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Aircraft Vortex Wakes and their Effects on Aircraft

by

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AIRCRAFT VORTEX WAKES AND THEIR EFFECTS ON AIRCRAFT

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SUMMARY

Tests have been made using a Venom traversing aircraft to determine the strength and decay, away from the ground, of vortex wakes behind Comet and Vulcan aircraft. Vortices have been found to decay rather less quickly than previously believed. The present tests show that the effects of an intersection at right angles to the wake reduce to a low level (less than 8 ft/sec equivalent gust) after 2 minutes. This result is unlikely to be any more severe for a transport aircraft. However, the estimated rolling disturbance from a glancing interception is still large at 3 minutes. Supersonic transport aircraft are expected to have similar behaviour to conventional transports.

Further tests to study vortices near the ground, and behind slender wing aircraft, are planned.

Replaces R.A.E. Tech Note No. Aero 2934 - A.R.C.25419

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1 INTRODUCTION

In flight an aircraft imparts momentum to the surrounding air, and as a consequence leaves in its wake disturbances which may upset other traffic. In fact, in the United States, increasing numbers of incidents and accidents, to light aircraft in particular, are reported which are the results of such wake encounters. Although so far in this country such occurrences are extremely rare, expected growth in air traffic may demand more positive measures to minimise the risk of such incidents, in particular in terminal areas with relatively high traffic densities.

To formulate regulations which are adequate to safeguard traffic under these conditions, and at the same time are not unduly restrictive, the nature of the wake behind an aircraft and the possible consequences of an interception of such a wake by following traffic must be known.

The disturbances created by an aircraft are due to three main effects:

(i) the engine-generated slipstream,

(ii) drag-imparted momentum,

(iii) trailing vortices associated with the generation of lift.

Flight tests with a Meteor aircraft[1] have shown that, in subsonic flight, the trailing vortices made by far the strongest contribution, and that by comparison engine slipstream and drag momentum can be neglected.

More recent flight experience has shown that in supersonic flight the effects of shock waves are also significant. These are manifested as sonic bangs to observers on the ground, and as large disturbances to other aircraft in the vicinity, which may, in extreme cases, cause structural failure.

However, the present note restricts itself to considerations of low speed flight and in particular to conditions in the terminal area of airports.

Exploratory flight tests with a Lincoln aircraft[2] have shown that its trailing vortices may persist for up to 3 minutes. Further flight tests have been made more recently to measure in detail the strength and rate of decay of the vortex wake behind a Comet 3 and a Vulcan 1 aircraft. These aircraft are more representative of current transport aircraft and the results, although not yet fully analysed are presented here as a contribution to a more realistic assessment of the problems of traffic separation for wake avoidance.

For a full assessment of the problem it is important not only to be able to predict the strength and persistence of the disturbance generated by a given aircraft, but also to consider the likelihood of this wake being intercepted by other traffic using the same airspace and in what circumstances these encounters may endanger such traffic.

Recent American work in Ref.3 has considered the latter problem in some detail on a theoretical basis.

2 TRAILING VORTEX SYSTEM

Before considering the flight results, it is useful to examine the nature of the vortex system shed from the lifting surfaces of an aircraft, flying in calm air away from the ground. Classical aerofoil theory states lift is generated on a wing by a bound vortex with a circulation for elliptic span loading of

$$K = \frac{4}{\pi \rho V}\left(\frac{L}{b}\right)$$

and in level flight, when L = W, this can be written as

$$K = \frac{4}{\pi \rho V}\left(\frac{W}{b}\right). \tag{1}$$

This vortex can be assumed to be shed from near the wingtips as a pair of free vortices, forming with the lifting vortex the familiar horseshoe system. Ignoring details in this very simplified picture as produced by the geometrical properties of the wing (planform, camber, twist etc.) which mainly affect the flow close behind the wing, at a distance of a few spans downstream of the aircraft this simple model is essentially correct, the trailing vortices being established in a fully rolled up form. This trailing vortex system is propelled downwards with a velocity given in Ref.3 as

$$\bar{w} = \frac{2K}{\pi^2 b} = \frac{8W}{\pi^3 \rho V b^2}. \tag{2}$$

In the case of a marked discontinuity in the span loading, for example a wing with part span flaps deflected, the simple model is not appropriate, as separate vortices are shed from both near the wing tips and the outboard part of the flaps.

The effect of the surrounding atmosphere on the vortex system is considered insignificant, except when there is turbulence of a sufficient magnitude physically to break up the pattern, and as a consequence lead to an early destruction of the vortex trail.

On the other hand viscous forces acting within the individual vortex result in a fairly rapid slowing down of the peak velocities occurring particularly in the vortex core. This redistribution of the velocities within the vortex was considered in Ref.2, where the following expression is given for the circumferential velocity distribution in a single vortex as a function of time t and radial distance r:

$$v = \frac{K}{2\pi r}\left[1 - \exp\left(\frac{-r^2}{4(\nu + \varepsilon)t}\right)\right] \tag{3}$$

where ν is the kinematic viscosity and ε the eddy viscosity. The latter effect is dominant and is caused by small scale turbulence within the vortex. The eddy viscosity is assumed to be proportional to the circulation

$$\varepsilon = aK \tag{4}$$

where a is an empirical constant whose precise value is difficult to define, but is believed to be in the range 10^{-3} to 10^{-4}.

It is worth noting that the decay produced by these viscous forces results in a noticeable increase in the diameter of the vortex core and a sharp reduction in the peak velocities without materially affecting the overall circulation in the vortex during the period of interest, i.e. in the first few minutes after the passage of the generating aircraft.

The trailing wake described by this model is illustrated in Fig.1.

Fig.2 shows the theoretical distribution of circumferential velocity derived from equation (3) in a plane passing through the centres of a pair of trailing vortices. The vortices are assumed to have been created by a 97,000 lb aircraft with a 115 ft span flying at an equivalent airspeed of 117 knots at 5,000 ft. This represents the Comet used in the present tests. The figure shows results for two stages in the life of the vortex system, namely immediately the vortices have rolled up approximately 1 second after being shed from the wing tips, and 49 seconds after the passage of the aircraft assuming an eddy viscosity of 0.0002K.

Fig.3 shows the theoretical decay of the positive and negative peak velocities of several vortex systems, including that of Fig.2. Calculations have not been made for a wake age of less than 12 seconds, as the theory does not hold for the initial decay. Both the positive and negative peaks decay at the same exponential rate, but the negative peak approaches the steady state downwash value whilst the positive peak approaches zero.

3 FLIGHT TESTS MADE

Table 1 gives relevant details of the Comet 3B and Vulcan 1 which were used in the present flight tests, including values of the span loading, circulation, and the ratio of circulation to span, for typical take-off and landing conditions. The circulation governs the initial strength of the vortices and the circulation/span ratio the downwards velocity of the vortex cores. Table 2 shows the speeds and heights at which the two aircraft were flown during the flight tests. All tests were made in the clean configuration in essentially calm air away from the ground.

In each case the wake was marked by injecting smoke into the vortex from canisters mounted near the wing tips of the aircraft. A Venom aircraft was then flown through the wake at right angles at a constant equivalent airspeed of 155 knots intercepting the wake several times at increasing distances behind the generating aircraft; Fig.4 shows the flight pattern adopted. By measuring the response of the Venom, when encountering the wake, a basis for determining the vortex strength and persistence was obtained. When the aircraft penetrated the vortex wake it encountered the equivalent of a normal gust with two positive peaks and a negative velocity trough.

In practice, the pilot of the Venom found it difficult to intercept the vortex cores, frequently missing the centre of either or both vortices. Since the penetrating aircraft was not equipped to measure changes of horizontal velocity it is not possible to extract the full value of circumferential velocity in these cases, but only its vertical component.

4 RESULTS OBTAINED

Fig.5 shows a flight record obtained when the Venom passed close to the centres of the vortices created by the Comet. The variation of uncorrected incidence, pitching velocity, and normal acceleration of the penetrating aircraft as it traversed the wake are shown, together with the vertical velocity component of the wake, obtained from the measured incidence, allowing for the dynamic response of the vane and the response of the aircraft. The response of the wind vane is seen to lead that of the normal accelerometer by approximately 0·07 seconds; this is mainly due to the wind vane being mounted on a nose boom 17 ft forward of the aircraft centre of gravity. The normal accelerometer and rate gyro used in the tests were not high quality instruments and no dynamic calibrations of these instruments were available. Thus the values of normal acceleration and rate of pitch should not be regarded as absolute, but only as giving an indication of the response of the aircraft. The minor oscillations apparent in the records are probably structural modes. It can be seen that during the relatively rapid wake traverse, the aircraft hardly has time to respond to the disturbance and as a consequence the recorded incremental incidence can be taken as a direct measure of the vertical velocity induced by the wake. Also shown in Fig.5 is a theoretical estimate[2] of the vertical velocity using an eddy viscosity of 0·0002 times circulation, which is in good agreement with experimental results.

In the following sections the important physical features of the vortices, namely the induced velocities produced and the way they decay, and the position of the wake in relation to the originating aircraft, are described, and also the accelerations produced on the aircraft intersecting the wake.

4.1 Vertical downwash velocities and position of the vortex wake

To show the strength of the intercepted Comet vortices, all the values obtained during the tests of the first and second positive peaks of the velocity and of the negative trough have been plotted against the age of the wake, in Fig.6. These values have been derived from wind vane readings without making any allowance for aircraft response, and whilst this analysis is not strictly accurate the results should be correct to within 2-3 ft/sec. Results were not obtained until 20 to 30 seconds after the passage of the generating aircraft as this would have subjected the Venom to uncomfortably large, especially negative accelerations. Nor was it possible to intercept the vortex trail at points more than 120 seconds downstream of the test aircraft as the smoke marking the vortices became too diffuse for identification. It should be noted that since many of the penetrations missed the centres of one or both of the vortex cores, the vertical velocities experienced are not, in many cases, the maxima that would have been measured if the aircraft had passed through the centres of the vortex cores. Nevertheless, since a fairly large number of penetrations were made, the envelope of the points should represent the maxima corresponding to perfect interceptions.

The theory discussed in Section 2 has shown that the velocity distribution in a vortex is

$$v = \frac{K}{2\pi r}\left[1 - \exp\left(-\frac{r^2}{4(\nu + aK)t}\right)\right] ,$$

Simple analysis for a pair of contra-rotating vortices shows that the maximum induced vortex velocity is of the form:

$$\left(\frac{v}{K}\right)_{y_{max}} = f(a, Kt) . \qquad (5)$$

As 'a' is a constant, although unknown so far, the maximum velocity data obtained with a given aircraft in various flight conditions (i.e. values of K) should collapse into a unique plot of v/K against Kt. The data are plotted in Fig.7a where curves for three different values of 'a' (a = 0·0001, 0·0002 and 0·0004) are also shown. The data in Fig.7a are seen to give a reasonable collapse. However, closer inspection of the data shows that many of the points occur in pairs which appear obviously displaced, suggesting that in these cases an incorrect datum incidence of the penetrating aircraft was chosen when computing the incremental values of $\Delta\alpha$ and therefore w. To make the data independent of such a datum, which is not uniquely defined in the flight records, incremental values between the 1st and 2nd peaks, and the 3rd and 4th peaks respectively, measured during each traverse (see sketch in Fig.7b) have been plotted instead in Fig.7b. They are compared with theoretical curves for three values of a. This plot is seen to provide a very convincing collapse of the experimental data and suggests that it can be fitted by a theoretical envelope with a value for the eddy viscosity coefficient of approximately a = 0·0002. This value is significantly smaller than that given previously[2] (a = 0·0004) on the basis of more limited experimental data.

The positions of the wake relative to the original flight path have been measured for each interception during the flight tests and some typical results are shown in Fig.8. The simple theory of Section 2 shows that the wake has a constant downwards velocity, and this has been used to estimate the vertical displacement of the wake from the original flight path; the agreement with the experimental results is, considering the accuracy of this type of flight measurement, very good. Fig.9 shows a comparison of the theoretical and experimental values of the vertical velocity of the wake for all measured interceptions, the agreement again being very good.

4.2 Aircraft accelerations resulting from interception of the vortex wake

Figs.10 and 11 show the maximum positive and negative accelerations experienced by the Venom when intercepting the vortex wakes created by the Comet and Vulcan respectively. No dynamic corrections have been applied to the accelerometer readings, but it is estimated that they will not be more than 10% greater than the true acceleration. It should be amphasised that whilst the peak accelerations correlate roughly with the peak vertical velocities experienced in the wake, they also depend critically on unsteady aerodynamics, the shape of the wake, and the structural modes of the Venom. Thus the acceleration records represent only the response experienced by a Venom intercepting the particular wakes investigated and may not be valid or indeed typical for other aircraft.

Within these reservations, the results plotted in Figs.10 and 11 show that the trailing wake shed from both the Comet and the Vulcan in low speed flight contains enough energy to create serious interference with other traffic when intercepted too closely. However, it appears that after little more than 120 seconds the vorticity has decayed sufficiently to be insignificant at least to an aircraft with the characteristics of a Venom. However, in view of the scatter of the data and their relative scarcity in the range of more than say 80 seconds separation, extrapolations beyond the range covered and even at the end of the range covered cannot safely be made.

5 THEORETICAL ASSESSMENT OF POSSIBLE VORTEX WAKE EFFECTS NEAR THE GROUND

5.1 Introduction

Before attempting an assessment of possible vortex wake effects in civil operations, it is useful to review briefly the way in which civil aircraft operate in practice.

In en route flying, the probability of an aircraft encountering wakes, is extremely small, because U.K. Civil Aviation procedures ensure separations of more than 3 minutes at any given altitude. Furthermore, due to the relatively small size of the vortices the probability of following traffic passing through them is very low and thus this type of encounter is not oonsidered a hazard.

However, during terminal operations at airports, encounters are much more probable. Also the circulation associated with the vortices will, in general, be larger due to the lower speeds in this flight regime. These hazards have been recognised, and a Flight Safety Warning note[4] issued to pilots. As air traffic control procedures improve, vortex wake effects may become the limiting factor. Further flight tests are required before separation minima may be defined. In the United States, an increasing number of incidents are reported of very severe disturbances in the wake of another aircraft, and in the case of light aircraft an increasing number of fatal accidents in the vicinity of airports have been ascribed to structural failure caused by the wake of large aircraft. Thus American experience seems far more serious than the British. This may be due to two reasons, firstly the large number of personal and executive light aircraft flown, particularly in close proximity to large heavy transport aircraft, and secondly the much higher movement rates at their airports.

The theory used here for the motion of the vortices close to the ground takes no account of ground friction which must reduce the strength and velocity of the vortices rapidly. There is no flight test evidence to establish the nature and magnitude of this effect, but it must be expected that it would considerably reduce the vortex induced velocities and thus any deductions should be treated with caution as they may overestimate the effects.

A recent U.S. paper[3] has considered more fully than hitherto the effects of vortex wakes on terminal operations. The theoretical model assumed is similar to that described in Section 2. In addition, the effect of ground is considered and it is shown that as the vortices approach the ground their vertical velocity is reduced and they start to move apart laterally. At a height of a semi-span the vertical motion has ceased and the vortices have a lateral velocity equal to the original vertical velocity. If the vortices are generated closer to the ground their initial lateral spread rate is faster.

A critical examination, in the light of our present knowledge, is briefly made of this theoretical model. The behaviour of a vortex wake in calm air away from the ground is reasonably well understood; flight tests confirm the vertical motion of the vortices and their decay. Results of present R.A.E. flight tests, discussed in Section 4.1 of this report, suggest that the empirical eddy viscosity constant a is 2×10^{-4}; Ref.3 assumes a somewhat higher value. In addition, atmospheric turbulence, which is of relatively large scale compared with the turbulence within the vortex, may act on the vortex system and break it up. At present, no experimental evidence is available to indicate what level of atmospheric turbulence is required to be come important in this respect. However, in this context it is significant to note that most of the reported flight incidents attributed to vortex wake encounters have occurred in calm air conditions.

The possible types and circumstances of vortex wake encounters in mixed traffic patterns containing various classes of aircraft ranging from a 2,000 lb light personal aircraft to a 300,000 lb heavy transport aircraft are considered in the following sections in the light of the results of the flight investigation.

5.2 Types of encounters and their effects

The crossing of a vortex wake at or near right angles, whilst typically lasting only $\frac{1}{2}$ second, is equivalent to the encounter of a gust and can result in quite large normal accelerations. The shape of this gust is quite complex, and its characteristics are best seen from the accelerometer records of Fig.5. An aircraft encountering the gust first experiences an increase in normal acceleration, followed by a rapid decrease to less than 1 'g' as the core of the first vortex is traversed. In the case of the Venom penetrating the wake of either a Comet or Vulcan, the maximum increment in acceleration appears to occur in the relatively steady downwash field between the two vortex cores, which produces the equivalent effect of a sharp-edged gust of about 40 ft/sec (for 60 seconds) and 8 ft/sec for 120 seconds separations.

Comparison of these equivalent gust velocity values with the measured downwash velocities of Fig.6 shows reasonable correlation at 60 seconds, but at 120 seconds the downwash velocity is about twice the equivalent gust velocity. This emphasises that the gust alleviation factor, which relates the acceleration to the gust velocity, depends critically on the shape of the gust. After 120 seconds the vortex core diameter has grown considerably, and hence the velocity gradients are less steep.

The magnitude of the accelerations experienced by other aircraft penetrating a wake of the Comet/Vulcan type depends on many factors, including the wing loading, aeroelastic effects and the size of the aircraft. For 150,000 lb transport aircraft penetrating the wake the response is likely to be no more severe than for the Venom, but for small lightly loaded aircraft, it could almost certainly be worse. This type of encounter is most likely to occur when aircraft are joining the terminal operations area and cross the take-off paths of other aircraft. It can be largely avoided by ensuring that aircraft join the circuit at a point above the climb out path of large aircraft.

The most likely type of wake interception is a glancing penetration at a small angle to the track of the vortex. If the penetrating aircraft approaches the centre of the wake from below the downwash may be sufficient to prevent an aircraft caught in it from maintaining its rate of climb. The most critical case is a small aircraft, with a low rate of climb, entering the wake of a large aircraft. The wake will in these circumstances act as an invisible barrier through which it is impossible to climb, and which will force following traffic, unfortunate enough to make the interception, into a flight path below unless lateral "evasive action" is, and can, be taken. The main danger arises because the pilot so affected may not recognise the nature of this obstacle and stall the aircraft in an attempt to force his way through the wake. Also since the wake is below the flight path of the generating aircraft, following traffic may be forced into dangerously shallow approach or climb out paths.

If the aircraft intercepts one of the two vortex cores, as has been reported in certain incidents of glancing wake penetrations, the following aircraft is subjected to a rolling moment which may be larger than can be countered by the controls. Again the smaller light aircraft is subjected to a larger rolling disturbance than a large transport when encountering a given wake. Ref.3 concludes, however, that even a large subsonic transport aircraft, because of the generally lower aileron power available, may reach a 20° bank angle within 2 seconds when penetrating the wake of a heavy transport aircraft after 3 minutes, assuming full corrective action is applied within 1·3 seconds.

For comparison, the same angle of bank will be generated in 2 seconds by a lateral gust of about 40 ft/sec. It should be noted that the simple estimate assumes the aircraft is instantaneously immersed in the vortex core, and thus pessimistically large angles of bank are calculated, since the pilot would have some warning of the approach to the vortex core and would initiate corrective action earlier than assumed.

5.3 Take-off encounters

Ref.3 gives results for the estimated vertical and lateral movement of the vortex wake relative to the take-off climb path of a 300,000 lb transport aircraft; these results, which assume zero wind, are reproduced in Fig.12. Using these results as a basis, the effects of various headwinds have been computed and are shown in Fig.13. Conditions beyond 1,000 ft height are not considered. Aircraft may level off and/or turn beyond this height and then wake encounters are less likely. A headwind moves the vortex wake back towards a slightly steeper climb path, and for a 30 knot headwind the vortex trail would remain almost stationary on the take-off path, and will persist there until the vortices have decayed.

Figs.14 and 15 show the effects of a 5 knot and 10 knot crosswind on the lateral movement of vortex wakes relative to the take-off track. It should be recalled that there is no experimental confirmation of the lateral motion of vortices assumed in these calculations close to the ground. It seems likely that the effects of ground friction will reduce rapidly the strength and velocity of vortices close to the ground. With either crosswind, the vortex trailing from the windward wingtip is seen to cross the runway at a point approximately 1,000 ft from lift-off and stays there for at least 2 minutes. Further along the take-off path, with either crosswind, the vortices drift away from the runway because of their lower horizontal velocity. With a 10 knot crosswind vortices created at the leeward wingtip have drifted over 2,000 ft from the runway after between 2 to 3 minutes; they could create a hazard for operations on a parallel runway. This point is considered further in a later section. Some illustrative examples of the implications of these vortex patterns on take-offs from the same runway are now briefly considered.

Let us consider first the case of consecutive take-offs of similar 300,000 lb transport aircraft. Typical piloting variations could result in the lift-off point being delayed by up to 1,000 ft and in climb angle errors of say $\pm 1^\circ$. Corresponding bands of possible take-off paths are shown in Figs.12 and 13. Neglecting the effects of atmospheric turbulence which are likely to accelerate the decay of the vortices the following results are obtained. Critical conditions pertain as long as a possible climb-out path could intersect a vortex shed by a preceding aircraft. In zero wind, critical conditions exist for 30 seconds, in 10 knots headwind, for almost 1 minute, in 20 knots headwind, for about $1\frac{1}{2}$ minutes and in 30 knots headwind for almost 2 minutes.

Currently take-off directors are being developed to enable pilots to achieve more consistent take-offs. With this type of aid the variation in climb-out path of similar aircraft would be small and vortex encounters would be less frequent.

With light crosswinds, of the order 5 knots (Fig.14), the following aircraft could encounter a vortex trail, if the vortex were not dissipated by ground friction effects, soon after lift-off for up to 2 minutes after the passage of the first aircraft. This type of encounter would produce a momentary upset in normal acceleration, potentially dangerous due to the relatively low velocity of the aircraft and its closeness to the ground at this phase. With a 10 knot crosswind, Fig.15 shows that a similar encounter could occur up to 1 minute after the passage of the first aircraft.

The general case of successive take-offs of aircraft of different types can result in a great variety of possibilities and each case must be considered on its merits. For a medium weight transport following a heavy aircraft, and a light aircraft following a medium weight aircraft the position appears not too critical, as in both cases, as a crude generalisation, the take-off run will be shorter than that of the preceding aircraft and the climb-out paths at least as steep. As a general rule, with aircraft having a take-off run at least 2,500 ft shorter than the preceding aircraft, and having a climb-out path at least as steep, no wake encounter is possible even allowing for a headwind of 30 knots.

In the case of a heavier aircraft following a lighter aircraft, the most adverse condition is for zero headwind when the vortices are propelled downwards towards the climb-out path of the second aircraft with no relieving effect of the headwind. As an example, Fig.16 shows a possible climb-out path of a 300,000 lb transport aircraft relative to the vortex pattern generated by a 150,000 lb transport with a 2,000 ft shorter take-off run. The longitudinal positions of the vortices are shown for several time intervals after the passage of the first aircraft. The second aircraft would encounter vortices for up to 1 minute after the passage of the first aircraft; beyond this time no vortices would be encountered, even with cross winds and if the vortices persisted close to the ground they would be propelled away laterally from the runway.

5.4 Landing encounters

Ref.3 shows the landing approach path of a 300,000 lb heavy transport aircraft and the vertical and lateral positions of the vortices at various time intervals after the passage of the aircraft for zero headwind and crosswind; these results are reproduced in Fig.17. The assumed slope of the glide path is 3°. Using these results, the effects of 10 knot and 20 knot headwinds on the vertical position of the wake relative to the flight path have been computed and are shown in Fig.18. With a headwind, increased power is used to maintain the same glide path and airspeed, however the rate of descent is reduced. In landings, headwinds are favourable, in that they carry the vortices further away from the flight path.

Figs.19 and 20 show the lateral positions of the vortices relative to the approach track for 5 knot and 10 knot crosswinds for various time intervals after the passage of a 300,000 lb aircraft. With a 5 knot crosswind, a relatively stationary vortex persists for almost 2 minutes and the vortex trail lies just above and almost normal to the runway about 2,000 ft short of the aimed touchdown point. For a 10 knot crosswind, similar conditions exist except tha t the vortex only persists for 1 minute. Again it should be recalled these vortices may be dissipated rapidly due to ground friction effects.

The implications of these vortex patterns on approaches under I.F.R. (instrument) conditions are now considered. Use of an approach aid, such as I.L.S., enables the pilot to control the glide path to within $\pm\frac{1}{2}^{\circ}$, although once the threshold is reached individual piloting variations can result in quite large variations in the touch-down point. The maximum deviation in the approach path is shown in Figs.17(a) and 18(a). The most critical conditions for landing are with a zero head wind. But even then, 30 seconds after the passage of the aircraft the vortices are well away from the region in which the following traffic may approach. Although a stationary vortex could possibly persist beneath the glide path for up to 2 minutes with no crosswind, this should present no problem as it is well below the glide path. Thus it appears that under I.F.R. conditions landings could be safely made, whatever the wind, behind a 300,000 lb aircraft within $\frac{1}{2}$ minute. To cater for a 150,000 lb aircraft with a lower circulation/span ratio, and hence lower induced vortex velocities, the minimum for safe landings would have to be increased to 1 minute. Although for smaller generating aircraft the interval required to avoid completely wake disturbances is longer than 1 minute, it is suggested that the magnitude of these effects would not be significant after 1 minute.

Under V.F.R. conditions much larger variations occur in the glide path. A particularly dangerous situation exists, of course, if a small aircraft encounters the wake of a large aircraft. To reduce the separation requirements to the minimum consistent with safety, it would be helpful if all large and medium size aircraft flew under I.F.R. control, that is use the I.L.S. beam, or some similar approach aid, to reduce glide path variations to the minimum. Small aircraft, with their potentially steeper glide paths and shorter landing runs, could touch down some distance down the runway and thus avoid all the wake effects.

5.5 Operations from parallel and crossing runways

Figs.14 and 15 show that for relatively light crosswinds, vortices created by a heavy aircraft during take-off will travel 1,000 ft to 2,000 ft laterally within 60 seconds if they persist in spite of the effects of ground friction, and thus they may still have considerable strength and effect on take-offs from a parallel runway. Although in the approach, in suitable crosswind conditions, aircraft can also cause vortices of similar strengths and distances from the approach path, they do not present a hazard to I.L.S. approaches on a parallel runway as the vortices lie below the glide path. Thus parallel runways of quite close spacing may be used safely providing each handles only take-offs or landings. A baulked landing could create a hazard on the parallel runway. If independent mixed operations are required from parallel runways, the lateral spacing must be adequate.

Operations from crossing runways could involve passage through a vortex trail and it is by no means certain that simple rules such as "one aircraft commencing take-off when the other aircraft has cleared the intersection" are adequate.

5.6 Operations of supersonic transport aircraft

So far only subsonic aircraft have been considered. The supersonic transport aircraft with its slender wing will have a much higher span loading than present day airliners and as a consequence its introduction into service needs careful appraisal.

As yet very little experimental or theoretical research on the flow behind slender wings has been undertaken, simply because the flow does not impinge on any part of the generating aircraft. Of course, the flow over a slender wing is reasonably well understood, vorticity is shed from the upper wing surface and rolls up into a vortex of the same sense as that generated from near the wing tip of a conventional attached flow wing. There is some unpublished evidence that suggests a contra-rotating vortex is generated behind a slender wing by the shear in flow at the trailing edge between the upper and lower surfaces created by the difference in the spanwise velocity components. This vortex is of the same sense as the much weaker one associated with the reattached flow on the upper wing surface. The contra-rotating vortex may wind itself around the primary vortex in a corkscrew fashion. Thus it is apparent that the wake behind a slender wing may be more complex than that behind a conventional wing and more research in this field is required. In the absence of more experimental data, some simple calculations have been made of the vortex wake effects for slender wings assuming that a single vortex pair exists. Because of the slenderness of the aircraft, the strength of the vortices, which is determined by the circulation, will be increased. For example, the circulation for the Concord at take-off and landing will be approximately 25% larger, and the downwards velocity induced by the mutual interaction of the vortices, dependent on the ratio of circulation to span, will be about $2\frac{1}{2}$ times larger* than for a current 300,000 lb subsonic transport aircraft, see Table 1. Thus the vortices shed by the Concord will be strong and have large vertical and horizontal induced velocities. The rate of decay of these vortices cannot be predicted with certainty, but as it may depend on the ratio of the circulation to span, it could be more rapid than for current transport aircraft. However, until firm experimental evidence is available to substantiate this theory, it is wise to assume the vortices decay no more rapidly than those observed in the tests described in this note, say in approximately 2 to 3 minutes.

Fig.21 shows the climb-out path of a supersonic transport aircraft and the positions of the vortices after the passage of the generating aircraft in different headwinds. Also shown in Fig.21 are the possible variations in the climb-out path of a following similar aircraft and a climb-out path of a 300,000 lb subsonic transport aircraft. Even in headwinds of up to 30 knots, following aircraft would not encounter the vortex wake after an interval of just over 1 minute. However, the effect of a moderately strong crosswind of 10-15 knots, may produce a stationary vortex trail across the runway persisting for perhaps 2 minutes, which following aircraft might encounter just after lift-off.

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*The induced velocity may be much larger as the rolled up position of the vortices behind a slender wing is almost certainly less than the theoretical value of $\pi b/4$ given by elliptic loading.

For the approach, the position is even more favourable as the most critical condition is for zero headwind, and the vortex wake will be at least 400 ft below the glide path only $\frac{1}{2}$ minute after the passage of the generating aircraft. This is well outside the maximum likely error in glide path control.

The response of a supersonic transport entering the wake of a 300,000 lb subsonic transport aircraft also needs consideration. Although the initial response of the supersonic transport to a rolling disturbance caused by a vortex wake will be slightly greater than for a subsonic jet transport, it is estimated that, because corrective action will be much more effective due to the relatively much more powerful lateral controls the supersonic transport is expected to posses, the bank angle will be no larger than that of current large subsonic jet aircraft.

6 CONCLUSIONS

6.1 Flight tests

Flight tests with a Comet 3B and Vulcan 1 aircraft have been made to measure the nature of the vortex trail behind these aircraft in low speed flight. The tests were made away from the ground in essentially calm conditions. The results show, that at least during the first two minutes after the passage of the aircraft considerable vorticity persists in the wake. The eddy viscosity coefficient has been reasonably well established as $a = 0.0002$; this is significantly lower than measured previously ($a = 0.0004$) in more limited flight tests. The downwards displacement of the wake from the original flight path agrees well with theoretical predictions.

The results show that the effects on an intersection at right angles to the wake reduce to a low level (less than 8 ft/sec equivalent gust) after 2 minutes. This result is unlikely to be any more severe for a transport aircraft. However, the estimated rolling disturbance from a glancing interception is still large at 3 minutes. Supersonic transport aircraft are expected to have similar behaviour to conventional transports.

6.2 Possible vortex wake effects near the ground

The present study has shown that in terminal areas air traffic may be endangered by encounters with vortices shed from other aircraft. Although the existence of these hazards is well supported by reports of a number of flight incidents, in particular in the U.S., the establishment of reliable separation minima requires a fuller understanding of the vortex breakdown and of the movement of vortices in particular in conditions near the ground.

Simple calculations have been made to assess the possibility of vortex encounters. Particular attention has been given to air traffic procedures and the effects of surface winds. It was found that crosswinds might cause a vortex to persist above a runway causing a particularly severe hazard. Also crosswinds can move vortex wakes to adjoining runways and endanger traffic movements there. It should be noted that the theoretical model used in the estimates took no account of ground friction and turbulence effects. Thus these conclusions should be treated with caution as they may overestimate the effects.

Finally, estimates have been made of probable wake effects generated behind a typical supersonic transport aircraft such as the Concord. If existing theory applies, it would appear that although being initially much stronger, the wake behind such an aircraft will move too rapidly out of the path of following traffic to be a real danger.

7 FUTURE WORK

The behaviour of vortices shed from conventional aircraft flying in calm air and away from the ground is now reasonably well understood. However, in practical traffic conditions the trailing wake may be powerfully affected by

(i) atmospheric turbulence leading to early break up of the vortices,

(ii) ground proximity affecting both the decay and the lateral spread of the vortex trail.

Also in view of the interest in slender wings such as proposed for supersonic transport aircraft it should be ascertained if the behaviour of the vortex trail generated by such a wing differs in any fundamental way from that shed from a conventional wing.

To obtain an insight into these outstanding questions and so to cover all the parameters required for the formulation of realistic air traffic separation minima, a further programme of experimental work is planned.

Qualitative investigations of ground reflection effects in various levels of atmospheric turbulence are planned by flying an aircraft low over a runway, again marking the vortex trails by injected smoke and to photograph these by cine cameras located on the ground and carried aloft by a helicopter.

The nature of the vortex trail behind a slender wing is to be investigated on the H.P.115 using a flight technique similar to that described in this note. More comprehensive instrumentation will be used, so that the level of atmospheric turbulence in these tests can also be established.

SYMBOLS

a	eddy viscosity coefficient	
b	wing span	ft
K	circulation	ft^2/sec
L	lift	lb
r	distance from vortex centre	ft
t	time	sec

SYMBOLS (CONTD)

V	aircraft speed	ft/sec
v	circumferential velocity in the vortex	ft/sec
w	vertical component of the velocity in the wake	ft/sec
$\bar{w}$	downwards velocity of the vortex trail	ft/sec
W	aircraft weight	lb
y	abscissa in the plane of the vortex trail, measured from the centre of the port vortex	ft
ε	eddy viscosity	ft^2/sec
ν	kinematic viscosity	ft^2/sec
ρ	air density	$slugs/ft^3$

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No.	Author	Title, etc.
1	Andrews, D.R.	A flight investigation of the wake behind a Meteor aircraft, with some theoretical analysis. A.R.C. Current Paper 282. December, 1954.
2	Kerr, T.H. Dee, F.W.	A flight investigation into the persistence of trailing vortices behind large aircraft. A.R.C. Current Paper 489. September, 1959.
3	Wetmore, J.W. Reeder, J.P.	Aircraft vortex wakes in relation to terminal operations. N.A.S.A. TN D-1777. A.R.C. 24851. April, 1963.
4	-	Flight safety warning turbulence caused by large aircraft. M.O.A. Civil Aviation Information Circular United Kingdom.
5	-	U.K. Air Pilot. Ministry of Aviation Publication.

TABLE 1

Parameters determining wake characteristics

Class of Aircraft	Type	Weight$^{\phi}$ W lb	Span b ft	$\left(\frac{W}{b}\right)$	Speed* V ft/sec	Circulation K ft^2/sec $\frac{4}{\pi \rho V}\left(\frac{W}{b}\right)$	$\frac{K}{\left(\frac{\pi b}{4}\right)}$ ft/sec
Aircraft on which flight tests have been made at R.A.E.	Comet 3B	100,000	115	870	195	2386	26·44
	Vulcan 1		99			2167	27·87
	Lincoln	66,000	120	550	186	1584	16·80

$^{\phi}$Weight at which R.A.E. flight tests have been made.

*Minimum speed at which R.A.E. flight tests have been made.

TABLE 2

Flight test conditions

Comet

5,000 ft		10,000 ft	
E.A.S. knots	Circulation ft^2/sec	E.A.S. knots	Circulation ft^2/sec
117	2550	117	2750
155	1900	155	2100
250	1250	250	1350

Vulcan

3,000 ft		5,000 ft		10,000 ft	
E.A.S. knots	Circulation ft^2/sec	E.A.S. knots	Circulation ft^2/sec	E.A.S. knots	Circulation ft^2/sec
155	2480	155	2710	155	2810
200	1870	200	2020	175	2410
300	1310	300	1390	200	2140
				225	1840
				300	1380

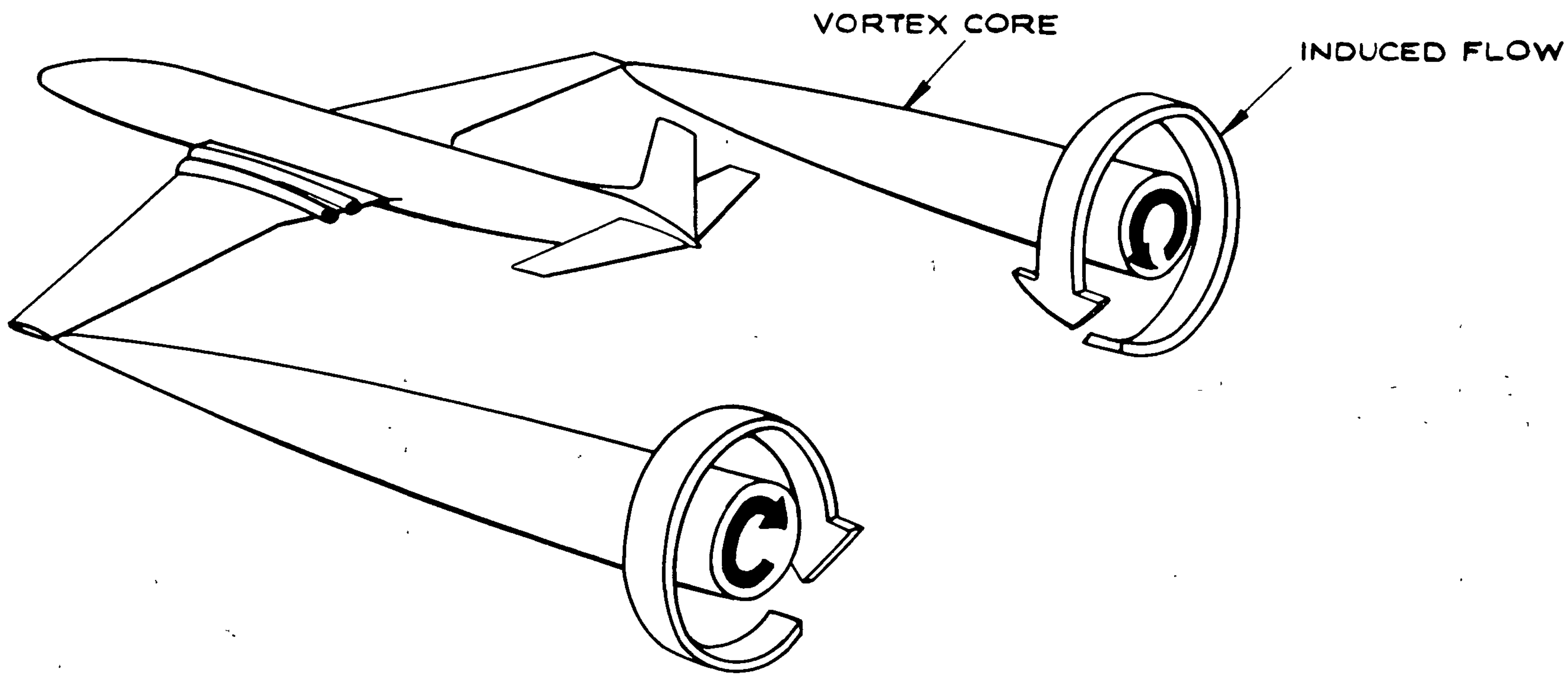


FIG. I. DIAGRAMMATIC ILLUSTRATION OF TRAILING VORTICES

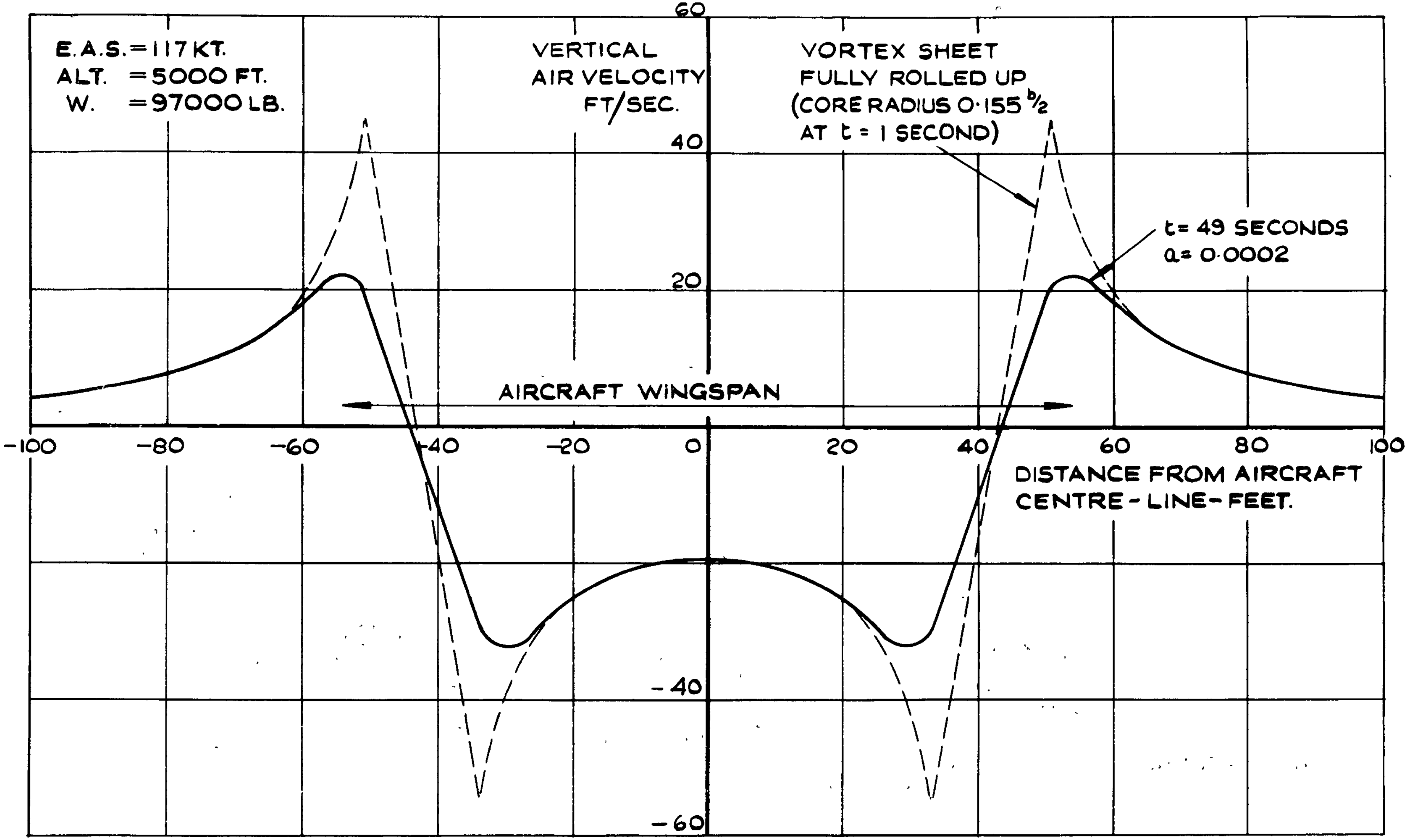


FIG. 2. THEORETICAL VERTICAL VELOCITY INDUCED BY WING-TIP VORTICES SHED BY COMET 3 B AIRCRAFT.

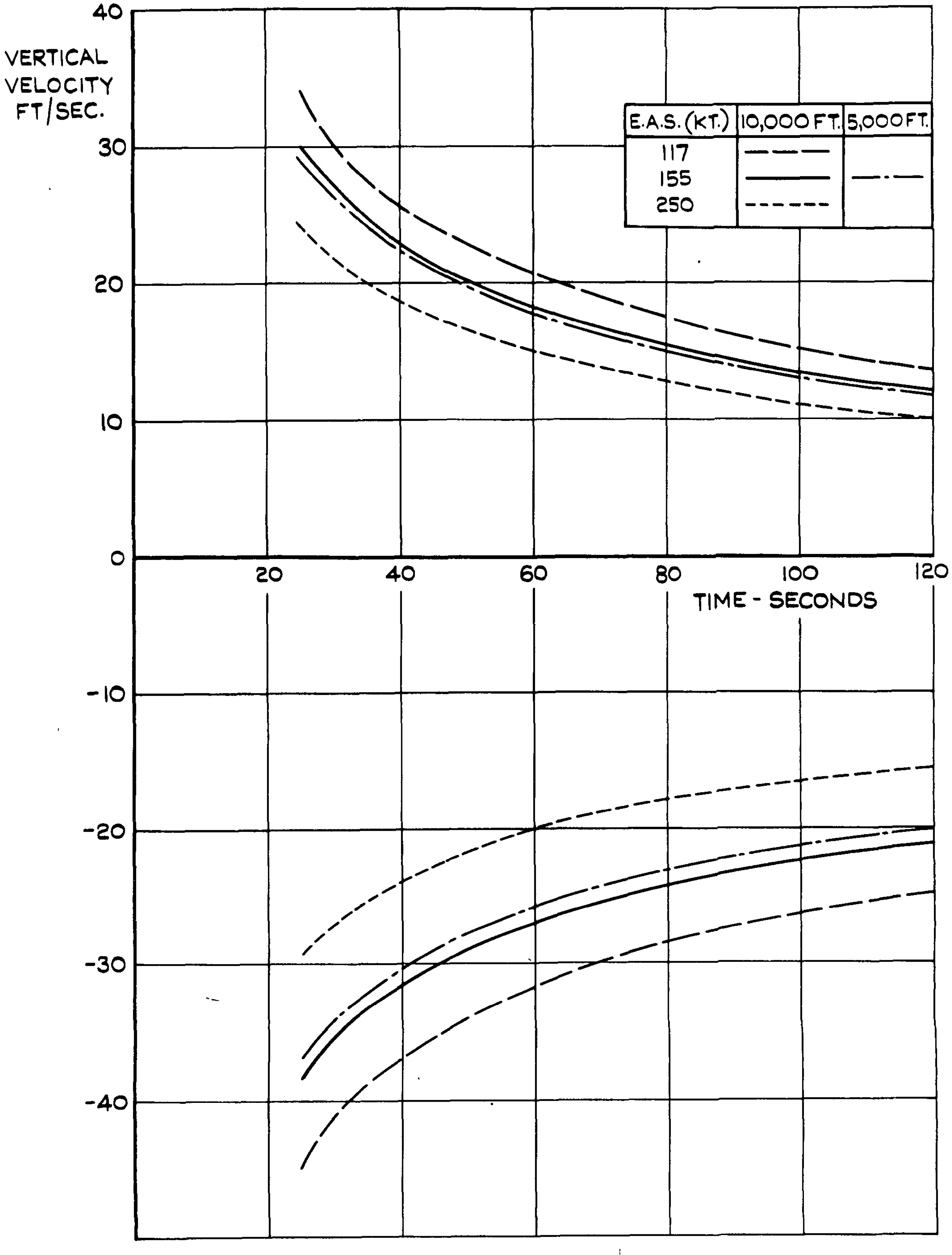


FIG. 3. THEORETICAL DECAY WITH TIME OF THE POSITIVE AND NEGATIVE PEAK VERTICAL VELOCITIES IN THE WAKE OF A COMET 3B AIRCRAFT.

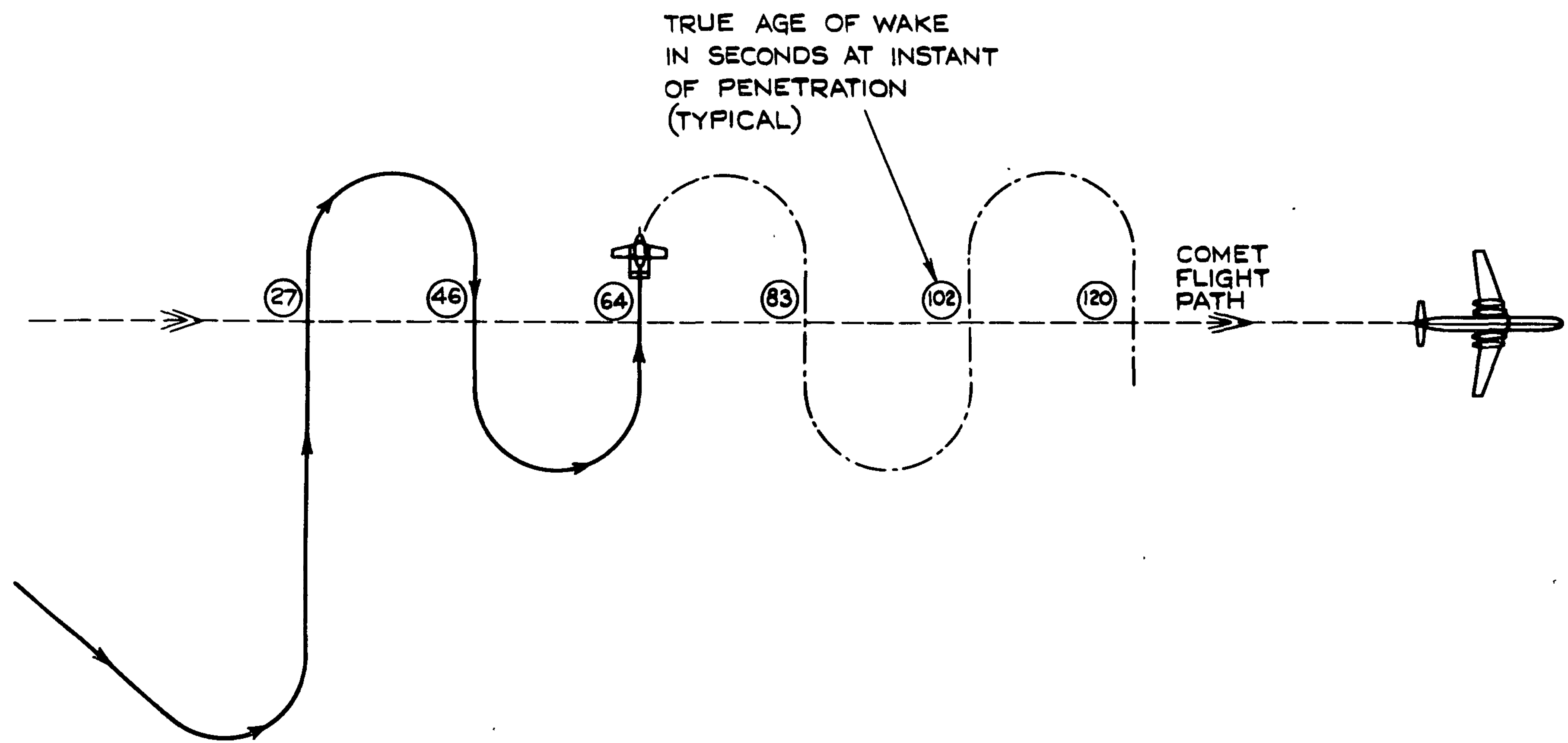
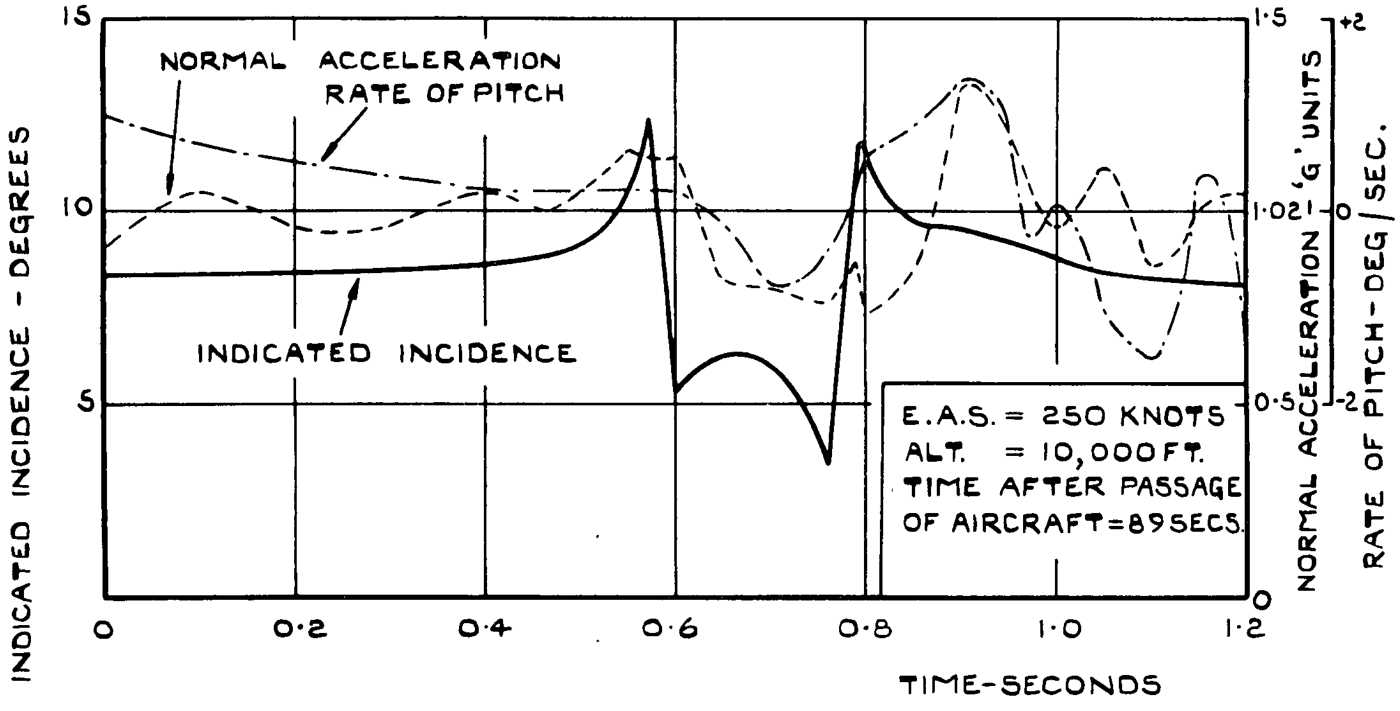


FIG. 4. DIAGRAMMATIC SKETCH OF WAKE PENETRATION TECHNIQUE. (NOT TO SCALE)



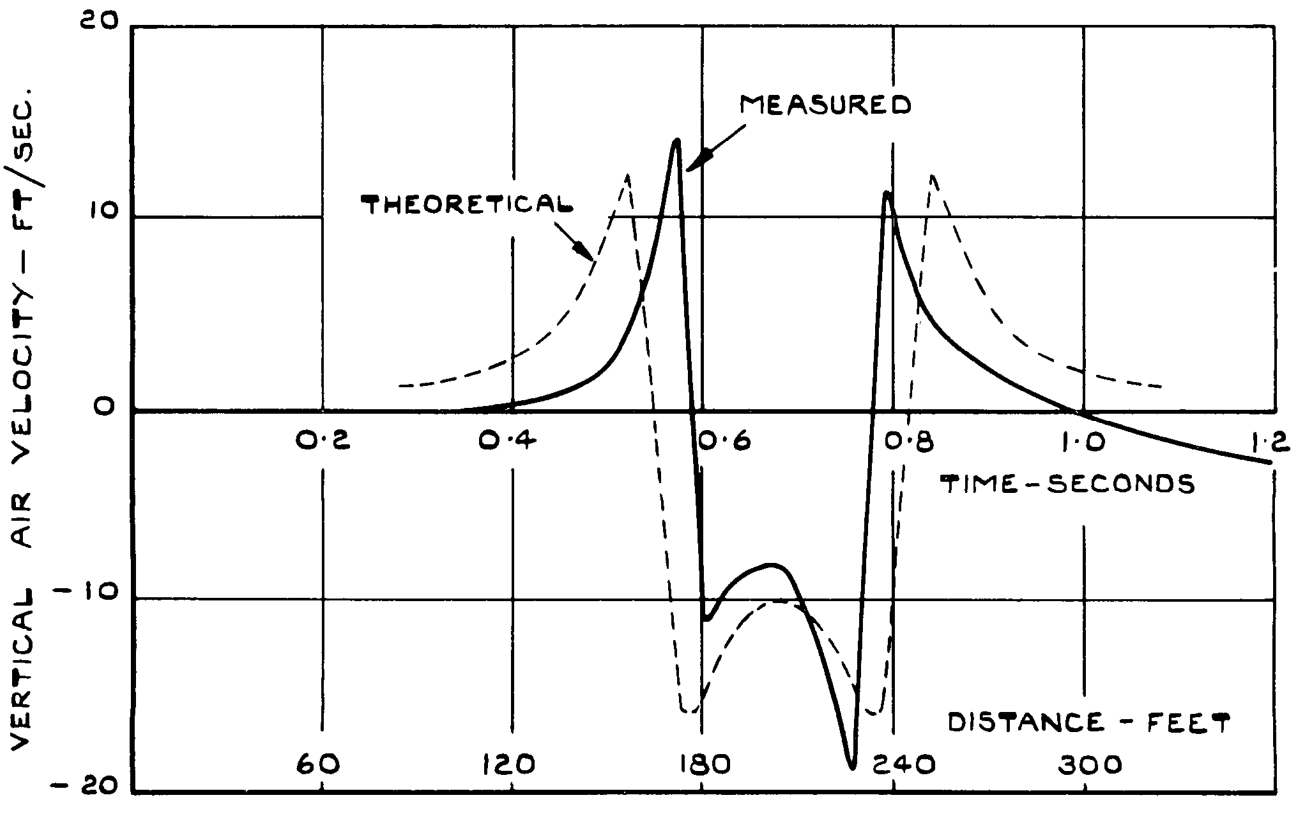


FIG.5. INDICATED INCIDENCE, NORMAL ACCELERATION, RATE OF PITCH, AND COMPUTED VORTEX-INDUCED VERTICAL AIR VELOCITY, RECORDED DURING THE TRAVERSE OF A COMET 3B WAKE.

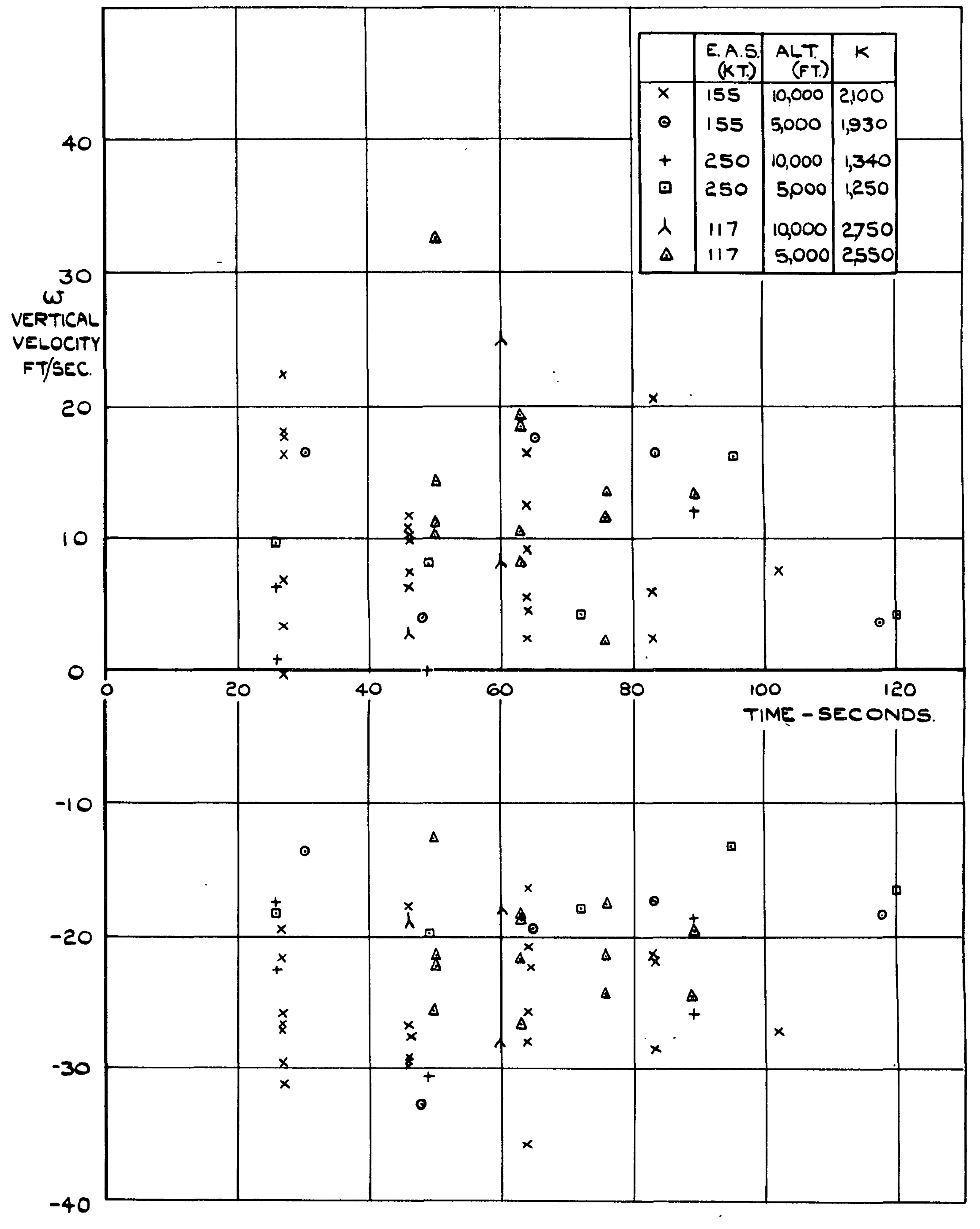


FIG. 6. POSITIVE AND NEGATIVE PEAK VERTICAL VELOCITIES DEDUCED FROM WIND VANE. COMET 3B.

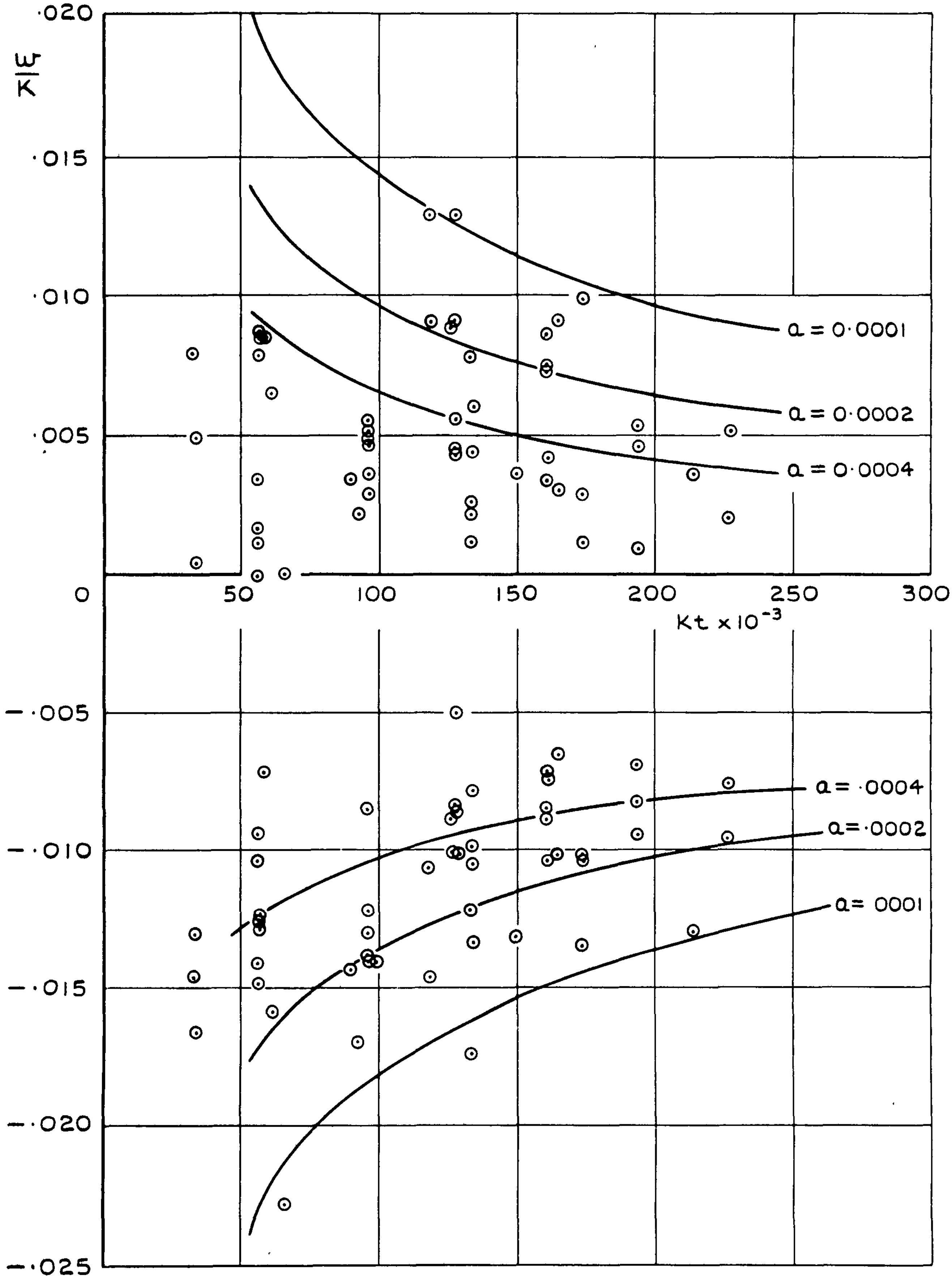


FIG. 7 (a) VARIATION OF POSITIVE AND NEGATIVE PEAK VALUES OF $\frac{\varpi}{K}$ WITH Kt.

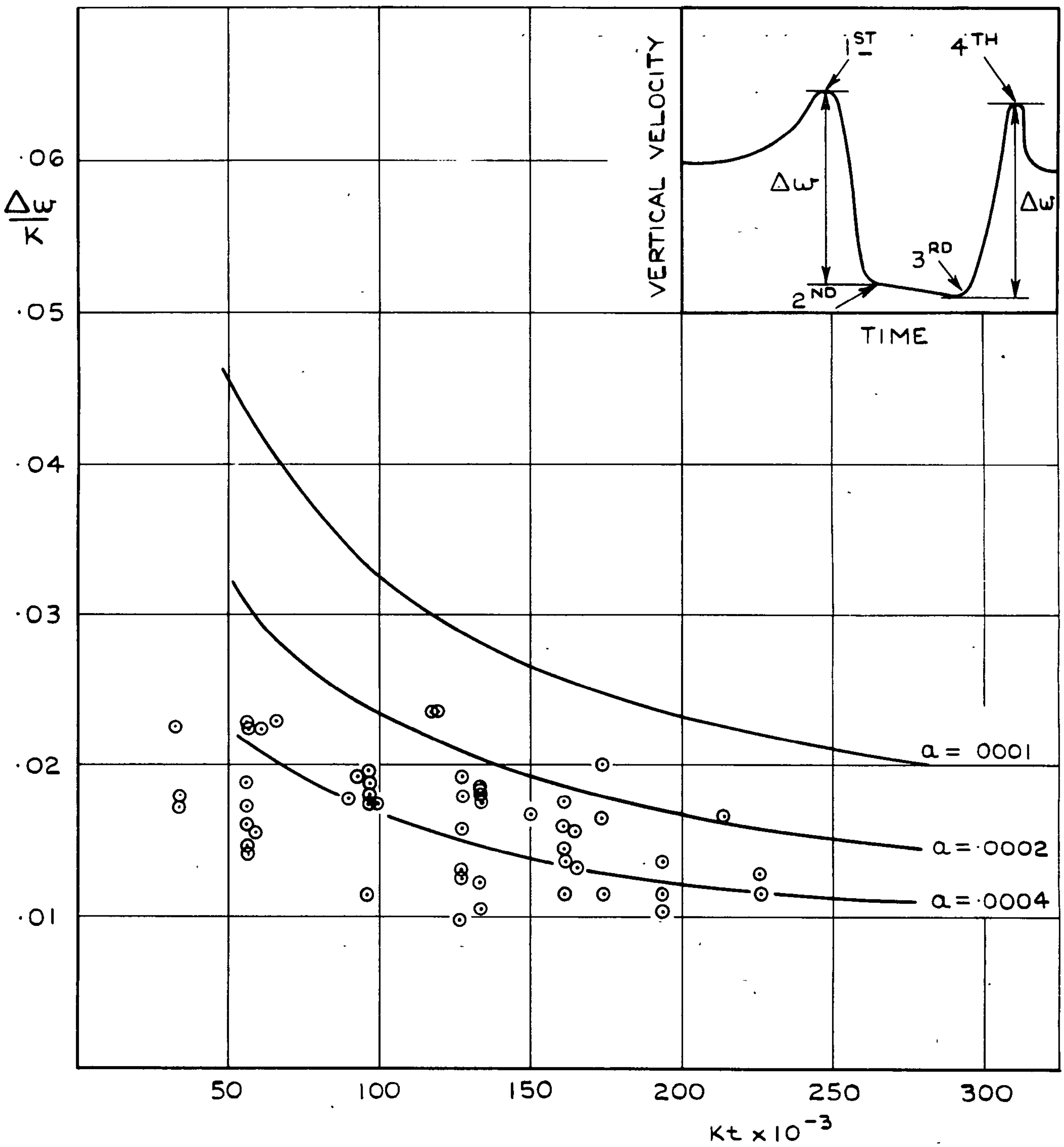
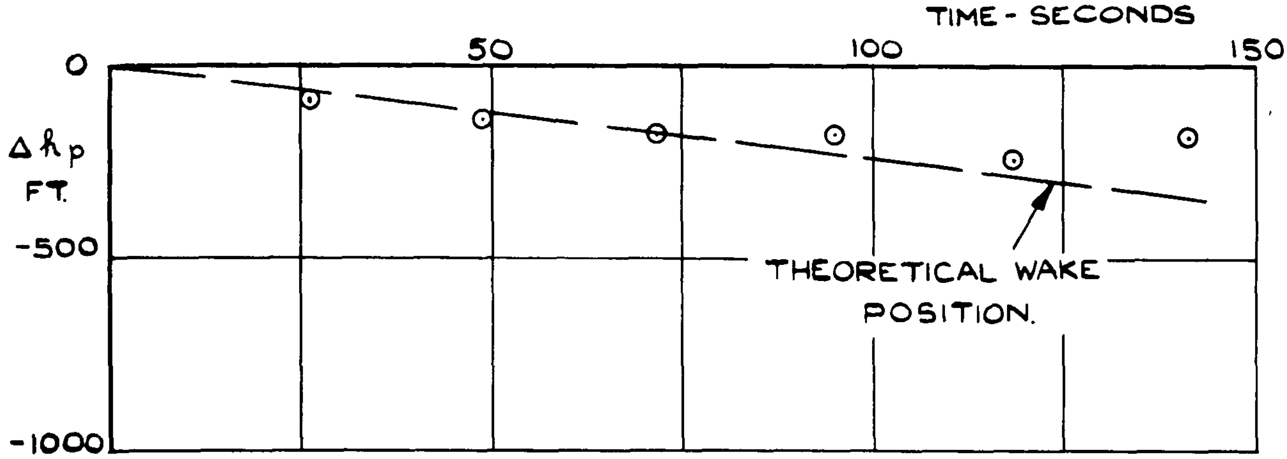
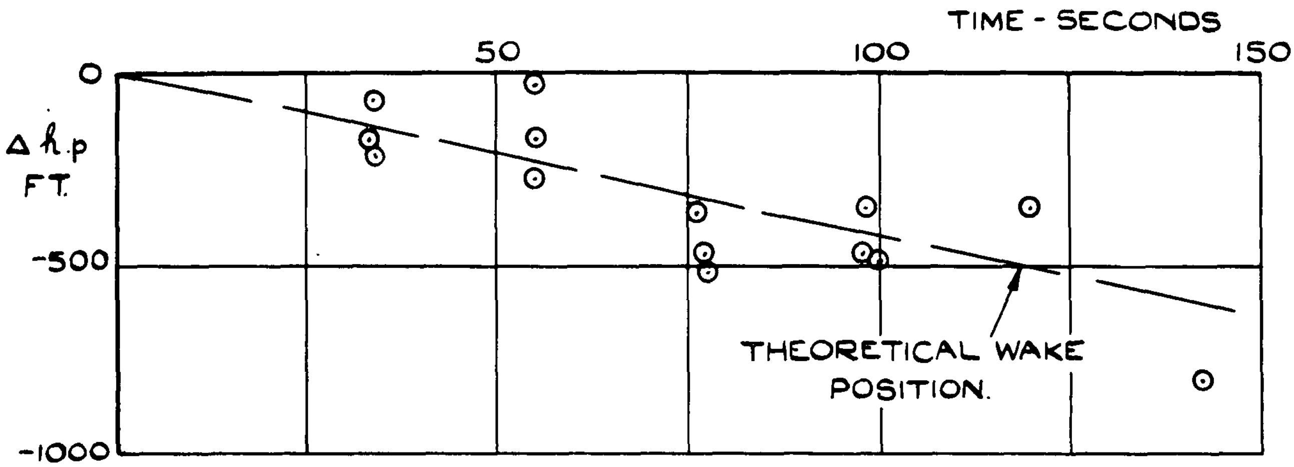


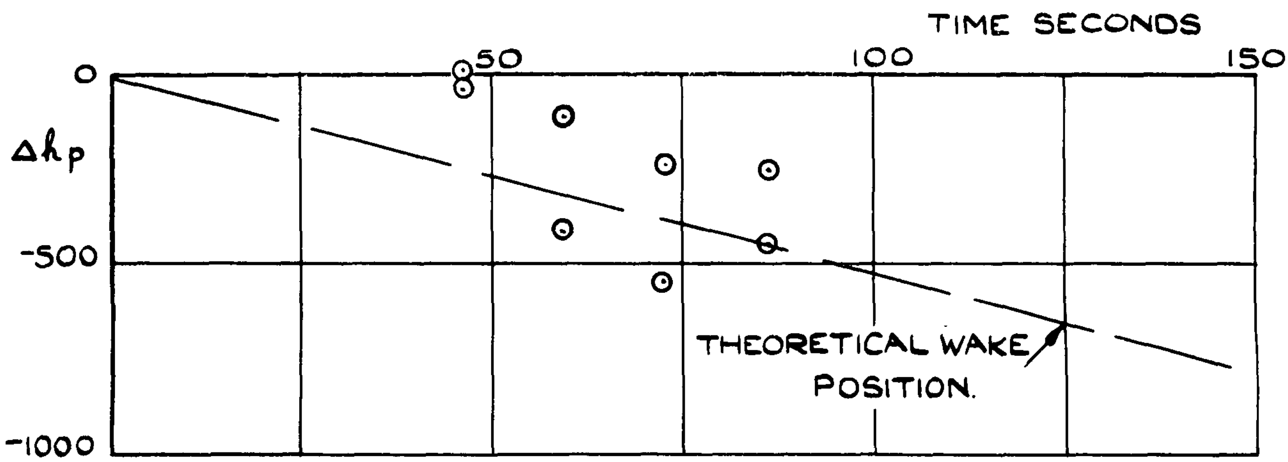
FIG. 7.(b) VARIATION OF $\frac{\Delta w}{K}$ WITH Kt.



COMET 3B AT 250 KT. E.A.S., 5,000 FEET. K=1250.



VULCAN AT 200 KT. E.A.S., 10,000 FEET. K=2040.



COMET 3B AT 115 KT. E.A.S., 10,000 FEET. K=2750.

FIG.8. COMPARISON OF MEASURED AND THEORETICAL WAKE POSITIONS RELATIVE TO THE FLIGHT PATH OF THE GENERATING AIRCRAFT.

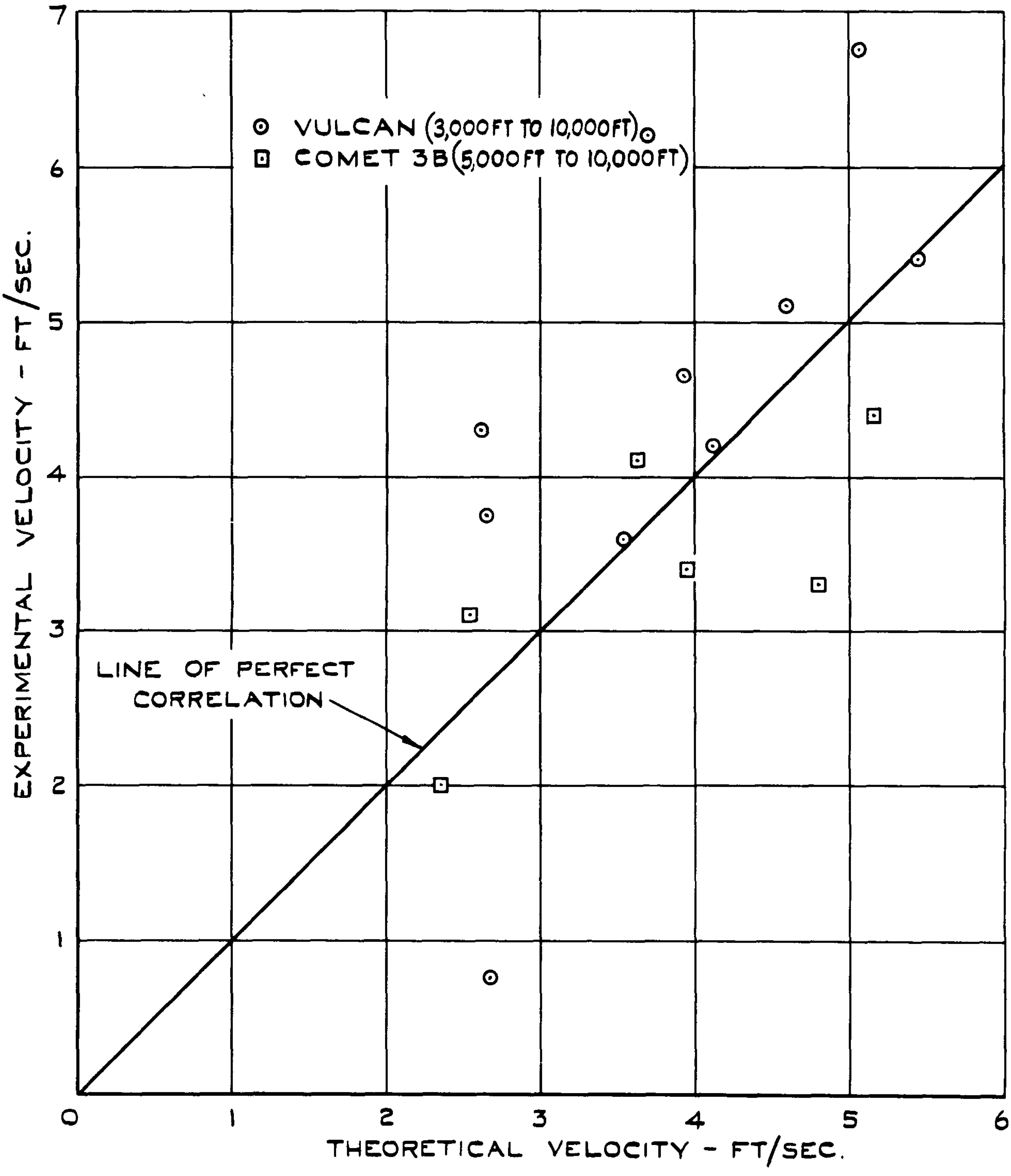


FIG. 9. COMPARISON OF THEORETICAL AND EXPERIMENTAL VALUES OF THE DOWNWARDS VELOCITY OF THE VORTEX WAKE.

ALT. (FEET) \ Vi (KT)	250	155	117
10,000	+	×	⅄
	K=1350	2100	2750
5,000	⊡	⊙	Δ
	K=1250	1900	2550

$$K = \text{CIRCULATION} = \frac{4W}{\rho V \pi b}$$

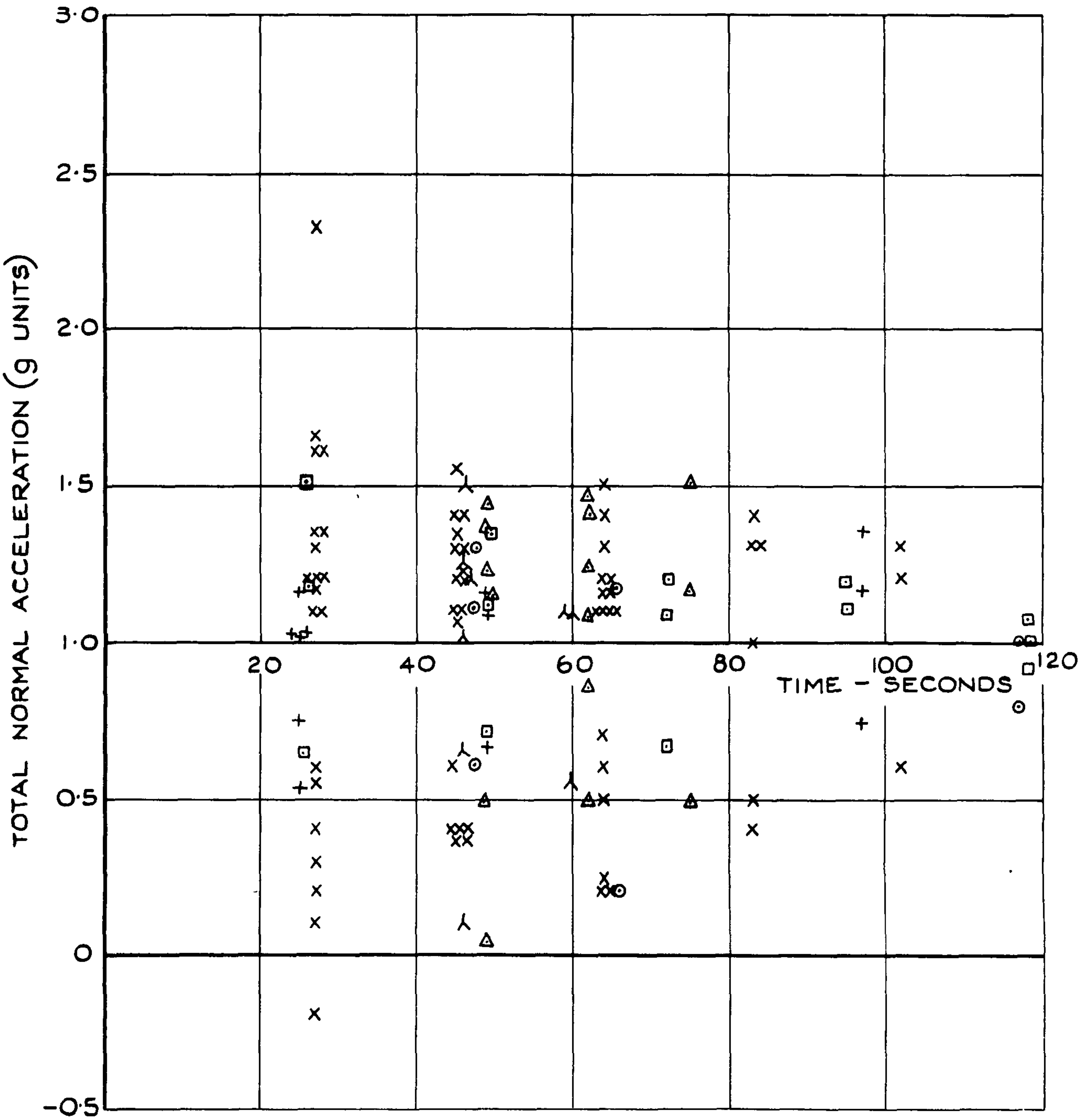


FIG. 10. MAXIMUM AND MINIMUM NORMAL ACCELERATIONS MEASURED DURING FLIGHT THROUGH COMET 3B WAKE

$K = \text{CIRCULATION} = \dfrac{4W}{\rho V \pi b}$

ALT (FEET) \ V_i (KT)	300	225	200	175	155
10,000	⊙	×	+	⊡	△
	K=1380	1840	2140	2400	2810
5,000	Y		◇		⅄
	K=1390		2020		2710
3,000	<		∨		▽
	K=1310		1870		2480

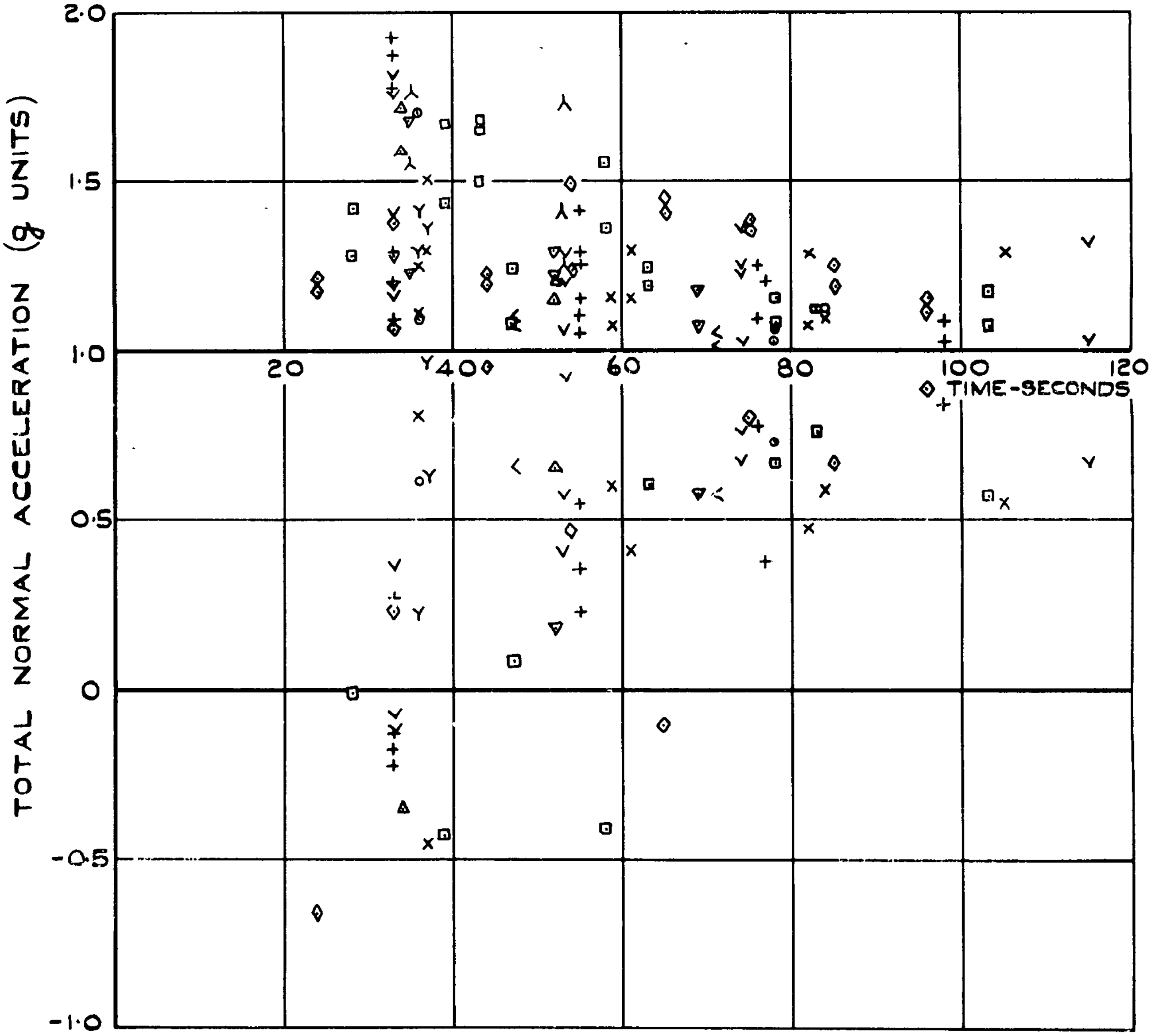
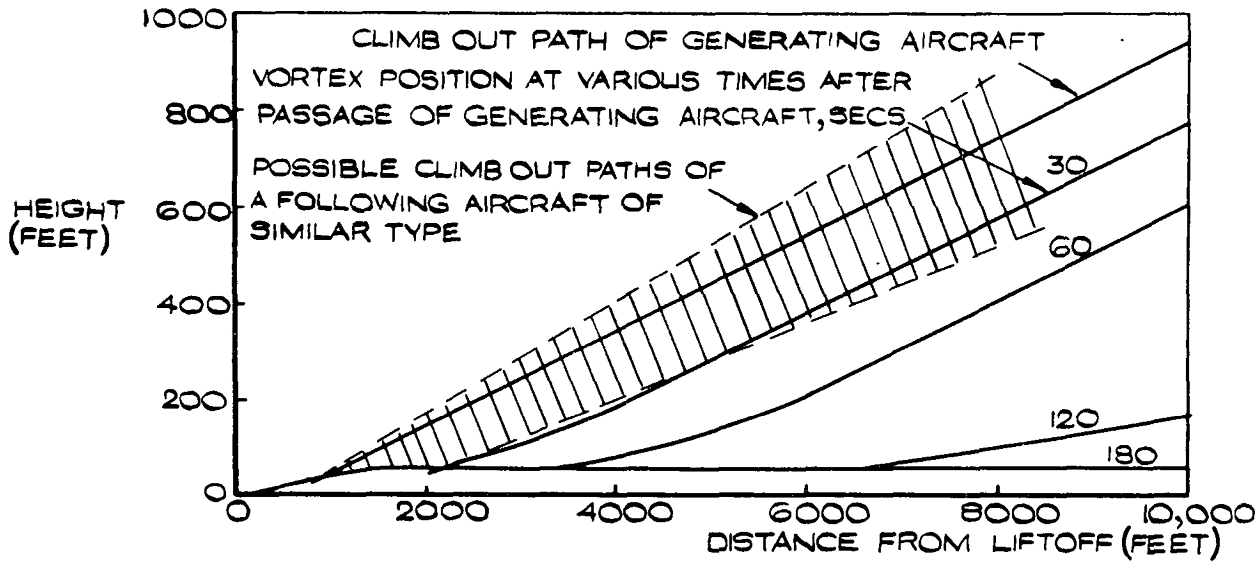
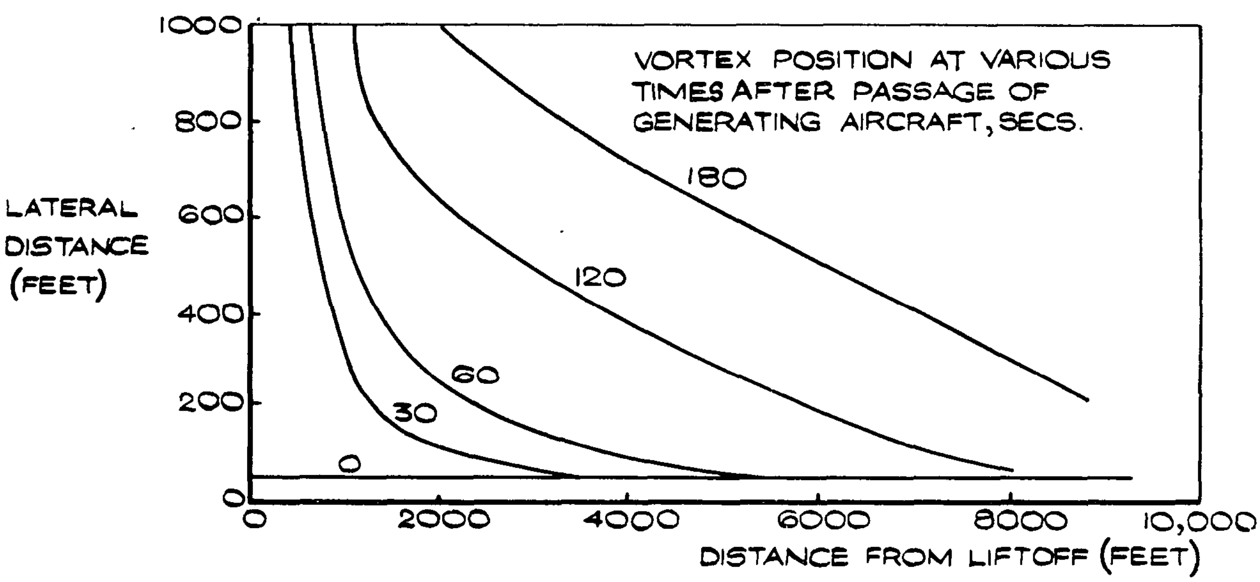


FIG. 11. MAXIMUM AND MINIMUM NORMAL ACCELERATIONS MEASURED DURING FLIGHT THROUGH VULCAN WAKE.



(a) VORTEX POSITION IN THE VERTICAL PLANE



(b) VORTEX POSITION IN THE HORIZONTAL PLANE

FIG.12. CALCULATED POSITIONS OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING TAKE-OFF, IN RELATION TO POSSIBLE TAKE-OFF PATHS OF FOLLOWING TRAFFIC. NO WIND.

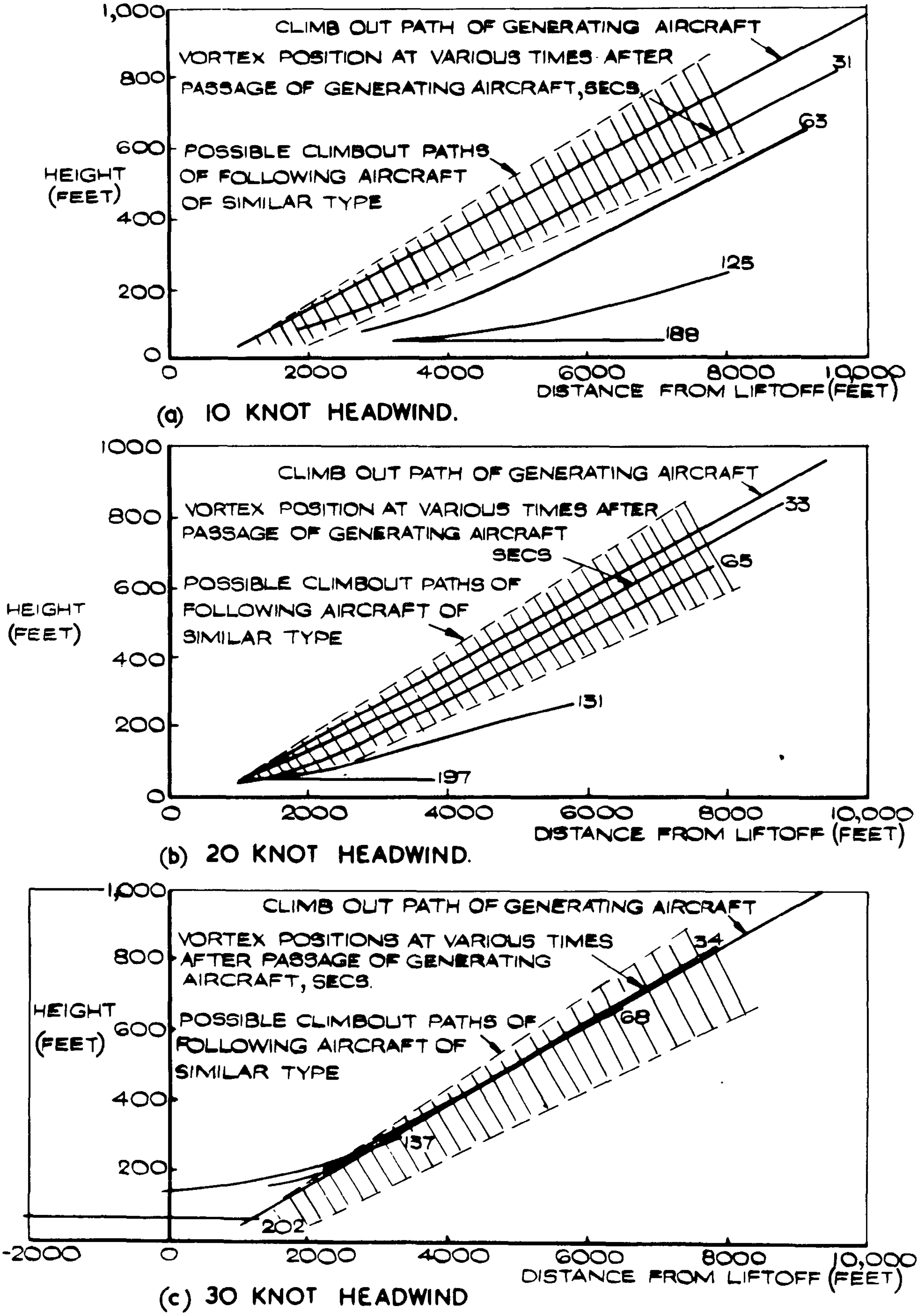


FIG. 13. EFFECT OF HEADWIND ON CALCULATED POSITIONS IN THE VERTICAL PLANE OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING TAKE-OFF, IN RELATION TO POSSIBLE TAKE-OFF PATHS OF FOLLOWING TRAFFIC.

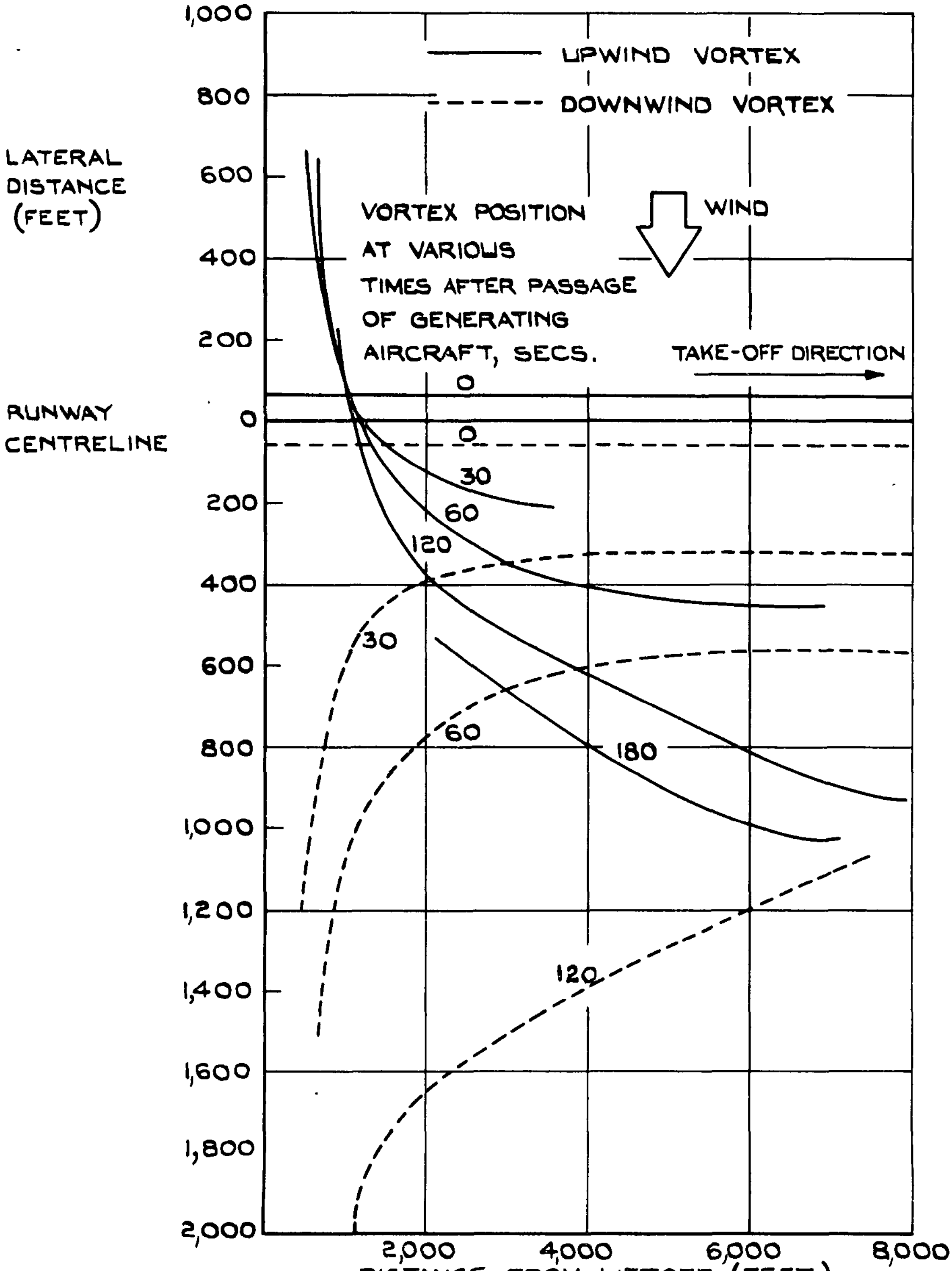


FIG.14. EFFECT OF 5 KNOT CROSSWIND ON CALCULATED POSITIONS IN THE HORIZONTAL PLANE OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING TAKE-OFF

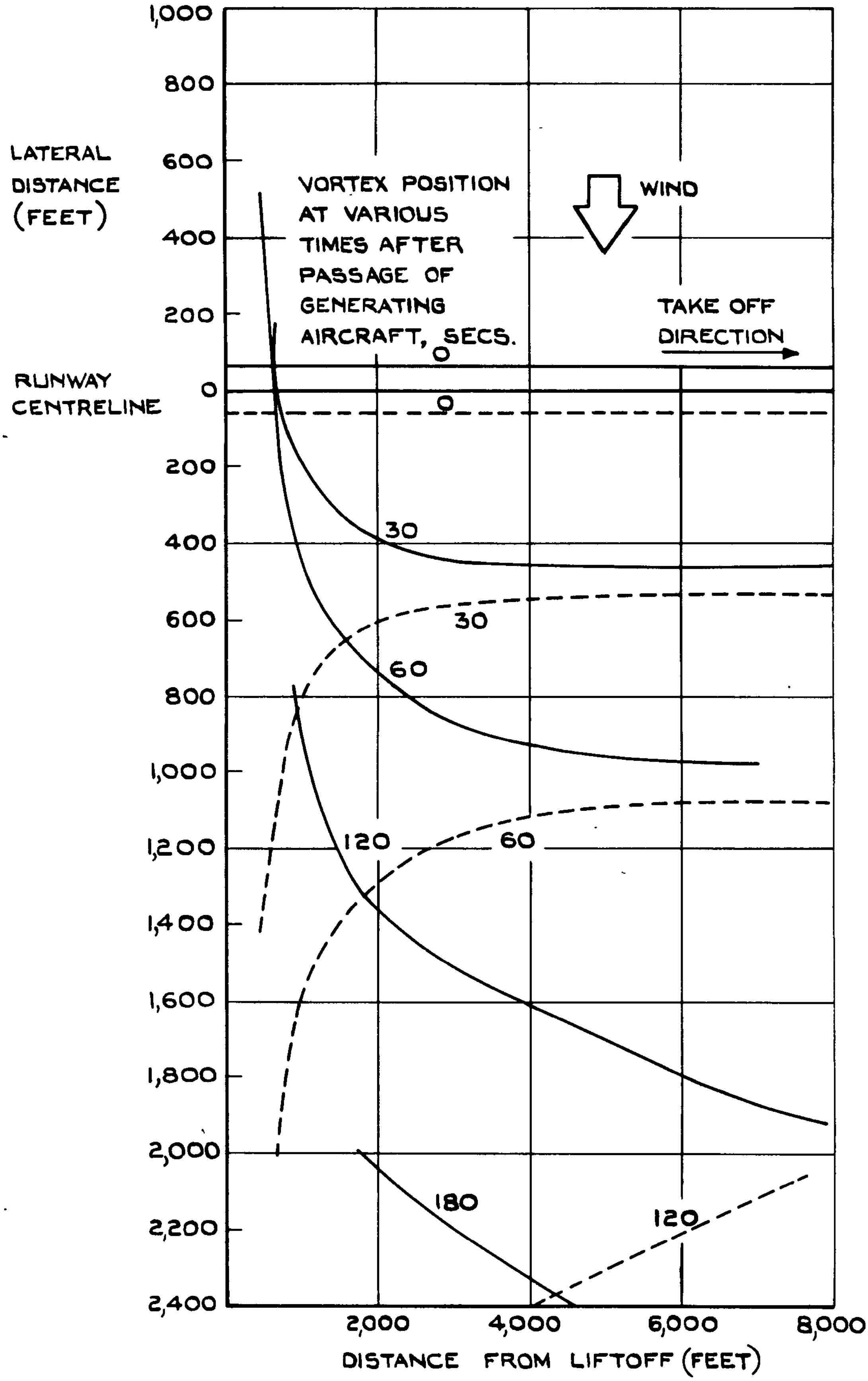


FIG.15. EFFECT OF 10 KNOT CROSSWIND ON CALCULATED POSITIONS IN THE HORIZONTAL PLANE OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING TAKE-OFF

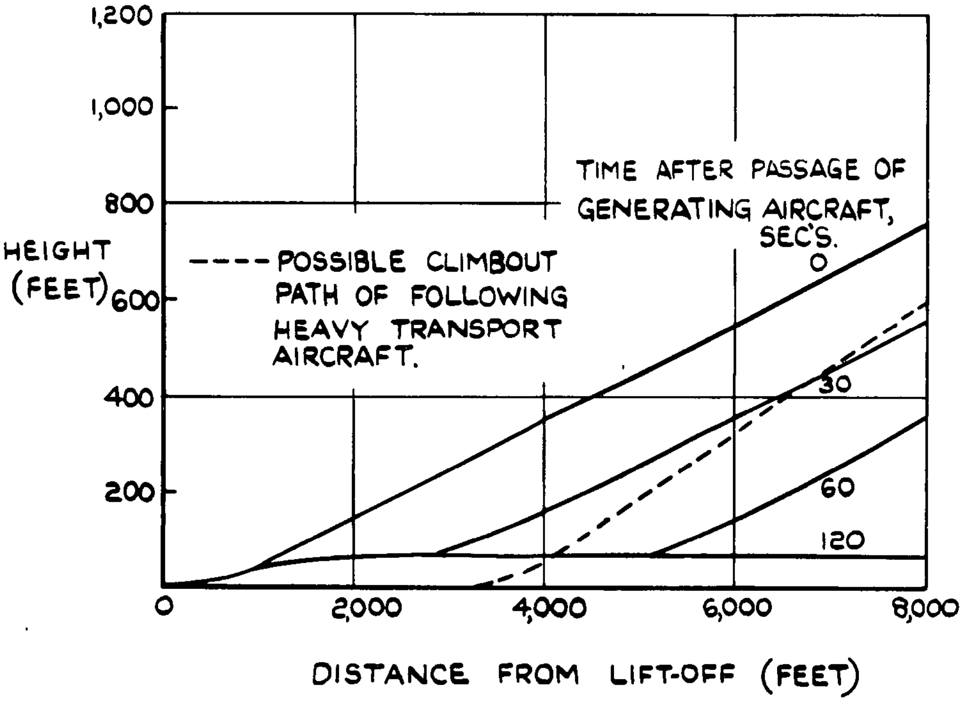
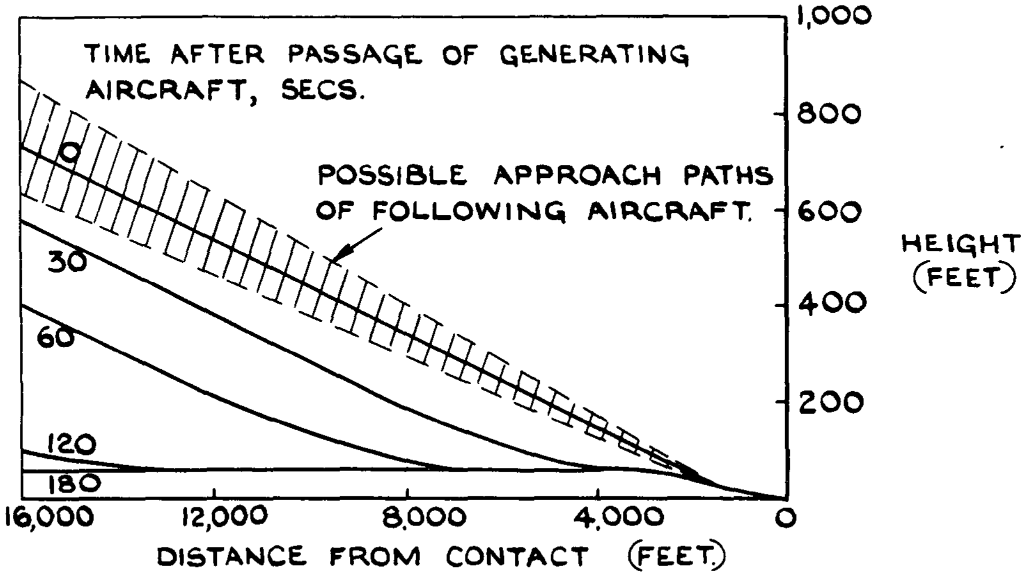
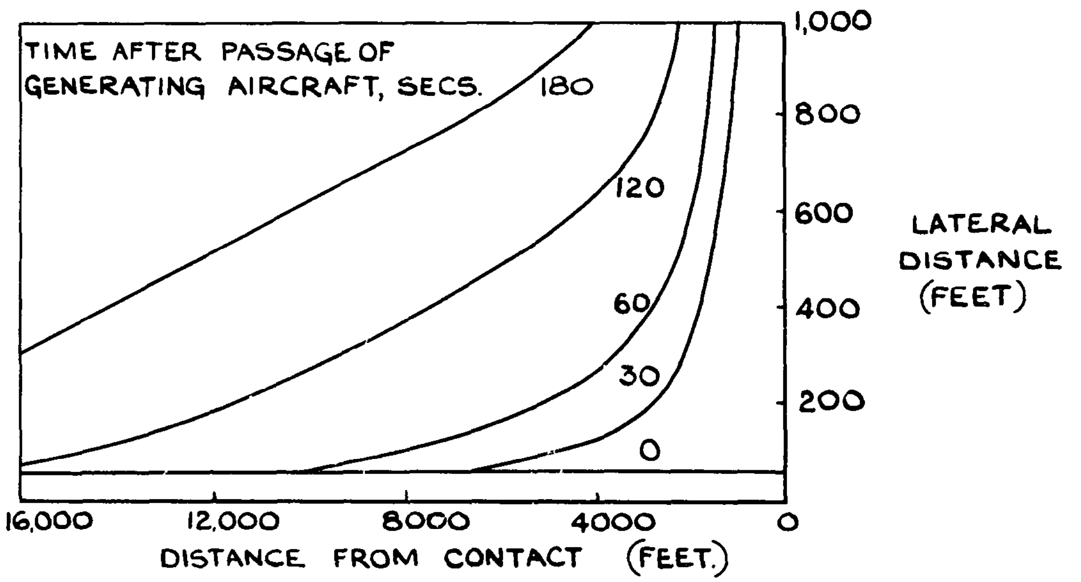


FIG. 16. CALCULATED POSITIONS IN VERTICAL PLANE OF VORTICES SHED FROM A 150,000 lb TRANSPORT AIRCRAFT DURING TAKE-OFF, IN RELATION TO POSSIBLE TAKE-OFF PATH OF FOLLOWING TRAFFIC.

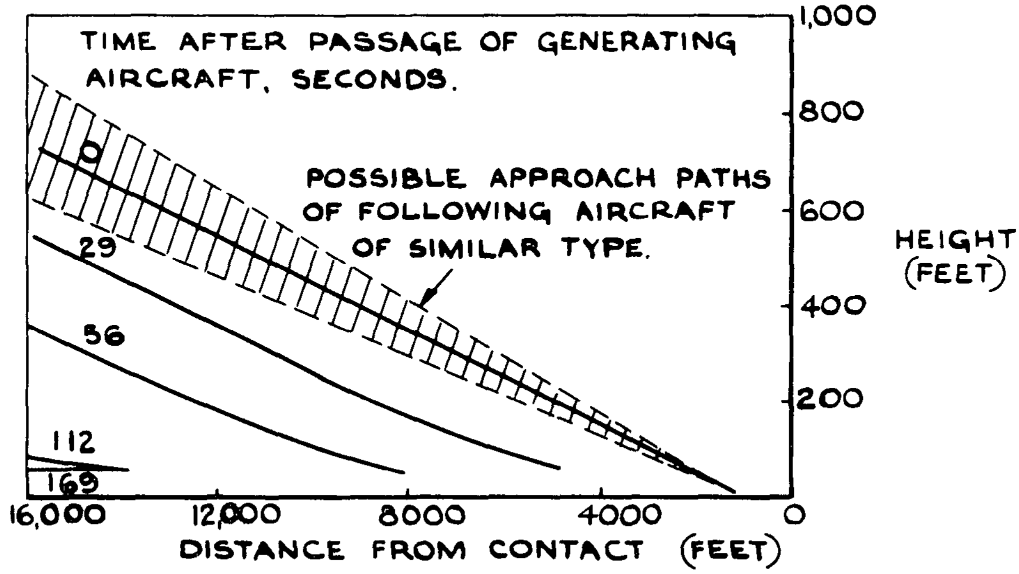


(a) VORTEX POSITION IN VERTICAL PLANE

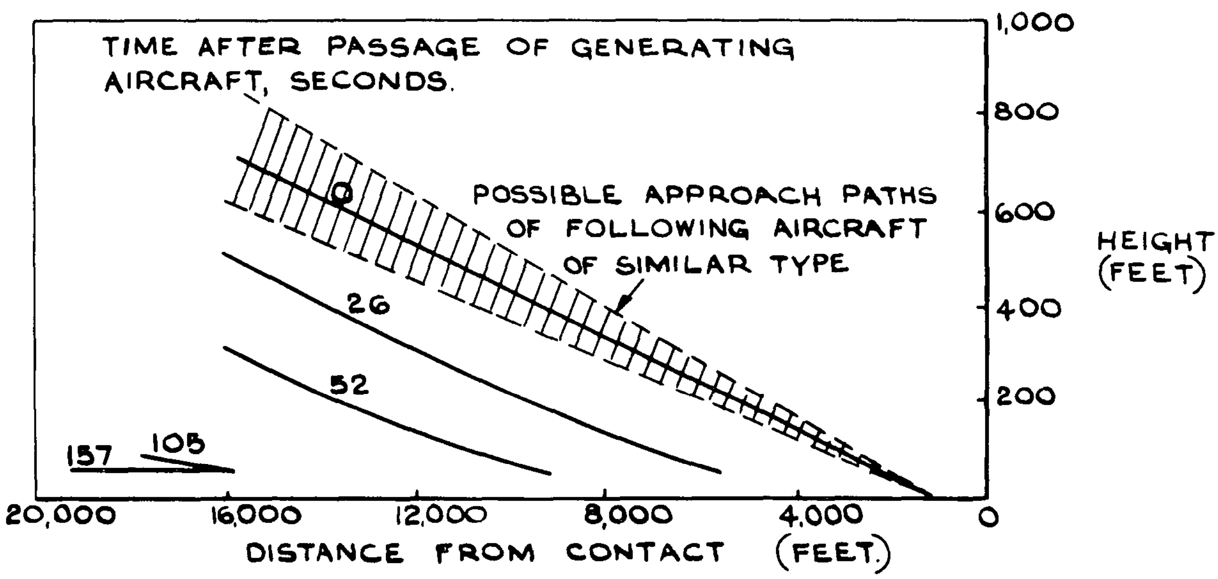


(b) VORTEX POSITION IN HORIZONTAL PLANE

FIG.17. CALCULATED POSITIONS OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING APPROACH, IN RELATION TO POSSIBLE APPROACH PATHS OF FOLLOWING TRAFFIC. NO WIND.



(a) 10-KNOT HEAD WIND



(b) 20-KNOT HEAD WIND

FIG.18. EFFECT OF HEADWIND ON CALCULATED POSITIONS IN THE VERTICAL PLANE OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING APPROACH, IN RELATION TO POSSIBLE APPROACH PATHS OF FOLLOWING TRAFFIC.

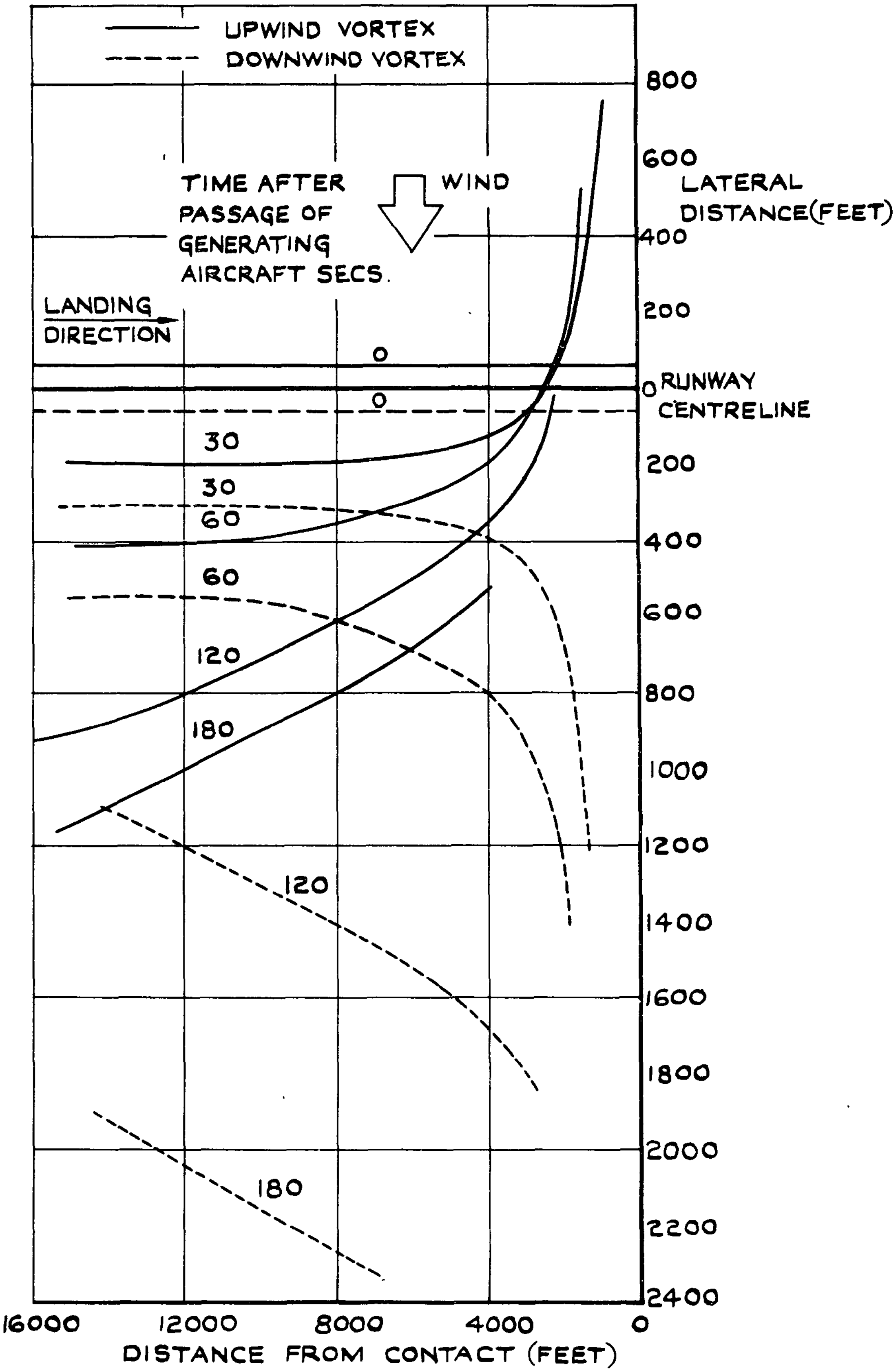


FIG.19. EFFECT OF 5 KNOT CROSSWIND ON CALCULATED POSITIONS IN THE HORIZONTAL PLANE OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING APPROACH.

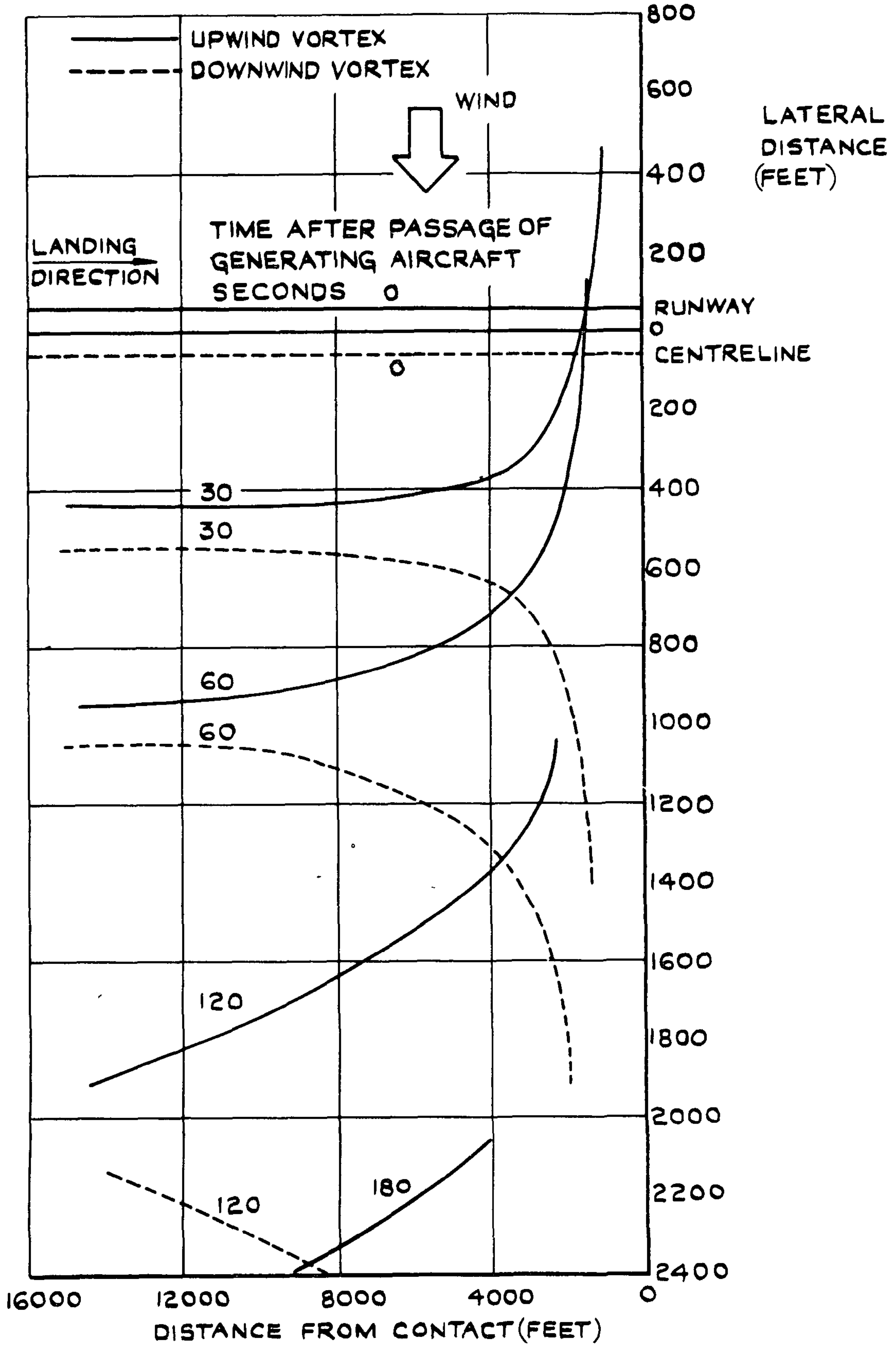
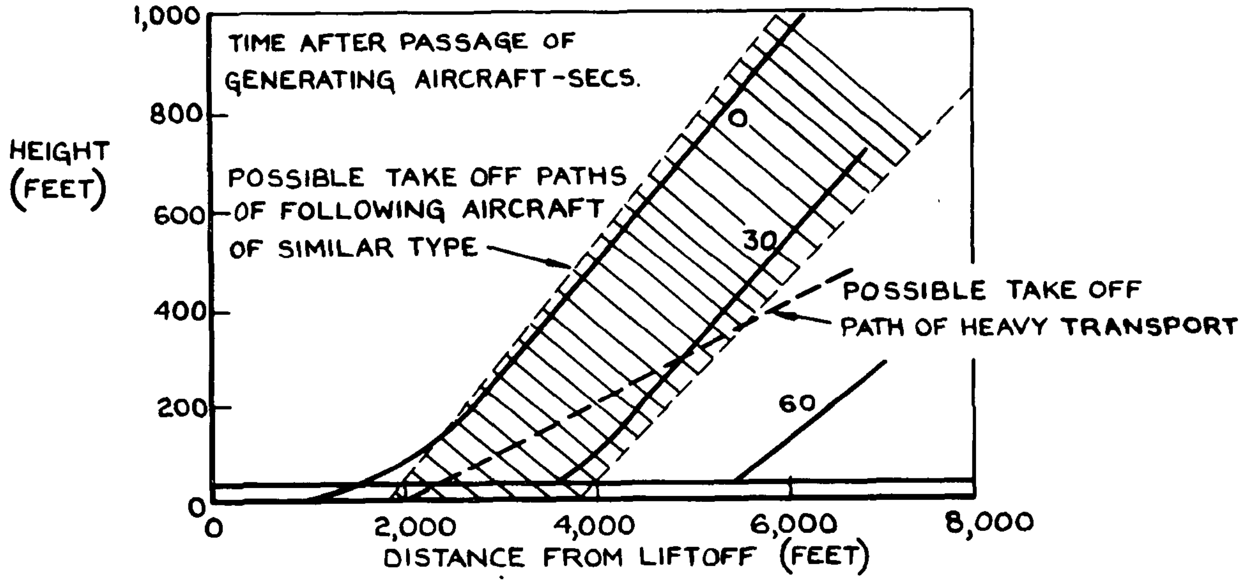
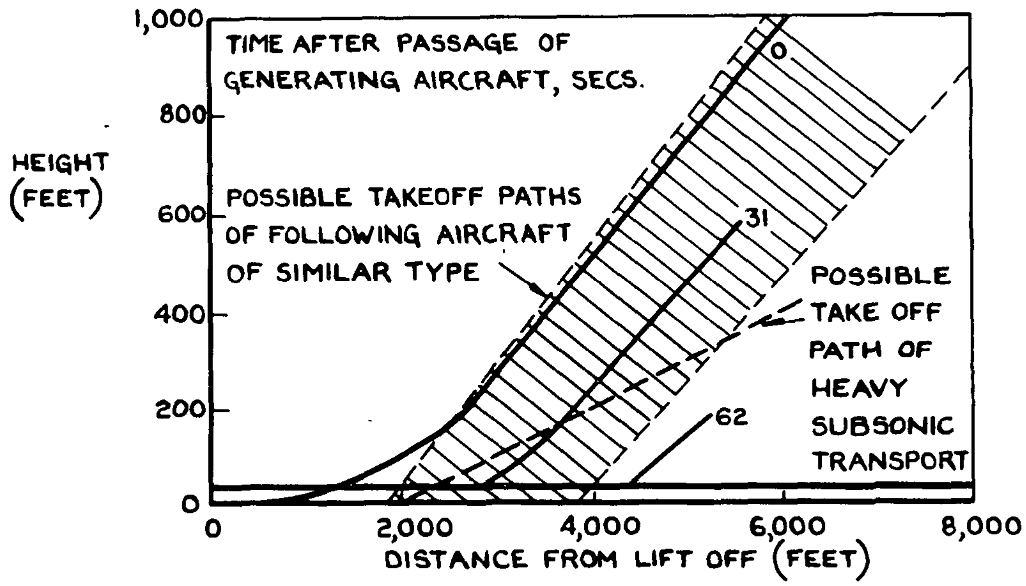


FIG. 20. EFFECT OF 10 KNOT CROSSWIND ON CALCULATED POSITIONS IN THE HORIZONTAL PLANE OF VORTICES SHED FROM A HEAVY TRANSPORT AIRCRAFT DURING APPROACH.

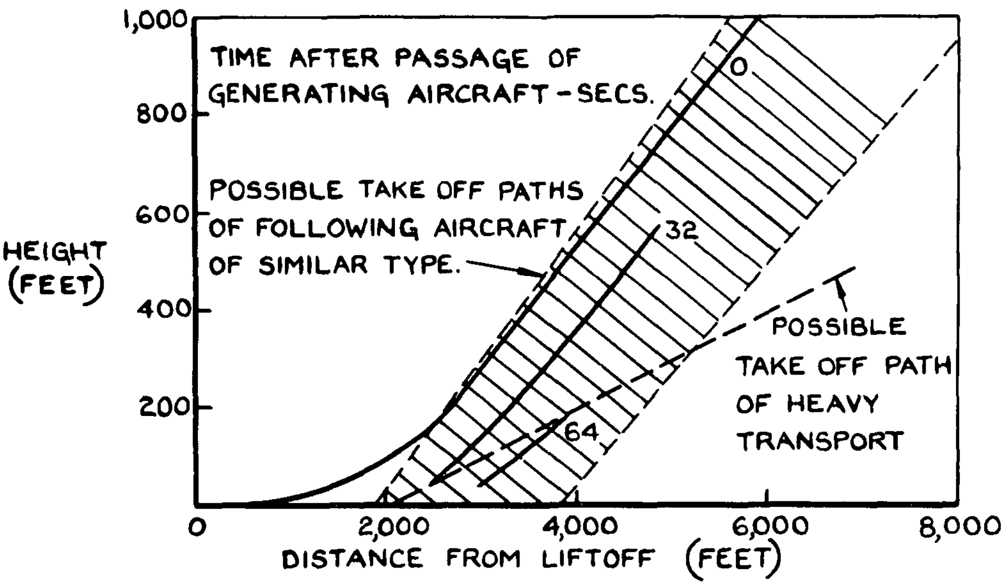


(a) NO WIND

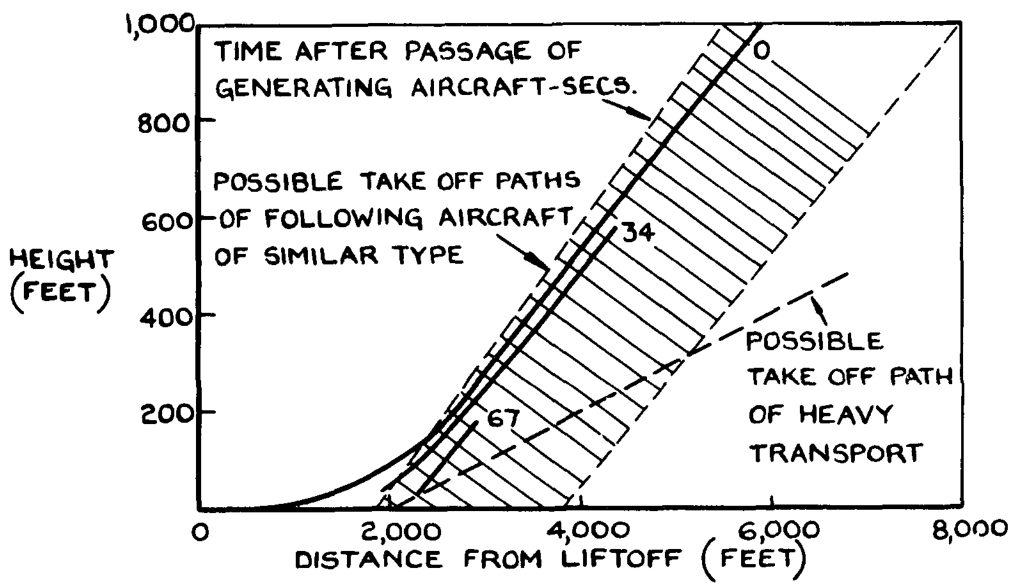


(b) 10 KNOT HEADWIND

FIG.21. CALCULATED POSITIONS OF VORTICES SHED FROM A SUPERSONIC TRANSPORT AIRCRAFT DURING TAKEOFF AND THEIR POSITION IN RELATION TO POSSIBLE TAKEOFF PATHS OF FOLLOWING TRAFFIC.



(C) 20-KNOT HEADWIND



(d) 30-KNOT HEADWIND

FIG. 21 (CONCLD.) CALCULATED POSITION OF VORTICES SHED FROM A SUPERSONIC TRANSPORT AIRCRAFT DURING TAKE OFF AND THEIR POSITION IN RELATION TO POSSIBLE TAKE OFF PATHS OF FOLLOWING TRAFFIC.

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A.R.C. C.P. No.795

533.6.048.3:
533.695:
533.6.013.43

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Rose, R. and Dee, F.W. December 1963.

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Further tests to study vortices near the ground, and behind slender wing aircraft, are planned.

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