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A Flight Study of the Sidestep Manoeuvre During Landing

By D. H. Perry, M.A., W. G. A. Port and
J. C. Morrall, B.Sc. Tech.

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Summary.

Flight measurements have been made of two types of manoeuvre which might be used to correct lateral errors occurring at the end of an instrument approach. These are, the true banked co-ordinated S turn, and the sideslipping turn with wings held level. The tests showed the true banked S turn to be the more effective method.

Measurements on fourteen aircraft showed that at least ten seconds might be needed to make corrections from quite small displacements, even with a very manoeuvrable aircraft. A simple theoretical analysis, which supported this conclusion, also allowed the minimum practical manoeuvre time for any initial displacement to be calculated, once the available rate of roll, and an overriding maximum angle of bank, had been established.

Measurements of the lateral characteristics of the test aircraft, which included a small delta-winged research aircraft and several large transports, enabled tentative requirements for satisfactory rolling performance to be proposed.

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1. *Introduction.*

The operation of civil and military aircraft under adverse weather conditions, which has been made possible largely through the widespread introduction of bad-weather approach aids, has led to several new problems in the lateral control of aircraft during landing. Foremost amongst these is the situation which occurs when a pilot, emerging from fog or cloud in the final stages of the approach, suddenly finds himself confronted with a considerable lateral displacement from the runway centre-line. This displacement may be due to limitations in the precision of the approach aid, or it may have arisen through errors in following the guidance information available, but in either case the pilot may be unaware of it until he actually sees the runway lights.

There are many aspects to this problem, touching on such different fields as the electronic performance of the approach aid, studies of runway lighting patterns, the manoeuvrability of the aircraft and the skill of the pilot. The tests described in this report were concerned primarily with these latter aspects of aircraft characteristics and piloting techniques, particularly those which affect the performance of the correction manoeuvre whereby the aircraft is brought back to the runway centre-line. Methods of making this manoeuvre, and aircraft characteristics which aid its performance, have not been studied particularly closely in the past, since the need for such a correction rarely arises under normal visual conditions. Lateral control requirements for take off and landing[1, 2] have been largely concerned with ensuring that adequate control power was provided for dealing with such problems as asymmetric engine failure, cross-wind landing and disturbances due to gusts. There has consequently been little guidance to designers as to whether this new bad-weather landing manoeuvre formed a critical case in deciding how much control power should be provided for landing.

The lack of any extensive study of this problem is reflected in the small volume of published work. In 1949 the N.A.C.A. reported[3] the results of a theoretical comparison between the effectiveness of co-ordinated and slipping turns for performing this manoeuvre, in the case of one particular type of aircraft. The effect of aircraft size on the ease of making the S-turn manoeuvre had also been considered theoretically at the R.A.E. in 1947[4]. Renewed interest has been shown in the subject recently, however, particularly with regard to aircraft configurations which might be suitable for a supersonic transport aircraft[5].

The present series of experiments was undertaken in order to provide comparative flight measurements of the different methods which might be used in making bad-weather lateral correction manoeuvres. Several different types of aircraft, each with different lateral characteristics, were used in the tests, so that the effect of these lateral characteristics could be investigated and desirable values of lateral control established. When making these test manoeuvres it was obviously desirable that they should be representative of manoeuvres which could reasonably be performed during ordinary commercial operations, bearing in mind such matters as passenger comfort and safety. It was also important that the range of control characteristics studied should be as wide as possible. These aims were realised, largely through the invaluable assistance and co-operation of the airline corporations, B.O.A.C. and B.E.A. By the generous loan of aircraft and crews these organizations greatly enhanced the scope of the investigation.

Most of the tests were made during 1955 and 1956. Some of the early results were presented at the 9th I.A.T.A. Technical Conference[6], San Remo, in May, 1956.

2. *Lateral Errors during Landing.*

The lateral errors which may face the pilot at the end of an instrument approach can arise from actual distortions in the path defined by the landing aid, due, for instance, to local irregularities in the terrain, or they may be caused by difficulties in following precisely the guidance information provided, particularly if the aircraft control characteristics are unsatisfactory, or if there are external disturbances, such as strong and varying cross winds.

The final error may consist of a lateral displacement from the correct flight path, with the aircraft heading parallel to the runway centre-line, or there may be a combination of displacement and heading errors.

Typical numerical values for these errors were required as a basis for the present tests and these were obtained from published measurements of errors during trials with various approach aids. The values used are shown in Table 1. It will be seen that displacement errors of several hundred feet were not unlikely and that these might be combined with tracking errors of up to 5°.

The difficulty of completing a satisfactory correction manoeuvre may depend not only on the size of the initial lateral error, but also on the distance from touch-down at which the lateral error is first detected. This, in turn, depends on the minimum 'break-off height'* from which a landing may be attempted and on the steepness of the approach glide path. At the time of the flight tests, the break-off height which was used by the airlines varied slightly, according to the airfield and the landing aid, but a value of 300 feet was generally used. With a glide-path steepness of 3°, this allowed a range of about 6,000 feet before touch-down, corresponding to a time interval of about 30 seconds for an aircraft travelling at 120 knots. Pilots stated, however, that they invariably wished to complete the lateral correction before starting the landing flare. Some sample measurements, on the larger transport aircraft tested, showed that the flare was generally started at a height of about 50 feet, so that the time actually available for assessing the aircraft's position, and then for making the lateral correction, would be about 25 seconds.

3. *Methods of Correcting the Lateral Errors.*

Two different techniques for correcting the lateral errors were frequently suggested in the discussions which preceded the flight measurements. These were the co-ordinated S turn, and the slipping turn with the wings held level. The basic principles of dynamics which are involved in the two methods are essentially similar, as may be seen by considering the motion across the approach path, independently of the general forward motion. To bring about the sideways

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* The 'break-off height' or 'obstacle clearance limit' is the height below which a pilot must not continue the approach unless he is in visual contact with the runway or lighting pattern.

displacement of the aircraft's flight path which is needed to align the aircraft with the runway centre-line, a transverse force across the initial flight path must first be applied in order to accelerate the aircraft towards the runway. Then, as it nears the correct path, a force in the opposite direction must be applied so that the aircraft reaches the centre-line with negligible transverse velocity. The differences between the two techniques arise from the different methods of generating these forces. If the co-ordinated-turn technique is chosen, the transverse forces are applied by banking the aircraft, so that a component of the wing lift is generated in the desired direction. With the slipping-turn technique, on the other hand, these forces must be produced by the inclination of the aircraft vertical surfaces, such as fuselage and fin, to the airstream. Aerodynamic data show, that for conventional aircraft at least, much larger forces may be obtained by banking the aircraft than those which can be produced by yawing it, so that from the purely dynamical point of view, the co-ordinated turn should prove to be the more effective method. This view was supported by the theoretical work of the N.A.C.A.[3].

It had been suggested, however, that pilots were unwilling to bank the aircraft, and thus produce a co-ordinated turn, when they were close to the ground in bad weather, and that they preferred the slipping-turn technique because it enabled them to keep the wings level. This reluctance to bank the aircraft arose, it was claimed, not only from natural caution, but from difficulties in assessing the aircraft's flight path, especially in the longitudinal plane, when the aircraft was banked. However, none of the 30 pilots who took part in the present tests advocated the slipping-turn manoeuvre.

Measurements which were made in flight to compare the effectiveness of the two methods are described in Section 4.3.

4. *Flight Measurements.*

4.1. *The Test Manoeuvre.*

The situation which formed the central problem in this investigation, that of correcting a lateral displacement at the end of an instrument approach, is, in practice, subject to many variations, depending on such factors as initial displacement and heading errors, visibility, wind and atmospheric conditions, runway length, etc. In devising a test to study the problem experimentally, a compromise was inevitably required between the degree of realism needed to make the results of value, and the simplifications which had to be introduced to prevent the investigation from becoming unwieldy. These issues were further compromised by the limited availability of many of the test aircraft.

Availability of the test aircraft largely dictated the time, and thus the weather conditions, under which the tests were made. This resulted in nearly all of the flights being made under normal visual conditions. The number of tests which could be made on each aircraft was also fairly limited so that it was necessary to devise a standard, and fairly simple task, which was nevertheless representative of the manoeuvre which a pilot must make when he emerges from cloud or poor visibility at the end of an instrument approach, and is confronted with a lateral error. Approach paths, parallel to the runway centre-line, but displaced from it laterally by known distances, were indicated by large marker boards, placed on the ground close to the runway threshold. (Fig. 1.) These markers could generally be seen from about four miles, and they were used as aiming points by the pilot who was flying the initial stages of the approach. The aircraft, which had been positioned at a given height above a known reference point at the beginning of each run, was flown down a laterally displaced approach path defined by one row of the markers, using a glide-path angle of 3°. At an indicated height of 300 feet a correction manoeuvre was started to align the aircraft with the runway centre-line. Pilots were told to ignore any small errors in their final alignment after the manoeuvre, but these were noted by an observer to provide a more accurate record of the displacement distance actually covered. Landings were not made from most of these approaches, overshoot action being taken when the pilot considered that he had completed the lateral correction. There was never any occasion to doubt, however, that a successful landing could have been made if required.

The largest offset distances tested, about 800 feet from the runway centre-line, were much larger than the lateral displacements which might be expected to occur in practice (Table 1), but Fig. 2 shows how a combination of a smaller and reasonable offset distance, say 400 feet, together with a possible tracking error of 4°, could be regarded as equivalent to the larger offset distance. No attempt was made to perform actual tests with various initial tracking errors because of the difficulty of setting up the initial conditions consistently, and because of the limited time available on each aircraft.

The piloting during most of these tests was shared between airline and R.A.E. pilots. The airline pilots were not briefed to perform any particular type of manoeuvre, but were merely asked to align the aircraft with the runway centre-line, using whatever technique they would normally employ during bad-weather commercial operations. In these tests the aircraft was flown in the initial stages of the approach by the co-pilot, and the pilot was asked to take over control, to look outside the aircraft and to perform the manoeuvre, only at the 300 foot point.

The R.A.E. pilots, on the other hand, were asked to perform the most rapid manoeuvre which they felt was possible with the aircraft and consistent with normal safety requirements. In most cases the R.A.E. pilots had no previous experience of piloting the commercial transport aircraft which were used in the tests, but they were probably more familiar with the test manoeuvre than the airline pilots.

4.2. *Instrumentation and Analysis of Flight Records.*

Many of the aircraft used in these tests were normally employed on regular commercial operations and they were only available for a brief period of time. It was therefore important that the recording equipment should involve the minimum disturbance to the normal aircraft services and that it should operate from the standard aircraft electrical power supply.

A small portable automatic observer was built, containing a free gyro measuring angle of bank and aircraft heading, two rate gyros measuring rates of roll and yaw, a lateral accelerometer and two type A-22 continuous-trace galvanometer recorders. The automatic observer, which measured 18 in. × 18 in. × 10 in. and weighed about 60 pounds, could be conveniently lashed to the floor in the cabin of the test aircraft.

The ranges and sensitivities of the instruments were:

Instrument	Range	Sensitivity
Angle of bank .	±90°	28·5° per cm
Heading angle .	±90°	15·5° per cm
Rate of roll . .	±25°/sec	10·5°/sec per cm
Rate of yaw . .	±15°/sec	7·4°/sec per cm
Lateral acceleration .	±1g	0·4g per cm

The recorders could be controlled to run at either 0·35 cm/sec or 2 cm/sec.

Airspeed and altitude readings were taken from the pilot's flight instruments. No attempt has been made to correct the readings for position error, but the errors in the speed range considered are thought to be small.

In one or two of the R.A.E. aircraft, which were more readily available, it was possible to mount position transmitters at the control surfaces, so that continuous records of aileron and rudder angles could be taken.

Continuous-trace recordings of each manoeuvre were made from shortly before the 300 foot point, until the pilot had completed the correction and had started to overshoot. Each record was analysed to find the peak values of the aircraft angular displacements and rates of rotation, and also the time taken for each manoeuvre. This time was measured from the beginning of the correction until the aircraft was aligned with the runway. Usually these points were self evident from the flight record, but an observer in the aircraft also operated an event marker which appeared on the record at the appropriate times. The times measured in this way represent the interval during which actual corrective movement of the aircraft was taking place; *they do not, therefore, include the time required by the pilot to assess the situation before the manoeuvre started.*

4.3. *Comparative Tests of Co-ordinated and Slipping Turns.*

Although none of the pilots who took part in the present tests supported the contention that lateral errors in bad weather should be corrected by slipping turns, some tests using the sideslipping method were made in order to examine any difficulties which might arise with this technique and to provide a comparison with manoeuvres made by the co-ordinated S turn. The pilot was asked to initiate the manoeuvre by moving the rudder and then to use the ailerons, either to oppose the rolling moment which developed with sideslip, and thus produce a true flat turn, or else to keep the ailerons in their neutral position so that a slipping turn with a small angle of bank resulted.

The times which were taken to make lateral corrections from various initial displacement distances for the two aircraft used in these tests, the *Lincoln* and the *Viking*, are shown in Figs. 3 and 4. The times for corrections using the co-ordinated-turn method are also shown in these figures, the results of the latter tests being discussed in detail in the next section. As might be expected, it was found that the manoeuvres using slipping turns took considerably longer than those using co-ordinated turns, especially at the larger offset distances. It was found, moreover, that precise control of the slipping-turn manoeuvre was more difficult, particularly in the final stages, when there was a tendency to overshoot the centre-line. While these difficulties may have been partly due to the unfamiliarity of the manoeuvre, it may be observed that the sideslipping control by the rudder was exercised through the lightly damped oscillatory yawing mode, in contrast with the aileron control which operated through the heavily damped rolling mode. It might have been expected that precise control would be inherently more difficult in the former case.

In view of the preferences stated by the pilots who took part in these tests, and of the ample evidence that the slipping-turn method was less effective than that using a co-ordinated turn, the remainder of the investigation, described in the following sections, was devoted to studying the latter manoeuvre.

4.4. *Manoeuvres using Co-ordinated Turns.*

Thirteen aircraft, ranging in size from the *Meteor* of 43 feet span and 17,500 lb A.U.W., to the *Britannia* of 142 feet span and 115,000 lb A.U.W., were used in the investigation of the co-ordinated-turn manoeuvre. Some additional measurements, forming part of another test programme and using different instrumentation, were made on the Avro 707B[7], a small tailless delta-wing aircraft. These latter measurements are discussed in Section 6. Apart from the Avro 707B and the *Comet*, all the aircraft were fairly conventional straight-wing designs. Data for them are given in Table 2.

Test manoeuvres were made on the aircraft using the procedure described in Section 4.1. A typical time history, taken from a flight record of the *Lincoln*, is reproduced as Fig. 5.

The times taken by the R.A.E. pilots to complete the lateral correction manoeuvre in all of their test approaches are shown in Fig. 6. Despite the diversity of aircraft tested the variation in the time for a given manoeuvre is smaller than might perhaps have been expected. Thus, for tests starting with an initial displacement of 150 feet, nearly all of the measurements lie between 9 seconds and 15 seconds, while those starting at 350 feet lie between 12 seconds and 18 seconds.

The differences in performance which might rightly be attributed to differences in the aircrafts' characteristics, for approaches made under nominally similar conditions, have almost inevitably become clouded by variations in piloting technique. Nevertheless it is possible to distinguish, at least for the approaches flown by the R.A.E. pilots, differences between the performance of several of the aircraft. This is illustrated in Fig. 7 where the measurements for the *Meteor* and *Lincoln* are compared with those for the other aircraft. It can be seen that these two aircraft represent the opposite extremes of performance, the times for the *Lincoln* being about 4 seconds longer than those for the *Meteor* at the smaller initial displacements, and up to 8 seconds longer at the larger distances. The remaining aircraft have been divided, for convenience, into heavy and medium classes. These show less clearly defined but nevertheless discernible differences. In the heavy class, Fig. 8, the pilots took longer to make corrections in the *Stratocruiser*, *Hastings* and *Comet* than in the *Constellation* and *Argonaut*. The measurements for the *Sperrin* and *Britannia* showed more scatter than for the other aircraft and their performance relative to the rest of the heavy class could not easily be judged. In the medium class, Fig. 9, the results for the *Pionair* show that this aircraft had a much poorer performance, particularly at the larger displacements, than that of the *Elizabethan*, *Viscount* or *Viking*.

The mean curves of Figs. 7, 8 and 9 are shown together in Fig. 10. The significance of the fairly small differences in manoeuvre time as a measure of desirable aircraft lateral characteristics is discussed in Section 6.

In the case of the approaches flown by the airline pilots it is more difficult to distinguish any consistent differences between the different types of aircraft. (Fig. 11.) No doubt this reflects the larger number of pilots who took part, and the wider scope allowed to them by their briefing, so that variation in piloting technique played a more significant part than with the R.A.E. pilots. But it is possible in the case of two of the aircraft, the *Stratocruiser* and the *Pionair*, which showed the poorest performance with the R.A.E. pilots, to detect a similar consistently poor performance with the airline pilots.

Some differences between the results obtained by airline and R.A.E. pilots have been mentioned above. A direct comparison between the manoeuvres made by these two classes of pilot, and comparisons between manoeuvres made by different individual pilots, are shown in Fig. 12 for the tests on the *Viscount*. In this case the results for the pilots within each class are quite consistent, but the manoeuvres made by the R.A.E. pilots took about three seconds less than those made by the airline pilots. This more rapid manoeuvre by the R.A.E. pilots is typical of the results for the other aircraft. It arises, quite naturally, from the different instructions which the pilots were given. The R.A.E. pilots were asked to perform the quickest possible lateral correction, whilst the airline pilots were asked to demonstrate what they would do during normal poor-weather operations, if presented with the test situation. Since the test allowed them adequate time for the manoeuvre (*see* Section 2), there was little incentive for the airline pilots to complete the manoeuvre more rapidly. There is little doubt, though, that they could have matched the performance of the R.A.E. pilots had it been necessary.

When confronted with the largest offset distances, some of the airline pilots said that they would not normally attempt to land from such a situation in bad weather, although they went on to make a successful correction manoeuvre.

Most of the tests were made in daylight and in good visibility. To determine whether these weather conditions had any significant effect on the performance, some measurements were made in poor visibility by day and also at night in clear weather. In these approaches, since the ground markers were not visible, the pilot was guided down a displaced flight path by a ground controller using a radar approach aid, and the lateral correction was made over a Calvert approach lighting pattern. The results of these tests are shown in Figs. 13 and 14. These measurements were not sufficiently numerous to establish any clear relationship between the visibility and the maximum angle of bank which pilots were prepared to use, but there appears to be no significant difference between the manoeuvre times measured in good visibility by day, in good visibility by night, and in poor visibility by day. It seems likely that the pilot takes much longer to assess the situation initially when the visibility is poor, but this assessment time has been explicitly excluded from the measurements.

In the previous paragraphs the *time* to complete the manoeuvre has been used as a criterion of the sidestep capabilities of the aircraft, partly because it was a convenient and easily measured variable, but also because it was expected to give the best basis for comparison when the effects of different aircraft lateral characteristics were being considered. It is shown in a later section that the same manoeuvre *time* should be needed for aircraft with similar lateral characteristics, irrespective of the aircrafts' approach speeds. From the operational point of view, however, this may not be the most useful criterion, for it is the *distance* travelled during the manoeuvre which is of most importance. This is illustrated in Fig. 15 which shows that the distance travelled by the *Pionair* was actually less than that needed by the *Viscount* for all but the largest initial displacements, because its approach speed was some 30 knots slower. Thus although the comparisons of this report have been made on the basis of manoeuvre *times* alone, the operational advantages of a slower approach speed in reducing the manoeuvre *distance* should be emphasised.

4.5. *Measurements of the Aircrafts' Rolling Characteristics.*

The aircrafts' lateral characteristics were generally measured on the same flight as the manoeuvring tests. The same instrumentation was used and a standard procedure was followed for all the aircraft. The measurements were made in the landing configuration with a power setting typical of that used on the approach, but the test altitude varied according to weather and traffic conditions. The lateral characteristics were usually measured at two airspeeds, one 20 knots higher than the instrument approach speed and the other 10 knots below it. This revealed any abnormal variation in the characteristics with speed and allowed the values for the speed of the manoeuvring tests to be obtained by interpolation.

In the case of the *Britannia*, a minor aircraft defect prevented measurements of the lateral characteristics from being made, although the manoeuvring tests were completed satisfactorily.

The aircrafts' rolling characteristics were measured in two types of test. The first, to establish the maximum steady rate of roll and to examine the behaviour in continuous rolling, was initiated from a true banked turn having a bank angle of about 30°. Full aileron control deflection was applied as rapidly as possible to roll the aircraft through the wings-level attitude. The rolling motion was allowed to continue until about 30° of bank in the opposite direction had been attained, to ensure that the full steady rate of roll was given time to develop.

The second type of test was used to investigate the initial rolling response of the aircraft to a step-aileron application. In this case the manoeuvre was started from wings-level flight, since this gave more consistent initial conditions, and either full or half aileron deflection was applied as rapidly as possible. In both types of test the rudder was held fixed.

The continuous-trace recordings made during these tests have been analysed to determine the maximum steady rate of roll, and the time taken to attain a bank angle of 20°, starting from the wings-level attitude. Records were made and analysed of tests using both full aileron deflection, and approximately half aileron deflection, but in the latter case reliance had to be placed on the pilot's judgment as to how much control-wheel travel to apply, so that the results of those tests are not considered to be so reliable.

In some cases the maximum rolling acceleration could also be roughly determined by measuring the slope of the rate-of-roll record.

The results of these measurements of rolling performance are shown in Table 3. In this form the results for the different aircraft are not strictly comparable, one with another, since the tests were made at a variety of heights. The data given in Table 4 have been derived from those given in Table 3 by correcting all the results to sea-level conditions and by interpolating, where necessary, between the test airspeeds, to obtain values of the rolling characteristics at the instrument approach speed. Comparable values for the Avro 707B, taken from previously published work[7], are shown in the same table.

The steady rates of roll measured in the present series of tests range from 10°/sec for the *Lincoln*, to 28°/sec for the *Meteor* (results reduced to sea-level conditions). The corresponding times to attain a bank angle of 20° are 2·5 seconds and 1·2 seconds, while the maximum rolling accelerations for these two aircraft are about $12°/\text{sec}^2$ and $55°/\text{sec}^2$.

Values for the 'rolling helix angle', $pb/2V$, a parameter which has frequently been used in the past as a measure of rolling performance, have been calculated for all of the test results and are shown in Tables 3 and 4, and also in Fig. 16. The characteristics of the test aircraft are compared diagrammatically in Fig. 16. It shows that about a quarter of them satisfy the rolling requirement[1, 9], that $pb/2V > 0 \cdot 07$.

The variation in rate of roll with airspeed shows no unusual features except in the case of the *Pionair*. For that aircraft the rolling velocity at the higher airspeed is slightly lower than that measured at an airspeed 30 knots slower. This is consistent, however, with the results of previous tests[8], in which the effect was attributed to stretching of the aileron control cables.

The time histories of the rolling motion in response to a sudden aileron application varied with the different types of aircraft, as is shown in Fig. 17. Aircraft such as the *Elizabethan* and *Viscount* displayed a steady rolling response, in contrast with such types as the *Constellation* and *Pionair* which show distinct fluctuations in the final rolling velocity. These fluctuations may usually be attributed to the effects of sideslip, induced by aileron yawing moments, but their effect on the rolling behaviour depends on a complex combination of the aircraft lateral characteristics, and a detailed investigation of these is beyond the scope of the present work. It has been established, however, from this and other flight studies, that pilots preferred the aircraft in which the yawing moments due to the ailerons were small.

4.6. *Measurements of the Characteristics of the Lateral Oscillation.*

Although the lateral oscillatory characteristics did not play a primary part in the particular manoeuvre which was being investigated, it is believed that they have a considerable influence on the ease with which the correct instrument approach path may be maintained, and on the general handling of the aircraft.

The aircrafts' oscillatory characteristics were measured under similar conditions to those of the rolling tests described in the previous section. The oscillation was initiated from straight flight by a rapid displacement of the rudder, which was then recentralized and held fixed. Measurements of the period, damping and rolling-to-yawing amplitude ratio were taken from the continuous-trace recordings of each oscillation. These results are shown in Table 5. Again, these results are not strictly comparable between the different aircraft, because of the variety of heights at which the tests were made. Results, corrected to sea-level conditions and interpolated to the airspeeds used in the manoeuvring tests, are shown in Table 6. These results are shown again, diagrammatically, in Fig. 18. Comparable measurements for the Avro 707B, taken from the previously published work[7], are also shown in Fig. 18 and Table 6.

For the measurements made in the present series of tests the period of the oscillation is in all cases fairly long (usually above six seconds), and the damping of all but two of the aircraft satisfies the requirement[1], that log. dec. $> 0 \cdot 69$. The two exceptions, the *Sperrin* and the *Comet*, also lie on the boundary of the satisfactory region defined by the requirements of Ref. 9. This requirement, which is shown in Fig. 19 is specified in terms of both damping and rolling-to-yawing amplitude ratio. The *Elizabethan* was exceptionally well damped.

4.7. *Pilots' Assessments of Handling Characteristics.*

Several of the R.A.E. pilots, who flew almost the complete range of aircraft tested, were asked to make a comparative judgment on various features of the aircraft, which, it was felt, might be important in making the lateral correction manoeuvre. Some of these characteristics were of a type which it was rather difficult to measure, like, for instance, control harmony. Others, such as the rolling response, had been the subject of the numerical measurements described in the previous sections, or were important physical characteristics of the aircraft; for example, the control-wheel travel needed to apply full aileron.

Pilots' assessments of these various characteristics are summarized in Table 7.

Most of the pilots felt that control harmony—the relationship between the characteristics of the aileron and rudder controls—was of considerable importance in making precise manoeuvres during the landing approach. Satisfactory harmony results from the correct balance of both control forces and control response between the aileron and rudder. In a surprising number of aircraft the control-wheel travel which was needed to apply full aileron was larger than that which could be applied comfortably. In the case of the *Pionair* especially (where 180° of control-wheel travel was needed for full aileron), this feature effectively limited the amount of aileron which pilots used.

One of the aims of the present investigation was to correlate pilot opinion with measured aircraft lateral characteristics, in order to determine desirable numerical values for these quantities. Table 8 shows a comparison of the pilots' rating for each aircraft alongside its measured characteristics. It is evident that no hard and fast relationship between pilot opinion and those aircraft characteristics which were measured can be deduced, but at the bottom of the table minimum values which seem to correspond to satisfactory behaviour have been suggested.

5. *Simplified Theoretical Relationships for the Co-ordinated-Turn Manoeuvre.*

A study of elementary flight dynamics shows that an aircraft's motion is completely defined by the time history of the angle of bank if the manoeuvre involves only correctly banked co-ordinated turns. Typical time histories of angle of bank actually measured during the present series of tests are shown in Fig. 20. Although some of them follow an ill defined and irregular curve, many of them approximate fairly closely to two half sine waves, having different amplitudes for each part of the manoeuvre. Moreover, the manoeuvres which followed this pattern were generally more rapid, and appeared to be more effective, than those of less regular appearance.

With the assumption of just such a sinusoidal variation of angle of bank with time, the following expression has been derived (Appendix I), relating the time for the manoeuvre T, the initial displacement distance d, and the peak angles of bank, ϕ_1 and ϕ_2, used in the two parts of the manoeuvre

$$T = \sqrt{\left\{\frac{\pi d}{g}\left(\frac{\phi_2 - \phi_1}{\phi_2\phi_1}\right)\right\}}\,. \tag{1}$$

A slightly more accurate representation of the manoeuvre may be obtained if account is also taken of the 'effective time lags'[4], which occur at the beginning and end of the manoeuvre. The nature of these lags is shown in Fig. 38, and allowing for them,

$$T' = 2t_0 + \sqrt{\left\{\frac{\pi d}{g}\left(\frac{\phi_2 - \phi_1}{\phi_2\phi_1}\right)\right\}}\,. \tag{2}$$

A value for t_0 of 0·5 sec has generally been used in this report. To test the validity of this expression the peak angles of bank actually measured during the flight tests have been substituted in equation (2), so that the manoeuvre times predicted by the theory could be directly compared with those measured in flight. Fig. 21 shows examples of such comparisons for several of the test aircraft. Although the theory is only strictly applicable to manoeuvres in which the time history of angle of bank follows the assumed sinusoidal pattern, the comparisons shown in Fig. 21 include all the results for a given aircraft, irrespective of the actual pattern of rolling time history used in the flight manoeuvre.

In Fig. 22 a comparison is made between predicted and measured times, using only those flight trials in which the time history of angle of bank followed, fairly closely, the assumed sinusoidal pattern. In this figure the results for the different aircraft are all shown together.

Both figures show very reasonable agreement between the values calculated from the theoretical relationship, (2), and those measured during the flight trials. The consistency with which the relationship holds for different aircraft, illustrated in Fig. 22, and for both R.A.E. and airline pilots, shown in Fig. 21, suggests that the measured differences in manoeuvre times between these classes may be attributed, primarily, to differences in the peak angles of bank which were used.

The symmetry of the theoretical relationship shows that the most rapid manoeuvre would be made if the peak angles of bank used in the two parts of the correction were similar, and as large as possible. In practice the bank angle used in the first part of the manoeuvre was almost invariably larger than that used in the second part, probably* because the latter demanded greater precision, in order to align the aircraft with the runway, and was therefore approached more cautiously. Nevertheless the manoeuvre with equal peak angles of bank forms an optimum against which the actual performance may be judged.

With equal peak angles of bank in the two parts of the manoeuvre $\phi_2 = -\phi_1 = -\phi$, equation (2) becomes:

$$T' = 2t_0 + \sqrt{\frac{2\pi d}{g\phi}}. \tag{3}$$

This expression (3) shows that the time taken to correct a given lateral displacement should depend primarily on the peak angle of bank used. This relationship is shown in Fig. 23, where the time vs. displacement curve is plotted for various peak angles of bank.

At the larger offset distances the manoeuvre inevitably took so long that even aircraft with fairly slow rates of roll could have attained very large peak angles of bank, had not the pilot arbitrarily curtailed the rolling motion so as to keep the bank angle within limits which he felt to be safe. Under these conditions it might have been expected that the time history of angle of bank would depart fairly radically from the sinusoidal pattern which has been assumed. In practice, however, it was found that the sinusoidal analysis remained reasonably representative, so that its mathematical simplicity, compared with a possibly more precise expression, could be retained.

It has been seen that the manoeuvre time may depend directly on the maximum angle of bank which the pilot is willing to use. The present series of tests were not well suited to determining values for these maxima, since they were mainly conducted in good weather and it seems likely that this limit in angle of bank might depend, perhaps predominantly, on the weather conditions encountered. For instance, a pilot might be expected to use rather smaller angles of bank when the visibility is poor and the horizon ill-defined than he would use when the cloud base is low but the visibility otherwise fairly good. The small amount of data collected under adverse weather conditions during this series of tests (Section 4.4) was insufficient to establish these trends.

Measurements of the peak angles of bank used in the present flight tests suggest that an upper limit may be placed at 30° for the large transport aircraft and 35° for the smaller, and generally more manoeuvrable, fighter types. These limits were, in fact, exceeded on one or two occasions during the flight measurements, the largest recorded angles being 39° on the *Meteor* and 36° on the *Viscount*, but these angles were used under ideal test conditions by practised pilots. The upper limits specified are felt to be more representative of those which would be used operationally, when the need for this manoeuvre only occurred infrequently.

For manoeuvres from smaller offset distances the aircraft's maximum rate of roll may well prevent these angles of bank from being attained in the limited time available. A measure of this effect is again given by the sinusoidal analysis; for the peak angle of bank which may be reached during the sine wave, if a given rate of roll, p, is not to be exceeded is:

$$\phi_{\max} = \frac{Tp}{2\pi} \tag{4}$$

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* It has been suggested that the angle of bank used in the second part of the manoeuvre was smaller because the aircraft was closer to the ground, but this was not specifically stated by any of the pilots who took part in the tests.

or combining equations (1) (with $\phi_2 = -\phi_1 = -\phi$) and (4)

$$\phi_{\max} = \left[\frac{p^2 d}{2\pi g}\right]^{1/3} . \tag{5}$$

The peak angles of bank given by this relationship are compared, in Figs. 24 to 27, with those actually achieved during the flight tests of several of the aircraft. For aircraft such as the *Stratocruiser*, having a very slow rate of roll, Fig. 25, this limitation may extend over the whole range of displacement distances, but where a higher rolling velocity was available, as in the *Viscount*, Fig. 24, and the *Meteor*, Fig. 26, this limitation was superseded at the larger displacements by the overriding restriction in angle of bank discussed in an earlier paragraph.

In the case of the *Pionair*, Fig. 27, the results suggest that, although a fairly rapid rate of roll was, in theory, available, some characteristic of the aircraft prevented its effective use. The excessive control-wheel travel of 180° for full aileron movement appears to be the most likely reason for this.

The relationship (5) for the maximum angle of bank which can be achieved when limited by the rate of roll can also be used, in conjunction with (3), to find the time for such manoeuvres:

$$T' = 2t_0 + \left[\frac{4\pi^2 d}{gp}\right]^{1/3} . \tag{6}$$

The time vs. displacement curves derived from this expression are shown in Fig. 28 for several values of the maximum rate of roll. The curve for manoeuvres which are restricted to a maximum angle of bank of 30°, the arbitrary upper limit which pilots who took part in this investigation seemed to employ, is also shown in this figure. Combination of these two curves, that for rate of roll at the smallest displacements and angle of bank for the larger displacements, allows the minimum manoeuvre time to be calculated for any aircraft, once the available rate of roll is known. Examples of some of these boundaries, and the corresponding times measured in the flight tests, are shown in Figs. 29 to 32. It will be seen that the theory is reasonably successful in predicting the minimum manoeuvre times for a fairly wide range of aircraft characteristics.

6. *Discussion.*

The analysis described in the previous section showed that many of the measured differences in the performance of the lateral correction manoeuvre might be explained by a simple theory, which considered only the available steady rate of roll and an overriding maximum angle of bank.

Once these parameters were established, the theory would also give guidance on the minimum possible time in which any particular initial lateral displacement could be corrected. In practice, of course, pilots took rather longer than the predicted minimum time to complete the manoeuvre, and this is shown in the frequency diagrams of Figs. 33 and 34. The frequency distributions show that the R.A.E. pilots would most probably exceed the minimum time by about $2\frac{1}{2}$ sec while the airline pilots would require a further 2 sec.

The results of the flight measurements, supported by this simple theory, lead to several conclusions which are especially important when the possibility of reducing the manoeuvre time is considered. Outstanding among these is that even the smallest correction, from displacements of 75 to 100 feet, will need about ten seconds to complete, even if very rapid rates of roll are available. When coupled with the time needed by the pilot to assess the situation, and the time which must be allowed for the landing flare, this result suggests that only restricted reductions in the cloud base and visibility limitations will be possible, until the precision of the approach aid is improved to the level at which negligible lateral errors occur.

The expression for the time needed to complete manoeuvres which are limited by the available rate of roll {equation (6) of Section 5}, shows that the manoeuvre time depends inversely on the cube root of the rate of roll, so that only comparatively small reductions in time may be achieved once the rate of roll has been improved above a certain level. This expression also shows that the beneficial effects which might be obtained from the more rapid rate of roll at a higher airspeed (p increasing linearly with V), are more than offset by the greater ground distance travelled; this arises from the fact that the increased rate of roll gives a reduction in ground distance which varies as $1/p^{1/3}$, and thus depends on $1/V^{1/3}$, while the ground distance travelled in a given time naturally increases directly as V.

It may be argued that, with a more rapid rolling acceleration available, the pilot might improve the situation by departing from the sinusoidal time history which has been assumed. Although smaller manoeuvre times might certainly be achieved, the motion would be more violent and would require even finer judgment in the use of the controls. It is felt that, in practice, the sinusoidal time history is fairly representative of the manoeuvre actually used by the pilot.

One of the aims of the present investigation was to determine desirable values of aircraft control characteristics by testing a range of aircraft having different characteristics and measuring their performance in specific tasks. Difficulties in this experimental technique have been met on several occasions[10] in the past. They are thought to arise because the pilot subconsciously improves his own performance in order to overcome the deficiencies in the control system. This behaviour may account for several of the anomalies which occurred in the flight measurements. For instance, the *Elizabethan* was severely criticised by the pilots for its very high control forces whilst its rate of roll was also fairly poor, but its average performance in the correction manoeuvre equalled that of the *Viscount*, an aircraft which had many satisfactory qualities. The pilots' ability to overcome these deficiencies does not make it any less desirable to eliminate them, and the importance of those handling characteristics which affect the co-ordinated turn on the satisfactory performance of the correction manoeuvre should be emphasised.

The present tests have been concerned predominantly with straight-winged aircraft. Although our investigations suggest that it may be difficult to improve on the performance of the best contemporary aircraft, it is equally important to ensure that the performance of more advanced aircraft will not fall below present standards. Flight measurements on small research aircraft with highly swept wings have shown that their rolling behaviour at approach airspeeds differs markedly from their straight-winged predecessors. Simulator tests on the larger designs which stem from them show that their behaviour may be similar.

The rolling response of the Avro 707B[7], a small delta-winged research aircraft, is shown by the time history reproduced in Fig. 35. The oscillatory nature of the response is much more severe than that encountered with any of the straight-winged aircraft, Fig. 17, but it appears to be fairly typical of other highly-swept-wing types. Lateral correction manoeuvres, similar to those described in the previous sections, were made with this aircraft, and the manoeuvre times, compared with those of the *Meteor* and *Lincoln*, are shown in Fig. 36. Although the maximum rate of roll measured in rolling tests, 35°/sec was rather larger than that for the *Meteor* (28°/sec), Fig. 36 shows that its performance in the correction manoeuvre was inferior over most of the limited range of displacement distances tested. It may be concluded that the more complex rolling characteristics of the highly-swept-wing aircraft may lead the pilot to use very much smaller rates of roll in practice than those which can momentarily be achieved during a specific rolling test.

7. *Conclusions.*

Flight measurements have shown that the true banked co-ordinated S turn is the most effective method by which a pilot may correct a lateral error during the final stages of the landing approach. It was found that manoeuvres made by this method took less time and could be more precisely controlled than those made by flat slipping turns. The times needed for the lateral correction, by pilots who had been asked to perform the quickest possible manoeuvre on 13 aircraft with widely different rolling capabilities, ranged between the following values:

Initial displacement,	150 feet	9 to 14 seconds
Initial displacement,	350 feet	12 to 18 seconds
Initial displacement,	750 feet	15 to 26 seconds.

These times do not include any allowance for the time which may be needed by the pilot to assess the situation before commencing the manoeuvre.

A simple theoretical analysis showed that the time needed for the manoeuvre depended primarily on the maximum angle of bank which was used, and this enabled relationships for the minimum manoeuvre time to be derived which depend only on the available rate of roll and on an overriding maximum angle of bank. This limiting angle of bank, which depended only on the pilot's judgment, has been tentatively assessed as 30° for the transport type of aircraft and 35° for the smaller and generally more manoeuvrable fighter type. The effect of bad weather and reduced visibility on this limiting angle of bank has not been clearly established however, and, since the present tests were conducted under almost ideal conditions, it is possible that the maximum bank angle used in practice might be lower than that given above.

The measurements, supported by the theoretical analysis, show that even for an aircraft with excellent rolling characteristics, a time interval of about ten seconds will be needed to correct the smallest errors which would warrant a separate and deliberate manoeuvre.

Aircraft with rates of roll of less than 12°/sec invariably gave a poor performance during the tests, and a minimum of at least 15°/sec appears to be desirable. Handling characteristics, such as control and breakout forces, control harmony and control-wheel travel are of considerable importance in these co-ordinated-turn manoeuvres.

Measurements of the correction manoeuvre on a small delta-wing research aircraft showed a performance which was inferior to that which might have been expected from measurements of its maximum rate of roll. It is believed that the complex rolling characteristics of the highly-swept-wing aircraft may cause the pilot to use very much smaller rates of roll in practice than those which can be momentarily achieved during a specific rolling test, and this may lead to larger manoeuvre times than those which are needed for a straight-winged aircraft of apparently comparable rolling performance. When associated with the trend towards higher landing approach speeds, the ground distances covered during lateral correction manoeuvres with this type of aircraft may be much larger than those currently experienced.

LIST OF SYMBOLS

Symbol	*Unit*	*Definition*
$C_{1/2}$	—	Cycles to half amplitude
d	feet	Lateral displacement
g	ft/sec^2	Acceleration due to gravity
p	deg/sec radians/sec	Steady rate of roll
T	seconds	Theoretical manoeuvre time without effective time lags
T'	seconds	Theoretical manoeuvre time including effective time lags
t_0	seconds	Effective time lag
ϕ_1	deg radians	Peak angle of bank used in the first part of the manoeuvre
ϕ_2	deg radians	Peak angle of bank used in the second part of the manoeuvre
$\frac{\lvert\phi\rvert}{\lvert V_e\rvert}$	deg per ft/sec	Ratio of angle of bank to sideslip velocity during lateral oscillations

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APPENDIX I

A Simplified Analysis of the S-Turn Manoeuvre

It may be shown that, provided the pilot uses correctly banked co-ordinated turns throughout the manoeuvre, the flight path is determined by the variation of the angle of bank with time which the pilot chooses to employ. Examination of the flight records of many of the manoeuvres made in the present series of tests showed that the bank angle often varied in the way shown in Fig. 37, where each part of the curve is approximately sinusoidal. The assumption of a sinusoidal variation of angle of bank with time allows a very simple relationship to be derived for the manoeuvre time in terms of the offset distance and the peak angles of bank used.

Using the notation:

ϕ	Angle of bank at any time t. (stbd. wing down +ve)
ψ	Heading change at any time t. (heading change to stbd. +ve)
y	Displacement towards the runway at any time t. (movement to stbd. +ve)
T_1, T_2	Times for first and second parts of the manoeuvre
V	Speed, assumed constant throughout
d	Initial offset displacement (displacement to port of runway centre-line +ve)
g	Acceleration due to gravity

where the suffixes 1 and 2 denote peak values during the two halves of the manoeuvre.

From elementary flight dynamics the condition for radial equilibrium during a true banked turn is:

$$\frac{d\psi}{dt} = \frac{g\phi}{V} \tag{1}$$

where the angle of bank, ϕ, is assumed to be reasonably small so that $\sin\phi \simeq \phi$.

The analysis of the S-turn manoeuvre is simplified if the manoeuvre is treated in two parts, since a discontinuity occurs at time $t = T_1$ (*see* Fig. 37).

For the first part of the manoeuvre, from $t = 0$ to $t = T_1$ let the angle of bank be varied in a sinusoidal manner:

$$\phi = \phi_1 \sin\frac{\pi t}{T_1}$$

Then from (1) the variation in heading angle, ψ, during this time is given by:

$$\frac{d\psi}{dt} = \frac{g\phi_1}{V}\sin\frac{\pi t}{T_1}$$

and starting from the initial condition $\phi = 0$, $\psi = 0$ at $t = 0$, the heading at any time $t[0 < t < T_1]$ is:

$$\psi = \frac{g\phi_1 T_1}{\pi V}\left[1 - \cos\frac{\pi t}{T_1}\right]. \tag{2}$$

When $t = T_1$ at the end of the first part of the manoeuvre the heading angle has changed to:

$$\psi_1 = \frac{2g\phi_1 T_1}{\pi V}. \tag{3}$$

It is now convenient to move the time origin to the beginning of the second part of the manoeuvre. Assuming that the variation of angle of bank with time is again sinusoidal, but of different amplitude:

$$\phi = \phi_2 \sin \frac{\pi t}{T_2}$$

then, from (1), the heading variation during this part of the manoeuvre is given by:

$$\frac{d\psi}{dt} = \frac{g\phi_2}{V} \sin \frac{\pi t}{T_2}$$

and starting from the initial conditions at the new time origin, $\phi = 0$, $\psi = \psi_1$ at $t = 0$:

$$\psi = \psi_1 + \frac{g\phi_2 T_2}{\pi V}\left[1 - \cos \frac{\pi t}{T_2}\right]. \tag{4}$$

When $t = T_2$, at the end of the second part of the manoeuvre, the heading has changed to:

$$\psi_2 = \psi_1 + \frac{2g\phi_2 T_2}{\pi V}. \tag{5}$$

In the type of manoeuvre described, the initial and final headings are the same, i.e. $\psi_2 = 0$. Under this condition comparison between (3) and (5) shows that:

$$\phi_1 T_1 = -\phi_2 T_2. \tag{6}$$

If the heading changes from the direction of the runway centre-line are reasonably small, so that $\sin\psi \simeq \psi$, the component of the aircraft's velocity towards the centre-line is:

$$\frac{dy}{dt} = V\psi. \tag{7}$$

Substitution of the expressions for the heading change derived at (2) and (4) gives for the first part of the manoeuvre:

$$\frac{dy}{dt} = \frac{g\phi_1 T_1}{\pi}\left[1 - \cos \frac{\pi t}{T_1}\right]$$

so that from the initial conditions, $y = 0$ at $t = 0$:

$$y = \frac{g\phi_1 T_1}{\pi}\left[t - \frac{T_1}{\pi} \sin \frac{\pi t}{T_1}\right]$$

and the total distance moved at the end of the first part is:

$$y_1 = \frac{g\phi_1 T_1^2}{\pi}. \tag{8}$$

For the second part of the manoeuvre, again with the time origin transposed to its beginning,

$$\frac{dy}{dt} = V\psi_1 + \frac{g\phi_2 T_2}{\pi}\left[1 - \cos\frac{\pi t}{T_2}\right]$$

so that, from the initial condition $y = y_1 = g\phi_1 T_1^2/\pi$

$$y = \frac{g\phi_1 T_1^2}{\pi} + V\psi_1 t + \frac{g\phi_2 T_2}{\pi}\left[t - \frac{T_2}{\pi}\sin\frac{\pi t}{T_2}\right]$$

and the distance moved at the end of the second part, equal to the total distance travelled, *d*, is:

$$d = \frac{g\phi_1 T_1^2}{\pi} + V\psi_1 T_2 + \frac{g\phi_2 T_2^2}{\pi} \tag{9}$$

The total time, *T*, for the manoeuvre is:

$$T = T_1 + T_2 \tag{10}$$

combining (9), (10), ~~(4)~~ and (6)

$$d = \frac{gT^2\phi_1\phi_2}{\pi(\phi_2 - \phi_1)}$$

so

$$T = \sqrt{\left\{\frac{\pi d}{g}\left(\frac{\phi_2 - \phi_1}{\phi_1\phi_2}\right)\right\}}.$$

TABLE 1

Measured Performance of Bad-Weather Approach Aids

Table showing 95% random spread displacements about mean paths followed; maximum displacements; maximum tracking errors and tracking errors associated with the quoted maximum displacements; all measured during approach success trials with various approach aids. Except in the case marked † the tracking errors associated with maximum displacements were such as to reduce the displacement.

	Range from touch-down	Approximate height on nominal 3° glide path	95% random spread	Maximum displacement measured and associated tracking error		Maximum tracking error recorded
	ft	ft	ft	ft	deg	deg
Decca 424	6,000	300	434	761	*	*
	3,000	150	340	500	*	*
Federal G.C.A.	6,000	300	222	225	3¼	4¾
	3,000	150	130	132	2¼	5
Remoted version of Federal G.C.A.	6,000	300	80	96	¼	2¼
	3,000	150	72	133	3½	4¼
British P.A.R.	6,000	300	220	269	4	4
	3,000	150	100	123	¾	2½
ARAA (E. K. Coles)	6,000	300	400	No records		
	3,000	150	280	No records		
Manual I.L.S.	6,000	300	436	540	¼†	17
	3,000	150	342	425	½	15
I.L.S. with zero reader	6,000	300	254	398	¼	4½
	3,000	150	172	266	¼	5¼

* No tracking errors available.

Notes

The data for Decca 424 taken from M.T.C.A. trials and A.I.E.U. trials per Tech. Note BL 38 dated August, 1954.

The data for Federal G.C.A., remoted Federal G.C.A., British P.A.R. and A.R.A.A. taken from M.T.C.A. trials.

The data for Manual I.L.S. and I.L.S. with zero reader taken from A.I.E.U. trials per Tech. Note BL 39 dated June, 1954.

Tracking errors listed for I.L.S. and I.L.S. with zero reader have been calculated from recorded displacement tracking velocities.

TABLE 2

Aircraft Data

Aircraft	Span	Wing area	Aspect ratio	Approximate weight	Wing loading	Aileron movement	Control-wheel movement
Avro 707B .	33 ft	360 sq. ft	2·97	9,500 lb	26 lb/ft^2	±15°	Stick
Meteor II .	43 ft	374 sq. ft	4·95	17,500 lb	47 lb/ft^2	Up 15° Down 12°	Stick
Viking . .	89·4 ft	882 sq. ft	9·0	30,000 lb	34 lb/ft^2	Up 19° Down 17°	±120°
Viscount .	93·7 ft	961 sq. ft	9·17	47,000 lb	49 lb/ft^2	±20°	±120°
Pionair . .	95·0 ft	987 sq. ft.	9·14	23,000 lb	23 lb/ft^2	Up 27° Down 18°	±180°
Sperrin . .	109·0 ft	1,896 sq. ft	6·25	80,000 lb	42 lb/ft^2	±16°	±90°
Hastings .	113·0 ft	1,408 sq. ft	9·10	65,000 lb	46 lb/ft^2	Up 29° Down 16°	—
Elizabethan .	115·0 ft	1,200 sq. ft	11·0	47,000 lb	39 lb/ft^2	Up 20° Down 16°	±95°
Comet 2 .	115·0 ft	2,027 sq. ft	6·5	74,000 lb	37 lb/ft^2	±22°	±90°
Argonaut .	117·5 ft	1,457 sq. ft	9·48	68,000 lb	47 lb/ft^2	Up 15° Down 11·5°	±90°
Lincoln . .	120·0 ft	1,421 sq. ft	10·12	55,000 lb	39 lb/ft^2	±11°	±95°
Constellation749	123·0 ft	1,650 sq. ft	9·17	87,000 lb	53 lb/ft^2	Up 25° Down 10°	±125°
Stratocruiser .	141·2 ft	1,769 sq. ft	11·58	110,000 lb	62 lb/ft^2	±25°	±140°
Britannia .	142·0 ft	2,077 sq. ft	9·76	115,000 lb	55 lb/ft^2	Up 21° Down 15°	±35°*

* Handlebar Type.

TABLE 3

Aircrafts' Measured Rolling Characteristics

Aircraft	Indicated airspeed	Test altitude	Measured rolling characteristics				
			Rate of roll full aileron	$pb/2V$ full aileron	Time to bank 20° full aileron	Time to bank 20° half aileron	Maximum rolling acceleration full aileron
Meteor II	120 kt	10,000 ft	30·0°/sec	0·047	1·2 sec	1·4 sec	55°/sec^2
Viking	110 kt	1,000 ft	16·0°/sec	0·068	1·8 sec	2·4 sec	22°/sec^2
Viscount	110 kt	7,000 ft	19·5°/sec	0·075	1·5 sec	2·4 sec	29°/sec^2
	130 kt	8,000 ft	22·9°/sec	0·074	1·5 sec	1·8 sec	29°/sec^2
Pionair	80 kt	2,500 ft	17·7°/sec	0·104	1·5 sec	2·3 sec	—
	110 kt	4,000 ft	15·9°/sec	0·071	1·5 sec	2·6 sec	—
Sperrin	110 kt	10,000 ft	14·6°/sec	0·064	—	2·2 sec	—
	140 kt	13,000 ft	19·6°/sec	0·064	1·4 sec	2·0 sec	—
Hastings	110 kt	8,000 ft	11·8°/sec	0·055	2·6 sec	3·0 sec	—
	140 kt	8,000 ft	13·9°/sec	0·052	2·3 sec	3·8 sec	—
Elizabethan	105 kt	5,000 ft	12·5°/sec	0·065	2·0 sec	2·7 sec	26°/sec^2
	135 kt	6,500 ft	15·5°/sec	0·062	1·7 sec	2·1 sec	32°/sec^2
Comet 2	115 kt	3,000 ft	17·0°/sec	0·084	1·7 sec	2·0 sec	24°/sec^2
Argonaut	110 kt	10,000 ft	15·1°/sec	0·071	1·8 sec	3·0 sec	21°/sec^2
	140 kt	10,000 ft	17·8°/sec	0·066	1·6 sec	2·0 sec	24°/sec^2
Lincoln	100 kt	10,000 ft	10·6°/sec	0·056	2·8 sec	4·7 sec	11°/sec^2
	120 kt	10,000 ft	12·4°/sec	0·055	2·3 sec	4·2 sec	13°/sec^2
Constellation 749	110 kt	7,000 ft	12·7°/sec	0·066	2·0 sec	4·5 sec	19°/sec^2
	140 kt	8,000 ft	16·6°/sec	0·068	1·6 sec	3·2 sec	27°/sec^2
Stratocruiser	120 kt	12,000 ft	12·6°/sec	0·064	2·3 sec	3·3 sec	18·0°/sec^2
	150 kt	9,000 ft	12·5°/sec	0·053	1·9 sec	2·8 sec	18·0°/sec^2

TABLE 4

Aircrafts' Measured Rolling Characteristics Corrected to Sea Level

Aircraft	Approach speed	Rolling characteristics			
		Rate of roll full aileron	$pb/2V$ full aileron	Time to bank 20° full aileron	Maximum rolling acceleration
Avro 707B*	135 kt	34·8°/sec	0·044	1·2 sec	—
Meteor II	130 kt	27·8°/sec	0·047	1·2 sec	55°/sec^{2}
Viking	110 kt	16·2°/sec	0·068	1·8 sec	22°/sec^{2}
Viscount	120 kt	18·6°/sec	0·075	1·5 sec	29°/sec^{2}
Pionair	90 kt	17·1°/sec	0·093	1·5 sec	—
Sperrin	120 kt	13·6°/sec	0·064	1·4 sec	—
Hastings	120 kt	11·1°/sec	0·054	2·5 sec	—
Elizabethan	115 kt	12·5°/sec	0·064	1·9 sec	28°/sec^{2}
Comet 2	115 kt	16·3°/sec	0·084	1·7 sec	24°/sec^{2}
Argonaut	120 kt	13·9°/sec	0·070	1·8 sec	22°/sec^{2}
Lincoln	110 kt	9·9°/sec	0·056	2·5 sec	12°/sec^{2}
Constellation 749	120 kt	12·6°/sec	0·066	1·9 sec	22°/sec^{2}
Stratocruiser	130 kt	11·5°/sec	0·064	2·2 sec	18°/sec^{2}

* Data from Ref. 7.

TABLE 5

Measured Characteristics of the Aircrafts' Lateral Oscillations

Aircraft	Indicated airspeed	Test altitude	Oscillatory characteristics		
			Period	Logarithmic decrement	Roll/yaw amplitude ratio
Meteor II	130 kt	8,000 ft	4·0 sec	0·82	0·92
Viking	110 kt	1,500 ft	5·5 sec	0·95	—
Viscount	130 kt	7,500 ft	5·7 sec	0·67	0·52
	110 kt	12,500 ft	6·6 sec	0·78	0·53
Pionair	115 kt	1,500 ft	4·3 sec	0·93	0·40
	80 kt	1,500 ft	5·5 sec	1·41	0·47
Sperrin	140 kt	7,000 ft	5·7 sec	0·55	0·43
	110 kt	7,000 ft	6·8 sec	0·42	0·67
Hastings	140 kt	8,000 ft	5·6 sec	0·85	0·50
	110 kt	8,000 ft	6·8 sec	0·96	0·46
Elizabethan	135 kt	5,000 ft	7·1 sec	≏2·0	—
Comet 2	115 kt	3,000 ft	7·5 sec	0·50	1·02
Argonaut	110 kt	10,000 ft	8·1 sec	0·95	0·80
	140 kt	10,000 ft	6·1 sec	0·90	0·86
Lincoln	110 kt	10,000 ft	9·2 sec	1·28	0·72
Constellation 749	110 kt	7,000 ft	8·5 sec	1·35	0·95
	140 kt	7,000 ft	7·0 sec	1·09	1·17
Stratocruiser	150 kt	11,000 ft	5·5 sec	0·79	0·51
	120 kt	9,000 ft	6·7 sec	0·92	0·51

TABLE 6

Characteristics of the Aircrafts' Lateral Oscillations Corrected to Sea Level

Aircraft	Approach speed	Oscillatory characteristics			
		Period	Damping		Roll/yaw amplitude ratio
			Log. dec.	$T_{1/2}$	
Avro 707B*	135 kt	3·8 sec	0·29	9·1 sec	2·70
Meteor II	130 kt	4·0 sec	0·92	3·0 sec	0·82
Viking	110 kt	5·5 sec	1·01	3·8 sec	—
Viscount	120 kt	6·25 sec	0·85	5·1 sec	0·45
Pionair	90 kt	5·1 sec	1·3	2·7 sec	0·44
Sperrin	120 kt	6·4 sec	0·47	9·4 sec	0·51
Hastings	120 kt	6·3 sec	0·99	4·4 sec	0·42
Elizabethan	115 kt	7·0 sec	2·0	2·4 sec	—
Comet 2	115 kt	7·5 sec	0·52	10·0 sec	0·98
Argonaut	120 kt	7·1 sec	1·07	4·6 sec	0·71
Lincoln	110 kt	9·2 sec	1·49	4·3 sec	0·62
Constellation	120 kt	7·9 sec	1·40	3·9 sec	0·92
Stratocruiser	130 kt	6·2 sec	1·00	4·3 sec	0·44

* Values taken from Ref. 7.

TABLE 7

Pilots' Assessments of Aircrafts' Lateral Characteristics

Aircraft	Steady rate of roll	Initial rolling response	Aileron force	Rudder force	Control harmony	Directional stability	Control-wheel travel	General comments
Viking .	Good	Poor	High	High	Satisfactory	—	Satisfactory	Good for correction manoeuvre. Control forces were high but well harmonized.
Viscount .	Good	Good	Light	Moderate	Satisfactory	Poor	Satisfactory	Good for correction manoeuvre.
Pionair .	Poor	—	Light	High	Poor	Satisfactory	Excessive	Poor for correction manoeuvre. The control harmony is poor. The ailerons produce considerable adverse yaw making turn co-ordination difficult. The excessive control-wheel travel gives the impression of a poor steady rate of roll.
Sperrin .	—	Good	Light	Light	Satisfactory	Poor	Satisfactory	Good for correction manoeuvre.
Elizabethan	—	Poor	High	High	Satisfactory	—	Satisfactory	Poor for correction manoeuvre because of the very high control forces. Difficult to reverse the angle of bank smoothly.
Comet 2 .	Good	Satisfactory	—	Excessive breakout force	Poor	Poor	Satisfactory	Poor for correction manoeuvre. The control breakout forces made turn co-ordination difficult. The ailerons produced considerable adverse yaw which initiated the lightly damped lateral oscillation.
Argonaut .	—	—	Moderate	High	Poor	Satisfactory	—	Satisfactory for correction manoeuvre.
Lincoln .	Poor	Poor	Moderate	Moderate	Satisfactory	—	Satisfactory	Poor for correction manoeuvre primarily because of its low rate of roll.
Constellation	Satisfactory	Satisfactory	Light	Moderate	Poor	—	Satisfactory	Satisfactory for correction manoeuvre. The seating position made aileron application difficult in some cases.
Stratocruiser	Poor	—	Light	Moderate	Poor	—	High	Poor for correction manoeuvre because of its low rate of roll. The rudder is over effective for making co-ordinated turns.

TABLE 8

Pilots' Assessments and Aircrafts' Measured Characteristics

Pilots' rating for lat. correction	Aircraft	Control-wheel travel	Max. rate of roll	$pb/2V$	Time to 20° bank	Max. rolling accel.	Time for manoeuvre		Reasons for pilots' rating
							From 100′ offset	From 500′ offset	
Good	*Viking*	±120°	16·2°/sec	0·068	1·8 sec	22°/sec^2	10·7 sec	16·0 sec	Control forces well harmonized, although high.
	Viscount	±120°	18·6°/sec	0·075	1·5 sec	29°/sec^2	10·7 sec	16·0 sec	
	Sperrin	± 90°	13·6°/sec	0·064	1·4 sec	—	—	—	
Satisfactory	*Argonaut*	± 90°	13·9°/sec	0·070	1·8 sec	22°/sec^2	10·7 sec	16·0 sec	
	Constellation	±125°	12·6°/sec	0·066	1·9 sec	22°/sec^2	10·7 sec	16·0 sec	Seating position poor.
Poor	*Pionair*	±180°	17.1°/sec	0·093	1·5 sec	—	11·1 sec	21·3 sec	Poor control harmony. Adverse aileron yaw. Excessive control-wheel travel.
	Elizabethan	± 95°	12·5°/sec	0·064	1·9 sec	28°/sec^2	10·7 sec	16·0 sec	High control forces.
	Comet 2	± 90°	16·3°/sec	0·084	1·7 sec	24°/sec^2	11·1 sec	19·0 sec	High control breakout forces. Aileron adverse yaw.
	Lincoln	± 95°	9·9°/sec	0·056	2·5 sec	12°/sec^2	13·0 sec	21·5 sec	Poor rolling performance.
	Stratocruiser	±140°	11·5°/sec	0·064	2·2 sec	18°/sec^2	11·1 sec	19·0 sec	Poor rolling performance.
Possible requirement		⩽100°	⩾15°/sec	⩾0·07	⩽2·0 sec	⩾20°/sec^2	—	—	

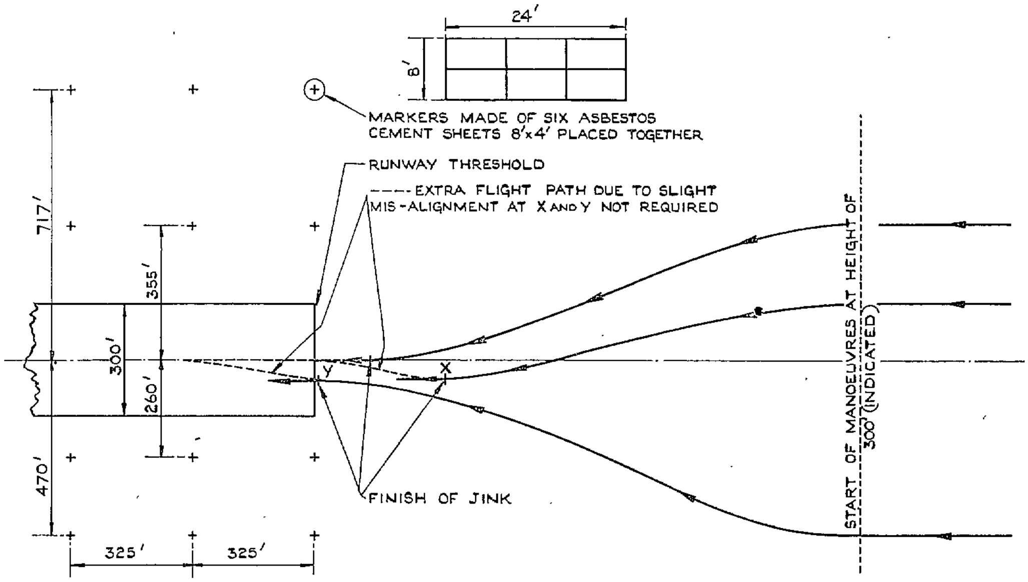


FIG. 1. Layout of ground markers.

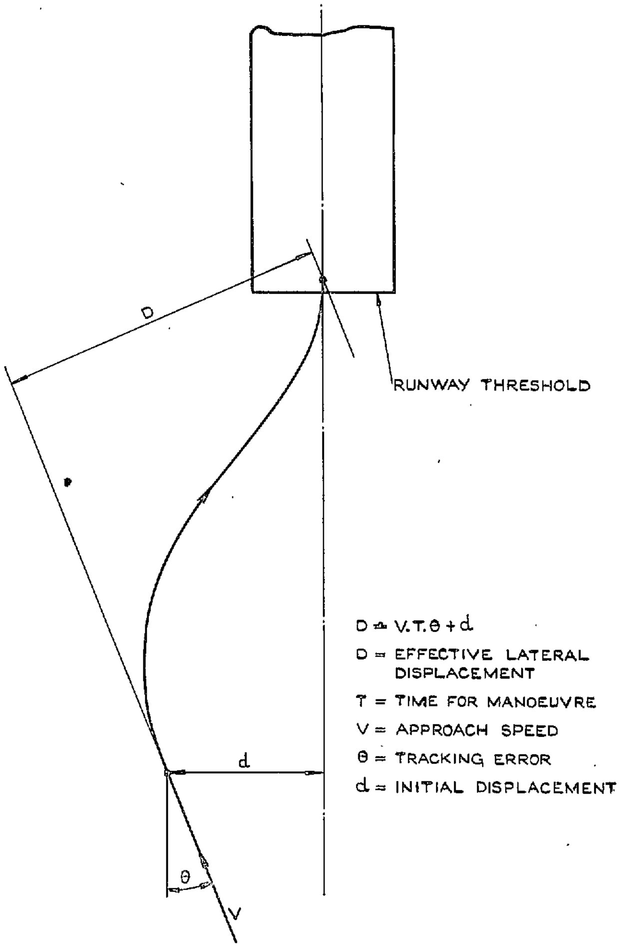


FIG. 2. Effective lateral displacement when a lateral displacement is combined with a tracking error.

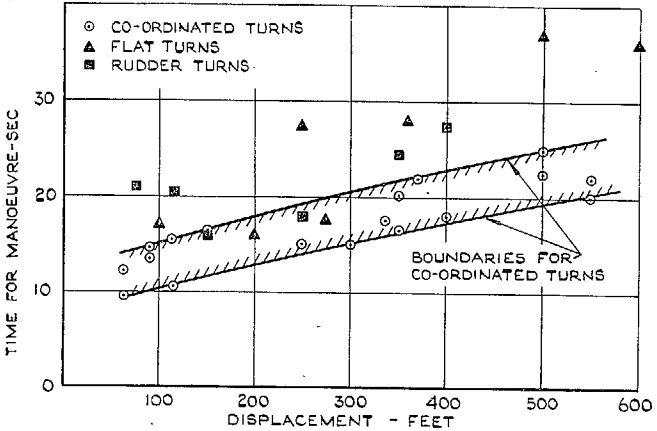


FIG. 3. Comparison between times taken to correct lateral displacements using co-ordinated and slipping turns—*Lincoln* aircraft.

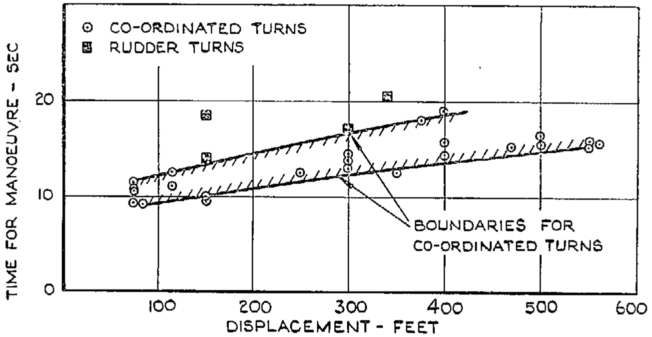


FIG. 4. Comparison between times taken to correct lateral displacements using co-ordinated and slipping turns—*Viking* aircraft.

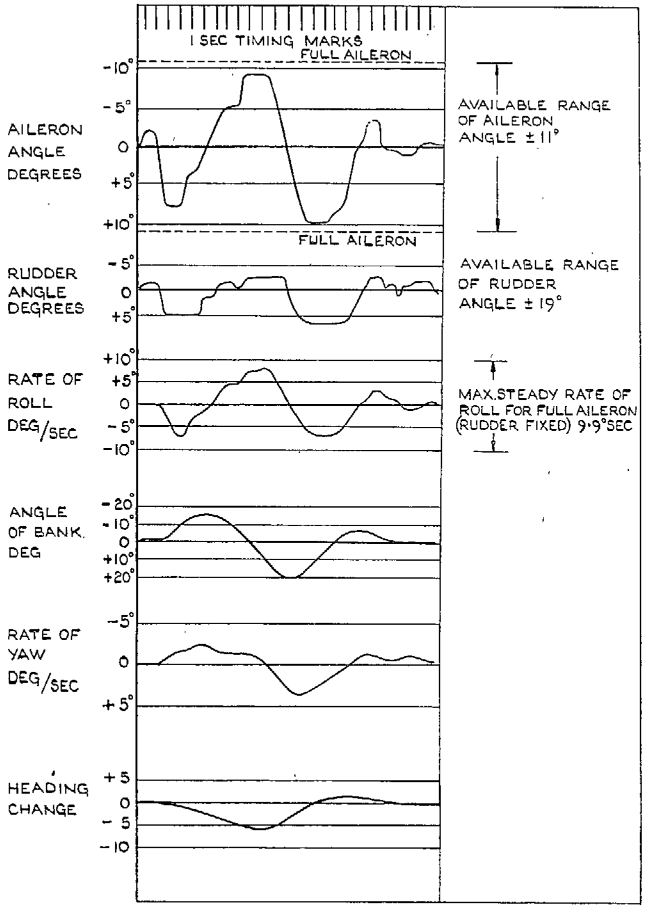


FIG. 5. Time history of a lateral correction manoeuvre by a *Lincoln* aircraft from a displacement of 280 feet.

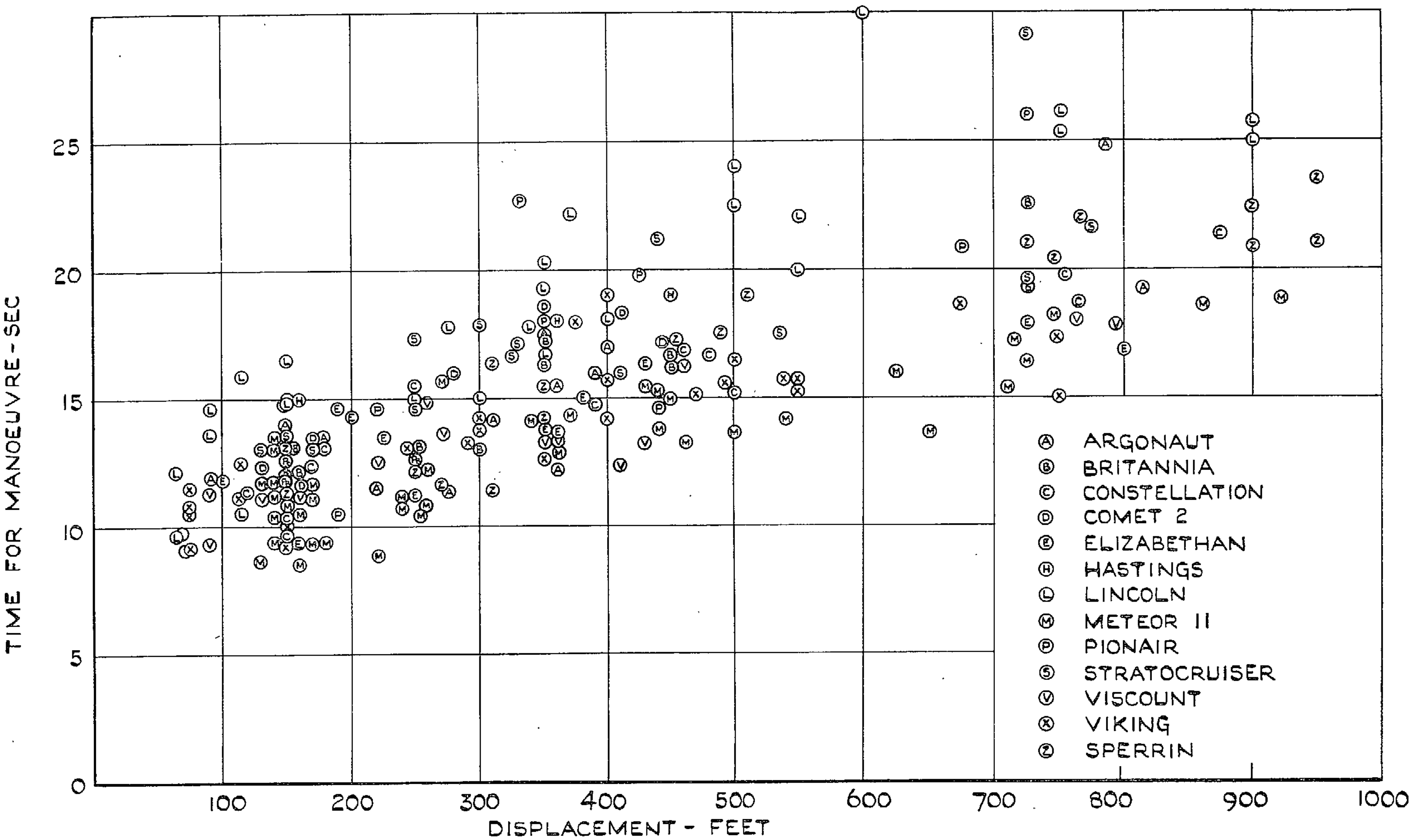


FIG. 6. Manoeuvre time vs. initial displacement for all approaches made by R.A.E. pilots.

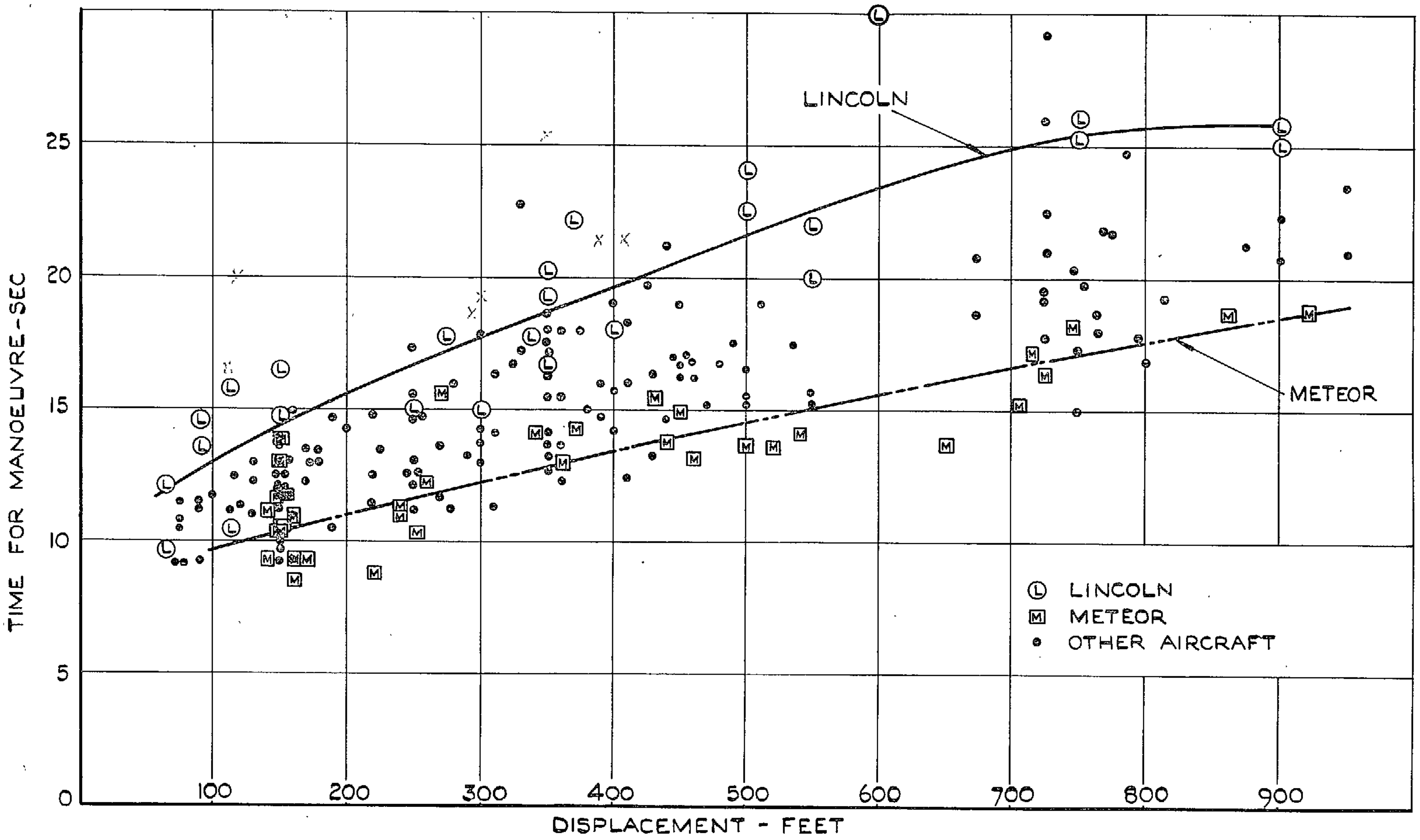


FIG. 7. Manoeuvre time vs. initial displacement. Comparison of *Lincoln* and *Meteor* with other aircraft flown by R.A.E. pilots.

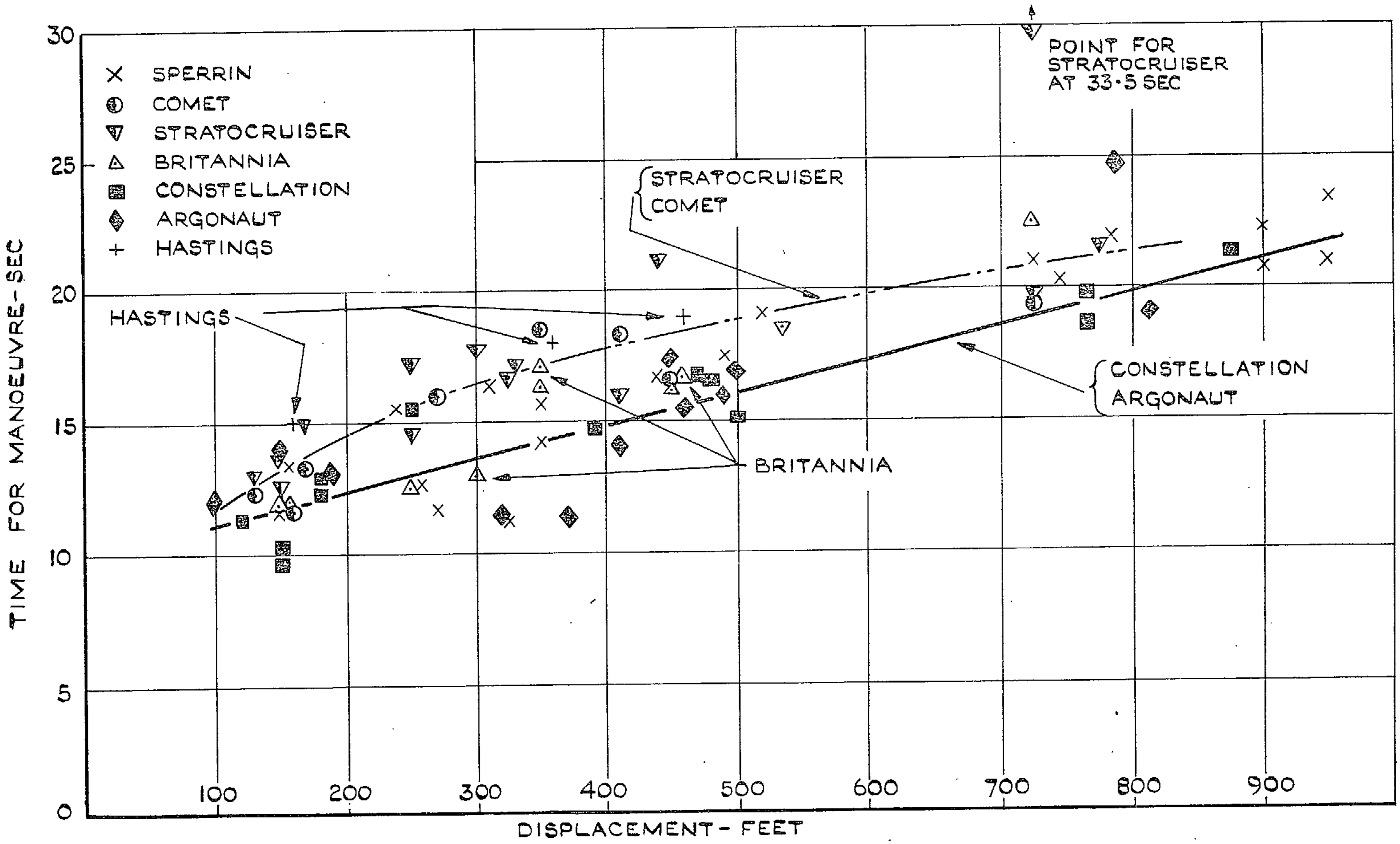


FIG. 8. Manoeuvre time vs. initial displacement. Performance of heavy aircraft flown by R.A.E. pilots.

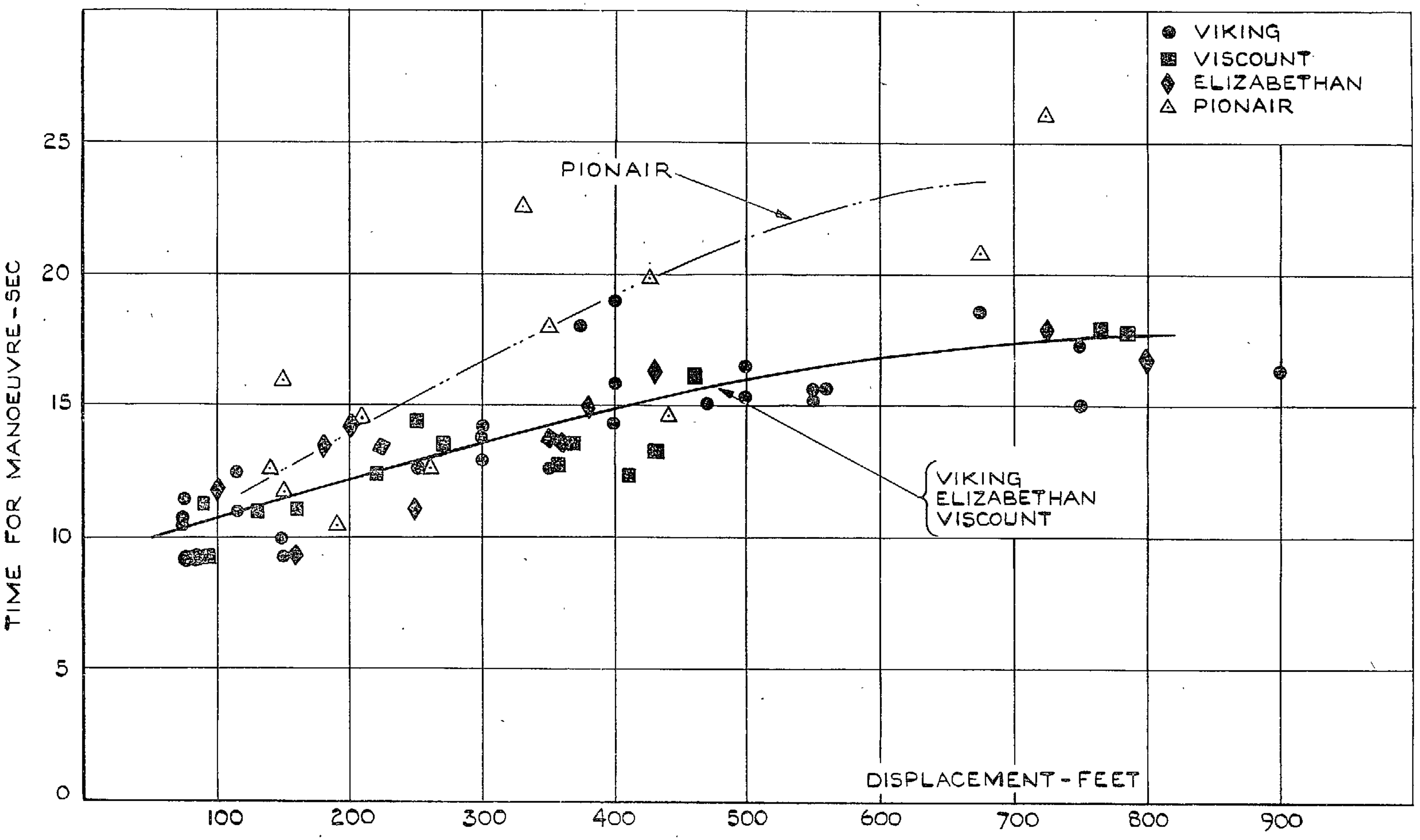


FIG. 9. Man oeuvre time vs. initial displacement. Performance of medium aircraft flown by R.A.E. pilots.

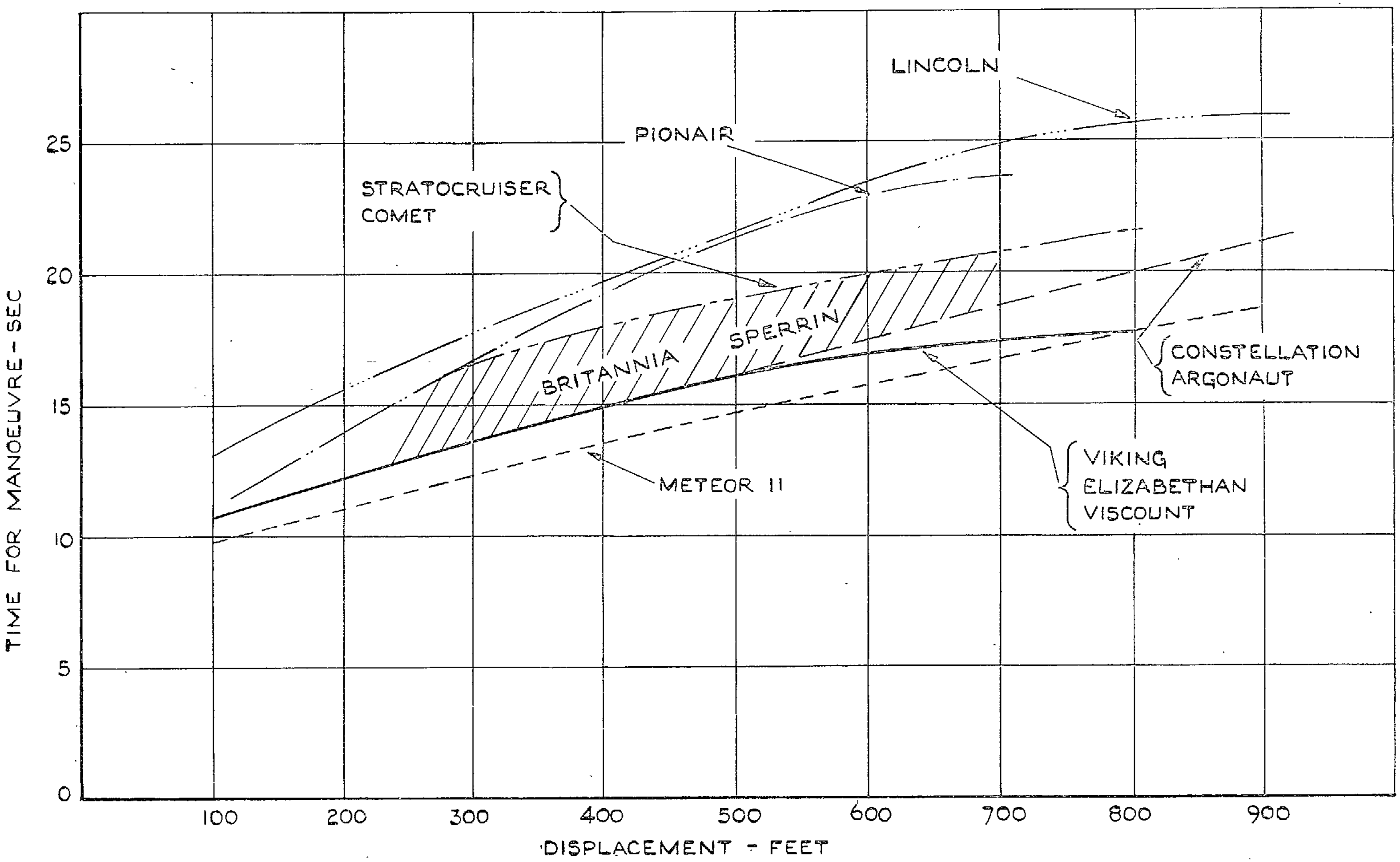


FIG. 10. Comparison between the mean curves of Figs. 7, 8 and 9.

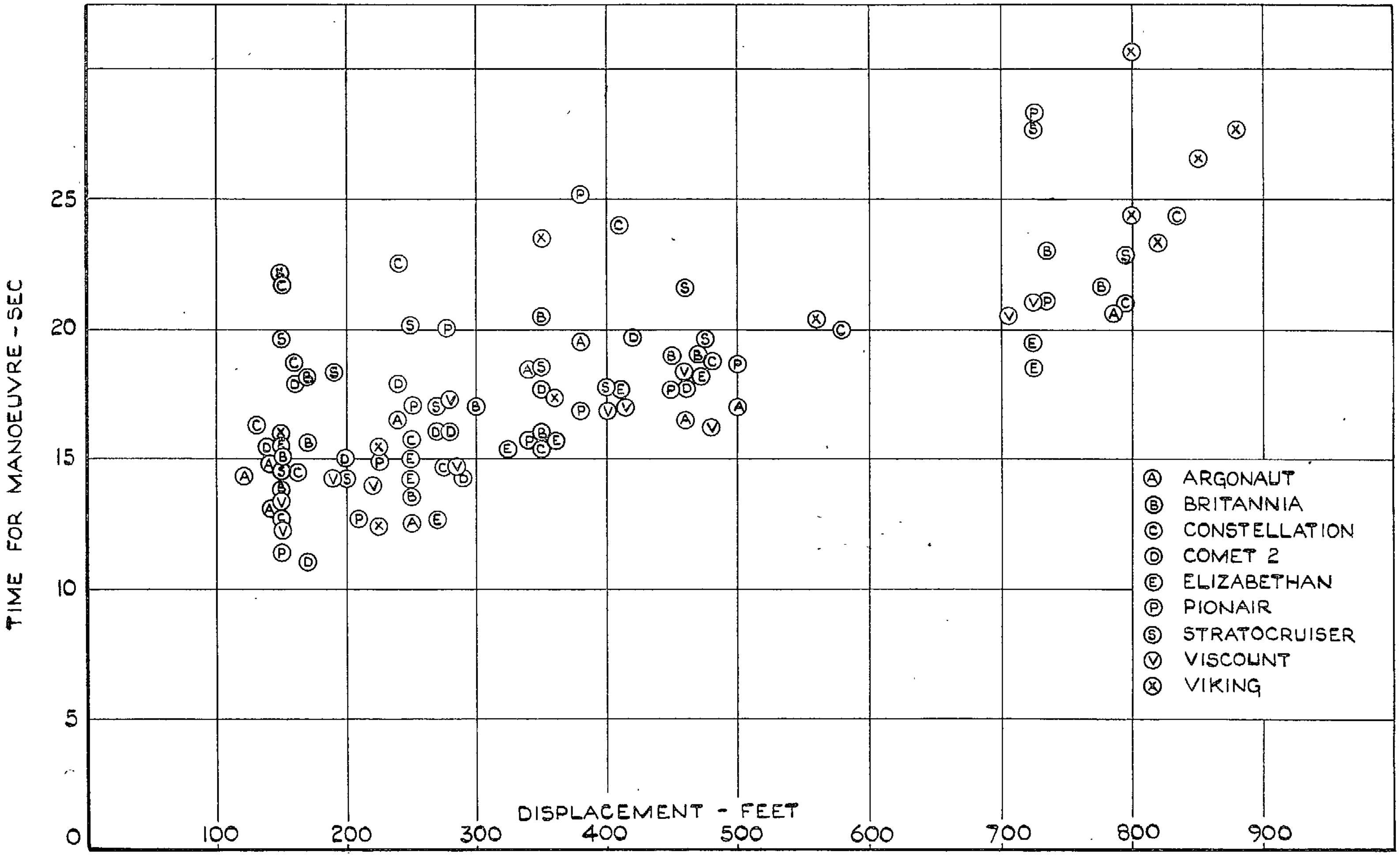


FIG. 11. Manoeuvre time vs. initial displacement for all approaches made by non-R.A.E. pilots.

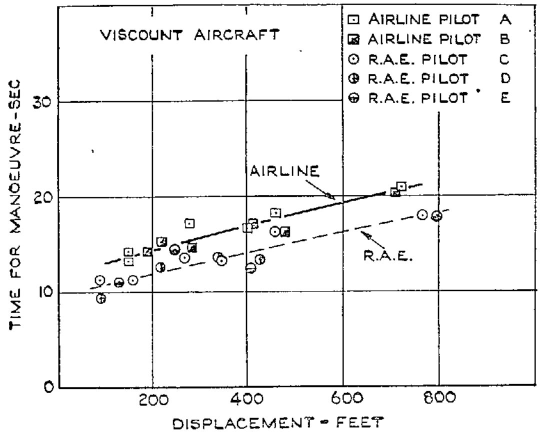


FIG. 12. Manoeuvre times for different pilots using the same aircraft.

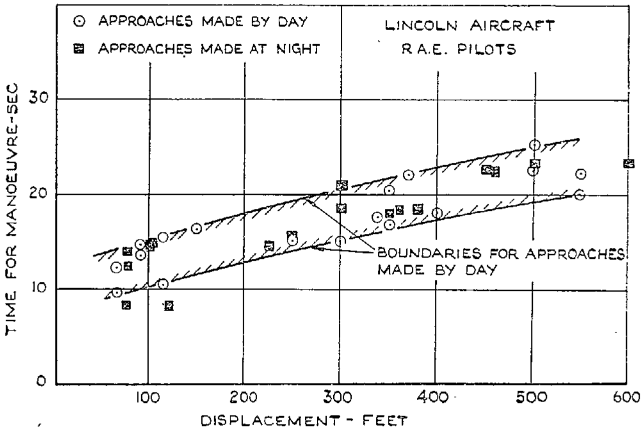


FIG. 13. Manoeuvre times for approaches made at night compared with those made by day. Clear visual conditions.

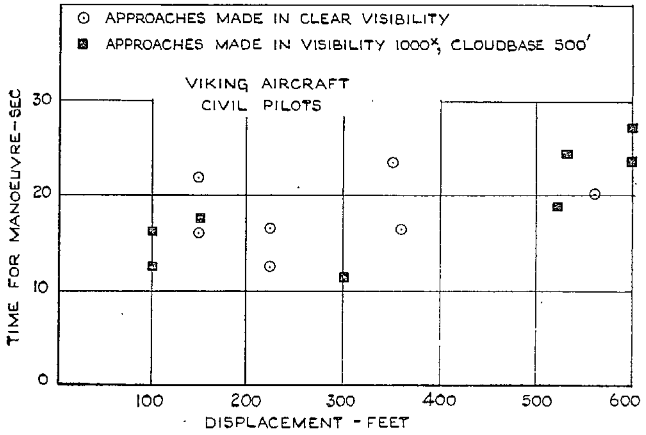


FIG. 14. Manoeuvre times for approaches made in poor visibility compared with those made in good visibility.

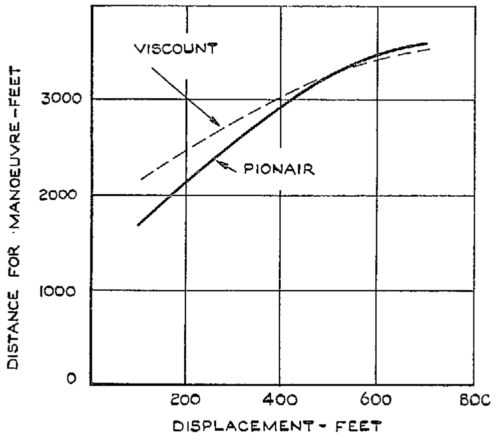
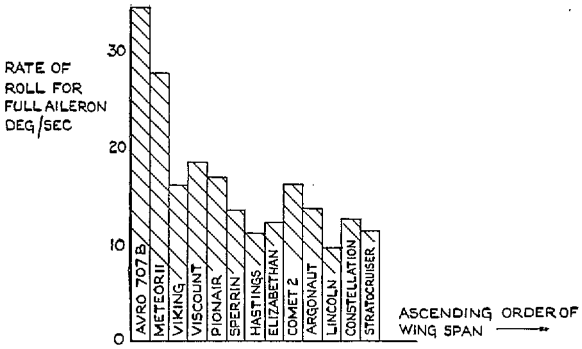
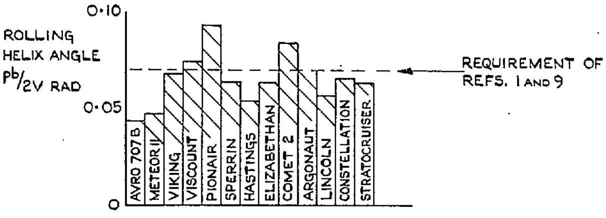


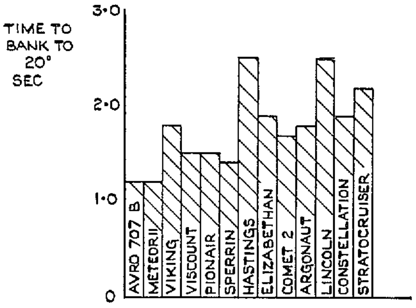
FIG. 15. Calculated distances travelled by *Pionair* and *Viscount* aircraft during the manoeuvre.



a. STEADY RATE OF ROLL



b. ROLLING HELIX ANGLE $pb/2V$



C. TIME TO BANK TO 20°

FIGS. 16a to c. Aircraft rolling characteristics using full aileron at sea level—Rudder fixed.

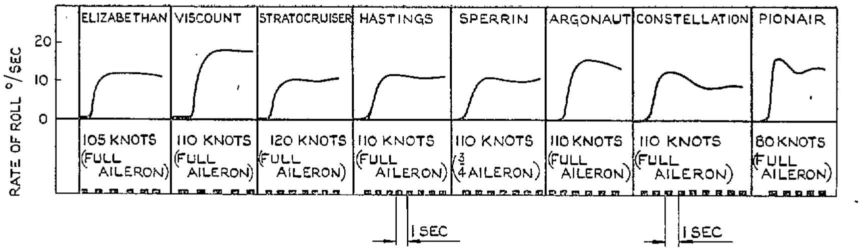
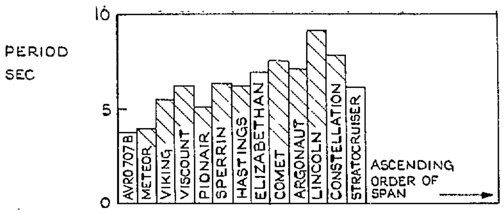
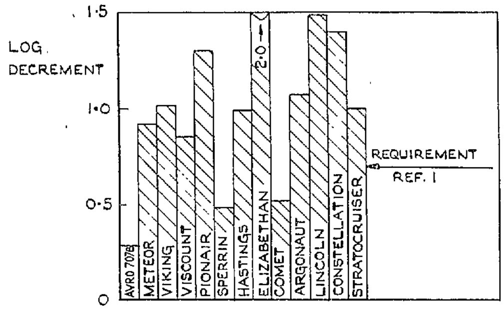


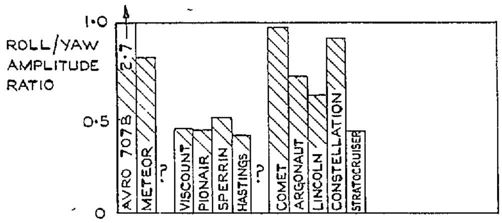
FIG. 17. Comparison between the rolling responses of several of the aircraft—Rudder fixed.



a. PERIOD OF OSCILLATION



b. DAMPING OF OSCILLATION



C. ROLL-YAW AMPLITUDE RATIO

FIGS. 18a to c. Characteristics of the aircrafts' lateral oscillations at sea level.

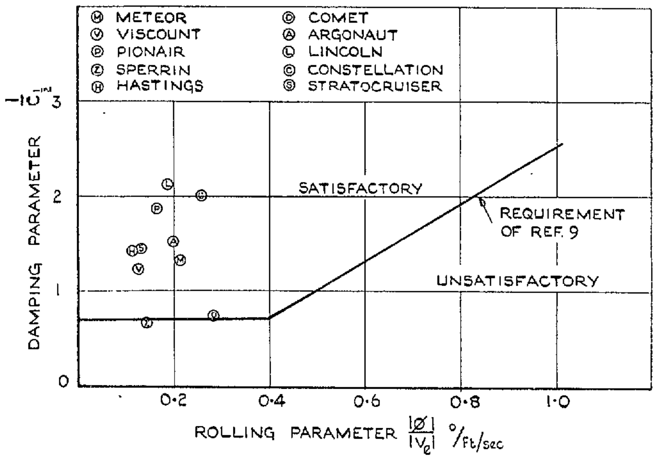
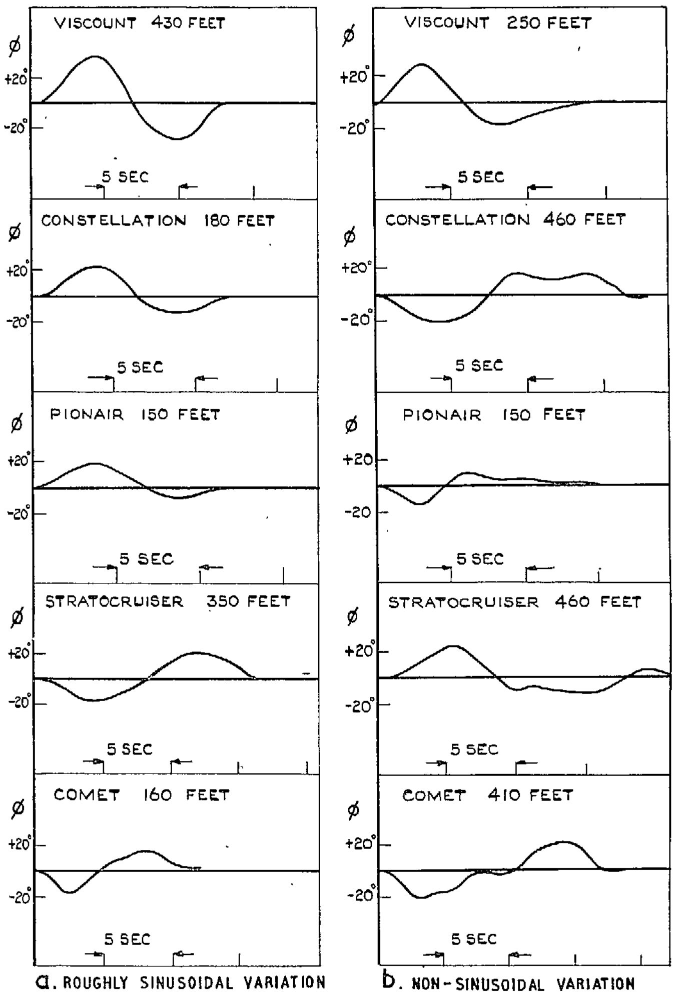


FIG. 19. Comparison of the characteristics of the aircrafts' lateral oscillation with the requirements of Ref. 9.



FIGS. 20a and b. Typical measured time histories of angle of bank during correction manoeuvres.

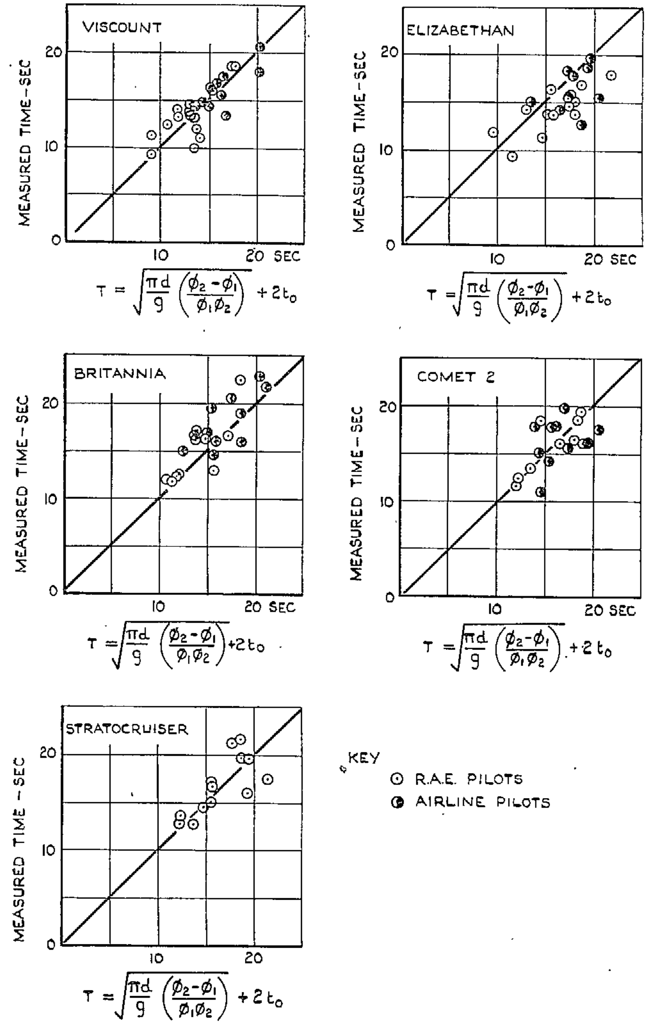


FIG. 21. Comparison between estimated and measured times required for lateral correction manoeuvres.

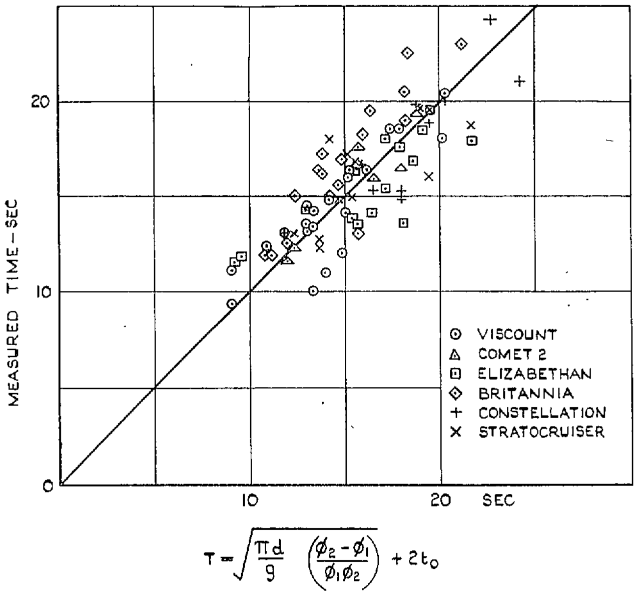


FIG. 22. Comparison between estimated and measured times for correction manoeuvres having roughly sinusoidal variation in angle of bank.

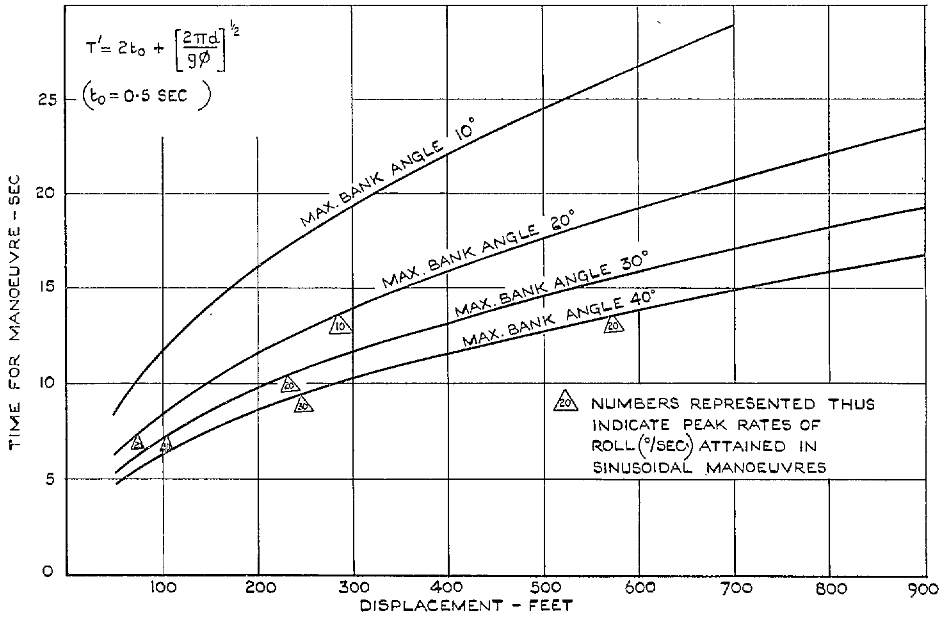


FIG. 23. Theoretical times for sinusoidal manoeuvres limited to various peak angles of bank.

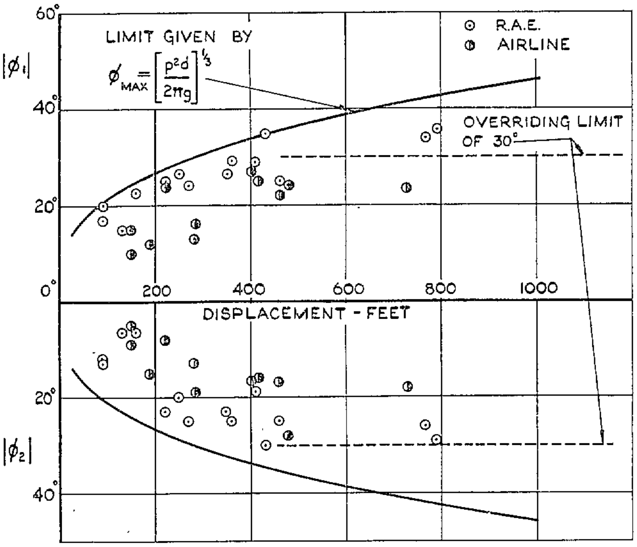


FIG. 24. Comparison between measured angles of bank and predicted maxima—*Viscount.*

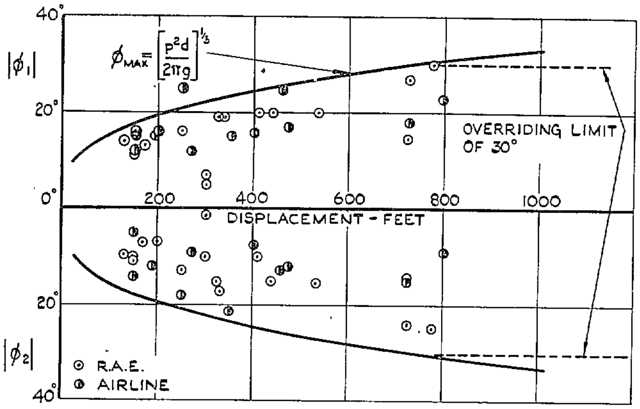


FIG. 25. Comparison between measured angles of bank and predicted maxima—*Stratocruiser.*

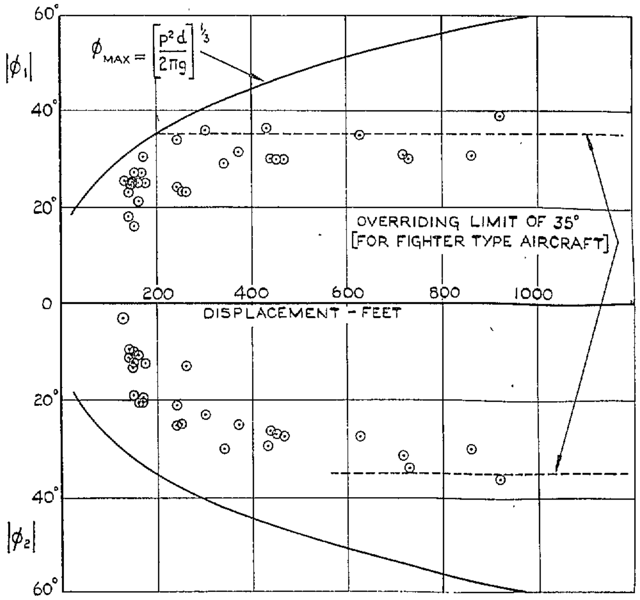


FIG. 26. Comparison between measured angles of bank and predicted maxima—*Meteor.*

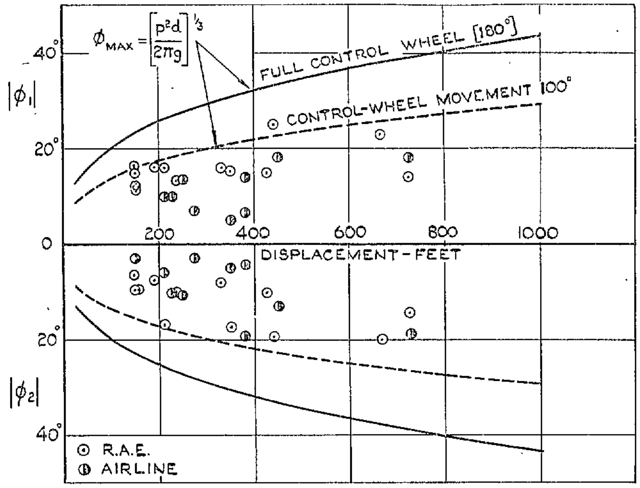


FIG. 27. Comparison between measured angles of bank and predicted maxima—*Pionair.*

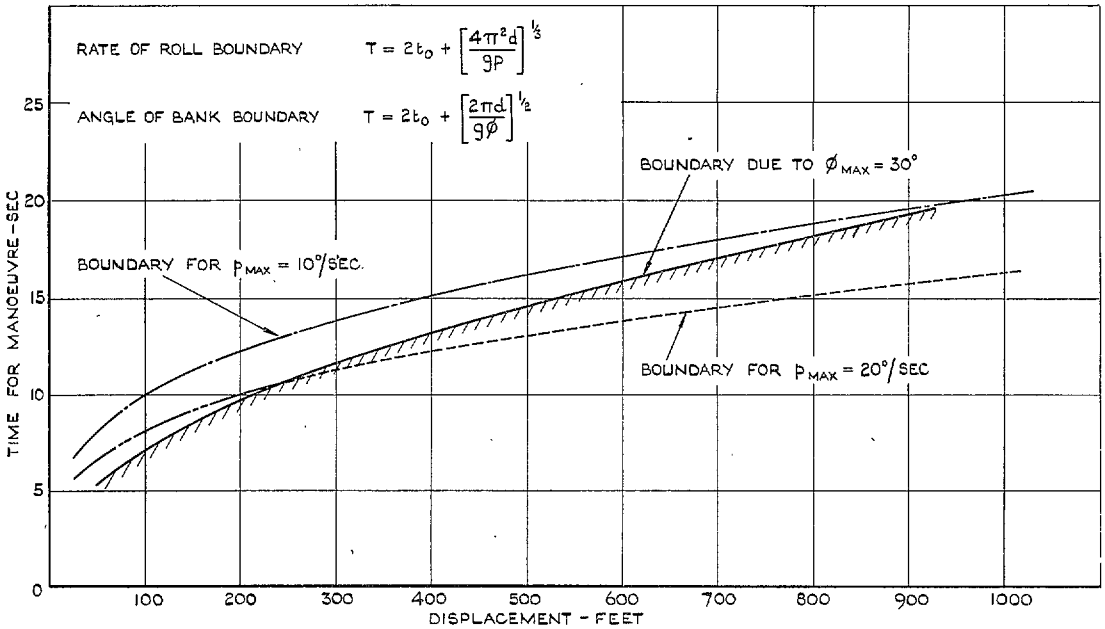


FIG. 28. Theoretical minimum times for sinusoidal manoeuvres limited by rate of roll.

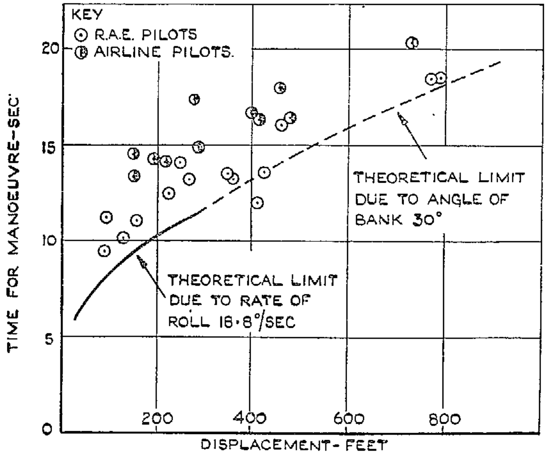


FIG. 29. Comparison of measured manoeuvre times with theoretical minima—*Viscount*.

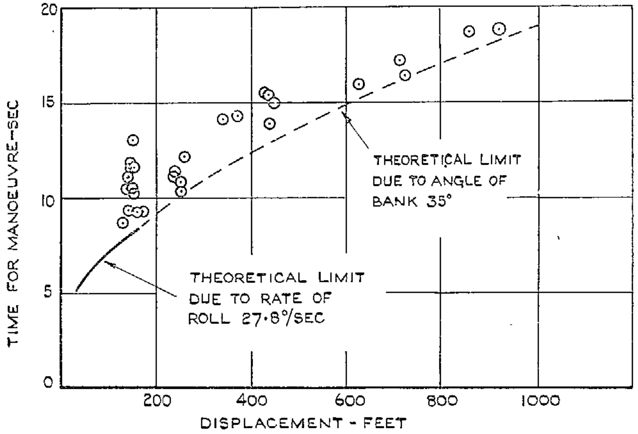


FIG. 31. Comparison of measured manoeuvre times with theoretical minima—*Meteor*.

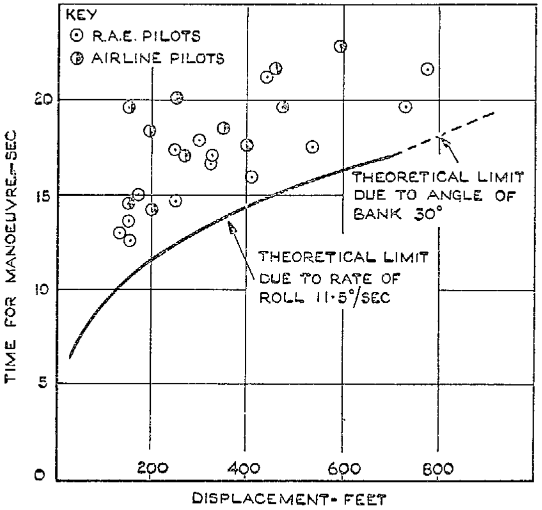


FIG. 30. Comparison of measured manoeuvre times with theoretical minima—*Stratocruiser*.

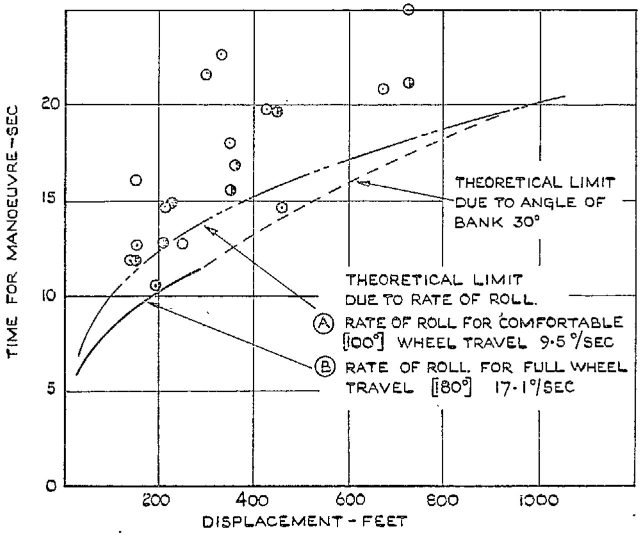


FIG. 32. Comparison of measured manoeuvre times with theoretical minima—*Pionair*.

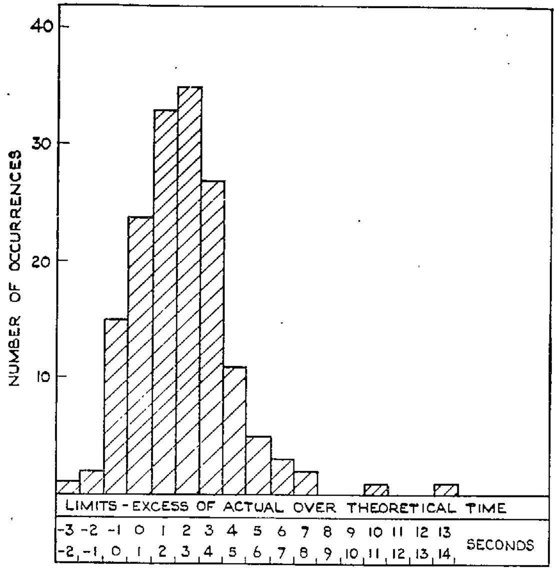


FIG. 33. Amounts by which R.A.E. pilots exceeded the theoretical minimum manoeuvre times.

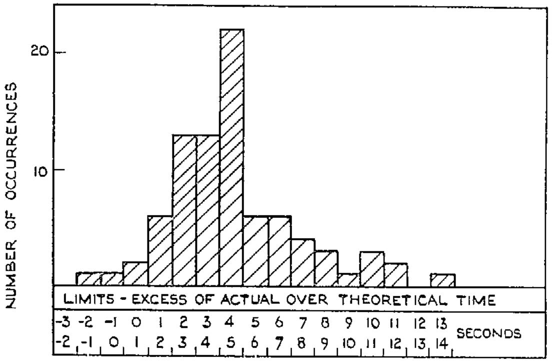


FIG. 34. Amounts by which airline pilots exceeded the theoretical minimum manoeuvre times.

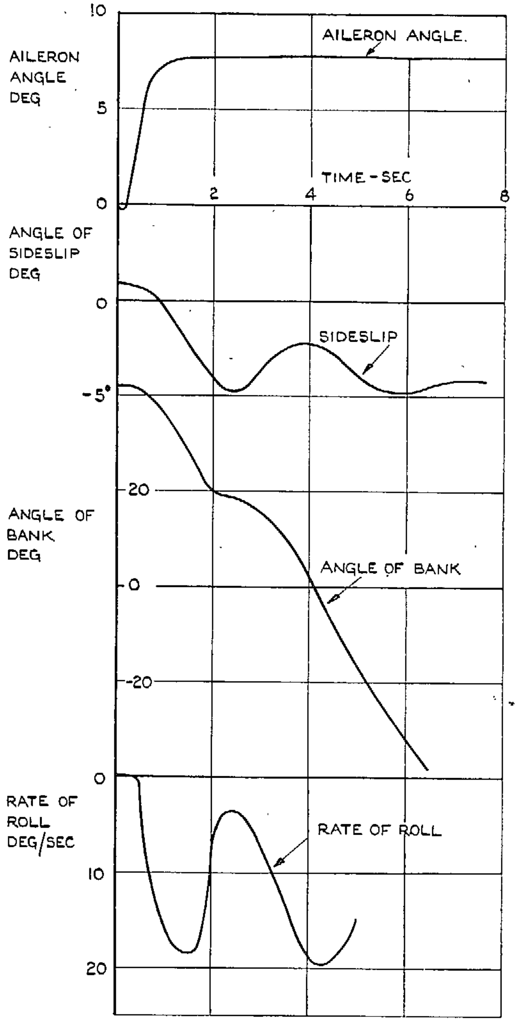


FIG. 35. Time history of the rolling response of the AVRO 707B to aileron application at 120 knots (from Ref. 7).

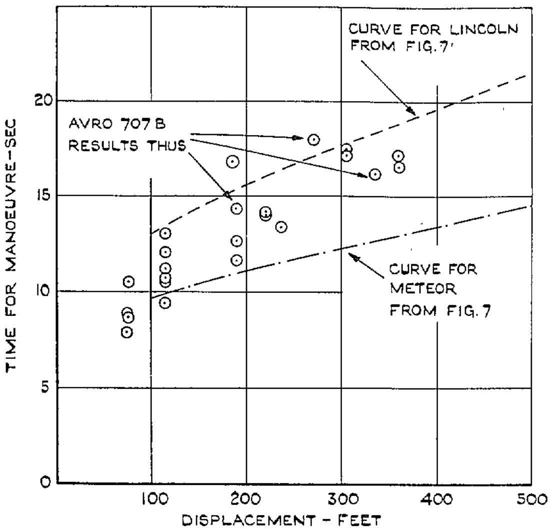


FIG. 36. Comparison of measured manoeuvre times for the Avro 707B with those for the *Meteor* and *Lincoln*.

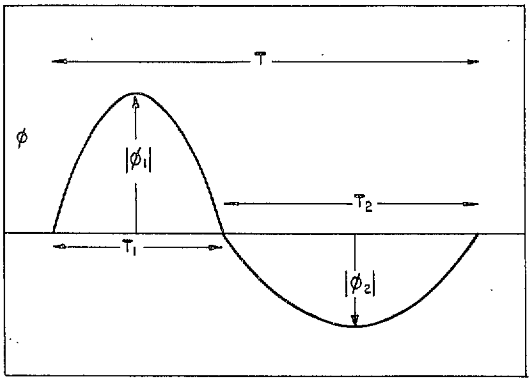


FIG. 37. Symbols used in the theoretical analysis.

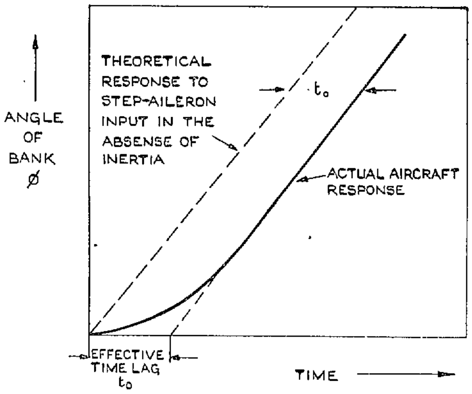


FIG. 38. Definition of the 'effective time lag t_0' in rolling response (after Ref. 4).

(88206) Wt..65/1418 K.5 1/64 Hw.

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