R. & M. No. 2567
(10,903)
A.R.C. Technical Report.



MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

# Note on the Effect of size of Aircraft upon the Difficulties involved in Landing an Aircraft

*By*

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COMMUNICATED BY THE PRINCIPAL DIRECTOR OF SCIENTIFIC RESEARCH (AIR)
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LONDON: HIS MAJESTY'S STATIONERY OFFICE
1951
PRICE 3s. 6d. NET

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*Reports and Memoranda No. 2567**

*June,* 1947

*Summary.*—The effect of aircraft size upon the response of an aircraft during those manoeuvres which are commonly employed in landing has been examined, and in this way an assessment has been made of the way in which the difficulties experienced by the pilot will go up as aircraft size increases.

On the basis of the work summarised in this note it is concluded that the problems associated with landing (from the pilot's point of view at any rate) are unlikely to be aggravated to such an extent, as the size of aircraft increases up to the limiting size considered in this report (300 ft span), as to make landing really difficult.

1. *Introduction.*—Up to the present time the largest landplanes flown in this country have been about 80,000 lb in weight, but in the course of the next year or so much bigger aircraft are to be developed (notably the Brabazon I which will be over 250,000 lb weight). In view of this rapid trend towards bigger aircraft the question as to the manner in which the increase of aircraft size is likely to affect piloting difficulties during approach and landing (particularly in conditions of bad visibility) is one of great interest to designers. It is the object of this note to throw some light on this problem.

In making our theoretical approach we have confined attention to the effect of aircraft size upon four typical landing manoeuvres listed below:—

(1) Flattening out—that is, checking the rate of descent once the aircraft has come close to the ground just before landing.

(2) making an S-turn in order to correct an error in alignment with the runway during the approach.

(3) Correction for wing drop after striking an asymmetric wind gust.

(4) During an approach in a cross-wind it is assumed that the pilot compensates for drift by pointing the nose of his aircraft into wind, while tracking along the runway line, keeping the wings of his machine at all times level. At the last moment he is assumed to slew the machine out of wind to make his touchdown at the instant his machine is aligned with the runway.

These manoeuvres between them involve the motions of the aircraft about all three axes, and they may therefore be expected to give a fairly representative idea of the way landing difficulties will go up with aircraft size.

*R.A.E. Report Aero. 2202—received 4th October, 1947.

Some attention has also been given in this note to the question of how the manoeuvrability of the aircraft at low speeds varies as the maximum rate of control movement is changed. This has some bearing on the design of power-operated control systems where it is important to keep the maximum rate of control as low as practicable in order to keep the weight of the installation down to a minimum. In section 6 this problem has been considered in relation to all three controls.

Throughout all our calculations we have postulated geometric similarity of the aircraft, and thus aircraft size is uniquely specified by some characteristic dimension.

The values of the aerodynamic derivatives, etc. given in Table 1 are to be taken as defining aerodynamic characteristics of the standard aircraft.

2. *Effect of Aircraft Size, etc., upon Response During Check of Rate of Descent when 'Flattening Out' Before Touching Down.*—Here at the outset we are faced with two difficulties ; in the first place of prescribing the action taken by the pilot during the manoeuvre, and secondly of deciding how his action is influenced by the size of the aircraft, if at all.

In the absence of reliable data we have supposed the pilot to take action (independent of aircraft size) along the following lines:—

(a) application of elevator at constant rate,

(b) once a specified elevator angle is reached the stick is held fast until a given $g$ is attained,

(c) thereafter the $g$ is maintained constant and the flight path assumes the form of the arc of a circle.

The initial angle made by the flight path with the horizontal has been taken as 5 deg which, for most aircraft, roughly corresponds to an approach made with low engine power.

Subject to the restrictions quoted above regarding rate of control application, maximum rate of control deflection and limiting $g$, our calculations will give the minimum height in which the check can be made, corresponding to the particular value of the angle of approach assumed. In practice this procedure may not be strictly adhered to, viz. his initial rate of application may not be linear ; furthermore the pilot will relax the $g$ as the flight path flattens out ; however, these deviations from the idealised case which serves as a basis for our calculations will not, it is thought, give rise to appreciable errors in individual cases, and will have even less effect when making comparison between any of the cases considered.

As the assumptions we have made imply the height lost to be directly proportional to wing loading the variation of wing loading is not represented in the figure.

In Fig. 1 the height lost during the check, which is taken as the measure of response, is plotted against aircraft size for various rates of elevator application and various values of the maximum elevator angle. Taking the results at their face value the height lost during the check shows surprisingly little variation with size of machine. There is a tendency for this variation to become more marked as the amount of elevator used in the course of the manoeuvre is reduced. Comparing the heights at which the hold-off of two machines must be commenced, one roughly the size of the Mosquito, the other about twice the size of the Brabazon I (these represent the extremes of aircraft size considered in this note), it is seen that with the limiting elevator angle restricted to 5 deg. and rate of application to 10 deg/sec the heights to hold off are 30 ft in the case of the Mosquito and about 42·5 ft in the case of the 500,000 lb machine.

Additional calculations have been made to obtain the effect of varying initial flight-path angle upon height to start the check (the results are not given in the figure). A decrease of flight-path angle to 3 deg reduces the height to hold off to a value of 11·5 ft in the case of the Mosquito and 16·5 ft in the case of the Brabazon I. This represents a greater proportionate change than in the previous case.

3. *Effect of Aircraft Size, etc., upon Forward Distance Covered Whilst Making an S-turn.*—The manoeuvre considered here is one which a pilot would make in correcting a sideways error in the alignment of the aircraft with the runway during his approach. It is assumed here that the pilot wishes to move onto a track parallel to, and 100 ft distant from, his original track. To do this it is assumed that he applies 20 deg of aileron at a constant rate of 30 deg/sec, and holds it for a short time; throughout this period the aircraft banks over and simultaneously turns off course. It may be necessary to limit the bank by returning the stick to central and holding it there, thus permitting the bank to settle down to a steady value (a maximum bank of 30 deg has been assumed throughout our calculations). His next move is to apply 20 deg of opposite aileron again at a linear rate of 30 deg/sec; this initiates a roll in the opposite direction, and by the time his angle of bank has been reduced to zero he will have traversed about half of the required lateral displacement. The manoeuvre is completed by repeating the procedure outlined above in the reverse direction. It is supposed that throughout the entire manoeuvre zero velocity of sideslip is maintained.

The pilot's action is specified diagrammatically in Fig. 2.

To ease the labour of computation as much as possible, all transitory rolling effects have been ignored, *i.e.* following upon the application of aileron the aircraft is assumed to instantaneously acquire a steady rate of roll after the elapse of a certain interval of time. A method of evaluating this effective time lag between each aileron movement and the establishment of a steady rate of roll is outlined in the Appendix.

The forward distance moved through during the S-turn has been evaluated on the assumption that the manoeuvre is completed by the time the ailerons are returned to central.

In practice the aircraft possesses a slight amount of residual momentum at the instant the control is finally centralised, and a little time is required for this residual motion to be damped out. However, this time lapse between the act of centralising the controls and the reattainment of a steady flight condition is so small that it is thought permissible to ignore it. The variation of forward distance traversed with aircraft size is shown in Fig. 2 and with rate of control application in Fig. 7.

The effect of the size of the aircraft upon response (as measured by forward distance travelled during the manoeuvre) is found to be on the whole small.

An aircraft of normal wing loading (about 40 lb/ft$^2$) and weighing about 20,000 lb will travel about 1,250 ft during the execution of an S-turn. Keeping the same wing loading but increasing the weight to 500,000 lb has the effect of increasing the distance to about 1,950 ft, a little over a 50 per cent increase on the initial figure. Increasing the wing loading has the effect of reducing the response, as we would expect.

4. *Effect of Aircraft Size, etc., upon Time Taken to Raise a Wing.*—A manoeuvre which might be expected to be more seriously affected by size changes and variations of rates of aileron application than the S-turn is that of the correction for wing drop resulting from an encounter with an asymmetric gust during approach. For this reason it was thought worth while to devote some attention to it.

The pilot is assumed to apply aileron at constant rate and subsequently remove it at the same rate. In all cases the maximum aileron is assumed to be 20 deg, as in the previous case, and the rate of roll is reduced to zero by the time the wings are levelled out. Apart from this the basic assumptions are the same as those made in the preceding section. It might be argued that in practice it is unlikely that sideslip will be zero at all times during the recovery; however, as its inclusion in our calculations will not appreciably affect the manner in which controllability varies with size and control rate we have thought it permissible to assume zero sideslip.

The effects of size upon the time to raise a wing through 20 deg are shown in Fig. 3 to be much larger than in the previous cases. With the higher rates of application considered, increasing aircraft dimensions by a factor 5 increases the time to correct by a factor of $2\frac{1}{2}$. It must be borne in mind, however, that the magnitude of the wing drop will probably fall off as the size of the aircraft increases, assuming gust intensity to remain the same. This may be deduced by consideration of the fact that the disturbing moment caused by a gust increases as the cube of the span, whereas both the damping and inertial terms vary as the fourth power of the span. This, in practice, may compensate for the reduction of response.

5. *Effect of Aircraft Size, etc., upon Response of Aircraft Whilst Making a Last Minute Correction for Drift During a Landing in a Cross Wind.*—The calculations which have been made in connection with this manoeuvre are based upon the form of pilot's action specified below.

Rudder is applied at a constant rate and subsequently removed at the same rate; this being just sufficient to destroy the angular momentum of the aircraft by the time the machine is aligned with the runway, thus enabling the pilot to make his touchdown with zero angular velocity of yaw.

It is appreciated that the technique adopted in conditions of normal visibility may differ widely from that suggested above, especially as the size of aircraft increases. Thus, it is quite usual in practice to start gradually aligning the aircraft's fore-and-aft axis with the runway during the approach, and compensating the resultant tendency to drift by dropping the windward wing; then this bank is taken off as the aircraft is held off. In conditions of zero visibility, however, it is quite probable that a procedure along the lines of those described above will have to be adopted.

The calculated values of the time to carry out the manoeuvre, and of the lateral velocity acquired during the manoeuvre, have been plotted against aircraft size factors in Figs. 4 and 5. Three wing loadings (20, 40 and 60 lb/ft$^2$) are covered by these figures, as well as variations in the rate of rudder application.

Size of aircraft in this case exerts a relatively large influence on both the time taken to make the manoeuvre and the rate at which the aircraft is moving sideways across the runway when the manoeuvre is completed. Roughly speaking increasing the linear dimensions of the aircraft by a factor 5 rather less than doubles the times involved and multiplies the lateral velocity by a factor of about $2\frac{1}{2}$.

Reduction of wing loading shortens the duration of the manoeuvre and decreases the lateral velocity at the instant of touchdown.

6. *Effect of Rate of Control Application upon the Manoeuvrability of an Aircraft.*—It has already been pointed out that the question of deciding upon the minimum value of the limiting rate of control application and the way in which it varies with aircraft size is one which is of very great interest to the designer of operating units for powered controls, as this is a major factor in the determination of the size and weight of the units. Some light is thrown upon this question by calculations which have been made on the effect of rate of control application upon the response of the aircraft to those manoeuvres considered previously in connection with variations of aircraft size. The results of these calculations are plotted in Figs. 6 to 10 inclusive. For the purpose of obtaining an indication of the values of the limiting rates of control application and the manner in which they vary with aircraft size we have superposed in Figs. 6 to 10 curves which at their intersection with the curve corresponding to appropriate aircraft size, define the rate of control movement at which response falls within 10 per cent of its asymptotic value (*i.e.* value corresponding to instantaneous control application).

A discussion of the results in the case of each of the three controls is given below.

6.1 *Elevator.*—The way in which the response of an aircraft, during the check manoeuvre, is influenced by rate of elevator application is considered in Fig. 6 for aircraft of different sizes (50,000, 200,000 and 500,000 lb) and for values of the limiting elevator angle of 5 deg and 10 deg. A third case in which it is assumed that elevator is continuously applied at a constant rate until specified $g$ is attained has also been considered. *N.B.* In all cases considered this results in an elevator angle of less than 30 deg up). Asymptotic values for those curves which refer to a limiting elevator angle of 10 deg have been calculated and used to compute values of the rate of elevator application to give response (as measured by height lost during check) within 10 per cent of its asymptotic value. In the case of the 50,000 lb aircraft this is 27 deg/sec and in the case of the 500,000 lb aircraft it is about 22·5 deg/sec.

6.2 *Aileron.*—This control has been dealt with in two cases,

(i) in connection with the S-turn (Fig. 7),

(ii) in connection with wing raising (Fig. 8).

As we should expect, the effect of rate of aileron movement is much more noticeable in the case of the correction for wing drop than in the case of the S-turn.

In the wing-dropping case, for the response to be within 10 per cent of its asymptotic value necessitates a control rate of about 22 deg/sec for the 500,000 lb aircraft and about 40 deg/sec with the 50,000 lb aircraft.

6.3 *Rudder.*—The variation of time required to make a correction for drift and the lateral velocity acquired whilst making the correction have been plotted against rate of control application in Figs. 9 and 10. Three curves are given in each figure corresponding to all-up weights of 50,000, 200,000 and 500,000 lb.

The rate of rudder movement needed to give a response within 10 per cent of the limiting value (viz. that corresponding to instantaneous application of full rudder of 25 deg) has been found to be of the order of 18 deg/sec. This value is not significantly altered by changes in aircraft size.

6.4 *General Discussion.*—The form of the curves given in Figs. 6 to 10 shows that quite a considerable reduction in maximum control rate may be made without seriously impairing the response of the aircraft. Past experience, however, has shown that a slight reduction of response may be unfavourably commented upon by the pilot. Spoiler control, for example, is nearly always criticised by the pilot on the grounds that the reponse to control movement is not sharp enough, whereas calculations, tests and measurements in flight often detect only an extremely small difference in the time lag between normal aileron and spoiler control. These adverse criticisms may be due to a dislike on the part of the pilot of feeling his control in any way hampered rather than to any really serious deterioration of manoeuvrability. In view of this our assumed figure of 10 per cent for the degree of reduction of response which will be acceptable to the pilot is purely an arbitrary one and must stand or fall in the light of experience.

Flight tests are at present being made at the R.A.E. on this question of the permissible lower limit of the maximum control rate and provide a check on these calculations. This flight work is being carried out on a Lancaster aircraft fitted with power-operated controls, the rate of control application being progressively limited by restricting the rate at which oil can be delivered to the jacks.

In passing it is worth noting that evidence secured to date confirms to some extent the values quoted, *i.e.* control is still satisfactory when the maximum obtainable rates for the elevator are about 30 deg/sec, and for ailerons somewhat higher, about 45 deg/sec.

It must be emphasised that these figures are only provisional, and it is probable that satisfactory control on the rudder and elevator will be obtained with even lower maximum rates.

7. *Conclusions.*—At the outset it would perhaps be as well to draw attention to the limitations to which these calculations are inevitably subject. These limitations must be borne in mind when interpreting the results.

In all cases examined in this note increase of aircraft size leads, as we would expect, to a reduction of response. This has been found to be most marked in those cases in which last minute correction is made for drift of the aircraft, prior to touching down, and in making correction for wing drop, though in the latter, as we have pointed out in section 4, some mitigation is perhaps to be expected from the increased inertia giving rise to smaller magnitude of initial wing drop. The remaining manoeuvres considered are by comparison only slightly affected.

Summing up with reference to the effects of aircraft size, we would say that while the slower response associated with the larger aircraft will mean that as aircraft dimensions increase ever greater demands are going to be made upon the pilot, we do not see any likelihood of these difficulties becoming insuperably large, at any rate for aircraft up to 500,000 lb in weight.

So far as the rate of control movement is concerned, this has been considered in section 6, and although it is at present impossible to lay down hard and fast rules for the minimum limiting rate allowable on controls, flight work at present proceeding at the R.A.E. suggests that the values deduced in this note for the rate of application corresponding to a 10 per cent reduction of response might be taken as giving a fairly reliable indication of the order of things. In the case of the rudder control this limiting figure for an aircraft of about 50,000 lb weight is about 18 deg/sec. The values associated with the elevator and aileron controls are somewhat larger, about 27 deg/sec and 40 deg/sec respectively. As the size goes up a slight reduction of these limiting rates might be expected, particularly in the case of elevator and aileron.

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## NOTATION.

| | | | | | |
|---|---|---|---|---|---|
| $m$ | | mass of aircraft | $\phi$ | | angle of bank |
| $c$ | | wing chord | $H_m$ | | manoeuvre margin (stick fixed) |
| $b$ | | wing span | $i_A$ | = | $4A/mb^2$, inertia in roll |
| $S$ | | wing area | $i_B$ | = | $B/ml^2$, inertia in pitch |
| $S'$ | | tailplane area | $i_C$ | = | $4C/mb^2$, inertia in yaw |
| $a$ | = | $\partial C_L/\partial\alpha$, lift slope of mainplane | $\xi$ | | aileron angle |
| $a_1$ | = | $\partial C_{LT}/\partial\alpha_T$, lift slope of tailplane | $l_\xi$ | = | $2L_\xi/\rho SV^2b$ |
| $l$ | | tail arm | $l_p$ | = | $4L_p/\rho SVb^2$, damping in roll |
| $\mu$ | = | $m/\rho Sl$ | $y_v$ | = | $Y_v/\rho SV$ |
| $\mu_2$ | = | $2m/\rho Sb$ | $n_v$ | = | $2N_v/\rho SVb$ |
| Unit of aerodynamic time | = | $m/\rho SV$ | $n_r$ | = | $2\,N_r/\rho SVb$, damping in yaw |

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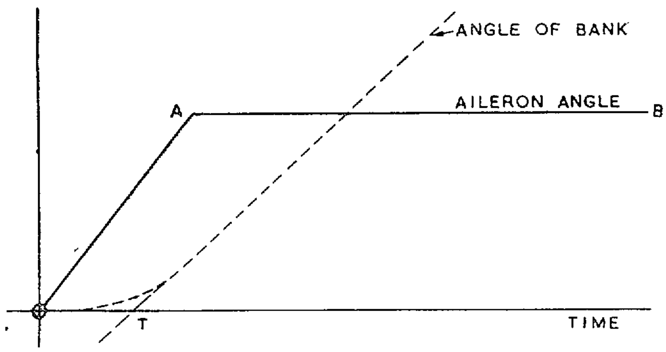
## REFERENCE.


| *Ref. No.* | *Author* | *Title, etc.* |
|---|---|---|
| 1. | Morgan and Bethwaite .. .. .. | Notes on Stick Force Characteristics During the Initiation and Reversal of an Aileron Roll. R. & M. No. 1985. (August, 1943). |

# APPENDIX.

As we have mentioned in section 3 when considering the effect of aircraft size upon forward distance covered whilst making an S-turn, the problem was greatly simplified by assuming the variation of rate of roll with time to assume a stepped form. The rate of roll resulting from each aileron movement is supposed after the elapse of a certain time interval termed the 'effective time lag' (depending upon the rate at which aileron is moved and the angle through which it is deflected) to instantaneously take up its final steady value. Check calculations have shown the answers obtained in this way to be fairly accurate, and it is thought that the method might profitably be applied to many calculations in which only a rough answer is required. For this reason we have set out below the derivation of the 'effective time lag' in the case of the aileron control.

The effective time lag is defined as follows. The aileron is assumed to be deflected through a certain angle at constant rate and then held fast. In the accompanying diagram this aileron movement is represented by OAB.




This action will produce a build-up of bank (shown dotted) which, after a short time, becomes linear.

The intercept OT obtained by extrapolating the linear portion of the curve back to meet the time axis (OT in the figure) defines the effective time lag.

The rolling motion resulting from an aileron movement OAB has been worked out in R. & M. 1895[1]. During the period AB the angle of bank is given by the equation

$$\phi = -\frac{\mu_2 \bar{g}}{l_p}\left\{\frac{\tau_1^{\,2}}{2} + \frac{i_A}{l_p}\tau_1 + \tau_1\tau + \left(\frac{i_A}{l_p}\right)^2 e^{\tau(l_p/i_A)}\left(1 - e^{\tau(l_p/i_A)}\right)\right\}, \quad \ldots \quad \ldots \quad (1)$$

where $\tau$ denotes time referred to a time origin at A expressed in aerodynamic units,

$\tau_1$ is time taken to apply aileron, expressed in aerodynamic units,

and $\bar{g}$ is proportional to the rate at which aileron was applied

($viz.$: $\bar{g} = l_\xi \dot{\xi}$).

Since $l_p/i_A$ is a negative quantity the fourth term in equation (1) can be disregarded after a time and thereafter the bank will increase linearly with time according to the equation:

$$\phi = -\frac{\mu_2 \bar{g}}{l_p}\left(\frac{\tau_1^{\,2}}{2} + \frac{i_A}{l_p}\tau_1 + \tau_1\tau\right). \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

The value of $\tau$ corresponding to the point $T$ in the figure is obtained by putting $\phi = 0$ and solving for $\tau$.

We then obtain

$$\tau = -0\cdot 5\ \tau_1 - \frac{i_A}{l_p}.$$

The effective time lag, given by OT is then equal to

$$\tau_0 = \tau_1 + \left(-0\cdot 5\ \tau_1 - \frac{i_A}{l_p}\right) = 0\cdot 5\ \tau_1 - \frac{i_A}{l_p}. \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

In a similar manner we may derive expressions for time lags associated with elevator and rudder controls. The relevant expressions are given below.

*Elevator control.*

$$\text{Effective time lag (aerodynamic units),} = 0\cdot 5\ \tau_1 + \frac{i_B + \dfrac{S'a_1'}{Sa_1}\left(1 - \dfrac{d\varepsilon}{d\alpha}\right)}{\mu \dfrac{c}{l} H_m},$$

where $\tau_1$ is time taken to apply elevator.

*Rudder control.*

$$\text{Effective time lag (aerodynamic units)} = 0\cdot 5\ \tau_1 + \frac{1}{y_v} + \frac{i_c y_v + n_r}{y_v n_r + \mu_2 n_v},$$

where $\tau_1$ is time taken to apply rudder.

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## TABLE 1.

*Particulars of Standard Aircraft.*

| | | | | | | |
|---|---|---|---|---|---|---|
| Aspect ratio, | $A$ | = | 6·25 | $i_B$ | = | 0·088 |
| Tailplane volume, | $\bar{V}$ | = | 0·57 | $i_C$ | = | 0·15 |
| $\dfrac{\partial C_L}{\partial \alpha}$, | $a$ | = | 4·0 | $y_v$ | = | $-$ 0·18 |
| | | | | $l_p$ | = | + 0·58 |
| $\dfrac{\partial C_{LT}}{\partial \alpha_T}$, | $a_1$ | = | 2·5 | $n_v$ | = | + 0·07 |
| | | | | $n_r$ | = | $-$ 0·10 |
| $\dfrac{\partial C_{LT}}{\partial \eta}$, | $a_2$ | = | 1·2 | $l_\xi$ | = | + 0·12 |
| $i_A$ | | = | 0·14 | $n_\xi$ | = | + 0·07 |

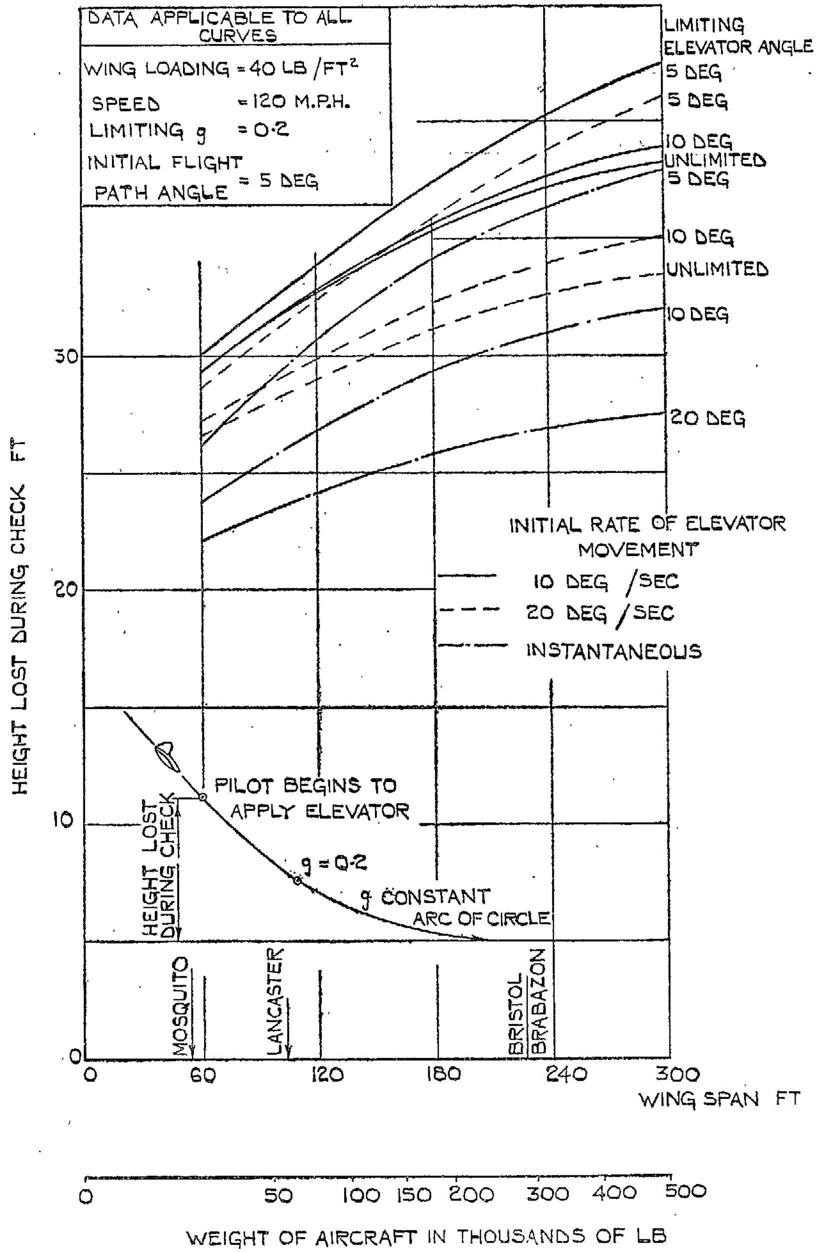


FIG. 1. Effect of aircraft size, etc. on height to start hold-off.

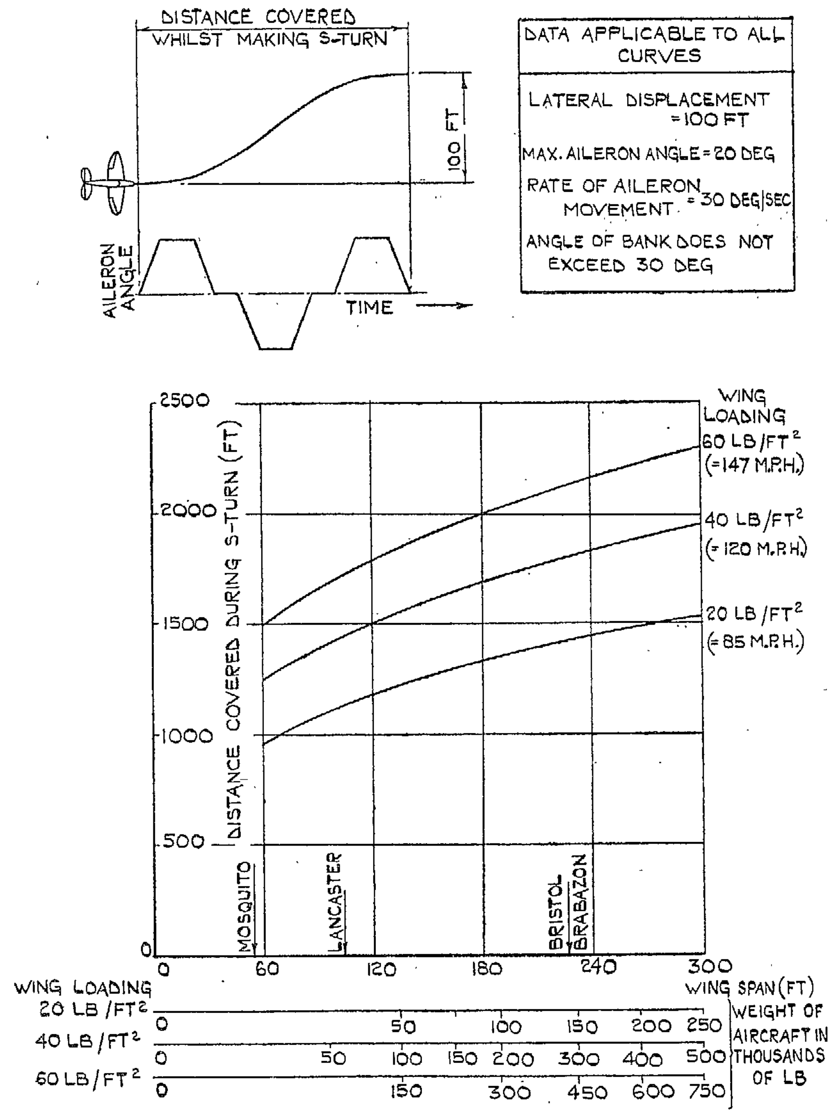


FIG. 2. Effect of aircraft size, etc. on distance travelled whilst making an S-turn.

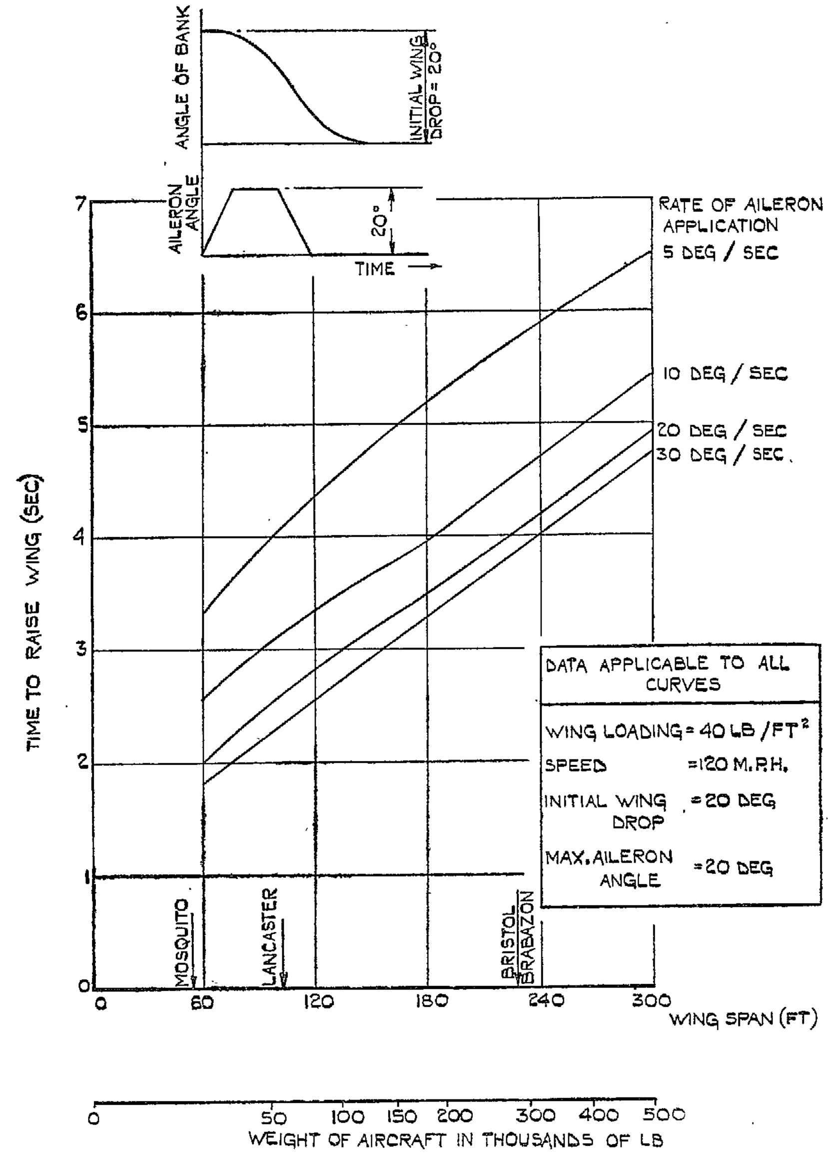


FIG. 3. Effect of aircraft size, etc. on time to correct for wing drop.

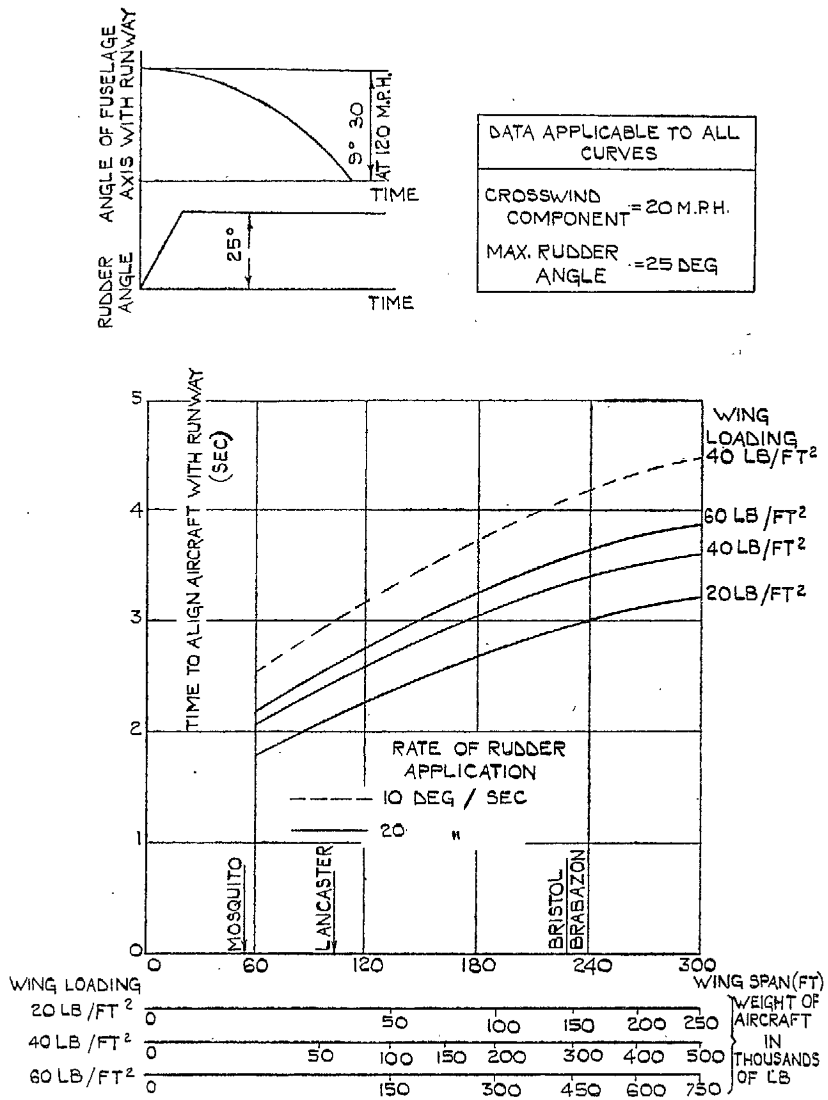


FIG. 4. Effect of aircraft size, etc. on time to correct for drift during approach in 20 m.p.h. crosswind.

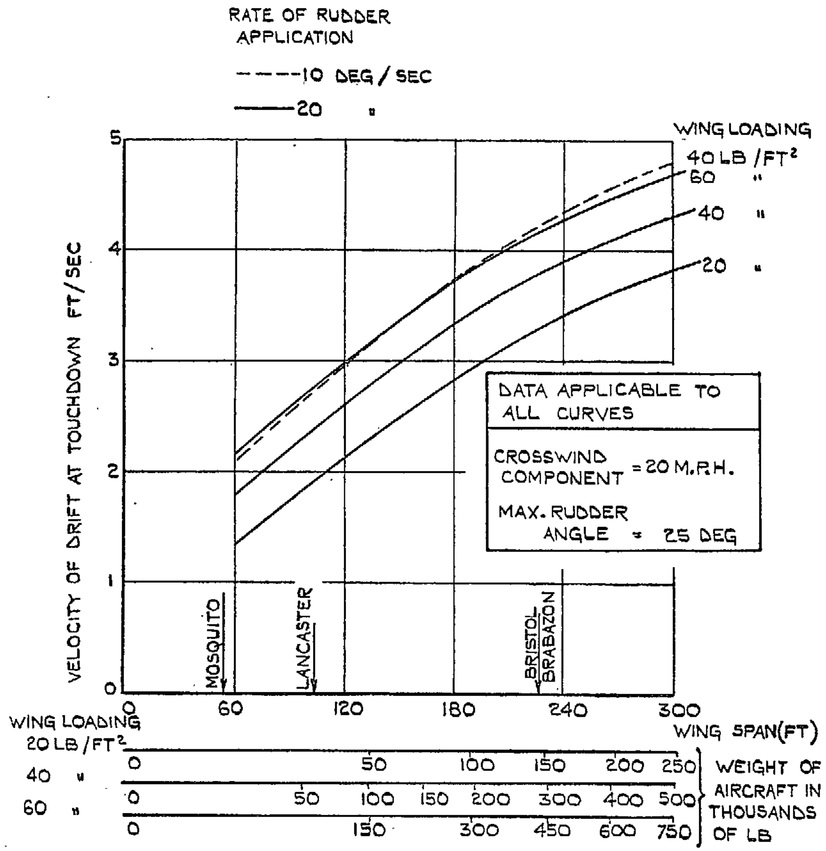


FIG. 5. Effect of aircraft size, etc. on lateral velocity acquired whilst making a correction for drift during approach in a 20 m.p.h. crosswind.

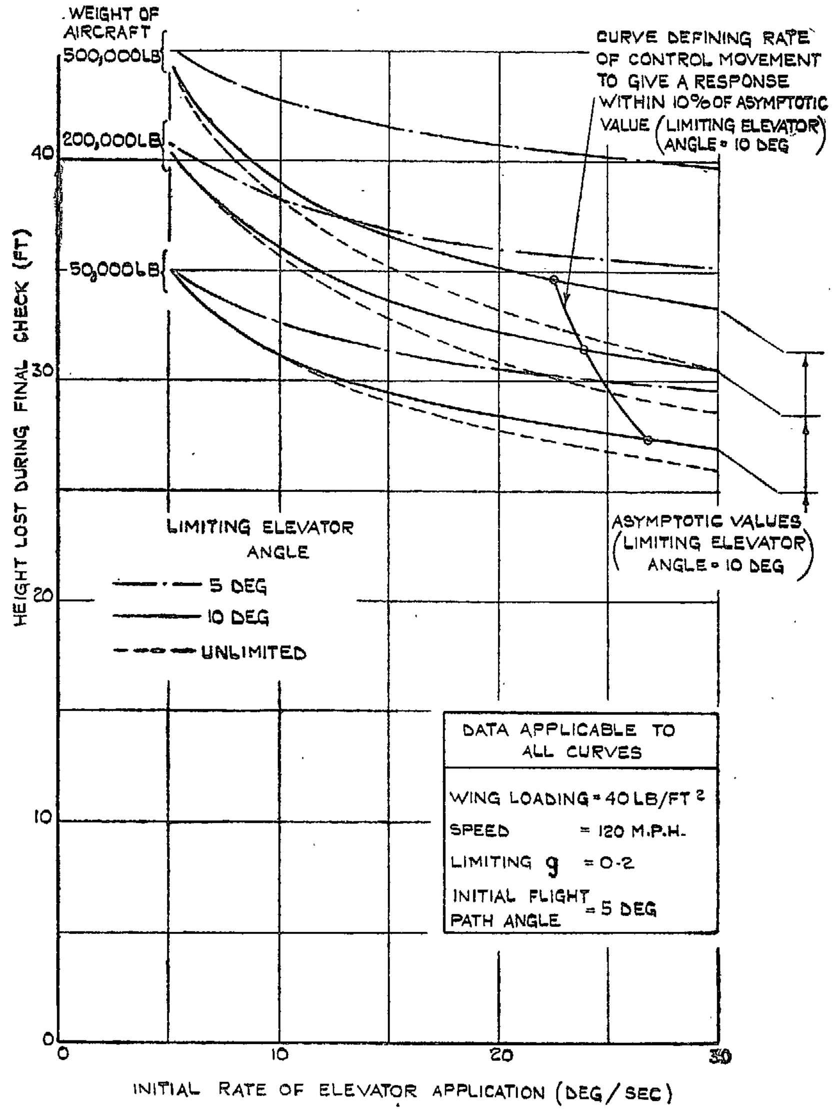


FIG. 6. Effect of initial rate of elevator application on height to start hold-off.

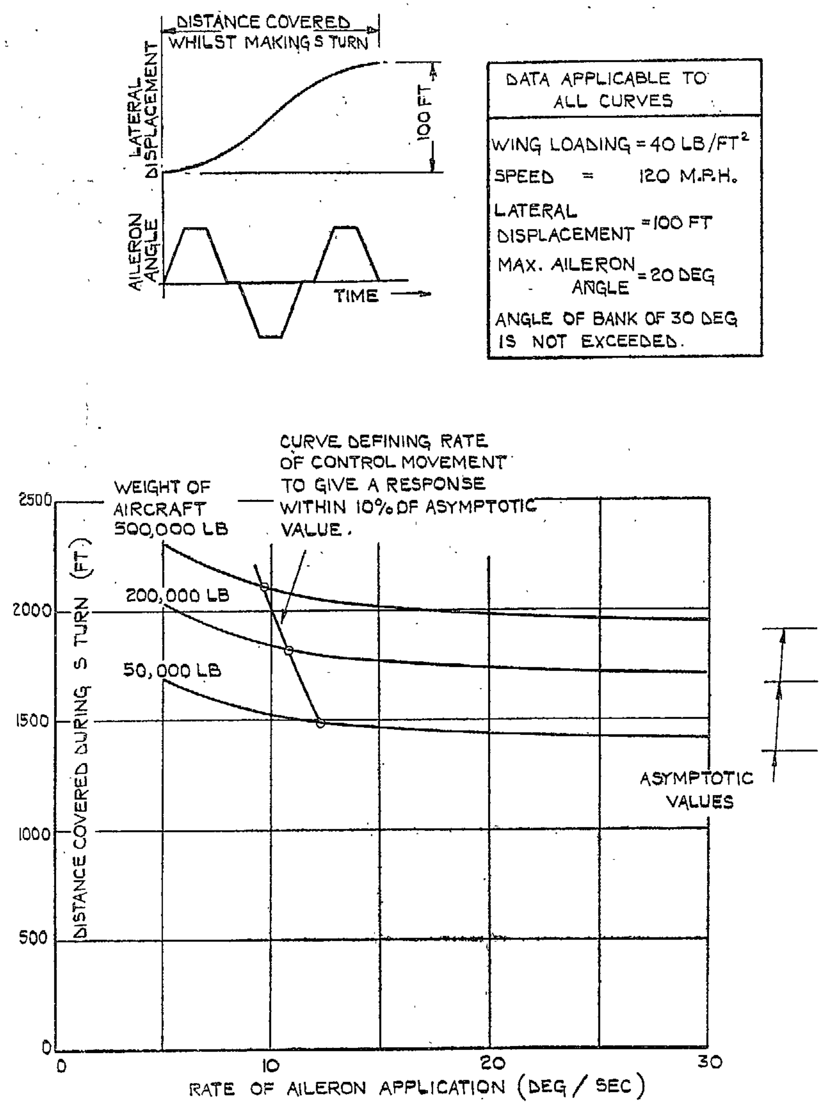


Fig. 7. Effect of rate of aileron movement on distance travelled whilst executing an S-turn.

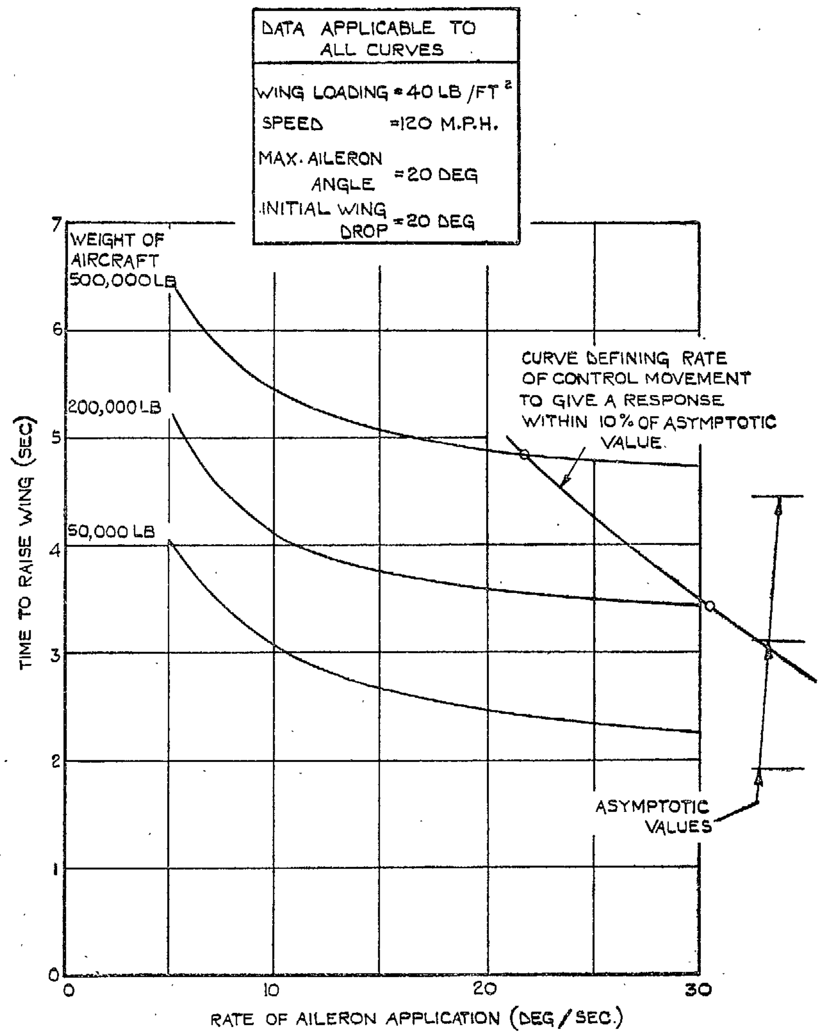


Fig. 8. Effect of rate of aileron application upon time required to correct for wing drop.

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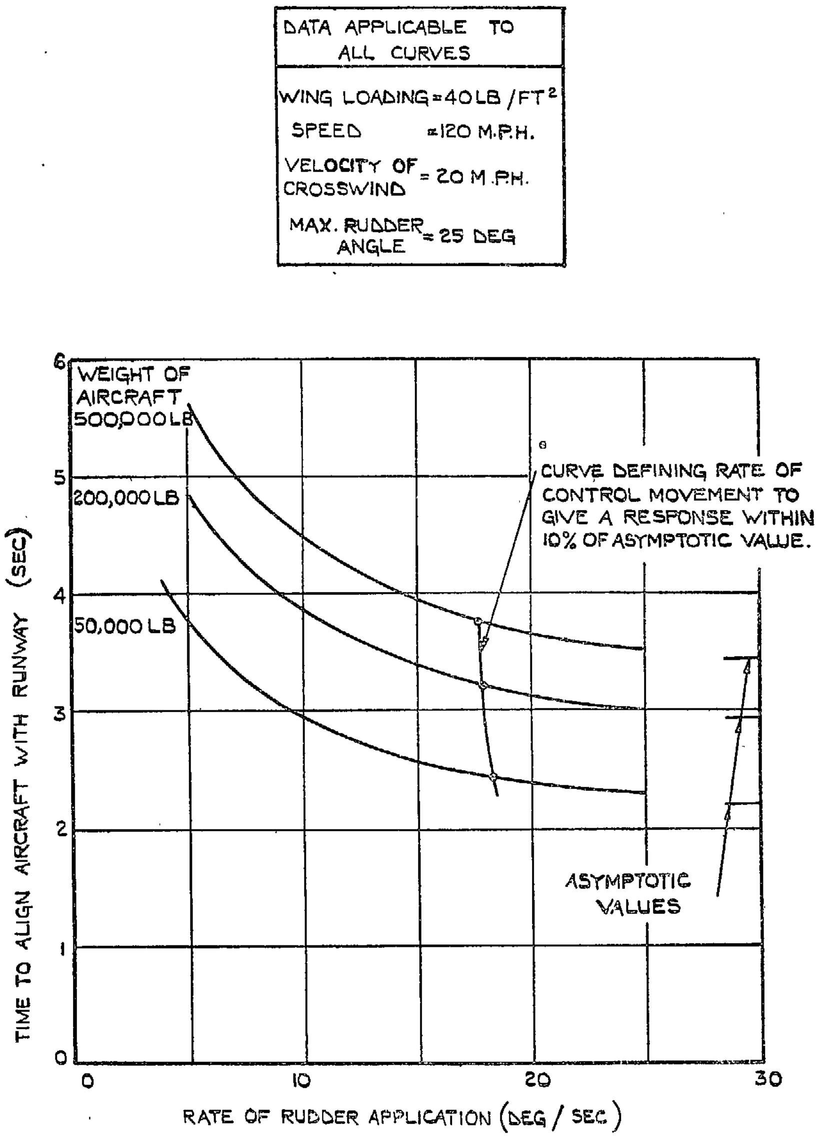


FIG. 9. Effect of rate of rudder application on time to correct for drift during approach in 20 m.p.h. crosswind.

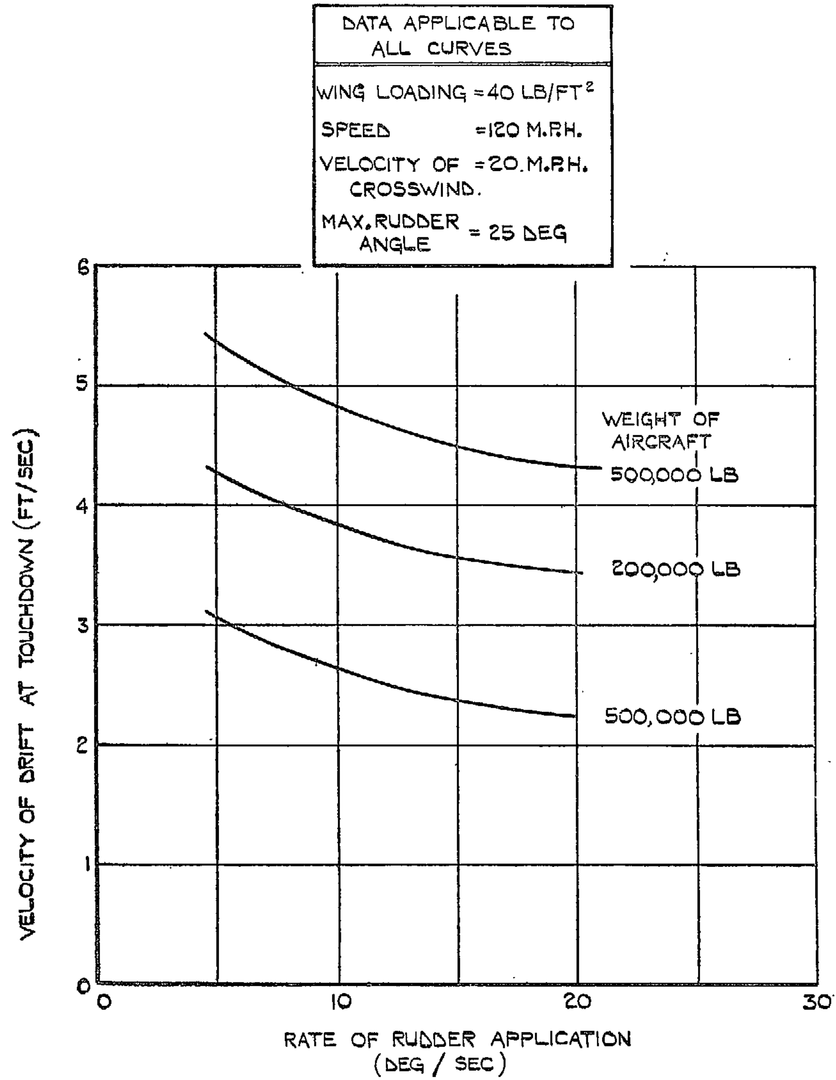


FIG. 10. Effect of rate of rudder application on lateral velocity acquired whilst making a correction for drift during approach in a 20 m.p.h. crosswind.

PRINTED IN GREAT BRITAIN

R. & M. No. 2567
(10,903)
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