\bar{0}{\cdot}10$	3°	−6·4	−2·6	0·5	1·9	·05	−·4

Longitudinal derivatives

	Z_α	M_α	M_q	M_η
1–3	−·75	−1·25	−1·35	−2·75

APPENDIX II

Definition of Turbulence Spectrum Used in Simulation.

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

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

where $\sigma =$ r.m.s. of turbulence intensity (ft/sec)

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

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

$\omega =$ frequency, rad/sec

and $\lambda =$ turbulence wave length, 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 in Fig. 18(a).

This circuit corresponds to a filter of the following type.

$$O \qquad \frac{O}{i}=\frac{R_2C_1S}{(1+R_2C_2S)(1+R_1C_1S)}\frac{R_4}{R_3}\frac{1}{(1+R_4C_3S)}.$$

Component values used were

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

giving a filter of the form $\frac{{\cdot}5S}{1+5S}\cdot\frac{10}{(1+S)^2}$. (*See* Fig. 18(b).)

The comparison of the power spectrum used with the Dryden Spectrum is shown in Fig. 00. Excitation of the aircraft's lateral and longitudinal short period modes is approximately correct.

The diagram in Fig. 17 shows the form of the non-linearity used in the simulation to produce occasional large gusts.

APPENDIX III

Pilot Briefing Sheet.

1. *The object of simulation* is to produce handling qualities data in the form of pilot opinions, measured on the new rating scale (which is virtually the same as the Cooper Scale). The control power in roll, and the level of lateral turbulence will both be varied, and the aircraft characteristics (apart from control power) will be kept constant.

2. *The aircraft* is a swept fighter type, something like the Lightning or Jaguar. Approach speed is 120 knots (fixed). Dutch roll period—4 seconds. Dutch roll damping—3 cycles to damp. Roll/yaw ratio 4.

3. *The task* is to fly a straight-in approach on roughly a 3 degree glide slope, but judged visually on display & V.S.I. Minimise the bank angle deviations. Use of rudder is allowed as necessary. No touchdown or ground effects are simulated; the approach should be terminated during the flare. Flying down the runway at minimum height is O.K., if it helps the assessment, but the real question is 'how easy or how difficult is the approach, and could a successful landing be accomplished?'

4. *The pilot rating* should be a measure of the ability to perform the task. For example, in turbulence, if good performance can be obtained by tight control, then a good rating should appear. (Otherwise we will get a rating of turbulence, and we know this already!)

5. *The cockpit.*
   - (i) Motion in roll only is provided.
   - (ii) The Feel system is a new one, using hydraulic jacks. The pitch feel is still imperfect—little twitches can occasionally be felt, but do not worry.
   - (iii) Instruments—not yet connected. We have installed a head-up display, head down, to overcome this. It gives bank angle, pitch angle, height, vertical speed and sideslip. The last two are on the flight director dot. (*See* Fig. 18(c).)

TABLE 1

Comparison of Research Aircraft with Known Aircraft.

AIRCRAFT	R	R	R	L	J	HUNTER	NAVION	DOVE	COMET	VC10
SPEED (KNOTS)	120	120	120	180	140	150	70	120	130	138·5
S	240			460	258	340	184		2,059	2,806
W	18,000			30,000	17,650	19,000	2,750	7,700	95,000	212,000
i_a	·054			·074	·046	·058	·05	·041	·153	·054
i_c	·535			·388	·461	·278	·10	·10	·266	·24
i_e	·016			0	·02	−·036			0	
C_L	1·58			·594	1·024	·730	0·92	0·47		1·16
α_0	3°			7°	7·5°				3°	
Y_β	−·10			−·178	−·146	−·070	−·18	·20	−·08	−·09
L_β	−12·8	−6·4	−6·4	−16·2	−24·5	−13·4	−6·7	−9·36	−1·3	−2·5
L_p	−1·3	−1·3	−2·6	−1·25	−1·73	−1·51	−4·7	−7·9	−0·97	−1·7
L_r	0·5			0·72	2·07	·72	1·18	1·83	0·72	1·22
$\dot{p}_M(L_\xi . \xi_M)$	VARIED ⟶					−1·55	−3·7	−2·4	−0·51	−1·15
L_ζ	0			2·12	2·94				0	·38
N_β	1·6	1·9	1·9	3·88	1·71	1·83	3·0	3·22	0·99	·396
N_p	·05			·029	−·060	−·051	−·12	−·60	−·117	−·09
N_r	−·40			−·41	−·345	−·205	−·47	−·61	−·20	−·12
N_ξ	VARIED TO KEEP $\omega\phi/\omega d$ CONSTANT ⟶						0	−·29	0	0
N_ζ	$N_\zeta . \zeta = 1{\cdot}5$ rad/sec^2 ⟶								−·63	−·25
$N_{\dot\beta}$	VARIED TO KEEP $\zeta_d = 0{\cdot}15$			0	0				−·63	−·25
ωd	1·46	1·47	1·46	2·45	2·07	1·91	1·77	1·96	1·03	0·96
ζ_d	0·02	0·1	0·14	0·147	0·054	·112	0·18	·07	·08	·026
$\zeta_d + N_{\dot\beta}$	0·15	0·15	0·15	—	—	—	—	—	—	—
T_d	4·3	4·3	4·3	2·59	3·04	3·3	3·5	3·18	6·1	6·55
ϕ/β	4·4	2·1	1·4	2·6	4·53		0·67	0·62	0·78	1·52
$\phi/_{VE}$	1·25	0·6	0·4	0·49	1·09					
$(\omega\phi/_{\omega d})^2$	0·95	0·95	0·95	0·688	0·9			·875	·945	·43
r_R	0·66	0·71	0·38	0·93	0·52	·65	0·21	·135	·8	·7
$T_{\frac{1}{2}}$	0·45	·49	·26	0·64	0·36					
r_S	4·7	12·7	26·0	17·5	13·7	28·6	25			
$T_{\frac{1}{2}}$	3·2	8·8	18·0	12·1	9·5					

$L_{\beta} = -12{\cdot}8$, $L_p = -1{\cdot}3$, *Motion On/Off.*

PILOT
MOTION ON

$\dot{p}_m$	TURB	A	A	B	B	C	C	D	E	MEAN
·32	2	4·0	3·0	9·0	8·0	5·0	10*	3·0	9·0	5·85
„	4	6·5	—	9·0	8·0	—	10*	7·0	9·5	8·0
„	6	7·0	7·5	9·0	7·5	—	—	8·0	10	8·15
„	8	7·5	—	9·0	9·0	—	—	7·0	10	8·5
1·0	2	3·0	—	6·0	4·0	3·0	3·0	4·0	7·0	4·3
„	4	4·0	—	7·0	5·0	6·0	5·5	5·5	8·0	5·85
„	6	5·0	5·0	7·0	5·5	5·5	4·0	4·0	9·0	5·65
„	8	5·5	—	6·0	7·0	7·0	7·0	2·0	9·0	6·2
3·2	2	2·5	2·5	1·0	1·0	2·0	3·0	1·0	5·0	2·25
„	4	3·5	—	2·0	2·5	4·0	4·0	2·0	4·5	3·2
„	6	5·5	—	2·0	2·0	5·0	4·0	2·5	6·0	3·85
„	8	5·0	—	1·0	2·0	3·0	—	4·0	7·0	3·65
6·4	2	3·5	4·0	—	—	2·0	4·0	2·0	7·0	3·85
„	4	3·5	3·5	—	—	3·0	5·0	3·0	7·0	4·15
„	6	6·0	5·5	—	—	4·0	5·5	3·0	7·0	5·15
„	8	5·0	—	—	—	3·0	7·5	5·0	8·0	5·7

*ONLY AILERON USED

MOTION ON

A	D	MEAN
4·0	3·0	3·5
6·5	7·0	6·75
7·0	8·0	7·5
7·5	7·0	7·25
3·0	4·0	3·5
4·0	5·5	4·75
5·0	4·0	4·5
5·5	2·0	3·75
2·5	1·0	1·75
3·5	2·0	2·75
5·5	2·5	4·0
5·0	4·0	4·5
3·5	2·0	2·75
3·5	3·0	3·25
6·0	3·0	4·5
5·0	5·0	5·0

MOTION OFF

A	D	MEAN
4·0	7·0	5·5
5·0	6·0	5·5
4·0	6·0	5·0
6·5	6·0	6·25
3·5	1·0	2·25
3·0	2·0	2·5
4·5	2·0	3·25
5·0	5·0	5·0
2·5	1·0	1·75
3·5	2·0	2·75
4·5	2·5	3·5
5·0	2·0	3·5
3·0	2·0	2·5
4·5	3·0	3·75
3·5	2·0	2·75
6·0	4·0	5·0

TABLE 3

$L_\beta = -6{\cdot}4$, $L_p = -1{\cdot}3$, *Motion On.*

PILOT

$\dot{p}_m$	TURB	A	A	B	C	C	E	F	G	H	I	I	J	K	MEAN
·10	2	5·5	—	7·0	—	—	10	—	6·0	7·0	6·0	—	—	—	6·9
„	4	6·0	—	9·0	—	—	10	—	8·0	9·0	9·0	—	—	—	8·5
„	6	7·5	—	9·0	—	—	—	—	8·5	9·0	8·0	—	—	—	8·4
„	8	8·5	—	8·0	—	—	—	—	9·5	10 „	—	—	—	—	9·0
·32	2	3·0	3·0	7·0	—	7·0	5·0	5·0	3·0	6·0	6·0	8·0	7·0	3·0	5·25
„	4	4·0	—	6·0	—	10	6·0	6·5	3·0	6·0	3·0	9·0	8·0	4·5	6·0
„	6	5·0	5·0	7·5	—	—	8·5	6·0	5·0	8·0	6·0	8·0	8·0	6·0	6·65
„	8	7·0	—	7·0	—	—	10	9·0	7·0	8·0	5·0	9·0	9·0	6·0	7·7
1·0	2	2·5	3·0	2·5	2·0	2·5	4·0	2·0	2·0	2·0	4·0	6·0	3·0	3·0	2·95
„	4	4·5	—	2·0	2·0	3·0	6·0	3·0	3·0	4·5	3·0	5·0	6·0	3·0	3·75
„	6	5·0	—	3·0	5·5	3·0	5·0	4·0	4·0	3·0	7·0	7·0	4·0	5·0	4·6
„	8	6·0	—	3·0	5·0	6·0	8·0	7·0	7·0	5·0	8·0	8·0	5·0	7·0	6·25
3·2	2	2·0	—	2·0	2·0	2·5	5·5	2·0	2·0	2·0	3·0	3·0	2·0	2·5	2·55
„	4	3·0	3·5	2·0	5·5	3·5	5·0	4·0	3·0	3·5	4·5	5·0	5·0	4·0	3·95
„	6	4·5	—	4·0	5·0	5·5	6·0	3·5	3·0	4·5	5·5	6·0	4·5	4·5	4·7
„	8	3·0	—	2·0	5·0	5·5	6·0	6·0	6·0	4·0	6·0	5·0	6·0	7·0	5·1
6·4	2	—	2·0	2·0	3·0	3·0	—	6·0	—	—		4·0	4·0	3·5	3·45
„	4	—	—	2·0	3·0	5·5	—	6·0	—	—		5·0	5·0	6·5	4·7
„	6	—	4·0	3·0	2·5	8·0	—	7·0	—	—		7·0	4·0	6·5	5·25
„	8	—	5·0	4·0	5·0	7·0	—	4·0	—	—		7·0	7·0	7·0	5·75

TABLE 4

$L_\beta = -6{\cdot}4$, $L_p = -2{\cdot}6$, *Motion On.*

PILOT

$\dot{p}_m$	TURB	A	B	G	H	MEAN
·32	2	3·0	8·0	3·0	6·0	5·0
,,	4	3·0	8·0	4·0	6·0	5·25
,,	6	4·0	8·0	3·0	4·5	4·9
,,	8	5·0	8·0	3·0	7·0	5·75
1·0	2	2·5	3·0	2·0	4·5	3·0
,,	4	3·5	4·0	2·0	5·0	3·6
,,	6	4·5	7·0	2·0	5·0	4·6
,,	8	4·0	4·0	3·5	5·0	4·1
3·2	2	2·5	2·0	2·0	2·0	2·1
,,	4	3·5	2·0	2·0	2·0	2·35
,,	6	3·5	2·0	4·0	2·0	2·9
,,	8	4·5	2·0	3·5	6·0	4·0
6·4	2	3·5	1·0	2·0	3·0	2·35
,,	4	4·0	1·0	3·0	2·5	2·6
,,	6	3·5	1·0	4·0	4·5	3·25
,,	8	5·5	1·0	3·0	4·0	3·4

TABLE 5

Aircraft L *and Aircraft* J.

		AIRCRAFT L PILOT					AIRCRAFT J
p_m	TURB	A	A	B	J	MEAN	K
·32	2	5·0	4·5	—	7·5	5·65	6·0
,,	4	5·5	—	—	7·0	6·25	7·0
,,	6	6·0	—	—	8·0	7·0	7·0
,,	8	8·0	8·0	—	8·0	8·0	8·0
1·0	2	3·5	—	—	4·0	3·75	3·5
,,	4	4·0	—	—	4·0	4·0	6·0
,,	6	4·5	6·0	5·0	5·5	5·25	7·0
,,	8	7·0	5·0	—	6·0	6·0	9·0
3·2	2	2·5	2·5	2·0	3·0	2·5	3·5
,,	4	3·5	3·5	3·5	4·0	3·6	3·5
,,	6	3·0	—	3·5	6·0	4·15	6·0
,,	8	7·0	—	3·0	3·0	4·3	8·0
6·4	2	3·0	—	—	2·5	2·75	3·0
,,	4	4·5	—	—	3·5	4·0	3·0
,,	6	4·0	4·0	2·0	2·5	3·1	6·0
,,	8	6·0	5·5	—	4·5	5·35	6·5

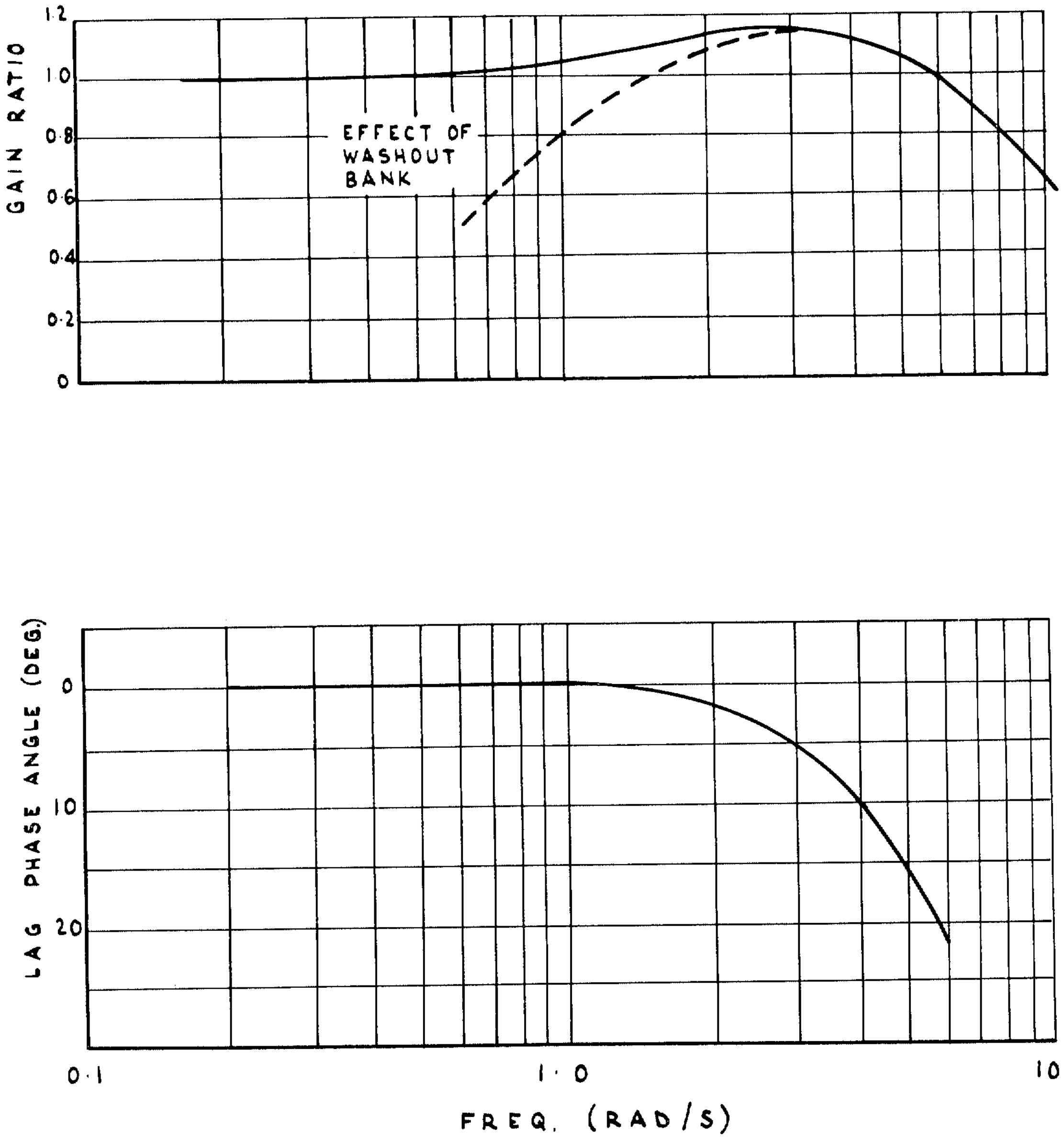

FIG. 1. Frequency response of roll system (± 1/10 amp).

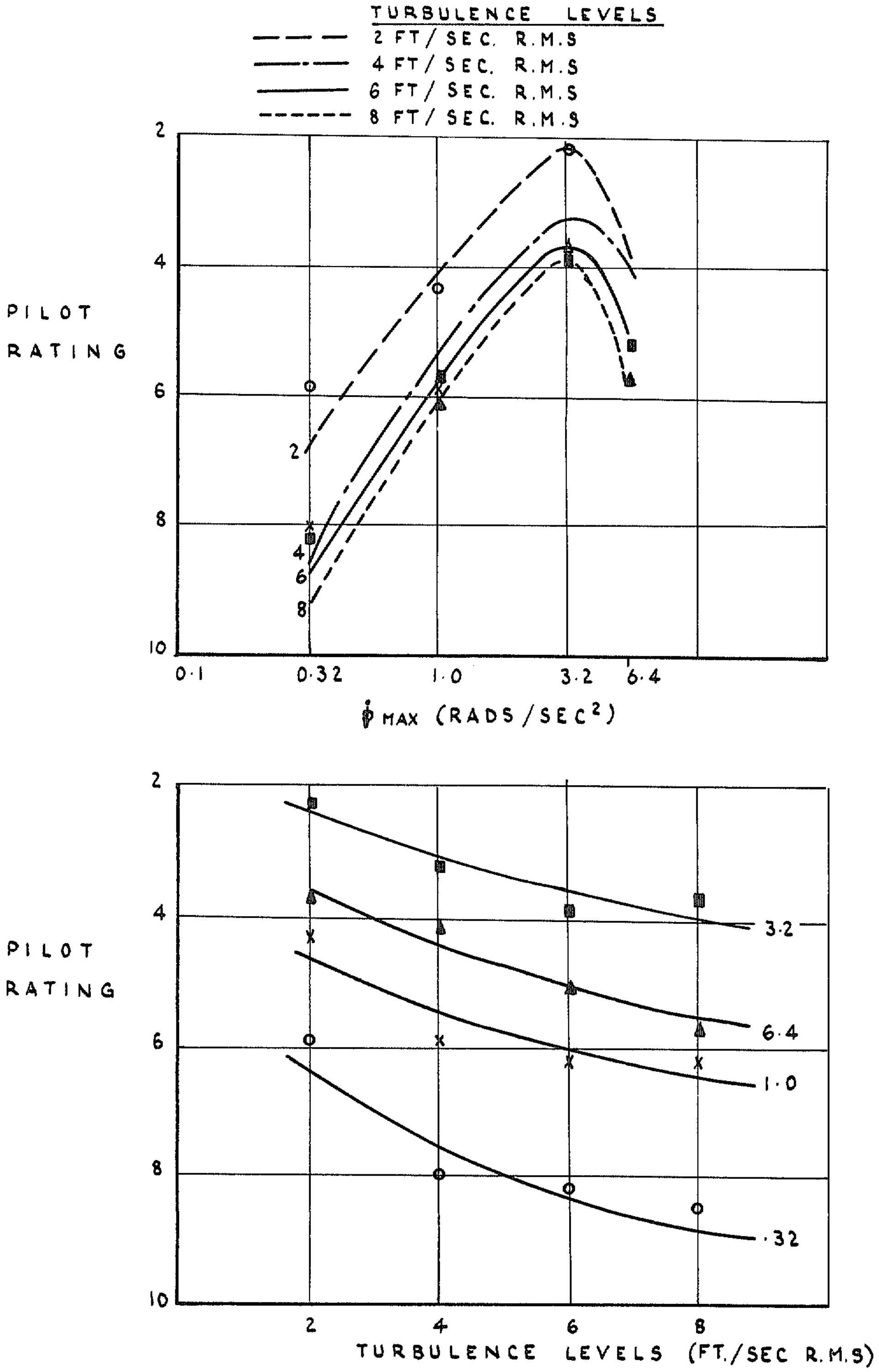

FIG. 2. $L\beta = -12{\cdot}8$, $Lp = -1{\cdot}3$.

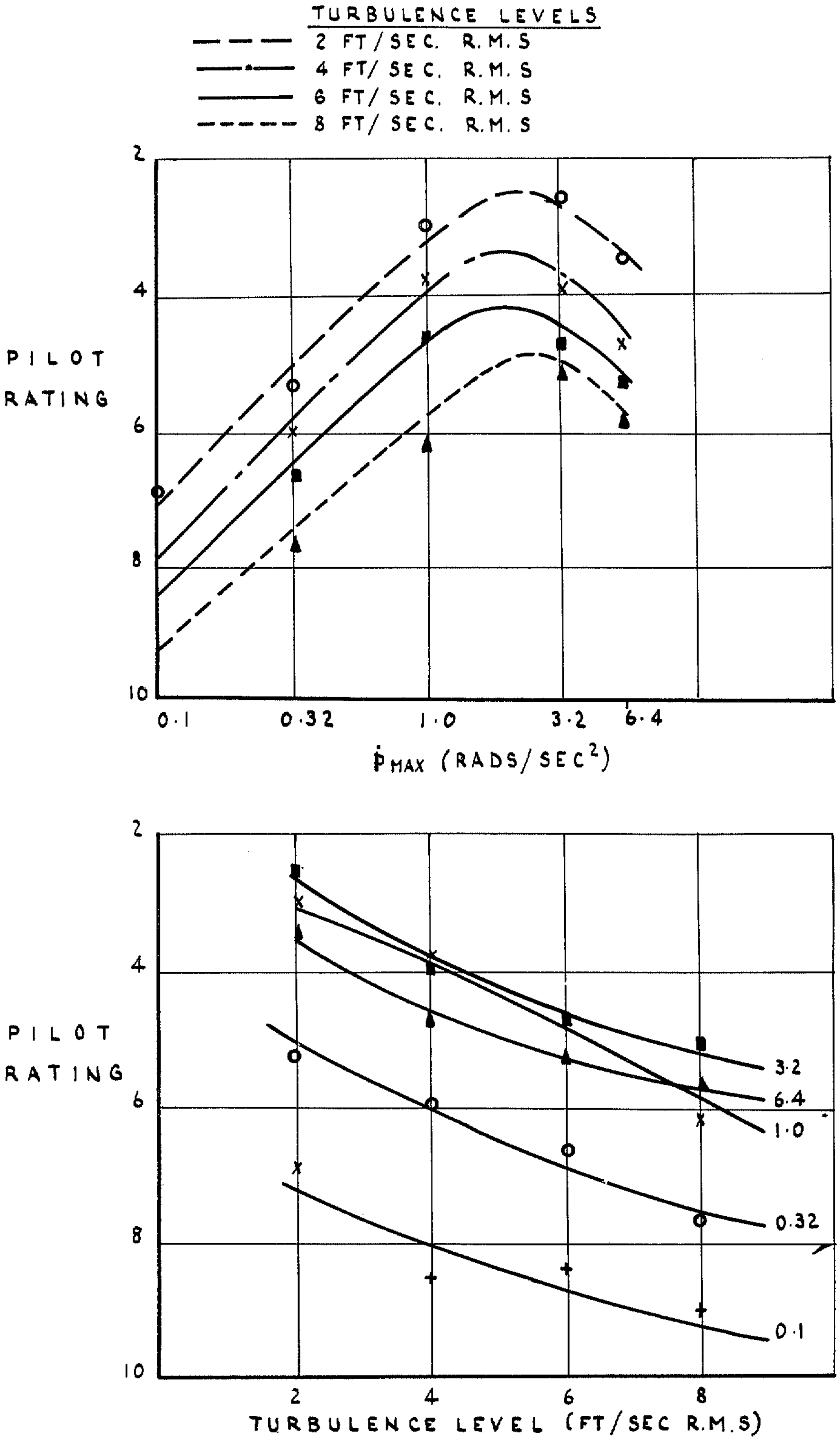

FIG. 3. $L\beta = -6{\cdot}4$, $Lp = -1{\cdot}3$.

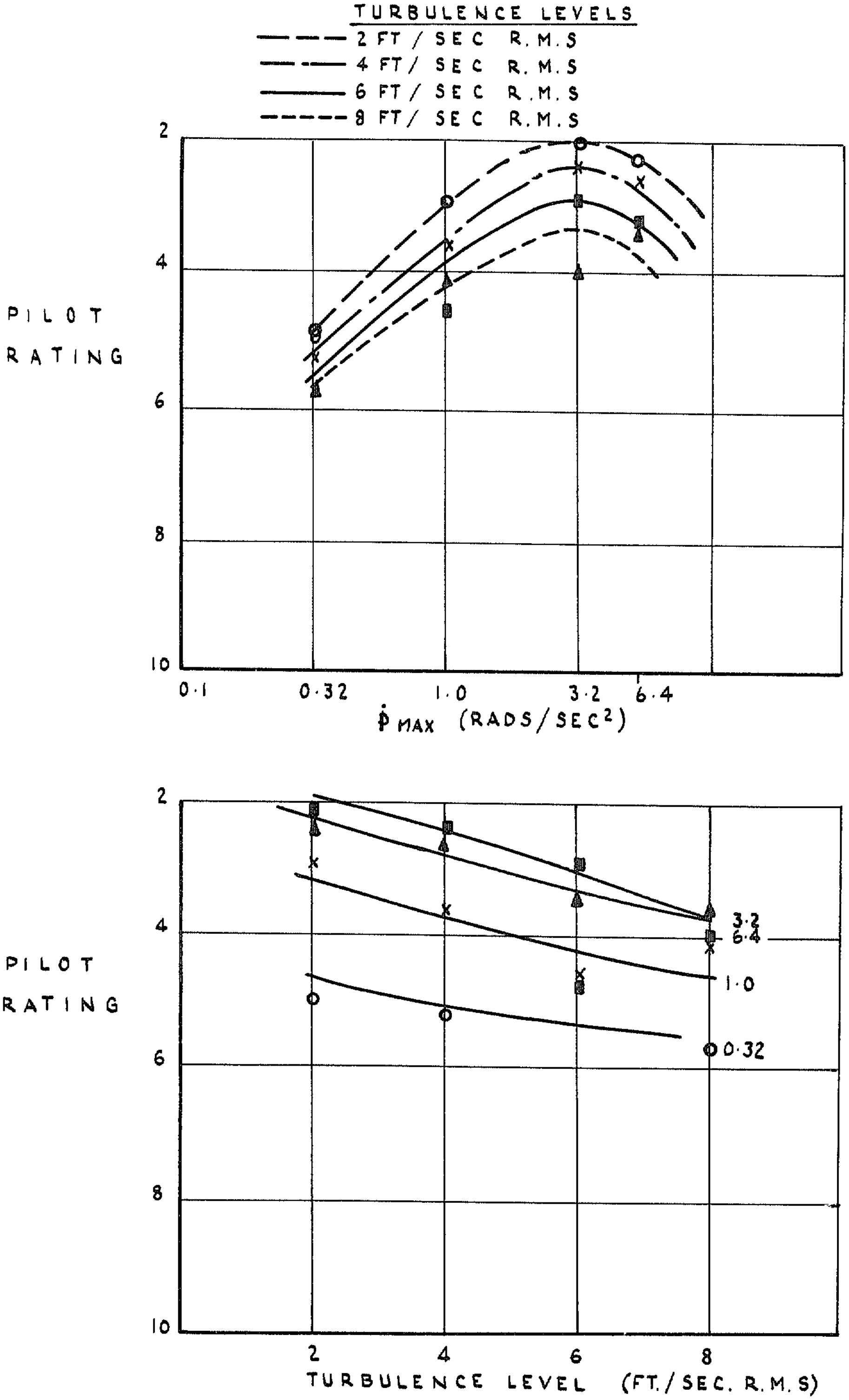

FIG. 4. $L\beta = -6{\cdot}4$, $Lp = -2{\cdot}6$.

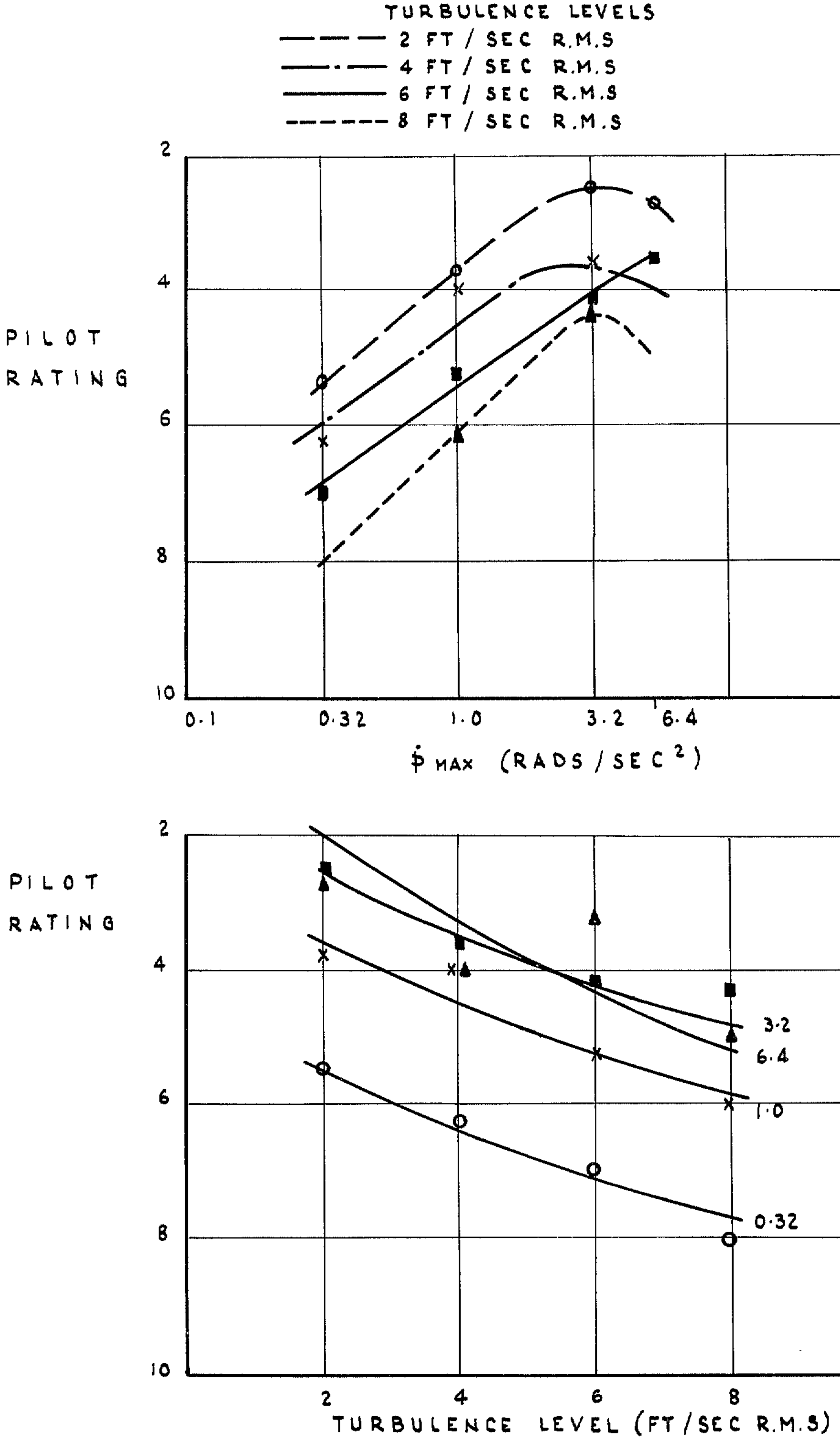

FIG. 5. Aircraft 'L'.

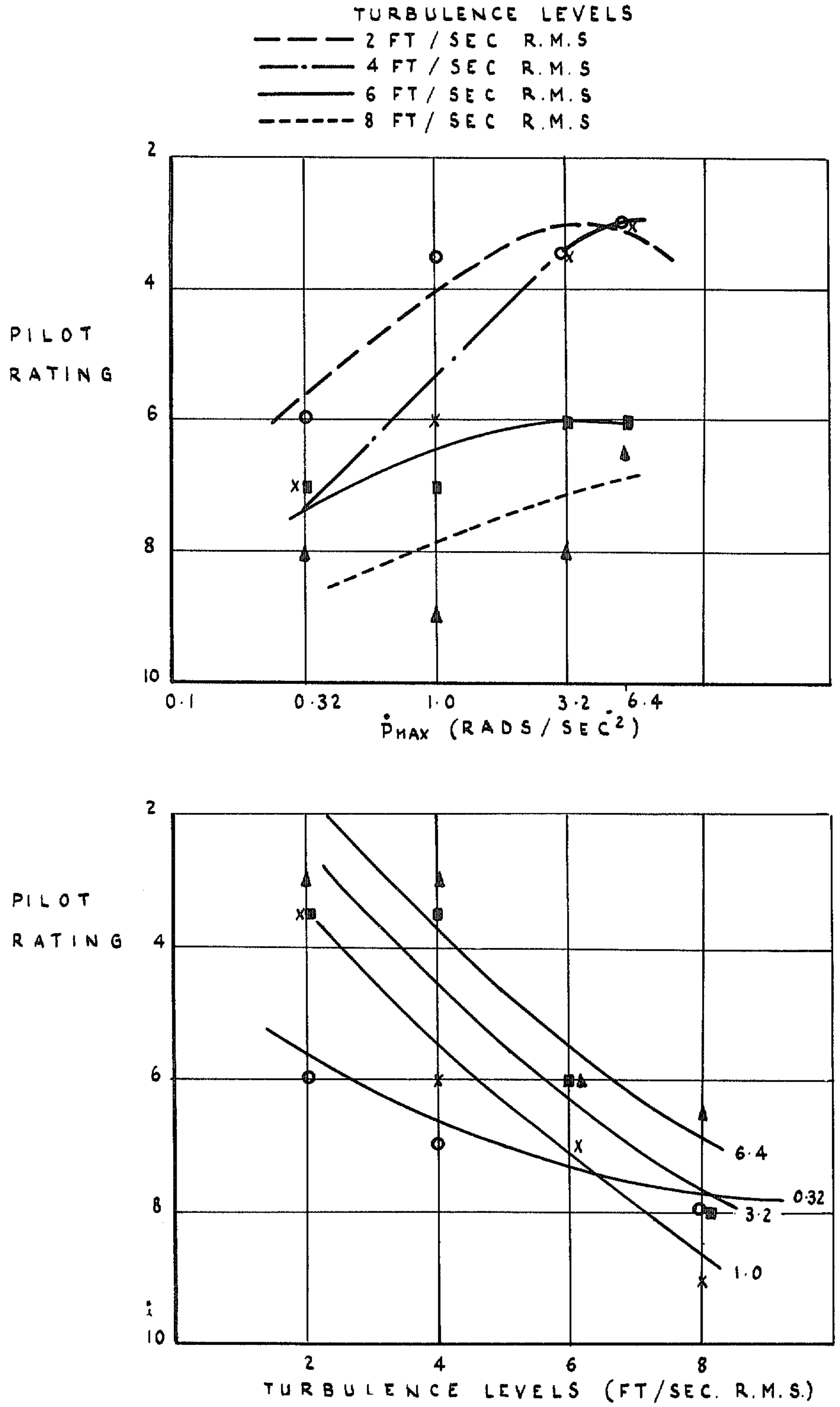

FIG. 6. Aircraft 'J'.

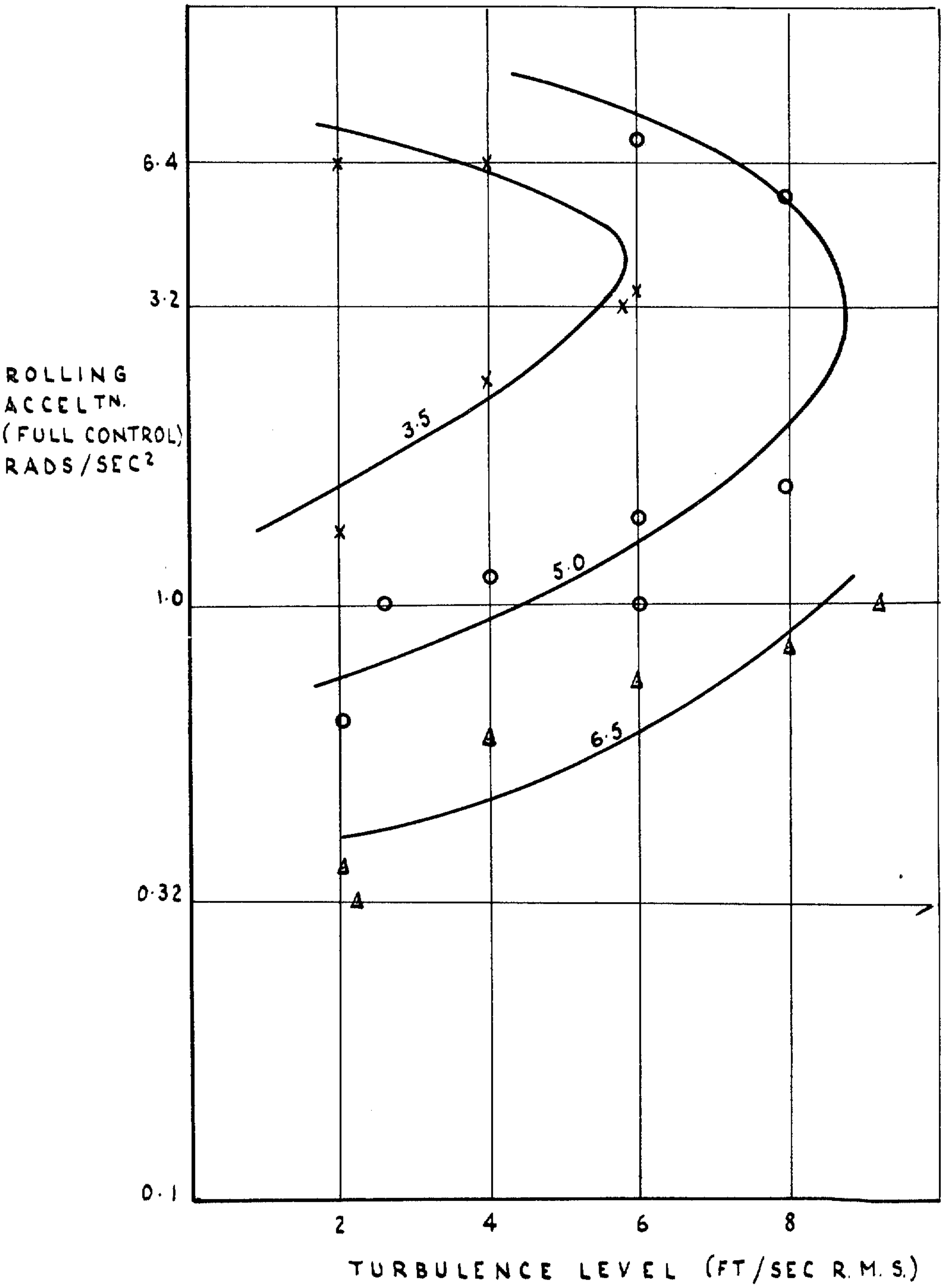

FIG. 7. $L\beta = -12{\cdot}8$, $Lp = -1{\cdot}3$. Pilot opinion boundaries.

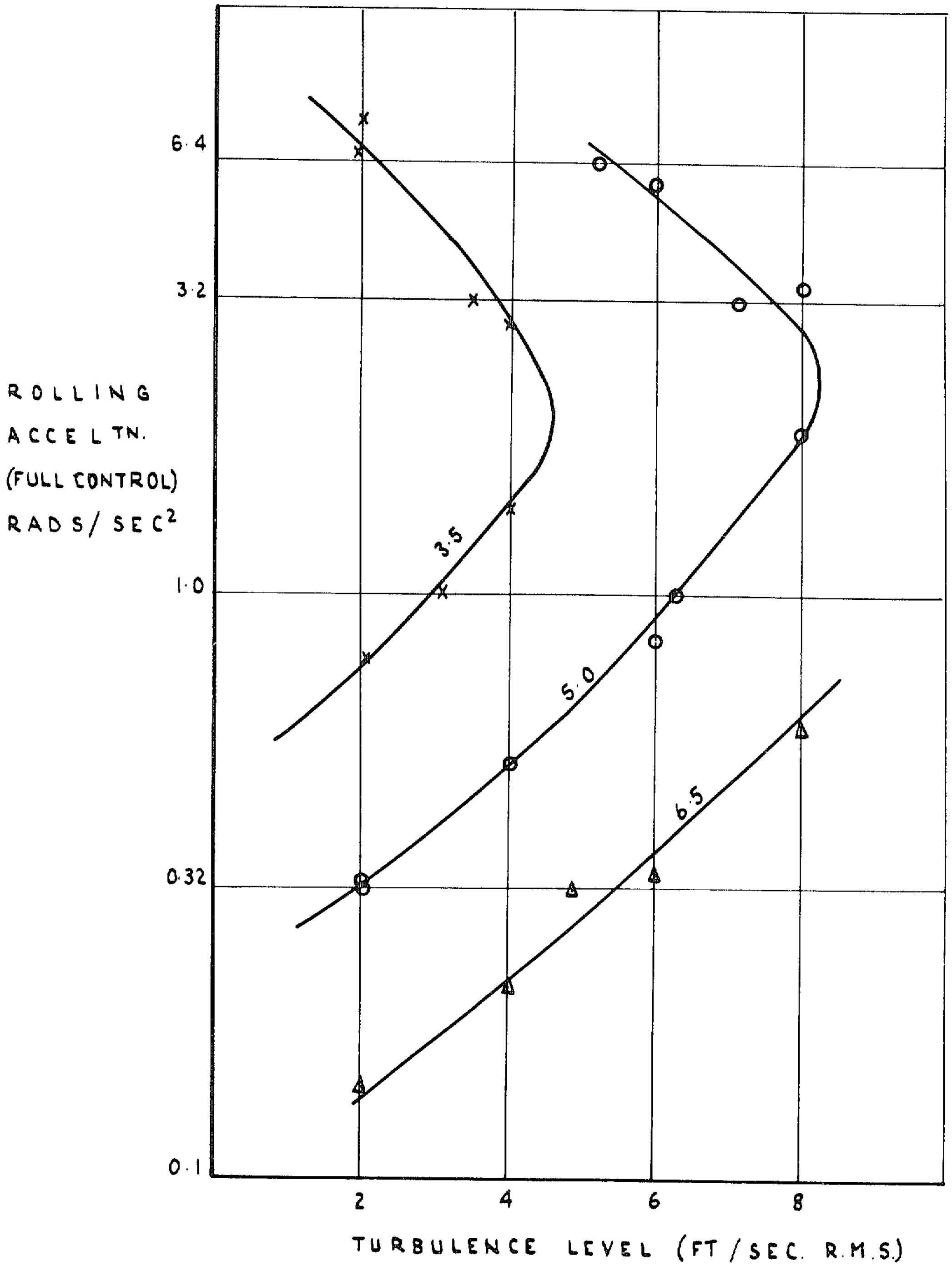

FIG. 8. $L\beta = -6{\cdot}4$, $Lp = -1{\cdot}3$. Pilot opinion boundaries.

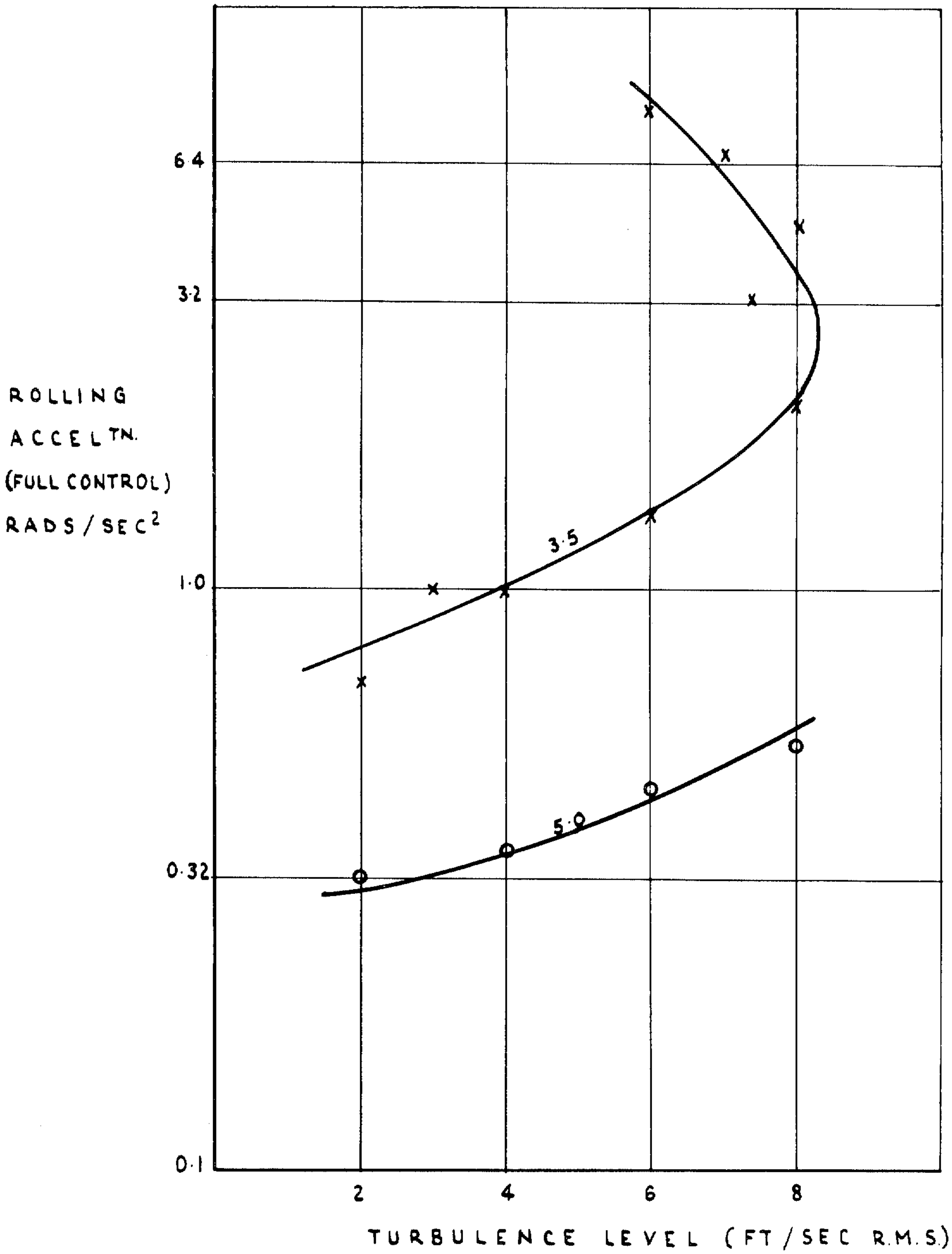

FIG. 9. $L\beta = -6{\cdot}4$, $Lp = -2{\cdot}6$. Pilot opinion boundaries.

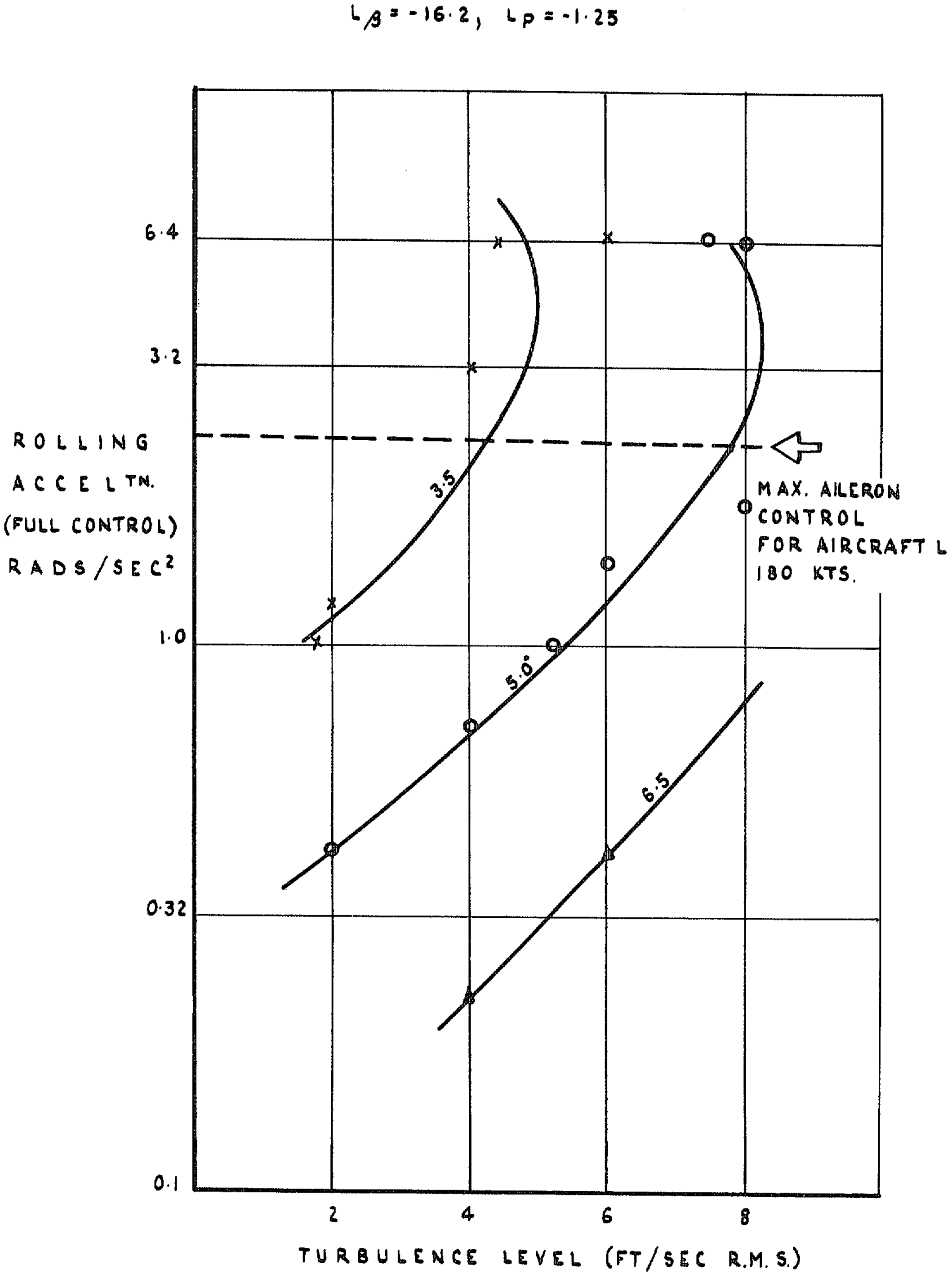

FIG. 10. Aircraft 'L'. Pilot opinion boundaries.

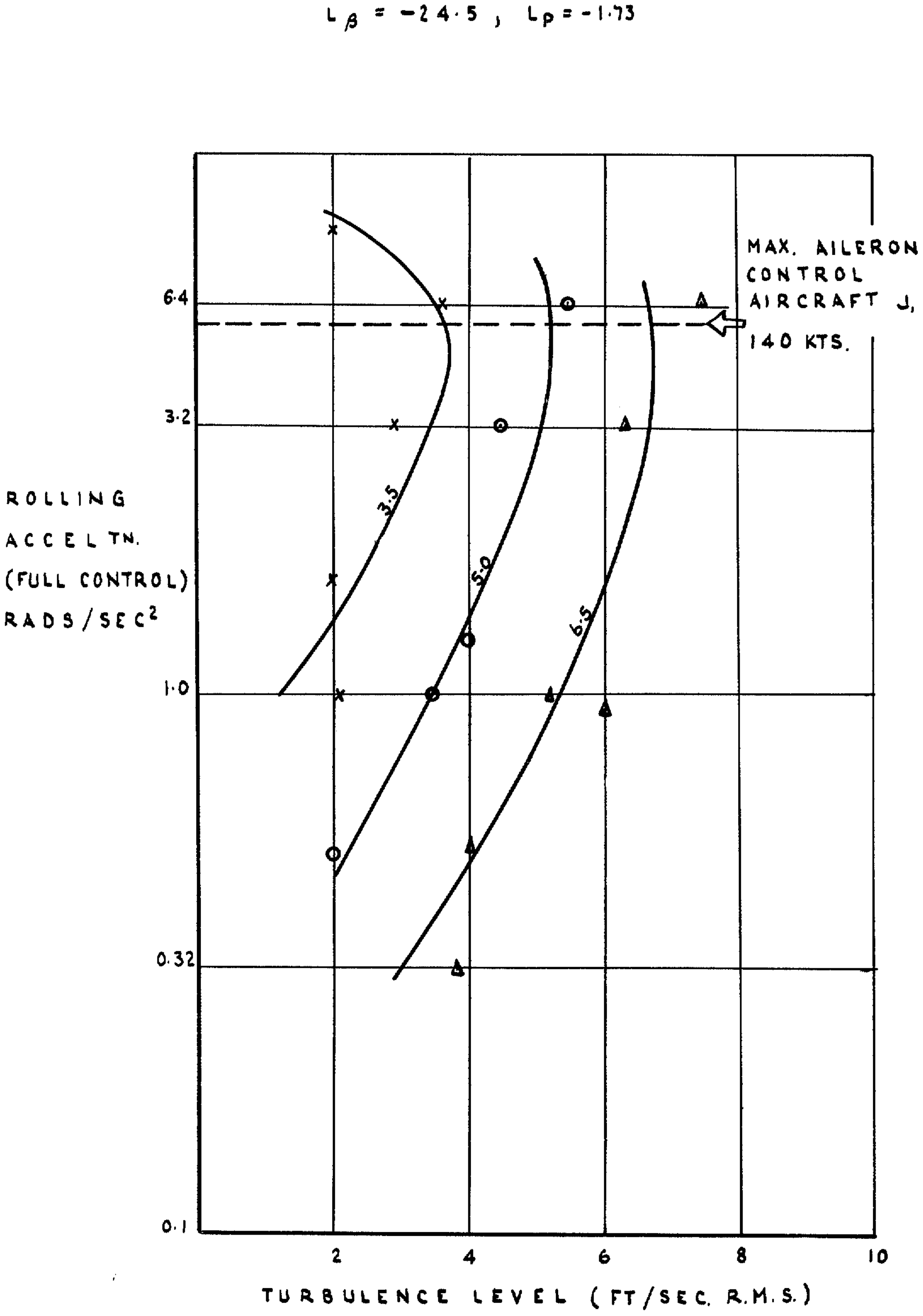

FIG. 11. Aircraft 'J'. Pilot opinion boundaries.

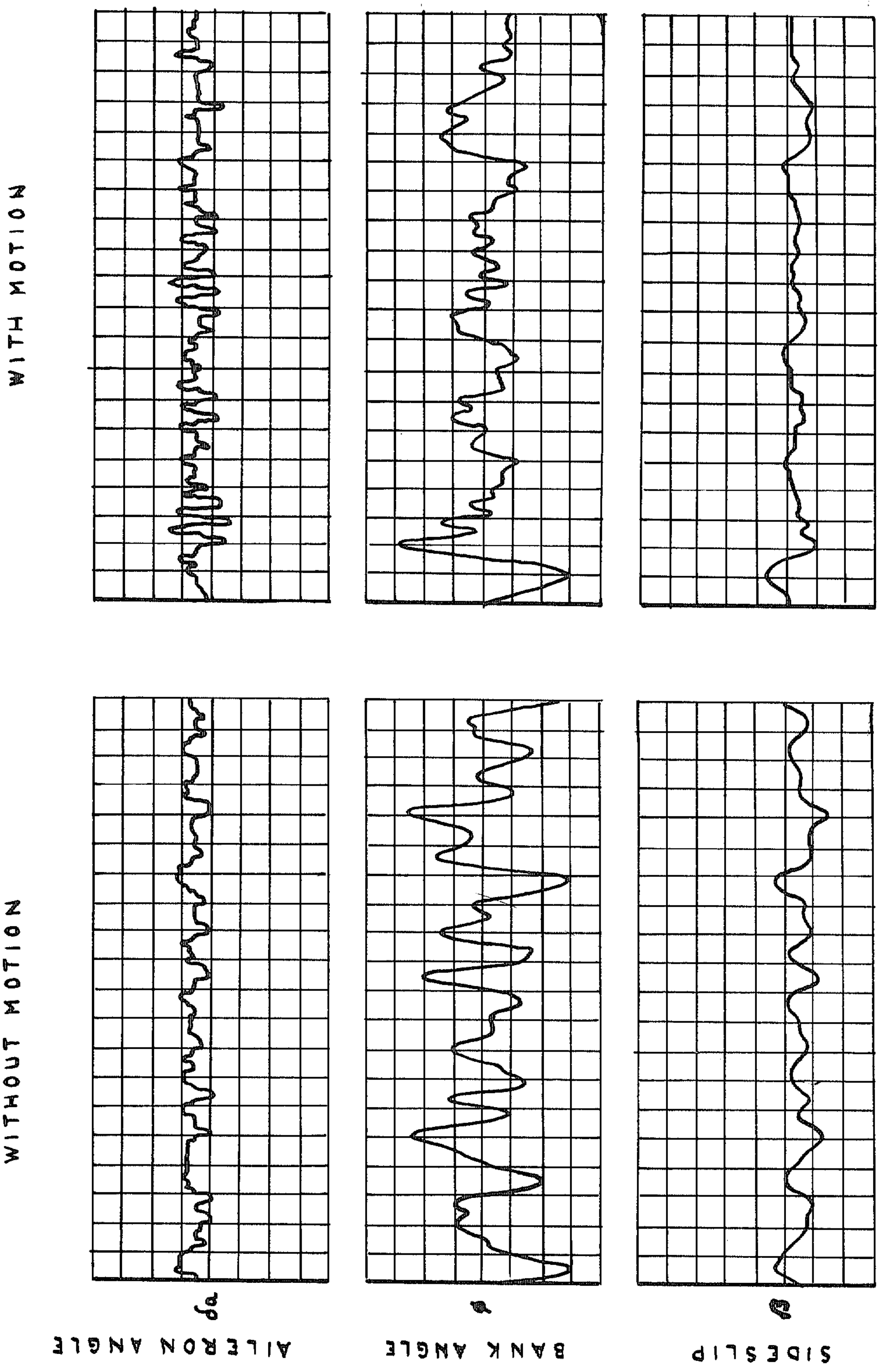

FIG. 12. Effect of cockpit motion.

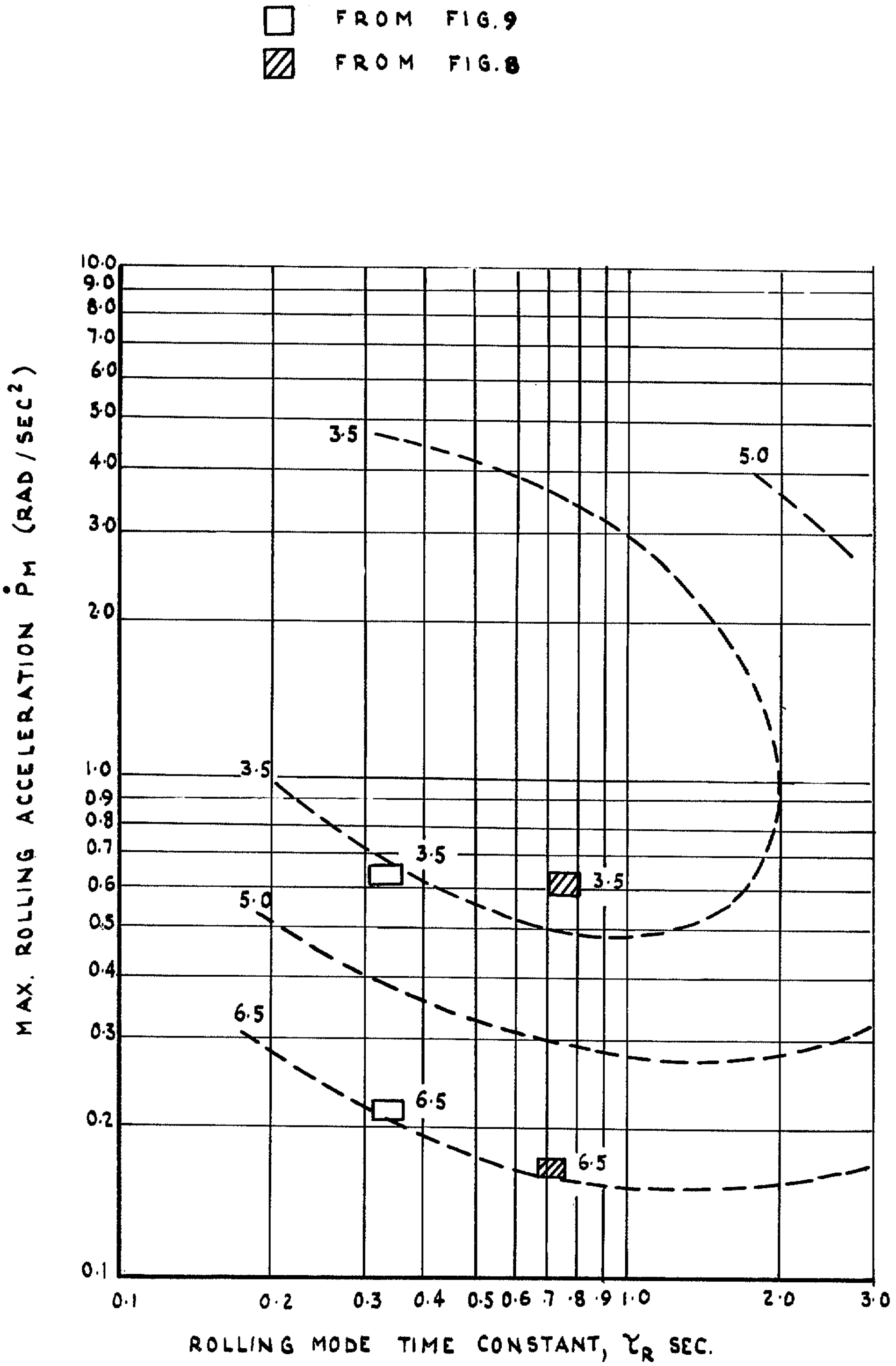

FIG. 13. Ref. 2 Boundaries (3 ft/sec r.m.s. turbulence).

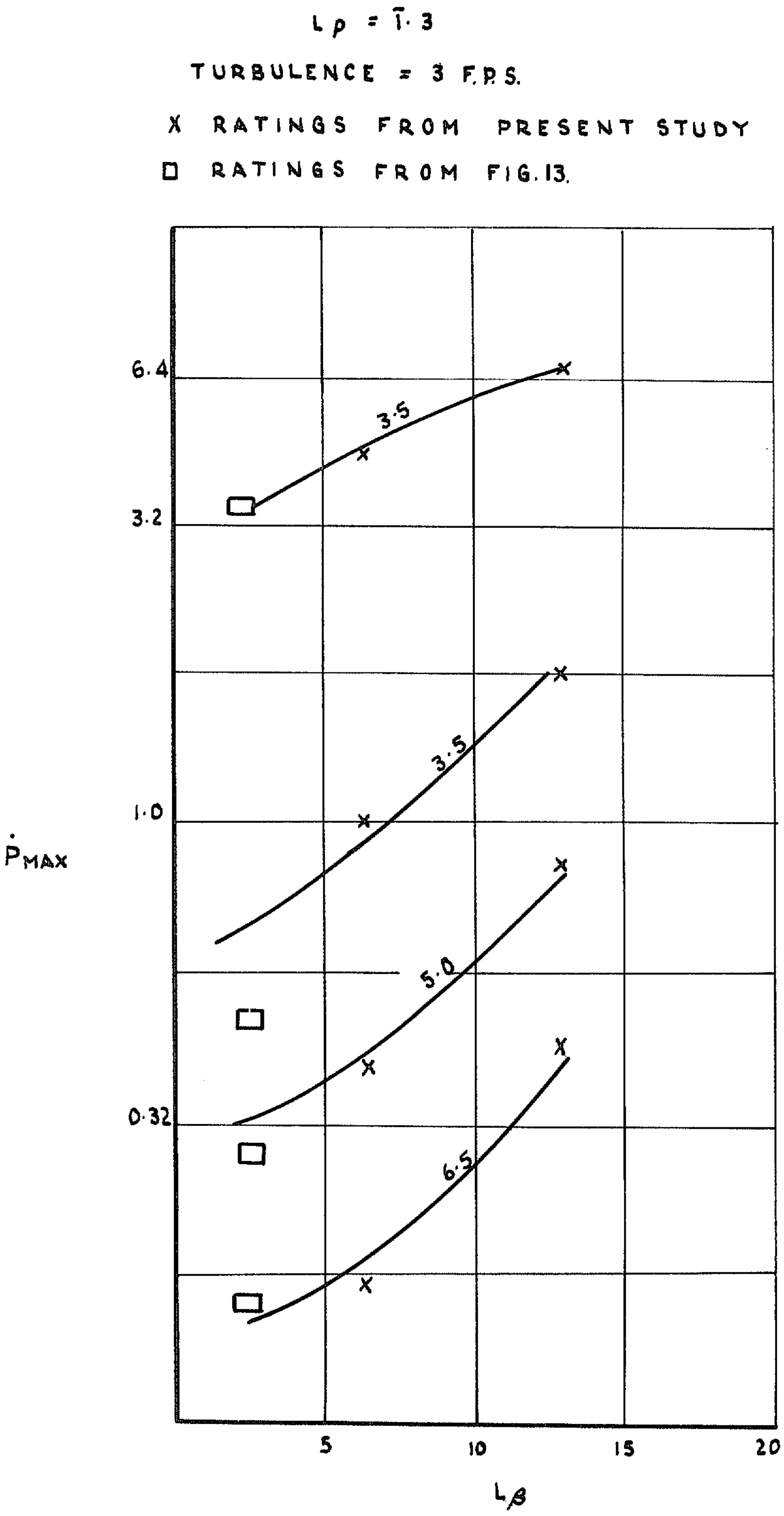

FIG. 14. Comparison of results with Ref. 2.

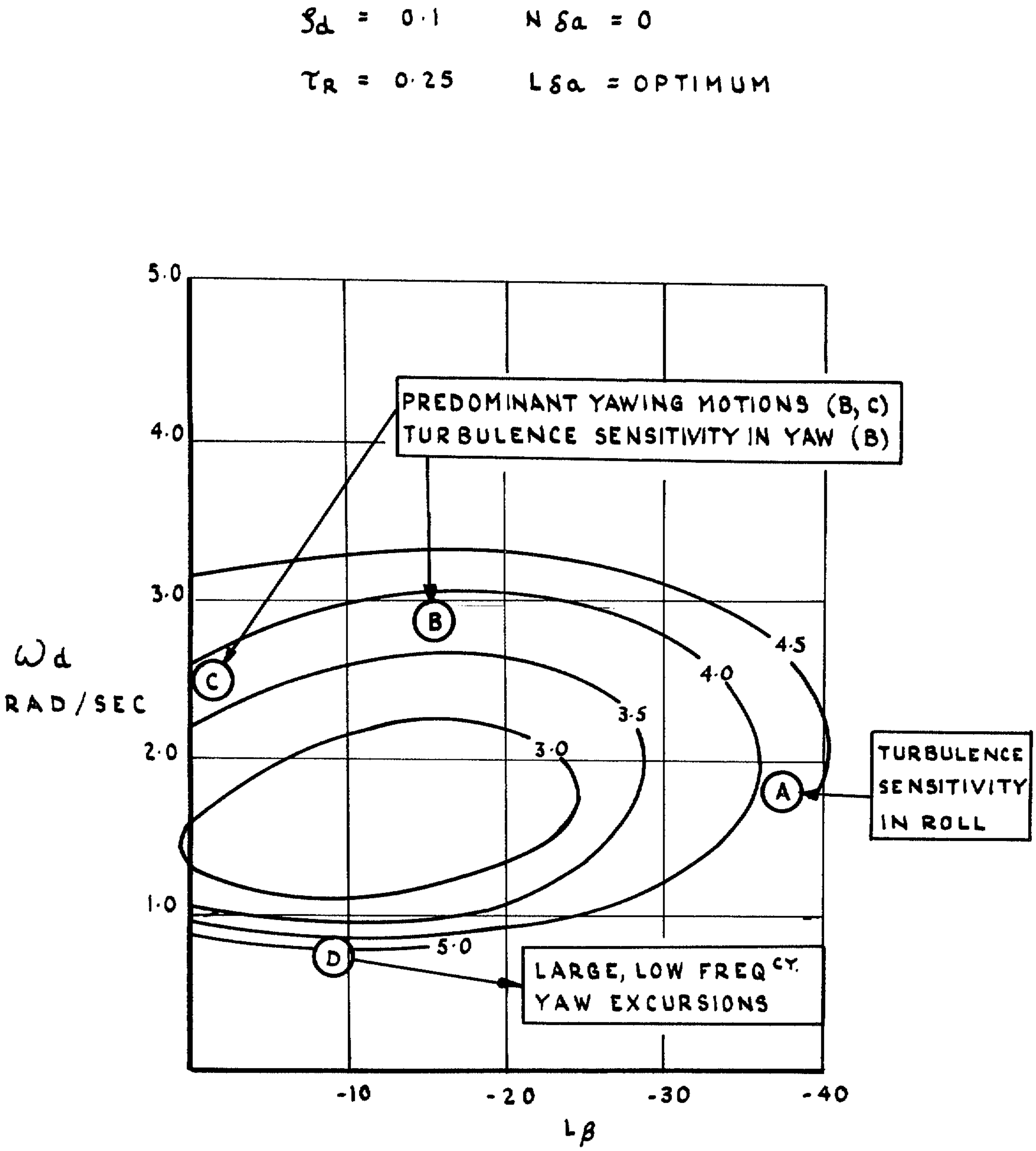

FIG. 15. Commentary regarding unsatisfactory configurations—low Dutch roll damping (Fig. 4 of Ref. 3).

$\zeta_d = 0{\cdot}1 \quad L\delta a \triangleq \text{OPTIMUM} \quad N_p = 0$

$\omega_d = 1{\cdot}8 \quad L_p = 0 \quad \dfrac{N\,\delta a}{L\,\delta a} = 0$

$\dfrac{1}{\tau_s} = 0 \quad N_r = -0{\cdot}222$

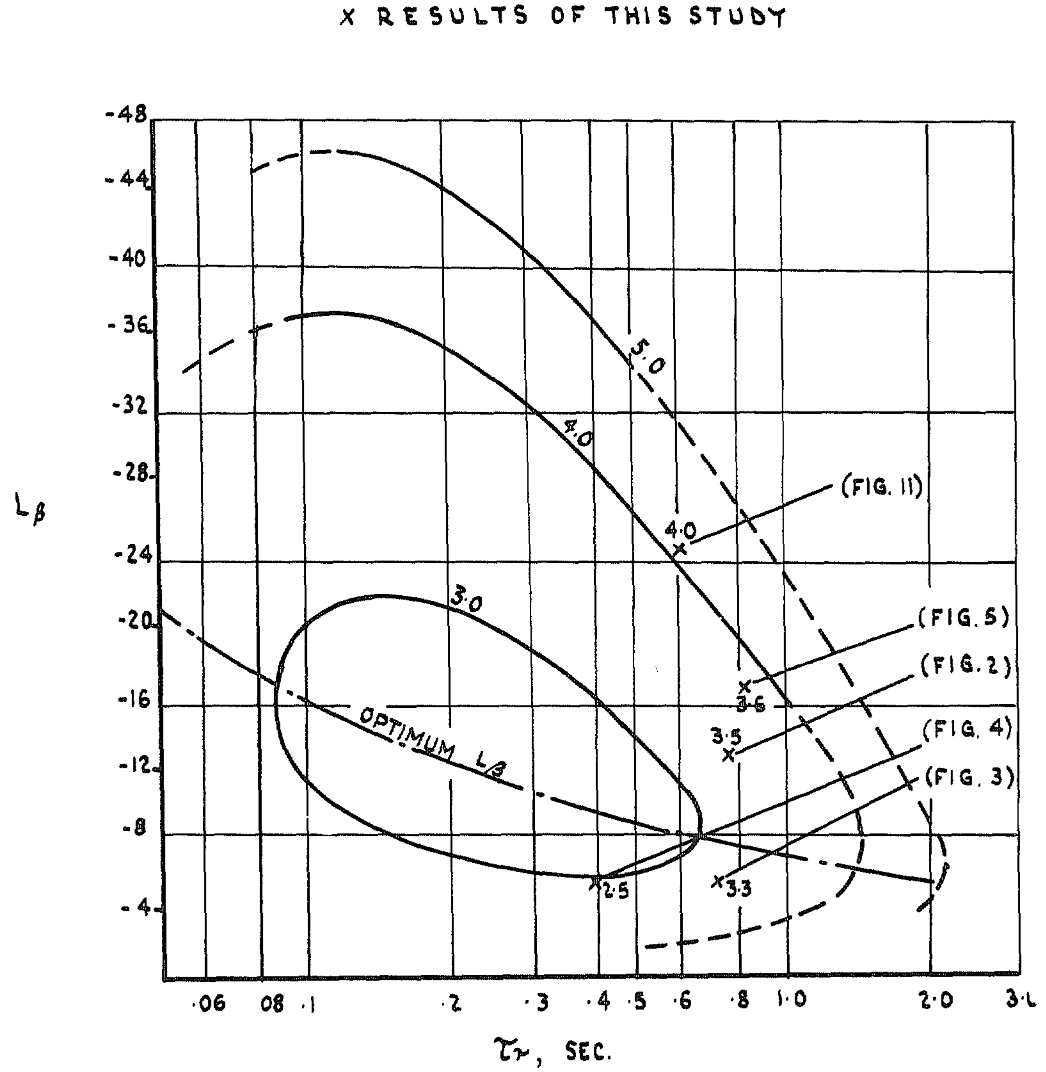

FIG. 16. Pilot opinion contours L_β v T_R (Fig. 3 of Ref. 3).

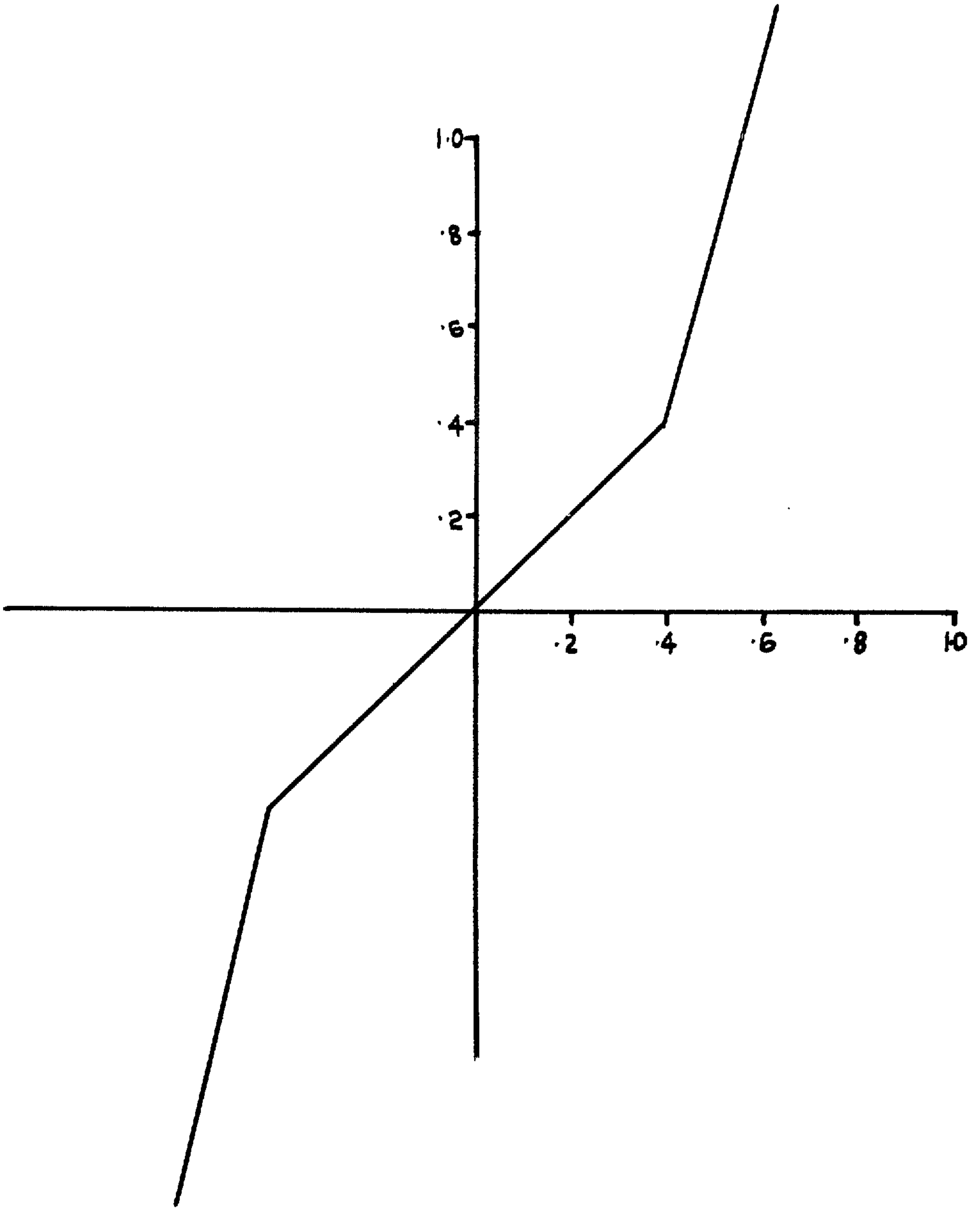

Fig. 17.

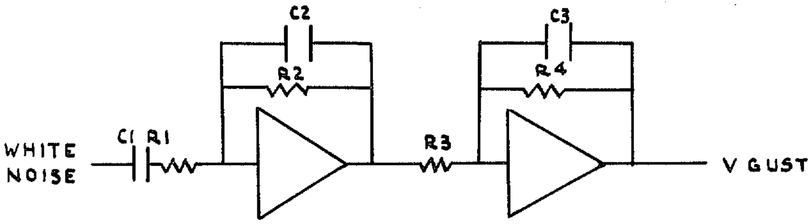

FIG. 18(a).

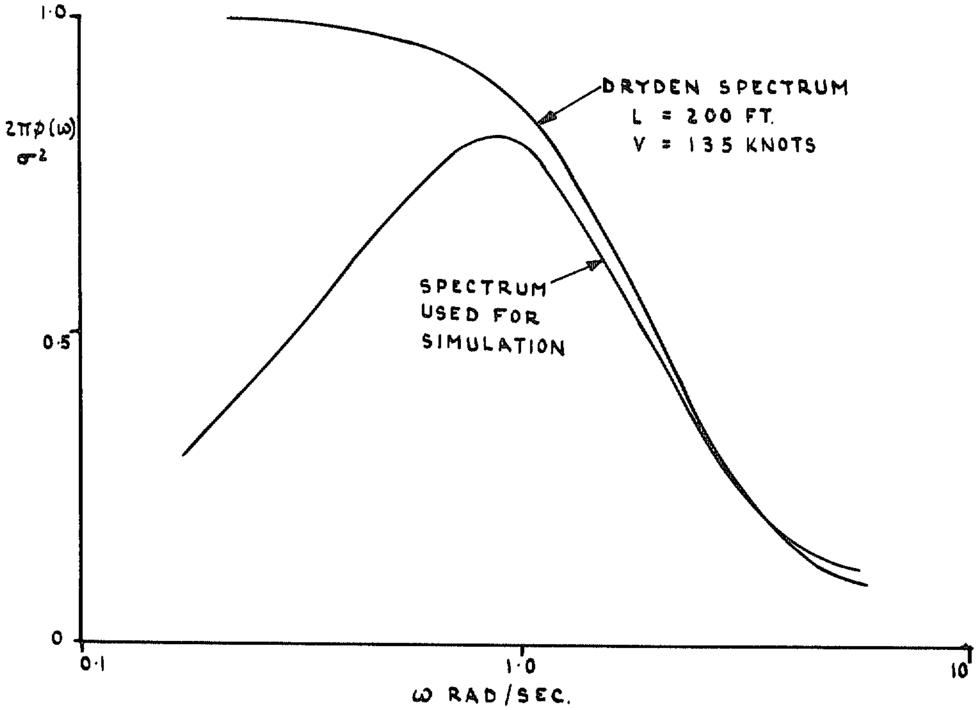

FIG. 18(b).

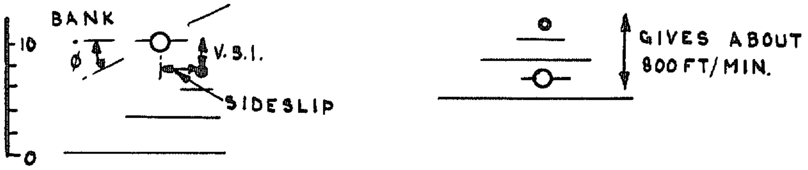

FIG. 18(c).

Printed in Wales for Her Majesty's Stationery Office by Allens Printers (Wales) Limited
Dd. 502110 K.5 4/72

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