WIND-TUNNEL WALL EFFECTS AT EXTREME FORCE COEFFICIENTS

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SUMMARY

The available linearized theory of wall effects for highly deflected wakes is discussed. Sample results of an extension of this theory to curved wakes are included. The primary limitation on the use of the theory is the present inability to adequately estimate the effect of interference gradients on the performance and stability of an arbitrary lifting system. The development of nonlinear theory at the University of Washington and the Boeing Company is discussed and sample results are included. A brief discussion of real-tunnel effects such as ground plane representation and lateral recirculation is also included.

INTRODUCTION

The wind tunnel, despite its limitations, remains as the single most useful tool in the design of an aircraft; however, the results of a wind-tunnel test are not exactly the same as flight. The lack of complete equivalence is caused by a number of effects in the wind tunnel which are not present in free air. These effects include static-pressure gradients, Reynolds number effects, mounting system tares and interference, solid blockage, and wall constraints. During the past 50 years methods of correcting wind-tunnel data have been developed, and the use of such corrections generally leads to data which are very similar to that obtained in flight.

Most of the corrections have been based implicitly upon the concept of a lightly loaded model; that is, the force coefficients are assumed to be small.

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V/STOL models at very low speeds severely violate the assumption of small force coefficients; thus most of the observed wind-tunnel effects can be expected to be somewhat different than in the case of a conventional aircraft model.

The present paper is confined to just one of the effects associated with wind-tunnel testing; namely, wall constraints. The magnitude of these effects in V/STOL testing has been shown experimentally (Ref. 1) to be large and to differ from the effects noted in conventional testing. The available theory for high lift coefficients is noted (Refs. 2 to 5); however, the largest portion of the paper is a progress report on theoretical work now in progress at NASA, the University of Washington (Refs. 6 and 7), and at the Boeing Company (Ref. 8).

Some of the real effects encountered in wind-tunnel testing are also discussed. These include the requirements for moving belts in ground effect testing (Ref. 9) and the recirculation limits on minimum speed which have been discovered in tests at the University of Washington (Ref. 10).

SYMBOLS

A	aspect ratio
b	span
B	semi-width of rectangular test section
c	chord
C_L	lift coefficient
D	jet exit diameter
h	height above ground
H	semi-height of rectangular test section
q	dynamic pressure

q_c corrected dynamic pressure

R radius of circular test section

t time

V wind-tunnel velocity

V_j jet-exit velocity

x distance downstream from center of lift

z distance above center of lift

α angle of attack

$\alpha_i = C_L/\pi A$

Γ_n circulation of nth vortex element

Δu horizontal interference velocity

Δw vertical interference velocity

$\Delta\alpha$ alteration to α from wall interference

θ pitch angle, positive nose up

θ_j initial inclination of jet, measured positive rearward from the vertical

χ wake skew angle measured positive rearward, from vertical to center-line of the wake as determined from momentum considerations

χ_e effective wake skew angle, $\frac{1}{2}(\chi + 90^\circ)$

LINEARIZED THEORY

NASA TR R-124

The initial concern with wall effects at extreme force coefficients centered on the helicopter (Ref. 2); however, the analysis was extended soon after to the case of an arbitrary lifting system (Refs. 3 and 4). Basically, these analyses assume that the fundamental difference between conventional and V/STOL testing is the large wake deflection caused by the extreme force coefficients in the latter case. This difference requires an alteration to the representation of the wake in the wind tunnel. As shown in Figure 1, the wake of the classical theory (for example, Refs. 11 and 12), which passes directly downstream, is allowed to pass downward as well in Reference 4. For simplicity, the wake is assumed to take the form of a straight line which intersects the floor and then turns and flows off along the floor. No real wake could possibly behave in this manner; however, these assumptions did at least introduce the rudiments of a highly deflected wake into the analysis.

The results of Reference 4 include the classical theory as a limit in high-speed forward flight. On the other hand, the theory also indicated that wall effects would be magnified at large wake deflections.

Numerous experimental studies have been, and are being, conducted to verify the theoretical predictions. These studies include a wide variety of lifting systems (Fig. 2). The published studies include rotors (Ref. 13), fan-in-fuselage models (Ref. 14), tilt-wing models (Ref. 15), fan-in-wing models (Ref. 16, also see Ref. 17), jet-flap models (Ref. 17), and jet-lift models (Ref. 18). Additional studies are now in progress on jet-lift models (at the Boeing Company and the Langley Research Center of NASA), rotors and lifting propellers (at the University of Washington), a blown-flap model (at the Boeing Company), and a tilt-wing model (at the National Research Council in Canada).

In these studies, the model, mounting systems, and all other controllable factors are retained as identically as possible during tests in different wind tunnels. Under these controlled conditions, the remaining differences in the data are confined to wall effects. In particular, differences ascribable to Reynolds number and tares are eliminated. In general, provided that the model conditions did not violate recirculation limits (to be discussed in a later section of this paper), substantially improved correlation between wind tunnels was obtained in all cases when the corrections of reference 4 were applied.

The degree of improvement in correlation varied with the particular investigation; however, the completeness of correction also varied. In general, those studies which considered the finite span of the model and which also used an effective skew angle to account approximately for wake roll-up (Ref. 17) showed the greatest improvement.

NONUNIFORM INTERFERENCE

The improved correlation shown in References 13 to 18 is somewhat surprising since none of these studies considered in detail the effect of the nonuniform interference field that is created by the walls. Figure 3 illustrates some of the effects of this nonuniform field on the model. It will be observed that, when the vertical interference velocities in the wind tunnel vary across the span, the wing sections in the tunnel experience the same local angles as a wing in free air only if the latter wing has a different twist distribution (or wash-in for the case shown). Thus the model in the wind tunnel effectively can be considered as a wing with the equivalent twist. This effect can substantially alter the stall angle in certain cases. Similarly, a longitudinal gradient of interference velocity produces a curved flow. In this flow, the model effectively has altered camber, an altered tail incidence, and an altered tail height. All of these effective changes in the model affect the longitudinal pitching moment and all must be accounted for in order to completely correct the model pitching moment. The altered tail incidence is reasonably simple to account for (Refs. 19 and 20); the remaining items can be substantially more difficult to treat.

Provided that the gradients of interference velocity are relatively linear, the effect of the gradients can be considered in still another form. As shown in Figure 4, a linear longitudinal gradient of vertical interference velocity is equivalent to the model being fixed at one angle of attack, but rotating at a constant rate in a uniform interference field.

Whether the nonuniform interference field is treated directly, as an aerodynamic distortion, or as an effective rate of rotation, it is evident that the forces and moments observed in the wind tunnel may be substantially altered by the nonuniformities. The extent and nature of such effects will vary with the model configuration. For example, Wheatley (Ref. 21) has shown that the effect of a longitudinal gradient on a centrally hinged rotor is only a small change in lateral flapping. On the other hand, identical calculations (Ref. 22) for a perfectly rigid rotor disclose a large pitching moment. The effect of such gradients on a device as complicated, for example, as a fan-in-wing system is unknown at present.

If the effects of the nonuniform field, or its equivalent distortions or rotations are amenable to calculation, then these effects may be removed from the data. Under these conditions, very large models and very large corrections can be tolerated. On the other hand, if these effects cannot be calculated, only very small models (perhaps as small as one-quarter of the wind-tunnel width) can be accepted.

Corrections With Curved Wake Shapes

As pointed out previously, the theory of Reference 4 is linearized to a straight-line wake which does not exist in practice. The use of an effective skew angle (Ref. 17) partially accounts for the distortions of a real wake; however, it seems obvious that in certain cases a more accurate representation of the wake could lead to superior corrections.

Reference 5 represents an early effort to include wake curvature in the analysis. Unfortunately, the author of Reference 5 had access to only limited digital computing equipment so that the numerical values are in error because of the inclusion of too few images. In addition, the analysis introduced wake decay terms which seem excessively large when compared to the rate of decay of a real V/STOL wake (Ref. 23).

Richard J. Margason at the Langley Research Center of NASA is presently conducting a theoretical investigation of wall effects using a constant strength wake whose shape (Fig. 5), determined especially from flow visualization studies, is given by

$$\frac{x}{D} = \frac{1}{4}\left(\frac{V}{V_j}\right)^2\left(-\frac{z}{D}\right)^3 \sec^2\theta_j + \left(-\frac{z}{D}\right)\tan\theta_j$$

This equation differs from that of References 24 and 25; however, the general form of the equation is substantiated at $\theta_j = 0$ by tests at the University of Washington (Ref. 26). This equation yields a reasonably good fit for values of θ_j between -45° and 90°. At more forward initial inclinations, the character of the flow is entirely altered, with large aperiodic distortions much like the vortex-ring state of the helicopter rotor (Ref. 27).

A few preliminary results from the wall effects study using this wake shape are shown in Figure 6. In these cases the width-height ratio of the wind tunnel is 1.5, the wake originates at the center of the wind tunnel, and the diameter of the jet is one-fifth of the full wind-tunnel height. Two ratios of forward velocity to jet velocity are considered: 0.25 and 0.50. In each case the results are compared with the equivalent corrections from Reference 4 using both the momentum skew angle and the effective skew angle (Ref. 17).

At $\frac{V}{V_j} = 0.25$, it will be observed that major differences in interference are observed between the curved wake analysis and Reference 4, irrespective of which skew angle is employed. The differences between the curved wake and Reference 4 are substantially less at the more moderate condition $\left(\frac{V}{V_j} = 0.50\right)$ provided that the effective skew angle is used. This result is the reason that the corrections of Reference 4 appear to help correlation even for jet-lift V/STOL models (Ref. 18) where large wake curvatures are encountered. On the other hand, Reference 4 should be applied with caution to such models since its limits are not yet fully explored.

NONLINEAR THEORY

Basis of Calculations

The theories discussed prior to this point are both linearized theories in that the wake shape is assumed in advance. It is further assumed that the wind-tunnel interference does not affect the shape of the wake. More recently studies have been initiated at both the University of Washington and at the Boeing Company in which these restrictions are being removed.

The walls of the wind tunnel are represented in References 2 to 5 by means of an external image system (Fig. 7). This procedure represents a straight-forward extension of the methods of Prandtl (Ref. 11) and Glauert (Ref. 12). In the newer theoretical developments (Refs. 6 to 8), which are necessarily designed for large digital computers, it has been found more convenient to represent the walls by means of a vortex lattice. Initially, the strengths of the vortex elements are unknown; however, it is possible to set up a system of equations in the unknown strengths so as to meet the appropriate boundary conditions at each point on the wall. These equations are solved on the computer in matrix form to obtain the required vortex strengths and, subsequently, the interference throughout the test section. These interference velocities are then used to reposition the wake within the wind tunnel. The process is repeated in iterative fashion until the numerical results converge.

The vortex-lattice method is convenient for this work since programs for matrix inversion, to orders of several hundred, already exist for many computers. An additional advantage is the flexibility inherent in this approach. The same basic method can be used to treat nonrectangular, slotted, or finite-length wind tunnels, and seems particularly suited to treat the case of a tandem test section (Ref. 7).

Circular Wind Tunnel

Figure 8 shows one case in which the nonlinear theory has been applied by Robert G. Joppa of the University of Washington. The wind tunnel is closed and circular (approximated by a regular dodecagon) in cross section. The wing, of aspect ratio 4, has a span equal to the wind-tunnel radius, and is operating at a lift coefficient of 4. The wing is assumed to be uniformly loaded; thus, its entire vortex system consists of a single horseshoe vortex.

As indicated in figure 8, the wind-tunnel walls have a substantial effect upon the location of the wake. The effect of the change in wake position is seen in the longitudinal distribution of interference velocity. It may be seen that the contribution to the total interference of the changed wake position is such as to completely alter the distribution of interference behind the model. It is noteworthy that the inteference at the wing itself is essentially unaltered by the effect of the walls on the wake position.

Figure 8 illustrates the versatility of the vortex-lattice method for numerical analysis of wall effects. Although the circular wind tunnel is the simplest wind tunnel to analyze by image methods at the center of lift (Ref. 11), the solution for the distribution elsewhere in the wind tunnel can be quite difficult (Ref. 28) since no simple image system satisfies the boundary conditions.

Slotted Wind Tunnel

Although many unconventional types of test section (such as Ref. 29) have been proposed for V/STOL testing, the most commonly mentioned configuration is the slotted wind tunnel. At the Boeing Company, Ishwar Bhateley (Ref. 7) has been utilizing vortex-lattice techniques to study the interference in slotted wind tunnels. The sample shown herein does not yet include the effect of the walls upon the wake position; however, the analysis is rapidly being extended to include this effect.

The wind tunnel considered has a width-height ratio of 1.25 and is shown in Figure 9. There are three slots in each side wall and four slots each in the floor and ceiling; however, the slots are not uniform in either size or spacing. The average open ratio of the wind tunnel is approximately 11 percent. This configuration, at low lift coefficients, appeared to produce the smallest interference gradients, both longitudinally and laterally, of the large number of configurations studied. The wing for which results are presented is of aspect ratio 4.5 and has a span equal to 0.6 of the full wind-tunnel width.

The wing is rectangular and unswept; however, the spanwise loading is not assumed to be uniform.

Calculated interferences are presented (Fig. 10) for two cases, for which the wake shapes are shown. In the first case, the wake is assumed to pass directly rearward since the lift coefficient is a relatively moderate 1.35. In the second case, with a lift coefficient of 2.4, the wake is allowed to deform, uniformly across the span, so as to approximate the shape that it obtains in free air. It is evident from Figure 10 that wake deflection had only a negligibly small effect on the calculated interference angle and velocity distribution along the longitudinal axis.

On the other hand, the example wing at a lift coefficient of 2.4 is operating at a wake skew-angle of about 80° or an effective skew angle of 85° (Refs. 2, 17, and 30). Under such conditions, Reference 4 indicates that, even in a closed wind tunnel, the interference is affected to only a small degree by wake inclination. The experimental results of Reference 17, although for a different slotted wind-tunnel configuration, also indicate little effect of wake deflection on interference at small wake inclinations; however, large changes in interference, particularly at the tail, were noted in that case when the wake inclination was large.

CHOICE OF CORRECTION THEORY

It will be observed that the complexity of wind-tunnel interference calculations increases rapidly as the wake is described more precisely. Conventional theory, in which the wake passes directly downstream is the simplest theory. In this case most required correction factors may be found directly in published papers with configuration effects, such as finite span, already included.

Reference 4, which allows the wake to deflect in a straight line, requires an additional parameter (skew angle) to define the wake. Although voluminous tables of interference factors (Refs. 31 to 35) have been published for Reference 4, the production of such tables was rendered economic only by the omission of span effects. The factors for finite-size models must be obtained for each case by superposition of the values given in the tables.

Correction theories utilizing a curved wake require at least two parameters (such as V/V_j and θ_j) to describe the wake. This additional complexity appears to make the production of generalized tables an economic impossibility. On the other hand, calculation of the interference factors is still reasonably simple and can probably be accomplished in a computer of the size found in many on-line data reduction systems.

At the present time, the complexity of the nonlinear analyses appears to be such that they are not practical except when computed on the largest available computers. It appears that the major use of these theoretical developments may be in searching for minimum correction wind-tunnel configurations and in evaluating the limits to which the simpler linearized theories can be employed.

EFFECTS IN REAL WIND TUNNELS

All theoretical calculations deal with an idealized wind tunnel. The incoming flow is considered to be uniform to the walls. There is neither boundary layer nor separation from the walls. Such wind tunnels do not exist in a real world.

In practice a substantial boundary layer exists on all four walls of the wind tunnel. This boundary layer has numerous effects. Even when separation from the walls is not present, the boundary layer introduces problems of the effective location and character of the boundary assumed in theory. When large velocity gradients produced by the model actually separate the flow from a wind-tunnel wall, a quasi-free boundary replaces the solid boundary assumed by theory. Finally, when model disturbances at a wall are allowed to propagate forward in the low-energy boundary layer, an entirely unrepresentative flow field may result, thus invalidating the data.

Ground Effect Testing

One of the most significant results of the wind-tunnel boundary layer is the effect upon tests conducted in ground effect by using the wind-tunnel floor to simulate the ground. Many artifices have been used to minimize boundary-layer effects in such tests, particularly tests of automobiles and trains (Ref. 36). At high lift coefficients the effect of the boundary layer on the floor is magnified still further. The flow studies of Reference 37 show that the flow may penetrate forward in the slow moving boundary layer (Fig. 11) and severely distort the data from very high lift systems even at substantial heights above the ground.

Recently considerable emphasis has been given to the use of moving belts to eliminate the boundary layer and provide a more perfect simulation of the ground. Comparative tests with and without the belt running indicate that the belt is required (Fig. 12) for those combinations of lift coefficient and height which produce a fixed wake impingement distance on the floor behind the model. When the momentum skew angle of Reference 29 is used, the calculated impingement distance is approximately equal to the span (or 2.5 spans if the effective skew angle is used).

Extrapolation of the simple impingement distance rule indicated that a moving belt ground plane may be required for very high lift models even if the model is mounted at or above the center of the wind tunnel. Similar treatment of the ceiling could alleviate ceiling separation as well; however, the mechanical complexity of such an arrangement may be impractical.

Lateral Recirculation

During the past year systematic tests of rotors at the University of Washington (Ref. 10) have disclosed a recirculation phenomenon that appears to limit the maximum attainable wake deflection at which usable results can be obtained in a closed wind tunnel. The wake of the lifting system (Fig. 13) when sharply deflected is observed to approach the floor, flow laterally toward and then up the walls, and finally pass downward again in the center of the wind tunnel. When the wake deflection is sufficiently severe this circulatory flow actually envelops the model. Under such conditions, the wind-tunnel flow does not adequately represent free-air conditions and the resulting data may be meaningless.

The data of Reference 10, for a wide range of wind-tunnel configurations, can also be correlated with impingement distance. This correlation is shown in Figure 14, where the impingement distance is calculated using the momentum theory skew angle of Reference 30. The abscissa is an unusual quantity, being the rectangularity of the wind tunnel; that is, either the width-to-height ratio or the height-to-width ratio, whichever is greater than one.

Note that the smallest impingement distance leads to the highest allowable downwash or, conversely, the lowest minimum speed. Thus, from Figure 14, it is evident that the square wind tunnel, particularly when it has corner fillets is the least desirable. Physically this observation simply indicates that it is easiest to start a circulatory flow in those wind tunnels which are most nearly circular. The most desirable wind tunnels, from the viewpoint of lateral recirculation, are those having rectangularities on the order of 1.25 to 1.5.

This phenomenon is not limited to rotors since data obtained at the Langley Research Center for jet-flap and tilt-wing models also fit this correlation curve as indicated. All of these configurations, however, have the lift distributed more or less uniformly across the span. Recent data on several multiple and single jet-lift VTOL models at the Boeing Company (Ref. 18 and unpublished data) indicate that the limiting conditions may be altered if the lift is concentrated in several discrete and widely separated points. Additional study of configuration effects appears to be warranted.

Numerous "fixes" for this problem can be envisioned. Preliminary unpublished studies of floor strakes by Rae at the University of Washington indicate that floor strakes can help; however, unless the strakes are placed at exactly the proper point on the floor, they appear to do more harm than good. It might be surmised that a belt, by retaining the full wind-tunnel velocity to the floor, would help to sweep the wake down the wind tunnel and thus delay the onset of difficulty. This has not yet been tried experimentally; however, this and similar experiments are planned at several laboratories.

CONCLUDING REMARKS

This survey of wall effects at extreme force coefficients indicates that the available linearized theory satisfactorily predicts the major part of wall effects for V/STOL models. The linearized theory is being extended to wakes of large curvature. Nonlinearized theories which include the effect of the walls on the wake position are also being developed. The techniques of the nonlinear theory are applicable to slotted, nonrectangular, and tandem test sections.

The complexity of the nonlinearized theory is such that its initial use probably will be limited to studies aimed at low correction tunnels and at determining the limits of linearized theory.

The major problem in applying wall effects theory to V/STOL data lies in evaluating the effect of nonuniform interference gradients on the model performance and stability. No adequate theory exists for many V/STOL configurations.

Several effects in the real wind tunnel tend to limit the range of conditions for which a wind tunnel may be used in V/STOL testing. Some treatment of the boundary layer on the floor is required for tests at very large lift coefficients. In addition, lateral recirculation tends to limit the maximum allowable downwash angle in the wind tunnel. Research aimed at alleviating this latter problem is now in progress.

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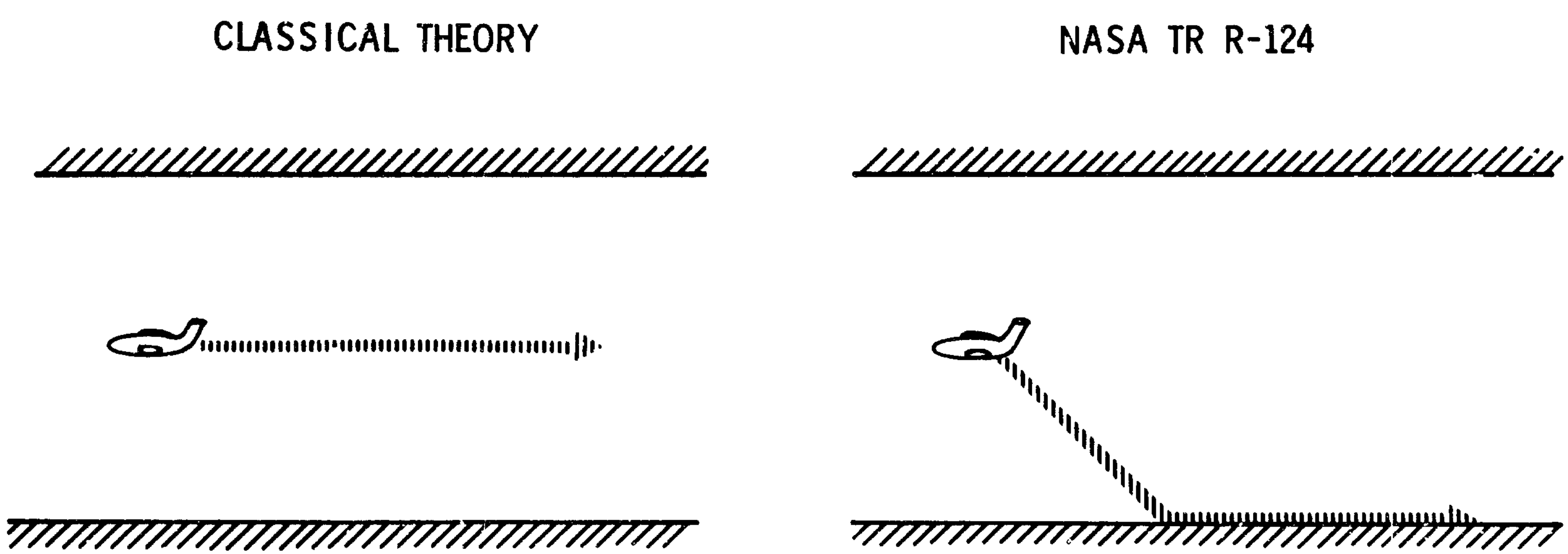

Figure 1.- Assumed wake.

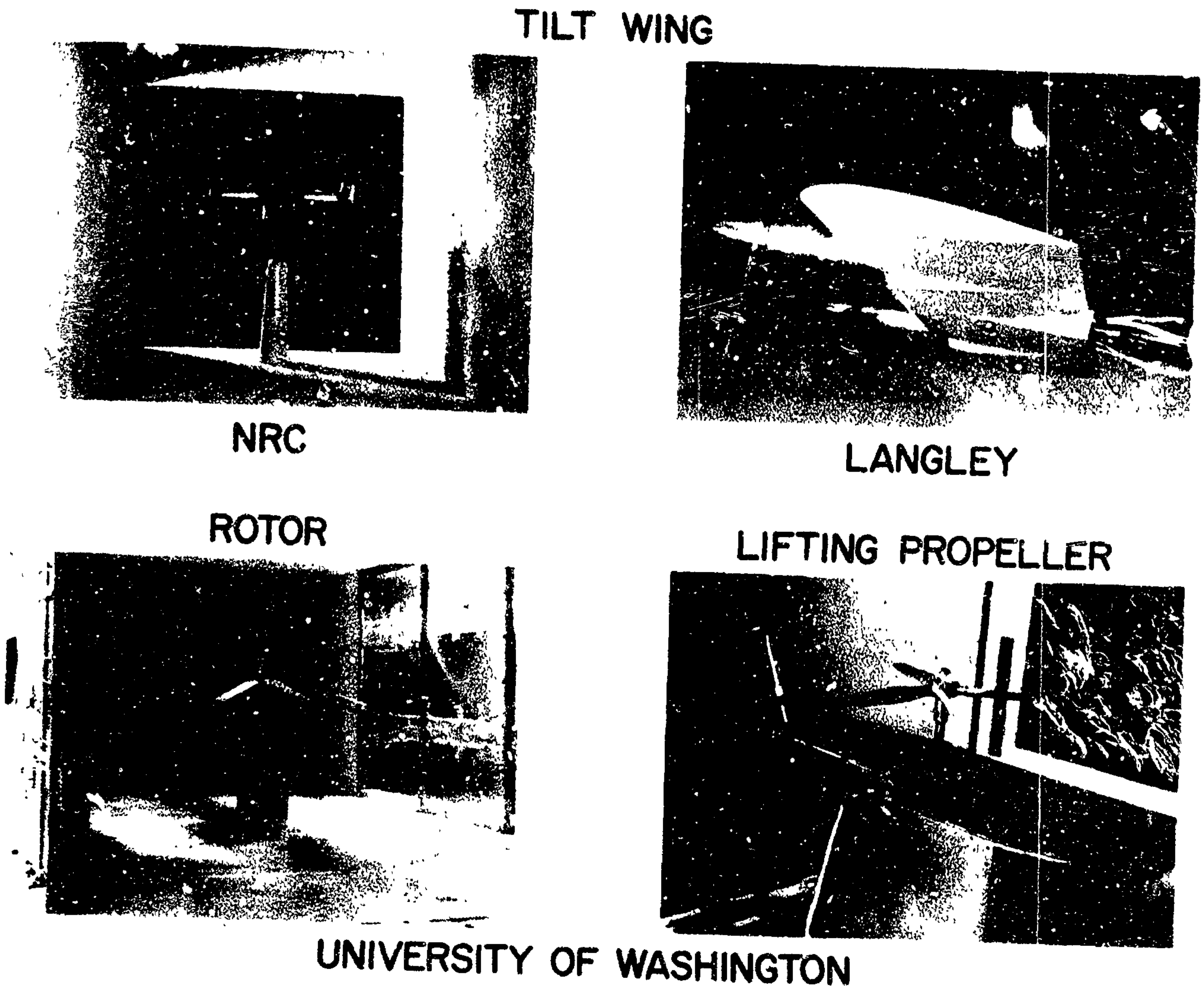

Figure 2.- Models tested in verifying theory of NASA TP R-124.

FAN IN FUSELAGE FAN IN WING

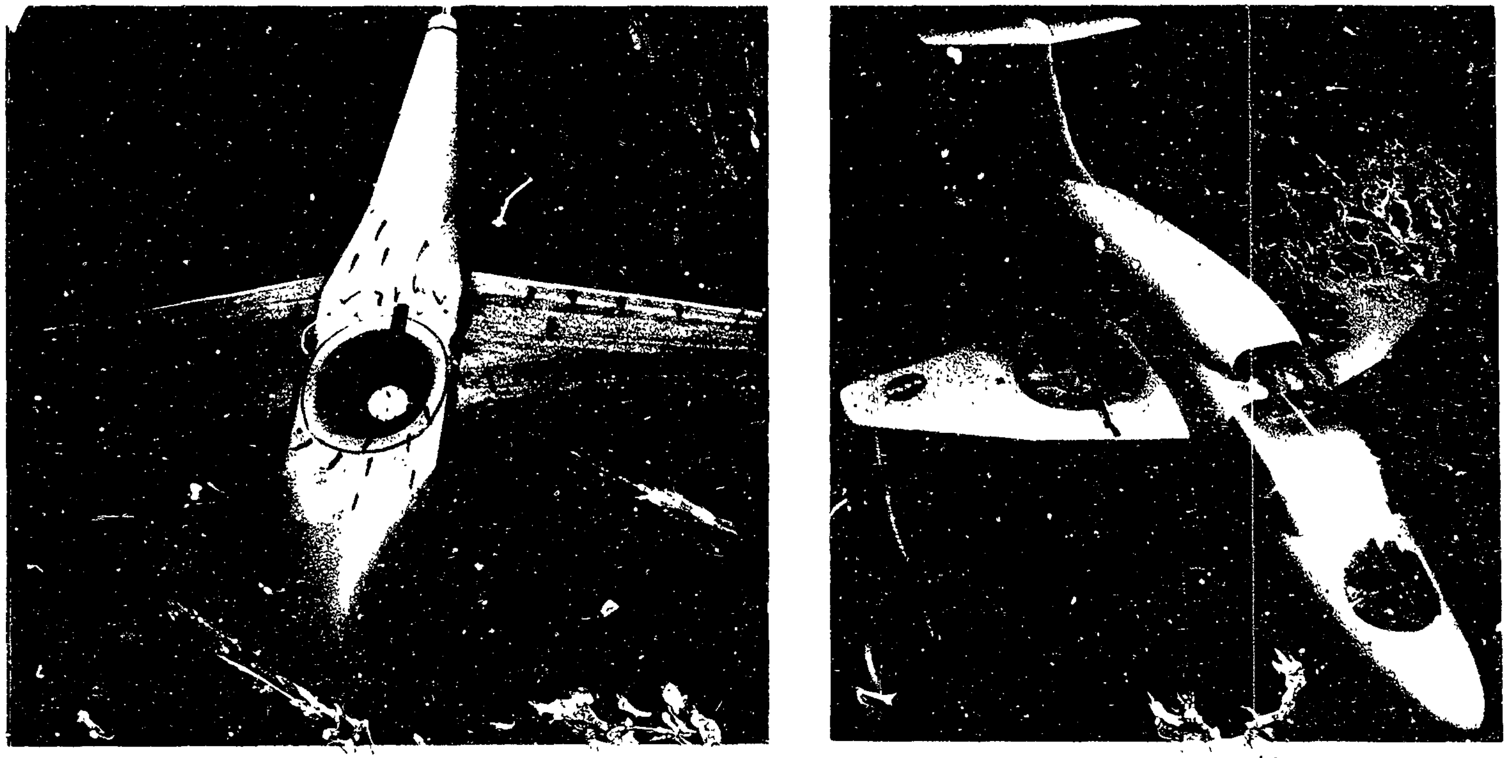

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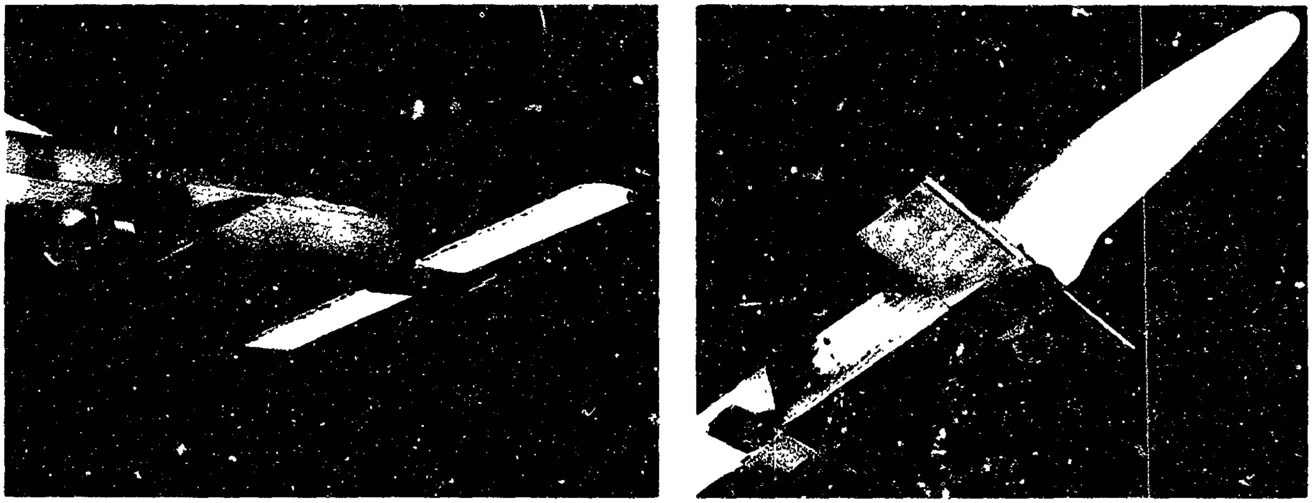
Figure 2.- Continued.



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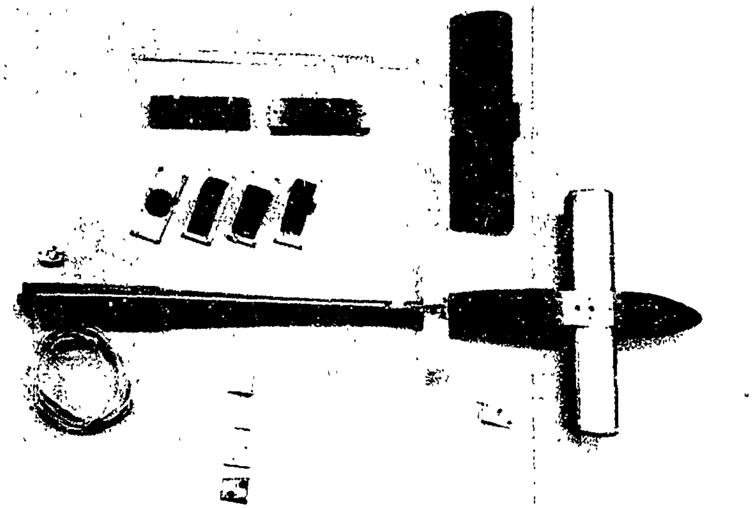

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Figure 2.- Concluded.

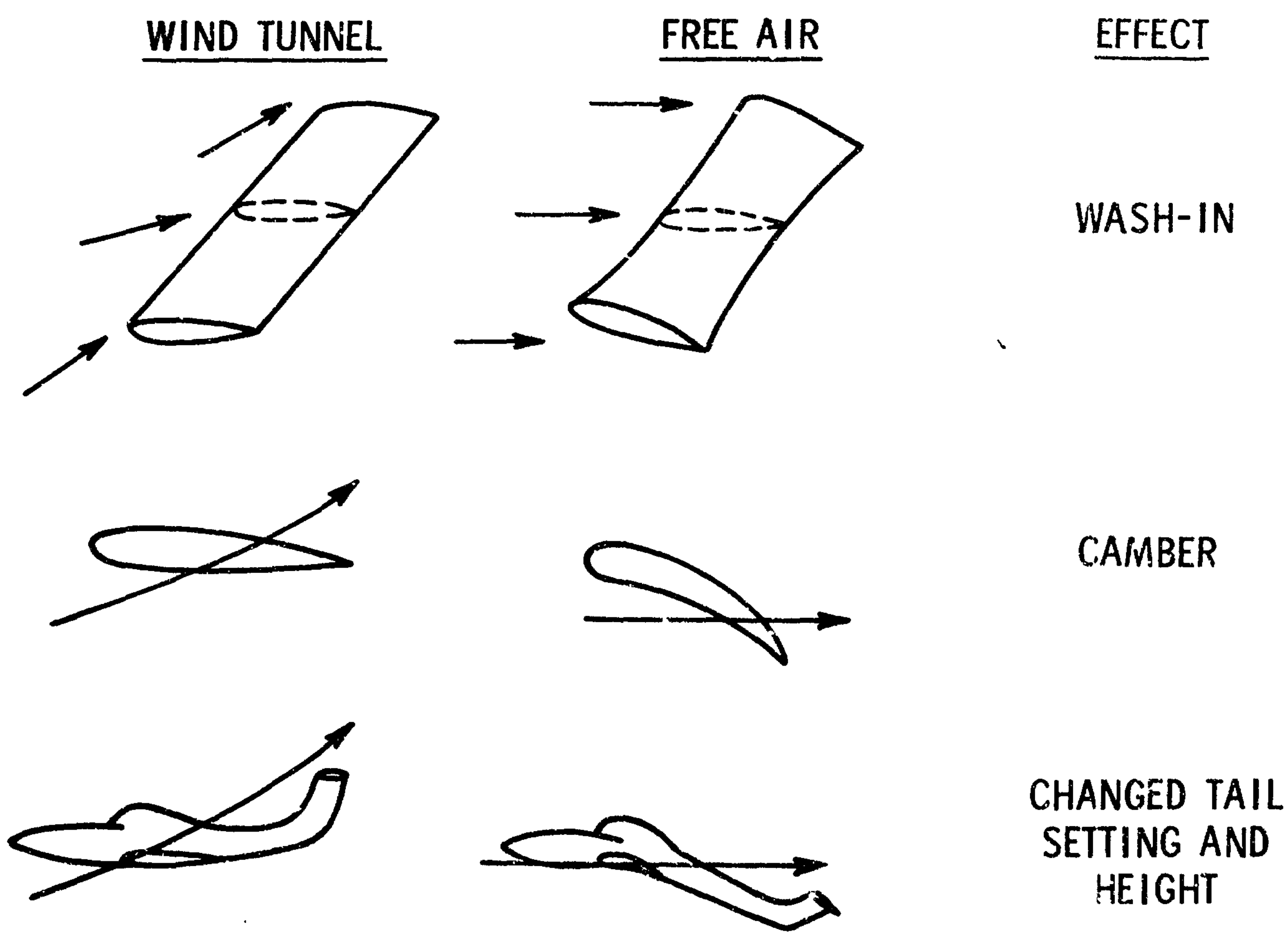


Figure 3.- Nonuniform interference as effective distortion.

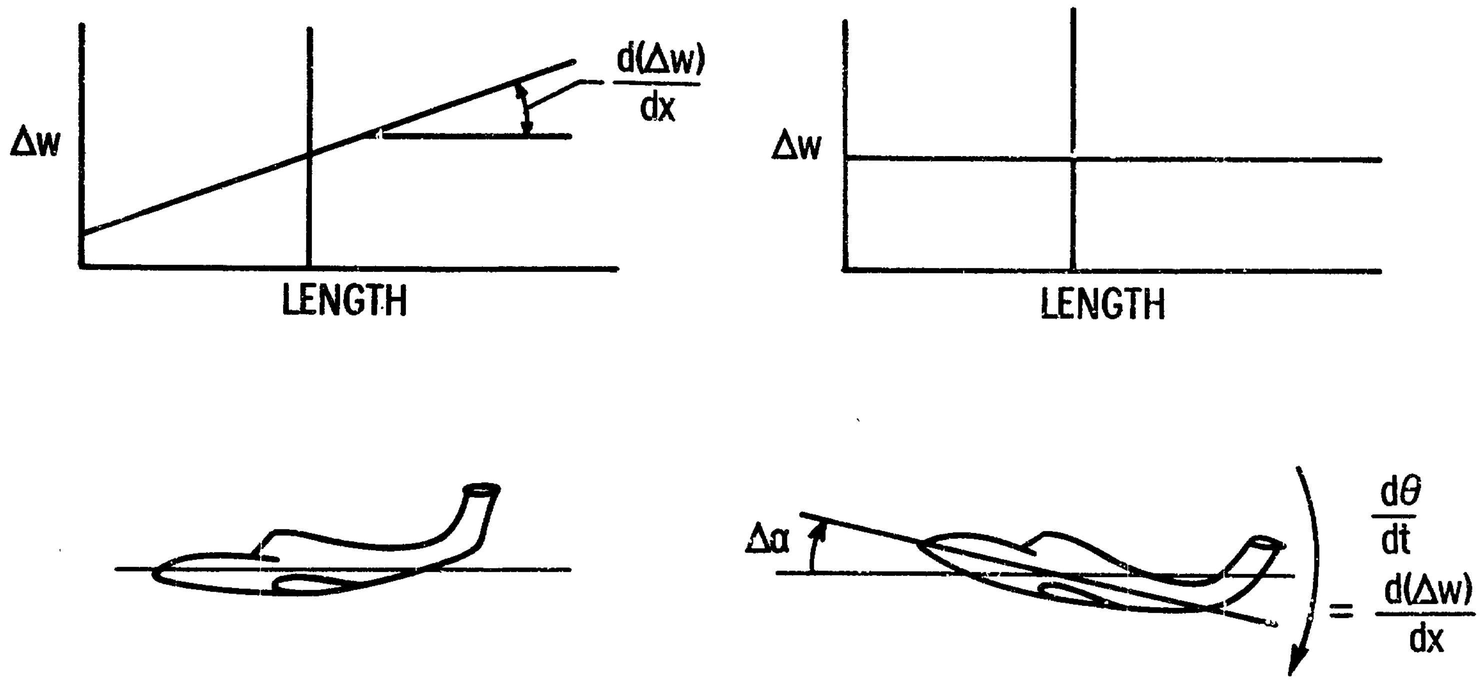
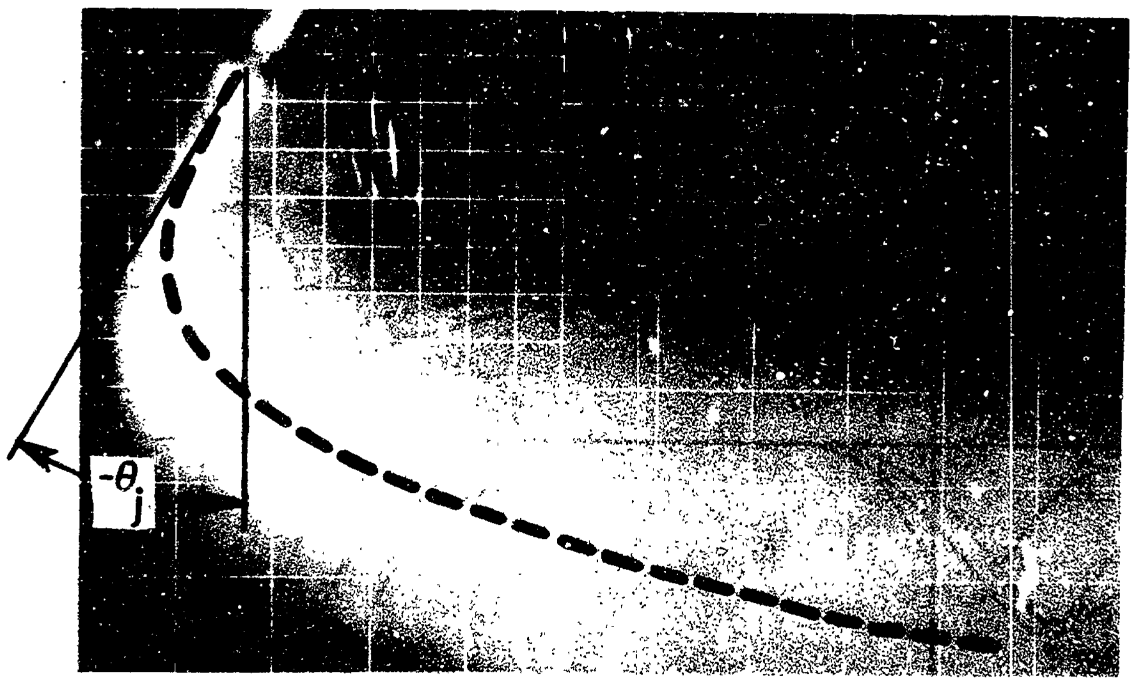


Figure 4.- Nonuniform interference as effective rotation.



$$\frac{x}{D} = \frac{1}{4}\left(\frac{V}{V_j}\right)^2 \left(\frac{-z}{D}\right)^3 \sec^2 \theta_j + \left(\frac{-z}{D}\right) \tan \theta_j$$

Figure 5.- Shape of jet wake.

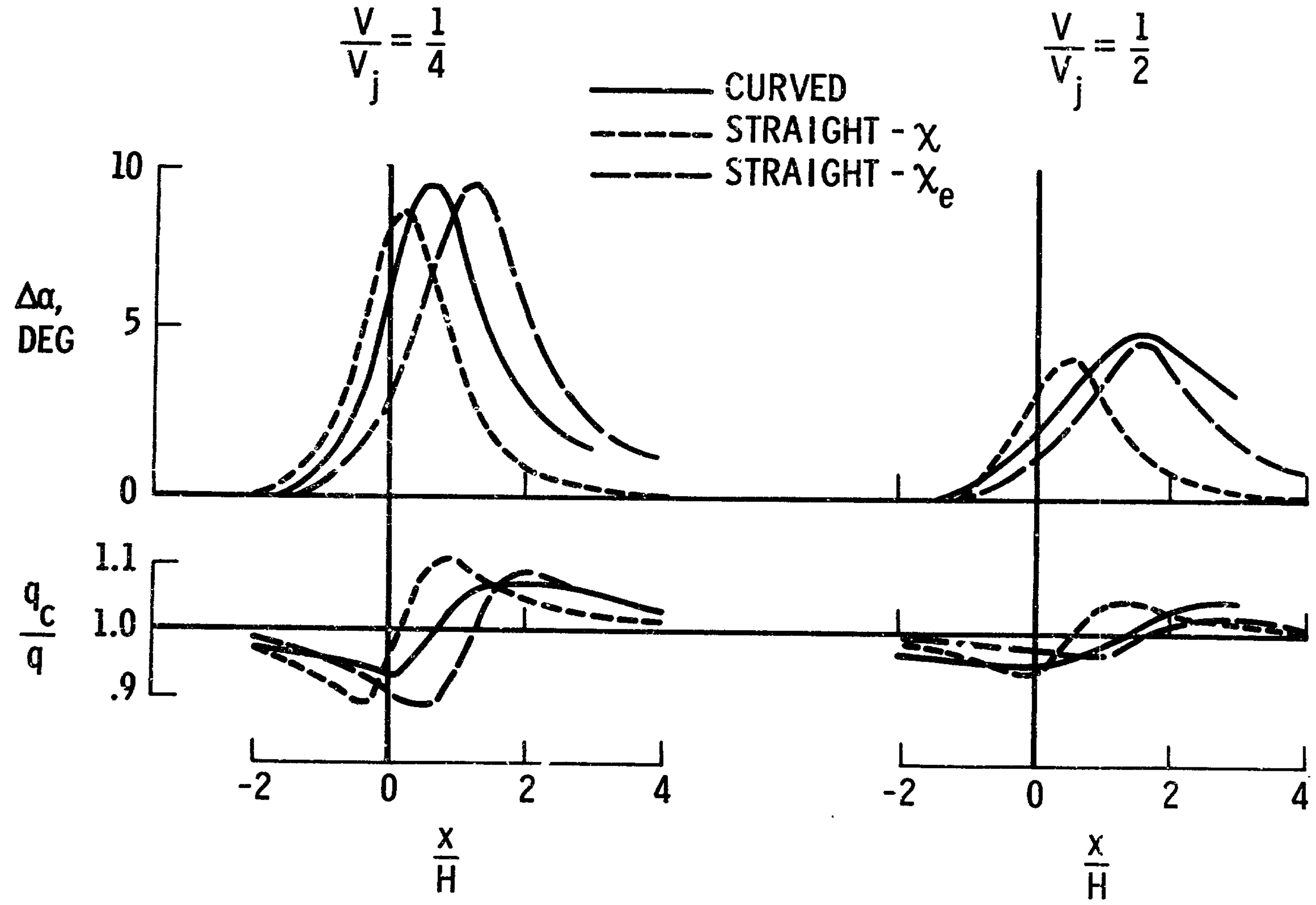


Figure 6.- Interference with curved wake.

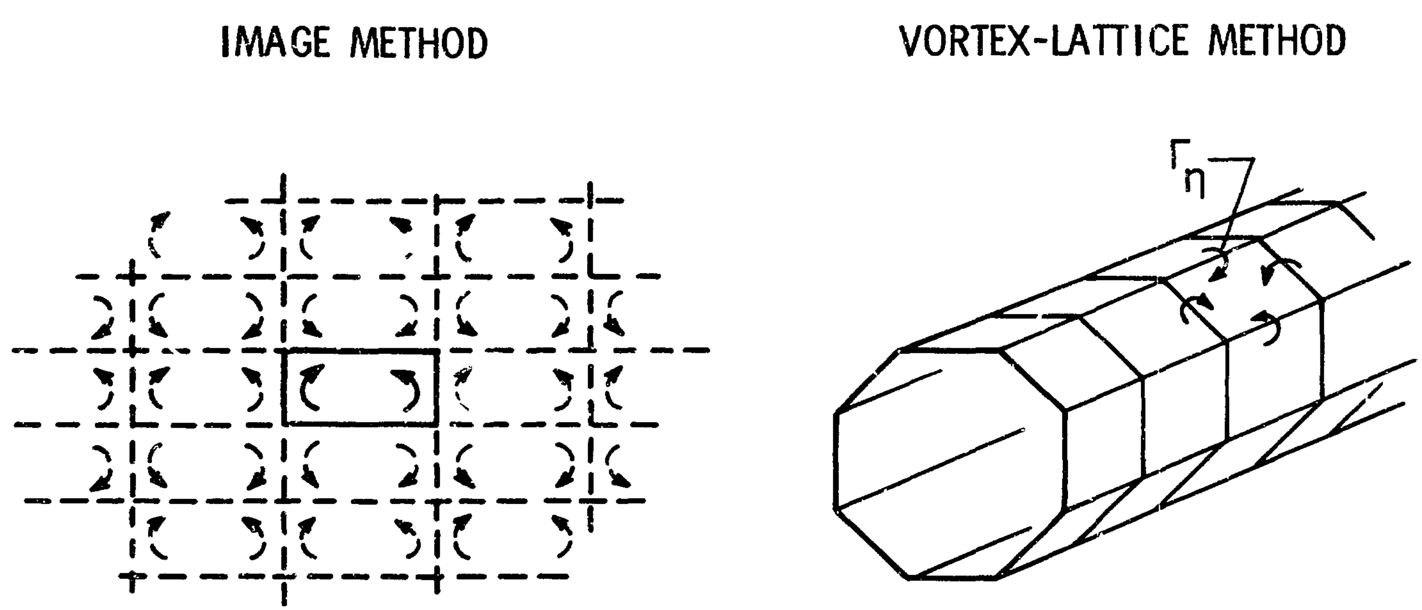


Figure 7.- Computing wall effects.

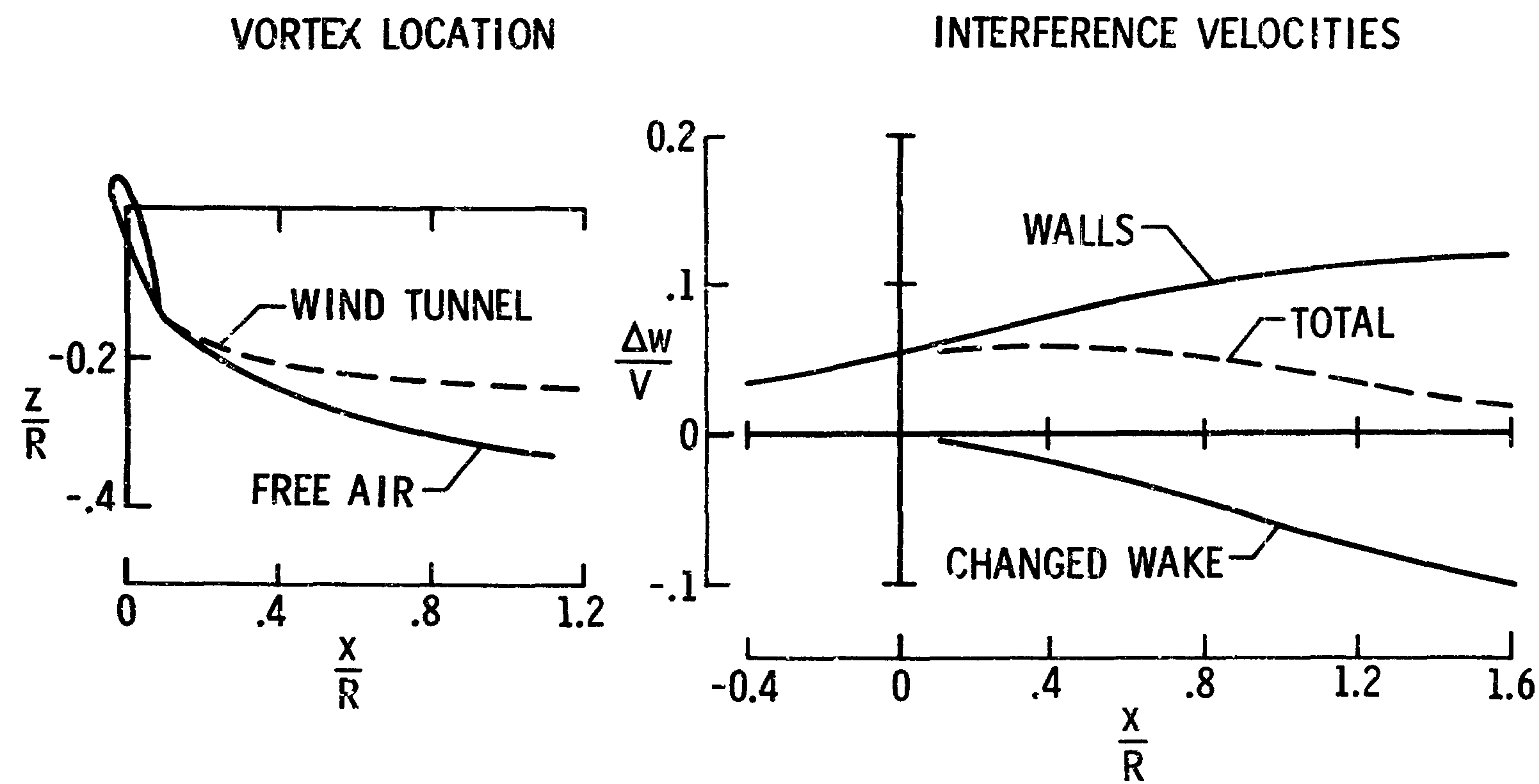


Figure 8.- Interference on axis of circular tunnel.

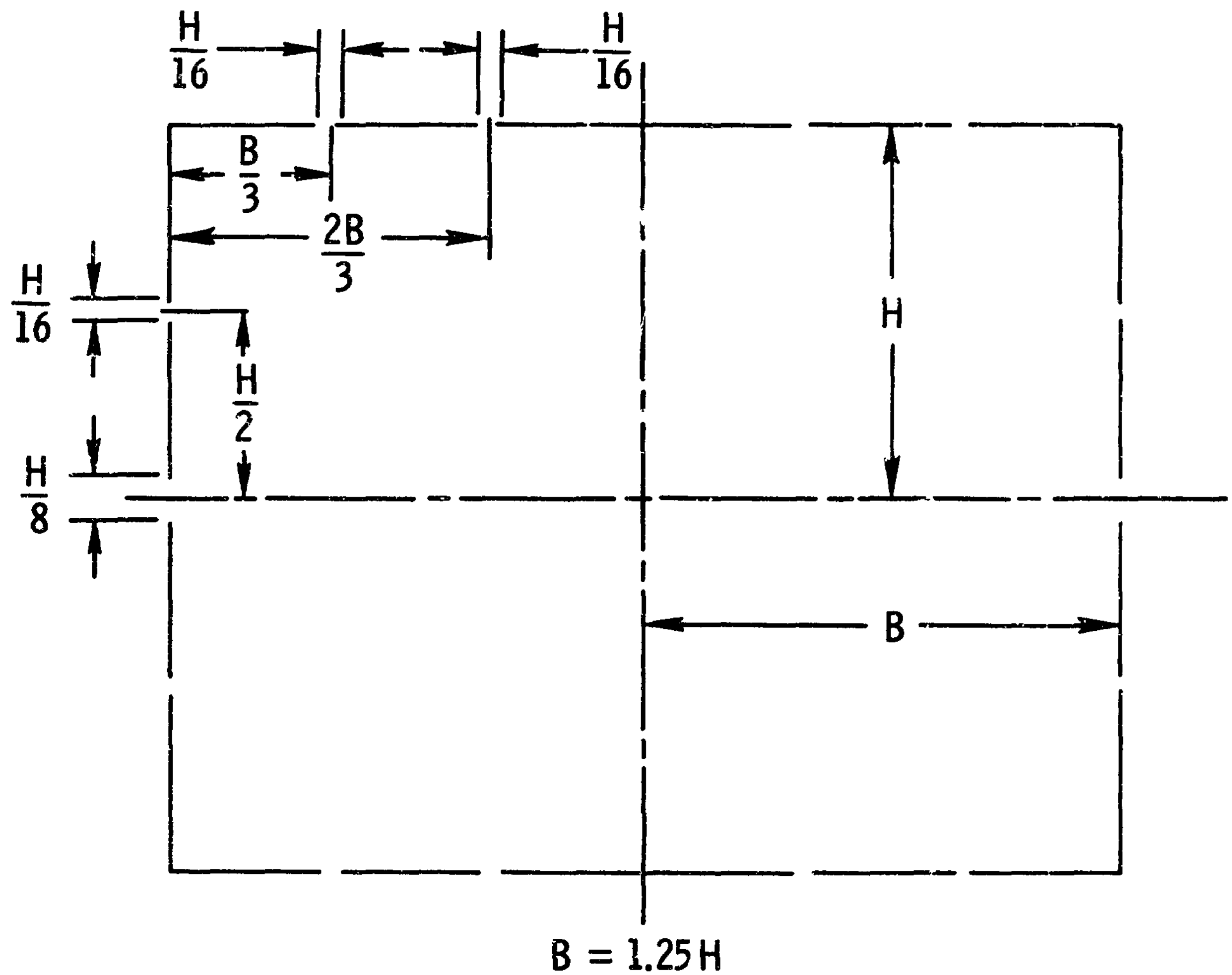


Figure 9.- Slotted wind tunnel.

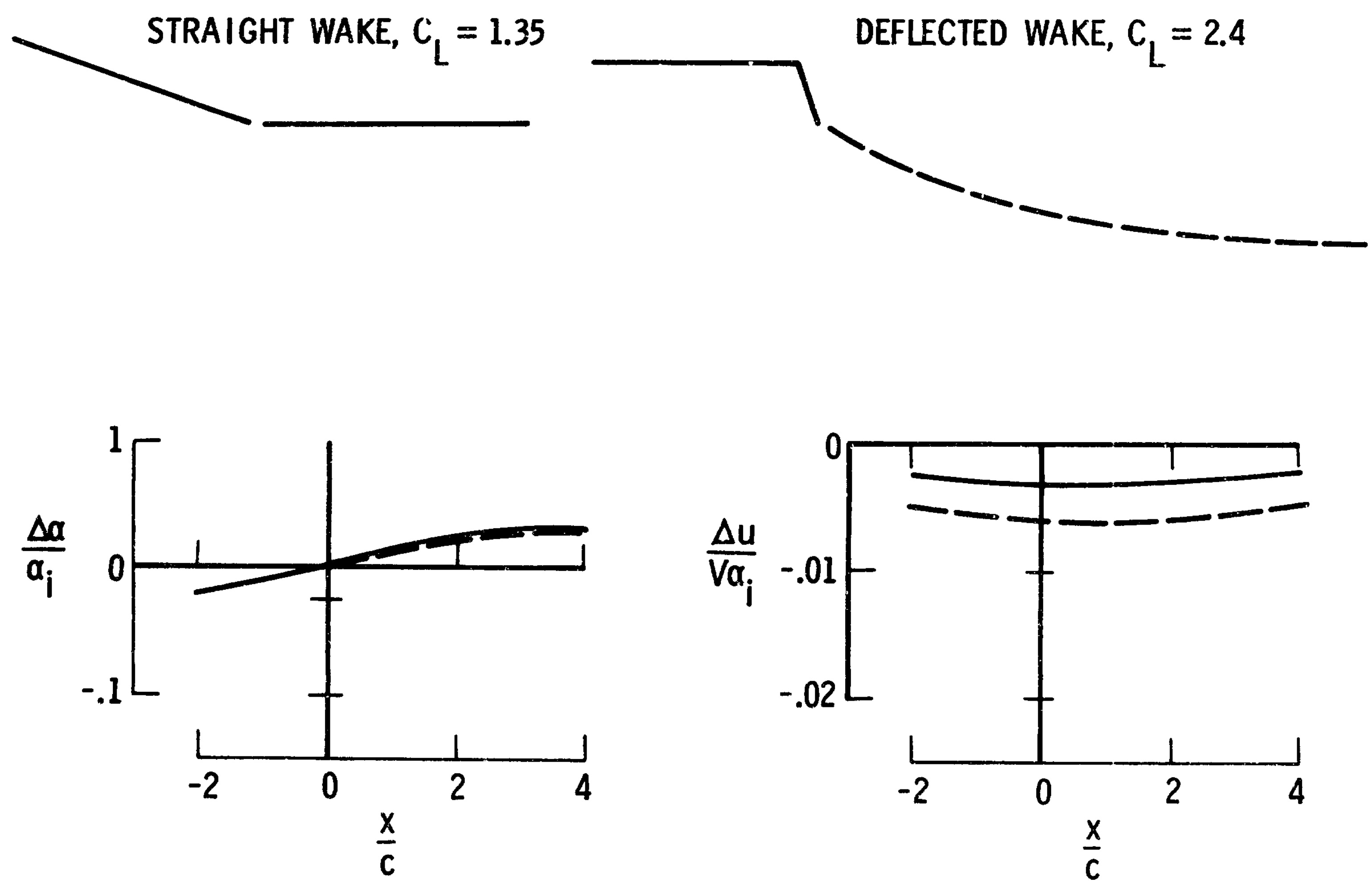


Figure 10.- Interference in slotted wind tunnel.

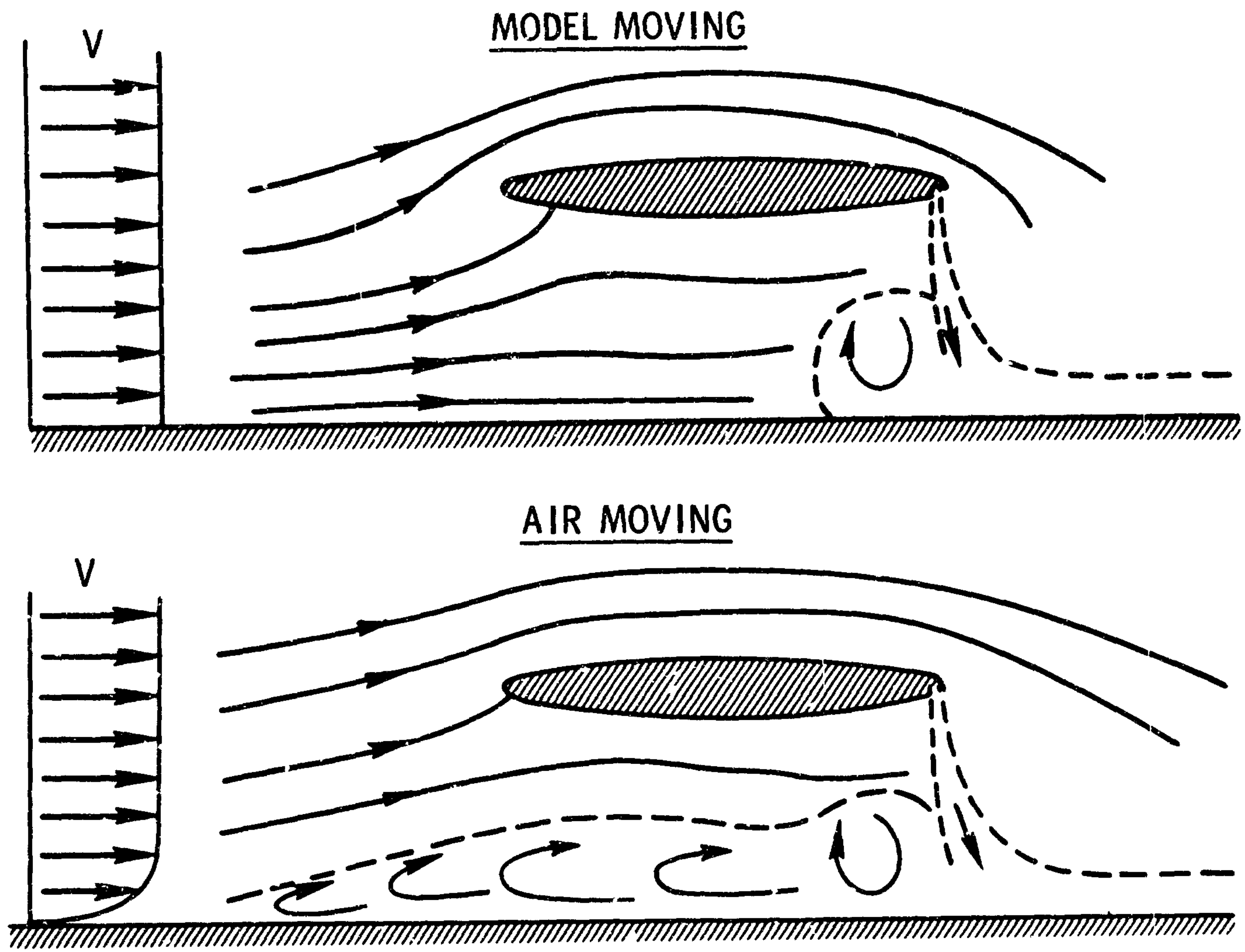


Figure 11.- Flow studies over ground plane.

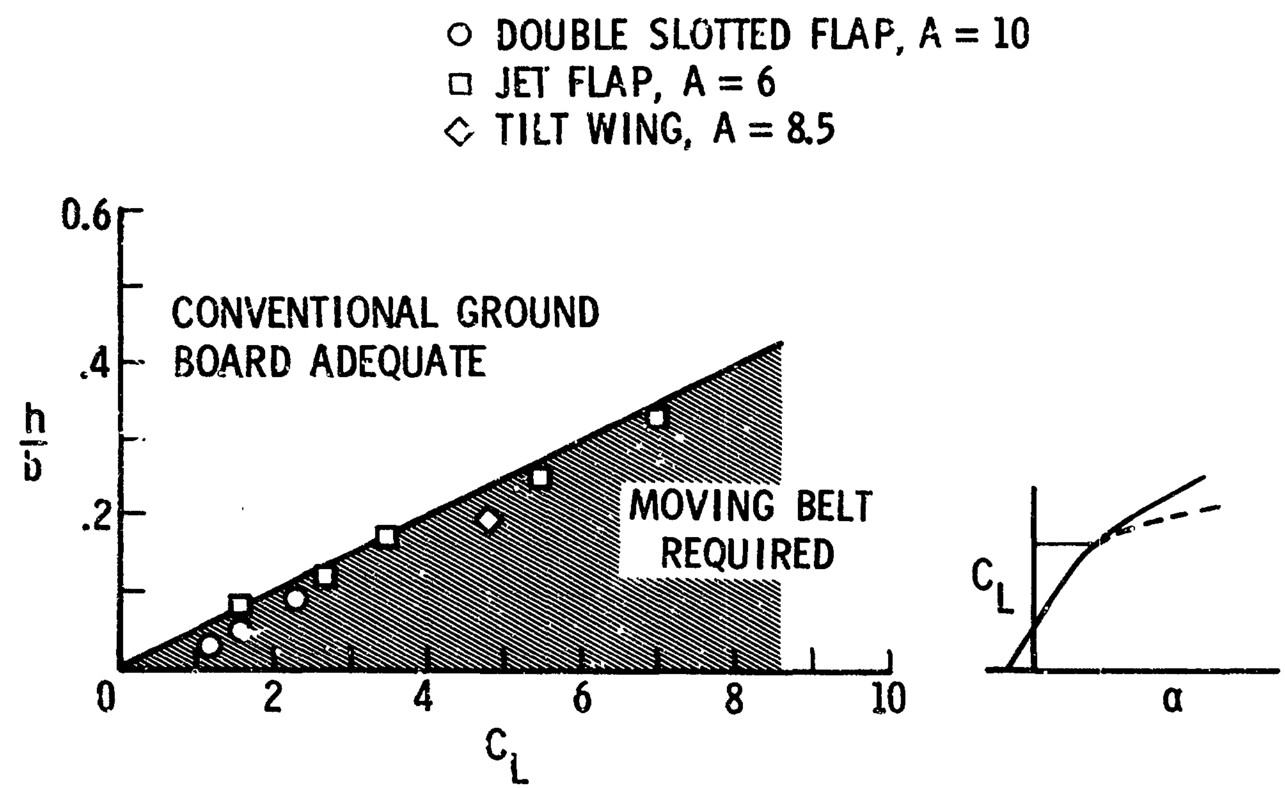


Figure 12.- Conditions requiring endless-belt ground plane.

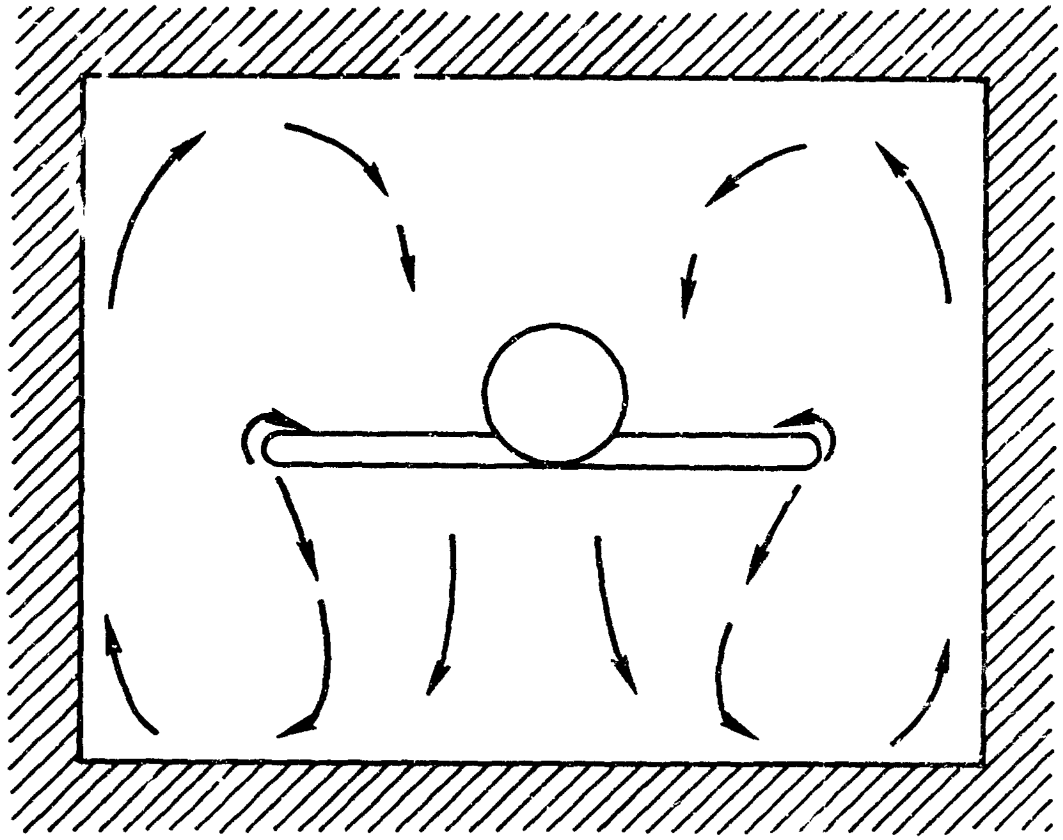


Figure 13.- Flow behind lifting model.

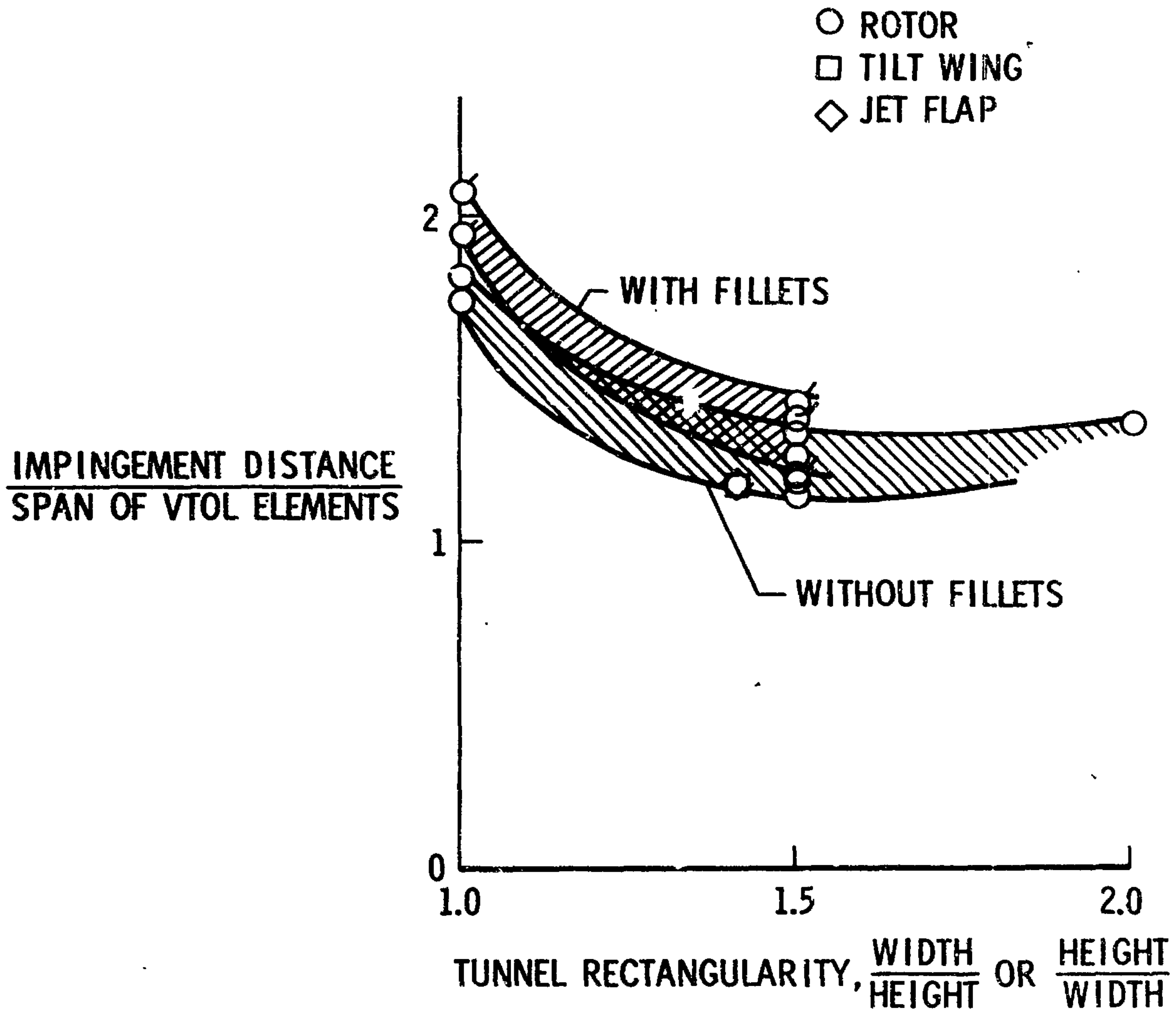


Figure 14.- Lateral recirculation limits.

NASA-Langley, 1967