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Measurements of the Paths of the Vortex Cores Shed from the Wings of a Typical Guided-Missile Model at $M = 1{\cdot}57$

By

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Summary.—The paths of the cores of the vortex sheets shed from the wings of a typical guided-missile model, having cruciform rectangular wings mounted on a long cone-cylinder body, have been traced in their movement downstream over a range of incidence and yaw from 5 to 20 deg and 0 to 20 deg respectively at $M = 1\cdot57$.

The measurements have shown that :

(*a*) the cores of the vortex sheets remain very close to the plane parallel to the free stream containing the line of the mid-chords of the wings from which the vortex sheets are shed

(*b*) the movement of the fully rolled-up cores in this plane can, for practical purposes, be attributed entirely to the flow induced by the other wing

(*c*) estimates of the paths of the vortex cores based on slender-body theory do not agree at all well in the regions investigated owing to the presence of strong shock waves and rapid expansions. Estimates of the paths of the vortex cores based on a semi-empirical analysis have shown reasonable agreement, however, and it is considered that approximations similar to those made in these estimates for this configuration would give reliable values for other configurations in the regions near the wings ; well downstream of this region a slender-body theory analysis would probably be satisfactory

(*d*) slender-body theory gives a reasonable estimate of the spacing of the cores of the fully rolled-up sheets at the zero yaw condition. Estimates of the characteristics of four rear surfaces using this vortex spacing have shown satisfactory agreement with experiment

(*e*) further tests to check these conclusions on a large range of missiles seem desirable.

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1. *Introduction.*—The use of tandem cruciform lifting surfaces mounted on a long cylindrical body is now almost universal in guided missile configuration. This type of configuration is known, however, to have undesirable aerodynamic characteristics at supersonic speeds, in particular under conditions of combined pitch and yaw, and it has been shown in wind-tunnel experiments that most of these undesirable effects are the results of the flow induced by the forward lifting surfaces on those at the rear.

The estimation of the forces and moments developed by the various components of such a configuration under conditions of combined pitch and yaw is extremely difficult, for the interaction of the effects of the horizontal and vertical wings and their associated trailing vortex sheets give rise to an induced flow field of considerable complexity. Although the flow field behind plane wings at incidence has been investigated by several theoretical methods, the only

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*R.A.E. Tech. Note Aero. 2296, received 3rd June, 1955.

method which appears to offer a practical solution to the problem of estimating the flow field behind cruciform wings mounted on a body is based on a distribution of line vortices[2] over the missile and flow field. This method has been used successfully in estimating the forces developed by the rear surfaces of a guided missile having only a pair of wings in line with the rear surfaces; adequate agreement with experiment was obtained by replacing the vortex system shed from the wings with a single horseshoe vortex.

It was expected that a simple extension of this method would also prove adequate for missiles having cruciform lifting surfaces under conditions of combined pitch and yaw if the correct location of the trailing vortices had been established. The tests reported in this note, in which the cores of the trailing vortex sheets shed from the wings of a typical guided-missile configuration were traced in their movement downstream, were undertaken to provide some data for checking the available methods of estimating the trailing vortex locations or, should these prove unsatisfactory, for indicating more satisfactory methods.

The tests were conducted at $M = 1 \cdot 57$ and atmospheric stagnation pressure on a typical guided-missile configuration (Fig. 1) in the No. 8 (10 in. $\times$ 9 in.) Supersonic Tunnel at the Royal Aircraft Establishment. Normal force and pitching-moment measurements had previously been made on this particular model at zero roll angle in the same tunnel and the performance of three rear control surfaces had been determined; the data relevant to these tests have been extracted and are included in this note.

The Reynolds number of the tests was approximately $0 \cdot 42 \times 10^6$ per in.

2. *Test Arrangement and Procedure.*—2.1. *Description of the Model and Test Equipment.*—A drawing of the model is given in Fig. 1 and, as will be seen, it consisted of a cone-cylinder body with a fineness ratio of $13 \cdot 35 : 1$ on which were mounted cruciform rectangular wings of gross aspect ratio $1 \cdot 201$. The wings were of modified double-wedge section and had a thickness/chord ratio of 4 per cent at the wing—body junction tapering linearly to about $0 \cdot 04$ per cent at the wing tips. Control surfaces could be mounted at the rear of the body but these were not used during these tests.

The model was supported on a sting attached to a geared quadrant (Fig. 2), which was driven by a small electric motor controlled from outside the tunnel. By this means the model incidence could be varied from minus 4 deg to plus 25 deg, an indication of the setting being obtained from a desynn transmitter mounted on one of the gear shafts. The whole of this support could also be rotated in the horizontal plane so that the model could be simultaneously yawed through a range of minus 5 deg to plus 20 deg (wind or tunnel axes). The accuracy of the pitch and yaw settings was about plus or minus $0 \cdot 05$ deg. The model support was mounted on the balance-chamber floor so that the model axis at zero incidence coincided with the centre-line of the jet.

For these tests the tunnel was run as an 'open jet' section (Fig. 2).

The traverse gear used for tracing the cores of the trailing vortex sheets shed from the wings of the model is fully described in Ref. 2. Additional fittings at the end of the support tube (Fig. 2) were necessary so as to reach parts of the flow field without fouling between the model, its support and the traverse gear. The pitot-tubes used throughout the tests were of 1 mm hypodermic tubing; it had previously been checked that there was no significant change in the indicated positions of the vortex cores within the accuracy of setting of the probes (estimated as about plus or minus $0 \cdot 007$ in., *see* section 3.1 also) when using $\frac{1}{2}$-mm probes; the change to the larger tubing was made in order to increase the rate of response of the manometer.

2.2. *Description of the Tests.*—The paths of the cores of the trailing vortex sheets shed from the wings of the model at each condition of pitch and yaw were traced by determining the positions of the points of minimum pressure as indicated by the pitot probes at a number of longitudinal stations $0 \cdot 5$ cm apart behind the wings. The cores could not be traced at positions much forward of the trailing edge of the wings due to unavoidable fouling of parts of the traverse gear or probes with the model or its support; nor were they traced further than the base of the body since their paths would thereafter be influenced by the conditions at the base.

The traces of the vortex-sheet cores were obtained in this way under the conditions of incidence and yaw listed below.

Yaw setting (β deg)	Incidences tested (α deg)
0	5, 10, 15, 20
−5	5, 10, 15, 20
10	10, 15, 20
15	15, 20
20	20

Since the model was symmetrical about both lateral axes, it could be assumed that the paths of the vortex cores under conditions of incidence and yaw of β deg and α deg could be obtained from the results at an incidence of α deg and yaw angle of β deg by rotating the respective axes through 90 deg. This assumption has been justified (*see* section 3.2) by the similarity of the paths of the vortex cores shed from each pair of wings under conditions of equal pitch and yaw.

The tests at a yaw angle of $|\, 5$ deg $|$ were made under conditions of negative yaw in order to obtain the path of the core of the vortex sheet shed from the lower vertical wing which would not have been possible under conditions of positive yaw.

3. *Results*.—The results of the measurements are presented in Figs. 3 to 16 in which, for each condition of pitch and yaw, the positions of the cores of the trailing vortex sheets as they move downstream from the wings are shown as viewed from the port side of the missile, and also from above and behind the missile. The results will be considered at each value of yaw angle.

3.1. *Angle of Yaw* = 0 *deg*.—The measured positions of the cores of the vortex sheet shed from the horizontal pair of wings are shown in Figs. 3 to 6 for incidences of 5 deg, 10 deg, 15 deg and 20 deg respectively. No detectable cores were found in the wake of the vertical wings.

It will be seen that at 5 deg incidence (Fig. 3) the vortex cores lie just inboard and slightly above the wing tips near the trailing edge of the wings. The cores come further inboard as they move downstream indicating that rolling-up of the vortex sheet is taking place and more vorticity is being drawn into the core ; the vertical location of the cores with respect to a system of wind or tunnel axes remains virtually unchanged however.

As the incidence is increased, the vortex cores move progressively inboard at all stations indicating a more rapid rolling-up of the vortex sheet but remain at an approximately constant vertical position at each incidence. It is noted that at all stations and incidences the vertical location of the cores is given closely by the plane parallel to the free stream containing the line of the mid-chords of the wing.

Near the wing and at low incidences the pressure at the centre of the cores was of the order of 10 in. Hg. Abs.; the gradients were steep so that the position of maximum depression could be easily determined and it is estimated that the accuracy of location of the vortex cores was about 1/100 inch. At stations further downstream the minimum pressure in the core increased, to about 13 in. Hg. Abs. at the base of the body station, and the pressure gradients became less steep indicating the diffusion of the vorticity by viscous effects. At any given streamwise station the minimum pressure became even lower with increasing incidence although the cores were of greater extent ; for example, at 20 deg incidence the minimum pressure in the core near the wing was only 2 in. Hg. Abs. However, owing to the increased size of the cores and the consequent flattening of the pressure profile, it was not possible to define the point of maximum depression with the former accuracy and for the more rearward stations the accuracy of location was probably not greater than 1/20 inch.

3.2. *Angle of Yaw* = 5 *deg*.—To deal first with the core of the vortex sheet shed from the horizontal wings : the effect of yawing the missile through 5 deg on these is mainly to displace their position with respect to the missile towards the leeward side of the body (*see* Figs. 7 to 10). At low incidences there appears to be little change in the distance between the vortex cores but at higher incidences there is a significant increase in their distance apart. The vertical location of the cores is sensibly unaltered at all stations at low incidences (Fig. 7) but at higher incidences and for stations close to the wings (Figs. 9 and 10) there is a tendency for the core from the starboard wing of the missile to be higher than that from the port wing. However, at the more rearward positions near the base of the body their positions are again approximately the same as in the unyawed condition.

For the symmetrical condition of 5 deg incidence and 5 deg yaw it will be seen from Fig. 7 that the behaviour of the cores of the vortex sheet shed from the vertical wings is more or less identical with that of those from the horizontal wings. At higher incidences these cores are displaced more and more in an upward direction with respect to the missile (Figs. 8 to 10) with only a slight change in their distance apart. The core of the vortex sheet shed from the top vertical wing also tends to move towards the port side of the missile and conversely for the core from the bottom wing.

It is again noted that the cores of the vortex sheet still remain at nearly all stations close to the planes parallel to the free stream through the line of the mid-chords of their associated wings.

3.3. *Results at Higher Angles of Yaw.*—It will be seen from Figs. 11 to 16 that the trends noted in the results at 5 deg yaw are continued at the higher yaw angles for stations close to the wing, namely, the displacement of the vortex cores associated with the horizontal wings towards the leeward side of the missile, while retaining a more or less constant vertical location as they move downstream, together with a slight increase in their distance apart. The behaviour of the vortex cores associated with the vertical wings under conditions of pitch and yaw can be inferred directly from the movements of those associated with the horizontal wings by consideration of the symmetry of the missile.

However it will be noted that, at the higher values of pitch and yaw, the paths of the vortex cores undergo rapid changes of direction, suggesting the presence of strong shock waves, rapid expansions and the essentially supersonic nature of the flow in which they are moving. This would indicate that an analysis of their movement by theories such as slender-body theory*[3,4], in which the effects of compressibility are excluded, is unlikely to give realistic answers. This will be discussed in greater detail in the next section.

4. *Estimates and their Comparison with Experiment.*—4.1. *'Normal Force Efficiency' of Rear Controls.*—Before attempting to estimate the positions of the vortex cores at any station, it is of primary interest to determine to what extent the measured locations of the vortex cores will be of use in estimating the characteristics of any rear surfaces. In order to investigate this, estimates have been made of the 'control normal force efficiency'** of the four rear control

*It is realised that slender-body theory is not strictly applicable to this configuration or incidences although some of the results of this theory (*e.g.*, lift at small incidences) may be satisfactory.

**The control normal force efficiency η_N is defined by:

$$\eta_N = \frac{C_{N\,(BWC)} - C_{N\,(BW)}}{C_{N\,(BC)} - C_{N\,(B)}}$$

where $C_{N\,(BWC)}$ = normal force on complete configuration at incidence α
$C_{N\,(BW)}$ = ,, ,, ,, wing body ,, ,, α
$C_{N\,(BC)}$ = ,, ,, ,, body control ,, ,, ,,
$C_{N\,(B)}$ = ,, ,, ,, body ,, ,, ,,

The estimated value is given by:

$$\eta_N = 1 - \frac{\bar{\varepsilon}}{\alpha\left(1 + \frac{d}{b_c}\right)}$$

where $\bar{\varepsilon}$ = mean downwash over exposed control span
d = body diameter
b_c = control gross span.

surfaces C_1, C_2, C_3, C_1^{45} whose characteristics at zero yaw angle had been previously determined. The strength of the vortices was obtained by equating the lift impulse of the horseshoe vortex, together with its image in the body, to the measured values of the 'derived' wing lift of the wing body combination. These are compared with the experimental results in Figs. 17 to 20, in which are also presented the estimates made using the spacing calculated from slender-body theory assumptions[3] (Fig. 7). It will be seen that, at low incidences, the agreement with the experimental results of the estimates using the measured vortex positions is no better, and in most cases far worse, than that with the estimates using the slender-body theory estimates of the vortex locations. It is considered that this arises from the fact that at these incidences the trailing vortex sheet is still in the process of rolling-up at the control station and therefore that there is still considerable vorticity inboard of the measured vortex location. Under these circumstances the replacing of the trailing vortex sheet by a fully rolled-up vortex core at the measured positions cannot be expected to give reliable results. At the higher incidences the difference between the estimates becomes small and, as will be seen from Figs. 3 to 6 in which the slender-body theory estimate of the vortex position is included, this is due mainly to the fact that the measured vortex-core locations become very close to the estimated positions. At about 20 deg incidence it also appears that, since the cores remain at approximately the same distance apart over most of their movement, the rolling-up process is more or less complete fairly close to the wing (Fig. 6).

[For comparison, the estimated distances behind the trailing edge, at which the vortex sheet is essentially rolled-up, have been calculated from the formula of Spreiter and Sacks[5] and the values for incidences of 5 deg, 10 deg, 15 deg and 20 deg are, in terms of wing chords, 2·17, 1·09, 0·74 and 0·56 respectively.]

It can therefore be concluded that slender-body theory gives a reasonable method of estimating the locations of the final rolled-up spacing of the vortex cores for this configuration at zero yaw. Further, in view of the agreement of the estimates using this calculated vortex spacing at low incidences also, it appears that, for the purpose of such estimates, the horseshoe vortex of this spacing gives an adequate representation of or replacement for the trailing vortex sheet, even when this is not fully rolled-up.

4.2. *Vortex-Core Paths.*—Since it seems that the measured vortex-core locations at the lower incidences are of little use for the purposes of estimating the performance of rear controls, we will confine our attention to trying to estimate the movement of the cores at the highest incidence only (20 deg) under the condition of varying yaw. Throughout it has been noted that the vortex cores shed from the wings of the missile under any condition of incidence and yaw and for all the downstream stations lie close to the plane parallel to the free stream containing the line of the mid-chords of the wing from which they were shed. This will therefore be used as a suitable approximation for the location of the vortex cores with respect to the wings in the cross-stream plane perpendicular to the spanwise direction of those wings. We have therefore to consider only the movements of the vortex cores in the plane parallel to the free stream containing the line of mid-chords of the wings.

The results at zero yaw (Fig. 6) show that the vortices shed from the wings move downstream in very nearly the free-stream direction at a constant distance apart ; this is in agreement with the results of an application of slender-body theory[3], although the configuration tested here does not meet the requirements of slender-body theory, and indicates that the wing from which the vortices are shed has negligible effect on the movement of the vortices in the spanwise direction of that wing. Hence the movement of the vortices in the plane parallel to the free stream containing the line of mid-chords of the wing from which they were shed can be attributed to the flow field induced by the other wing, together with additional body effects. An extension of the slender-body theory analysis[4] to the case of a missile with cruciform wings has indicated that the additional body effects introduced by yawing the missile are again small and, in order to make the estimation as simple as possible, these effects have been ignored ; the closeness of the agreement of the estimates with the experimental paths will indicate whether this procedure is justified.

The vortex cores, which in the estimates will be treated as point vortices, will follow the streamlines in their movement downstream. In order to obtain their paths therefore, we must calculate the flow direction at each point in the path, integrating step by step. This procedure would be impractical both in respect of labour and because there is no satisfactory method of calculating the induced velocities in this region of a wing–body combination*. We have therefore to make further simplifications and approximations as indicated by the probable nature of the flow round the missile.

Since the region, in which we have to determine the flow angles, is the plane parallel to the free stream containing the line of mid-chords of the wing under consideration and therefore close to the plane of symmetry of the other pair of wings and as the reduced aspect ratio ($=A\sqrt{(M^2-1)}$, where A is the aspect ratio and M is the Mach number) is about $1\cdot5$, it seems reasonable to assume that the flow angles in the plane under consideration may not differ greatly from those that would be induced if these other wings (and its associated piece of the body) were replaced by an infinite flat plate of the same chord and at the same incidence. These values will therefore be used to see if they will explain, qualitatively at least, the movements of the vortex cores in this plane.

Fig. 21 shows the plan view of the missile under conditions of combined pitch and yaw. It has been assumed that the only thing that will give a movement in the plane of the paper to any particle of fluid is the flow field induced by the wing perpendicular to the plane of the paper (this has been replaced by an infinite flat plate). Thus a particle moving along a streamline will travel in the free-stream direction until it reaches the expansion region which originates from the leading edge of the plate (or the shock wave if it moves on the other side of the missile). It will be deflected towards the missile passing through the expansion, its path being determined by splitting up the expansion into several discrete expansions and assuming that the direction of the path within each step is the mean of the directions at the start and finish of the step. At the end of the expansion zone, the particle will be moving parallel to the plate until it meets the shock wave originating at the trailing edge of the plate when it will be deflected back to a direction very close to the free-stream direction. The paths of the vortex cores can be determined in this manner once a suitable point of origin has been selected. In the unyawed case (Ref. 1, for example), it has been assumed that the vortices originated at the wing mid-chord with a spacing as given by slender-body theory and that they moved downstream in the same vertical plane ; these assumptions have been justified by the results of these tests (Fig. 22). In the same way it can be assumed that, when the missile is yawed, the vortex cores again originate at the wing mid-chord with the ' slender-body ' spacing. Estimates of the vortex-core paths have been made on the premises outlined above and using this point of origin and these are compared with the experimental results, as Estimate I, in Figs. 22 to 26 in which further estimates based on a slender-body theory analysis[4] are included. It will be seen that for the vortex core originating from the wing with the leading tip (the wing on the windward side of the missile) the agreement on the path is reasonably good except for a region near the end of the body at higher values of yaw. It is considered that the discrepancy in this region is mainly due to the additional body effects which had been ignored in the estimate ; at greater distances downstream where the distance of the core from the body is increasing, the position of the vortex core again agrees reasonably well with the estimate. However the estimated location of the vortex core shed from the wing on the leeward side of the missile is considerably in error at all stations but, as can be seen from the figures, this poor comparison arises mainly from the discrepancy in the assumed starting point. The reason for the poor agreement in this case and reasonable answers for the other wing is not difficult to see from physical considerations. The cores of the vortex sheet will originate from the tips of the wing leading edge, their position thereafter being determined by the rolling-up process and the flow field induced by the other pair of wings. Now in the case of the wing on the windward side of the body, the vortex core starts further inboard with

*The only method available for dealing with wing–body combinations of this nature, *viz.*, by a distribution of line vortices over the missile and its wake, will not give reliable answers so close to the missile unless detailed pressure distributions over wing and body are available.

relation to the assumed position on the line of the wing mid-chords but this is counter-balanced by the large amount of vorticity that is being shed outboard of the line through the wing leading-edge tip parallel to the free stream. This may be so great at the higher yaw angles as to cause the vortex core to move outboard instead of inboard from its starting point. The net effect of these two counterbalancing effects seems to be to make the assumed location for the point of origin of the vortices a satisfactory choice. However for the other wing, there is no such counter-balancing movement of the shed vorticity and the rolling-up process is much the same as in the unyawed case. This suggests that a more suitable choice for the estimated point of origin of the vortices would be along a streamwise line the same distance inboard of the wing leading-edge tip as in the case at zero yaw. Further estimates of the paths of the vortex cores have been made using this assumption for the initial location of the cores and these are also shown, as Estimate II, in Figs. 22 to 26. It will be seen that these estimates give satisfactory agreement with the experimental results for the core shed from the wing on the leeward side of the body but, as is to be expected from the considerations already discussed, are quite unsuitable for the path of the core from the other wing.

From these comparisons it can be concluded that satisfactory estimates of the vortex-core locations can be made using the assumptions of Estimate I for the wing on the windward side of the missile and those of Estimate II for the wing on the leeward side. Further, these estimates confirm that the movements of the vortex cores in the plane parallel to the free stream containing the line of mid-chords of the wing from which they were shed are almost entirely due to the flow induced by the other wings and that, in particular, the rapid changes in direction which the cores undergo at the higher angles of yaw are the results of the shock waves and expansions associated with the flow about these wings. It is therefore apparent (Figs. 22 to 26) that an analysis based on the assumptions of slender-body theory, from which the effects of Mach number are excluded, do not compare at all well with these results. This is of course in part due to the fact that this configuration does not meet the requirements of slender-body theory and that the region of interest in these tests, namely near the wings, is one in which the effects of Mach number are most noticeable. It is, moreover, probable that a slender-body theory analysis, such as that of Ref. 6, will only be applicable in those downstream regions in which the shock waves and expansions associated with the wings are not present even for those configurations which meet the requirements of slender-body theory. A more complicated analysis is needed in the regions close to the wings in order to determine the initial positions of the vortices from which a slender-body theory analysis could be started. It must be realised that the method used in the estimates for this configuration may not be applicable to other configurations and further tests seem advisable to check the assumptions made over a much wider range of configuration. However, it can be expected to give reasonable results for other rectangular wings of similar or higher reduced aspect ratio and trapezoidal wings of low leading-edge sweepback. For other configurations some other approximation can probably be made by consideration of the known characteristics of the flow about such configurations.

5. *Conclusions.*—From the rather limited measurements made in these tests the following tentative conclusions can be drawn :

(*a*) At zero yaw the vortex sheets shed from the wings appear to be fully rolled-up quite close behind the wing at high incidence (*c.* 20 deg); this confirms the estimated distance of 0·56 chords behind the trailing edge as given by Spreiter and Sacks. At all incidences the vortex cores retain an approximately constant vertical location as they move downstream and this position is given with reasonable accuracy by the plane parallel to the free stream through the line of the mid-chords of the wing.

(*b*) Under conditions of combined pitch and yaw, the vortex cores at all stations remain close to the plane parallel to the free stream containing the line of mid-chords of the wing from which the cores were shed. The displacements of the vortex cores from any wing in this plane can be ascribed almost entirely to the effects of the other wing.

(*c*) A semi-empirical analysis for the configuration tested has shown reasonable agreement with experiment in the region of the wings and it seems probable that similar approximations could be found for other configurations. Owing to the presence of shock waves and rapid expansions in this region, an analysis based on slender-body theory cannot be expected to give reliable answers for the vortex-core paths near the wings.

(*d*) However, slender-body theory predicts the location of the rolled-up vortex cores for the zero yaw condition with adequate accuracy and will probably be suitable for analyses of the vortex paths well away from the regions of the wings.

(*e*) In estimates of the characteristics of rear surfaces the position of the fully rolled-up vortices can be used in a method based on line-vortex theory ; a single horseshoe vortex with this spacing proved on this configuration an adequate representation of the vortex sheet when unrolled also. The measured locations of the vortex cores at incidences and stations when the sheet is not fully rolled-up are of no use for this purpose for obvious reasons.

(*f*) Further tests covering many more configurations seem desirable to check whether the conclusions derived from these tests are applicable to other configurations and to check the validity of the assumptions used in the estimates of the core paths.

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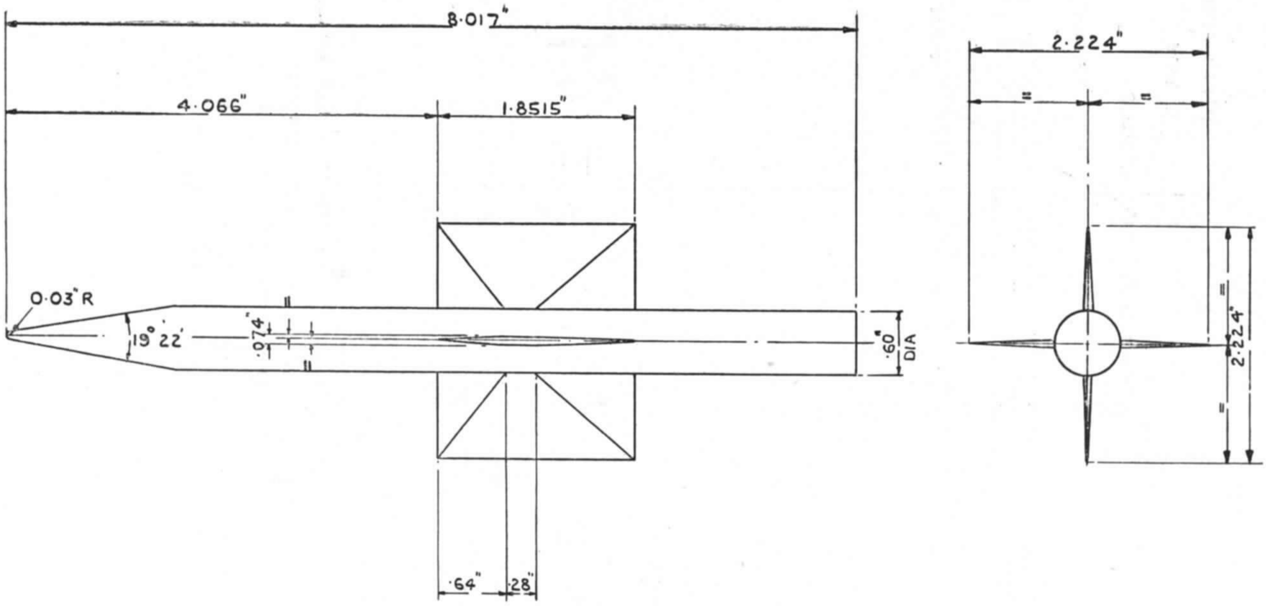

Fig. 1. Sketch of model.

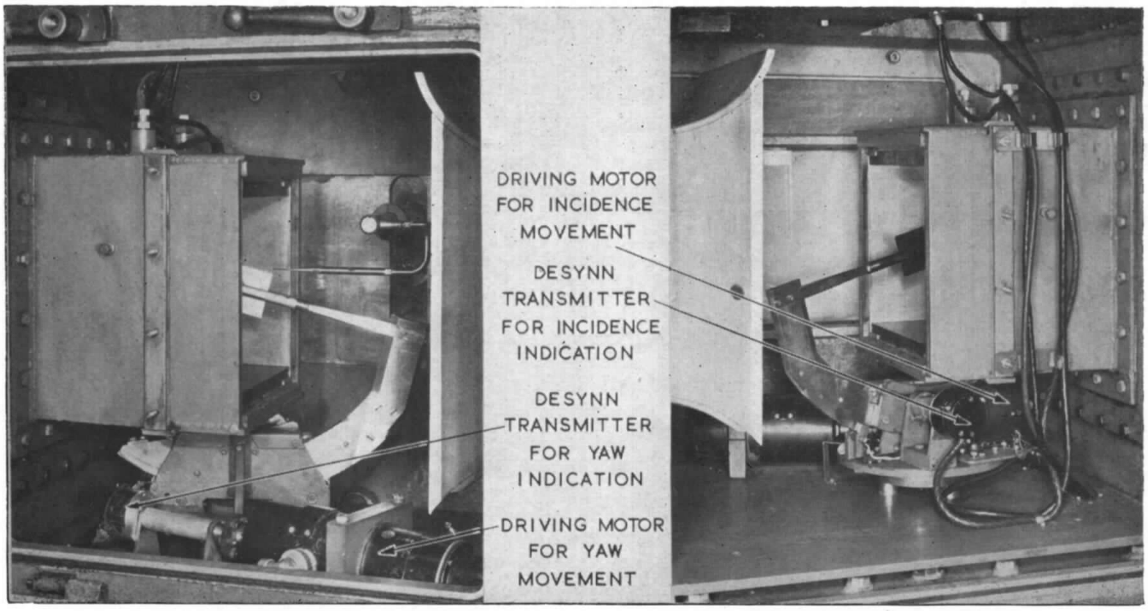

Fig. 2. Model installation in No. 8 (10 in. × 9 in.) Supersonic Tunnel.

B

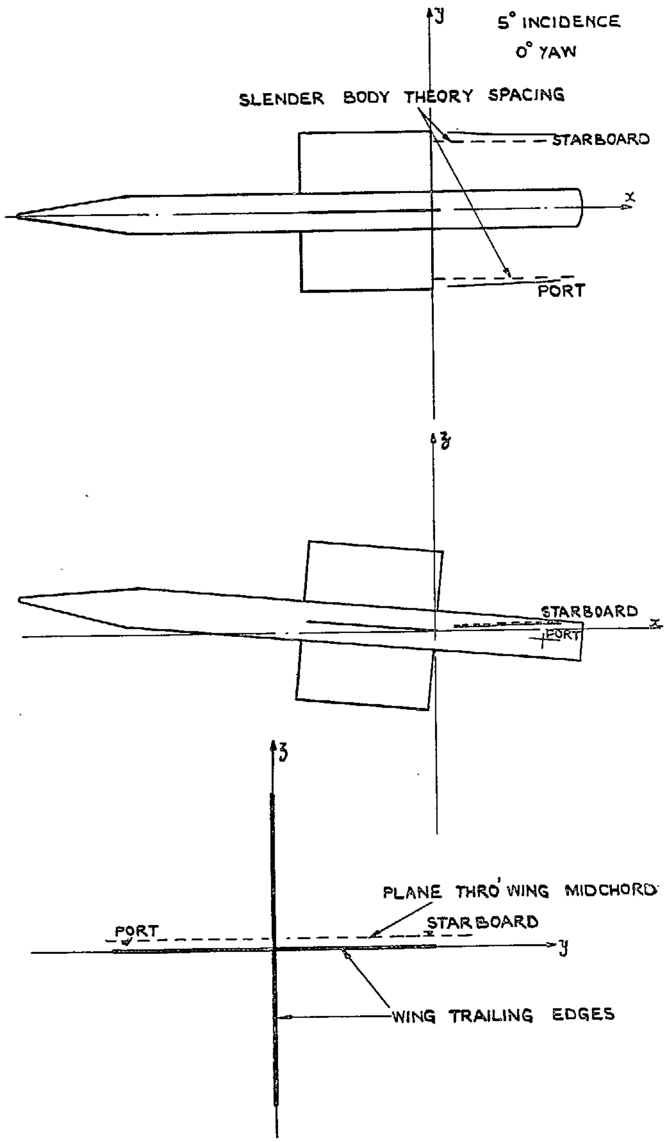

FIG. 3. Vortex-core paths—
incidence = 5 deg, yaw = 0 deg

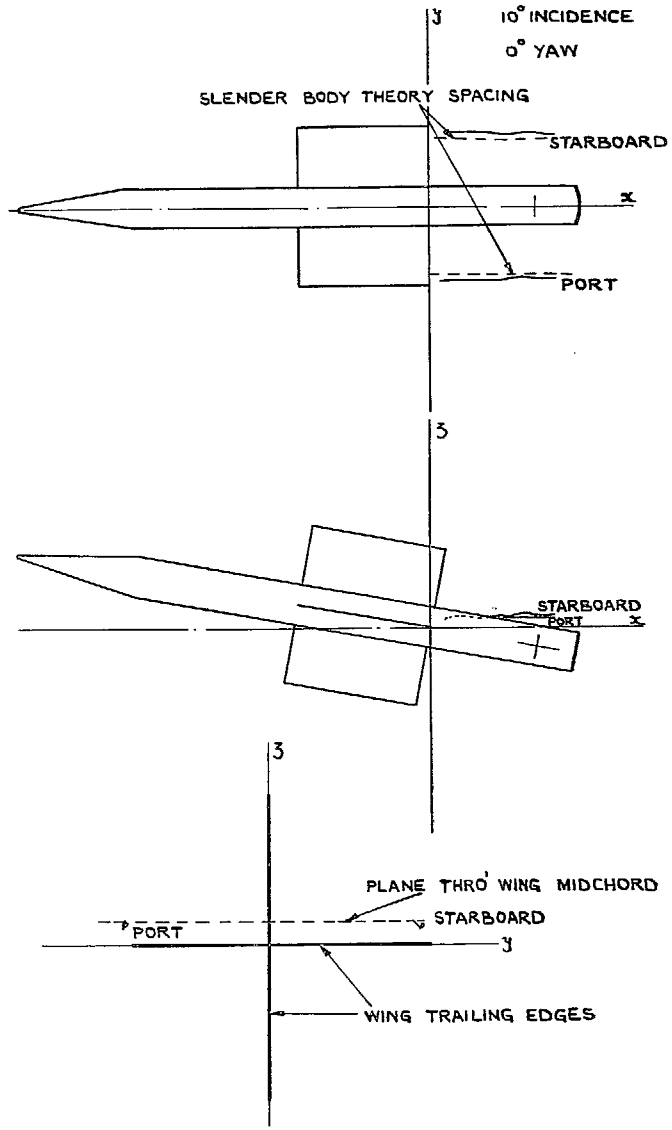

FIG. 4. Vortex-core paths—
incidence = 10 deg, yaw = 0 deg.

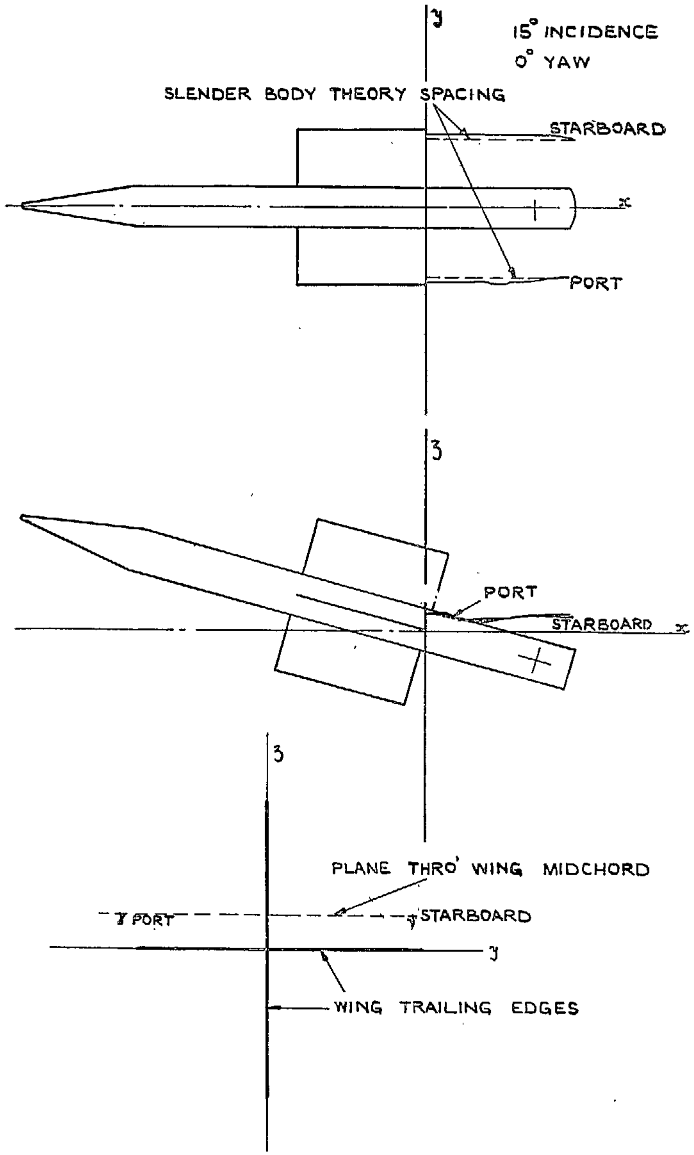

Fig. 5. Vortex-core paths—
incidence = 15 deg, yaw = 0 deg.

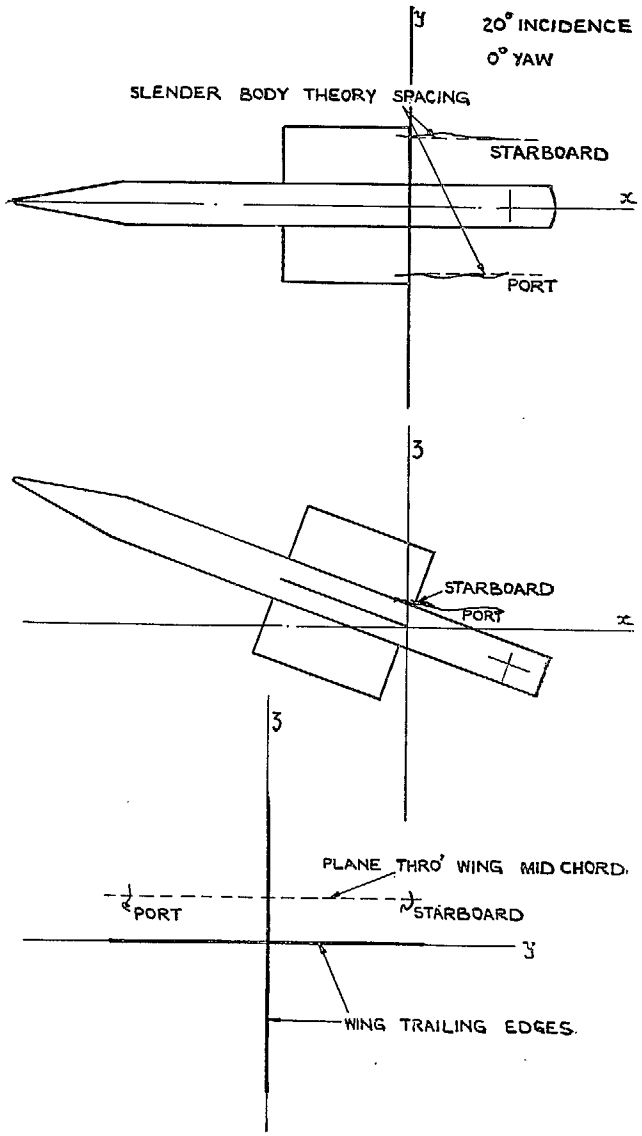

Fig. 6. Vortex-core paths—
incidence = 20 deg, yaw = 0 deg.

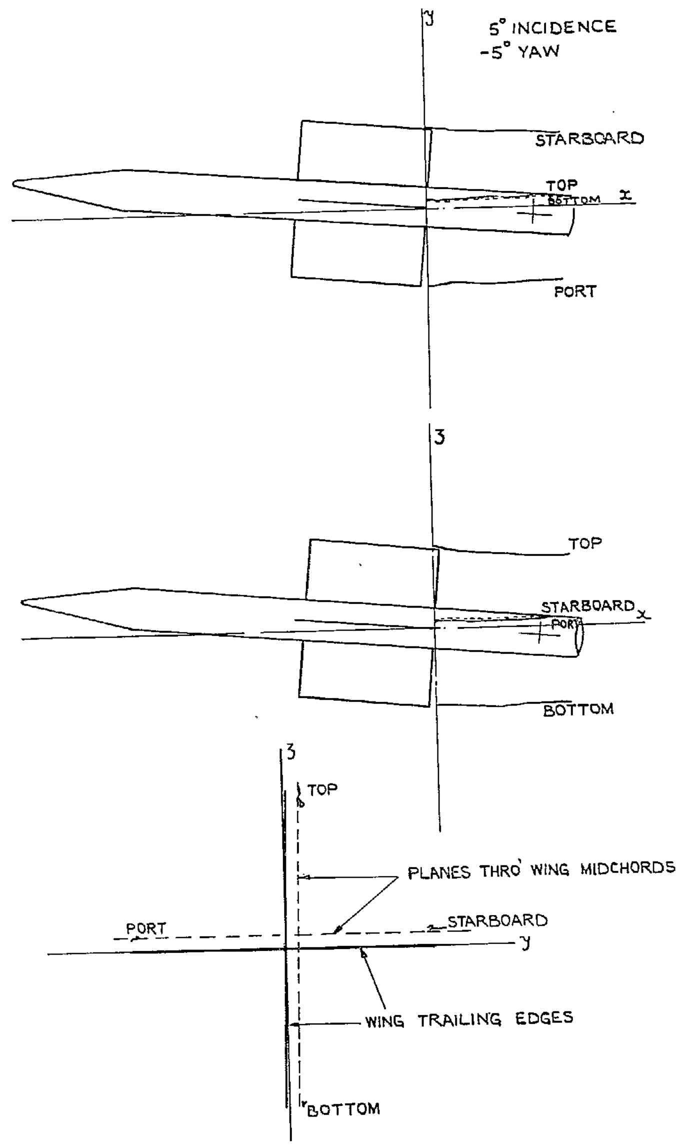

FIG. 7. Vortex-core paths—incidence = 5 deg, yaw = − 5 deg.

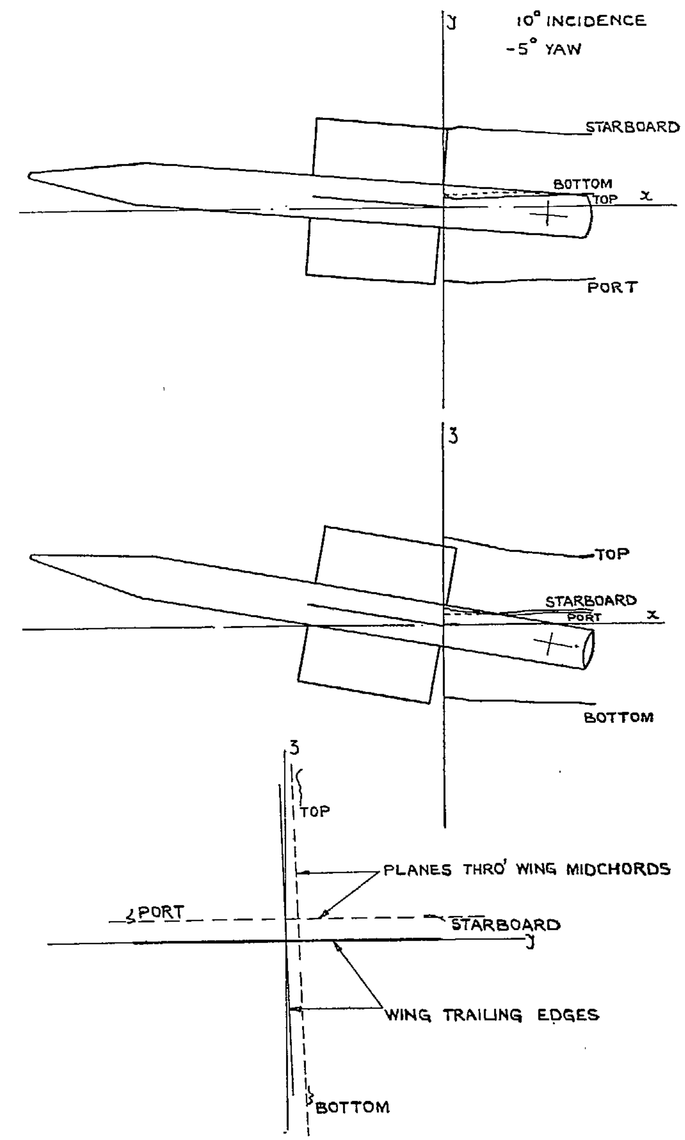

FIG. 8. Vortex-core paths—incidence = 10 deg, yaw = − 5 deg.

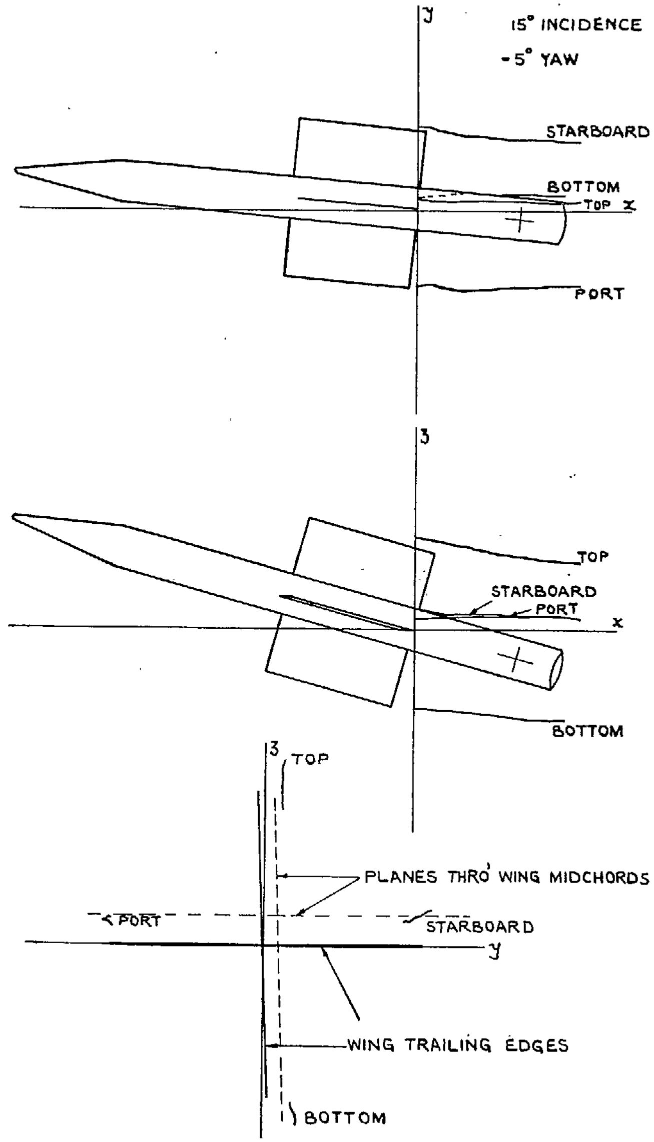

FIG. 9. Vortex-core paths—incidence = 15 deg, yaw = — 5 deg.

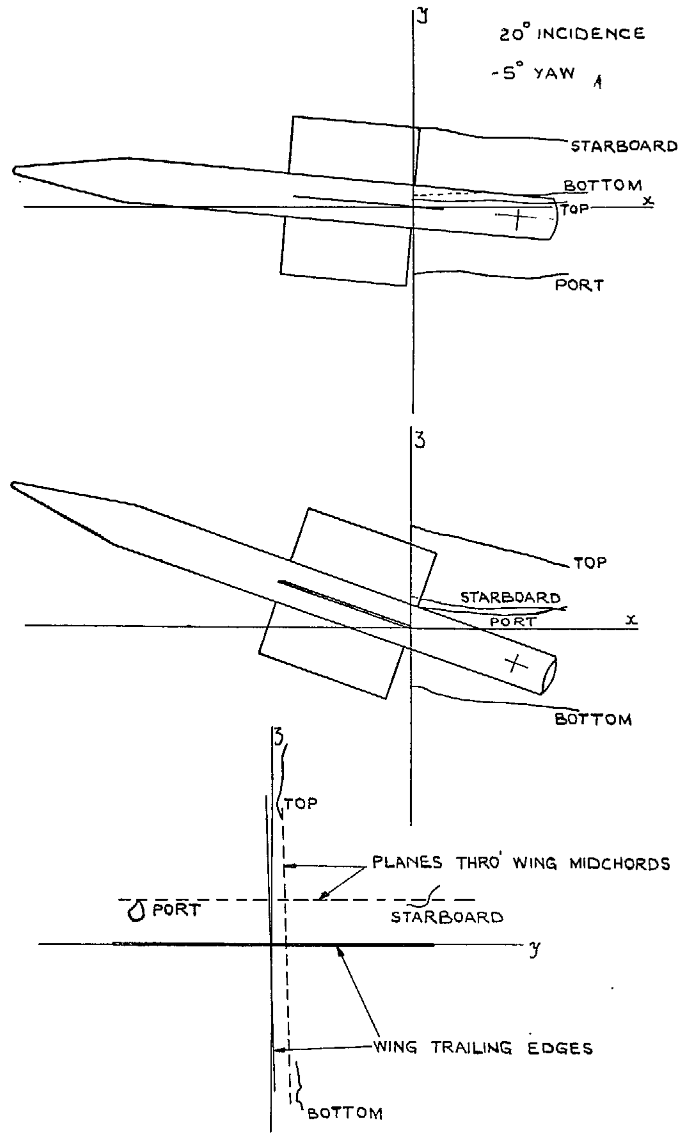

FIG. 10. Vortex-core paths—incidence = 20 deg, yaw = — 5 deg.

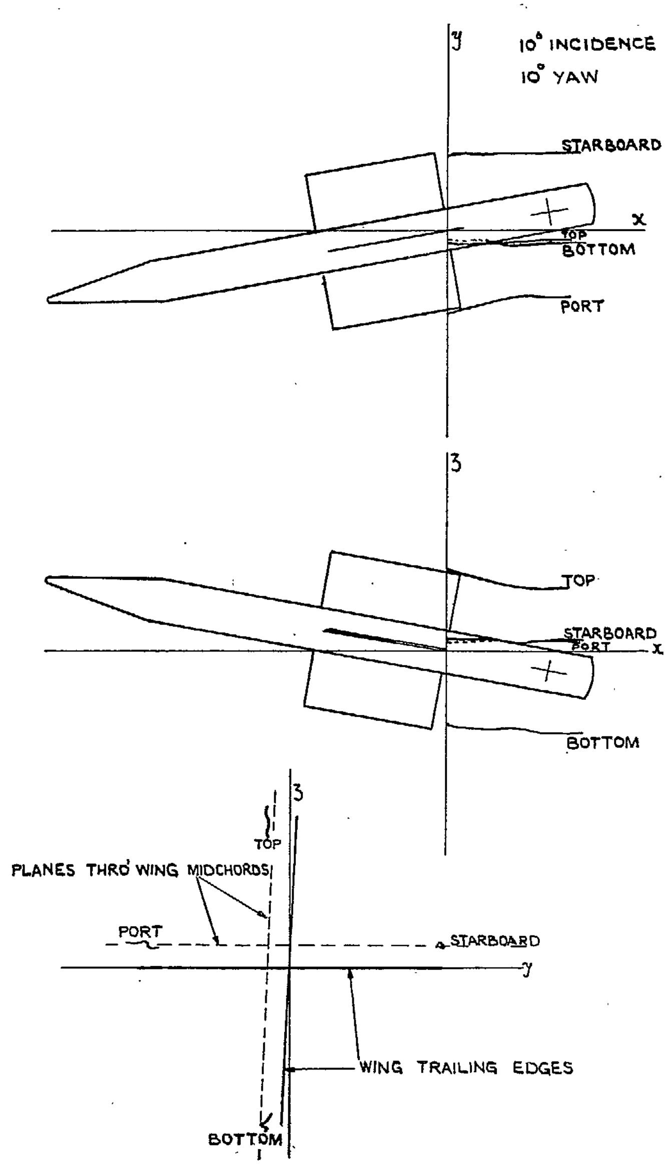

FIG. 11. Vortex-core paths—
incidence = 10 deg, yaw = 10 deg.

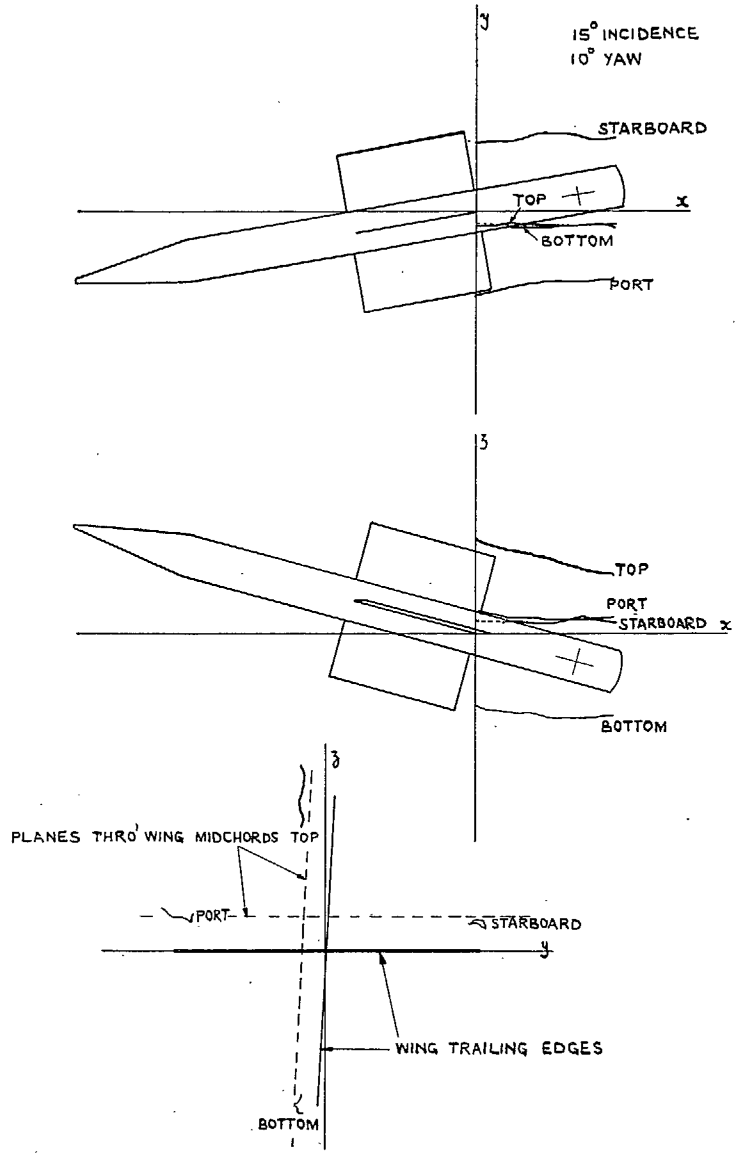

FIG. 12. Vortex-core paths—
incidence = 15 deg, yaw = 10 deg.

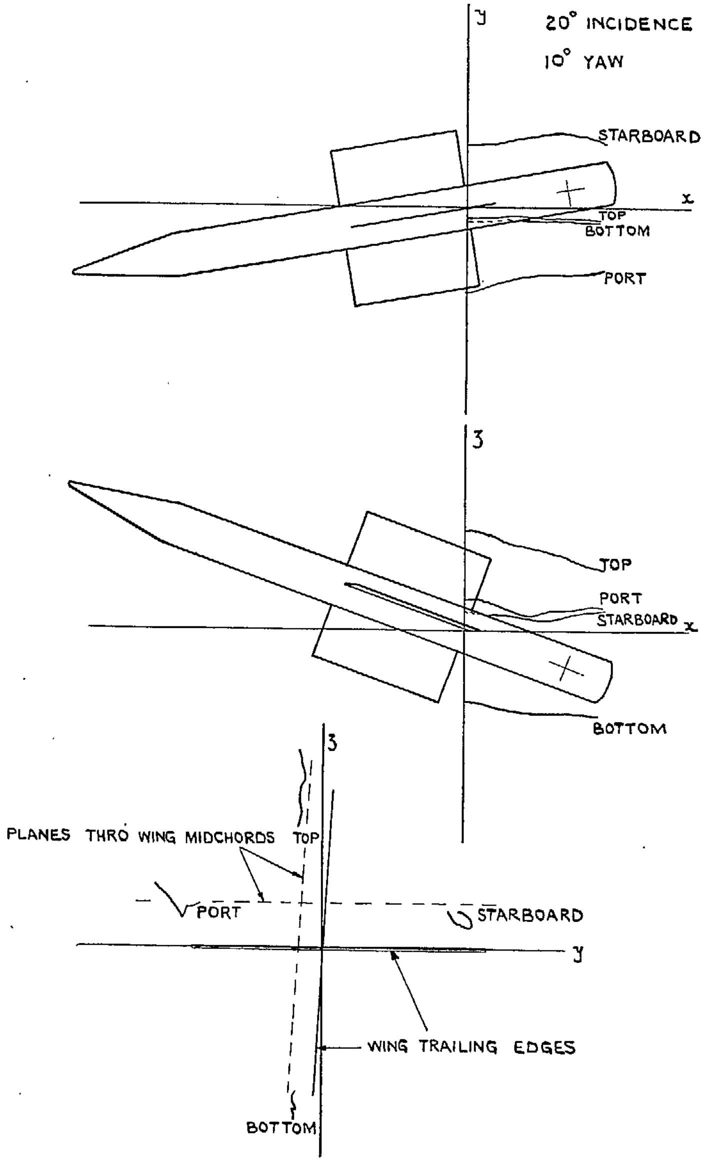

FIG. 13. Vortex-core paths—incidence = 20 deg, yaw = 10 deg.

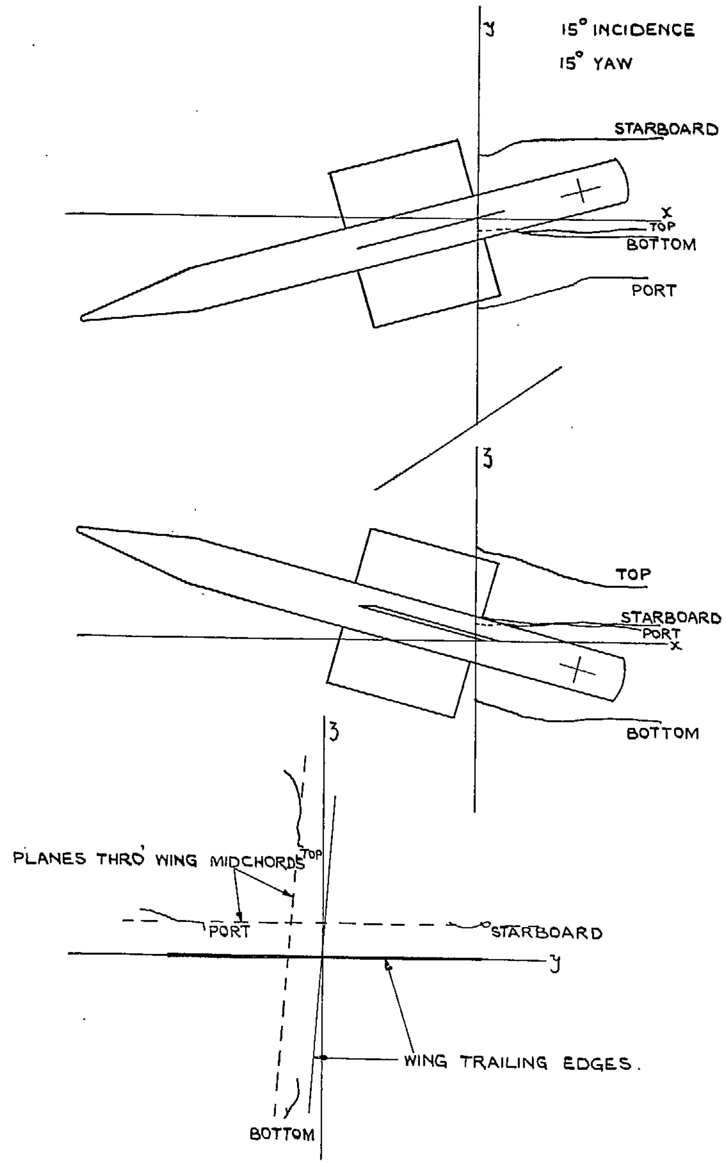

FIG. 14. Vortex-core paths—incidence = 15 deg, yaw = 15 deg.

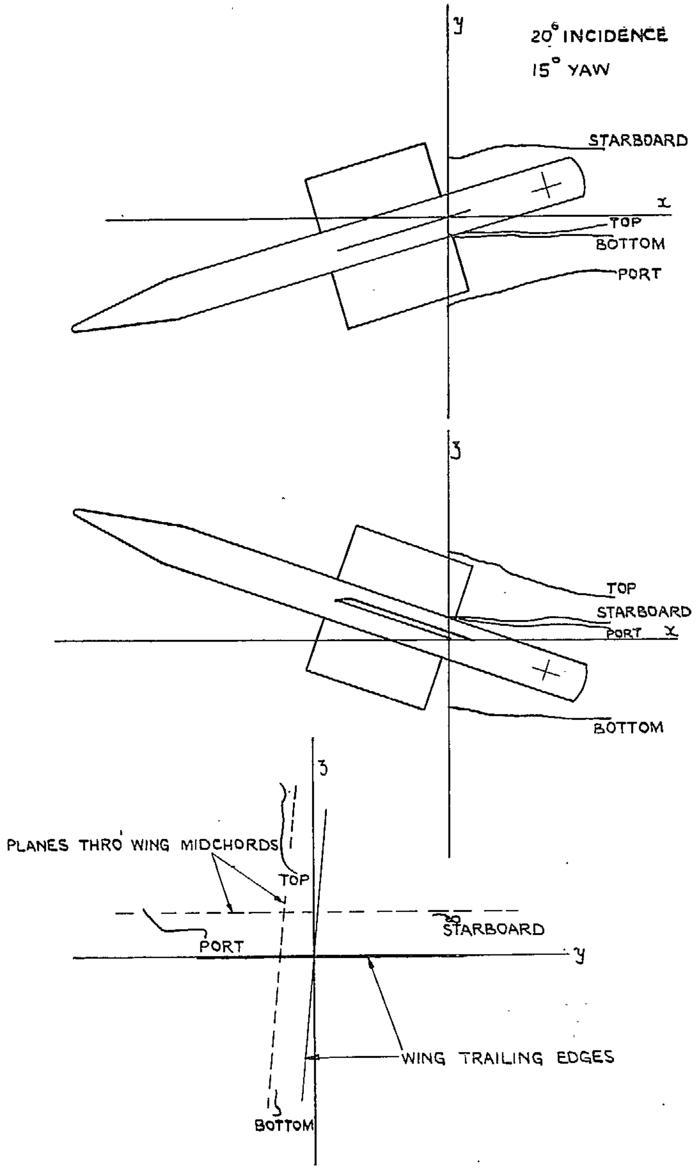

FIG. 15. Vortex-core paths—
incidence = 20 deg, yaw = 15 deg.

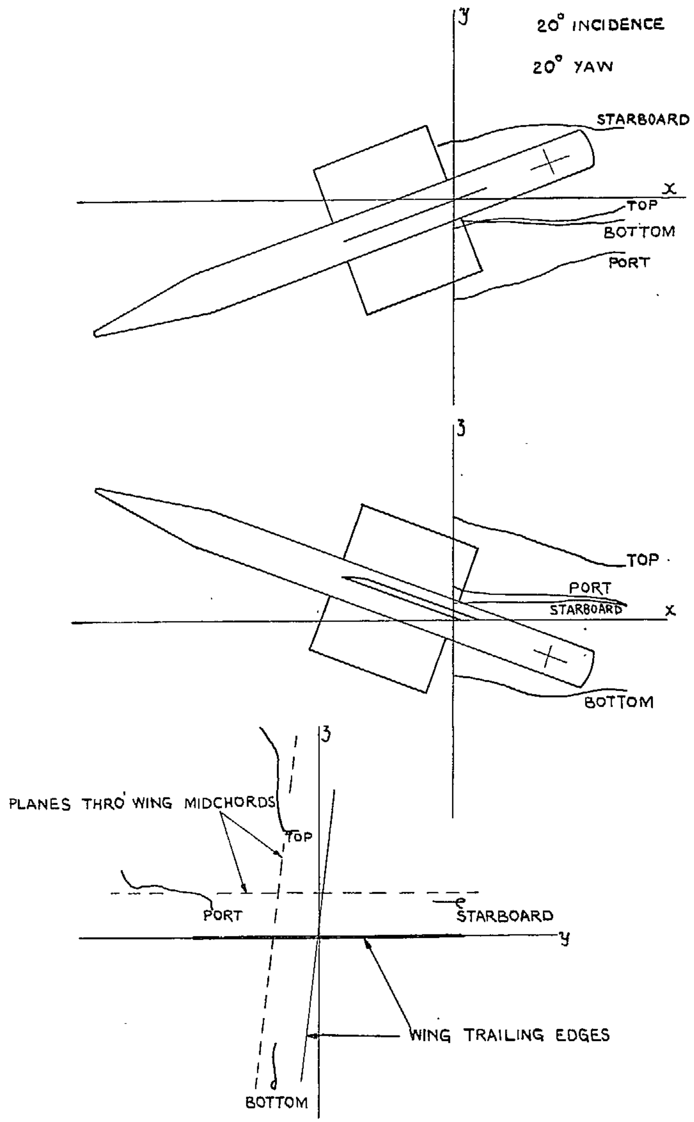

FIG. 16. Vortex-core paths—
incidence = 20 deg, yaw = 20 deg.

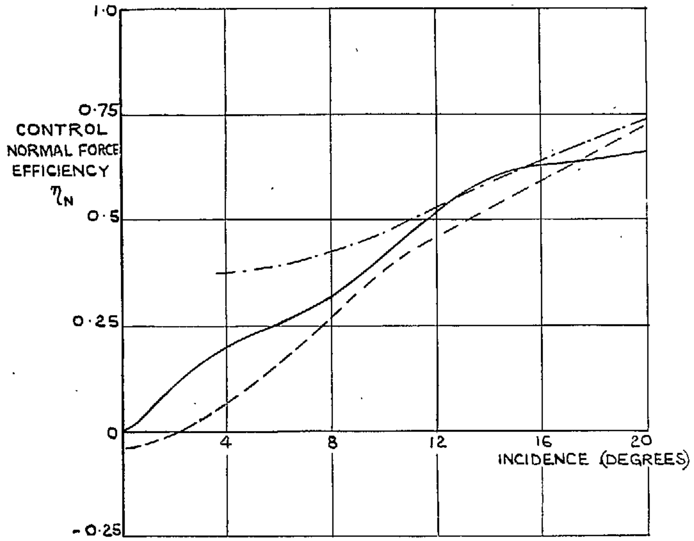

FIG. 17. Control C_2 (Control span = 1·630 in.).

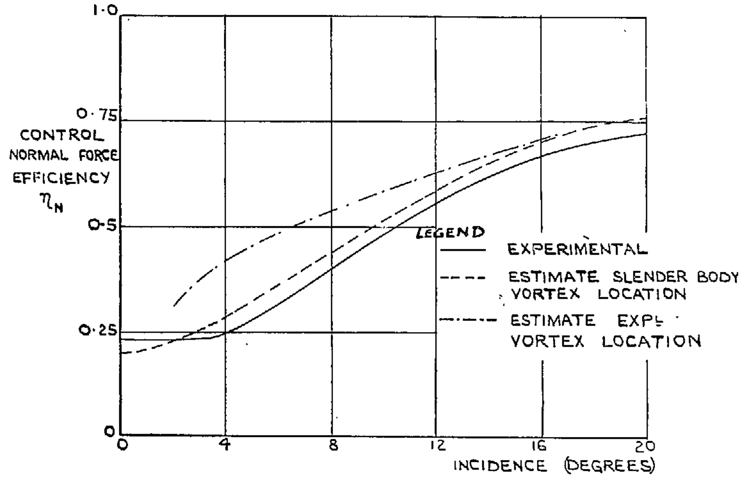

FIG. 18. Control C_1 (Control span = 2·144 in.).

FIGS. 17 and 18. Comparison of estimated and experimental control normal force efficiencies. Controls C_2 and C_1.

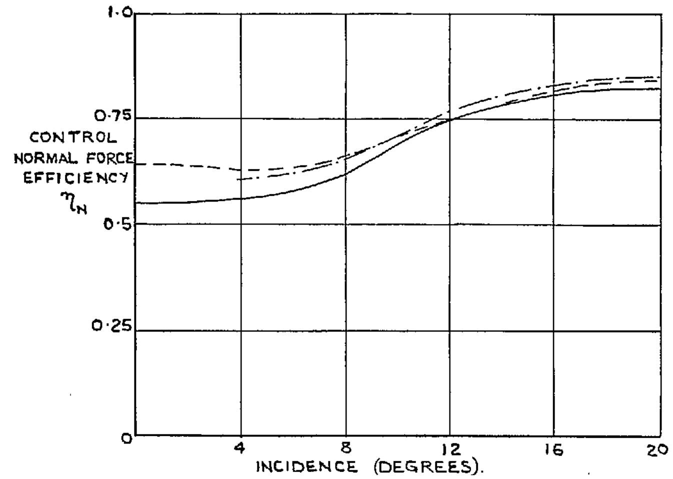

FIG. 19. Control C_3 (Control span = 2·665 in.).

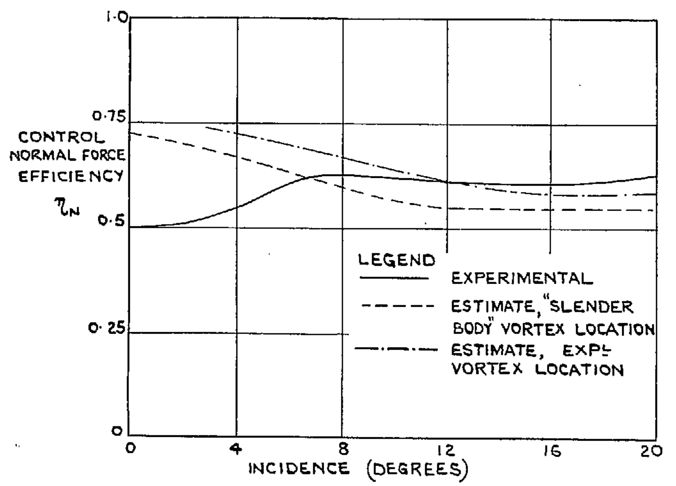

FIG. 20. Control C_1^{45} (Control span = 2·144 in.).

FIGS. 19 and 20. Comparison of estimated and experimental control normal force efficiencies. Controls C_3 and C_1^{45}.

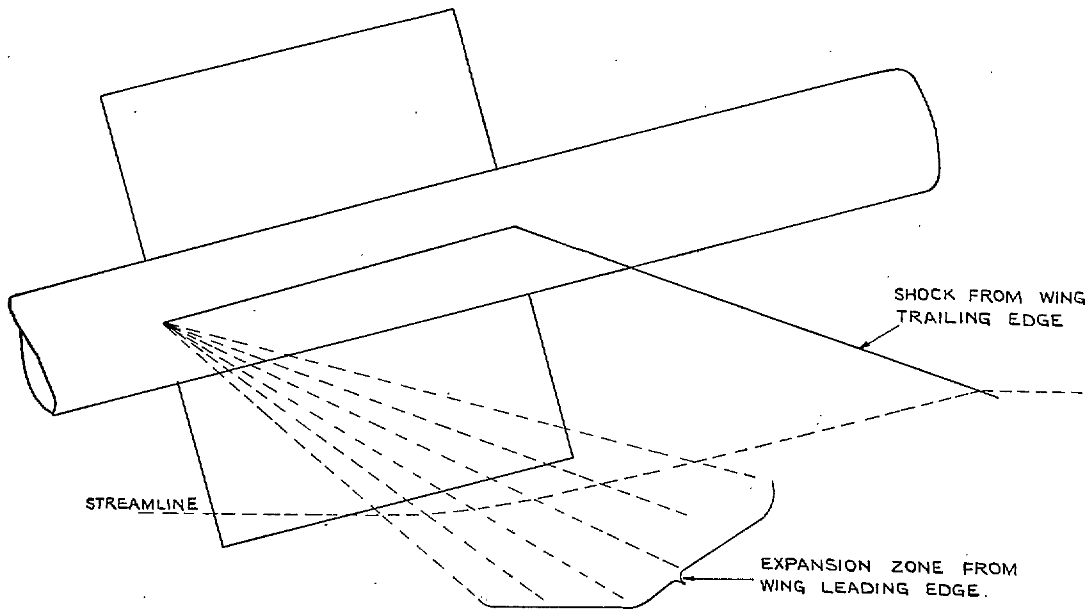

FIG. 21. Sketch showing method of tracing streamline.

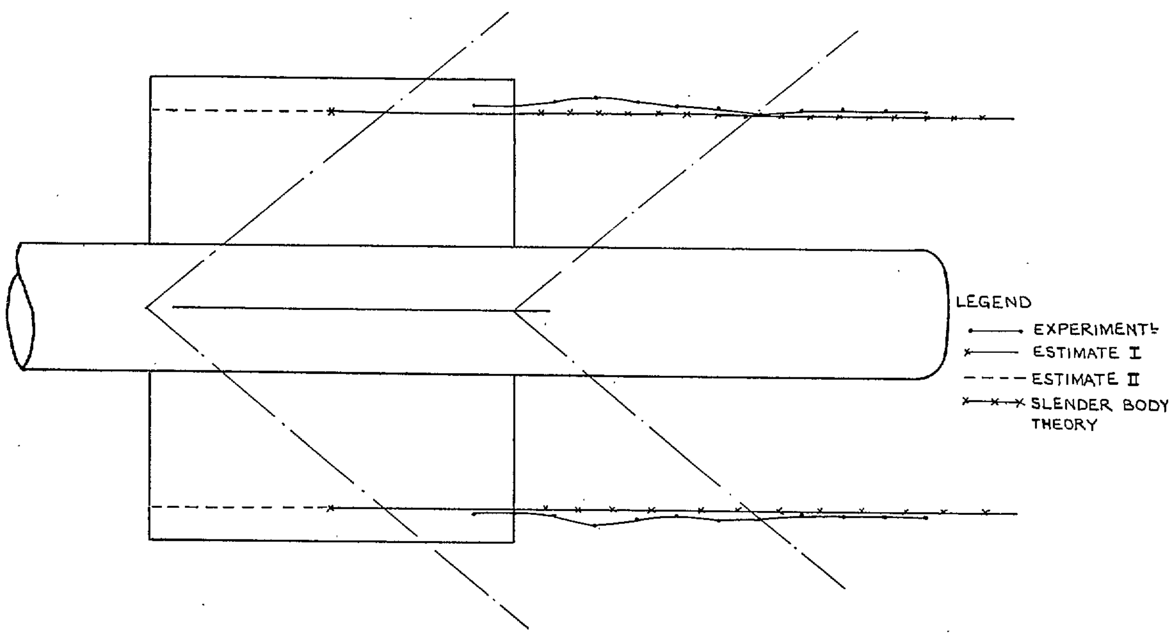

FIG. 22. Vortex-core paths—comparison of estimates with experimental results.
Incidence = 20 deg, yaw = 0 deg.

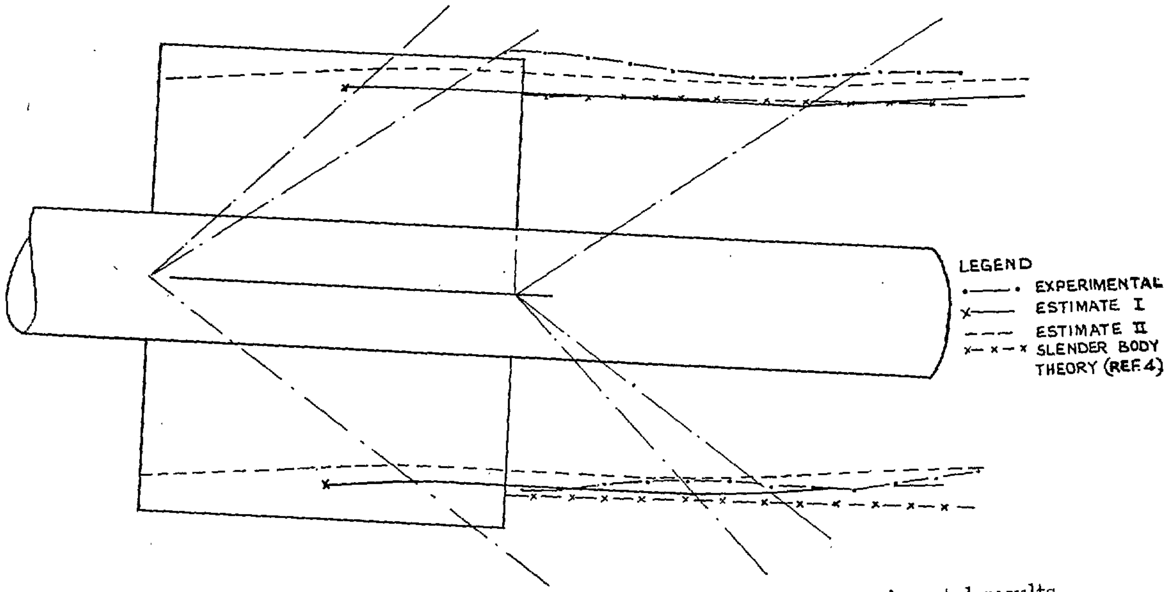

FIG. 23. Vortex-core paths—comparison of estimates with experimental results. Incidence = 20 deg. yaw = − 5 deg.

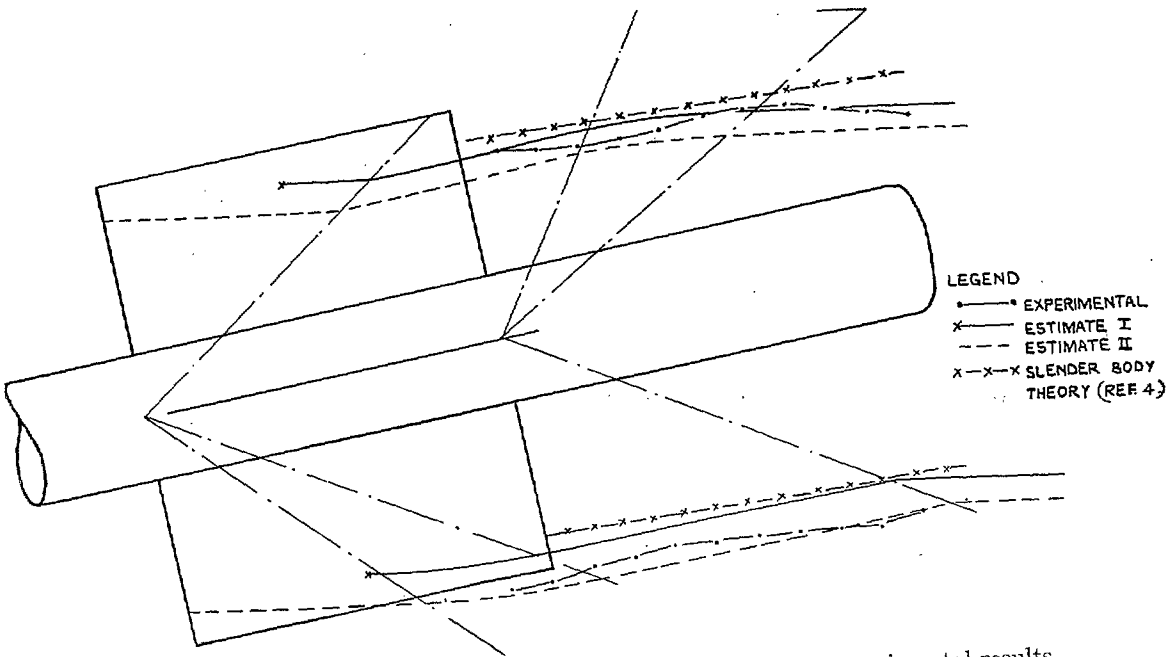

FIG. 24. Vortex-core paths—comparison of estimates with experimental results. Incidence = 20 deg, yaw = 10 deg.

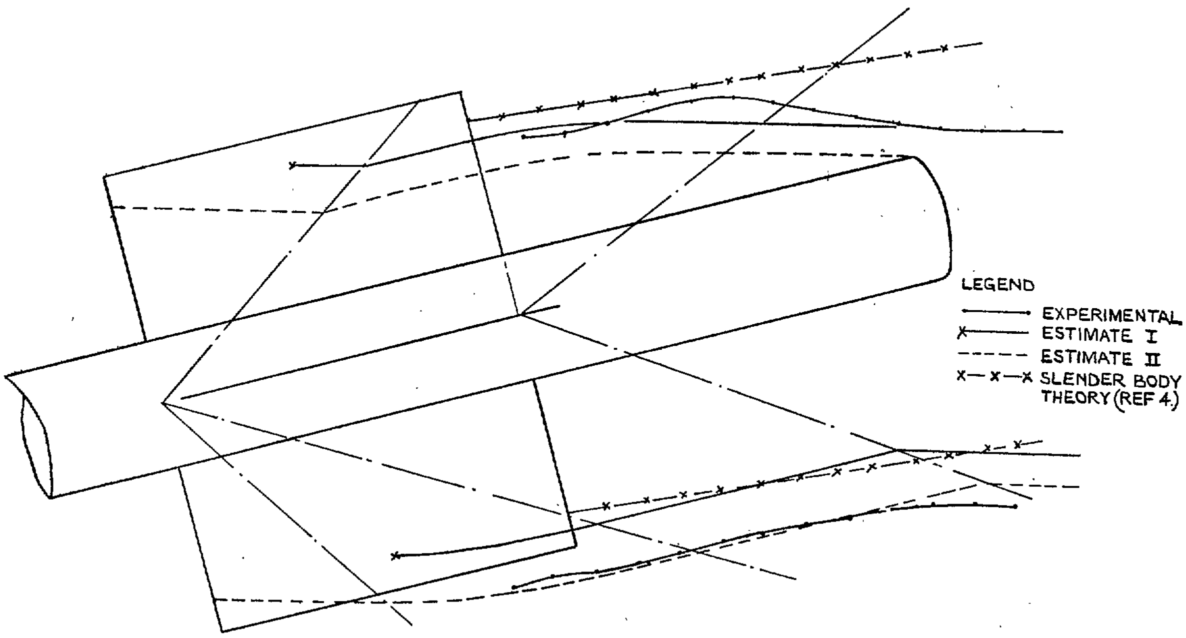

FIG. 25. Vortex-core paths—comparison of estimates with experimental results. Incidence = 20 deg, yaw = 15 deg.

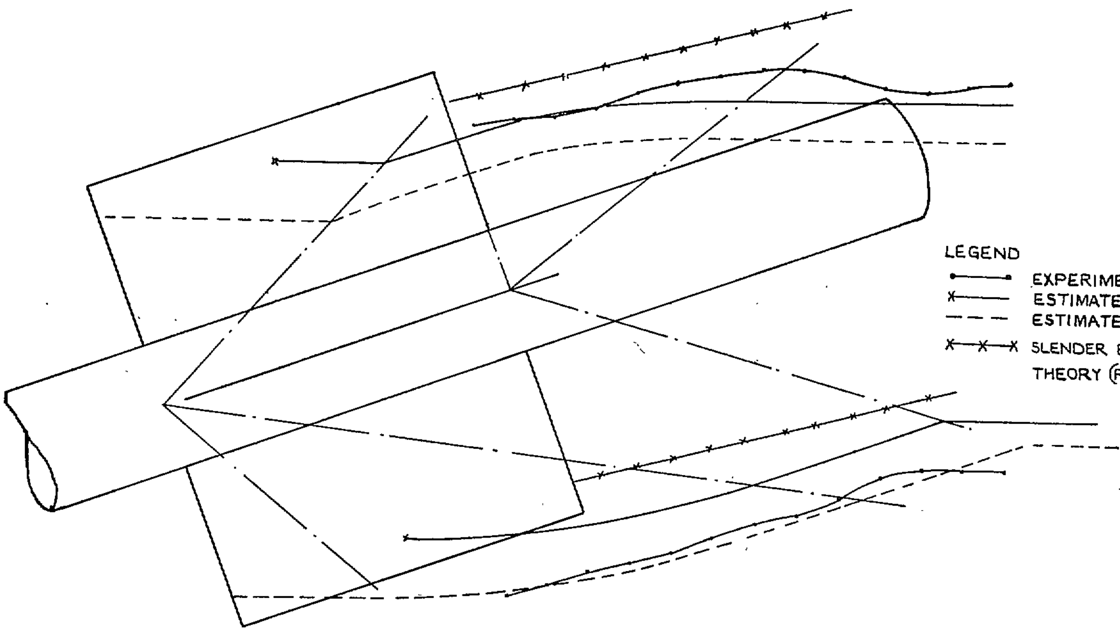

FIG. 26. Vortex-core paths—comparison of estimates with experimental results. Incidence = 20 deg, yaw = 20 deg.

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