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by

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A PILOTED FLIGHT SIMULATOR STUDY OF SPEED INSTABILITY DURING THE LANDING APPROACH

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SUMMARY

The effects of speed stability and turbulence level on the handling of a small research aircraft were systematically studied by four pilots on a fixed base simulator. Pilot opinion ratings were compared with those obtained in flight trials of the real aircraft. Accuracy of speed and flight path holding was also determined on the simulator.

Some discussion of such effects as inter-pilot variability, learning, the choice of performance measures, and the use of pilot opinion rating scales is included.

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* Replaces R.A.E. Technical Report 66138 - A.R.C. 28363

CONTENTS

1 INTRODUCTION

The purpose of this paper is to describe an experimental study of aircraft handling characteristics, made on the Aerodynamics Department simulator at Bedford, shortly after it had been re-commissioned following an extensive rebuild. Although the study was concentrated on one particular aspect of aircraft handling, namely the influence of speed instability during the landing approach, it is felt that the results are of wider interest, inasmuch as they show some of the difficulties which attend almost any attempt to study aircraft handling qualities systematically. This Report is therefore intended as a general contribution towards the developing subject of handling qualities research and the use of simulation.

The whole subject of aircraft handling qualities has always been somewhat elusive, largely no doubt because it depends so much on the subjective judgement of human beings, (even though they may be skilled test pilots who are trained to make such judgements). The usual practice in attempting systematic handling qualities studies is to isolate one particular handling feature (for instance speed stability, or 'dutch roll' characteristics), and to note how the 'controllability' of the aircraft changes as that feature is varied. It must be admitted that such an approach is artificial, in that, for the results of these tests to have any generality, it must be assumed that the overall handling of an aircraft is in some way related to an amalgamation of such particular features. However it is difficult to see what other approach could reasonably be adopted.

The feature studied in this investigation, stability of speed holding during the landing approach, is an important aircraft characteristic, affecting the overall work load experienced by the pilot when making a landing, possibly to the extent of being the primary factor in determining the landing approach speed[1].

Recent trends in aircraft design towards higher wing sweep, lower aspect ratio, and enhanced aerodynamic cleanliness, which have been adopted in the interests of efficiency at high speed, have reacted upon the aircraft's dynamic characteristics at landing approach speeds so as to produce lower margins of speed stability than formerly. A need has therefore arisen to study a pilot's ability to fly an aircraft with small, or even negative values of speed stability so that the possible requirement for automatic control of airspeed can be assessed. And should such a requirement be established, a knowledge of the pilot's own unaided ability is still of value in deciding the degree of reliability which must be built into the automatic equipment.

One of the reasons for selecting this particular topic as a first study on the new simulator was that flight investigations of speed stability, on a specially equipped Avro 707A aircraft, were being made at the R.A.E.[2] at about the same time. A measure of direct comparison between flight and simulator, by the same pilots, was therefore possible. In this flight experiment, artificial changes in the aircraft's speed stability were produced by varying engine thrust with airspeed by means of an automatic throttle control. Some of the pilots who took part in this experiment felt that the aircraft behaviour with the speed stability modified in this way was not quite the same as it would have been with the equivalent speed stability determined solely by an aircraft's aerodynamic characteristics. For instance, they felt that the engine thrust changes needed to produce the artificial instability were too intrusive. An attempt to check this point was made on the simulator by doing two series of tests, the first with the stability varied by engine thrust, as in the flight experiment, and the second with the stability varied by changing the aerodynamic characteristics.

In both tests two types of data were collected. Firstly, measurements were made of the overall accuracy with which the pilot flew a defined flight path, and maintained a desired approach speed, and of positional and airspeed accuracy at the end of each approach. Secondly, the pilots were asked to assess subjectively the ease or otherwise of making an approach, using a numerical rating scale to summarize their opinions, as well as giving more extended verbal comment.

Because this was the first exercise on virtually a new simulator, several equipment deficiencies came to light in the course of the trials. The general effect of these deficiencies was to make the simulator rather more difficult to fly than the real aircraft. It is therefore believed that the detailed results presented in this Report may tend to overemphasise the difficulties of flying an aircraft with reduced speed stability, if its other handling characteristics are satisfactory. The data may be more directly applicable to an aircraft which also has some other undesirable handling qualities. Notwithstanding these provisos it is felt that the data concerning such matters as inter-pilot variability, the effects of learning, etc. which were gathered during the tests are of more general application, and provide useful information for other handling qualities work.

Preliminary results from this series of tests were previously reported in Ref.3.

2 REPRESENTATION OF THE AIRCRAFT ON THE SIMULATOR

A description of the Aerodynamics Department Simulator at R.A.E. Bedford is contained in Ref.11. It consists essentially of a cockpit, containing the usual pilots flight instruments and flying controls, a simplified representation of his view of the outside world, and an electronic analogue computer.

A complete representation of the aircraft's behaviour in response to the pilot's control demands was obtained in the usual manner by continuous solution of the equations of motion on the computer. The equations were written in the conventional small perturbation form, except in the case of the drag equation, where a more detailed, non-linear form was necessary to give an adequate representation of the speed stability. The details of the analogue computation are given in Appendix A.

The numerical data for the aircraft's aerodynamic and inertial characteristics were mostly obtained from full scale measurements on the actual Avro 707A aircraft, or on the very similar Avro 707B[4,5].

Variations in the speed stability from that of the basic aircraft were obtained in the first series of tests by representing an automatic throttle control, which could be made to reduce the speed stability if operated in the reverse of the usual sense. This was also the method used in the full scale flight trials. A second series of simulator trials was made in which the aerodynamic data used in the analogue computation was changed from that of the real Avro 707, so as to produce alterations in the speed stability characteristics. The range of speed stability parameters tested is described in more detail in section 3.

The behaviour of the simulated aircraft was depicted to the pilot by means of flight instruments, and by a simple visual projection of a horizon and cloudscape. (Although this simulator is now fitted with a two axis cockpit motion system, the equipment was not functioning at the time of the tests, which were consequently made with the cockpit fixed.) The cockpit layout and flight instrument display are shown in Figs.1 and 2. The flight instrument dials were accurate replicas of real aircraft instruments, but they were not arranged in the panel in quite the same way as those in the aircraft. An additional feature was the I.L.S. indicator which was not fitted in the real Avro 707A aircraft.

A general view of the cockpit and horizon projector is shown in Fig.3. The projector was servo-driven in pitch, roll and yaw so as to provide an indication of aircraft attitude. The lower half of the projected picture was merely darkened to represent the ground, no actual ground features being portrayed.

The cockpit was provided with conventional stick and rudder controls, similar to those in the aircraft. One of the main deficiencies of the simulation, however, was the poor force feel characteristics of the simulated controls, particularly of the elevator. This was largely due to excessive friction in the control circuit, which resulted in a lack of positive stick self centering over the middle portion of the stick travel, even when the strongest force break out unit available was fitted. These characteristics are illustrated in Fig.4. Modifications to the control circuit, made since the tests reported here, have now eliminated this undesirable feature.

3 SPEED STABILITY CHARACTERISTICS

The theoretical aspects of speed stability have been studied in some detail by Neumark[6]; this analysis showed that for flight in which the aircraft is 'constrained' to fly along a given rectilinear path, for instance by using the elevator control to follow a linear glide slope, the motion following a speed disturbance will take the simple exponential form:-

$$U = U_o e^{-\frac{2g}{V}\left(\frac{C_D}{C_L} - \frac{dC_D}{dC_L}\right)t} \tag{1}$$

The time constant of this motion is therefore:-

$$\tau = -\frac{V}{2g\left(\frac{C_D}{C_L} - \frac{dC_D}{dC_L}\right)} \text{ sec} \tag{2}$$

where changes of engine thrust with airspeed have been ignored.

Previous investigators have used different, but related parameters to characterise the aircraft's speed stability. Thus Lean[1] has used the function:-

$$F = -\frac{C_L}{W/S}\left(\frac{C_D}{C_L} - \frac{dC_D}{dC_L}\right) \tag{3}$$

which is essentially a measure of the divergence or convergence of speed disturbances with distance travelled, rather than with time. Comparison of the parameters (2) and (3) shows that they are related by the expression:-

$$F = -\frac{1}{\rho V g\,\tau} \tag{4}$$

Staples[2] has used the time constant of the motion τ, but quoted in the more general form:-

$$\tau = -\frac{W}{g\left(\frac{\partial D}{\partial V} - \frac{\partial T}{\partial V}\right)} \tag{5}$$

so that the effects of an automatic throttle control can be taken into account. (In practice it is rather more convenient to use the inverse of the time constant, $1/\tau$, since this has the value zero when the speed stability is neutral.)

Bray[7] has simply used the slope of the drag v speed curve for trimmed conditions, represented by the derivative $\partial\left(\frac{T_{RLF}}{W}\right)/\partial V$, where T_{RLF} is the thrust required for level flight. Comparing this with the other parameters we have that:-

$$\partial\left(\frac{T_{RLF}}{W}\right)/\partial V = -\frac{1}{g\tau} = -\rho VF \tag{6}$$

The parameter chosen as being most convenient for the present tests was the inverse of the speed stability time constant, $1/\tau$ $\sec^{-1}$.

The numerical values of this parameter tested in the present experiment ranged from -0.014 to +0.205 $\sec^{-1}$ (mildly stable to severely unstable, according to pilots comments) in the first set of trials, and from -0.035 to +0.06 $\sec^{-1}$ in the second set.

4 EXPERIMENTAL DESIGN

The effects of any reduction in aircraft speed stability will be most apparent to the pilot when he is attempting to hold the aircraft to a closely defined flight path[1], such as that fixed by most instrument landing aids. The task represented in the simulator was therefore that of flying an I.L.S. approach, using a cross-pointer instrument to indicate horizontal and vertical deviations from the flight path. However, the information presented on this cross-pointer instrument differs from that normally presented in flight in two ways. Firstly, the sensitivity of the instrument, in terms of the pointer deflection for a given aircraft deviation from the approach path, was held constant throughout the approach, whereas with a real I.L.S. the sensitivity usually increases as the touch down point is approached. This feature of the simulation was adopted merely to ease the computational problem on the analogue computer. The actual value of sensitivity chosen was that which would normally occur at an altitude of about 600 ft on a real I.L.S. approach. (i.e. F.S.D. in elevation occurred for 100 ft deviation from the glide slope; F.S.D. in azimuth occurred for 700 ft lateral offset.)

The second feature which differed was in the lateral information presented on the cross-pointer instrument. In elevation the pointer movement was simply the deviation from the desired glide slope, and thus corresponded to the 'raw' I.L.S. information sometimes used in flight. But in azimuth the information was 'phase advanced' by the inclusion of heading and angle of bank signals. The azimuth presentation was thus of the 'zero-reader, flight director' type, the pointer deflection, δ, following the law:-

$$\delta = [S/700 + 5\psi^\circ + 2.5\phi^\circ]\,\delta_{F.S.D.}$$

This feature was adopted in an attempt to make the overall ease of the pilots' task on the simulator comparable with that in the Avro 707A flight experiment[2]. As discussed later (5.3), it was not possible to provide a true instrument approach system in the real aircraft, and a quite different method of defining the flight path had to be adopted.

The actual experimental design adopted in the first of the simulator tests is shown diagrammatically in Fig.5. It was arranged as a factorial experiment between four different pilots, three levels of speed stability and three levels of atmospheric turbulence. A further, more unstable speed condition was also tested, so as to span completely the range covered by the flight experiment, but the results from these tests were not included in the factorial analysis, because of the frequency with which very large values were recorded following loss of control. The different levels of speed stability were denoted by K_0, K_1 and K_2 (K_3) for the first experiment and S_0, S_1 and S_2 for the second. They had the values:-

K_0 -0.014
K_1 +0.026
K_2 +0.118
K_3 +0.205

S_0 -0.035
S_1 0
S_2 +0.060

The atmospheric turbulence was represented on the simulator by random signals from an electronic noise generator, which were filtered to give a power spectrum shape similar to that measured in real turbulence. The same noise generator was used to represent the vertical, horizontal, and lateral components of the turbulence, so that these were in fact correlated, but this imperfection in the simulation did not seem to be apparent to the pilots. When asked to assess the level of turbulence subjectively they generally described the 3 ft/sec rms gusts as being from 'mild' to 'moderate', and the 6 ft/sec rms gusts as being from 'moderate' to 'severe'.

All the pilots who took part in these tests were qualified test pilots. Three had taken a major part in the flight experiment on the Avro 707A, and they were therefore rather more conversant than usual with the characteristics of a speed unstable aircraft. The fourth, pilot C, took only a minor part in the flight experiment, but he was rather more experienced in making I.L.S. instrument approaches than the others, who had had relatively little practice in that technique.

The data which were collected during the tests are also listed in Fig.5. Six of the items were measures of actual pilot performance in the approach task, while the seventh was a subjective judgement by the pilot as to the ease or difficulty of controlling the aircraft. For the latter assessment, use was made of a pilot opinion rating scale of the type originally proposed by Cooper[8]. Although the numerical rating points on the scale used in the present tests were intended to correspond to the same degree of difficulty as those on Cooper's scale, the actual verbal descriptions used were somewhat different. They are given in Table 1 and were specially compiled for the Avro 707A flight experiment[2]. As with other rating scales the present descriptions were not found to be entirely free from ambiguity, and the widespread adoption of this particular form is not advocated. The measures of pilot performance used in the simulator studies were as follows: the mean modulus deviations of height, lateral displacement and airspeed taken over the whole approach, (i.e. deviations taken without regard to their sign), together with the instantaneous values of these parameters measured at the end of the approach phase, which was taken to be at an altitude of 300 ft. In evaluating the time integral of the deviations, needed for calculating the mean modulus errors described above, no account was taken of very small deviations from the desired flight path and airspeed. This was done because it was felt that the pilot would happily allow such small errors to remain without making any attempt to correct them. The limits of this acceptable 'corridor' were set, rather arbitrarily, at ±20 ft in height,

±140 ft in lateral displacement, and ±2.4 kt (4 ft/sec) in airspeed. (For the I.L.S. deviations these limits corresponded to being within the centre circle of the I.L.S. meter, Fig.2.) The data given in the tables for mean deviations therefore refer to deviations in excess of this zone, but the instantaneous deviations at the end of each approach, (i.e. at the 300 ft point), are quoted as absolute values.

The pilots taking part in the experiment were briefed on the methods of measurement that were being used, and realised that they had to try to keep the aircraft within the acceptable corridor just described. Several of them mentioned that they thought that this was a slightly artificial exercise, in that it required them to correct any deviations as rapidly as possible. In flight they said that they would not be too anxious to eliminate errors as quickly as this, provided the correct trends were present, and that they were confident of reaching the desired condition in the later stages of the approach. In the light of these comments it is felt that care is needed in interpreting the results from measurements of mean deviation recorded over the whole length of instrument approaches.

When running the experiment each simulated approach started at a height of about 1800 ft, with the aircraft trimmed for the approach flight path and speed. Measurements were not started until the aircraft passed through 1500 ft; they then continued down to the 'break off' height of 300 ft, giving an average time for the measured portion of each run of about two minutes. Nine runs were made in each session, covering the 3 × 3 combinations of different levels of speed stability and turbulence intensity. The various conditions were presented in a random order, and the pilot was not told what variations were being made from run to run.

5 RESULTS AND DISCUSSION

5.1 Pilot's overall impressions of the simulation

The validity of the simulation, as a guide to speed stability problems in real flight, obviously depends upon the realism of the simulation. While the purely computational aspects could be checked by matching time histories of the computer outputs with trace recordings made in flight, the realism, from the pilot's point of view, may depend equally on the general environment of the simulator, and on the methods which are used to inform the pilot of the aircraft's behaviour. These are largely subjective matters which are not amenable to precise analysis.

Although only four pilots took part in the systematic speed stability experiment, a total of fifteen qualified pilots assessed the simulator for overall realism. All but two of these had flown the actual Avro 707A aircraft. The range of pilot opinion was very large, one or two pilots, in particular, finding it unusually difficult to adjust to the different environment of the simulator. For them there was little realism, and one described how he found himself gazing at the flight instruments in a curiously detached manner, which made it quite impossible for him to integrate or relate their readings into a meaningful flying task.

For the majority of the pilots however the simulation, with the exception of the features mentioned below, represented the characteristics of the Avro 707A aircraft reasonably well, and this was certainly the case for the four pilots who took part in the systematic study. The features which were felt to be unrepresentative were:-

1 The force feel characteristics of the flying controls, particularly the elevator, which were poor. Excessive friction prevented the attainment of positive self centering in the middle of the stick travel. (see Fig.4)

2 The simulator appeared to be more sensitive laterally than the aircraft, both to control application and to the effects of gusts. In the light of subsequent experience with this simulator, it is thought that this subjective impression was largely due to the lack of cockpit motion.

3 There appeared to be a hesitation in the operation of the artificial horizon, so that pitching response to the controls was not immediately apparent on that instrument. (This feature, which was due to servo lags, has since been eliminated.)

The overall effect of these simulator imperfections was to make the simulator rather more difficult to control than the real aircraft.

5.2 Pilot opinion data from the factorial experiment on speed stability and turbulence

As explained earlier, two sets of tests were made in this experiment, one with the speed stability varied by representing an automatic throttle control, as used in the flight experiment, and the other with the speed stability changes brought about by variation of the aerodynamic characteristics. As far as the actual dynamic behaviour of the aircraft was concerned the principal differences arising from these two methods were those introduced by the engine lag, and by the limited authority of the autothrottle. However the latter feature was only apparent for the very unstable conditions, which needed such a high autothrottle gearing that the throttle was sometimes driven onto its limits. The effect of the engine lag was probably too small to be readily distinguished by the pilot. But there were considerable differences between the two methods in such features as engine noise and rpm indicator variations.

Pilot opinions, expressed in terms of the numerical rating scale described in table 1, are listed in tables 2 and 3 for the two series of tests. (The ratings given by a fifth pilot, who did not take part in the complete series of tests are also listed in table 3.) In making their evaluations pilots were asked to assess the acceptability of each configuration for general use by service pilots, rather than for the somewhat artificial conditions of test flying. (As noted in table 2, this briefing was mis-understood on one occasion.)

In most cases the whole series of tests was repeated at least once, and sometimes twice by each pilot. This replication was intended to test the assessments for consistency, and to reveal any time variant effects, for instance due to learning. The various conditions were tested in a random, (and therefore different), order in each trial, and the pilot was not told which condition he was testing, either before or after the run. The interval between the replications was usually a day or two.

The data for these repeated trials, given in tables 2 and 3, show that individual pilots were, generally speaking, consistent to within one rating point in either direction for a given test condition. There did not appear to be any distinctive trend in pilot opinion with repeated tests, a feature which is noteworthy, since it will be shown later that the measures of pilot performance did, in some cases, exhibit an improvement which was consistent with learning.

The variation of pilot opinion rating with speed stability and turbulence level is shown separately for each pilot in the four plots of Fig.6. The data for both series of tests (i.e. speed instability produced by reversed autothrottle, and modified aerodynamic characteristics) are presented together, since, except where specifically mentioned below, there was no inconsistency between them.

All the plots in Fig.6 show the expected trend towards more adverse opinion ratings with decreasing speed stability, but otherwise there are notable differences between the data from the various pilots. In the case of pilots A and B the opinion ratings appear to be well correlated with the level of turbulence and speed stability, so that we may deduce that these two parameters were the major factors affecting the pilots assessments. However the ratings given by pilot A were more affected by the turbulence level than were those of pilot B and, for the still air case, B's ratings were some one and a half points further down the rating scale than A's, for a given level of speed stability.

Pilot C's rating data were less well correlated with the two experimental variables, but this pilot made only one trial in each series of tests, compared with the three made by pilots A and B, so that the smoothing effect of averaging was absent. His data tend to agree with that of pilot A rather than pilot B.

Pilot D's rating data were rather poorly correlated with the two experimental variables. One reason may be given, the lack of repeated trials with this pilot, but a more important effect seems to be a consistent difference in the ratings between the tests made with reversed autothrottle, ($1/\tau$ values of -0.014, +0.026 and +0.118 sec^{-1}) and those with the speed instability produced by modifying the aerodynamic characteristics, ($1/\tau$ values of -0.035, 0 and +0.06 sec^{-1}). In order to study these differences in pilot rating in more detail a further analysis has been made, based on pilots own assessments of the level of speed stability and turbulence.

It will be remembered that the pilot was not told which condition he would be testing during a run. At the end of the approach, however, he was asked to give his own assessment of the severity of the turbulence and speed instability, using such terms as 'mild', 'moderate' or 'severe'. This assessment was in addition to his pilot opinion rating of the overall 'acceptability' of the condition and any other comment he cared to make. In Fig.7 the pilot opinion ratings have been replotted against the pilots own assessments of the test conditions.

Comparison of these plots for pilots A and B shows, once again, that pilot B tended to rate a condition about one and a half points lower on the scale than A, even though they both used the same general terms to describe it. Subsequent discussion with these pilots revealed some basic differences in their attitude to opinion rating, which, while not specifically explaining this discrepancy, did point out some factors which need to be covered by careful briefing in future tests of this sort.

Pilot A maintained that the assessment was meaningful only when aircraft characteristics and the operating conditions were defined. Thus, since the difficulty of flying an aircraft almost invariably increases with the severity of the turbulence, a corresponding trend towards more adverse ratings with increased turbulence was to be expected. In theory, at least, it would always be possible to find some level of turbulence at which the aircraft became uncontrollable, and therefore qualified for an 'unacceptable' rating.

Pilot B's method of assessment, which, it will be remembered, produced superficially the most convincing data, (Fig.6) was, perhaps, less satisfactory, since it evidently depended mainly on assigning the rating according to his assessment of the speed stability, and seemed to contain a much smaller element of judgement as to how difficult these changes really made the flying task.

Pilot C's ratings, when plotted against his own assessment of the speed instability and turbulence level, Fig.7, show rather better correlation than when plotted against the actual numerical values of these parameters. In either case the ratings vary with both the level of speed stability and turbulence in a manner which indicates that his rating method is that of pilot A rather than pilot B.

Pilot D's ratings do not correlate well when plotted against his own assessments of speed stability and turbulence. Moreover his additional comments do not explain the consistent differences in his ratings between the tests with reversed autothrottle and with aerodynamically produced speed instability. These differences therefore remain something of a mystery.

From the foregoing a somewhat confused impression of the pilots' assessments of speed stability variation emerges. However when account is also taken of the extended verbal comment made during the trials a few general conclusions may be suggested. At the severest levels of speed instability tested (i.e. an exponential divergence of time constant 5 sec) control was almost invariably lost at some stage of the approach, and it is considered that such a characteristic would be quite unacceptable, even for the semi-emergency condition after an automatic throttle had failed. Divergence time constants between 10 and 20 seconds would be unacceptable as a standard aircraft condition, but might be allowable for the rare eventuality of an automatic equipment failure. Over the remainder of the range tested, i.e. from motions which diverge with time constants greater than 20 sec, to motions which converge with time constants greater than about 30 sec, there were indications of a progressive improvement in handling as stability of speed holding was increased. It might be expected therefore that even shorter time constants would be needed before the speed holding problem disappeared entirely.

5.3 Comparison of pilot opinion data obtained in the simulator with that from flight trials

As mentioned in section 4, three of the pilots who took part in the simulator trials (A, B and D), had also played a major part in the flight trials. For them a direct comparison between their opinion ratings given in flight and on the simulator is therefore possible. This is shown in Fig.8.

There were however some differences between the flight and simulator experiment which should first be mentioned. It will be recalled that in the simulator the task was to fly an instrument approach using an I.L.S. meter type presentation. It was not possible to fit such an instrument approach aid to the real aircraft, and in consequence a ground controlled "talk down" method was adopted, using a theodolite sight where a very precise flight path was required, or radar equipment for a task more representative of real bad weather approaches.

Another difficulty in comparing the flight and simulator trials lay in determining the level of atmospheric turbulence in the flight experiments. Pilots were asked to make their own subjective judgements of the turbulence intensity, and the known correlation of turbulence with mean windspeed could also be used as a guide, but these assessments were obviously less precise than on the simulator, where the turbulence could be set at any desired level. The ratings shown in Fig.8 are from trials in which the pilot assessed the turbulence as being between mild and moderate.

Comparison between the flight and simulator ratings for pilot A (Fig.8) shows very good agreement. Pilot B, on the other hand, always rates the real aircraft less severely than the simulator, and he finds the deterioration in handling qualities with speed instability much less troublesome in the air than on the ground. Once again, Pilot D's ratings show a pattern which is different from the others, his assessment remaining virtually constant at "average, some unpleasant characteristics" over the range of speed instability tested.

5.4 Discussion of pilot opinion data

The overall impression given by this pilot opinion data is one of some confusion, particularly as regards the variability between different pilots. Although genuine differences of opinion as to the handling qualities of an aircraft are, of course, to be expected amongst different pilots, it is felt that the lack of consistency evident in the present test results may also be due to other factors.

Chief amongst these is probably the lack of an agreed meaning for the rating scale itself. An instance already cited is whether the rating should be gauged only on the conditions of workload, turbulence, etc. actually experienced during the test, or whether it should be a more comprehensive assessment, containing a measure of extrapolation by the pilot to cover situations which he knows may be met with in practice. In the latter case only one rating may be expected, covering the worst circumstances likely to be experienced, while with the former usage a whole range of ratings appropriate to the different conditions are to be sought.

In the present tests reliance was placed, perhaps too heavily, on the wording of the rating scale itself. It was felt at the time that there was a danger in promoting too much discussion on the interpretation of the rating scale, prior to the tests, in that it might then become so rigidly defined as to eliminate any element of subjective judgement. With the benefit of hindsight it is felt that this fear was over-valued, and that, in so far as pilot opinion scales can be used to obtain worthwhile data, their use must be based on previous discussion and agreement by the subject pilots as to their meaning. While accepting the use of opinion rating scales as being a concise method of classifying and recording pilots' assessments, it is felt that they in no way diminish the need for recording and studying the pilots' extended verbal comment on each configuration.

Comparison of the results of the present study with other published work has not been included in this Report as it will form part of a more comprehensive paper[10] on aircraft handling qualities.

5.5 Measures of pilot's performance in the simulator

The parameters used as measures of pilot performance in the simulated approach task have been described in section 4 and they are also listed in Fig.5. The data collected in the present tests are given in table 4, for the trials with reversed automatic throttle control, and in table 5 for the trials where speed instability was produced by variation of the aircraft's aerodynamic characteristics.

As a preliminary exercise the parameter which was taken to be the best overall measure of speed holding, (i.e. the mean modulus speed error from the desired approach speed), was studied by a straightforward analysis of variance for the three factors; level of speed stability, level of turbulence, and individual pilot. This analysis showed significant differences (to the 0.1%

level) in the speed holding with different levels of speed stability and with different pilots, but the different levels of turbulence did not appear to affect the speed holding (to the 5% level). The same result was found for both methods of producing the variation in speed stability, (i.e. reversed autothrottle and 'aerodynamic').

In this first analysis the data from all the repeated trials by different pilots was included. Subsequently, when it was found that there was considerable evidence of an improvement in performance as the trials progressed, the analysis of variance was repeated, but using only the last trial made by each pilot. This re-analysis gave the same result; a significant difference in speed holding with level of speed stability, and between different pilots, but no effect due to different levels of turbulence.

The data for mean speed deviation for two of the pilots, A and B, are shown in histogram form in Figs.9 and 10. The three groups across the page represent different levels of turbulence, while variations in speed stability are shown within each group. Results for the three trials made by each of these pilots are shown in order down the page.

The most obvious feature of Fig.9 is the consistently lower speed errors achieved by pilot A in his third trial. The mean speed errors fall from values of around one or two knots in the first two trials, to values of a fraction of a knot in the last trial. On the other hand pilot B, (Fig.10), shows a rather better performance on his second trial than on his first and last. For both pilots the trends shown by the statistical analysis of variance, (i.e. dependence of speed holding on speed stability, but not on turbulence intensity), are apparent in the histogram plots.

The possibility of there being a learning effect, which led to progressively improved performance during the experiment, has been studied in more detail with the aid of plots such as Figs.11 and 12. These show the six measures of performance plotted simply in the serial order in which the test runs were made. Considerable scatter is therefore to be expected, since 'easy' and 'difficult' conditions are randomly intermixed, but any learning effect should show up as a consistent trend towards reduced errors as the experiment progressed. One additional point to note is that trials 1, 2 and 3 were for the speed stability varied by the reversed autothrottle, while trials 4, 5 and 6 were for the speed stability varied by changing the aircraft's aerodynamic characteristics.

Pilot A's performance data, shown in Fig.11, does give a fairly clear indication of learning, particularly between the first, second, and subsequent trials, and this is apparent in all six measures of performance. On the other hand the data for pilot B, given in Fig.12, seems to support the previous impression gained from the histogram plots, that there was little systematic change in this pilot's performance as the trial progressed. The exception to this is in the lateral accuracies where some improvement is evident.

These results suggest that a general statement as to whether a given level of speed stability will result in an acceptable performance may not be entirely meaningful, without some consideration of the pilots training and recent practice. As an example, Fig.13 shows the variation of speed and height errors at the end of the approach, with different levels of speed stability, in two sets of plots. Those on the left show data from each pilot's first trial, and indicate a deterioration in performance with each successive reduction in speed stability. The plots on the right show data from each pilot's last trial, and there is now no important difference between the stable and mildly unstable conditions (Fig.13(a) and (b)). Only when the speed characteristics become moderately unstable does a significant deterioration in performance occur.

Pilots comments on the use of mean deviation from the desired approach conditions, measured over the whole run, as a performance criteria have already been noted in section 4. From the practical point of view of approach success it is, of course, the deviations close to the break off point which are important. It is of interest to determine whether there is a close correlation between the mean error measured over the whole run and the instantaneous error at the break off height. In the present tests, it will be remembered, the integral error used for determining the mean excluded small errors, (less than ±2.4 knots in the case of speed), so that the significance of a direct comparison of the present data is a little uncertain. Nevertheless Fig.14, in which the mean speed error is plotted against the error at break off, suggests that the correlation is rather weak.

6 CONCLUSIONS

Simulation of the Avro 707A aircraft, at about the same time as full scale flight trials were taking place, allowed a direct comparison by pilots of the simulated and actual handling characteristics. In general pilots found that the simulation represented the aircraft reasonably faithfully, although there were some features which made the simulator rather more difficult to control than the real aircraft.

A systematic study of the effect of varying speed stability and turbulence on the aircraft's handling showed the following features:-

1 Over the range of speed stability tested, (i.e. convergent motion with a time constant of 30 seconds, through to divergent motion with a time constant of 5 seconds), pilot opinion became progressively more adverse as the stability was reduced. At the worst condition, ($\tau \simeq + 5$ sec), control was frequently lost altogether, and such characteristics would consequently be unacceptable for any type of operation. The level of speed stability at which the handling became just unacceptable was by no means firmly established, due to the general difficulty of making subjective judgements of this sort which led to large variations of opinion between different pilots. There was some indication that divergent motions with time constants of not less than 20 seconds, might be acceptable, (although undesirable), given conditions which were otherwise favourable.

2 A statistical analysis of the accuracy of the approach, as measured by the speed error from the desired approach speed, (meaned over the whole run), showed significant differences for different levels of speed stability, and between individual pilots. Changes in turbulence intensity, however, produced no significant changes in the accuracy of speed holding. The correlation between speed error at the moment of passing through the 300 foot break off height, and speed error meaned over the whole run, was unexpectedly weak.

3 For at least one pilot, significant learning effects on performance were noted over the first twenty or so approaches, (not counting any additional approaches made before the systematic trials started). It is evident therefore that a pilot's performance in flight may depend on the extent to which he is 'in practice'.

This was the first study on this facility in which a systematic investigation of an aircraft handling parameter had been attempted. It was also the first study to be made on the simulator following an extensive rebuild. Apart from revealing a few equipment deficiences, the following more general conclusions regarding this type of work have been reached.

(i) The use of pilot opinion rating scales for aircraft handling qualities assessments needs considerable care. Agreement between the participating pilots as to the meaning of the scale, and the exact basis on which assessments are to be made, should be reached prior to the trial. The rating scale should be supplemented by pilot's verbal comment.

(ii) Despite these precautions inter-pilot variability is to be expected and an adequate sample of pilots should be used.

(iii) Significant learning effects may be present and the state of practice at which performance measurements are required must be decided.

(iv) Care is needed in choosing the measures of performance used. While 'end results' may be of the greatest practical significance, means taken over an extended period can also be used, and perhaps provide a better indication of task difficulty.

Appendix A

ANALOGUE COMPUTATION OF THE AIRCRAFT'S EQUATIONS OF MOTION

A.1 Translational motion

The equations governing the translational motion of the aircraft's centre of gravity were related to an axis system based on the flight path. In this system the X (or forward) axis was aligned along the instantaneous flight path direction; the Z (or normal) axis was perpendicular to it, and in the plane of symmetry of the aircraft, while the Y (or lateral) axis was mutually perpendicular to the other two.

The translational motion was defined by three variables; the acceleration along the flight path $(\dot{V})$, and the components of flight path angular velocity in the XZ and XY planes. The latter were denoted by (Q_W) and (R_W) respectively. The complete equations of motion for a rigid aircraft in these terms have been previously derived by, for instance, Howe[9]. In the present case all the variables in the equations were considered as perturbations from those obtaining in trimmed level flight at the datum approach speed. Small angle approximations were also made, where appropriate, and particularly in resolving the force components from 'body' or 'stability' axes onto the flight path axes.

Variable quantities in the following equations are shown thus ( ). The fixed coefficients in these equations were based on data for the mean flight condition and these are listed in section A.

The translational equations of motion used were:-

For acceleration along the flight path

$$m(\dot{V}) = (\Delta T) - qS\left[\frac{2C_D}{V}(\Delta V) + \frac{dC_D}{d\alpha}(\Delta\alpha) + \frac{dC_D}{d\eta}(\Delta\eta)\right]$$

$$+ qS\left[\frac{dC_Y}{d\beta}(\beta) + \frac{dC_Y}{d\zeta}(\zeta)\right](\beta) - mg\sin(\theta_W) \qquad (A1)$$

For flight path angular velocity in the XZ (normal) plane

$$mV(Q_W) = (\Delta T)[\alpha + (\Delta\alpha)] + T(\Delta\alpha) + qS\left[\frac{2C_L}{V}(\Delta V) + \frac{dC_L}{d\alpha}(\Delta\alpha) + \frac{dC_L}{d\eta}(\Delta\eta)\right]$$

$$- mg[1 - \cos(\theta_W)\cos(\phi_W)] \qquad (A2)$$

For flight path angular velocity in the XY (lateral) plane

$$mV(\dot{R}_W) = -(\Delta T)(\beta) + qS\left[\frac{dC_Y}{d\beta}(\beta) + \frac{dC_Y}{d\zeta}(\zeta)\right]$$

$$+ qS\left[\frac{2C_D}{V}(\Delta V) + \frac{dC_D}{d\alpha}(\Delta\alpha) + \frac{dC_D}{d\eta}(\Delta\eta)\right](\beta)$$

$$+ mg\cos(\theta_W)\sin(\phi_W) \qquad (A3)$$

A.2 Rotational motion

The equations governing the rotational motion about the aircraft's centre of gravity were related to an axis system fixed in the aircraft. In this case the X (or rolling) axis was aligned along the aircraft body datum line, the Z (or yawing) axis was perpendicular to it and in the aircraft plane of symmetry, while the Y (or pitching) axis was mutually perpendicular to the other two. Since aerodynamic data is conventionally presented with respect to the body-fixed, stability axis system, (which is inclined to the body datum at the angle of incidence), it was necessary to resolve both aerodynamic moments and rotational velocities from one axis system to the other*. Small angle approximations were assumed in making these resolutions. In the following equations the symbols R_B, P_B, Q_B denote rotational velocity components about the body axis system defined above, while R_S and P_S denote rotational velocity components about the stability axis system. The approximate (small angle) relationships between them, used in this simulation were:-

$$(P_S) = (P_B) + (R_B)[\alpha + (\Delta\alpha)] \qquad (A4)$$

$$(R_S) = -(P_B)[\alpha + (\Delta\alpha)] + (R_B) \qquad (A5)$$

The equations of motion used were:-

For pitching rotation

$$I_{YY}(\dot{Q}_B) = qS\bar{\bar{c}}(\Delta C_M) \qquad (A6)$$

---

* This resolution merely takes account of the changing orientation of the stability axis system in the body as the incidence is changed. As far as rotational motion is concerned, both sets of axes are body-fixed.

where

$$(\Delta C_M) = \frac{dC_M}{d\alpha}(\Delta\alpha) + \frac{dC_M}{d\eta}(\Delta\eta) + \frac{dC_M}{d\left[\frac{Q\bar{\bar{c}}}{2V}\right]}\frac{\bar{\bar{c}}}{2V}(Q_B) + \frac{dC_M}{d\left[\frac{\dot{\alpha}\bar{\bar{c}}}{2V}\right]}\frac{\bar{\bar{c}}}{2V}(\dot{\alpha}) \qquad (A7)$$

For rolling and yawing motions

$$I_{XX}(\dot{P}_B) = qSb\,(\Delta C_\ell) - qSb\,(\Delta C_n)\,[\alpha + (\Delta\alpha)] + I_{XZ}(\dot{R}_B) \qquad (A8)$$

$$I_{ZZ}(\dot{R}_B) = qSb\,(\Delta C_n) + qSb\,(\Delta C_\ell)\,[\alpha + (\Delta\alpha)] + I_{XZ}(\dot{P}_B) \qquad (A9)$$

where

$$(\Delta C_\ell) = \frac{dC_\ell}{d\beta}(\beta) + \frac{dC_\ell}{d\xi}(\xi) + \frac{dC_\ell}{d\zeta}(\zeta) + \frac{dC_\ell}{d\left[\frac{P_S b}{2V}\right]}\frac{b}{2V}(P_S) + \frac{dC_\ell}{d\left[\frac{R_S b}{2V}\right]}\frac{b}{2V}(R_S) \qquad (A10)$$

$$(\Delta C_n) = \frac{dC_n}{d\beta}(\beta) + \frac{dC_n}{d\xi}(\xi) + \frac{dC_n}{d\zeta}(\zeta) + \frac{dC_n}{d\left[\frac{P_S b}{2V}\right]}\frac{b}{2V}(P_S) + \frac{dC_n}{d\left[\frac{R_S b}{2V}\right]}\frac{b}{2V}(R_S) \qquad (A11)$$

A.3 Euler angle computations and other kinematic relationships

The orientation of the flight path axis system with respect to earth was defined by the three Euler angles, θ_W, ψ_W and ϕ_W. These are related to the angular velocities of the flight path axis system, Q_W, R_W and P_W by the well-known equations:-

$$\dot{\theta}_W = Q_W \cos\phi_W - R_W \sin\phi_W \qquad (A12)$$

$$\dot{\phi}_W = P_W + \dot{\psi}_W \sin\theta_W \qquad (A13)$$

$$\dot{\psi}_W = (R_W \cos\phi_W + Q_W \sin\phi_W)\sec\theta_W \qquad (A14)$$

The equations for Q_W and R_W, in terms of the forces applied at the aircraft centre of gravity, are given in section A.1 above. It may be shown[9] that the angular velocity of the flight path system about the X (or forward) axis is given by the expression.

$$P_W \cos \beta \;=\; P_S + Q_W \sin \beta \tag{A15}$$

Making the usual approximations for small angles, equations (A14) and (A15), may be reduced to the simpler forms used for this simulation:-

$$(\dot{\psi}_W) \approx (R_W) \cos (\phi_W) + (Q_W) \sin (\phi_W) \tag{A16}$$

and

$$(P_W) \approx (P_B) + (R_B) [\alpha + (\Delta\alpha)] + (Q_W)(\beta) \tag{A17}$$

The kinematic relationships for incidence and sideslip, in terms of the variables already discussed, are also derived by Howe[9]. Strictly they are:-

$$(\dot{\beta}) \;=\; (R_W) - (R_S) \tag{A18}$$

and

$$\dot{\alpha} \;=\; Q_S - Q_W \cos \beta - P_W \sin \beta \tag{A19}$$

since β is always small, however, the following approximation was used in the simulation.

$$(\dot{\alpha}) \;=\; (Q_S) - (Q_W) - (P_W)(\beta) \tag{A20}$$

Finally it was necessary to compute the Euler angles of aircraft attitude from the flight path Euler angles, together with the angles of incidence and sideslip. Although, in theory, these Euler attitude angles could have been computed directly from the angular motions given by (A6), (A8) and (A9), this would have involved parallel integration on the computer, with its attendant problems of drift and accuracy.

The following approximations have been derived from the exact equations given by Howe[9].

$$(\theta_B) \mathrel{\widehat{=}} (\theta_W) + (\alpha) \tag{A21}$$

$$(\phi_B) \simeq (\phi_W) \tag{A22}$$

$$(\psi_B) \simeq (\psi_W) - (\beta) \tag{A23)*}$$

A.4 Effects of turbulence

As mentioned in section 4 turbulence was represented by random signals from an electronic noise generator. These signals were added to the perturbations in incidence, sideslip and speed, obtained from solution of the kinematic equations given above, to produce the effective incidence, sideslip and speed used for computing the aerodynamic forces and moments. In resolving forces and moments from wind axes to body axes however only the kinematic contribution to incidence and sideslip was required.

A.5 Numerical data used for the simulation

Datum flight speed	V	120 kt (202.5 ft/sec)
A.U.W.		9820 lb
Wing area	S	408 sq ft
Aerodynamic mean chord	$\bar{\bar{c}}$	14.54 ft
Span	b	34.16 ft
Pitching moment of inertia	I_{YY}	17415 slug - ft^2
Rolling moment of inertia	I_{XX}	6358 slug - ft^2
Yawing moment of inertia	I_{ZZ}	22079 slug - ft^2
Product of inertia	I_{XZ}	275 slug - ft^2

Aerodynamic data

Datum C_L	0.48
Datum C_D	0.088
Datum α	12^o
Datum η	-2.8^o
Datum thrust	1795 lb
$dC_L/d\alpha$	2.64 per rad
$dC_L/d\eta$	0.57 per rad
$dC_D/d\alpha$	0.372 per rad**
$dC_D/d\eta$	0.073 per rad

---

*Care is needed in using the approximation (A23) where the angles of incidence are appreciable. A more satisfactory approximation is then

$$\psi_B \simeq \psi_W - \beta + \phi_W\,\alpha$$

**For the second series of experiments the empirical expression $\frac{dC_D}{d\alpha} = 0.0336\,(0.0875 + 0.0415\,\alpha_B^o)$ was used. Variations in speed stability were obtained by flying at different values of α_B.

$dC_M/d\alpha$	-0.154 per rad
$dC_M/d\eta$	-0.197 per rad
$dC_M/d\left[\frac{Q\bar{c}}{2V}\right]$	-1.452 per rad
$dC_M/d\left[\frac{\dot{\alpha}\bar{c}}{2V}\right]$	+0.428 per rad
$dC_Y/d\beta$	-0.448 per rad
$dC_Y/d\zeta$	+0.103 per rad
$dC_\ell/d\beta$	-0.106 per rad
$dC_\ell/d\xi$	-0.0795 per rad
$dC_\ell/d\zeta$	+0.0035 per rad
$dC_\ell/d\left[\frac{P_Sb}{2V}\right]$	-0.300 per rad
$dC_\ell/d\left[\frac{R_Sb}{2V}\right]$	+0.095 per rad
$dC_n/d\beta$	+0.0557 per rad
$dC_n/d\xi$	+0.015 per rad
$dC_n/d\zeta$	-0.0334 per rad
$dC_n/d\left[\frac{P_Sb}{2V}\right]$	-0.025 per rad
$dC_n/d\left[\frac{R_Sb}{2V}\right]$	-0.080 per rad

Table 1

Pilot opinion rating scale used in flight and simulator studies of speed stability

Satisfactory	1 Excellent	One of the easiest of its type
	2 Good	Well above average, pleasant to fly on approach
	3 Satisfactory	Above average, midly unpleasent only
Unsatisfactory	4 Acceptable	Average, some unpleasant characteristics
	5 Poor	Below average, unacceptable for normal operation
	6 Very poor	Well below average, acceptable for emergency operation only
Unacceptable	7 Dangerous	May have to overshoot
	8 Very dangerous	Probably have to overshoot (on more than 50% of occasions)
	9 Barely controllable	Likely to break something no matter how many overshoots
	10 Catastrophic	Certain to break something

Table 2

Consistency of pilot ratings during repeated trials speed stability varied by autothrottle

	Stab. / Trial	Still air			rms gust vel. 3 ft/sec			rms gust vel. 6 ft/sec		
		K0	K1	K2	K0	K1	K2	K0	K1	K2
Pilot A	1st	2	2	4	3	4	5	4	4	5
	2nd	3	3.5	5	4	4	7.5	5	6	7
	3rd	3	3	4.5	4	4	5	5	5.5	6
Pilot B	1st	4	4.5	5	4.5	5	6	5	4.5	7
	2nd	4	5	6	4.5	5	6	5	6	6
	3rd	4	5	7	4	4.5	7	5	4.5	6.5
Pilot C	1st	2*	2*	2*	3*	3*	3*	4*	4*	5.5*
	2nd	2⌿	5⌿	5.5⌿	3⌿	4⌿	6.5⌿	6⌿	6⌿	7.5⌿
Pilot D	1st	3.5	3	4.5	4	3	4	5.5	5.5	9
	2nd	2	3	5	4	5	4	5.5	7	7.5

*Acceptability for test pilot under experimental conditions

⌿Acceptability for general service use

Table 3

Consistency of pilot ratings during repeated trials

speed instability due to aerodynamic effects

		Still air			rms gust vel. 3 ft/sec			rms gust vel. 6 ft/sec		
	Stab. / Trial	S0	S1	S2	S0	S1	S2	S0	S1	S2
Pilot A	1st	2	2.5	3	3.5	4	5	4	6	5.5
	2nd	4	3	5	4	3	6	5	6	5.5
	3rd	1	3	4	3	4	4.5	4.5	5.5	5
Pilot B	1st	4	3.5	5.5	5	5	5	5	5	6
	2nd	3.5	4	5.5	4.5	4	5.5	5	5	5.5
	3rd	3	4	5	4	4	5	4	5	6
Pilot C	1st	2	3	3	3	5	6.5	3	6	5.5
Pilot D	1st	2	1.5	2	2.5	2.5	3	3.5	3.5	4
Pilot E	1st	2	2	5	3	3	4	9	5	9.5

Table 4

Collected data for trials with speed stability varied by autothrottle

Test condition					Measurements						
					Modulus mean error			Final error			
Date	Run No.	Pilot	Gust level ft/sec rms	Speed stability	Height ft	Lateral ft	Speed kts	Height ft	Lateral ft	Speed kts	Pilot rating
16.3.62	1	A	3	K3	OS	47.5	OS	OS	OS	+21.9	8
"	2	"	6	KO	1.2	2.9	0.2	- 9	- 31	+ 3.2	4
"	3	"	3	K2	14.6	14.6	5.8	-23	+175	+ 3.2	5
"	4	"	3	KO	0.4	1.4	0.8	+11	+ 21	- 0.4	3
"	5	"	0	K1	6.2	24.8	1.6	- 6	+269	- 4.8	2
"	6	"	3	K1	1.9	0	0.8	-30	+118	- 4.5	4
"	7	"	0	K2	13.7	12.0	1.9	+30	+154	- 4.6	4
"	8	"	0	K3	8.3	14.5	3.4	-20	+140	- 0.1	4.5
"	9	"	6	K3	8.7	13.5	1.9	-50	+ 14	- 1.6	8
"	10	"	6	K2	5.8	3.2	2.7	-10	- 42	- 6.8	5
"	11	"	0	KO	4.0	4.6	2.0	- 6	+ 35	+ 4.1	2
"	12	"	6	K1	1.4	1.8	1.0	-23	-154	- 3.3	4
20.3.62	1	B	6	K3	OS	120.0	OS		Abandoned		9
"	2	"	3	K1	2.2	44.0	1.9	+46	-189	+ 3.8	5
"	3	"	0	KO	1.0	0	0.3	+ 9	+ 45	0	4
"	4	"	3	K2	17.4	7.6	2.3	-22	-154	- 0.6	6
"	5	"	0	K1	1.6	0	1.6	+20	+ 7	- 1.7	4.5
"	6	"	6	KO	2.9	17.2	0.7	-30	+ 14	- 0.4	5
"	7	"	6	K1	2.2	13.4	1.0	-13	+ 49	- 4.4	4.5
"	8	"	0	K3	2.1	4.7	1.8	+39	+ 7	+ 8.9	7
"	9	"	3	KO	1.3	11.2	0.3	-18	+ 63	+ 0.4	4.5
"	10	"	0	K2	2.5	21.4	0.9	- 4	+ 28	- 1.7	5
"	11	"	3	K3	47.5	35.0	6.1	+114	+140	+ 4.4	9
"	12	"	6	K2	6.4	22.5	1.5	+ 2	-210	+ 5.4	7
22.3.62	1	A	0	K2	13.0	0	3.4	+85	+ 84	+11.3	5
"	2	"	3	KO	0.5	1.9	0	+10	+196	+ 3.0	4
"	3	"	3	K1	0.8	9.5	0.7	+ 1	+ 42	+ 4.7	4
"	4	"	6	KO	0.5	7.0	0.3	+ 2	-101	+ 1.8	5
"	5	"	0	K1	3.0	1.7	1.0	+19	+175	- 5.9	3.5
"	6	"	3	K2	32.8	15.3	3.4	+ 9	+ 3	- 2.4	7.5
"	7	"	6	K1	3.5	0	1.9	+30	+115	+ 8.0	6
"	8	"	6	K2	7.5	0	4.5	-25	- 91	-11.5	7
"	9	"	0	KO	1.1	11.2	1.2	+33	+196	- 4.7	3
22.3.62	1	C	3	K2	11.1	7.2	1.2	+40	+189	+ 0.6	3*
"	2	"	0	K2	3.1	18.1	0.6	+ 6	+112	+ 0.3	2*
"	3	"	6	KO	3.2	3.8	0.1	- 2	+133	0	4*
"	4	"	0	K1	1.0	0	0.3	+18	+147	- 0.8	2*
"	5	"	6	K2	7.9	61.5	0.5	-29	+140	+ 2.4	5.5*
"	6	"	3	K1	1.1	33.8	0.1	- 2	+133	+ 1.8	3*
"	7	"	6	K1	2.0	27.8	0.2	-29	+259	+ 2.4	4*
"	8	"	0	KO	0	19.5	0	-12	+161	+ 2.4	2*
"	9	"	3	KO	1.1	45.5	0.1	- 2	+164	+ 0.3	3*
22.3.62	1	B	0	KO	0.5	0	0.2	-11	+ 77	+ 3.0	4
"	2	"	3	K1	2.6	0	0.6	-27	+ 87	+ 1.2	5
"	3	"	0	K2	5.5	0	1.6	+ 8	+129	+ 7.1	6
"	4	"	6	KO	4.0	18.8	0.6	-24	+ 98	0	5
"	5	"	6	K1	5.2	7.6	1.9	-46	- 7	+ 5.0	6
"	6	"	3	KO	1.6	15.0	0.3	- 9	+ 94	- 2.4	4.5
"	7	"	0	K1	0.6	4.9	0.7	+ 4	+210	+ 4.1	5
"	8	"	3	K2	4.4	0	1.2	+30	+140	+ 7.6	6
"	9	"	6	K2	5.8	2.0	0.9	+18	+140	+ 6.8	6

*For operation by test pilots rather than for general service use

Table 4 (Contd)

Test condition					Measurements						
Date	Run No.	Pilot	Gust level ft/ sec rms	Speed stability	Modulus mean error			Final error			Pilot rating
					Height ft	Lateral ft	Speed kts	Height ft	Lateral ft	Speed kts	
23.3.62	1	A	6	K2	3.6	0	0.8	+17	- 56	+ 3.8	6
"	2	"	0	KO	1.1	0	0	- 5	- 56	-	3
"	3	"	3	KO	0	0	0	+19	- 53	- 1.6	4
"	4	"	3	K2	2.0	0	0.2	- 8	- 26	+ 1.4	5
"	5	"	3	K1	0	0	0	- 6	+ 7	- 2.5	4
"	6	"	6	K1	0.6	0	0.4	- 4	- 23	- 3.5	5.5
"	7	"	0	K1	0	0	0.2	- 7	+ 4	- 0.2	3
"	8	"	6	KO	0	0	0.1	+ 6	+ 38	- 1.5	5
"	9	"	0	K2	1.2	0	0.4	- 9	- 49	- 4.2	4.5
23.3.62	1	B	0	KO	0	0	0	- 9	+ 31	- 2.4	4
"	2	"	6	K1	0.7	0	1.0	-11	+ 31	+11.7	4.5
"	3	"	3	K1	0.9	0	1.1	- 6	+ 28	+ 0.4	4.5
"	4	"	6	KO	1.3	2.4	0	-23	+ 21	- 1.2	5
"	5	"	0	K1	0.4	11.7	0.6	- 9	-112	- 1.2	5
"	6	"	0	K2	30.6	6.2	7.8	+32	- 21	+14.2	7
"	7	"	3	K2	6.8	0	4.0	+26	+ 35	+12.6	7
"	8	"	3	KO	0	0	0.3	-11	+ 4	+ 1.6	4
"	9	"	6	K2	3.5	0	1.6	-26	+ 31	0	6.5
26.3.62	1	D	3	K1	2.5	133	0.2	-19	- 25	+ 1.3	3
"	2	"	0	K1	0.4	6.4	0	-10	-131	+ 0.3	3
"	3	"	3	K2	1.0	106	0.6	+27	+224	+ 5.7	4
"	4	"	0	K2	12.0	62.1	0.7	+24	+356	+ 1.1	4.5
"	5	"	0	KO	0.2	0	0	+ 2	+ 17	- 0.6	3.5
"	6	"	6	K2	32.4	593	2.7	-44	OS	- 6.2	9
"	7	"	6	K1	2.9	119.2	0.5	-30	-130	- 1.2	5.5
"	8	"	3	KO	1.4	11.7	0	+ 2	+203	+ 1.0	4
"	9	"	6	KO	1.4	28.2	0.3	+10	-	- 3.4	5.5
27.3.62	1	C	0	KO	0	0	0	0	0	- 1.8	2
"	2	"	3	KO	0.2	0	0.1	- 8	- 14	- 0.4	3
"	3	"	6	K1	7.6	0	0.1	-10	- 38	- 0.7	6
"	4	"	3	K2	1.1	0	0.2	+ 9	- 38	+ 3.5	6.5
"	5	"	0	K2	1.1	0	0.1	+22	- 35	+ 0.6	5.5
"	6	"	6	K2	0.6	0	1.2	-16	+ 17	0	7.5
"	7	"	6	KO	1.6	0	0.2	-23	+ 14	- 1.1	6
"	8	"	0	K1	0.5	0	0	- 6	- 28	+ 1.4	5
"	9	"	3	K1	0	0	0.1	+ 4	- 42	+ 1.8	4
27.3.62	1	D	0	K1	0	0	0.1	- 1	+ 70	- 0.6	3
"	2	"	3	K2	2.4	1.1	0.8	+16	- 35	- 0.2	4
"	3	"	3	KO	4.4	26.2	0	+18	+161	+ 3.4	4
"	4	"	6	K2	5.9	67.0	1.0	+30	+490	+ 5.8	7.5
"	5	"	3	K1	1.6	0	0.1	+ 1	- 35	- 0.1	5
"	6	"	0	K2	8.0	2.9	0.2	+11	+189	+ 0.5	5
"	7	"	6	K1	1.6	43.5	0.2	+16	+364	- 3.1	7
"	8	"	6	KO	4.8	0	0	+33	+ 98	+ 3.1	5.5
"	9	"	0	KO	0	0	0	+ 5	+ 31	- 1.0	2

Table 5

Collected data for trials with speed stability varied by drag characteristics

Test condition					Measurements						
Date	Run No.	Pilot	Gust level ft/sec rms	Speed stability	Modulus mean error			Final error			Pilot rating
					Height ft	Lateral ft	Speed kts	Height ft	Lateral ft	Speed kts	
30.3.62	1	B	6	S2	2.8	1.6	2.9	-15	- 42	+ 1.5	6
"	2	"	0	S1	0	0	0	- 1	+ 24	+ 1.1	3.5
"	3	"	6	S1	1.7	0	0.7	- 9	+ 31	+ 8.9	5
"	4	"	0	S2	0.2	0	1.2	-15	+ 10	+ 5.9	5.5
"	5	"	0	S0	1.9	0	0.1	+ 1	+ 49	+ 1.9	4
"	6	"	6	S0	1.7	0	0.5	+10	+ 10	+ 0.7	5
"	7	"	3	S2	1.6	0	2.2	-36	- 31	+ 9.8	5
"	8	"	3	S1	0.5	0	0.4	-19	+ 42	+ 4.7	5
"	9	"	3	S0	0	0	0.1	- 9	- 24	0	5
2.4.62	1	E	3	S0	1.2	0	0.3	-10	+ 7	+ 1.2	3
"	2	"	0	S0	0.8	1.9	0.2	+10	-182	+ 0.1	2
"	3	"	0	S2	9.2	18.5	2.1	+ 2	0	+ 3.6	5
"	4	"	6	S1	3.2	1.9	0.7	+ 4	+ 3	- 0.8	5
"	5	"	0	S1	2.7	24.5	0.4	+ 4	- 42	- 0.2	2
"	6	"	6	S0	14.4	66.1	0.7	+26	-560	- 4.9	9
"	7	"	3	S2	2.3	9.5	2.0	+ 8	+ 17	+ 5.3	4
"	8	"	6	S2	18.8	1.6	OS	OS	+ 21	+21.9	9.5
"	9	"	3	S1	15.5	14.0	5.1	+28	- 35	+ 5.0	3
4.4.62	1	A	6	S1	4.1	0	-	- 5	- 21	+ 7.7	6
[A.M.]	2	"	3	S1	2.1	0	-	+ 4	+ 42	- 0.6	4
"	3	"	0	S2	1.8	0	-	- 1	- 17	+ 2.1	3
"	4	"	3	S0	0.7	0	-	+15	+ 45	- 0.3	3.5
"	5	"	6	S2	6.1	0	-	- 3	- 38	+ 1.6	5.5
"	6	"	6	S0	0	0	-	+ 1	- 28	+ 0.2	4
"	7	"	0	S0	0	0	-	+ 2	- 84	+ 1.0	2
"	8	"	0	S1	0	0	-	0	- 91	- 1.8	2.5
"	9	"	3	S2	2.2	0	-	+ 2	- 56	+ 2.7	5
4.4.62	1	B	0	S1	0	0	-	+ 1	- 28	- 0.6	4
"	2	"	3	S0	2.4	0	-	-30	- 32	- 1.0	4.5
"	3	"	3	S2	0.8	0	-	+28	+ 42	+ 8.7	5.5
"	4	"	0	S2	1.1	0	-	- 4	- 10	+ 4.0	5.5
"	5	"	6	S1	0.3	16.0	-	-27	+ 17	+ 1.2	5
"	6	"	6	S2	0.8	0	-	-31	0	- 2.6	5.5
"	7	"	3	S1	0	0	-	- 6	- 35	+ 1.8	4
"	8	"	0	S0	0	0	-	0	+ 17	+ 1.2	3.5
"	9	"	6	S0	1.4	0	-	-25	+ 14	- 1.5	5
4.4.62	1	D	6	S0	2.5	0	-	+ 2	+ 35	+ 3.6	3.5
"	2	"	3	S1	1.2	0	-	+ 4	- 38	+ 0.4	2.5
"	3	"	0	S2	1.4	2.0	-	+17	-182	+ 2.6	2
"	4	"	0	S0	1.8	0	-	+13	- 52	+ 1.4	2
"	5	"	6	S1	2.3	34.2	-	+18	+322	+ 0.3	3.5
"	6	"	3	S0	2.1	0	-	+12	-203	+ 0.7	2.5
"	7	"	6	S2	1.8	0	-	-13	-112	+ 5.7	4
"	8	"	0	S1	0	0	-	+ 9	- 73	+ 0.3	1.5
"	9	"	3	S2	0	0	-	- 2	- 70	- 3.4	3
4.4.62	1	A	0	S2	4.5	1.6	-	+ 2	- 38	+ 0.9	5
[P.M.]	2	"	6	S1	1.1	0	-	- 5	- 35	0	6
"	3	"	3	S1	0.6	0	-	- 4	- 7	+ 1.4	3
"	4	"	0	S0	1.2	0	-	- 4	- 14	- 0.9	4
"	5	"	0	S1	0	0	-	+12	- 95	+ 1.1	3
"	6	"	6	S2	0.3	0	-	+16	0	+ 5.9	5.5
"	7	"	6	S0	0.3	0	-	- 7	+ 32	- 1.2	5
"	8	"	3	S2	2.3	0	-	+ 1	- 35	+ 1.4	6
"	9	"	3	S0	0	0	-	- 8	+ 49	- 0.3	4

Table 5 (Contd)

Test condition					Measurements						
					Modulus mean error			Final error			
Date	Run No.	Pilot	Gust level ft/sec rms	Speed stability	Height ft	Lateral ft	Speed kts	Height ft	Lateral ft	Speed kts	Pilot rating
5.4.62	1	A	6	S1	0.8	0	0.3	-21	-28	-4.7	5.5
"	2	"	0	S1	0	0	0	- 3	- 3	+1.5	3
"	3	"	6	S0	0.9	0	0.2	- 3	+38	+2.4	4.5
"	4	"	0	S0	0	0	0	- 5	+ 3	+2.2	1
"	5	"	0	S2	0.8	1.7	1.1	- 4	-98	+3.7	4
"	6	"	3	S2	0	0	0.8	- 8	-14	+2.2	4.5
"	7	"	3	S0	0	0	0	- 5	-10	+1.0	3
"	8	"	3	S1	0	0	0.2	0	-42	+1.7	4
"	9	"	6	S2	0.2	0	0.6	+12	-14	+0.7	5
6.4.62	1	B	0	S1	0	0	0	- 8	+24	+1.5	4
"	2	"	6	S2	0.5	0	3.5	-30	-91	+4.1	6
"	3	"	3	S2	0.5	0	1.5	+ 3	-10	+4.4	5
"	4	"	0	S0	0	0	0	+ 6	-59	+0.3	3
"	5	"	6	S0	0.3	0	0	+ 8	+ 7	-1.4	4
"	6	"	3	S0	0	6.7	0.2	-10	+49	+1.8	4
"	7	"	0	S2	0	0	1.1	+13	+ 7	+3.0	5
"	8	"	6	S1	1.9	0	1.7	-48	+10	+2.4	5
"	9	"	3	S1	0	0	0.3	+ 4	+ 7	+0.6	4
9.4.62	1	C	6	S1	0	0	0.2	+ 6	+21	+0.6	6
"	2	"	3	S0	0	0	0	+ 7	- 7	-0.6	3
"	3	"	0	S2	0	0	0	- 4	- 7	0	3
"	4	"	6	S2	0	0	0.4	-24	-52	0	5.5
"	5	"	0	S0	0	0	0	+ 7	-38	+0.4	2
"	6	"	0	S1	0	0	0	- 2	-45	-0.9	3
"	7	"	3	S2	0	0	0.4	-10	-94	+0.3	6.5
"	8	"	3	S1	0	0	0.1	+24	-21	+2.0	5
"	9	"	6	S0	0	0	0	+ 3	+ 3	+0.2	3

SYMBOLS

Symbol	Meaning
b	wing span
C_L, C_D, C_Y	lift, drag and sideforce coefficients
C_M, C_ℓ, C_n	pitching, rolling and yawing moment coefficients
F	speed stability parameter, see equation (3)
g	acceleration due to gravity
I_{XX}, I_{YY}, I_{ZZ}	moments of inertia about the rolling, pitching and yawing axes
I_{XZ}	product of inertia
K_0, K_1, K_2, K_3	levels of speed stability in first experiment
P_S, Q_S, R_S	angular velocities of aircraft in roll, pitch and yaw w.r.t. stability axes
P_B, Q_B, R_B	angular velocities of aircraft in roll, pitch and yaw w.r.t. body axes
P_W, Q_W, R_W	flight path angular velocities defined in Appendix A
q	dynamic pressure
S	wing area
S_0, S_1, S_2	levels of speed stability in second experiment
s	lateral offset from I.L.S. beam
T	engine thrust
$T_{R.L.F.}$	thrust required for level flight
V	speed
W	aircraft weight
α	aircraft incidence
β	angle of sideslip
ζ	rudder angle
η	elevator angle
θ_W, θ_B	wind and body axis Euler angles in pitch
ξ	aileron angle
ρ	density
τ	time constant of speed convergence or divergence
ϕ_W, ϕ_B	wind and body axis Euler angles in roll
ψ_W, ψ_B	wind and body axis Euler angles in yaw
ε_V, ε_Y, ε_Z	measured errors during I.L.S. approaches

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No.	Author	Title, etc.
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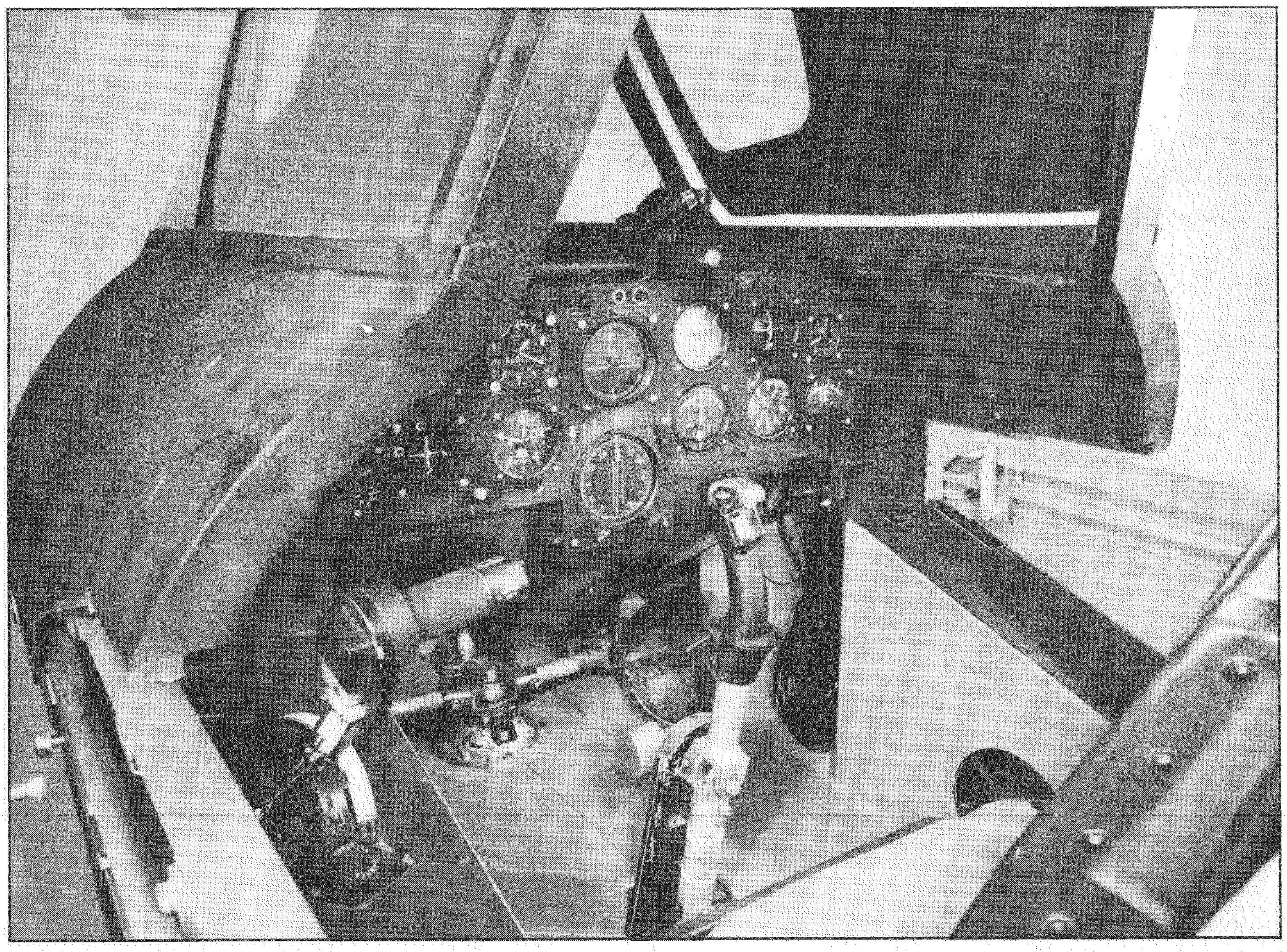


Fig.1 Layout of simulator cockpit and instrument panel

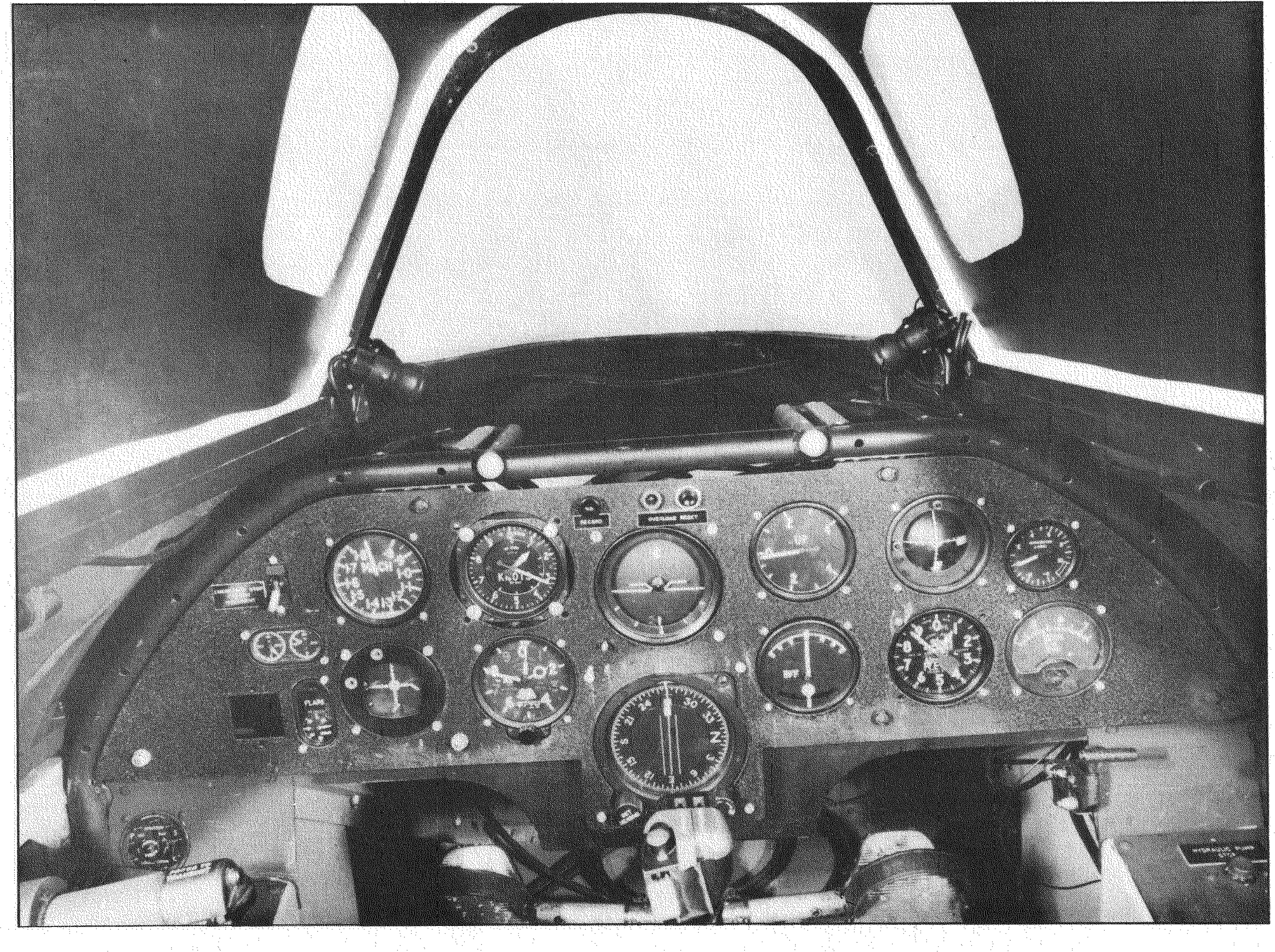


Fig.2 Layout of simulator instrument panel

Fig.3 General view of simulator cockpit and projected horizon

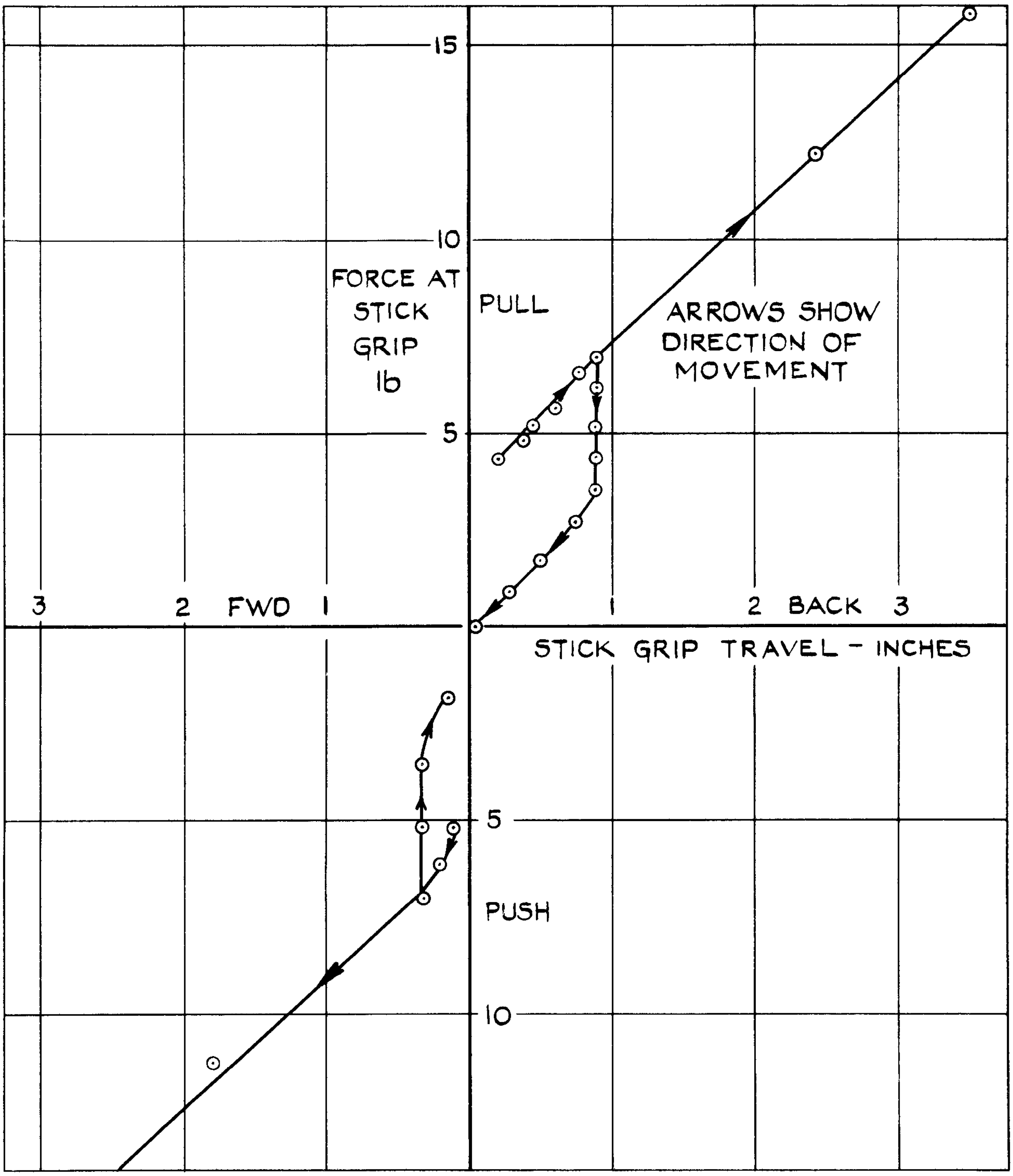
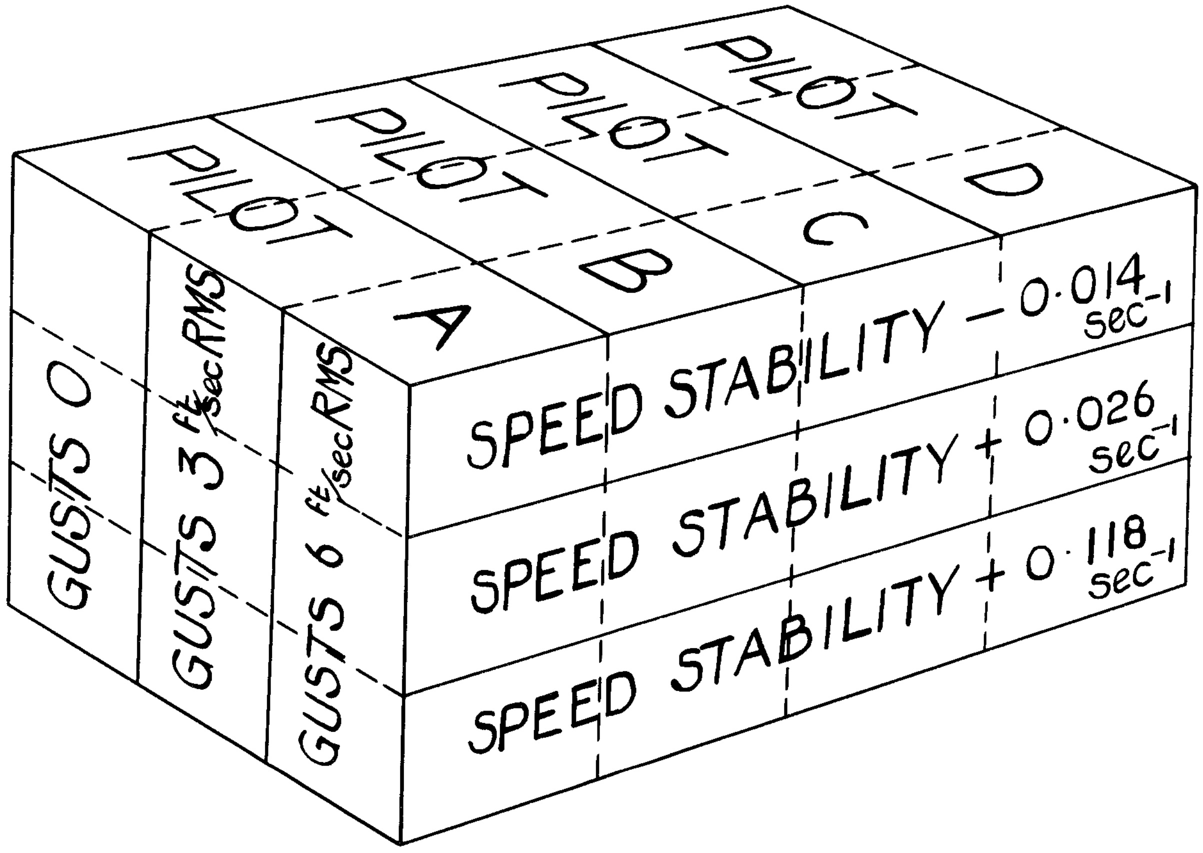


FIG. 4 TYPICAL ELEVATOR FORCE v DISPLACEMENT CURVES SHOWING HYSTERISIS DUE TO EXCESSIVE FRICTION

FACTORS IN THE EXPERIMENT



QUANTITIES MEASURED

P.R	PILOT'S HANDLING ASSESSMENT ON 'COOPER' NUMERICAL RATING SCALE
$\int \lvert \epsilon_V \rvert dt$	TIME INTEGRAL OF THE MODULUS OF AIRSPEED ERROR FROM DESIRED APPROACH AIRSPEED
$\int \lvert \epsilon_Z \rvert dt$	TIME INTEGRAL OF THE MODULUS OF HEIGHT ERROR FROM THE I.L.S APPROACH PATH
$\int \lvert \epsilon_Y \rvert dt$	TIME INTEGRAL OF THE MODULUS OF LATERAL DISPLACEMENT FROM THE I L.S APPROACH PATH
ϵ_V	SPEED ERROR FROM DESIRED APPROACH SPEED AT THE INSTANT OF BREAKOUT [300 ft]
ϵ_Z	HEIGHT ERROR FROM THE I L.S APPROACH PATH AT THE INSTANT OF BREAKOUT [300 ft]
ϵ_Y	LATERAL DISPLACEMENT FROM THE I L.S. APPROACH PATH AT THE INSTANT OF BREAKOUT [300 ft]

FIG. 5 DESIGN OF THE EXPERIMENT

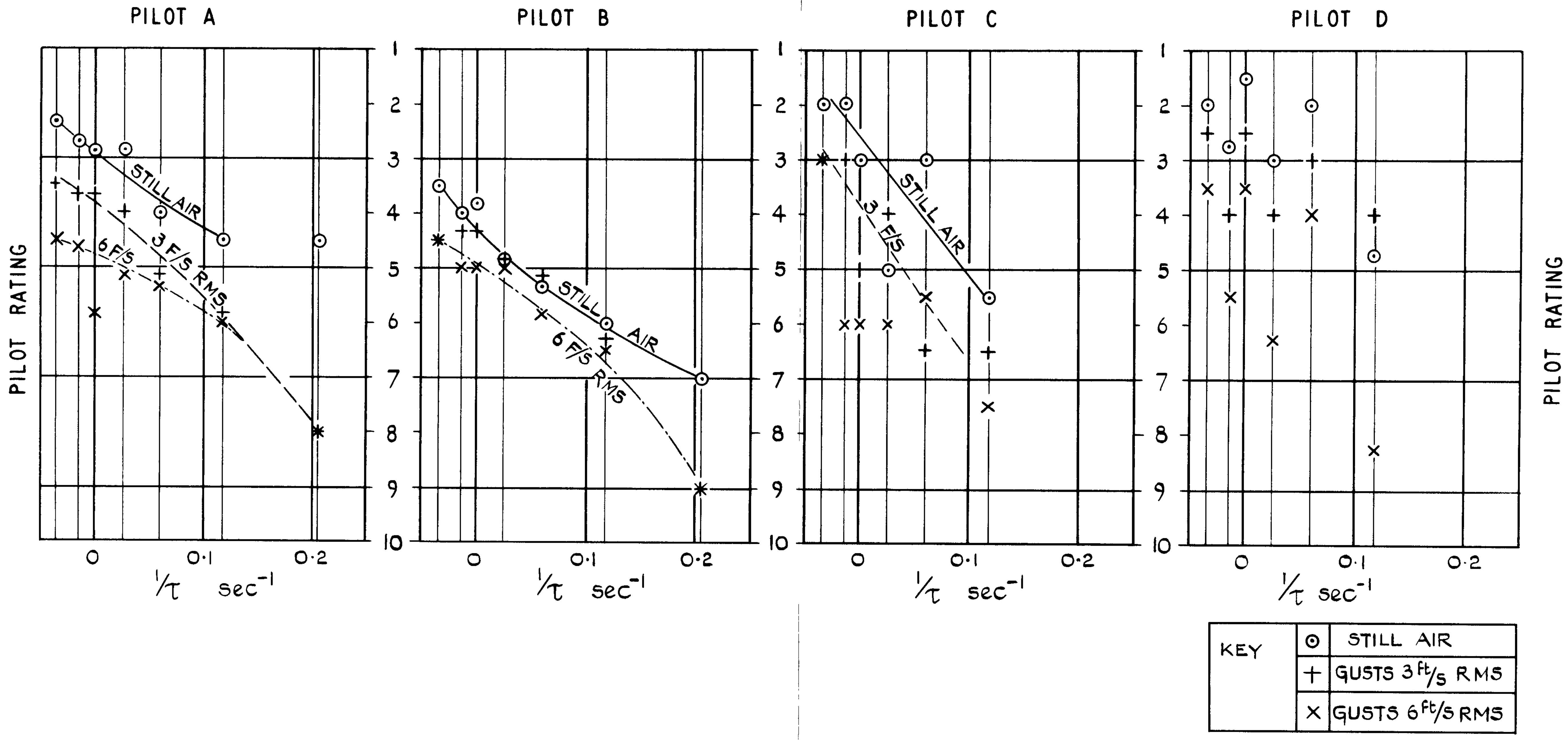


FIG. 6 VARIATION OF PILOT OPINION RATING WITH SPEED STABILITY AND TURBULENCE LEVEL AS ASSESSED ON THE SIMULATOR

FLYING QUALITIES RATINGS GIVEN BY PILOT A

		PILOTS DESCRIPTION OF SPEED INSTABILITY			
		NIL	MILD OR SLIGHT	MODERATE	SEVERE
PILOTS DESCRIPTION OF TURBULENCE	NIL	2 2 2 3½ 3 3 2 2½ 4 1 3 1	3 4	5 4 4½ 5 5½ 3 5	
	MILD LIGHT SLIGHT	3 4 4 3½ 3 4 3	4 4	5 6 4½	8 4 7½ 5½
	MODERATE	4 4 5 4 4½	4 4	5	
	SEVERE	5 6 5	6 6 6 5½	4½ 7 5½ 5½	8

FLYING QUALITIES RATINGS GIVEN BY PILOT B

		PILOTS DESCRIPTION OF SPEED INSTABILITY			
		NIL	MILD OR SLIGHT	MODERATE	SEVERE
PILOTS DESCRIPTION OF TURBULENCE	NIL	5 4½ 4 4 3½ 4 3½ 3	5½ 4 5 5 7 4 4	7 6 5½ 5½ 5 5	9 7
	MILD LIGHT SLIGHT	4 4½ 4½ 4 4	5½ 4 4½ 4 5 4	7 5 5½ 5½	9 10 9 9 6
	MODERATE	6 5 6 4½ 5 4½ 5 4	4½ 6 5 5 5	6½ 6 6 6½	9
	SEVERE	5 5 5 5 5	6	7 6	

FIG. 7 PILOT OPINION RATINGS COMPARED WITH PILOTS OWN ASSESSMENTS OF SPEED INSTABILITY AND TURBULENCE

FLYING QUALITIES RATINGS GIVEN BY PILOT C

		PILOTS DESCRIPTION OF SPEED INSTABILITY			
		NIL	MILD OR SLIGHT	MODERATE	SEVERE
PILOTS DESCRIPTION OF TURBULENCE	NIL	2 2 2	3 3		5½ 5
	MILD LIGHT SLIGHT	3½ 3	4 5		6½ 6½
	MODERATE	3 3		6 6 5½	
	SEVERE		6		7½

FLYING QUALITIES RATINGS GIVEN BY PILOT D

		PILOTS DESCRIPTION OF SPEED INSTABILITY			
		NIL	MILD OR SLIGHT	MODERATE	SEVERE
PILOTS DESCRIPTION OF TURBULENCE	NIL	3 2 2 1½	3	2	5
	MILD LIGHT SLIGHT		3 4 4 2½ 2½	4½	3
	MODERATE	4	3½ 4 5 3½	5½ 3½	4
	SEVERE	5½	7	5½	9 7½

FIG.7(CONT.) PILOT OPINION RATINGS COMPARED WITH PILOTS OWN ASSESSMENTS OF SPEED INSTABILITY AND TURBULENCE

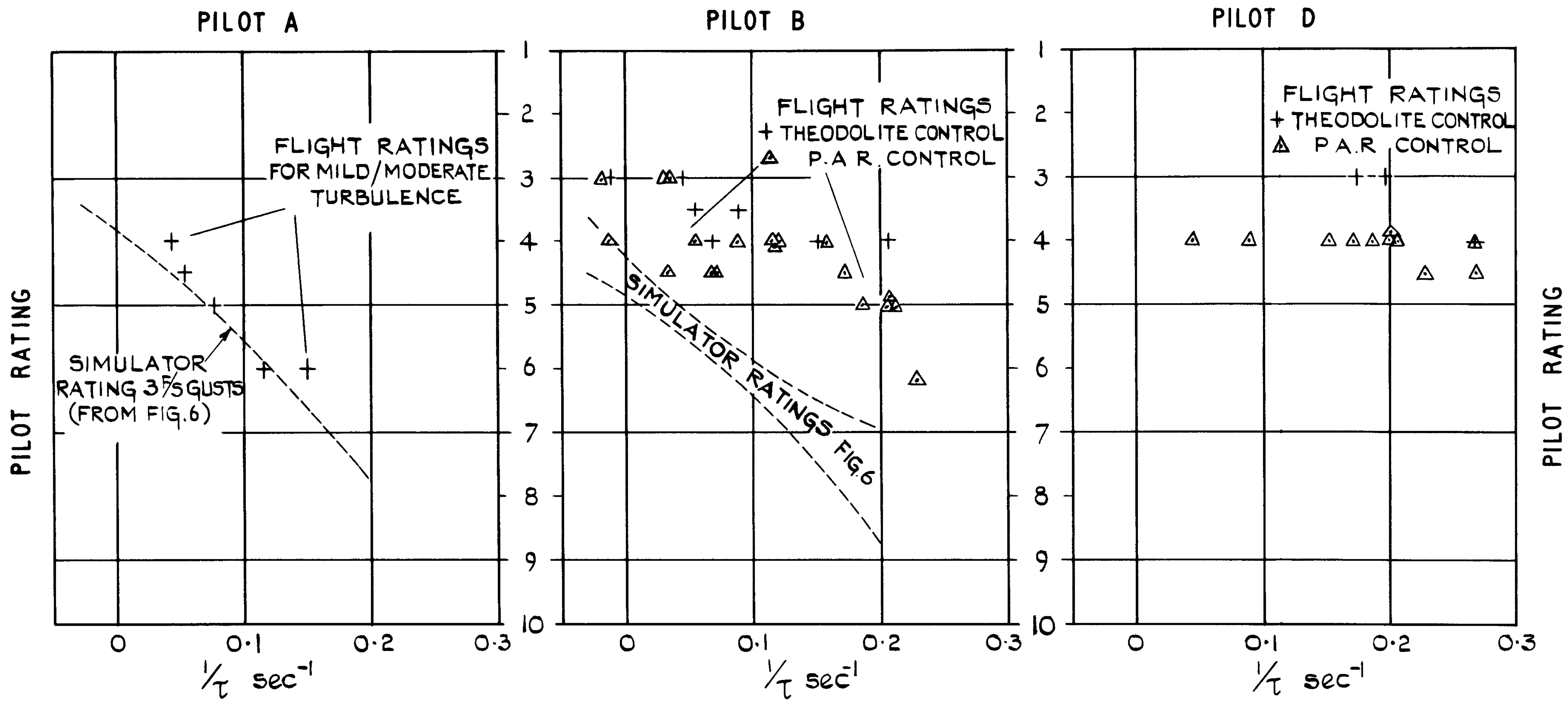


FIG. 8 VARIATION OF PILOT OPINION RATING WITH SPEED STABILITY AS ASSESSED IN FLIGHT

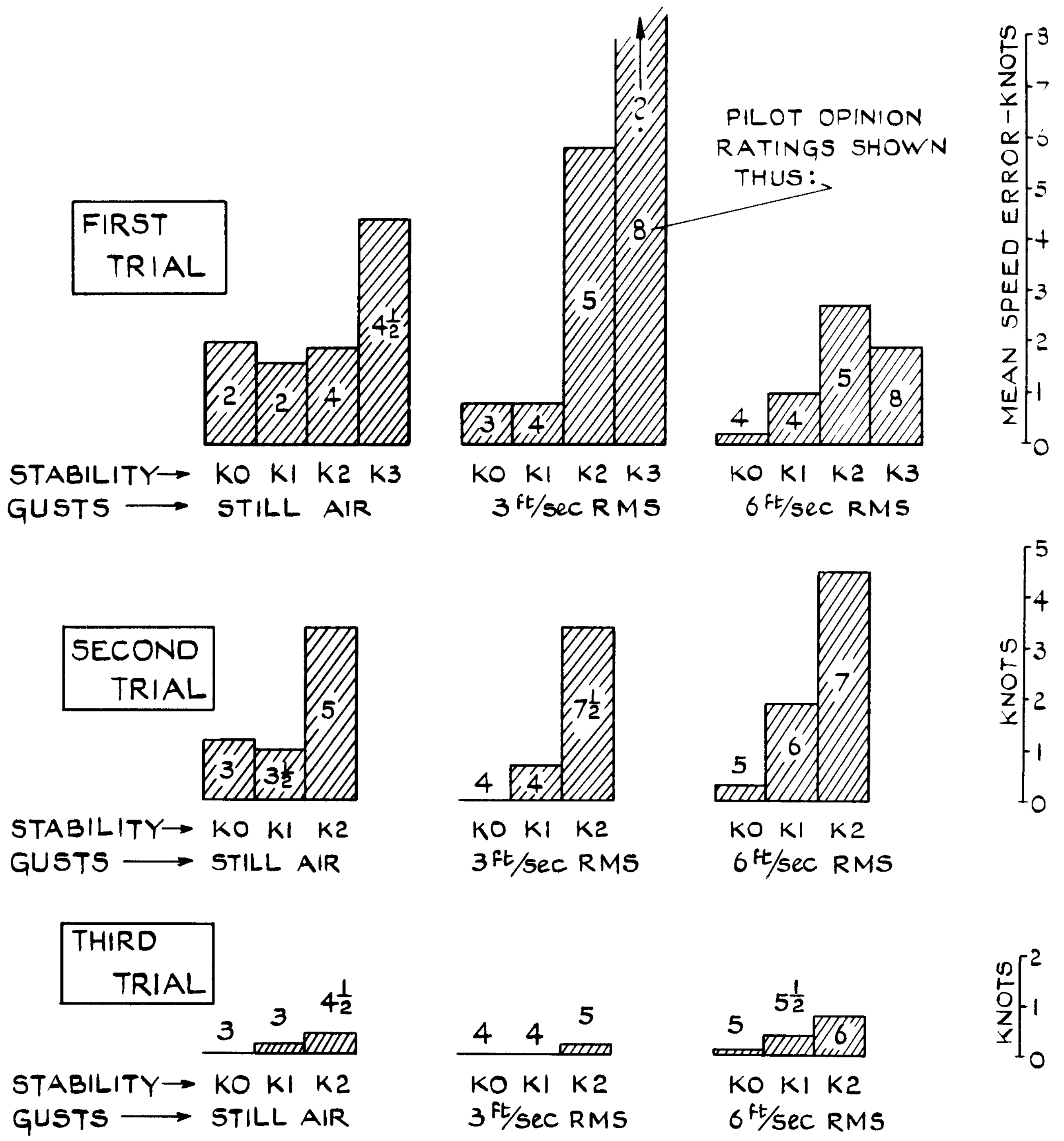


FIG. 9 COMPARISON OF SPEED ERRORS AND PILOT OPINION RATINGS DURING REPEATED TRIALS WITH PILOT A

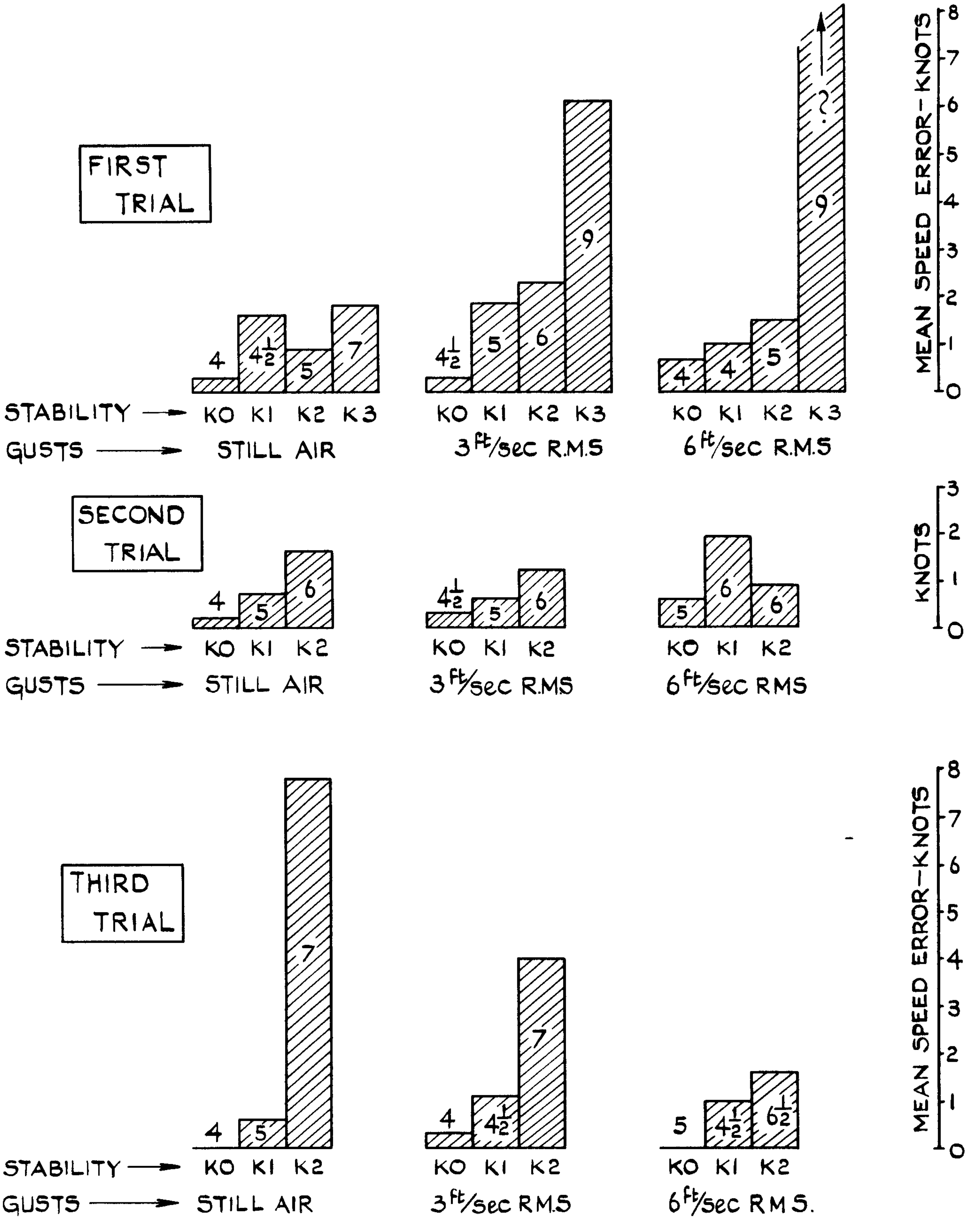


FIG. 10 COMPARISON OF SPEED ERRORS AND PILOT OPINION RATINGS DURING REPEATED TRIALS WITH PILOT B

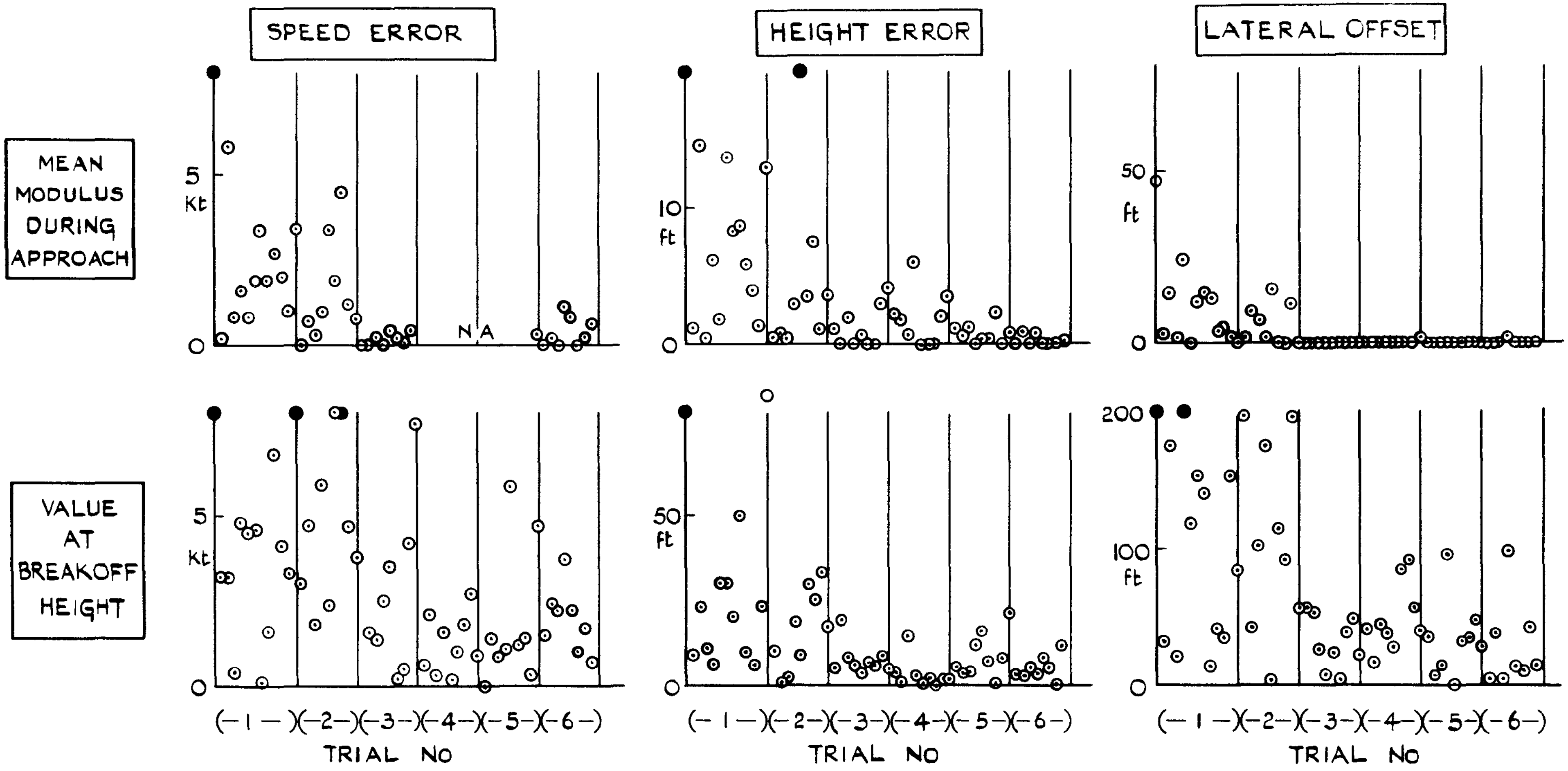


FIG. 11 PROGRESSIVE PLOT OF PERFORMANCE MEASUREMENTS DURING THE TRIAL TO REVEAL ANY LEARNING EFFECT. PILOT A

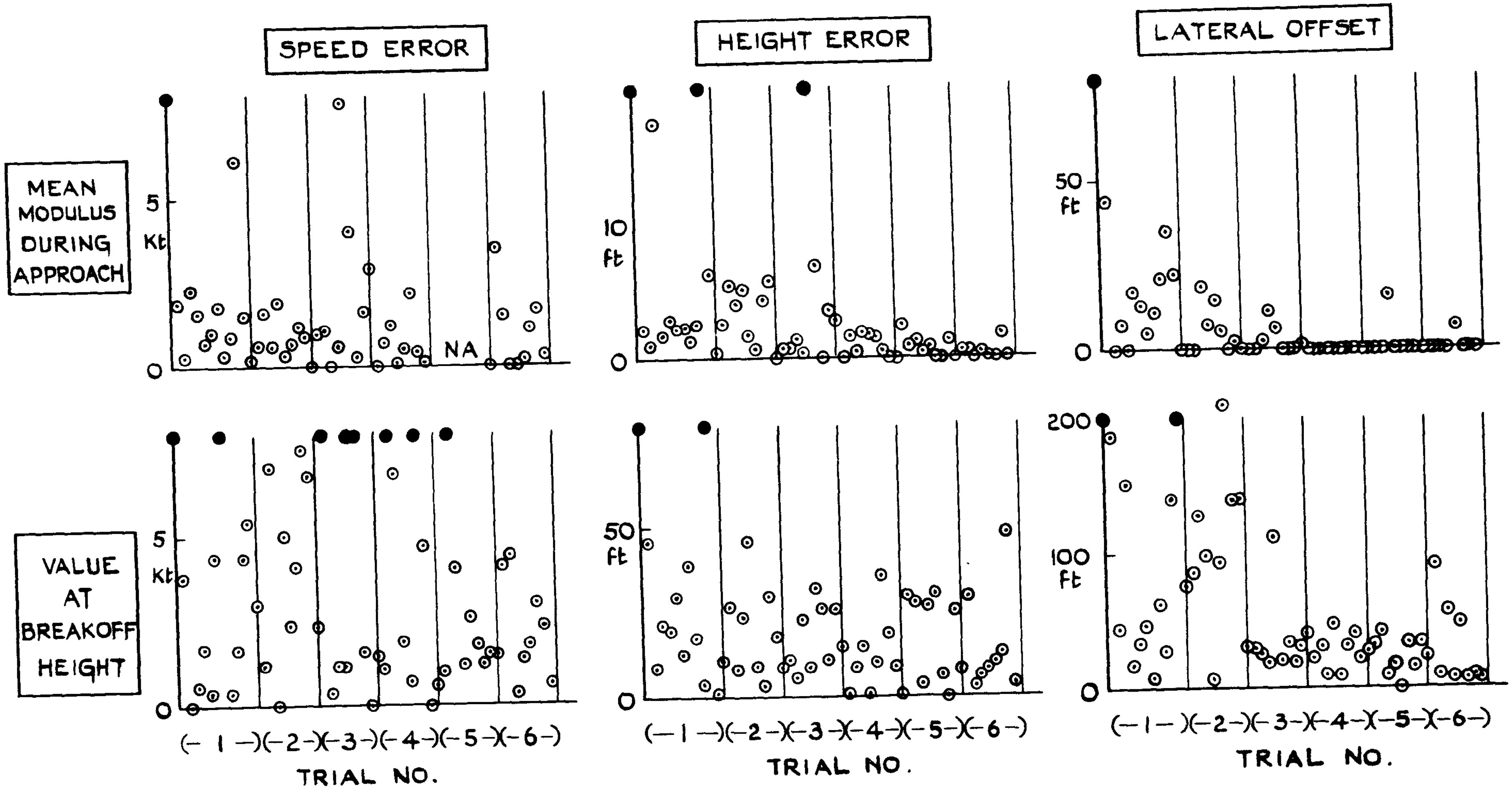


FIG.12 PROGRESSIVE PLOT OF PERFORMANCE MEASUREMENTS DURING THE TRIAL TO REVEAL ANY LEARNING EFFECT. PILOT B

DATA FROM PILOTS' FIRST TRIALS

DATA FROM PILOTS' LAST TRIALS

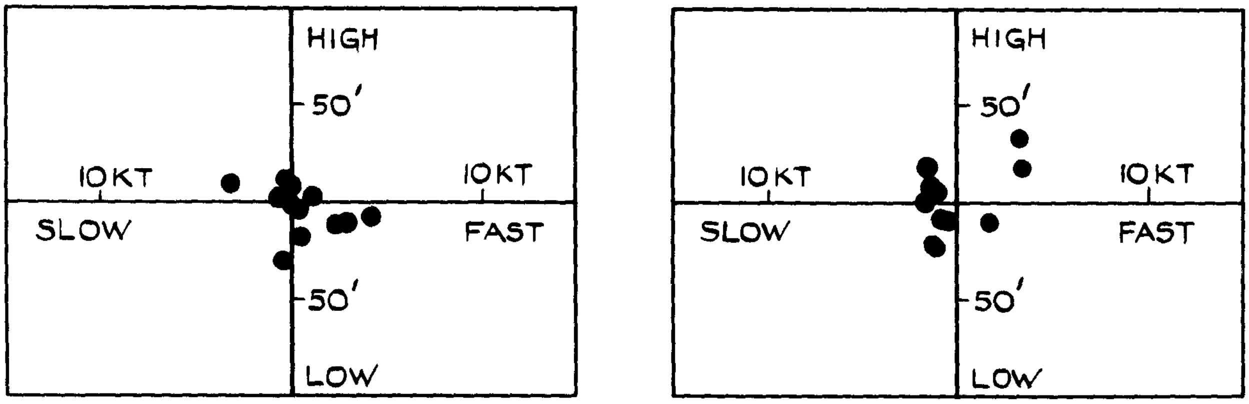


FIG.13 (a) SPEED STABLE $1/\tau = -0{\cdot}014\ \text{sec}^{-1}$

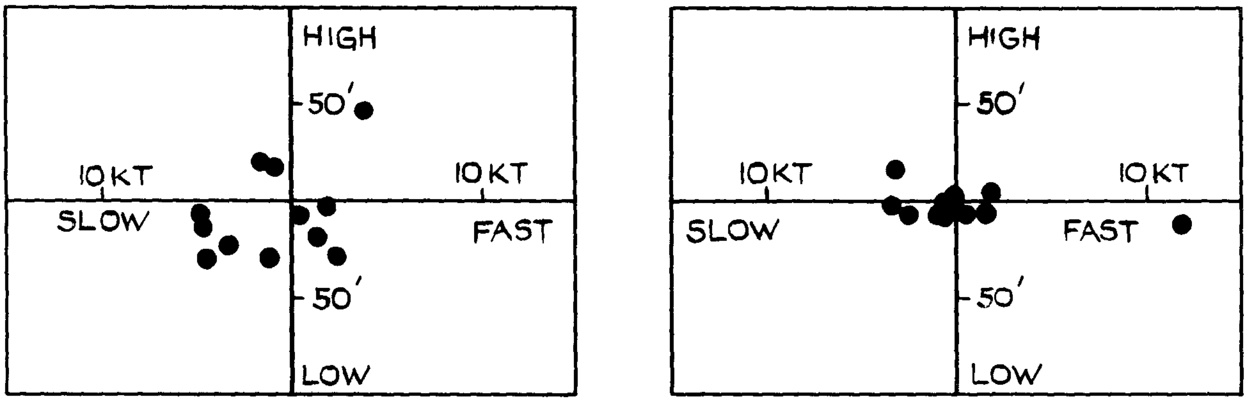


FIG.13 (b) SPEED MILDLY UNSTABLE $1/\tau = +0{\cdot}026\ \text{sec}^{-1}$

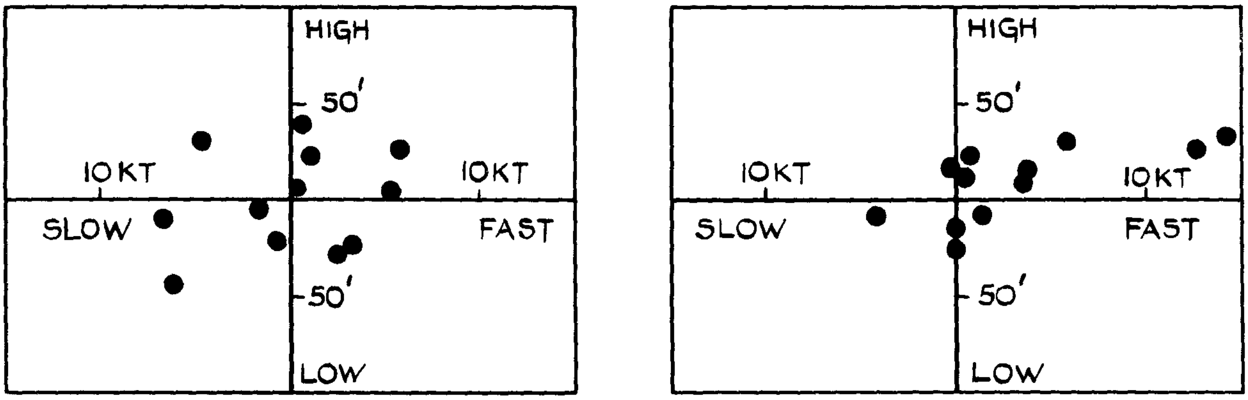


FIG.13 (c) SPEED MODERATELY UNSTABLE $1/\tau = +0{\cdot}118\ \text{sec}^{-1}$

FIG. 13 COMPARISON OF DATA FROM PILOTS' FIRST AND LAST TRIALS FOR ERRORS AT BREAKOFF HEIGHT

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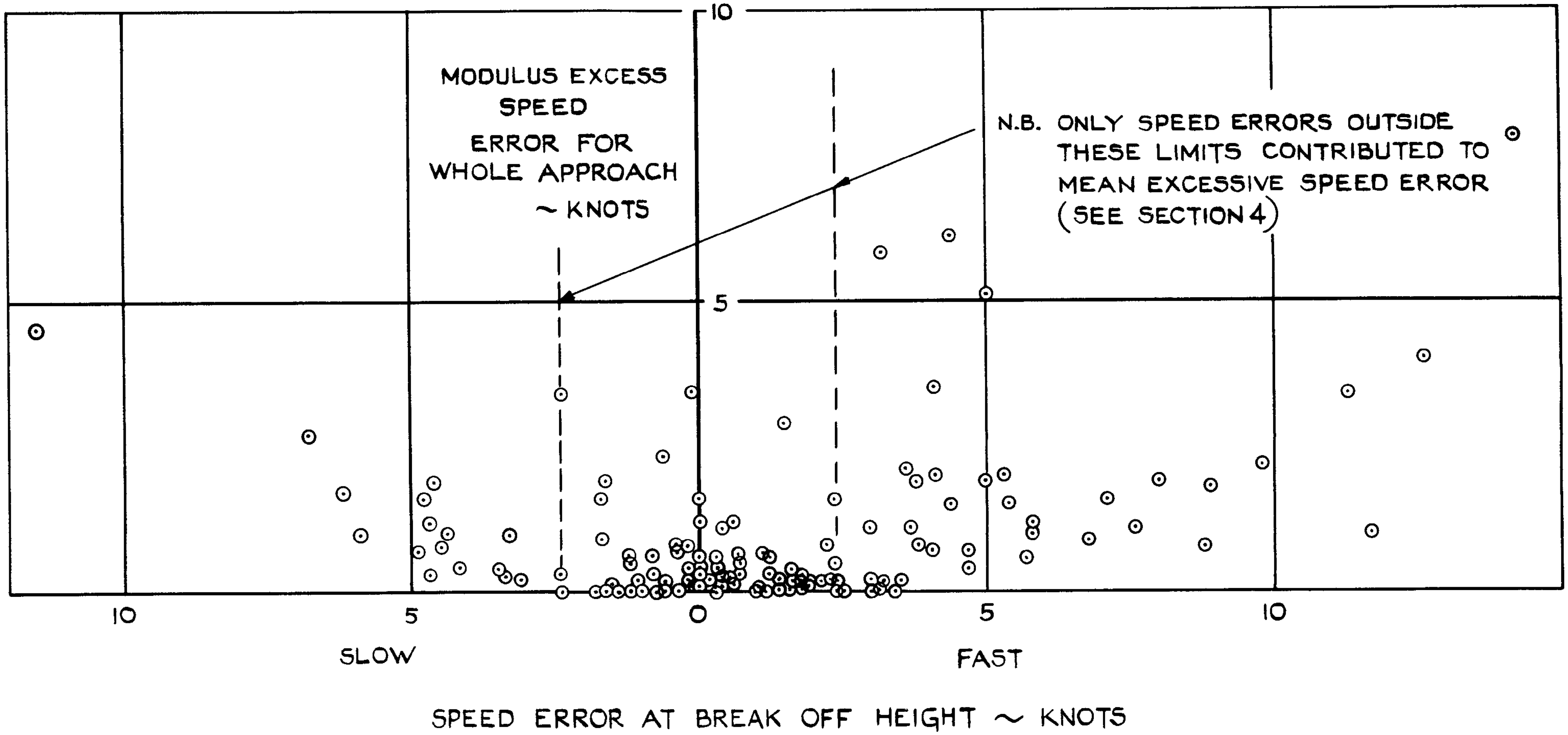

FIG. 14 SPEED ERRORS AT THE BREAK OFF HEIGHT COMPARED WITH MEAN SPEED ERRORS THROUGHOUT THE APPROACH

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April 1966

Perry, D.H.

629.13.074 :
629.13.075 :
629.13.087 :
5.001.58

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The effects of speed stability and turbulence level on the handling of a small research aircraft were systematically studied by four pilots on a fixed base simulator. Pilot opinion ratings were compared with those obtained in flight trials of the real aircraft. Accuracy of speed and flight path holding was also determined on the simulator.

Some discussion of such effects as inter-pilot variability, learning, the choice of performance measures, and the use of pilot opinion rating scales is included.

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DETACHABLE ABSTRACT CARDS

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A PILOTED FLIGHT SIMULATOR STUDY OF SPEED INSTABILITY DURING THE LANDING APPROACH

The effects of speed stability and turbulence level on the handling of a small research aircraft were systematically studied by four pilots on a fixed base simulator. Pilot opinion ratings were compared with those obtained in flight trials of the real aircraft. Accuracy of speed and flight path holding was also determined on the simulator.

Some discussion of such effects as inter-pilot variability, learning, the choice of performance measures, and the use of pilot opinion rating scales is included.

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