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Some Flight Measurements of Crosswind Landings on a Small Delta Aircraft (Avro 707A)

By K. J. Staples

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Some Flight Measurements of Crosswind Landings on a Small Delta Aircraft (Avro 707A)

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Summary.

Pilots' control movements and the accuracy of touchdown have been analysed for two distinct cross-wind landing techniques. The sideslipping technique gave generally better accuracy at touchdown. On the other hand, the crabbing technique required slightly less control power and was more comfortable for the pilot, but it made considerable demands on pilot judgement in the drift removal manoeuvre.

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1. *Introduction.*

No agreed analytical procedure is available for the assessment of the crosswind landing capabilities of aircraft. To establish such a procedure would require:

(a) Means for determining the 'best' technique, taking into account the lateral characteristics of a particular aircraft.

(b) Assumptions on the control inputs to be used, in magnitude and timing; and in particular, determination of the additional control margin required by the pilot over and above the minimum needed to execute the prescribed manoeuvre.

(c) Knowledge of the acceptable errors at touchdown, so that the sensitivity of the manoeuvre to errors in control inputs could be assessed.

A solution to the problem is of some immediate importance, exemplified by the recent interest in slender-wing aircraft, which with their high rolling moment due to sideslip, limited aileron power, and low moment of inertia about the rolling axis, have presented difficulties in the assessment of their landing performance in crosswinds. Further, the relatively high yawing moment of inertia of these aircraft suggests problems of pilot judgement in the precise control of the heading change which may be required during kicking off drift in a crabbed approach. Another facet of the problem for aircraft in general is presented by the continuing emphasis on reduction in approach speed while still retaining relatively high crosswind velocity requirements, with the result that large sideslip angles are obtained when the aircraft is both tracking and heading down the runway centreline.

To obtain some 'feel' for these problems, a brief series of flight experiments has been completed using the Avro 707A research aircraft. The tests made were designed to provide some preliminary and basic information on the pilots' control actions and landing accuracy in crosswinds. The results of this investigation are strictly applicable only to aircraft similar to that of the test vehicle; more general conclusions would require the use of many aircraft of widely different characteristics so that the significance of aircraft stability and control derivatives, moments of inertia, approach speed, size, etc., would be determined in a variety of crosswinds and atmospheric turbulence. No such extensive programme has been attempted here.

2. *Description of the Aircraft.*

The Avro 707A is a single seat research aircraft powered by one turbo-jet engine. It is tailless and of essentially cropped delta planform with leading-edge sweep back of 50 deg. The wing trailing edge contains inboard trim (dive recovery) flaps, elevators, and outboard ailerons. Elevators and ailerons are irreversible power controls with manual reversion, the former having spring and 'q' feel and the latter simple spring feel. The rudder is manually operated. Full geometric details are given in Table 1, a general arrangement drawing in Fig. 1 and photographs of the aircraft in Fig. 2. The aircraft lateral derivatives, obtained from straight sideslips on this aircraft and deduced from flight measurements on the Avro 707B, are given in Table 2, which also includes certain other relevant approach data.

3. *Instrumentation.*

The aircraft instrumentation relevant to the present tests consisted of potentiometers transmitting rudder and port aileron angles, a vane mounted on the aircraft nose boom detecting sideslip angle, an accelerometer of $\pm 1g$ range detecting lateral acceleration, and a two-axis free gyro measuring angles of bank and yaw with a range of ± 25 deg about each axis. Records were obtained on a single 6 channel Hussenot A 22 continuous trace recorder running at approximately $\frac{1}{8}$ in/sec. Two G.S.A.P. 16 mm cine cameras, running at 16 frames/sec, were mounted externally on the underside of the fuselage about 2 ft aft of the main wheels; one camera pointed forwards and slightly downwards, giving an extended view of the runway during the final stages of the approach, and the other pointed vertically downwards when the aircraft was in its normal, average, touchdown attitude.

The wind velocity was measured at the runway edge alongside the expected touchdown point by a transmitting cup anemometer and wind vane mounted on a pole and about 8 ft above the runway surface. Continuous records of wind strength and direction throughout each approach were obtained on a Hussenot A 22 recorder.

A tape recorder was mounted in the aircraft for pilot comments during and after each approach.

4. *Crosswind Approach and Landing Techniques.*

Two basic crosswind landing techniques can be distinguished; these are illustrated diagrammatically in Fig. 3 and discussed in detail below. In practice a crosswind approach may contain elements of both techniques.

4.1. *Sideslipping Approach.*

When executed perfectly this technique gives an aircraft heading and track which are identical with the heading of the runway in use. The aircraft is therefore flown with 'crossed controls' in a so-called straight sideslip with angle of sideslip determined by the aircraft airspeed and the wind component normal to the runway direction. Bank, rudder, and aileron angles are required to counteract respectively the sideforce, yawing and rolling moments due to sideslip. Immediately prior to touchdown the pilot may level the wings and complete the landing before any appreciable drift velocity (velocity normal to the aircraft plane of symmetry) has had time to develop; alternatively, provided the wing tip clearance is adequate and the undercarriage strength sufficient, the bank can be maintained until touchdown. By touching down with one wheel first, the undercarriage will experience a drift velocity component resolved from the bank angle and vertical velocity.

4.2. *Crabbed Approach.*

In this technique the aircraft track should again lie along the runway extended centreline but the aircraft heading during the approach is offset upwind of the runway heading by the drift angle so that the sideslip is zero; the drift angle is now determined by the airspeed and crosswind component. In the steady state, bank, rudder, and aileron angles are zero and the aircraft is flown in a normal manner. To remove the heading error the pilot applies rudder prior to touchdown, maintaining the wings level by use of aileron to counteract any rolling moment due primarily to the sideslip developed but also due in small part to the rate of yaw and possibly rudder angle. After the removal of the heading angle, and with the wings level, there is a lateral acceleration resulting from the unbalanced sideforce due to sideslip, and touchdown must be accomplished quickly if an appreciable drift across the runway is to be avoided. Note, if the heading change to remove the drift angle could be accomplished instantaneously then the sideslip angle would be identical to that in a sideslipping approach immediately prior to touchdown.

5. *Test Programme.*

The results from eight crosswind flights have been analysed, each flight containing approaches using the two basic techniques in an arbitrary order. A total of 29 crabbed approaches and 25 sideslipping approaches were made. The maximum crosswind component velocity was 20 knots and the maximum absolute wind velocity was 26 knots, the speeds being measured at the instant of touchdown. In addition, one flight of 5 approaches was made with substantially zero crosswind component, the absolute wind velocity being between 12 knots and 17 knots.

The trace records cover, on average, the last 36 seconds of the approach and landing prior to touchdown, the shortest record being of 12 seconds duration and the longest of 88 seconds duration. The G.S.A.P. cameras were switched on about 7 seconds before touchdown on average.

Further cracking of an already heavily welded jet pipe, a few flying hours before the time expiry of several lifted items of aircraft equipment, curtailed the flying programme slightly.

6. *Analysis of Recorded Data.*

Figs. 4 to 8 show the data obtained from analysis of the trace records and G.S.A.P. camera films.

Fig. 4 shows the maximum control angles used during the approach and landing, plotted against crosswind component. The full lines show the trim control angle required, i.e. for the sideslipping approaches the angles required to maintain the straight sideslip, and for the crabbed approaches the angles required to hold a steady state immediately following instantaneous removal of heading (kick-off). The dotted lines have been drawn parallel to the trim lines so that all, or all but one, of the experimantal points lie below them; this gives an indication of the excess usage of the controls over that required for trim.

Fig. 5 shows the bank angles and heading errors at touchdown; the full lines show the corresponding steady trim conditions during the approach.

Fig. 6 has been compiled to show the lateral motion of the aircraft at the moment of touchdown, again separated into results obtained from sideslipping and crabbed approaches.

In the presence of a crosswind V_c the lateral velocity of the aircraft normal to the runway (v_c) is given by

$$v_c = V_c + \beta V + \psi V \tag{1}$$

where β is the sideslip angle and ψ the heading with respect to the runway centreline. Alternatively equation (1) can be expressed in terms of angles

$$\frac{v_c}{V} = \chi = \frac{V_c}{V} + \beta + \psi \tag{2}$$

where χ is the angle of the aircraft track and $\frac{V_c}{V}$ can be described as the wind drift angle.

On the other hand the component of ground velocity normal to the aircraft plane of symmetry, i.e. the lateral velocity component producing a lateral load on the undercarriage is

$$v_y = V_c + \beta V + \phi \frac{dH}{dt} \tag{3}$$

where ϕ is the bank angle and $\frac{dH}{dt}$ the vertical velocity. Again this relationship can be expressed in angles

$$\frac{v_y}{V} = \frac{V_c}{V} + \beta + \phi\,\gamma \tag{4}$$

$\frac{v_y}{V}$ is the drift angle of the undercarriage and γ the instantaneous glide angle.

Ignoring the last term in equations (3) and (4), e.g. assuming bank angle and/or rate of descent $\frac{dH}{dt}$ to be small, we can simply write

$$\bar{v}_y = V_c + \beta V = v_c - \psi V \tag{5}$$

or

$$\frac{\bar{v}_y}{V} = \frac{V_c}{V} + \beta \quad = \chi - \psi \tag{6}$$

$\bar{v}_y$ is now the component of the horizontal velocity of the aircraft over the ground normal to the aircraft centreline, i.e. drift velocity.

These quantities have been plotted in Figs. 6a and b to give an indication of the lateral touchdown conditions, experienced during the flight tests. To help in the interpretation of this complex graph, Fig. 7 should first be consulted. It should be noted that the recorded crosswinds may be in error, as they were not determined in all cases sufficiently close to the actual touchdown point, therefore the lateral velocities, derived generally from the difference between the crosswind and other terms of similar magnitude, may be grossly inaccurate.

In a few cases it was possible to obtain a more direct measurement of the aircraft lateral motion at touchdown from analysis of the G.S.A.P. cine films. These results were used to compute the velocity component over the ground normal to the aircraft plane of symmetry, i.e. the drift velocity of the undercarriage at touchdown, and are plotted in Fig. 8. The flagged symbols in Fig. 8b indicate that the drift angle was removed too early, the numbers showing the time in seconds prior to touchdown at which zero heading error was obtained.

Fig. 9 shows the times from touchdown at which drift kick-off was initiated, the open symbols indicating a late (or correct) kick-off time, with the numbers giving the heading error at touchdown, and the crosses showing an early kick-off with the numbers indicating the time in seconds prior to touchdown at which zero heading error was obtained.

7. *Implications of the Two Basic Techniques.*

Before discussing the flight results it is useful to consider the general piloting problems of crosswind landing and the theoretical aircraft dynamics in the final phase immediately prior to touchdown.

7.1. *Handling Problems.*

7.1.1. *Sideslipping technique.* Certain difficulties are apparent during the approach phase when the sideslipping technique is used. While the coincidence of the runway heading and the required aircraft heading make it easy for the pilot to determine whether he is tracking along the runway extended centreline, any displacement in azimuth is difficult to correct. Change in angle of bank, while maintaining the required heading, effects a lateral displacement but is not an easy manoeuvre for the pilot to perform, flying as he is in an unnatural 'crossed controls' condition while attempting to hold an accurate glide path. There is a tendency therefore to remove the sideslip, in part at least, and perform a turning manoeuvre to regain the runway centreline. As a consequence the pilot is unwilling in the steady state to trim out entirely the rudder and aileron forces in the straight sideslip and an approach of any length becomes tiring. Further, the steady state rudder and aileron angles required leave correspondingly less control available to counteract the response due to gusts. Particular difficulties arise on an instrument approach; it is difficult to set up and hold a straight sideslip condition without external reference and the pilot has no direct information on how much sideslip is required. With the talkdown type of control, azimuth corrections are normally passed to the pilot as heading requirements and with the 'raw' I.L.S. display, in which displacement information is available, all the difficulties previously discussed for azimuth corrections are accentuated by flight on instruments, particularly since the gyro horizon will not, in general, indicate zero bank angle in the steady state. The 'zero reader' director instrument would require a bank angle selector since it takes cognizance of lateral displacement, heading error and bank angle, and normally gives a null indication when all are zero or when the pilot is taking the correct action to bring all to zero.

Immediately prior to touchdown the sideslipping approach gives the pilot a very simple manoeuvre to perform. On the Avro 707A, and in general, a reduction in aileron angle is required to level the wings. To maintain the heading, an increase in rudder angle is required to balance the change in yawing moment from the ailerons; the rudder requirement due to rate of roll is negligible for any practical manoeuvre. In practice the accuracy of performing the wings levelling manoeuvre is often not critical, the main consideration being adequate wing tip, external store, etc., clearance.

7.1.2. *Crabbing technique.* In contrast to the sideslipping technique the approach phase using the crabbing technique presents the pilot with few difficulties other than those always present during an approach. The aircraft is flown in a normal manner with wings level, the lateral controls being in the neutral position in the trim state and turning manoeuvres being used to correct lateral errors. The selection of the correct heading, by trial and error, is more difficult than in the sideslipping approach, but probably little different to the difficulty of setting up the right sideslip. In visual conditions the view of the runway is generally improved on single seater aircraft but may be degraded with side-by-side seating. Under instrument conditions the aircraft is flown in the conventional manner and the approach is consistant with the talkdown and 'raw' I.L.S. types of control; with 'zero reader' a heading different to that of the runway has to be set but this is dependent only on approach speed and crosswind component and not on aircraft type, unlike the bank angle in the sideslipping approach.

However, the crabbed approach presents the pilot with a far more difficult problem immediately prior to touchdown. The drift angle has to be removed to align the aircraft with the runway. This is done by the application of rudder, the wings being held level on the ailerons. The application of ailerons itself causes a yawing moment which must be balanced by the rudder. The yaw rate should also be approximately zero at the moment of touchdown. The control co-ordination required is thus quite difficult and the timing of the manoeuvre is important. During the course of the manoeuvre velocity perpendicular to the runway centreline is generated by the unbalanced sideforce due to the sideslip, if the wings are held level, so that when the runway heading is achieved, there will also be some drift velocity of the undercarriage with respect to the ground, which continues to increase until the moment of touchdown. It might therefore be important that the manoeuvre be performed quickly and that touchdown follows immediately after completion.

7.2. *Aircraft Dynamics.*

The aircraft dynamics during the approach phase are conventional but it is of some interest to consider conditions during the period immediately prior to touchdown. Two important aspects of this phase are the response to rudder input during the drift-removal manouvre following a drifting approach and the lateral motion of the aircraft relative to the runway after the runway heading, wings level condition has been achieved following either a sideslipping or drifting approach.

7.2.1. *Drift removal.* Fig. 10 shows the 707A heading response calculated for a step rudder input at 120 knots, using the derivatives listed in Table 2, and illustrates the considerable overshoot available compared with the 'steady' state. Where adequate aileron power is available (which is not so on the 707A), it is therefore theoretically possible to achieve landings with perfectly aligned heading in crosswinds greater than those requiring full rudder deflection in the steady state. However, in order to achieve this advantage the rudder input must be sudden and touchdown must be effected within a very limited period of time, between say 1 and 2 seconds after the rudder kick. If touchdown is achieved between say, 2 and 4 seconds after the input the resulting heading change will be less than the 'steady' state value and/or a high rate of yaw will exist, with the possibility of large undercarriage sideloads and handling problems on the runway. The increase of the crosswind limits by utilizing the available overshoot thus seems to place excessive demands on the pilots' judgement of touchdown, at least for an aircraft with a dutch roll period as short as that of the 707A. With a doubling of the period to 6 seconds, the overshoot would be favourable on touchdown during the interval of say between 2 and 4 seconds from the initiation of drift kick-off; this would give a more reasonable task for the pilot with touchdown times similar to those actually achieved on the 707, but it is still doubtful whether this manoeuvre could be made sufficiently consistently to be a practical and safe operational procedure.

7.2.2. *Lateral motion relative to runway.* To gain some insight into the importance of the accurate judgement of touchdown time in relation to the wings-levelling or drift-removal manoeuvre, calculations have been made, using the formulae in the Appendix of the lateral velocity and displacement following this manoeuvre. Fig. 11 shows the results for the Avro 707A assuming that the pilot can instantaneously achieve a wings level, runway heading condition with initially zero lateral velocity.

The pilots participating in the flight tests were asked what they considered to be tolerable limits of lateral divergence before touchdown. No clear statements were made with respect to lateral velocity, a quantity obviously difficult to judge from the cockpit, but the pilots were unanimous in their opinion that they would not willingly exceed a lateral displacement of 10 ft from the intended touchdown point. This is not necessarily the runway centreline and in fact a number of approaches were aimed at a line well off the centre. This 10 ft limit appears excessively restrictive in view of the generous width (300 ft) of the runway used in the tests. When this was pointed out to them, the pilots nevertheless maintained this criterion: their object may be not so much to achieve positional accuracy, as to avoid high lateral velocities. It is interesting to note that even for a lateral velocity of 10 ft/sec, estimates given in Fig. 11 show that for the 707 it is generally the lateral displacement which limits the time within which touchdown must be effected. Only with crosswinds greater than 50 ft/sec ($\sim$ 30 knots) would the lateral velocity limitations become important. With a moderate crosswind component, say 20 ft/sec ($\sim$ 12 knots), rather less than 4 seconds will have elapsed before the displacement reaches 10 ft, whereas 10 ft/sec lateral velocity is not obtained for almost 10 seconds, by which time the displacement is over 50 ft. If it appears to the pilot that the displacement limit is going to be exceeded he will again head into wind to check the lateral motion, with a consequent very large increase in drift velocity. When it is appreciated that a heading error at touchdown of 3 deg at 120 knots represents a drift velocity for the undercarriage of over 10 ft/sec it is apparent that the very tight displacement limit of 10 ft, with the consequent short time allowed before touchdown, places a very high premium on pilot skill in judging the touchdown time and in achieving zero heading error. Thus, from the point of view of undercarriage side loads it would be better if the pilot could tolerate a much larger lateral displacement, giving himself more time to achieve an accurate heading.

It is of some interest to note the influence of the aileron yawing-moment derivative, n_ξ, on the results. Reducing the value to zero increases the time for 10 ft displacement in a 20 ft/sec (12 knot) crosswind from 3·8 seconds to 5·7 seconds. Reversing the sign of n_ξ to give proverse yaw results, in this particular case, in a yawing moment such that the rudder required to balance it and the associated sideslip is so great that the sideforce from the deflected rudder is larger than that provided by y_v, giving an upwind displacement. A straight sideslip approach in these conditions would have required bank away from the direction of the crosswind component. However, in general, y_v and n_v are the more important derivatives, since with $n_\xi = 0$, the exponent, A, of the exponential in the equations of the Appendix reduces to:

$$A = \frac{\rho V S}{m}\left[y_v - y_\zeta \frac{n_v}{n_\zeta}\right]$$

which may be written

$$A = \frac{\rho V S}{m}\left[y_v + n_v \frac{b}{2l_F}\right]$$

where b is the wing span and l_F the fin moment arm. In practice, the removal of the drift angle, or the levelling of the wings, is not performed instantaneously so that at the completion of the manoeuvre some lateral velocity and displacement are already present, thus reducing the time permitted before touchdown. However, the overall time from the start of the manoeuvre to touchdown will be increased, and this is an advantage if it is assumed that the touchdown time can be controlled to some extent during the manoeuvre.

8. *Discussion of Flight Results.*

8.1. *Control Usage.*

Fig. 4 shows that the excess aileron power used during approach and landing is considerably greater in the sideslipping than the crabbed approach. This might, of course, be expected since during the slipping approach considerable aileron is required to maintain the steady sideslip whereas when drifting it will be zero except during the kick-off. It should be noted that Fig. 4b includes the control usage during kick-off. During the latter phase and ignoring inputs due to gusts, over control, etc., the value required for trim will only be reached when the full sideslip has developed, i.e. when the heading error has been reduced to zero. With a late kick-off, zero heading error may never be achieved (*see* Fig. 9). Furthermore, the time during which the mean aileron angle is other than zero, i.e. during kick-off, is very short so that the chance of meeting a large gust when the aileron is already displaced is greatly reduced compared with the sideslipping approach.

On the other hand, the demands on rudder power are somewhat greater in the crabbed approach than in the sideslipping approach. The arguments considered above on trim position and the chances of meeting a gust apply also to the rudder. The difference is that, whereas the aileron input during the kick-off is required only to maintain the wings level condition, the rudder input is required to manoeuvre the aircraft to the correct heading. The nearer to touchdown that this input is applied the smaller the drift velocity developed and the larger the input required, assuming that the heading error is in fact reduced to zero. No such input is required in the sideslipping approach although aileron should be applied to level the wings; the latter input, however, is in the sense to reduce the amount of aileron from that required for trim and thus does not appear as an additional aileron requirement.

Evidently about half the available aileron angle is used in excess of that required for trim in the crabbed approach and rather more in the sideslipping approach. Nevertheless, if this margin is not available successful approaches and landings can still be made. However, with crosswind components greater than about 15 knots, the component normally accepted as limiting prior to these tests, the pilots complained of the excessive frequency of reaching the aileron limits. In all, 10 approaches were made with crosswind components greater than 15 knots, 6 sideslipping, and 4 crabbed, and on one of the sideslipping approaches with a crosswind of about 18 knots, the pilot was forced to overshoot due to excessive bank angle arising from a sidegust when the aileron was at the limit.

Fig. 4 also shows that the controls are not well harmonized for crosswind landing as evinced by the frequency with which the aileron limits are reached whereas on no occasion is full rudder applied. In the steady state some 30 per cent of the rudder travel is still available when the ailerons are at full deflection. Since, in addition, the initial rolling response to lateral gusts is far greater than the heading response this is particularly embarrasing in the sideslipping approach, where an excess of aileron travel would be desirable. If, in fact, the controls had been perfectly matched, i.e. full aileron requiring full rudder in the steady state sideslip, then about half the available rudder angle would have been required in excess of steady values in the sideslipping approach and rather more in the drifting approach.

8.2. *Conditions at Touchdown.*

Fig. 5 shows the bank angles and heading errors at touchdown. There is little discernible trend with crosswind component nor is there much difference in the bank angle at touchdown between sideslipping and crabbed approaches. Since, for this aircraft, bank angles at touchdown up to about 5 deg appear reasonable to the pilot, there is little incentive for him to attempt to remove the bank angle in the sideslipping approach; the trimmed bank angle is greater than 5 deg only for crosswinds greater than 17·5 knots. It is of interest to note that the windward wing tends to be down more frequently than up, both in sideslipping and drifting approaches. This is to be expected with the sideslipping approach but with the crabbed approach the windward wing would tend to rise during the kick-off if no aileron is applied. If the opposite happens this suggests over control on the ailerons and it is possible that the pilot instinctively applies sufficient aileron to achieve a straight (i.e. banked), rather than a wings level, sideslip. Such a manoeuvre would lessen the tendency for a lateral velocity to develop and would thus reduce the lateral displacement at touchdown.

The heading errors at touchdown following a crabbed approach are somewhat greater than those following a sideslipping approach. At touchdown the nose of the aircraft points most frequently into wind, even following a sideslipping approach; this suggests that the pilot perhaps anticipates the drift angle which will be required when on the runway in order that the aircraft tracks along the runway heading. (This is necessary so that the aerodynamic sideforce generated by the crosswind can be balanced by an appropriate side load on the wheels.)

The triangular symbols in Fig. 6 represent the lateral velocity of the aircraft across the runway, i.e. the velocity which generates lateral displacement. The circular symbols give the drift velocity normal to the aircraft centreline, i.e. the velocity component responsible for side loads on the undercarriage. The lateral velocity is not, in general, equal to the drift velocity; the two are equal only when the heading error is zero and more strictly when in addition the product of bank angle and rate of descent is also zero.

As explained in Section 6 a detailed analysis of the results of Fig. 6 is not justified as the crosswind at the instant of touchdown was not always recorded with sufficient accuracy. It should be noted that in this connection a 1·8 knot error in crosswind would represent a one degree change in sideslip angle. Nevertheless it is interesting to note that a number of triangles lie above the datum indicating a lateral velocity tending to produce an upwind displacement on the runway. This is most noticeable on the sideslipping approaches and could be caused by wind shear reducing the crosswind component as the ground is approached so that the sideslip set up earlier in the approach is excessive at touchdown. Pilots commented on this tendency to find themselves overslipping near touchdown. Those drifting approaches showing an upwind lateral velocity are associated, with one exception, with large heading errors at touchdown, suggesting little attempt by the pilot to remove the drift angle. An excessive lateral drift can also be produced by wind shear but the magnitude and frequency of the indication on the figure of an upwind velocity scarcely justifies pursuing this further.

The drift velocities shown in Fig. 8 include two results for each approach. The circles give the total value of drift velocity measured, and the crosses show that part of the total which can be attributed solely to the heading error. It is seen that the latter contributes most of the total velocity. The flagged symbols in Fig. 8b indicate that the drift angle was removed too early, the numbers showing the time in seconds prior to touchdown at which zero heading error was obtained, so that at touchdown some of the error was again present. The other rather large drift velocity in Fig. 8b, at a crosswind of 9·1 knots, corresponds to a point (Fig. 9) where the kick-off was initiated 10 seconds before touchdown with a very small rudder input (1·3 deg) and seems to indicate that little effort was made by the pilot to remove the drift. In fact it is difficult to determine whether the rudder input was for drift removal or merely in response to a disturbance to the aircraft.

Fig. 9 shows the times from touchdown at which the drift kick-off was initiated. Examination of the trace records showed that the rudder application was, in general, remarkably rapid, usually taking about 0·5 second and rarely more than 1 second. The response in yaw will therefore be similar to that shown in Fig. 10 with the peaks delayed about 0·5 to 1 second and possibly less pronounced. This is consistant with the evidence of Fig. 9 that the most satisfactory touchdown performance in terms of heading error is generally obtained when drift kick-off is initiated between 1·5 and 3 seconds from touchdown. Earlier kick-off results in a premature zero heading error whereas later kick-off allows insufficient time for adequate response. The scatter is considerable and masks any definite trend with crosswind, but the fact that less than 50 per cent of the kick-off initiations are within the time band for greatest heading accuracy with minimum control movement indicates that demands on pilot judgement for this manoeuvre are quite critical.

9. *Conclusions.*

Because of the limited nature of the flight experiment no definite conclusions as to the optimum crosswind approach and landing technique can be drawn. Several interesting results have, however, been obtained.

It appears from theoretical considerations that, to the pilot, limitations on lateral displacement at touchdown on the runway are more severe than those arising from lateral velocity.

Flight tests show that the sideslipping type of approach requires rather more aileron power than the crabbing type but rather less rudder. Had the controls been perfectly matched in the sense that full aileron just trimmed the sideslip produced by full rudder, then about half the available aileron would have been required for dynamic control in the drifting approach and about half the available rudder in the sideslipping approach, although successful approaches and landings can be made in crosswinds where these margins are not available.

The sideslipping type of approach results in rather greater accuracy in terms of heading error at touchdown; there is little difference between the two techniques in terms of bank angle at touchdown.

The drift removal manoeuvre places great demands on pilot judgement; on less than half the occasions was the manoeuvre initiated within the time band where greatest accuracy in heading would be obtained with the minimum of control usage.

The sideslipping approach is not compatible with existing instrument flying systems and is more uncomfortable and tiring for the pilot than the crabbing technique.

Drift Velocity and Lateral Displacement

Assumptions

Instantaneous removal of drift angle, drifting approach,
or, instantaneous levelling of wings, sideslipping approach.
Initial lateral velocity zero (normal to runway centreline).
Rudder angle to hold aircraft on runway heading.
Contribution from rate of change of sideslip derivatives negligible.

The lateral equations of motion are then:

$$l_v \beta + l_\xi \xi + l_\zeta \zeta = 0$$

$$n_v \beta + n_\xi \xi + n_\zeta \zeta = 0$$

$$y_v \beta + y_\xi \xi + y_\zeta \zeta = \frac{m}{\rho V^2 S} \dot{v}_c$$

where v_c is the lateral velocity relative to the runway.

From the rolling equation:

$$\xi = -\frac{l_\zeta \zeta + l_v \beta}{l_\xi}$$

Substituting in the yawing equation:

$$\zeta = \frac{n_\xi l_v - n_v l_\xi}{n_\zeta l_\xi - n_\xi l_\zeta} \beta$$

Substituting in the sideforce equation, with $y_\xi = 0$:

$$\left[y_v + y_\zeta \frac{n_\xi l_v - n_v l_\xi}{n_\zeta l_\xi - n_\xi l_\zeta} \right] \beta = \frac{m}{\rho V^2 S} \dot{v}_c$$

But,

$$\beta = \frac{V_c - v_c}{V}$$

where V_c is the crosswind component.

Therefore the lateral velocity,

$$v_c = \frac{\rho V S}{m} \left[y_v + y_\zeta \frac{n_\xi l_v - n_v l_\xi}{n_\zeta l_\xi - n_\xi l_\zeta} \right] \int (V_c - v_c) \, dt$$

or,

$$v_c = V_c \quad 1 - e \left\{ \frac{\rho VS}{m} \left[y_v + y_\zeta \frac{n_\xi l_v - n_v l_\xi}{n_\zeta l_\xi - n_\xi l_\zeta} \right] t \right\} = V_c \left[1 - e^{At} \right] \text{ say}$$

and the lateral displacement, s, is given by:

$$s = \int v_c \, dt = V_c \left\{ t - \frac{e^{At}}{A} \right\} - \frac{V_c}{A}$$

with $s = 0$ when $t = 0$.

LIST OF SYMBOLS

b	Wing span
$C_{L\,\mathrm{trim}}$	Trimmed lift coefficient
H	Height
i_A	Rolling-inertia coefficient
i_c	Yawing-inertia coefficient
i_E	Product of inertia coefficient
l_F	Fin arm
l_p	Rolling-moment derivative due to rate of roll
l_r	Rolling-moment derivative due to rate of yaw
l_v	Rolling-moment derivative due to sideslip
l_ζ	Rolling-moment derivative due to rudder
l_ξ	Rolling-moment derivative due to aileron
m	Aircraft mass
n_p	Yawing-moment derivative due to rate of roll
n_r	Yawing-moment derivative due to rate of yaw
n_v	Yawing-moment derivative due to sideslip
n_ζ	Yawing-moment derivative due to rudder
n_ξ	Yawing-moment derivative due to aileron
S	Wing area
s	Lateral displacement
t	Time

$\hat{t}$	Unit of aerodynamic time
V	Airspeed
V_c	Crosswind-component velocity
v_c	Lateral velocity
v_y	Drift velocity (normal to aircraft plane of symmetry)
y_v	Sideforce derivative due to sideslip
y_ζ	Sideforce derivative due to rudder
y_ξ	Sideforce derivative due to aileron
β	Angle of sideslip
γ	Instantaneous glide angle
ζ	Rudder angle
μ_2	Aircraft relative density
ξ	Aileron angle
ρ	Air density
ϕ	Angle of bank
ψ	Angle of yaw, heading error
χ	Angle of track relative to runway centreline

TABLE 1

Avro 707A – Geometric Details

Wings	
Gross area, ft^2	408
Span, ft	34·167
Aspect ratio	2·86
Geometric mean chord, ft	11·94
Aerodynamic mean chord, ft	14·537
Chord at centreline, ft	21·825
Chord at tip, ft	2·225
Sweepback, leading edge	49·9°
Sweepback, trailing edge, root to 29·8% semispan	0°
Sweepback, trailing edge, outboard of 29·8% semispan	3·54°
Wing-body setting	2·5°
Wing section, 29·8% semispan	NACA 0010
Wing section, tip	RAE 101
Elevators	
Area, aft of hinge, each, ft^2	12·865
Span along hinge line, ft	6·248
Spanwise extent, % semispan	29·8 to 64·7
Mean chord aft of hinge line, ft	2·072
Hinge-line sweepback	11·5°
Neutral setting to wing chord line	0°
Range	8° down to 20° up
Trim (dive recovery) flaps	
Area, aft of hinge line, each, ft^2	6·05
Span, ft	2·93
Spanwise extent, % semispan	12·7 to 29·8
Chord aft of hinge line, ft	2·06
Hinge-line sweep	0°
Neutral setting to wing chord line	2° up
Range	2° up to 16·5° up

TABLE 1—*continued*

Air brakes	
Gross projecting frontal area, upper, each, ft^2	1·414
Gross projecting frontal area, lower, each, ft^2	1·9
Span, upper and lower, each, ft	2·396
Spanwise extent, upper and lower, % semispan	14·3 to 28·35
Chord, plate, upper, ft	0·5
Chord, plate, lower, ft	0·72
Mean distance from wing trailing edge upper and lower, ft	11·5
Ailerons	
Area, aft of hinge, each, ft^2	7·616
Span, ft	5·696
Spanwise extent, % semispan	64·7 to 100
Mean chord, aft of hinge line, ft	1·343
Hinge-line sweepback	11·5°
Neutral setting to wing chord line	3° up
Range	15° up to 9° down
Fin	
Area (above fuselage), ft^2	27·777
Span, ft	6·1
Rudder	
Area, aft of hinge line, ft^2	6·785
Span, ft	4·568
Mean chord, aft of hinge line, ft	1·487
Miscellaneous	
All-up weight, full fuel, 180 lb pilot, C.G. 0·286 $\bar{c}$, lb	10660
Fuel capacity, gallons	196
Engine	Derwent Mk. 8
Nominal maximum thrust, lb	3600
Engine thrust line to wing chord line	−2·5°

TABLE 2

Avro 707A Lateral Derivatives on the Approach

Weight	= 9540 lb	y_v	= −0·224
$C_{L\text{ trim}}$	= 0·480	l_v	= −0·086
V	= 120 knots	l_p	= −0·300
μ_2	= 17·84	l_r	= 0·095
$\hat{t}$	= 1·504	n_v	= 0·056
i_A	= 0·072	n_p	= −0·025
i_C	= 0·226	n_r	= −0·080
i_E	= −0·025	l_ξ	= −0·080
		l_ζ	= 0·0035
		n_ξ	= 0·015
		n_ζ	= −0·0335
		y_ζ	= 0·103
		y_ξ	= 0

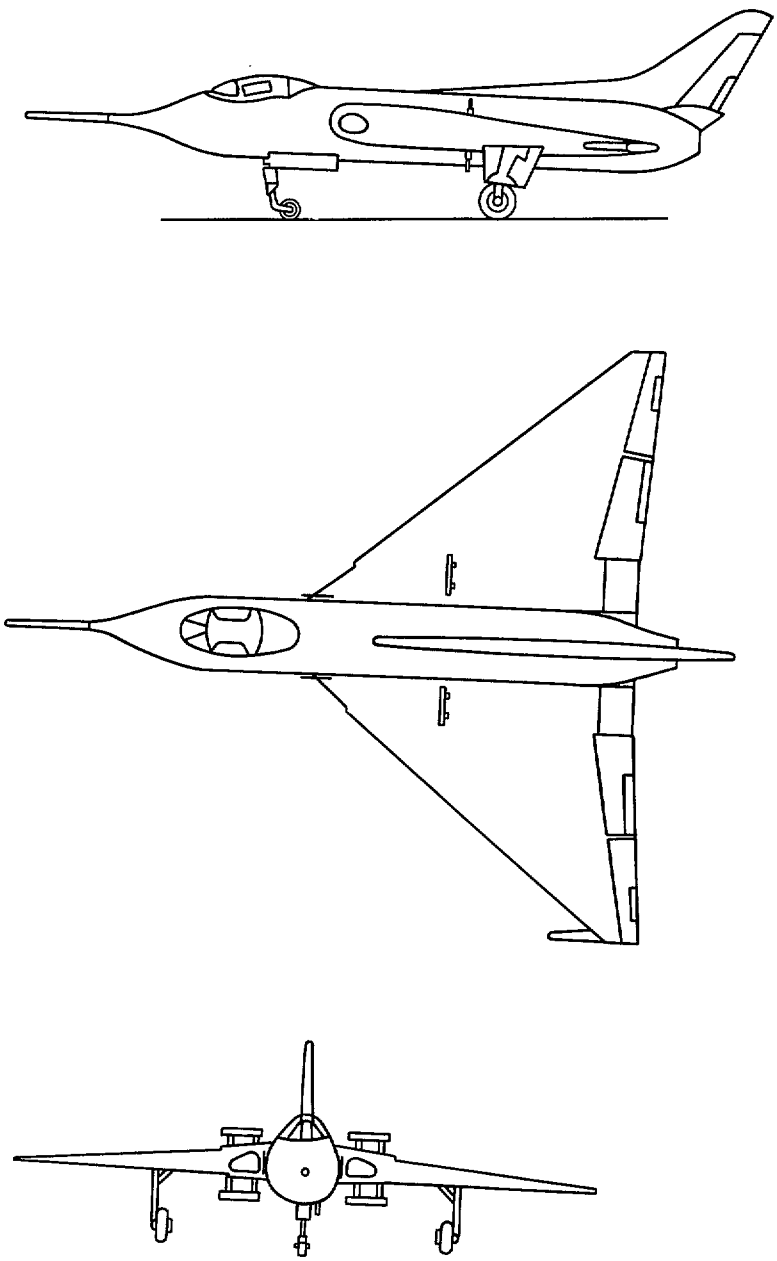


FIG. 1. Avro 707A, WZ 736. General arrangement—landing configuration.

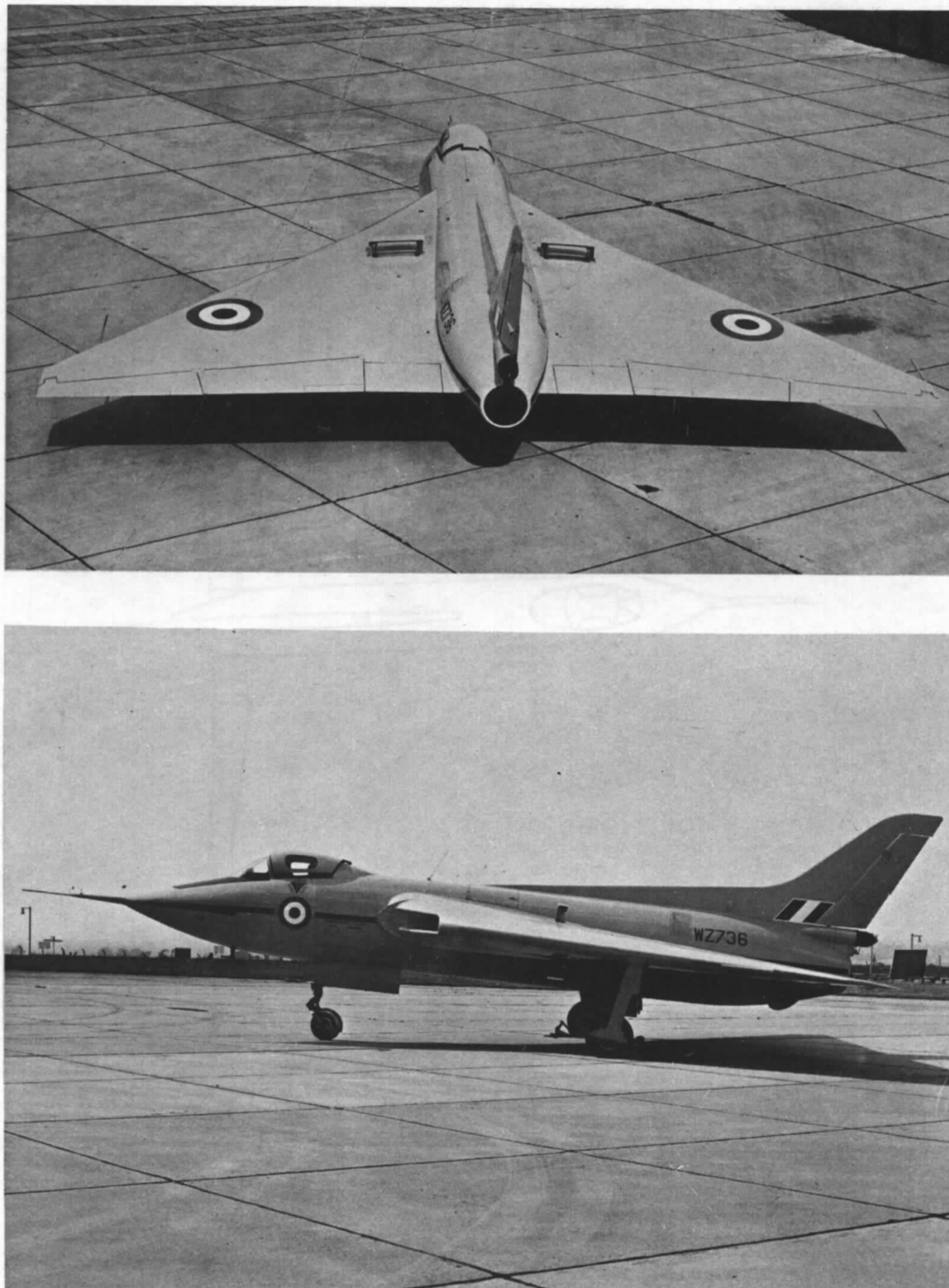


FIG. 2. Avro 707A.

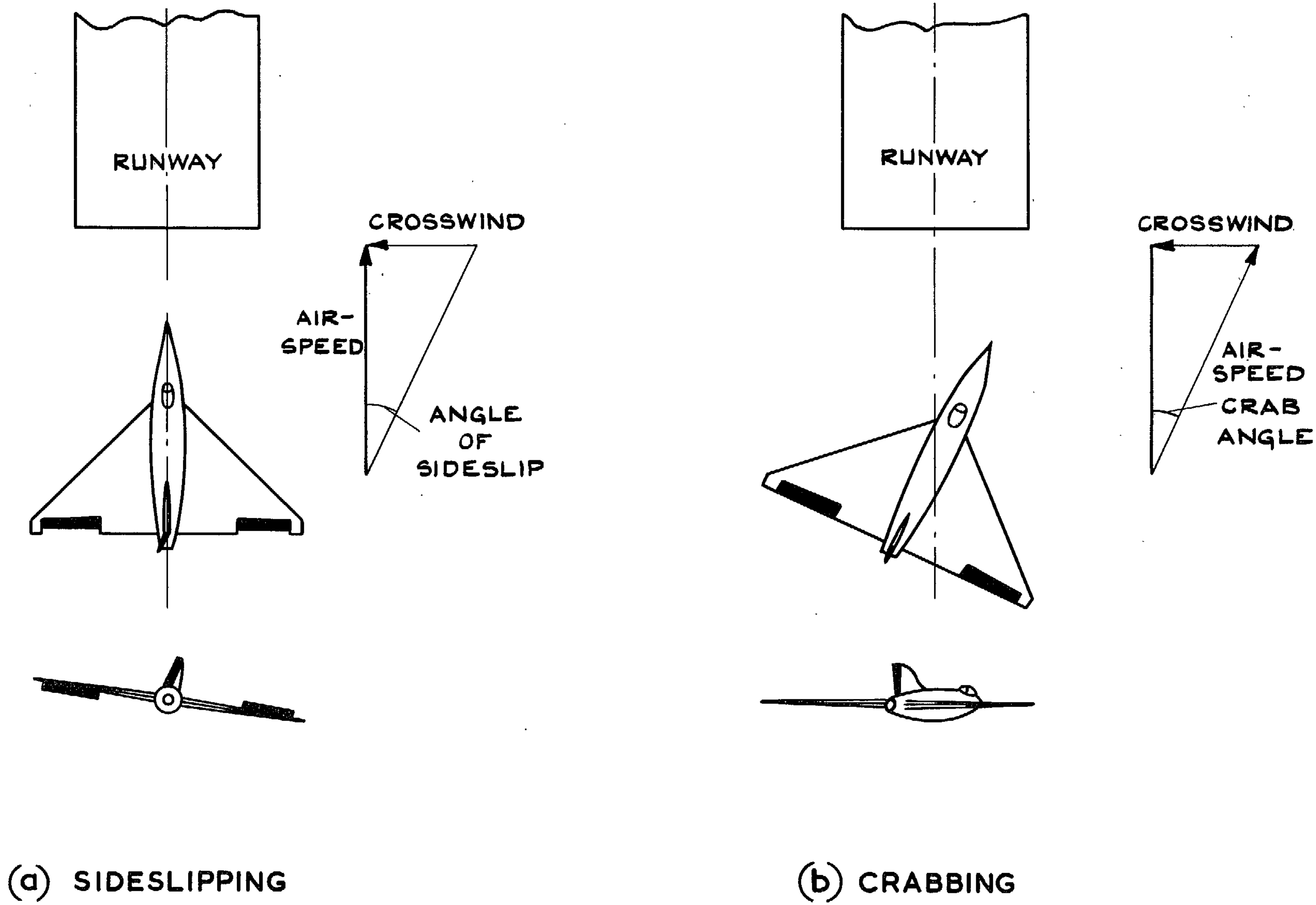


FIG. 3 (a & b). Basic crosswind landing techniques.

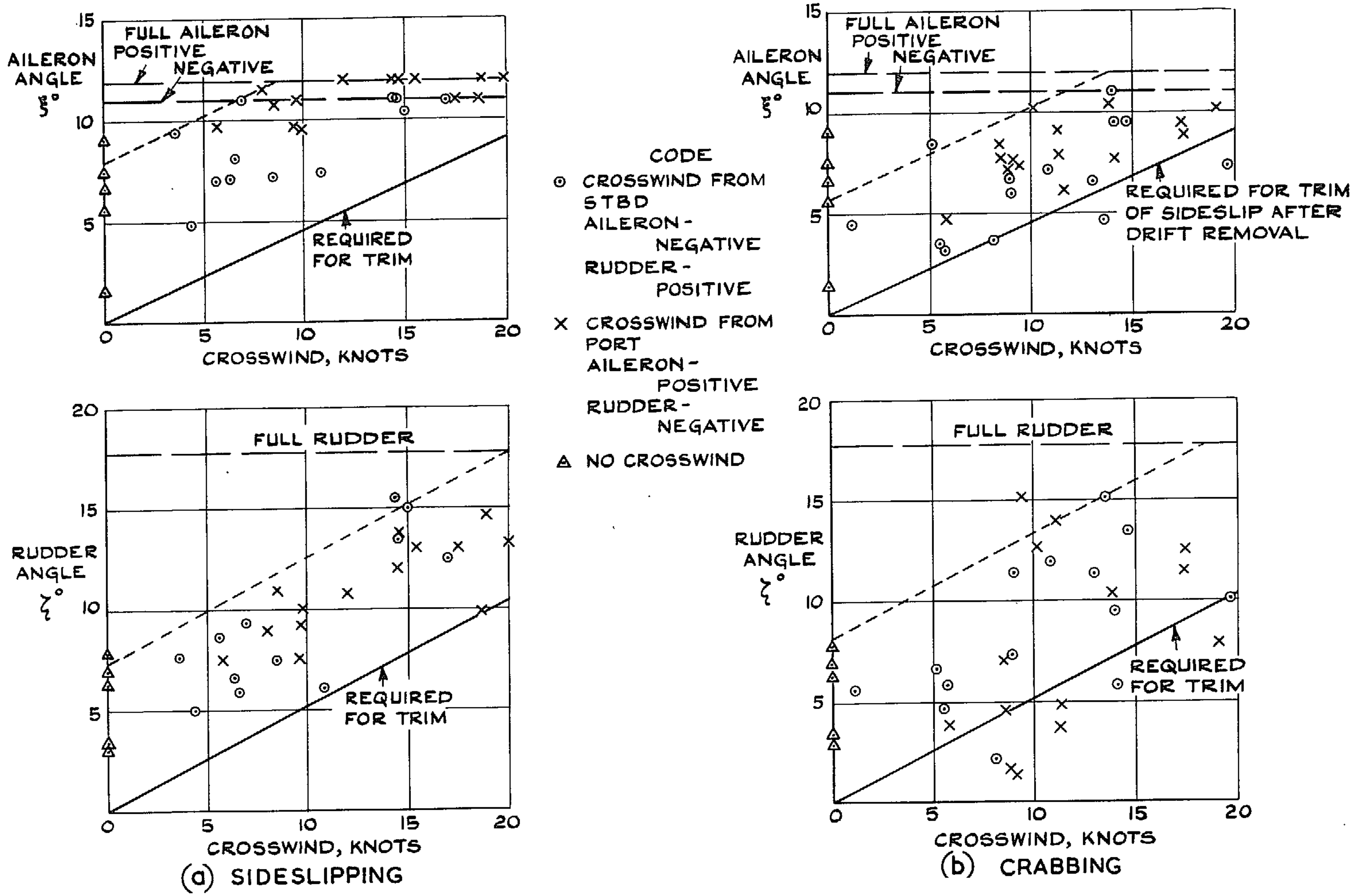


FIG. 4 (a & b). Maximum control angles used during approach and landing.

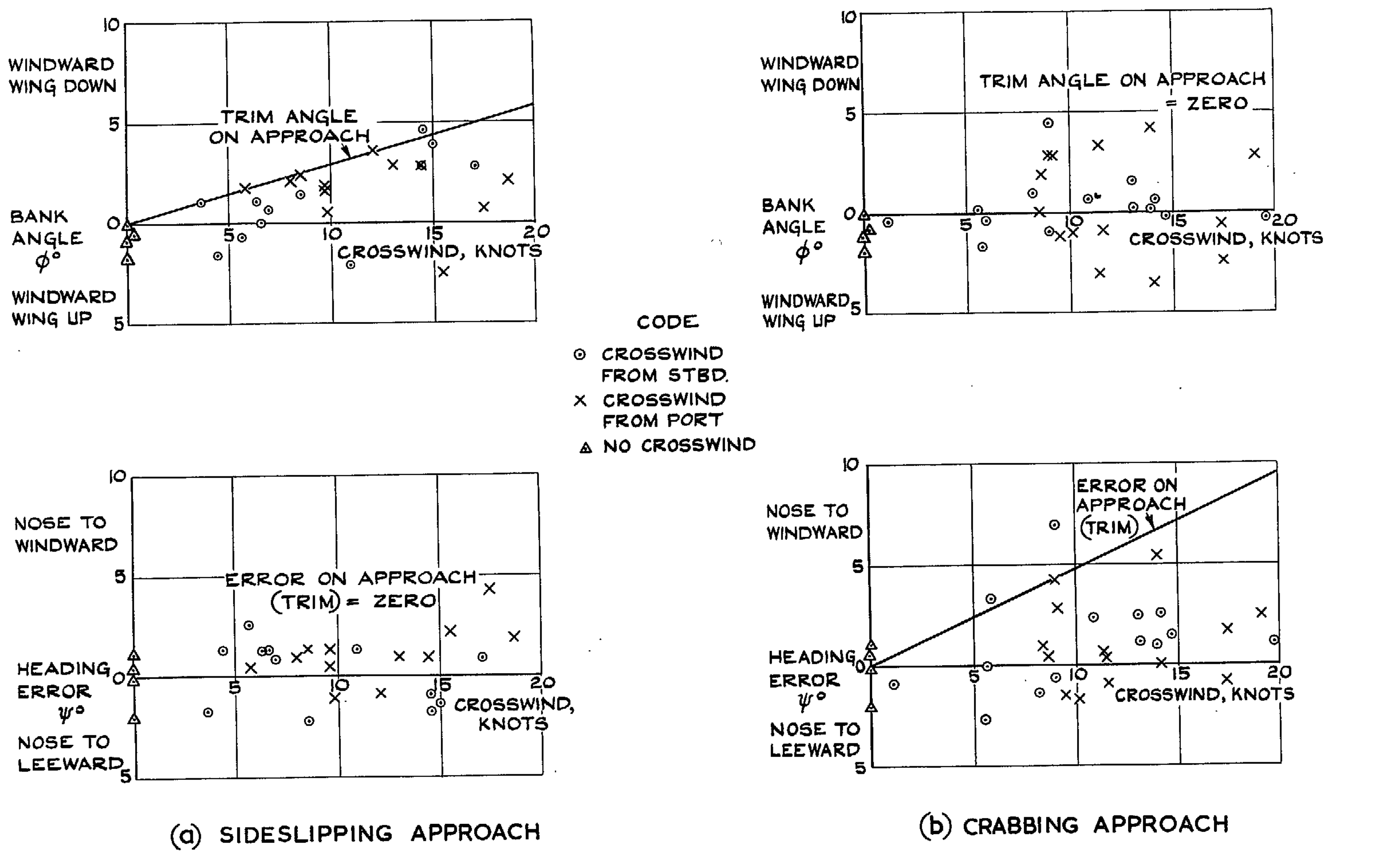
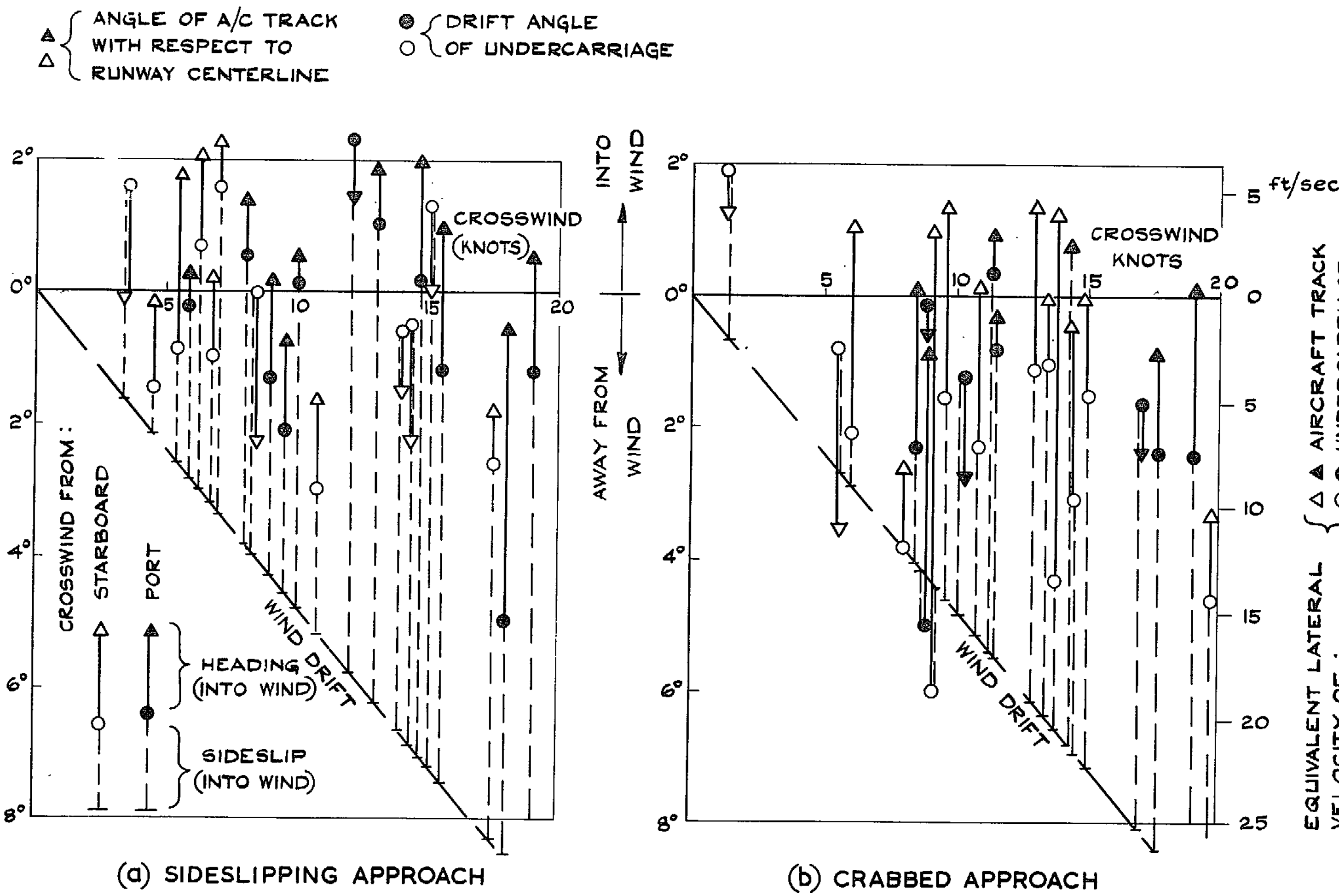


FIG. 5 (a & b). Back angle and heading error at touchdown.



6 (a & b). Lateral velocity at touchdown derived from recorded aircraft heading, sidelip and crosswind.

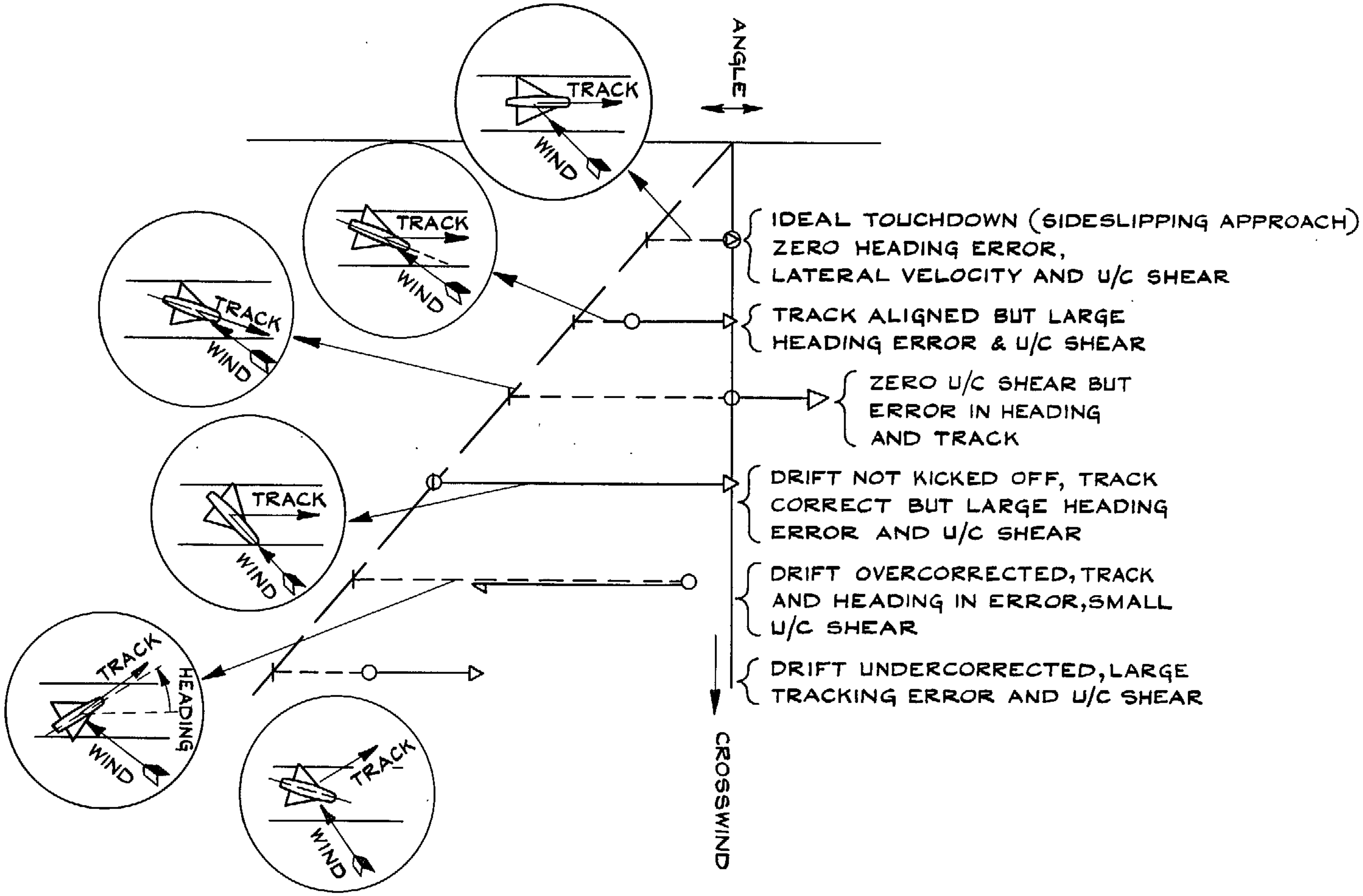


FIG. 7. Explanatory examples of the touchdown conditions recorded in fig. 6 (a & b).

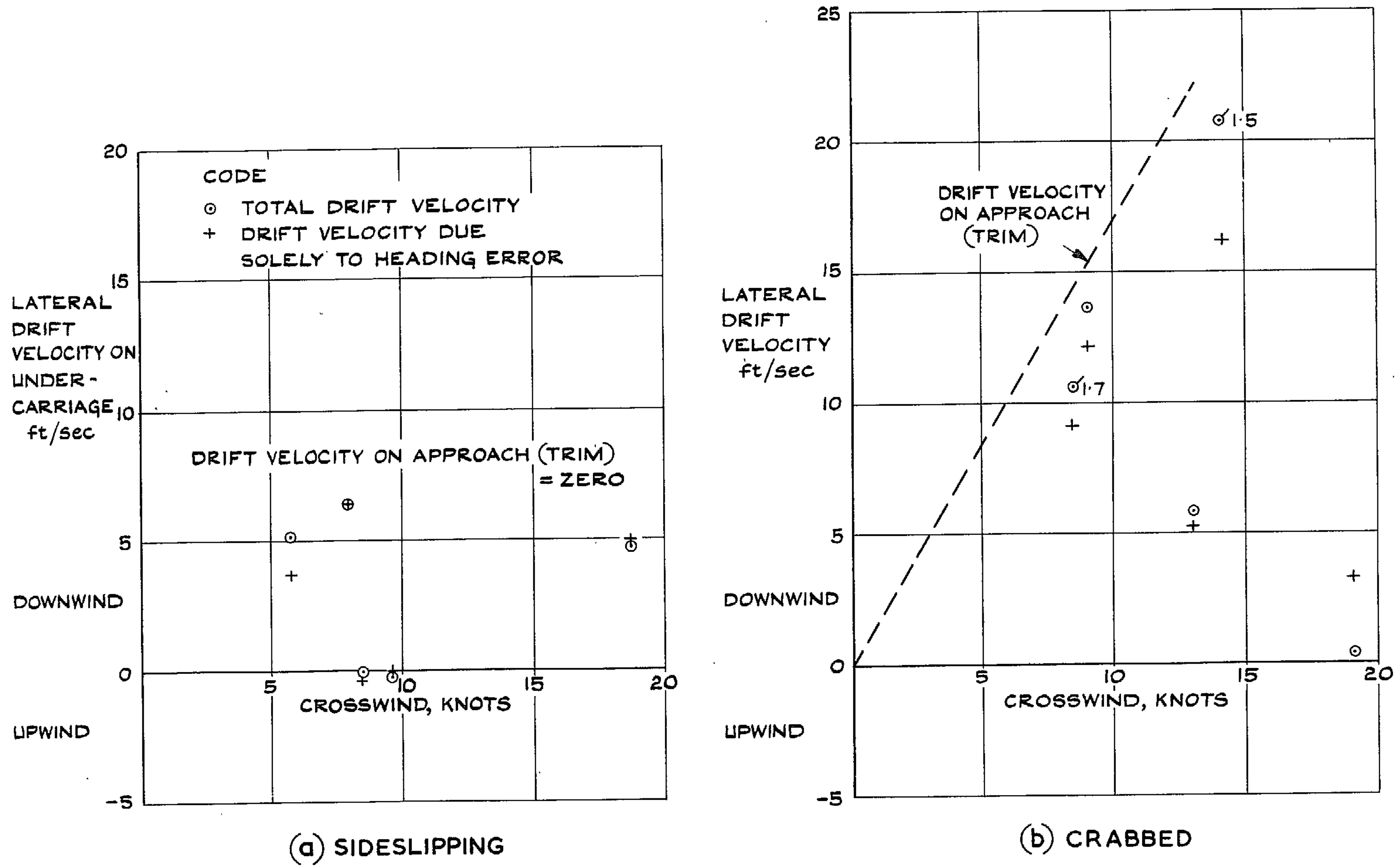


FIG. 8 (a & b). Drift velocity at touchdown, main wheels.

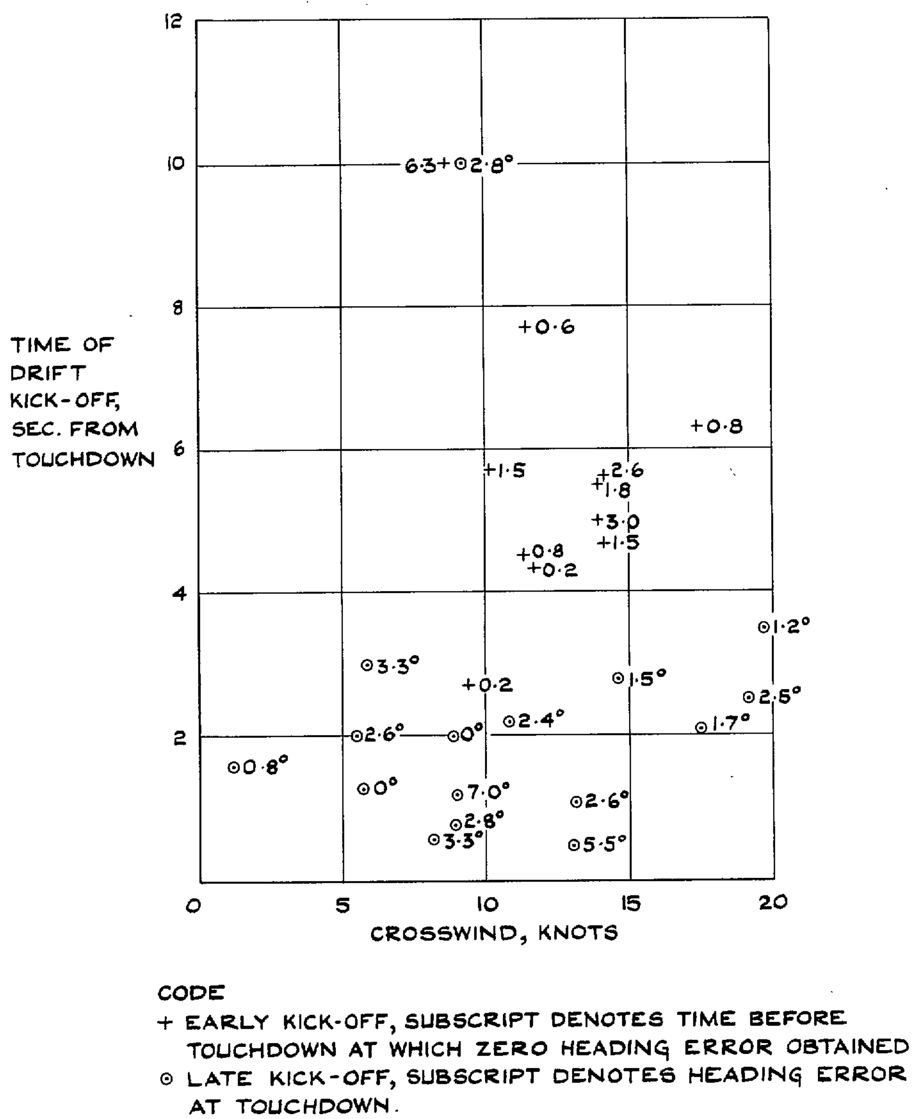


FIG. 9. Drift kick-off.

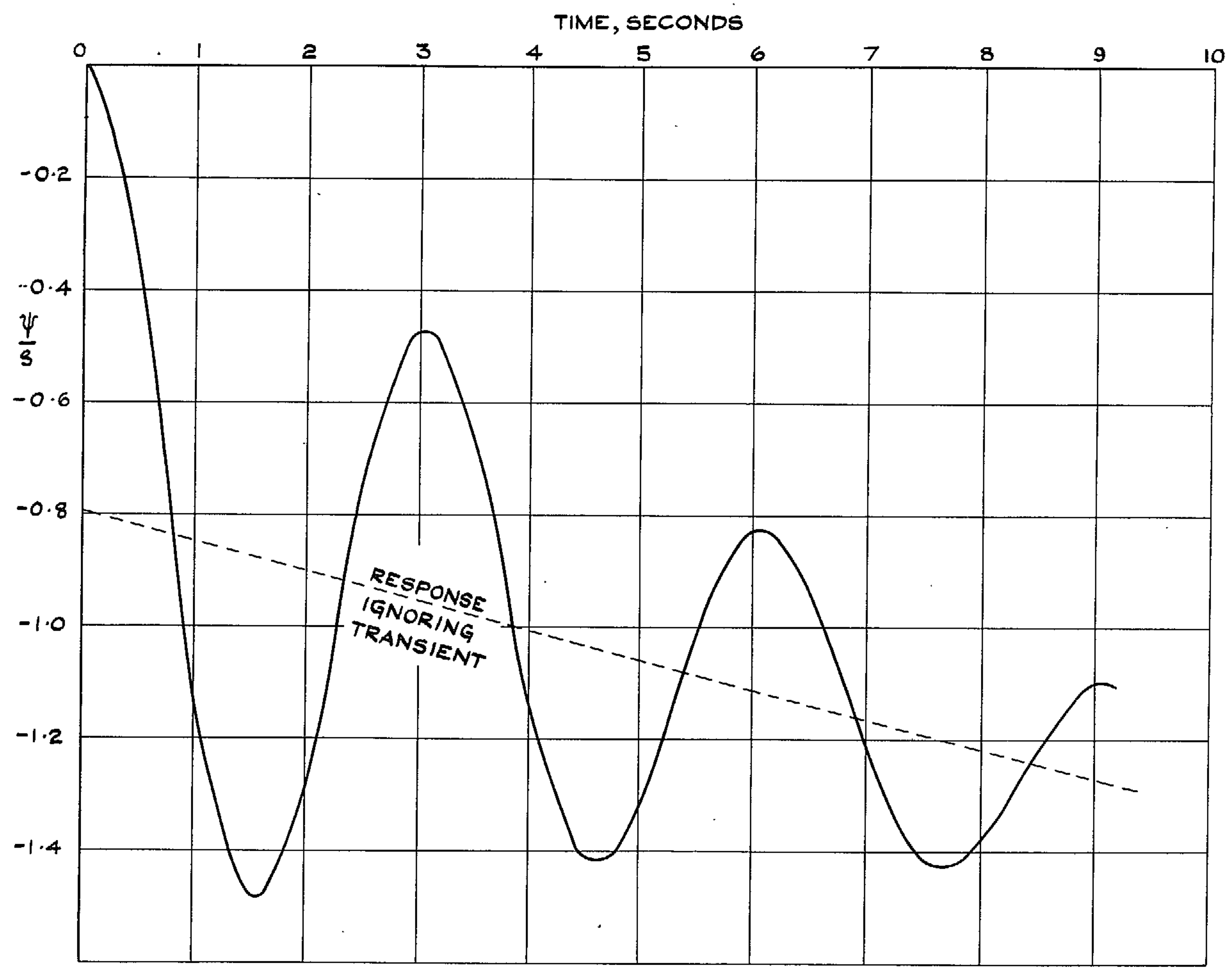


FIG. 10. Heading response to step input of rudder, bank angle held zero by ailerons.

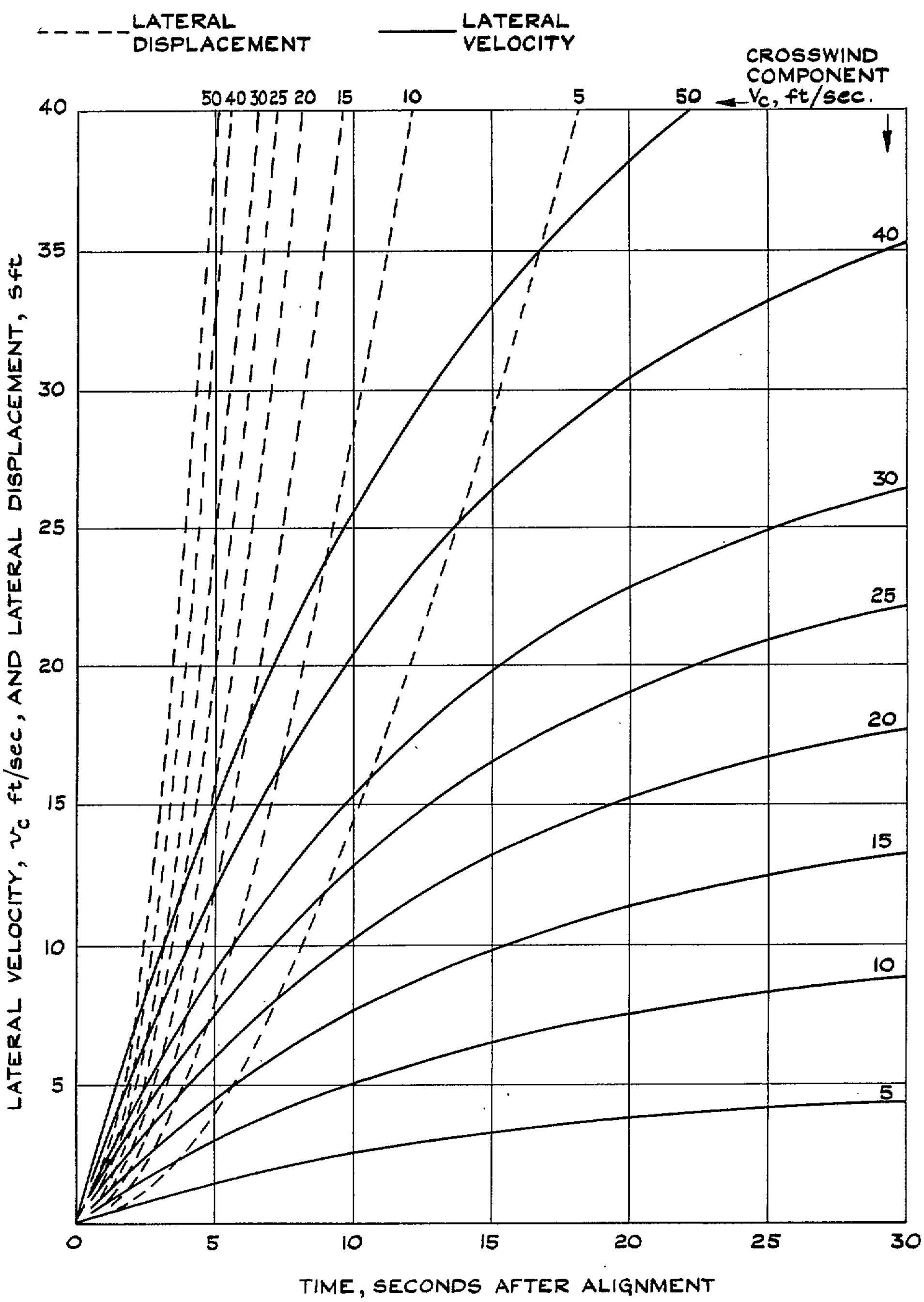


FIG. 11. Lateral velocity and displacement following instantaneous, wings level, alignment with runway.

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