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THEORETICAL STUDY OF THE USE OF VARIABLE GEOMETRY IN THE DESIGN OF MINIMAL-CORRECTION V/STOL WIND TUNNELS

by Harry H. Heyson

Langley Research Center
Langley Station, Hampton, Va.

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SUMMARY

Theoretical study indicates that, if either the width-height ratio or the model height is properly scheduled, the vertical interference velocities at the lifting system can be reduced to zero in closed-on-bottom-only tunnels. Reductions in interference at the tail, nonuniformity of interferences, and minimum speed for recirculation-free testing can be obtained simultaneously; however, these reductions are much greater in the case of variable width-height ratio. Variable width-height-ratio operation of a closed tunnel can reduce the interference at the lifting system by a factor of 2 or 3. This configuration, at low speeds, can reduce interference at the tail, nonuniformity of interference, and minimum speed for recirculation-free testing to almost negligible values.

INTRODUCTION

The large magnitude of wind-tunnel wall interference in V/STOL testing has been documented for several years (for example, ref. 1). The magnitude of these wall effects is calculable by theory (refs. 2 to 4), and substantial experimental evidence indicates that the theoretical results can be used to correct wind-tunnel data for wall effects (refs. 5 to 11). On the other hand, there is little comfort to be found in applying theoretical corrections for large wall-induced angularities (which may exceed 10°) when it is recognized that large corrections, with the associated large flow distortions, may effectively alter the configuration of the model from a viewpoint of aerodynamic equivalence. Furthermore, omission in the corrections, whether by simplification or oversight, of factors which influence the corrections (for example, finite span, load distribution, changes in model or tail position as a function of angle of attack (ref. 12) may produce significant errors when the corrections are large. Thus, it is highly desirable to find some means whereby the magnitude of V/STOL wall effects can be significantly reduced; however, unless the wall effects are actually reduced to zero, it is still required that a means be available to calculate and correct data for such wall effects that remain.

If all other considerations are equal, wall effects depend directly upon the ratio between an area associated with the model and the cross-sectional area of the wind-tunnel test section. Thus, the classic solution to the problem of large wall effects has been to either run the tests in a larger wind tunnel or to reduce the size of the model. While this procedure reduces wall interferences, a larger wind tunnel may not be available, and there are limits (occasioned by both Reynolds number and the minimum physical size of motors and other model components) to the minimum-size model that can be utilized. In the case of full-scale wind-tunnel tests of an actual aircraft, little or nothing can be done to reduce the corrections by means of reducing the area ratio, since the model size is fixed and only one or two wind tunnels in the world possess the physical size necessary to mount the model.

Wall-interference theory, in general, obtains only the wall-induced distortions of the flow field near the model. In order to correct wind-tunnel data, the effect of the field distortion on the model performance must be obtained from the available theoretical treatments of the model aerodynamics in free air. The rigorous conversion from interference field to correction may prove difficult even in the case of simple conventional airplanes for which 50 years of theoretical studies provide a vast body of material with which to work. For many V/STOL models, essentially no theoretical background exists. Under such circumstances, it may prove impossible to use the wall-interference calculations to provide rigorous corrections.

The alternative is to develop test-section configurations with zero or near-zero wall effects. Several such configurations have been found and utilized in conventional testing where the wake essentially passes directly downstream (refs. 13 and 14). In addition, studies (such as ref. 15) of slotted wind tunnels developed primarily from the consideration of transonic choking, have disclosed numerous other configurations which possess zero, or near zero, "lift interference" for the case of an undeflected wake. At the present time, a number of slotted tunnels intended for low-speed V/STOL testing are under construction. Wall interference in these tunnels is under study, both theoretically and experimentally (refs. 16 to 20). Theoretically, it should be noted that zero longitudinal interference is not obtained simultaneously with zero vertical interference at a single slot opening under undeflected-wake conditions (ref. 15). It is not reasonable to assume that this trend will be changed by the inclusion of large wake deflections; indeed, experimental observations (refs. 10, 19, and 20) indicate that the two interferences do not vanish simultaneously in V/STOL testing. Slots markedly reduce the wall interference in all cases tested. The reduction is not completely to zero, however, and the current lack of an adequate theory to account for the remaining interference when testing with highly deflected wakes poses a certain element of risk in the use of slotted tunnels.

References 10, 19, and 20 report tests in which a closed tunnel is completely opened behind a given longitudinal station in the test section. This truncated test section yielded very small corrections when the opening commenced at the model location. Such results might be anticipated from the theoretical study presented in reference 21. It will be noted, however, that references 19 and 21 indicate large longitudinal gradients of interference. Thus, the truncated test section would be expected to show large wall interferences on pitching moments and even on the performance of very long lifting systems (such as tandem-rotor helicopters). In addition, the theoretical treatment of wall interference in such sections is exceedingly difficult (ref. 21) even for an undeflected wake.

The streamline matching technique of reference 22 appears feasible and is presently under study. In this technique, the free-air flow field of the model is calculated at the location of the walls, and the flow angles at the walls are then adjusted (by means of louvers, air jets, etc.) to coincide with the calculated free-air field. Theoretically, this technique totally removes the wall interference. The calculation of the flow field for an arbitrary high-lift model is difficult and may require several hours on a large digital computer. It will be noted that the calculation is, in general, a far-field calculation (allowing some simplification) except at the regions where the free-air wake is at the wall locations. The detail to which the flow in this latter area must be computed in order to obtain acceptable results is unknown at present. Experimental studies are underway (ref. 22) in order to determine the degree of accuracy in streamline matching that is actually required in practice.

References 2 to 4, which are theoretical treatments of wall effects in more conventional test sections, note that no single configuration was found which yielded a zero-correction test section for all wake-deflection angles (or skew angles). On the other hand, several configurations, such as the closed-on-bottom-only tunnels, were found in which the vertical interference due to lift (corresponding to the classical lift interference) becomes zero at one wake deflection angle. It would appear that a judicious application of variable-geometry to such configurations, with the geometry alterations applied as a function of wake deflection, would result in a wind tunnel with zero vertical interference due to lift. This single component of interference, in general, produces most of the observed wall interference. There would remain much smaller contributions from the horizontal interference due to lift as well as from both horizontal and vertical interference due to induced drag. These remaining contributions produce only small effects on the model characteristics, and the theoretical corrections can be applied with confidence.

Reference 9 points out that the deflection of the rolled-up wake should be used in applying the theory of references 2 to 4. This deflection is in contrast to the original usage of the deflection as obtained directly from momentum theory. Since the rolled-up wake has only approximately half the momentum deflection (at the center of lift), it is necessary to provide only sufficient variable geometry to null the correction over a much smaller range of wake deflections. This feature alone significantly reduces the severity of the required changes.

Several classes of wind tunnels are considered herein. These include closed-on-bottom-only configurations in which either the model height or the tunnel width-height ratio is varied as a function of wake deflection. Similar closed-tunnel arrangements are also considered since, even though the interference factor cannot be nulled in these tunnels, it can be minimized.

Since the corrections are conditioned by the model size and configuration, calculated results are presented for straight wings of various span-width ratios as well as for a vanishingly small lifting system. The effect of configuration is indicated by calculated results for wings of differing sweep and for a lifting rotor of finite size.

The corrections at the model tail are also considered since these corrections differ from those at the lifting system. Calculations for several different tail lengths are made and presented. The variation of interference with tail length provides an indication of the magnitude of the interference gradients at the lifting system itself. These latter gradients are significant since they can produce significant effects on wind-tunnel data, particularly with regard to pitching moment (ref. 18).

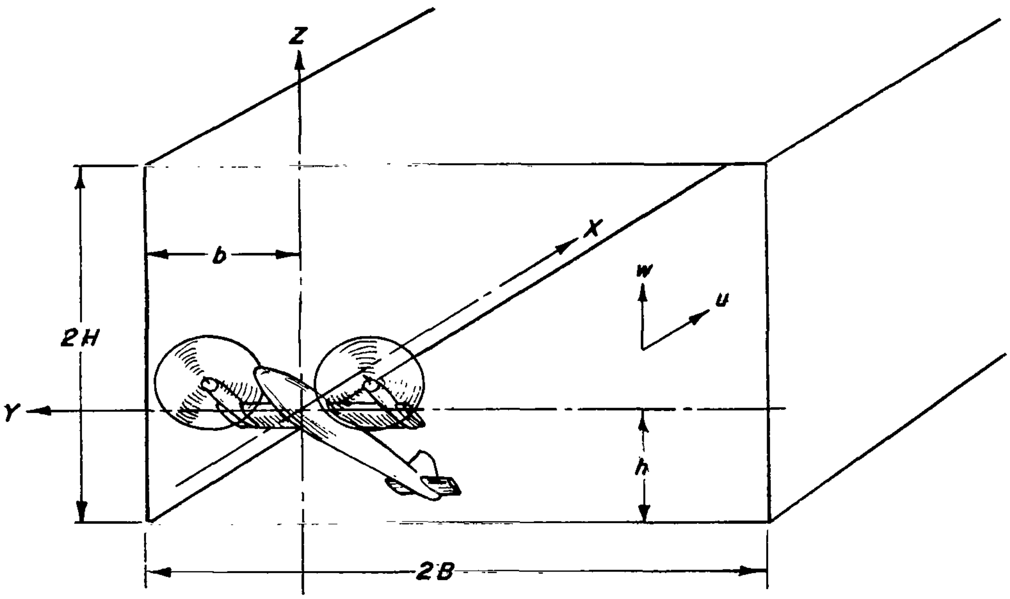
The lateral distribution of interference over wings with finite span-width ratio in the variable-geometry tunnels is studied briefly. Comparisons are made between the distributions in the fixed and variable-geometry tunnels.

One of the most significant developments in V/STOL testing has been the recent discovery by Rae of the University of Washington (ref. 23, see also refs. 18 and 24) of the effect of recirculation on limiting the minimum speed at which acceptable data can be obtained in a closed wind tunnel. Similar effects may be expected in the closed-on-bottom-only configuration as well, if for no other reason than the presence of a boundary layer on the closed floor of the wind tunnel (ref. 25). In any event, the occurrence of this phenomenon can be related to the downstream distance of the intersection between the theoretically straight wake and the floor. Thus, this effect is studied herein by examining the relative behavior of the foregoing impingement distance in the various wind-tunnel configurations.

The provision of variable geometry in a wind tunnel poses many related practical problems in the design of the entrance, diffuser, balance, fan, and drive systems. Several of these problems are discussed briefly in connection with each of the tunnel configurations examined herein. In certain types of variable-geometry tunnel, the same features used to negate V/STOL wall interference can be used to provide test capabilities other than those usually available in a fixed geometry wind tunnel. Several of these additional capabilities are noted.

SYMBOLS

The selection of a single set of symbols and definitions for the wide variety of aerodynamic systems encountered in wind-tunnel work does not allow complete conformity with existing practice. The following list sets forth the terminology used herein. Positive directions are self-consistent, that is, all forces, directions, and velocities are positive when directed in the positive sense of the chosen axes, as illustrated in the sketch below. Similarly, all moments and angles are positive in the direction of the right-hand rule with the chosen axes. Certain unusual features result (e.g., a negative induced velocity w_0 results from a positive lift L). The reader should carefully consider the following definitions and make appropriate conversions for his own use. It should be noted that these definitions as applied to wings differ from reference 12 in that the origin is chosen to be at the aerodynamic center in the present paper.



A_m momentum area of lifting system

A_T cross-sectional area of test section

b distance from right-hand side of test section (viewed from behind) to origin in model

B	semiwidth of test section
C_L	lift coefficient
COB	abbreviation for closed on bottom only
D_i	induced drag
h	height of model aerodynamic center above test-section floor
H	semiheight of test section
l_t	tail length, distance of tail aerodynamic center behind model aerodynamic center at zero angle of attack
L	lift
R	rotor radius
s	semispan of wing
u	interference velocity in x-direction
u_0	mean, or momentum theory, value of model induced velocity along X-axis, positive rearward
V	tunnel airstream velocity
w	interference velocity in z-direction
w_0	mean, or momentum theory, value of model induced velocity along Z-axis, positive upward
w_h	hovering induced velocity, value of w_0 when hovering with both zero forward speed and drag
x_f	theoretical impingement distance of straight-line wake on floor measured from model

$(x_f)_{\mathfrak{C}}$ value of x_f when model is fixed at center of the tunnel

x,y,z distances from origin along X,Y,Z axes, positive when in positive direction of axis

X,Y,Z Cartesian axes with origin at the model aerodynamic center, parallel to tunnel axes; X positive rearward, Y positive to right when viewed from behind, Z positive upward

α angle of attack

γ width-height ratio of tunnel, B/H

$\delta_{u,D}$ interference factor for horizontal interference velocity due to drag, defined implicitly by $\Delta u_D = \delta_{u,D} \frac{A_m}{A_T} u_0$

$\delta_{u,L}$ interference factor for horizontal interference velocity due to lift, defined implicitly by $\Delta u_L = \delta_{u,L} \frac{A_m}{A_T} w_0$

$\delta_{w,D}$ interference factor for vertical interference velocity due to drag, defined implicitly by $\Delta w_D = \delta_{w,D} \frac{A_m}{A_T} u_0$

$\delta_{w,L}$ interference factor for vertical interference velocity due to lift, defined implicitly by $\Delta w_L = \delta_{w,L} \frac{A_m}{A_T} w_0$

ΔH height of model aerodynamic center or rotor center above wind-tunnel centerline

Δu_D horizontal interference velocity due to drag

Δu_L horizontal interference velocity due to lift

Δw total vertical interference velocity

Δw_D vertical interference velocity due to drag

Δw_L vertical interference velocity due to lift

$\Delta\delta_{w,L}$ difference between interference factors for vertical interference velocity due to lift at the tail and at the center of lift

ζ ratio of test-section semiheight to height of model aerodynamic center above floor, H/h

Λ wing sweep angle, angle between lateral axis of model and lifting line, positive rearward

σ span-width or diameter-width ratio, s/B or R/B

σ_t span-width ratio of tail, $\frac{\text{Tail semispan}}{B}$

χ effective wake skew angle, angle between effective center of rolled-up wake and negative Z-axis, positive rearward

χ_m momentum-theory value of wake skew angle at the lifting system

Superscript:

* referenced to high-speed section with $\gamma = 2.0$ $\left(\text{for example } \delta^*_{w,L} = \delta_{w,L} \frac{A^*_T}{A_T}\right.$ so that $\left.\Delta w_L = \delta^*_{w,L} \frac{A_m}{A^*_T} w_0\right)$

RESULTS AND DISCUSSION

General Observations

Closed tunnels.- Figure 1 displays the interference factors in closed tunnels for the vertical interference velocity due to lift $\delta_{w,L}$ calculated for a zero-span model (refs. 4 and 12) as a function of the effective wake skew angle χ. Figure 1(a) compares the interference factors for tunnels of different width-height ratio γ. Figure 1(b) presents a comparison of the interference factors for different heights above the centerline ΔH in a tunnel with $\gamma = 1.5$. The results presented in figure 1(b) were obtained from the computer programs described in reference 12 by noting that

$$\frac{\Delta H}{H} = \frac{1}{\zeta} - 1 \tag{1}$$

Irrespective of the combination of vertical model position $\Delta H/H$ or tunnel width-height ratio γ chosen, the interference factor $\delta_{w,L}$ is always negative. This fact indicates the presence of an upwash at the model, which is expected since the completely closed tunnel, by restricting the normal downwash required for lift, effectively presents an upwash to the model. It is obvious that no scheme of altering the wind-tunnel proportions or model position can result in a completely closed tunnel with zero interference. Nonetheless, it may be possible to reduce the interference somewhat by a judicious choice of these parameters as a function of wake angle. Since, at the outset, the degree of reduction of interference appears small, discussion of such tunnels will be deferred to subsequent sections of this paper.

Closed-on-bottom-only tunnels.- A similar set of comparisons, again for a zero-span model, for the closed-on-bottom-only tunnels is presented in figure 2. In this class of tunnels, it is possible to balance the upwash engendered by the restriction of the solid floor against the effective downwash produced by the three open boundaries in such a manner as to produce either upwash $\left(\delta_{w,L} < 0\right)$ or downwash $\left(\delta_{w,L} > 0\right)$. In particular, it is noted that certain combinations of wake skew angle χ and either width-height ratio γ or vertical model position $\Delta H/H$ result in zero vertical interference due to lift $\left(\delta_{w,L} = 0\right)$. This result is not totally unexpected since reference 13 (confirmed by ref. 4) has already pointed out that for a small model with an undeflected wake ($\chi = 90^{o}$), the closed-on-bottom-only tunnel with $\gamma = 2$ is a "zero-correction" tunnel. Figure 2 shows clearly that a similar result may be obtained for the deflected-wake case as well, provided that either γ or $\Delta H/H$ is chosen appropriately for the actual effective wake deflection.

More specifically, if a small computer is tied into the balance system to compute the effective wake angle, and then used to adjust γ or $\Delta H/H$ to a predetermined schedule of values (as a function of χ), it should be entirely possible to obtain essentially zero boundary interference even for low-speed (high-wake-deflection) tests of V/STOL models. Such data would not be totally free of interference effects since there would still be horizontal interference velocities and smaller interferences due to drag; however, elimination of the vertical interference due to lift would reduce the overall corrections to reasonable and acceptable values.

Closed-On-Bottom-Only Tunnel With Variable Width-Height Ratio

General concept of configuration.- Schematically, the test section of a closed-on-bottom-only tunnel of variable width-height ratio might appear as in figure 3, in which a three-dimensional inlet of moderate contraction ratio, say 3 or 4, is followed by a variable two-dimensional contraction. The ground plane and the upper and lower lips of the exit cone would move with the corresponding members of the entrance cone.

The cross-sectional area of the tunnel varies with width-height ratio when this ratio is altered by moving only one pair of boundaries. If the upper and lower boundaries are moved, the area of the tunnel is greatest at the lowest width-height ratios; if the side boundaries are moved, the area is greatest at the largest width-height ratios. Figure 2(a) indicates that the lowest speeds (lowest values of χ) require low width-height ratios in order to negate $\delta_{w,L}$. As will become evident in subsequent sections, neither the residual interferences $\left(\delta_{u,L}, \delta_{w,D}, \text{ and } \delta_{u,D}\right)$ nor the interferences at the tail become zero simultaneously with the average value of $\delta_{w,L}$ over the primary lifting system. For constant lift, the largest values of these interferences should be expected at the lowest speeds since u_0, w_0, and C_L are large. It is desirable to have the largest tunnel area occur at low speeds, thus accruing the advantages of a low ratio of model area to tunnel area for the most severe conditions. Furthermore, at the lower speeds, the installed wind-tunnel power is capable of driving a much larger test section than the test section provided for at the maximum wind-tunnel speed. Consequently, an increase in tunnel cross-sectional area as the speed is reduced tends to provide more efficient use of the installed power. Therefore, the arrangement shown in figure 3, where the floor and upper boundary move, is preferable to the alternate arrangement where the side boundaries are movable.

The usual form of wind-tunnel speed control is by means of rotational speed changes of a fixed pitch fan. This type of speed control is generally relatively sluggish because of the large inertias of the heavy rotating equipment and may not be able to cope with the more rapid speed changes resulting from the area changes in the tunnel test section. Since test programs generally require data at constant speeds, satisfactory operation of such a tunnel may require the more rapid action provided by a variable-pitch fan together with some form of automatic velocity compensation.

It should be noted that the additional geometric changes to reduce the tunnel area still further and to fold the floor around the stream to form a slotted transonic test section are not so severe as to preclude possible consideration. This additional reduction in tunnel area would result in a tunnel of extraordinarily large contraction ratio (on the order of 50) which, by itself, should be of considerable advantage in obtaining excellent flow quality (low turbulence level, uniform velocity field, and absence of wake shadow). Further discussion of this possibility is beyond the scope of this report; however, figure 4 illustrates schematically the physical changes that would be required. These changes include further reducing the tunnel height, folding the inner surfaces of the sidewalls inward, folding the ground plane around the smaller stream, and finally opening slots in the new closed section.

Computer programs.- The required schedule of width-height ratio in order to obtain $\delta_{w,L} = 0$ (averaged over the lifting system) has been calculated by using the computer programs developed in reference 12. Only minor alterations were required in order to have the computer search for the particular value of width-height ratio required for a given wake angle and a given wing or rotor configuration. The interference effects at the tail are computed simultaneously in order to economize on computer time. In order to provide a proper comparison of the effective values of interference, the interference factors are altered so as to be referenced at all times to the cross-sectional area of the high-speed ($\gamma = 2.0$) section. Other quantities such as semiheight of the tunnel are also referenced to the high-speed-section values. A listing of the complete computer program for swept wings is provided in appendix A. A similar listing for rotors is provided in appendix B.

The programs given in the appendixes offer a choice of either of two loadings: for wings, the span loading may be either uniform or elliptic; for rotors, the disk-load distribution may be either uniform or triangular. All numerical results presented herein are for uniform loading, and the interference values presented represent an average over the lifting system. Note that results for the variable width-height ratio tunnel are presented in terms of $\delta^*_{w,L} = \delta_{w,L} \frac{A^*_T}{A_T}$ in order to include the effect of the changing cross-sectional area of the tunnel.

Required schedule of tunnel width-height ratio for wings.- Figure 5(a) shows the required schedule of γ to obtain $\delta_{w,L} = 0$ for unswept wings of varying span-width ratio. The wings are all assumed to be mounted in the center of the tunnel. It may be seen that larger values of width-height ratio are required at the higher skew angles as the relative span of the model increases. Indeed, an extreme value of $\gamma = 3.6$ is required for a wing with $\sigma = 0.75$ when the effective skew angle is on the order of 70°.

Very flat wind tunnels (in excess of $\gamma = 2$) are undesirable for several reasons. In general, the spanwise distribution of boundary interference tends to become substantially more nonuniform. More significantly, inadequate clearance exists between the tail and the floor at large angles of attack, and, in consequence, extreme pitching-moment corrections may be required. On the other hand, figure 5 which compares the interference factors for the variable γ tunnel $\left(\delta^*_{w,L} = 0\right)$ with those for both closed and closed-on-bottom-only tunnels ($\gamma = 2$) indicates that only a relatively small interference would be encountered by arbitrarily limiting the maximum width-height ratio to 2.0. An alternative procedure is to mount large models slightly below the center of the tunnel. Figures 6 and 7 present similar results for the same series of wings when mounted below the tunnel centerline by distances equal to 0.1 and 0.2 times the semiheight of the high-speed ($\gamma = 2$) section. Figure 8 shows, as a function of span-width ratio, the required distance below the centerline in order to obtain $\delta_{w,L} = 0$ at $\chi = 90^{\circ}$ and $\gamma = 2$. It can be observed that only small displacements $\Delta H/H$ are required provided that the model span is held to moderate values of one-half or less of the wind-tunnel width.

Effect of model configuration.- Figures 9 to 11 indicate the effect of configuration variables on the required schedule of γ for minimum interference by comparing the computed schedules for several wing sweep angles and for a rotor. For all configurations, the model span-width ratio σ is 0.5 and the angle of attack is zero. For moderately heavily loaded conditions ($\chi \approx 75^{\circ}$), it can be seen that the configuration considered may call for a tunnel width-height ratio as much as 10- to 20-percent different from the values given in figures 5 to 7. These differences are calculable, however, and once the wind-tunnel procedures are established, it should only be necessary to provide the control computer with a table of values computed for the specific configuration being tested.

Effect of angle of attack.- A change in angle of attack slightly alters the relative position of each portion of the model with respect to the tunnel boundaries and consequently alters the interference caused by these boundaries (ref. 12). In the present context of a minimal-interference tunnel, this change in interference requires that the width-height ratio be altered slightly to retain a zero value of $\delta_{w,L}$. The magnitude of the required changes for a wing (represented by a lifting line) with 45° of sweep and for a rotor are shown in figures 12 to 14. Irrespective of mounting height, the changes in width-height ratio required by changes in angle of attack are small. Note that for wings of lesser sweep than 45°, the effect of angle of attack is even less; for example, an unswept wing has correction coefficients which are independent of angle of attack (ref. 12).

If simplicity of operation is desired, it should be acceptable to simply ignore the effect of angle of attack when testing models without tails. On the other hand, it is feasible, if desired, to supply the computer with a doubly ordered set of width-height ratios (as functions of both χ and α) for use in a double interpolation routine. If on-line data reduction is anticipated, the latter procedure is preferable, since angle of attack has large effects (refs. 12 and 26) on the corrections to pitching moment due to the tail.

Interference at tail.- Figure 15(a) displays the interference factors in the variable width-height ratio tunnel for a zero span model (at $\alpha = 0^{\circ}$) at the center of lift $l_t/H^* = 0$ and at tail lengths l_t/H^* of 0.5, 1.0, and 1.5. These values are compared with the values for the equivalent fixed closed and closed-on-bottom-only tunnels having a width-height ratio of 2.0. It is evident that, in general, the use of variable geometry decreases the interferences by as much as an order of magnitude. It is evident that pitching moments due to the tail will be subject to some correction even in the variable-geometry test section; however, the required corrections should be much smaller than in the fixed-geometry tunnels.

More properly, corrections to pitching moment are nearly proportional to the difference in interference factors at the tail and at the center of lift (ref. 26). A similar comparison of this difference is presented in figure 15(b). This form of presentation does not alter the curves showing the interference at the tail for the variable-geometry tunnel; however, $\Delta\delta^*_{w,L}$ is markedly smaller than $\delta^*_{w,L}$ for any given tail length in the fixed-geometry tunnels since the interference at the center of the lift is of the same sign as the interference at the tail in these tunnels. Nevertheless, the variable-geometry tunnel still displays remarkably reduced interference effects on pitching moment. Furthermore, examination of the trend with increasing tail length indicates that the rate of change of interference with distance downstream is substantially reduced; thus induced camber and other similar effects (ref. 18) will also be reduced.

Obviously, finite span, configuration differences, and angle of attack may have large effects on the absolute values of the results presented in figure 15. Complete discussion of these effects would necessitate an extremely protracted discussion. Several sample calculations (not presented herein) indicate that the qualitative conclusions already drawn are not altered. Readers interested in particular cases are directed to the computer programs in the appendixes.

Distribution of interference factors.- The distribution of interference over models in the variable-geometry tunnel is examined and compared with the distributions in fixed-geometry tunnels in figures 16 to 19. In each case, the model spans one-half of the tunnel width and is centered in the tunnel with $\alpha = 0^\circ$. The spanwise distribution of interference over an unswept wing is shown in figure 16; the spanwise distribution over a wing having 45° of sweep in figure 17; and the lateral and longitudinal distributions over a rotor in figures 18 and 19. In each case, it is obvious that the model in the variable-geometry tunnel experiences essentially no interference nonuniformity in dramatic contrast to the large nonuniformities which, in general, are found in the fixed-geometry tunnels. Figures 16 to 19 collectively indicate that data from the variable-geometry tunnel should be essentially free of induced camber and twist effects (ref. 18).

Residual interference.- It is noted that the variable-geometry feature of the test section has been used to reduce the vertical interference due to lift $(\delta_{w,L})$ to zero. There remains a vertical interference due to drag $(\delta_{w,D})$ and streamwise or horizontal interferences due to both lift $(\delta_{u,L})$ and drag $(\delta_{u,D})$. In general, these interferences do not become zero simultaneously with $\delta_{w,L}$; however, the effect of these interference factors on the data is so much less than the effect of $\delta_{w,L}$ that their nonzero values are not too troublesome.

Figure 20 compares the values of the residual interference factors in the variable and fixed-geometry tunnels. Except for conditions near $\chi = 90^\circ$, where these factors are essentially zero in the fixed-geometry closed tunnel, the values are somewhat smaller in the variable-geometry tunnel. The most significant reduction that results from the use of variable geometry is in $\delta^*_{u,L}$ at low speeds (low χ); under such circumstances, this interference factor can result in significant reductions in the effective speed of a fixed tunnel.

If the induced drag-lift ratio of the model is known within reasonable limits prior to the test, it is possible to develop a schedule of width-height-ratio that reduces all vertical interference to zero at the model, leaving only a velocity (or "q") correction. The total vertical interference velocity is (from refs. 3 and 4)

$$\Delta w = \delta_{w,L} \frac{A_m}{A_T} w_0 + \delta_{w,D} \frac{A_m}{A_T} u_0 \tag{2}$$

However, from reference 27

$$\frac{u_0}{w_0} = \frac{D_i}{L} \tag{3}$$

so that equation (2) may be written as

$$\Delta w = \left(\delta_{w,L} + \frac{D_i}{L} \delta_{w,D}\right) \frac{A_m}{A_T} w_0 \tag{4}$$

For a rotor at low or moderate tip-speed ratios, where the resultant force is essentially perpendicular to the rotor disk, equation (4) may be written as

$$\Delta w = \left(\delta_{w,L} + \delta_{w,D} \tan \alpha\right) \frac{A_m}{A_T} w_0 \tag{5}$$

Provided only that D_i/L (or, in the case of a rotor, α) is known within reasonable limits, it is possible to modify the programs in the appendixes to reduce the bracketed sum in parentheses in equation (4) or (5) rather than just $\delta_{w,L}$ to zero. This refinement has not been provided in the programs provided herein; however, the required modifications are straightforward.

Effect on recirculation limits.- The most significant recent development in low-speed V/STOL wind-tunnel testing has been the discovery (refs. 23 and 24) of minimum speed limits below which the flow in the tunnel recirculates in a manner unrepresentative of free air. These limits can be expressed (ref. 18) in terms of a minimum distance behind the model for the intersection of the floor and the theoretically straight wake. The exact minimum distance depends upon the wind-tunnel proportions and certainly upon the tunnel configuration (for example, the presence of corner fillets has a strong influence).

The investigations of references 23 and 24 explored recirculation limits for closed tunnels only. It appears, however, that some similar restriction will hold in almost any wind tunnel even though the value of the limiting impingement distance is not known at present except for the closed tunnels. In this paper, discussion of recirculation limits is confined simply to the ratio of the impingement distance in the variable-geometry section to that in a fixed-geometry section. Even though such a simplistic presentation ignores many known effects, it at least provides a qualitative guide to the merit of a particular arrangement with regard to minimum test speeds.

For a model mounted in the center of the tunnel, the impingement distance behind the model is

$$x_f = H \tan \chi \tag{6}$$

In the present case, where the width of the test section is fixed, $H = B/\gamma$; so that

$$\frac{x_f}{x_f^*} = \frac{\frac{B}{\gamma}\tan \chi}{\frac{B}{\gamma^*} \tan \chi} = \frac{\gamma^*}{\gamma} = \frac{2}{\gamma} \tag{7}$$

Figure 21 shows the variation of x_f/x_f^* as a function of wake skew angle for several unswept wings of differing span-width ratio. The schedules of γ previously given by figure 5(a) are used. The large-span wings of this group are shown to be at a disadvantage with respect to recirculation at the higher wake skew angles. As noted previously, however, only a very mild correction is encountered if the width-height ratio is limited to a maximum of 2.0. If such a limit is imposed, the curves of figure 21 would be at $x_f/x_f^* = 1.0$ until the curves shown actually cross that line. When minimum speed is the primary concern, this procedure is preferable to the alternate procedure of mounting the model below the centerline since a low mounting height also reduces x_f. Except for the high-skew-angle region just discussed, it is obvious that the use of a variable width-height-ratio tunnel greatly increases the impingement distance ratio – by factors as great as 4 – and thus allows recirculation-free testing to substantially lower speeds than are allowable in a fixed-geometry tunnel.

Additional applications of variable γ tunnel.- The same features required to provide the variable geometry in the tunnel can be used to add several additional test capabilities. A few of these capabilities are sketched in figure 22.

Asymmetric motion of the entrance cone and diffuser can provide an inclined-flow facility suitable for unpowered free-flight tests of models with low lift-drag ratios, such as parawings and lifting reentry bodies. No equivalent large-scale test facility exists at present and such work must normally be conducted under less controlled conditions in actual flight tests.

Both entrance cone and diffuser can be moved upward simultaneously to provide for ground-effect testing. This procedure is far preferable to lowering the model if the wind tunnel employs an external mechanical balance system since it obviates the need for moment transfers through the large distances between the balance and model moment-centers.

Either the floor alone or the floor together with the entrance and exits can be raised to the level of the model to provide a convenient height at which to work on the model. The value of this feature in a very large tunnel will be apparent to anyone who has ever worked in one of the so-called full-scale tunnels.

Closed-On-Bottom-Only Tunnel With Variable Model Height

General concept of configuration.- The second type of variable-geometry wind-tunnel test section to be discussed is the closed-on-bottom-only tunnel with fixed boundaries but with the model mounting height programed as a function of wake deflection. This configuration is of particular interest since a tunnel utilizing a test section of this type having a width-height ratio of 1.5 is presently under construction at the NASA Langley Research Center (ref. 28). Figure 23 is a photograph of a model of this test section, illustrating not only the general type of test section under consideration herein, but also one manner in which removable walls may be employed in order to provide complementary closed or slotted sections for other types of work.

The variable model-height tunnel is considerably simpler and cheaper to construct than the variable width-height ratio tunnel previously discussed. In many tunnels employing sting balances, most of the mechanical elements required for this class of tunnel are already present since sting mounts are generally capable of considerable vertical motion. Essentially the only requirements (other than removable walls and ceiling and an exit collector cone) are the provision of a control computer with suitable velocity and force transducers. No intrinsic design problems appear to exist other than insuring a stable airstream without severe oscillations or pulsations. In this regard, there is considerable past work (for example, refs. 29 and 30) to provide guidance in obtaining a clean basic test-section flow.

Computer programs.- Computer programs for the variable-model-height tunnel are also included in the appendixes. Appendix C provides a computer program for wings; appendix D provides a similar program for rotors.

Required schedule of model height for wings.- Since the wall effects and their changes with vertical model position are both functions of the width-height ratio of the wind tunnel, it is necessary to examine, at least initially, a family of tunnels with variable model height. Figures 24, 25, 26, and 27 show the required schedule of model height for unswept wings of varying span-width ratio in tunnels having width-height ratios of 2.0, 1.5, 1.0, and 0.5, respectively. In each case, the resulting interference $\left(\delta_{w,L} = 0\right)$ is compared with the interference factors in both closed and closed-on-bottom-only tunnels of the same width-height ratio when the model is retained in a central mounting position.

For the cases studied, the maximum range of vertical motion is not extraordinarily large, ranging from about 0.6 of the tunnel semiheight H for the widest ($\gamma = 2.0$) tunnel, to about 0.8 H for the deepest ($\gamma = 1.0$ and 0.5) tunnels. The required positions are, however, lower in the tunnel as the width-height ratio decreases. In the most extreme case ($\gamma = 0.5$ and $\sigma = 0.75$), the model would be within one-quarter of a semiheight of the floor in the high-speed ($\chi = 90^{\circ}$) condition. This result should be expected since the deeper tunnels of this type have a greater ratio of open-boundary perimeter to closed-boundary perimeter than the wider tunnels; consequently, the model must be moved closer to the solid boundary in order to increase effect of the floor (upwash) to the point where it is exactly equal to the effect of the open boundaries (downwash).

The consequences of the proximity to the floor in the deeper tunnels will be explored more thoroughly in succeeding sections of this paper. It is obvious at the outset, however, that the deep tunnels of this class will present certain operational problems with regard to clearance of (and interference at) the tail with large angles of attack as well as problems in reaching low speeds without violating recirculation limits.

Interference at tail.- The effect of variable model-height operation on the interference at the tail in the same family of tunnels is explored in figures 28 to 31. Compared to a fixed central location, the effectiveness of variable model height in reducing the corrections to pitching moment decreases with both decreasing width-height ratio and increasing tail length. Indeed, in the deepest tunnel ($\gamma = 0.5$), the correction to pitching moment caused by the tail would be decidedly increased, and in the square tunnel ($\gamma = 1.0$), on balance, the same order of correction would be obtained.

Variable model-height operation does not reduce pitching-moment corrections to the same low level as could be achieved in the closed-on-bottom-only tunnel of variable width-height ratio (fig. 15). This relative disadvantage is a price that must be paid for the greater simplicity and lesser costs of the variable model-height configuration.

In the wider tunnels of this family ($\gamma = 2.0$ and 1.5), it is observed that a significant improvement in pitching-moment interference is obtained provided that the tail length is not extreme. Modest tail lengths on the order of $l_t/H = 0.5$ will require pitching-moment corrections of about one-half those normally encountered.

The fact that the improvement in $\Delta\delta_{w,L}$ is greatest for the shortest tail lengths is significant since it indicates that the longitudinal gradient of interference velocity at the model lift-center is probably greatly reduced. Thus, this type of tunnel should produce only small induced-camber effects.

Residual interference.- The effect of variable model-height operation on the residual interference factors $\delta_{u,L}$, $\delta_{u,D}$, and $\delta_{w,D}$ for the same four tunnels is shown in figures 32 to 35. No truly significant change in the level of these factors is evident. As in the case of the variable width-height ratio tunnel, the programs given in appendixes C and D can be modified to eliminate the vertical interference due to drag provided that the drag-lift ratio of the model can be approximated within reasonable limits.

Effect of model configuration.- The effect of model configuration as exemplified by a rotor and wings of varying sweep, all having span-width ratios of 0.5, are illustrated in figure 36 for one width-height ratio ($\gamma = 1.5$). (Results for the remaining three width-height ratios are omitted for conciseness in this and the following several sections. Equivalent information for other width-height ratios can be obtained, if required, by use of the programs given in appendixes C and D.) At least for $\gamma = 1.5$, figure 36 indicates that the effect of configuration is so small that it could be neglected unless extreme precision is required in the data.

Effect of angle of attack.- The effect of angle of attack on the required model-height schedule for minimal interference is illustrated in figure 37. The same tunnel and span are considered as in figure 36. Figure 37(a) presents the results for a wing with 45° of sweep; figure 37(b) presents the results for a rotor. In the cases considered herein, it is obvious that the effect of angle of attack is negligible. On the other hand, it has been observed previously that this type of variable-geometry tunnel will require corrections to pitching moment. As noted in references 12 and 26, angle of attack would be expected to have significant effects on this pitching-moment correction.

Distribution of interference.- The effect of variable model-height operation of the closed-on-bottom-only tunnel on the distribution of interference for wings having 0° and 45° of sweep is illustrated in figures 38 and 39. Corresponding results for the distribution of interference along the lateral and longitudinal axes of a rotor are given in figures 40 and 41. It will be noted in each case that the interference distribution is usually better in the variable model-height tunnels than in the tunnels with fixed, centrally located, models. In particular, the longitudinal distribution of interference over the rotor (fig. 41) is significantly flattened by properly varying the model height. This result is in accordance with the previous observations about the longitudinal gradient of interference discussed earlier in relation to the interference at the tail.

Effect of recirculation limits.- The comparison of the variable model-height closed-on-bottom-only tunnels of different width-height ratios with respect to relative recirculation limits is more complex than might be apparent at first glance. Note that in this case, the impingement distance is

$$x_f = h \tan \chi \tag{8}$$

and, since $\zeta = H/h$

$$\frac{x_f}{(x_f)_{\mathrm{¢}}} = \frac{\dfrac{H \tan \chi}{\zeta}}{\dfrac{H \tan \chi}{1}} = \frac{1}{\zeta} = \frac{\Delta H}{H} + 1 \tag{9}$$

Equation (9) may be used to compare the effect of using variable model height in tunnels of any given width-height ratio. The results of such a comparison are presented in figure 42 for unswept wings of varying span in tunnels having each of the four different width-height ratios considered herein. In general, it would appear that the use of a variable model height is deleterious at the high skew angles but that it may be helpful in the wider tunnels if the wake is depressed sufficiently from the horizontal.

In comparing the various width-height ratios, it should be noted that if all of the tunnels have the same area (which, for a given maximum speed, generally determines the cost of constructing the tunnel), the tunnel semiheight (used in eq. (9)) will be different in each tunnel. Note that the tunnel cross-sectional area is $A_T = 4BH = 4\gamma H^2$ so that the ratio of semiheights for equal A_T is

$$\frac{H}{H^*} = \sqrt{\frac{\dfrac{A_T}{4\gamma}}{\dfrac{A_T}{4(2)}}} = \sqrt{\frac{2}{\gamma}} \tag{10}$$

Thus, proceeding as before, the following result is found for equal area tunnels

$$\frac{x_f}{(x_f)^*_{\mathrm{¢}}} = \frac{x_f}{(x_f)_{\mathrm{¢}}}\left[\frac{H}{H^*}\right] = \frac{x_f}{(x_f)_{\mathrm{¢}}}\left[\sqrt{\frac{2}{\gamma}}\right] \tag{11}$$

A comparison on this basis is presented in figure 43 for models of fixed span-width ratios of 0 and 0.5. Overall, it would appear from figure 43 that the square tunnel ($\gamma = 1.0$) of this class is superior from a viewpoint of recirculation limits. More realistically, however, an experimenter designing a model for testing will find that his model size is physically fixed and that it is not possible to "rubberize" the model design to obtain a fixed span-width ratio. In general, the physical size of the model is fixed rather than the span-width ratio.

Observe that the model semispan in tunnels of constant A_T is

$$s = \sigma B = \sigma\gamma H = \sigma\gamma(H/H^*)H^* = \sqrt{2\gamma}H^*\sigma$$

and

$$\frac{s}{s^*} = \frac{\sqrt{2\gamma}\sigma}{\sqrt{2(2)}\sigma^*}$$

or

$$\frac{\sigma}{\sigma^*} = \sqrt{\frac{2}{\gamma}} \tag{12}$$

Thus, for fixed span models in fixed area tunnels, both H/H^* and σ/σ^* must vary in the identical manner (eqs. (10) and (12)). On this basis, the comparison of the various tunnels is unaltered from figure 43(a) when $\sigma = \sigma^* = 0$; however, for finite span-width ratios of $\sigma^* = 0.25$ and 0.5, the comparison of the different tunnels is as in figure 44. Note that the result for $\gamma = 0.5$ and $\sigma^* = 0.5$ is not shown since in that case the model wing tips actually touch the side boundaries. Examination of figure 44 indicates that, on an overall basis, the wide tunnels of this class are probably superior from the viewpoint of recirculation limits for models of practical spans. The penalties of variable model-height operation in these tunnels are very small and are confined to the higher speed conditions (high χ) where recirculation is not likely to be a limiting factor.

For severe conditions (low χ), the wider tunnels provide a substantial improvement in the relative recirculation limits. On the other hand, it is observed that the improvement found in this case is significantly less than that obtained in the variable width-height ratio tunnel discussed previously (fig. 21).

Choice of width-height ratio.- In view of the conflicting requirements of different types of wind-tunnel testing, particularly when nonaeronautical applications (that is, forces on bridges, trains, etc.) are considered, the choice of the optimum proportions for a wind tunnel is always somewhat imprecise and intuitive. In the present paper, where very low-speed tests of V/STOL vehicles are the primary concern, the impact of recirculation limits on tunnel utility and useful speed-range would appear to rule out the choice of a deep tunnel. The knowledge that pitching-moment corrections due to interference at the tail are not reduced in the square tunnel by variable model-height operation makes the square tunnel significantly less attractive. Furthermore, the fact that a model of given span has a smaller span-width ratio when tested in a tunnel of larger width-height ratio (thus reducing the lateral nonuniformity of wall interference) indicates that the tunnel should be substantially wider than square.

If the width-height ratio is chosen to be very large, then, for fixed tunnel areas, the floor is found to be quite close to the model. In a practical sense, the clearance from the floor of the model tail at high angles of attack can be restrictive. In addition to the problem of physical clearance, the result is interference at the tail which is a severe function of angle of attack; in certain cases such interference has been found to produce increases in apparent longitudinal static stability that were of the same order as the basic stability of the model.

On an overall basis, it would appear that a width-height ratio on the order of 1.5 would be satisfactory and would still yield most of the advantages of variable model-height operation. This is the value chosen for the tunnel presently being constructed at the Langley Research Center. It is noted in passing that width-height ratios substantially equal to 1.5 (that is, 7×10 and 8×12) have generally proven quite satisfactory in the past.

Operation for zero moment-correction.- Since one of the main shortcomings of the variable model-height configuration is the minor relief from pitching-moment correction, it is interesting to examine the possibility of operating the tunnel so as to minimize pitching-moment corrections rather than the corrections at the center of lift. Figure 45 shows the interference factors $\delta_{w,L}$ for both the wing and the tail for one tail length and one angle of attack as calculated by the method of reference 12. The circled points in figure 45 show the intersections at which the two interferences are equal so that $\Delta\delta_{w,L} = 0$. For these conditions, there is essentially no correction required for pitching moment due to the tail.

This procedure has been carried through graphically (but in more detail) for a variety of width-height ratios, tail lengths, and angles of attack. The results are presented in figures 46 to 49. The most significant observations to be drawn from these figures is that operation for zero moment-correction is only possible for a limited range of skew angles, tail lengths, and angles of attack; the range depends to a large extent upon the width-height ratio, being largest for the tunnels of greatest depth. Furthermore, the corrections at the center of lift can become very large in the downwash $\left(\delta_{w,L} > 0\right)$ direction. The corrections at the center of lift, in general, are significantly larger in absolute magnitude than when operating with the model fixed at the center of the tunnel. (Compare figs. 46 to 49 with figs. 24 to 27.)

Except under unusual circumstances, it would appear that operation in this mode is contraindicated. Consequently, no further examination of this possibility is included herein, and no computer programs similar to those in the appendixes have been developed.

Closed Tunnel With Variable Width-Height Ratio

General concept of configuration.- Even though it is not possible to reduce $\delta_{w,L}$ to zero, it is of value to explore the extent to which interference can be reduced by applying variable-geometry concepts to closed tunnels. The first type of closed tunnel to be discussed is the variable width-height-ratio closed tunnel.

In appearance, such a tunnel would look very much like that shown in figure 3 except that the walls of the two-dimensional contraction would continue along the sides of the test section and a closed ceiling would be carried with the upper lips of the entrance and exit. The operational features, additional applications, and developmental problems of such a tunnel are essentially the same as those discussed previously for the similar closed-on-bottom-only tunnel. One advantage to the closed version is that it is considerably simpler to achieve a clean nonpulsating flow in a completely closed test section. Furthermore, the boundary conditions to be satisfied at all the boundaries are more firmly known, since there are no small perturbation assumptions in the development of these conditions (ref. 31). As a partial balance against the firmness of the boundary conditions, the possibility of separation from the ceiling under conditions of extreme force coefficients (ref. 1) should be pointed out.

Computer programs for variable γ closed tunnel.- Only minor modifications (largely to reduce input values to correspond always to the high-speed-section values) are required to use the programs developed in reference 12 for calculation of the interferences in the tunnel under discussion. Appendixes E and F present programs for wings and rotors with these modifications already made.

Optimum schedule of γ.- The interference factor $\delta^*_{w,L}$ is presented in figure 50 for several different models and for a range of width-height ratios. This presentation is strikingly different than that of figure 1(a) since the increase in tunnel area with decreasing width-height ratio is accounted for by the use of $\delta^*_{w,L}$ rather than $\delta_{w,L}$.

Since the interference decreases monotonically with γ, it is obvious that the optimum manner of operation is to decrease γ (thus increasing cross-sectional area) as rapidly as the required test speed permits. Thus, all speed control in the upper speed range of the tunnel could be vested in the control of the tunnel area rather than in either fan rotational speed or fan pitch. This feature could significantly simplify design of the speed control system in the tunnel.

As was indicated in figure 1(a), the interference factors $\delta_{w,L}$ increase after the width-height ratio is decreased below some optimum value. It is obvious from figure 50 that the increase in $\delta_{w,L}$ becomes big enough to largely overcome the advantage of the increases in area for width-height ratios on the order of 1.0 or less; that is, the reduction in $\delta^*_{w,L}$ is small for reducing γ to values much less than 1.0. Thus, it would appear from figure 50 that the tunnel need only have a range of γ from 1.0 to 2.0 in order to achieve essentially all of the possible beneficial results of this type of operation. Other factors modify this conclusion to a certain extent as will appear in subsequent discussion.

Interference for particular models.- It is obvious from examination of figure 50 that the interference experienced by a given model will be dependent upon its own variation of skew angle with forward velocity as the tunnel area and speed change with changes in width-height ratio. If it is assumed for simplicity that the power required is proportional to $A_T V^3$ (equivalent to assuming that the energy ratio is unaltered by changes in the tunnel opening), and $A_T = 4BH = (4/\gamma)B^2$, so that for a constant-power opening of the tunnel

$$\text{Power} \sim \frac{4}{\gamma^*} B^2 (V^*)^3 = \frac{4}{\gamma} B^2 V^3 \tag{13}$$

Solving equation (13) for V, nondimensionalizing the result by w_h, and taking $\gamma^* = 2$ yields

$$\frac{V}{w_h} = \left(\frac{\gamma}{2}\right)^{1/3} \frac{V^*}{w_h} \tag{14}$$

From reference 27, with D_i/L taken as zero (note that the assumption that $D_i = 0$ may require the presence of some negative D_i, or thrust, from some portion of the model)

$$\left(\frac{w_0}{w_h}\right)^4 = \frac{1}{1 + \left(\frac{V}{w_0}\right)^2} = \frac{1}{1 + \left(\frac{V}{w_h}\right)^2 \left(\frac{w_h}{w_0}\right)^2} \tag{15}$$

and, also from reference 27

$$\left(\frac{w_0}{w_h}\right)^2 = \cos \chi_m \tag{16}$$

Substitute (16) into (15) and solve for $\cos \chi_m$ to obtain

$$\cos \chi_m = \frac{1}{2}\left[\sqrt{4 + \left(\frac{V}{w_h}\right)^4} - \left(\frac{V}{w_h}\right)^2\right] \tag{17}$$

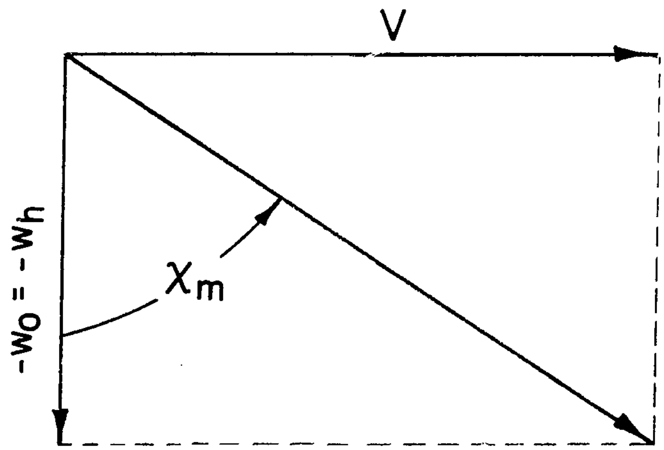
Substitution of equation (14) into equation (17) yields

$$\chi_m = \cos^{-1}\left\{\frac{1}{2}\left[\sqrt{4 + \left(\frac{\gamma}{2}\right)^{4/3}\left(\frac{V^*}{w_h}\right)^4} - \left(\frac{\gamma}{2}\right)^{2/3}\left(\frac{V^*}{w_h}\right)^2\right]\right\} \tag{18}$$

Then the "effective skew angle" (ref. 9) may be taken with sufficient accuracy as

$$\chi = \frac{\chi_m + 90^o}{2} \tag{19}$$

The foregoing result is satisfactory for "aerodynamic systems" in which the forces are produced by changes in velocity and direction of a constant mass of air which enters at infinity upstream and leaves at infinity downstream. These conditions are violated in the case of cold jets supplied from within a model to simulate jet engine flows. For such systems, equation (14) is still valid; however, the momentum skew angle is more appropriately taken from the vector diagram in the sketch.



Thus

$$\chi_m = \tan^{-1}\left(-\frac{V}{w_h}\right) = -\tan^{-1}\left[\left(\frac{\gamma}{2}\right)^{1/3}\frac{V^*}{w_h}\right] \tag{20}$$

Actually, of course, the wake of the jet must leave the model tangent to the exit nozzle and then curve rearward until the inclination to the free stream is negligible at very large distances downstream. The results of reference 18, as well as a comparison with the flow photographs of reference 32, indicate that the appropriate effective skew angle is again as given by equation (19).

The relationship between χ and γ is given by the solution of equation (18) (or eq. (20), if appropriate) and of equation (19) and depends only upon the reference velocity w_h, which in turn (ref. 27) is only a function of the equivalent "disk-loading." The dashed lines in figure 50 represent the paths followed by models having several different ratios of w_h/V^*. For a 300-knot tunnel, the curve labeled $w_h/V^* = -0.06$ might represent either a helicopter rotor or a very heavily flapped wing; the curve labeled $w_h/V^* = -0.2$ might represent a tilt-wing VTOL aircraft; the curve labeled $w_h/V^* = -0.6$ might represent a fan-in-wing design; and the curve labeled $w_h/V^* = -2.0$ might represent a jet-lift VTOL design. (The first three cases were computed using equation (18); the final case used equation (20).)

In the highest speed condition, the tunnel is always operating under the same interference conditions that it would experience if the tunnel were a fixed-geometry tunnel with $\gamma = 2$; however, as the speed is reduced, the interference reduces rapidly to values that are on the order of one-half to one-third those of the fixed tunnel. The entire opening from $\gamma = 2.0$ to $\gamma = 0.5$ occurs in the upper one-third of the speed range of the tunnel. For all lower speeds, the interference is given by the curves for $\gamma = 0.5$. It is noted that during operation at points above the maximum opening, the tunnel velocity is comparatively large. Under these conditions the force coefficients (and, consequently, u_0 and w_0) are small so that the interference of the walls is small. It is at low speeds, where the force coefficients and mean induced velocities are large, that wall effects become truly significant. It is precisely this range in which the variable width-height-ratio operation of the closed tunnel reduces the wall effects.

Interference at the tail.- The interference at the tail, in terms of $\Delta\delta^*_{w,L}$, is shown for zero span and for three tail lengths in figure 51. It will be noted that, for low speeds, corrections for pitching moment at the tail will be extremely small as a result of variable-geometry operation. In particular, if the tunnel opens to as small a width-height ratio as 0.5, such corrections almost vanish; this tunnel reduces tail corrections to even lower values than the variable γ closed-on-bottom-only tunnel previously discussed. (Compare fig. 15 and fig. 51.) The greater reduction in the present case is entirely due to the more rapid opening schedule.

Residual interference.- Figure 52 presents the effect of variable-geometry operation of this tunnel on the interference factors $\delta^*_{u,L}$, $\delta^*_{u,D}$, and $\delta^*_{w,D}$. It is evident that these factors are also drastically reduced. In particular, it is noted that the streamwise interference is reduced to negligible values at low speeds.

Distribution of interference.- Figures 53 to 56 present the distribution of $\delta^*_{w,L}$ over the same models studied with respect to the previously discussed wind-tunnel configurations. If the curves for $\gamma = 2.0$ are compared with the curves for the appropriate γ (taken from the intersections of the solid and dashed curves of fig. 50), it is obvious that variable γ operation of the closed tunnel results in dramatic reduction of the nonuniformity of interference at low speeds.

Effect on recirculation limits.- The effect of variable γ operation on the impingement distance is shown in figure 57 as a function of either χ or V/V^*. It is possible, of course, to include in this figure the effect of γ on the allowable recirculation distance (refs. 18 and 23); however, this has not been included in figure 57 primarily in order to provide a more consistent comparison with the previously discussed tunnel configurations.

The rapid opening schedule of the variable γ closed tunnel results in sudden and rapid increases in impingement-distance ratio. The extent of the increase is limited only by the maximum opening of the tunnel. If the tunnel is intended primarily for work in the low-speed V/STOL transition regime of flight, it is obvious that the maximum desirable opening (or lowest γ) is the maximum opening that is economically feasible. When the minimum value of γ is about 2/3 or less, it is obvious that this type of tunnel will provide tests free of recirculation effects at speeds (or χ) lower than any other tunnel considered herein.

Closed Tunnel With Variable Model Height

It remains to consider the possibility of variable model-height operation of a closed tunnel. For each of four width-height ratios, the schedule of model height required to produce minimum $\delta_{w,L}$ (determined for $\sigma = 0$ from the computer programs developed in ref. 12), is shown, together with the effect on $\delta_{w,L}$ in figures 58 to 61. It is evident that the reductions in interference achieved by this technique in the closed tunnel are only minor and are probably not worth the expense and difficulty of achieving the required motion of the model.

CONCLUSIONS

This study of variable-geometry wind tunnels, using changes in either width-height ratio or model height, to minimize boundary interference in wind-tunnel tests of V/STOL aircraft has indicated that several promising possibilities exist:

1. The closed-on-bottom-only configuration with properly scheduled width-height ratio can reduce the vertical interference velocities to zero at the lifting system itself.

Simultaneous major improvements in uniformity of interference, pitching-moment corrections, and minimum speed for recirculation-free testing are obtained.

2. Closed-on-bottom-only tunnels, wider than square, can also be used to reduce the vertical interference velocity at the lifting system to zero if the model height is properly scheduled. Improvements in uniformity, pitching-moment corrections, and minimum recirculation-free test speed are also obtained; however, these latter improvements are significantly less than those obtained in the variable width-height ratio configuration.

3. At low speeds, closed tunnels having variable width-height ratio offer the possibility of reducing wall effects by factors of 2 or 3 at the lifting system. Such tunnels reduce, at low speeds, the nonuniformity of interference and pitching-moment corrections to the vanishing point. These tunnels can also provide the lowest speeds for recirculation-free testing.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 24, 1969,
721-01-00-20-23.

APPENDIX A

FORTRAN PROGRAM FOR COMPUTING INTERFERENCE OVER WINGS IN A VARIABLE WIDTH-HEIGHT-RATIO CLOSED-ON-BOTTOM-ONLY TUNNEL

THIS PROGRAM WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS PROGRAM HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

NOTE THAT ALL INPUT AND OUTPUT VARIABLES ARE REFERENCED TO THE GAMMA=2.0 TEST SECTION. INPUT IS AT ADDRESS 1 IN FORMAT 900 (TWO CARDS PER CASE). THE REQUIRED INPUT VARIABLES ARE

LI	SPAN LOAD-DISTRIBUTION INDICATOR, LI=1 FOR UNIFORM LOADING, LI=2 FOR ELLIPTIC LOADING
ZETA1	SEMIHEIGHT OF GAMMA=2 SECTION DIVIDED BY HEIGHT OF AERODYNAMIC CENTER ABOVE FLOOR IN GAMMA=2 SECTION
ETA1	DISTANCE FROM AERODYNAMIC CENTER TO RIGHT-HAND WALL DIVIDED BY TUNNEL SEMIWIDTH
SIGMA	RATIO OF WING SPAN TO TUNNEL WIDTH
LAMBDA	WING SWEEP ANGLE, DEG
ALPHA	ANGLE OF ATTACK OF WING, DEG
ITAIL	NUMBER (0 TO 9) OF TAIL POSITIONS, PROPORTIONATELY INCREASED IN TAIL LENGTH AND HEIGHT, AT WHICH INTERFERENCE IS REQUIRED. USE SMALLEST LENGTH AND HEIGHT AS INPUT.
SIGMAT	RATIO OF TAIL SPAN TO TUNNEL WIDTH
TL	DISTANCE OF TAIL BEHIND AERODYNAMIC CENTER, NONDIMENSIONALIZED WITH RESPECT TO SEMIHEIGHT OF GAMMA=2 SECTION
TH	HEIGHT OF TAIL ABOVE AERODYNAMIC CENTER, NONDIMENSIONALIZED WITH RESPECT TO SEMIHEIGHT OF GAMMA=2 SECTION

THIS PROGRAM REQUIRES SUBROUTINE DLTAS (SEE APPENDIX G) AND SUBROUTINE VARLET (SEE APPENDIX H).

```
      PROGRAM WINDTUN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)              (A 1)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)                (A 2)
      DIMENSION XLE(10),XLOAD(10),XDELTA(28),C(8),STORE(8)                (A 3)
      REAL LAMBDA                                                         (A 4)
```

APPENDIX A

```
      DATA (C(I),I=1,8)/20.,30.,40.,50.,60.,70.,80.,90./
      XLE(1)=XLE(10)=0.43579
      XLE(2)=XLE(9)=0.71422
      XLE(3)=XLE(8)=0.86603
      XLE(4)=XLE(7)=0.95394
      XLE(5)=XLE(6)=0.99499
    1 READ (5,900) LI,ZETA1,ETA1,SIGMA,LAMBDA,ALPHA,ITAIL,SIGMAT,TL,TH
      IF (EOF,5) 999,47
   47 IF (LI.EQ.1) GO TO 804
      IALPHA=8HELLIPTIC
      SUML=0.0126104
      DO 808 M2=1,10
  808 XLOAD(M2)=XLE(M2)
      GO TO 160
  804 SUML=0.01
      IALPHA=8HUNIFORM
      DO 809 M2=1,10
  809 XLOAD(M2)=1.0
  160 WRITE (6,901)  SIGMA,IALPHA,LAMBDA,ZETA1,ETA1,ALPHA
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      AALP=ALPHA
      ALAM=LAMBDA
      ATL=TL
      ATH=TH
      AZETA=ZETA1
      RAD=0.0174532925199
      ALPHA=ALPHA*RAD
      LAMBDA=LAMBDA*RAD
      CONST1=1.0
      DO 41 K=1,8
      DO 803 L1=1,28
      DELTA(L1)=0.
  803 XDELTA(L1)=0.
      GAMMA=GMA1=2.0
      INK=1
      IF (SIGMA.NE.0.) GO TO 811
      M7=N7=1
      XLOAD(1)=1.0
      SUML=1.
      GO TO 812
  811 IF (ETA1.NE.1.) GO TO 813
      M7=5
      N7=10
      CONST1=2.
      GO TO 812
  813 M7=N7=10
  812 AC=0.5*SIGMA*TAN(LAMBDA)*GAMMA
      IF (LI.NE.1)  AC=0.848*AC
      ZETA1=AZETA/(1.0+AC*AZETA*SIN(ALPHA))
      ZETA1=2.0/(2.0+GAMMA*(1.0-ZETA1))
      DO 801 M1=1,M7
      DO 802  N1=1,N7
      XSTAR=(11.-2.*FLOAT(M1))/10.
```

```
      YSTAR=(2.*FLOAT(N1)-11.)/10.
      ZSTAR=(11.-2.*FLOAT(N1))/10.
      ETA=ETA1+YSTAR*SIGMA
      ZETA=ZETA1/(1.-ABS(YSTAR)*SIGMA*GAMMA*ZETA1*TAN(LAMBDA)*SIN(ALPHA)
     1)
      XOVERH=SIGMA*GAMMA*TAN(LAMBDA)*COS(ALPHA)*(ABS(XSTAR)-ABS(ZSTAR))
      YOVERH=(FLOAT(M1)-FLOAT(N1))*SIGMA*GAMMA*(-.2)
      ZOVERH=SIGMA*GAMMA*TAN(LAMBDA)*SIN(ALPHA)*(ABS(ZSTAR)-ABS(XSTAR))
      IF (INK.EQ.7)  GO TO 850
      CALL VARLET  (C(K))
******************** SEE APPENDIX H FOR SUBROUTINE VARLET ********************
      GO TO 832
  850 CALL DLTAS   (C(K))
********************* SEE APPENDIX G FOR SUBROUTINE DLTAS *********************
  832 DO 805 L1=1,28
  805 XDELTA(L1)=XDELTA(L1)+(DELTA(L1)*XLOAD(N1))
  802 CONTINUE
  801 CONTINUE
      IF (INK.EQ.7)  GO TO 835
      DELTA(5)=XDELTA(5)*SUML*CONST1
      IF (ABS(DELTA(5)).LT.0.00005)  GO TO 833
      DEL2=DELTA(5)
      IF (INK.NE.1)  GO TO 831
      DEL1=DELTA(5)
      GAMMA=GMA2=1.0
      INK=2
      XDELTA(5)=0.0
      GO TO 812
  831 IF (ABS(DELTA(5)).LT.0.00005)  GC TO 833
      GAMMA=GAMMA-(GMA2-GMA1)*DEL2/(DEL2-DEL1)
      IF (GAMMA.LE.0.1)  GAMMA=0.1
      DEL1=DEL2
      GMA1=GMA2
      INK=3
      GMA2=GAMMA
      IF (GMA2.EQ.GMA1)  GO TO 836
      XDELTA(5)=0.0
      GO TO 812
  836 STORE(K)=0.01
      GO TO 41
  833 INK=7
      XDELTA(5)=0.0
      STORE(K)=GAMMA
      GO TO 812
  835 DO 807 L3=1,28
  807 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.)
      WRITE (6,149)  C(K),GAMMA
      WRITE (6,150) (DELTA(I),I=1,25,4)
      WRITE (6,151) (DELTA(I),I=2,26,4)
      WRITE (6,152) (DELTA(I),I=3,27,4)
      WRITE (6,153) (DELTA(I),I=4,28,4)
      IF (SIGMA.EQ.0.) GO TO 822
      IF (C(K).EQ.90.) GO TO 820
      XS1=TAN(C(K)*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      CHIM=2.0*C(K)-90.
      XS2=TAN(CHIM*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      WRITE (6,120)  XS1,XS2
      GO TO 822
  820 WRITE (6,119)
  822 DO 814  L4=1,28
  814 XDELTA(L4)=0.
```

```
      IF (GAMMA.LT.2.0005)  GO TO 41
      GAMMA=2.0
      GO TO 812
   41 CONTINUE
      IF (ITAIL.EQ.0)  GO TO 1
      SUML=0.031526
      IF (LI.EQ.1) SUML=0.025
      IF (SIGMAW.EQ.0..AND.SIGMAT.EQ.0.)  GO TO 450
      IF (SIGMAW.EQ.0..AND.SIGMAT.NE.0.)  GO TO 455
      IF (SIGMAW.NE.0..AND.SIGMAT.EQ.0.)  GO TO 460
      M7=4
      N7=10
      CONST1=1.0
      IF (ETA1.NE.1.)  GO TO 412
      M7=2
      CONST1=2.0
      GO TO 412
  450 M7=N7=1
      XLOAD(1)=1.0
      SUML=0.025
      CONST1=40.0
      GO TO 412
  455 M7=4
      N7=1
      XLOAD(1)=1.0
      SUML=0.025
      CONST1=10.0
      IF (ETA1.NE.1.)  GO TO 412
      M7=2
      CONST1=20.0
      GO TO 412
  460 M7=1
      N7=10
      CONST1=4.0
      IF (ETA1.NE.1.)  GO TO 412
      N7=5
      CONST1=8.0
  412 DO 420  ITL=1,ITAIL
      WRITE (6,901)  SIGMA,IALPHA,ALAM,AZETA,ETA1,AALP
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      DO 91  K=1,8
      GAMMA=STORE(K)
  399 AC=0.5*SIGMA*TAN(LAMBDA)*GAMMA
      IF (LI.NE.1)  AC=0.848*AC
      TL=(ATL*FLOAT(ITL)*GAMMA/2.0)+AC
      TH=ATH*FLOAT(ITL)*GAMMA/2.0
      ZETA1=AZETA/(1.0+AC*AZETA*SIN(ALPHA))
      ZETA1=2.0/(2.0+GAMMA*(1.0-ZETA1))
      DO 400  L2=1,28
      XDELTA(L2)=0.
  400 DELTA(L2)=0.
      DO 401  M1=1,M7
      DO 402  N1=1,N7
```

```
      XSTAR=(2.*FLOAT(N1)-11.)/10.0
      YSTAR=(11.-2.*FLOAT(N1))/10.0
      ZSTAR=(5.-2.*FLOAT(M1))/4.0
      ETA=ETA1+XSTAR*SIGMA
      ZETA=ZETA1/(1.-ABS(YSTAR)*SIGMA*GAMMA*ZETA1*TAN(LAMBDA)*
     1      SIN(ALPHA))
      XOVERH=TL*COS(ALPHA)+TH*SIN(ALPHA)-SIGMA*GAMMA*TAN(LAMBDA)*
     1      COS(ALPHA)*ABS(YSTAR)
      YOVERH=ZSTAR*SIGMAT*GAMMA-YSTAR*SIGMA*GAMMA
      ZOVERH=TH*COS(ALPHA)-TL*SIN(ALPHA)+SIGMA*GAMMA*TAN(LAMBDA)*
     1      SIN(ALPHA)*ABS(YSTAR)
      CALL DLTAS  (C(K))
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS ********************
      DO 405 L1=1,28
  405 XDELTA(L1)=XDELTA(L1)+(DELTA(L1)*XLOAD(N1))
  402 CONTINUE
  401 CONTINUE
      DO 407 L3=1,28
  407 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.0)
      TL=ATL*FLOAT(ITL)
      TH=ATH*FLOAT(ITL)
      WRITE (6,148)  C(K),GAMMA,SIGMAT,TL,TH
      WRITE (6,150)  (DELTA(I),I=1,25,4)
      WRITE (6,151)  (DELTA(I),I=2,26,4)
      WRITE (6,152)  (DELTA(I),I=3,27,4)
      WRITE (6,153)  (DELTA(I),I=4,28,4)
      DO 414  L4=1,28
  414 XDELTA(L4)=0.0
      IF (GAMMA.LT.2.0005)  GO TO 91
      GAMMA=2.0
      GO TO 399
   91 CONTINUE
  420 CONTINUE
      GO TO 1
  119 FORMAT (5X*IMPINGEMENT DISTANCE IS INFINITE*)
  120 FORMAT (5X*IMPINGEMENT DISTANCE (SPANS) USING CHI (EFFECTIVE) IS*
     1F10.2,5X*USING CHI (MOMENTUM) IS*F10.2)
  148 FORMAT (//5H CHI=F5.1,5X6HGAMMA=F7.3,5X*INTERFERENCE AT TAIL*5X
     1*SIGMA(TAIL)=*F6.3,5X*TL/H=*F7.3,5X*TH/H=*F7.3/)
  149 FORMAT (//5H CHI=F5.1,5X6HGAMMA=F7.3,5X*INTERFERENCE AT WING*/)
  150 FORMAT (3X5H(W,L)7(F17.4))
  151 FORMAT (3X5H(U,L)7(F17.4))
  152 FORMAT (3X5H(W,D)7(F17.4))
  153 FORMAT (3X5H(U,D)7(F17.4))
  210 FORMAT (1X131(1H-))
  211 FORMAT (1X1HI11X1HI31X61HCORRECTICN FACTORS FOR CORRECTING FROM A
     1WIND TUNNEL WHICH IS25X1HI)
  212 FORMAT (1X1HI11X1HI117(1H-)1HI)
  213 FORMAT (1X1HI11X1HI16X1HI5X6HCLOSED5X1HI16X1HI2X12HCLOSED FLOOR2X1
     1HI6X4HOPEN6X1HI16X1HI5X6HCLOSED4X1HI)
  214 FORMAT (1X1HI3X5HDELTA3X1HI5X6HCLCSED5X1HI4X9HON BOTTOM3X1HI6X4HOP
     1EN6X1HI6X4HONLY6X1HI5X5HFLOOR6X1HI5X6HCLOSED5X1HI3X9HON BOTTOM3X1H
     2I)
  215 FORMAT (1X1HI11X1HI16X1HI6X4HONLY6X1HI16X18HI(GROUND EFFECT) I6X4H
     1ONLY6X1HI16X1HI6X4HCNLY5X1HI)
  216 FORMAT (1X1HI11X1HI84(1H-)1HI32(1H-)1HI)
  217 FORMAT (1X1HI11X1HI36X11HTO FREE AIR37X1HI8X16HTO GROUND EFFECT8X1
     1HI)
  218 FORMAT (1X131(1H-))
  900 FORMAT (I1,F9.3,4F10.3/I1,F9.3,2F10.3)
  901 FORMAT (1H1///40X*AVERAGE INTERFERENCE OVER A SWEPT WING OF FINITE
     1 SPAN*//30X*GAMMA CCMPUTED TO YIELD ZERO DELTA(W,L) IN A CLOSED-ON
     2-BOTTOM-ONLY TUNNEL*///29X*SIGMA =*F6.3,16X,A8* LOADING*15X,
     3*LAMBDA =*F7.3//29X*ZETA  =*F6.3,18X*ETA =*F7.3,17X*ALPHA  =*
     4F7.3///35X*ALL VALUES ARE REFERENCED TO THE HIGH-SPEED (GAMMA=2.0)
     5 SECTION*/39X*ALL DIMENSIONS ARE MEASURED FROM THE AERODYNAMIC CEN
     6TER*//)
  999 STOP
      END
```

APPENDIX B

FORTRAN PROGRAM FOR COMPUTING INTERFERENCE OVER ROTORS IN A VARIABLE WIDTH-HEIGHT-RATIO CLOSED-ON-BOTTOM-ONLY TUNNEL

THIS PROGRAM WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS PROGRAM HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

NOTE THAT ALL INPUT AND OUTPUT VARIABLES ARE REFERENCED TO THE GAMMA=2.0 TEST SECTION. INPUT IS AT ADDRESS 1 IN FORMAT 900 (TWO CARDS PER CASE). THE REQUIRED INPUT VARIABLES ARE

LI	DISK-LOAD DISTRIBUTION INDICATOR, LI=1 FOR UNIFORM LOADING, LI=2 FOR TRIANGULAR LOADING
ZETA1	SEMIHEIGHT OF GAMMA=2 SECTION DIVIDED BY HEIGHT OF ROTOR CENTER ABOVE FLOOR IN GAMMA=2 SECTION
ETA1	DISTANCE FROM ROTOR CENTER TO RIGHT-HAND WALL DIVIDED BY TUNNEL SEMIWIDTH
SIGMA	RATIO OF ROTOR DIAMETER TO TUNNEL WIDTH
ALPHA	ANGLE OF ATTACK OF ROTOR TIP-PATH PLANE, DEG
ITAIL	NUMBER (0 TO 9) OF TAIL POSITIONS, PROPORTIONATELY INCREASED IN TAIL LENGTH AND HEIGHT, AT WHICH INTERFERENCE IS REQUIRED. USE SMALLEST LENGTH AND HEIGHT AS INPUT.
SIGMAT	RATIO OF TAIL SPAN TO TUNNEL WIDTH
TL	DISTANCE OF TAIL BEHIND ROTOR CENTER, NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS
TH	HEIGHT OF TAIL ABOVE ROTOR CENTER, NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS
ALPHAB	ANGLE OF ATTACK OF BODY CARRYING TAIL, DEG

THIS PROGRAM REQUIRES SUBROUTINE DLTAS (SEE APPENDIX G) AND SUBROUTINE VARLET (SEE APPENDIX H).

SINCE THE TAIL LOCATIONS ARE NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS, THIS PROGRAM CAN NOT ACCOMMODATE, AND WILL REJECT, TAIL INTERFERENCE CALCULATIONS FOR CASES INVOLVING SIGMA = 0, HOWEVER, THE INTERFERENCE AT THE CENTER OF LIFT WILL BE CALCULATED FOR SUCH CASES. TAIL INTERFERENCE FOR SUCH CASES CAN BE OBTAINED FROM THE CORRESPONDING PROGRAM FOR WINGS, SINCE, WHEN SIGMA IS ZERO, THE REPRESENTATION OF WINGS AND ROTORS IS IDENTICAL.

APPENDIX B

```
      PROGRAM WINDTUN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)
      DIMENSION XDELTA(28),PSI(20),XLOAD(20),RUNIF(20),RTRIA(20),
     1    C(8),STORE(8)
      DATA (RUNIF(I),I=1,20)/4*0.2981,8*0.6255,8*0.8921/
      DATA (RTRIA(I),I=1,20)/4*0.4386,8*0.7296,8*0.9262/
      DATA (C(I),I=1,8)/20.,30.,40.,50.,60.,70.,80.,90./
      RAD=0.0174532925199
      PI=3.14159265358979
      PSI(1)=(PI/4.)
      PSI(2)=3.*PSI(1)
      PSI(3)=5.*PSI(1)
      PSI(4)=7.*PSI(1)
      PSI(5)=PSI(13)=(PI/8.)
      PSI(6)=PSI(14)=3.*PSI(5)
      PSI(7)=PSI(15)=5.*PSI(5)
      PSI(8)=PSI(16)=7.*PSI(5)
      PSI(9)=PSI(17)=9.*PSI(5)
      PSI(10)=PSI(18)=11.*PSI(5)
      PSI(11)=PSI(19)=13.*PSI(5)
      PSI(12)=PSI(20)=15.*PSI(5)
    1 READ (5,900)  LI,ZETA1,ETA1,SIGMA,ALPHA,ITAIL,SIGMAT,TL,TH,ALPHAB
      IF (EOF,5) 999,47
   47 IF (LI.EQ.1) GO TO 804
      IALPHA=10HTRIANGULAR
      DO 808 M2=1,20
  808 XLOAD(M2)=RTRIA(M2)
      GO TO 160
  804 IALPHA=10H UNIFORM
      DO 809 M2=1,20
  809 XLOAD(M2)=RUNIF(M2)
  160 WRITE (6,901)  IALPHA,SIGMA,ALPHA,ZETA1,SIGMAT,ALPHAB,ETA1
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      SUML=0.0025
      CONST1=1.
      AZETA=ZETA1
      ATL=TL
      ATH=TH
      ALPR=ALPHA
      ALPB=ALPHAB
      ALPHA=ALPR*RAD
      ALPHAB=ALPB*RAD
      DO 41  K=1,8
      DO 803 L1=1,28
      DELTA(L1)=0.
  803 XDELTA(L1)=0.
      INK=1
      GAMMA=GMA1=2.0
      M7=N7=20
      IF (SIGMA.NE.0.) GO TO 811
```

```
      N7=M7=1                                                            (B 59)
      CONST1=400                                                         (B 60)
      GO TO 812                                                          (B 61)
  811 IF (ETA1.NE.1.)  GO TO 812                                         (B 62)
      CONST1=2.                                                          (B 63)
  812 DO 801  M1=1,M7                                                    (B 64)
      DO 802  N1=1,N7                                                    (B 65)
  836 IF (ETA1.NE.1.)  GO TO 840                                         (B 66)
      IF (PSI(N1).GT.PI) GO TO 802                                       (B 67)
  840 ETA=ETA1-(XLOAD(N1)*SIGMA *SIN(PSI(N1)))                           (B 68)
      ZETA1=2.0/(2.0+GAMMA*(1.0-AZETA))                                  (B 69)
      ZETA=1./((1./ZETA1)-(XLOAD(N1)*SIGMA *SIN(ALPHA)*COS(PSI(N1))*GAMM (B 70)
     1A))                                                                (B 71)
      XOVERH=SIGMA *GAMMA*COS(ALPHA)*(XLOAD(M1)*COS(PSI(M1))-XLOAD(N1)*C (B 72)
     1OS(PSI(N1)))                                                       (B 73)
      YOVERH=SIGMA *GAMMA*(XLOAD(M1)*SIN(PSI(M1))-XLOAD(N1)*SIN(PSI(N1)) (B 74)
     1)                                                                  (B 75)
      ZOVERH=-SIGMA *GAMMA*SIN(ALPHA)*(XLOAD(M1)*COS(PSI(M1))-XLOAD(N1)* (B 76)
     1COS(PSI(N1)))                                                      (B 77)
      IF (INK.EQ.7)  GO TO 850                                           (B 78)
      CALL VARLET (C(K))                                                 (B 79)
******************** SEE APPENDIX H FOR SUBROUTINE VARLET ********************
      GO TO 832                                                          (B 80)
  850 CALL DLTAS  (C(K))                                                 (B 81)
********************* SEE APPENDIX G FOR SUBROUTINE DLTAS ********************
  832 DO 805 L1=1,28                                                     (B 82)
  805 XDELTA(L1)=XDELTA(L1)+(DELTA(L1))                                  (B 83)
  802 CONTINUE                                                           (B 84)
  801 CONTINUE                                                           (B 85)
      IF (INK.EQ.7)  GO TO 835                                           (B 86)
      DELTA(5)=XDELTA(5)*SUML*CONST1*(GAMMA/2.0)                         (B 87)
      IF (ABS(DELTA(5)).LT.0.00005)  GO TO 833                           (B 88)
      DEL2=DELTA(5)                                                      (B 89)
      IF (INK.NE.1)  GO TO 831                                           (B 90)
      DEL1=DELTA(5)                                                      (B 91)
      GAMMA=GMA2=1.0                                                     (B 92)
      INK=2                                                              (B 93)
      XDELTA(5)=0.0                                                      (B 94)
      GO TO 812                                                          (B 95)
  831 IF (ABS(DELTA(5)).LT.0.00005)  GO TO 833                           (B 96)
      GAMMA=GAMMA-(GMA2-GMA1)*DEL2/(DEL2-DEL1)                           (B 97)
      IF (GAMMA.LE.0.1)  GAMMA=0.1                                       (B 98)
      DEL1=DEL2                                                          (B 99)
      GMA1=GMA2                                                          (B 100)
      INK=3                                                              (B 101)
      GMA2=GAMMA                                                         (B 102)
      IF (GMA2.EQ.GMA1)  GO TO 837                                       (B 103)
      XDELTA(5)=0.0                                                      (B 104)
      GO TO 812                                                          (B 105)
  837 STORE(K)=0.01                                                      (B 106)
      GO TO 41                                                           (B 107)
  833 INK=7                                                              (B 108)
      XDELTA(5)=0.0                                                      (B 109)
      STORE(K)=GAMMA                                                     (B 110)
      GO TO 812                                                          (B 111)
  835 DO 807  L3=1,28                                                    (B 112)
  807 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.)                        (B 113)
      WRITE (6,149)  C(K),GAMMA                                          (B 114)
      WRITE (6,150) (DELTA(I),I=1,25,4)                                  (B 115)
      WRITE (6,151) (DELTA(I),I=2,26,4)                                  (B 116)
      WRITE (6,152) (DELTA(I),I=3,27,4)                                  (B 117)
```

```
      WRITE (6,153) (DELTA(I),I=4,28,4)                                  (B 118)
      IF (SIGMA.EQ.0.)  GO TO 822                                        (B 119)
      IF (C(K).EQ.90.)  GO TO 820                                        (B 120)
      XS1=TAN(C(K)*RAD)/(2.0*SIGMA*GAMMA*ZETA1)                          (B 121)
      CHIM=2.0*C(K)-90.                                                  (B 122)
      XS2=TAN(CHIM*RAD)/(2.0*SIGMA*GAMMA*ZETA1)                          (B 123)
      WRITE (6,120)  XS1,XS2                                             (B 124)
      GO TO 822                                                          (B 125)
  820 WRITE (6,119)                                                      (B 126)
  822 DO 814 L4=1,28                                                     (B 127)
  814 XDELTA(L4)=0.                                                      (B 128)
      IF (GAMMA.LT.2.0005)  GO TO 41                                     (B 129)
      GAMMA=2.0                                                          (B 130)
      GO TO 812                                                          (B 131)
   41 CONTINUE                                                           (B 132)
      IF (ITAIL.EQ.0)  GO TO 1                                           (B 133)
      IF (SIGMA.NE.0.) GO TO 400                                         (B 134)
      WRITE (6,901) IALPHA,SIGMA,ALPR,AZETA,SIGMAT,ALPB,ETA1             (B 135)
      WRITE (6,904)                                                      (B 136)
      GO TO 1                                                            (B 137)
  400 SUML=0.0125                                                        (B 138)
      IF (SIGMAT.NE.0.)  GO TO 411                                       (B 139)
      M7=1                                                               (B 140)
      CONST1=4.0                                                         (B 141)
      GO TO 412                                                          (B 142)
  411 IF (ETA1.NE.1.)  GO TO 413                                         (B 143)
      M7=2                                                               (B 144)
      CONST1=2.0                                                         (B 145)
      GO TO 412                                                          (B 146)
  413 M7=4                                                               (B 147)
      CONST1=1.0                                                         (B 148)
  412 DO 420  ITL=1,ITAIL                                                (B 149)
      TL=ATL*FLOAT(ITL)                                                  (B 150)
      TH=ATH*FLOAT(ITL)                                                  (B 151)
      WRITE (6,901)  IALPHA,SIGMA,ALPR,AZETA,SIGMAT,ALPB,ETA1            (B 152)
      WRITE (6,210)                                                      (B 153)
      WRITE (6,211)                                                      (B 154)
      WRITE (6,212)                                                      (B 155)
      WRITE (6,213)                                                      (B 156)
      WRITE (6,214)                                                      (B 157)
      WRITE (6,215)                                                      (B 158)
      WRITE (6,216)                                                      (B 159)
      WRITE (6,217)                                                      (B 160)
      WRITE (6,218)                                                      (B 161)
      DO 91 K=1,8                                                        (B 162)
      GAMMA=STORE(K)                                                     (B 163)
  399 ZETA1=2.0/(2.0+GAMMA*(1.0-AZETA))                                  (B 164)
      DO 401  M1=1,M7                                                    (B 165)
      DO 402  N1=1,20                                                    (B 166)
      ETA=ETA1-(XLOAD(N1)*SIGMA*SIN(PSI(N1)))                            (B 167)
      ZETA=1./((1./ZETA1)-XLOAD(N1)*SIGMA*GAMMA*SIN(ALPHA)*COS(PSI(N1))) (B 168)
      XOVERH=SIGMA*GAMMA*((TL*COS(ALPHAB))+(TH*SIN(ALPHAB))-(XLOAD(N1)   (B 169)
     1     *COS(ALPHA)*COS(PSI(N1))))                                    (B 170)
      XM1=FLOAT(M1)                                                      (B 171)
      YOVERH=SIGMA*GAMMA*(-((2.*XM1-5.)/4.)*(SIGMAT/SIGMA)-(XLOAD(N1)    (B 172)
     1     *SIN(PSI(N1))))                                               (B 173)
      ZOVERH=SIGMA*GAMMA*((TH*COS(ALPHAB))-(TL*SIN(ALPHAB))+(XLOAD(N1)   (B 174)
     1     *SIN(ALPHA)*COS(PSI(N1))))                                    (B 175)
      CALL DLTAS  (C(K))                                                 (B 176)
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS ********************
      DO 405 L1=1,28                                                     (B 177)
```

```
  405 XDELTA(L1)=XDELTA(L1)+DELTA(L1)
  402 CONTINUE
  401 CONTINUE
      DO 407 L3=1,28
  407 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.0)
      WRITE (6,148)  C(K),GAMMA,TL,TH
      WRITE (6,150) (DELTA(I),I=1,25,4)
      WRITE (6,151) (DELTA(I),I=2,26,4)
      WRITE (6,152) (DELTA(I),I=3,27,4)
      WRITE (6,153) (DELTA(I),I=4,28,4)
      DO 414 L4=1,28
  414 XDELTA(L4)=0.0
      IF (GAMMA.LT.2.0005)  GO TO 91
      GAMMA=2.0
      GO TO 399
   91 CONTINUE
  420 CONTINUE
      GO TO 1
  119 FORMAT ( 5X*IMPINGEMENT DISTANCE IS INFINITE*)
  120 FORMAT ( 5X*IMPINGEMENT DISTANCE (SPANS) USING CHI (EFFECTIVE) IS*
     1F10.2,5X*USING CHI (MOMENTUM) IS*F10.2)
  148 FORMAT (//5X*CHI =*F7.3,5X*GAMMA =*F7.3,5X*INTERFERENCE AT TAIL*5X
     1*TL/R =*F6.3,5X*TH/R =*F6.3/)
  149 FORMAT (//5H CHI=F5.1,5X6HGAMMA=F7.3,5X*INTERFERENCE AT ROTOR*/)
  150 FORMAT (3X5H(W,L)7(F17.4))
  151 FORMAT (3X5H(U,L)7(F17.4))
  152 FORMAT (3X5H(W,D)7(F17.4))
  153 FORMAT (3X5H(U,D)7(F17.4))
  210 FORMAT (1X131(1H-))
  211 FORMAT (1X1HI11X1HI31X61HCORRECTICN FACTORS FOR CORRECTING FROM A
     1WIND TUNNEL WHICH IS25X1HI)
  212 FORMAT (1X1HI11X1HI117(1H-)1HI)
  213 FORMAT (1X1HI11X1HI16X1HI5X6HCLOSED5X1HI16X1HI2X12HCLOSED FLOOR2X1
     1HI6X4HOPEN6X1HI16X1HI5X6HCLOSED4X1HI)
  214 FORMAT (1X1HI3X5HDELTA3X1HI5X6HCLCSED5X1HI4X9HON BOTTOM3X1HI6X4HOP
     1EN6X1HI6X4HONLY6X1HI5X5HFLOOR6X1HI5X6HCLOSED5X1HI3X9HON BOTTOM3X1H
     2I)
  215 FORMAT (1X1HI11X1HI16X1HI6X4HONLY6X1HI16X18HI(GROUND EFFECT) I6X4H
     1ONLY6X1HI16X1HI6X4HCNLY5X1HI)
  216 FORMAT (1X1HI11X1HI84(1H-)1HI32(1H-)1HI)
  217 FORMAT (1X1HI11X1HI36X11HTO FREE AIR37X1HI8X16HTO GROUND EFFECT8X1
     1HI)
  218 FORMAT (1X131(1H-))
  900 FORMAT (I1,F9.3,3F1C.3/I1,F9.3,3F10.3)
  901 FORMAT (1H1////42X*AVERAGE INTERFERENCE OVER A ROTOR OF FINITE SPA
     1N*//30X*GAMMA COMPUTED TO YIELD ZERO DELTA(W,L) IN A CLOSED-ON-BOT
     2TOM-ONLY TUNNEL*///55X,A10* DISK LOADING*//30X*SIGMA(ROTOR) =*
     3F6.3,8X*ALPHA(ROTOR) =*F7.3,10X*ZETA =*F6.3//30X*SIGMA(TAIL)  =*
     4F6.3,8X*ALPHA(TAIL)  =*F7.3,10X*ETA  =*F6.3//35X*ALL VALUES ARE RE
     5FERENCED TO THE HIGH-SPEED (GAMMA=2.0) SECTION*//)
  904 FORMAT (///40X*TAIL IS OMITTED - EQUATIONS ARE NOT VALID WHEN SIGM
     1A(ROTOR) = 0.*///)
999   STOP
      END
```

APPENDIX C

FORTRAN PROGRAM FOR COMPUTING INTERFERENCE OVER WINGS IN A VARIABLE MODEL-HEIGHT CLOSED-ON-BOTTOM-ONLY TUNNEL

THIS PROGRAM WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS PROGRAM HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

INPUT IS AT ADDRESS 1 IN FORMAT 9CC (TWO CARDS PER CASE). THE REQUIRED INPUT VARIABLES ARE

LI	SPAN LOAD-DISTRIBUTION INDICATOR, LI=1 FOR UNIFORM LOADING, LI=2 FOR ELLIPTIC LOADING
ETA1	DISTANCE FROM AERODYNAMIC CENTER TO RIGHT-HAND WALL DIVIDED BY TUNNEL SEMIWIDTH
GAMMA	WIDTH-HEIGHT RATIO OF WIND TUNNEL
SIGMA	RATIO OF WING SPAN TO TUNNEL WIDTH
LAMBDA	WING SWEEP ANGLE, DEG
ALPHA	ANGLE OF ATTACK OF WING, DEG
ITAIL	NUMBER (0 TO 9) OF TAIL POSITIONS, PROPORTIONATELY INCREASED IN TAIL LENGTH AND HEIGHT, AT WHICH INTERFERENCE IS REQUIRED. USE SMALLEST LENGTH AND HEIGHT AS INPUT.
SIGMAT	RATIO OF TAIL SPAN TO TUNNEL WIDTH
TL	DISTANCE OF TAIL BEHIND AERODYNAMIC CENTER, NONDIMENSIONALIZED WITH RESPECT TO TUNNEL SEMIHEIGHT
TH	HEIGHT OF TAIL ABOVE AERODYNAMIC CENTER, NONDIMENSIONALIZED WITH RESPECT TO TUNNEL SEMIHEIGHT

THIS PROGRAM REQUIRES SUBROUTINE DLTAS (SEE APPENDIX G) AND SUBROUTINE VARLET (SEE APPENDIX H).

```
      PROGRAM WINDTUN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)            (C  1)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)              (C  2)
      DIMENSION XLE(10),XLOAD(10),XDELTA(28),C(8),STORE(8)              (C  3)
      REAL LAMBDA                                                       (C  4)
      DATA (C(I),I=1,8)/20.,30.,40.,50.,60.,70.,80.,90./                (C  5)
      XLE(1)=XLE(10)=0.43579                                            (C  6)
      XLE(2)=XLE(9)=0.71422                                             (C  7)
```

```
      XLE(3)=XLE(8)=0.86603
      XLE(4)=XLE(7)=0.95394
      XLE(5)=XLE(6)=0.99499
    1 READ (5,900) LI,ETA1,GAMMA,SIGMA,LAMBDA,ALPHA,ITAIL,SIGMAT,TL,TH
      IF (EOF,5) 999,47
   47 IF (LI.EQ.1) GO TO 804
      IALPHA=8HELLIPTIC
      SUML=0.0126104
      DO 808 M2=1,10
  808 XLOAD(M2)=XLE(M2)
      GO TO 160
  804 SUML=0.01
      IALPHA=8HUNIFORM
      DO 809 M2=1,10
  809 XLOAD(M2)=1.0
  160 WRITE (6,901)  SIGMA,IALPHA,LAMBDA,GAMMA,ETA1,ALPHA
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      AALP=ALPHA
      ALAM=LAMBDA
      ATL=TL
      ATH=TH
      CONST1=1.0
      RAD=0.0174532925199
      ALPHA=ALPHA*RAD
      LAMBDA=LAMBDA*RAD
      AC= 0.5*SIGMA*GAMMA*TAN(LAMBDA)
      IF (LI.NE.1)  AC=0.848*AC
      DO 41  K=1,8
      DO 803 L1=1,28
      DELTA(L1)=0.
  803 XDELTA(L1)=0.
      INK=1
      ZETA1=ZET1=1.0
      IF (SIGMA.NE.0.) GO TO 811
      M7=N7=1
      XLOAD(1)=1.0
      SUML=1.
      GO TO 812
  811 IF (ETA1.NE.1.) GO TO 813
      M7=5
      N7=10
      CONST1=2.
      GO TO 812
  813 M7=N7=10
  812 DO 801  M1=1,M7
      DO 802  N1=1,N7
      XSTAR=(11.-2.*FLOAT(M1))/10.
      YSTAR=(2.*FLOAT(N1)-11.)/10.
      ZSTAR=(11.-2.*FLOAT(N1))/10.
      ETA=ETA1+YSTAR*SIGMA
      ZETA=ZETA1/(1.-ABS(YSTAR)*SIGMA*GAMMA*ZETA1*TAN(LAMBDA)*SIN(ALPHA)
     1)
      XOVERH=SIGMA*GAMMA*TAN(LAMBDA)*COS(ALPHA)*(ABS(XSTAR)-ABS(ZSTAR))
```

```
      YOVERH=(FLOAT(M1)-FLOAT(N1))*SIGMA*GAMMA*(-.2)
      ZOVERH=SIGMA*GAMMA*TAN(LAMBDA)*SIN(ALPHA)*(ABS(ZSTAR)-ABS(XSTAR))
      IF (INK.EQ.7)  GO TO 850
      CALL VARLET  (C(K))
******************** SEE APPENDIX H FOR SUBROUTINE VARLET ********************
      GO TO 832
  850 CALL DLTAS   (C(K))
******************** SEE APPENDIX H FOR SUBROUTINE VARLET ********************
  832 DO 805 L1=1,28
  805 XDELTA(L1)=XDELTA(L1)+(DELTA(L1)*XLOAD(N1))
  802 CONTINUE
  801 CONTINUE
      IF (INK.EQ.7)  GO TO 835
      DELTA(5)=XDELTA(5)*SUML*CONST1
      IF (ABS(DELTA(5)).LT.0.00005)  GC TO 833
      DEL2=DELTA(5)
      IF (INK.NE.1)  GO TO 831
      DEL1=DELTA(5)
      ZETA1=ZET2=0.9
      INK=2
      XDELTA(5)=0.0
      GO TO 812
  831 IF (ABS(DELTA(5)).LT.0.00005)  GO TO 833
      ZETA1=ZETA1-(ZET2-ZET1)*DEL2/(DEL2-DEL1)
      DEL1=DEL2
      ZET1=ZET2
      INK=3
      ZET2=ZETA1
      XDELTA(5)=0.0
      GO TO 812
  833 INK=7
      XDELTA(5)=0.0
      STORE(K)=ZETA1
      GO TO 812
  835 DO 807 L3=1,28
  807 DELTA(L3)=XDELTA(L3)*SUML*CONST1
      BZETA=ZETA1/(1.0-AC*ZETA1*SIN(ALPHA))
      HCL=(1.0/BZETA)-1.0
      WRITE (6,149)  C(K),BZETA,HCL
      WRITE (6,150) (DELTA(I),I=1,25,4)
      WRITE (6,151) (DELTA(I),I=2,26,4)
      WRITE (6,152) (DELTA(I),I=3,27,4)
      WRITE (6,153) (DELTA(I),I=4,28,4)
      IF (SIGMA.EQ.0.)  GO TO 822
      IF (C(K).EQ.90.)  GO TO 820
      XS1=TAN(C(K)*RAD)/(2.0*SIGMA*GAMMA*BZETA)
      CHIM=2.0*C(K)-90.
      XS2=TAN(CHIM*RAD)/(2.0*SIGMA*GAMMA*BZETA)
      WRITE (6,120)  XS1,XS2
      GO TO 822
  820 WRITE (6,119)
  822 DO 814 L4=1,28
  814 XDELTA(L4)=0.
   41 CONTINUE
      IF (ITAIL.EQ.0)  GO TO 1
      SUML=0.031526
      IF (LI.EQ.1) SUML=0.025
      IF (SIGMAW.EQ.0..ANC.SIGMAT.EQ.0.)  GO TO 450
      IF (SIGMAW.EQ.0..AND.SIGMAT.NE.0.)  GO TO 455
      IF (SIGMAW.NE.C..AND.SIGMAT.EQ.0.)  GO TO 46C
      M7=4
```

APPENDIX C

```
      N7=10                                                             (C 128)
      CONST1=1.0                                                        (C 129)
      IF (ETA1.NE.1.)  GO TO 412                                        (C 130)
      M7=2                                                              (C 131)
      CONST1=2.0                                                        (C 132)
      GO TO 412                                                         (C 133)
  450 M7=N7=1                                                           (C 134)
      XLOAD(1)=1.0                                                      (C 135)
      SUML=0.025                                                        (C 136)
      CONST1=40.0                                                       (C 137)
      GO TO 412                                                         (C 138)
  455 M7=4                                                              (C 139)
      N7=1                                                              (C 140)
      XLOAD(1)=1.0                                                      (C 141)
      SUML=0.025                                                        (C 142)
      CONST1=10.0                                                       (C 143)
      IF (ETA1.NE.1.)  GO TO 412                                        (C 144)
      M7=2                                                              (C 145)
      CONST1=20.0                                                       (C 146)
      GO TO 412                                                         (C 147)
  460 M7=1                                                              (C 148)
      N7=10                                                             (C 149)
      CONST1=4.0                                                        (C 150)
      IF (ETA1.NE.1.)  GO TO 412                                        (C 151)
      N7=5                                                              (C 152)
      CONST1=8.0                                                        (C 153)
      DO 400  L2=1,28                                                   (C 154)
      XDELTA(L2)=0.                                                     (C 155)
  400 DELTA(L2)=0.                                                      (C 156)
  412 DO 420  ITL=1,ITAIL                                               (C 157)
      TL=ATL*FLOAT(ITL)+AC                                              (C 158)
      TH=ATH*FLOAT(ITL)                                                 (C 159)
      WRITE (6,901)  SIGMA,IALPHA,ALAM  ,GAMMA,ETA1,AALP                (C 160)
      WRITE (6,210)                                                     (C 161)
      WRITE (6,211)                                                     (C 162)
      WRITE (6,212)                                                     (C 163)
      WRITE (6,213)                                                     (C 164)
      WRITE (6,214)                                                     (C 165)
      WRITE (6,215)                                                     (C 166)
      WRITE (6,216)                                                     (C 167)
      WRITE (6,217)                                                     (C 168)
      WRITE (6,218)                                                     (C 169)
      DO 91  K=1,8                                                      (C 170)
      ZETA1=STORE(K)                                                    (C 171)
      DO 401  M1=1,M7                                                   (C 172)
      DO 402  N1=1,N7                                                   (C 173)
      XSTAR=(2.*FLOAT(N1)-11.)/10.0                                     (C 174)
      YSTAR=(11.-2.*FLOAT(N1))/10.0                                     (C 175)
      ZSTAR=(5.-2.*FLOAT(M1))/4.0                                       (C 176)
      ETA=ETA1+XSTAR*SIGMA                                              (C 177)
      ZETA=ZETA1/(1.-ABS(YSTAR)*SIGMA*GAMMA*ZETA1*TAN(LAMBDA)*          (C 178)
     1     SIN(ALPHA))                                                  (C 179)
      XOVERH=TL*COS(ALPHA)+TH*SIN(ALPHA)-SIGMA*GAMMA*TAN(LAMBDA)*       (C 180)
     1     COS(ALPHA)*ABS(YSTAR)                                        (C 181)
      YOVERH=ZSTAR*SIGMAT*GAMMA-YSTAR*SIGMA*GAMMA                       (C 182)
      ZOVERH=TH*COS(ALPHA)-TL*SIN(ALPHA)+SIGMA*GAMMA*TAN(LAMBDA)*       (C 183)
     1     SIN(ALPHA)*ABS(YSTAR)                                        (C 184)
      CALL DLTAS  (C(K))                                                (C 185)
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS ********************
      DO 405 L1=1,28                                                    (C 186)
  405 XDELTA(L1)=XDELTA(L1)+(DELTA(L1)*XLOAD(N1))                       (C 187)
```

```
  402 CONTINUE
  401 CONTINUE
      DO 407 L3=1,28
  407 DELTA(L3)=XDELTA(L3)*SUML*CONST1
      BZETA=ZETA1/(1.0-AC*ZETA1*SIN(ALPHA))
      TTL=ATL*FLOAT(ITL)
      WRITE (6,148)  C(K),BZETA,SIGMAT,TTL,TH
      WRITE (6,150)  (DELTA(I),I=1,25,4)
      WRITE (6,151)  (DELTA(I),I=2,26,4)
      WRITE (6,152)  (DELTA(I),I=3,27,4)
      WRITE (6,153)  (DELTA(I),I=4,28,4)
      DO 414  L4=1,28
  414 XDELTA(L4)=0.0
   91 CONTINUE
  420 CONTINUE
      GO TO 1
  119 FORMAT ( 5X*IMPINGEMENT DISTANCE IS INFINITE*)
  120 FORMAT ( 5X*IMPINGEMENT DISTANCE (SPANS) USING CHI (EFFECTIVE) IS*
     1F10.2,5X*USING CHI (MOMENTUM) IS*F10.2)
  148 FORMAT (//5H CHI=F5.1,5X5HZETA=F7.3,5X*INTERFERENCE AT TAIL*5X
     1*SIGMA(TAIL)=*F6.3,5X*TL/H=*F7.3,5X*TH/H=*F7.3/)
  149 FORMAT (//5H CHI=F5.1,5X5HZETA=F7.3,5X*INTERFERENCE AT WING*
     15X*H(CL)/H=*F6.3/)
  150 FORMAT (3X5H(W,L)7(F17.4))
  151 FORMAT (3X5H(U,L)7(F17.4))
  152 FORMAT (3X5H(W,D)7(F17.4))
  153 FORMAT (3X5H(U,D)7(F17.4))
  210 FORMAT (1X131(1H-))
  211 FORMAT (1X1HI11X1HI31X61HCORRECTICN FACTORS FOR CORRECTING FROM A
     1WIND TUNNEL WHICH IS25X1HI)
  212 FORMAT (1X1HI11X1HI117(1H-)1HI)
  213 FORMAT (1X1HI11X1HI16X1HI5X6HCLOSED5X1HI16X1HI2X12HCLOSED FLOOR2X1
     1HI6X4HOPEN6X1HI16X1HI5X6HCLOSED4X1HI)
  214 FORMAT (1X1HI3X5HDELTA3X1HI5X6HCLOSED5X1HI4X9HON BOTTOM3X1HI6X4HOP
     1EN6X1HI6X4HONLY6X1HI5X5HFLOOR6X1HI5X6HCLOSED5X1HI3X9HON BOTTOM3X1H
     2I)
  215 FORMAT (1X1HI11X1HI16X1HI6X4HONLY6X1HI16X18HI(GROUND EFFECT) I6X4H
     1ONLY6X1HI16X1HI6X4HCNLY5X1HI)
  216 FORMAT (1X1HI11X1HI84(1H-)1HI32(1H-)1HI)
  217 FORMAT (1X1HI11X1HI36X11HTO FREE AIR37X1HI8X16HTO GROUND EFFECT8X1
     1HI)
  218 FORMAT (1X131(1H-))
  900 FORMAT (I1,F9.3,4F10.3/I1,F9.3,2F10.3)
  901 FORMAT (1H1///40X*AVERAGE INTERFERENCE OVER A SWEPT WING OF FINITE
     1 SPAN*//31X*ZETA COMPUTED TO YIELD ZERO DELTA(W,L) IN A CLOSED-ON-
     2BOTTOM-ONLY TUNNEL*///30X*SIGMA =*F6.3,15X,A8* LOADING*15X,
     3*LAMBDA =*F7.3//30X*GAMMA =*F6.3,17X*ETA =*F7.3,17X*ALPHA  =*
     4F7.3//41X*ALL DIMENSIONS MEASURED FROM THE AERODYNAMIC CENTER*//)
999   STOP
      END
```

APPENDIX D

FORTRAN PROGRAM FOR COMPUTING INTERFERENCE OVER ROTORS IN A VARIABLE MODEL-HEIGHT CLOSED-ON-BOTTOM-ONLY TUNNEL

THIS PROGRAM WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS PROGRAM HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

INPUT IS AT ADDRESS 1 IN FORMAT 900 (TWO CARDS PER CASE). THE REQUIRED INPUT VARIABLES ARE

LI	DISK-LOAD DISTRIBUTION INDICATOR, LI=1 FOR UNIFORM LOADING, LI=2 FOR TRIANGULAR LOADING
ETA1	DISTANCE FROM ROTOR CENTER TO RIGHT-HAND WALL DIVIDED BY TUNNEL SEMIWIDTH
GAMMA	WIDTH-HEIGHT RATIO OF WIND TUNNEL
SIGMA	RATIO OF ROTOR DIAMETER TO TUNNEL WIDTH
ALPHA	ANGLE OF ATTACK OF ROTOR TIP-PATH PLANE, DEG
ITAIL	NUMBER (0 TO 9) OF TAIL POSITIONS, PROPORTIONATELY INCREASED IN TAIL LENGTH AND HEIGHT, AT WHICH INTERFERENCE IS REQUIRED. USE SMALLEST LENGTH AND HEIGHT AS INPUT.
SIGMAT	RATIO OF TAIL SPAN TO TUNNEL WIDTH
TL	DISTANCE OF TAIL BEHIND ROTOR CENTER, NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS
TH	HEIGHT OF TAIL ABOVE ROTOR CENTER, NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS
ALPHAB	ANGLE OF ATTACK OF BODY CARRYING TAIL, DEG

THIS PROGRAM REQUIRES SUBROUTINE DLTAS (SEE APPENDIX G) AND SUBROUTINE VARLET (SEE APPENDIX H).

SINCE THE TAIL LOCATIONS ARE NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS, THIS PROGRAM CAN NOT ACCOMMODATE, AND WILL REJECT, TAIL INTERFERENCE CALCULATIONS FOR CASES INVOLVING SIGMA = 0, HOWEVER, THE INTERFERENCE AT THE CENTER OF LIFT WILL BE CALCULATED FOR SUCH CASES. TAIL INTERFERENCE FOR SUCH CASES CAN BE OBTAINED FROM THE CORRESPONDING PROGRAM FOR WINGS, SINCE, WHEN SIGMA IS ZERO, THE REPRESENTATION OF WINGS AND ROTORS IS IDENTICAL.

```
      PROGRAM WINDTUN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)
      DIMENSION XDELTA(28),PSI(20),XLOAD(20),RUNIF(20),RTRIA(20),
     1    C(8),STORE(8)
      DATA (RUNIF(I),I=1,20)/4*0.2981,8*0.6255,8*0.8921/
      DATA (RTRIA(I),I=1,20)/4*0.4386,8*0.7296,8*0.9262/
      DATA (C(I),I=1,8)/20.,30.,40.,50.,60.,70.,80.,90./
      RAD=0.0174532925199
      PI=3.14159265358979
      PSI(1)=(PI/4.)
      PSI(2)=3.*PSI(1)
      PSI(3)=5.*PSI(1)
      PSI(4)=7.*PSI(1)
      PSI(5)=PSI(13)=(PI/8.)
      PSI(6)=PSI(14)=3.*PSI(5)
      PSI(7)=PSI(15)=5.*PSI(5)
      PSI(8)=PSI(16)=7.*PSI(5)
      PSI(9)=PSI(17)=9.*PSI(5)
      PSI(10)=PSI(18)=11.*PSI(5)
      PSI(11)=PSI(19)=13.*PSI(5)
      PSI(12)=PSI(20)=15.*PSI(5)
    1 READ (5,900)  LI,ETA1,GAMMA,SIGMA,ALPHA,ITAIL,SIGMAT,TL,TH,ALPHAB
      IF (EOF,5) 999,47
   47 IF (LI.EQ.1) GO TO 804
      IALPHA=10HTRIANGULAR
      DO 808 M2=1,20
  808 XLOAD(M2)=RTRIA(M2)
      GO TO 160
  804 IALPHA=10H UNIFORM
      DO 809 M2=1,20
  809 XLOAD(M2)=RUNIF(M2)
  160 WRITE (6,901)  IALPHA,SIGMA,ALPHA,GAMMA,SIGMAT,ALPHAB,ETA1
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      SUML=0.0025
      CONST1=1.
      ATL=TL
      ATH=TH
      ALPR=ALPHA
      ALPB=ALPHAB
      ALPHA=ALPR*RAD
      ALPHAB=ALPB*RAD
      DO 41  K=1,8
      DO 803 L1=1,28
      DELTA(L1)=0.
  803 XDELTA(L1)=0.
      INK=1
      ZETA1=ZET1=1.0
      M7=N7=20
      IF (SIGMA.NE.0.) GO TO 811
      N7=M7=1
      CONST1=4C0
      GO TO 812
  811 IF (ETA1.NE.1.)  GO TO 812
```

```
      CONST1=2.
  812 DO 801  M1=1,M7
      DO 802  N1=1,N7
  836 IF (ETA1.NE.1.)  GO TO 840
      IF (PSI(N1).GT.PI) GO TO 802
  840 ETA=ETA1-(XLOAD(N1)*SIGMA *SIN(PSI(N1)))
      ZETA=1./((1./ZETA1)-(XLOAD(N1)*SIGMA *SIN(ALPHA)*COS(PSI(N1))*GAMM
     1A))
      XOVERH=SIGMA *GAMMA*COS(ALPHA)*(XLOAD(M1)*COS(PSI(M1))-XLOAD(N1)*C
     1OS(PSI(N1)))
      YOVERH=SIGMA *GAMMA*(XLOAD(M1)*SIN(PSI(M1))-XLOAD(N1)*SIN(PSI(N1))
     1)
      ZOVERH=-SIGMA *GAMMA*SIN(ALPHA)*(XLOAD(M1)*COS(PSI(M1))-XLOAD(N1)*
     1COS(PSI(N1)))
      IF (INK.EQ.7)  GO TO 850
      CALL VARLET (C(K))
******************** SEE APPENDIX H FOR SUBROUTINE VARLET ********************
      GO TO 832
  850 CALL DLTAS  (C(K))
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS *********************
  832 DO 805 L1=1,28
  805 XDELTA(L1)=XDELTA(L1)+(DELTA(L1))
  802 CONTINUE
  801 CONTINUE
      IF (INK.EQ.7)  GO TO 835
      DELTA(5)=XDELTA(5)*SUML*CONST1
      IF (ABS(DELTA(5)).LT.0.00005)  GC TO 833
      DEL2=DELTA(5)
      IF (INK.NE.1)  GO TO 831
      DEL1=DELTA(5)
      ZETA1=ZET2=0.7
      INK=2
      XDELTA(5)=0.0
      GO TO 812
  831 IF (ABS(DELTA(5)).LT.0.00005)  GC TO 833
      ZETA1=ZETA1-(ZET2-ZET1)*DEL2/(DEL2-DEL1)
      DEL1=DEL2
      ZET1=ZET2
      INK=3
      ZET2=ZETA1
      XDELTA(5)=0.0
      GO TO 812
  833 INK=7
      XDELTA(5)=0.0
      STORE(K)=ZETA1
      HCL=(1.0/ZETA1)-1.0
      GO TO 812
  835 DO 807  L3=1,28
  807 DELTA(L3)=XDELTA(L3)*SUML*CONST1
      WRITE (6,149)  C(K),ZETA1,HCL
      WRITE (6,150) (DELTA(I),I=1,25,4)
      WRITE (6,151) (DELTA(I),I=2,26,4)
      WRITE (6,152) (DELTA(I),I=3,27,4)
      WRITE (6,153) (DELTA(I),I=4,28,4)
      IF (SIGMA.EQ.0.)  GO TO 822
      IF (C(K).EQ.90.)  GO TO 820
      XS1=TAN(C(K)*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      CHIM=2.0*C(K)-90.
      XS2=TAN(CHIM*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      WRITE (6,120)  XS1,XS2
      GO TO 822
```

```
  820 WRITE (6,119)
  822 DO 814 L4=1,28
  814 XDELTA(L4)=0.
   41 CONTINUE
      IF (ITAIL.EQ.0)  GO TO 1
      IF (SIGMA.NE.0.) GO TO 400
      WRITE (6,901) IALPHA,SIGMA,ALPR,GAMMA,SIGMAT,ALPB,ETA1
      WRITE (6,904)
      GO TO 1
  400 SUML=0.0125
      IF (SIGMAT.NE.0.)  GO TO 411
      M7=1
      CONST1=4.0
      GO TO 412
  411 IF (ETA1.NE.1.)  GO TO 413
      M7=2
      CONST1=2.0
      GO TO 412
  413 M7=4
      CONST1=1.0
  412 DO 420  ITL=1,ITAIL
      TL=ATL*FLOAT(ITL)
      TH=ATH*FLOAT(ITL)
      WRITE (6,901)  IALPHA,SIGMA,ALPR,GAMMA,SIGMAT,ALPB,ETA1
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      DO 91 K=1,8
      ZETA1=STORE(K)
      DO 401  M1=1,M7
      DO 402  N1=1,20
      ETA=ETA1-(XLOAD(N1)*SIGMA*SIN(PSI(N1)))
      ZETA=1./((1./ZETA1)-XLOAD(N1)*SIGMA*GAMMA*SIN(ALPHA)*COS(PSI(N1)))
      XOVERH=SIGMA*GAMMA*((TL*COS(ALPHAB))+(TH*SIN(ALPHAB))-(XLOAD(N1)
     1     *COS(ALPHA)*COS(PSI(N1))))
      XM1=FLOAT(M1)
      YOVERH=SIGMA*GAMMA*(-((2.*XM1-5.)/4.)*(SIGMAT/SIGMA)-(XLOAD(N1)
     1     *SIN(PSI(N1))))
      ZOVERH=SIGMA*GAMMA*((TH*COS(ALPHAB))-(TL*SIN(ALPHAB))+(XLOAD(N1)
     1     *SIN(ALPHA)*COS(PSI(N1))))
      CALL DLTAS  (C(K))
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS ********************
      DO 405 L1=1,28
  405 XDELTA(L1)=XDELTA(L1)+DELTA(L1)
  402 CONTINUE
  401 CONTINUE
      DO 407 L3=1,28
  407 DELTA(L3)=XDELTA(L3)*SUML*CONST1
      WRITE (6,148) C(K),ZETA1,TL,TH
      WRITE (6,150) (DELTA(I),I=1,25,4)
      WRITE (6,151) (DELTA(I),I=2,26,4)
      WRITE (6,152) (DELTA(I),I=3,27,4)
      WRITE (6,153) (DELTA(I),I=4,28,4)
      DO 414 L4=1,28
  414 XDELTA(L4)=0.0
```

```
  91 CONTINUE                                                            (D 181)
 420 CONTINUE                                                            (D 182)
     GO TO 1                                                             (D 183)
 119 FORMAT ( 5X*IMPINGEMENT DISTANCE IS INFINITE*)                      (D 184)
 120 FORMAT ( 5X*IMPINGEMENT DISTANCE (SPANS) USING CHI (EFFECTIVE) IS* (D 185)
    1F10.2,5X*USING CHI (MOMENTUM) IS*F10.2)                             (D 186)
 148 FORMAT (//5X*CHI =*F7.3,5X*ZETA =*F7.3,5X*INTERFERENCE AT TAIL*5X  (D 187)
    1*TL/R =*F6.3,5X*TH/R =*F6.3/)                                       (D 188)
 149 FORMAT (//5H CHI=F5.1,5X5HZETA=F7.3,5X*INTERFERENCE AT ROTOR*      (D 189)
    15X*H(CL)/H=*F6.3/)                                                  (D 190)
 150 FORMAT (3X5H(W,L)7(F17.4))                                          (D 191)
 151 FORMAT (3X5H(U,L)7(F17.4))                                          (D 192)
 152 FORMAT (3X5H(W,D)7(F17.4))                                          (D 193)
 153 FORMAT (3X5H(U,D)7(F17.4))                                          (D 194)
 210 FORMAT (1X131(1H-))                                                 (D 195)
 211 FORMAT (1X1HI11X1HI31X61HCORRECTICN FACTORS FOR CORRECTING FROM A  (D 196)
    1WIND TUNNEL WHICH IS25X1HI)                                         (D 197)
 212 FORMAT (1X1HI11X1HI117(1H-)1HI)                                     (D 198)
 213 FORMAT (1X1HI11X1HI16X1HI5X6HCLOSED5X1HI16X1HI2X12HCLOSED FLOOR2X1 (D 199)
    1HI6X4HOPEN6X1HI16X1HI5X6HCLOSED4X1HI)                               (D 200)
 214 FORMAT (1X1HI3X5HDELTA3X1HI5X6HCLCSED5X1HI4X9HON BOTTOM3X1HI6X4HOP (D 201)
    1EN6X1HI6X4HONLY6X1HI5X5HFLOOR6X1HI5X6HCLOSED5X1HI3X9HON BOTTOM3X1H (D 202)
    2I)                                                                  (D 203)
 215 FORMAT (1X1HI11X1HI16X1HI6X4HONLY6X1HI16X18HI(GROUND EFFECT) I6X4H (D 204)
    1ONLY6X1HI16X1HI6X4HCNLY5X1HI)                                       (D 205)
 216 FORMAT (1X1HI11X1HI84(1H-)1HI32(1H-)1HI)                            (D 206)
 217 FORMAT (1X1HI11X1HI36X11HTO FREE AIR37X1HI8X16HTO GROUND EFFECT8X1 (D 207)
    1HI)                                                                 (D 208)
 218 FORMAT (1X131(1H-))                                                 (D 209)
 900 FORMAT (I1,F9.3,3F10.3/I1,F9.3,3F10.3)                              (D 210)
 901 FORMAT (1H1////42X*AVERAGE INTERFERENCE OVER A ROTOR OF FINITE SPA (D 211)
    1N*//30X*ZETA COMPUTED TO YIELD ZERO DELTA(W,L) IN A CLOSED-ON-BOTT (D 212)
    2OM-ONLY TUNNEL*///55X,A10* DISK  LOADING*//30X*SIGMA(ROTOR) =*     (D 213)
    3F6.3,8X*ALPHA(ROTOR) =*F7.3,10X*GAMMA =*F6.3//30X*SIGMA(TAIL)  =*  (D 214)
    4F6.3,8X*ALPHA(TAIL)  =*F7.3,10X*ETA   =*F6.3//)                     (D 215)
 904 FORMAT (///40X*TAIL IS OMITTED - EQUATIONS ARE NOT VALID WHEN SIGM (D 216)
    1A(ROTOR) = 0.*///)                                                  (D 217)
999   STOP                                                               (D 218)
      END                                                                (D 219)
```

APPENDIX E

FORTRAN PROGRAM FOR COMPUTING INTERFERENCE OVER WINGS IN A VARIABLE WIDTH-HEIGHT-RATIO CLOSED TUNNEL

THIS PROGRAM WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS PROGRAM HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

NOTE THAT ALL INPUT AND OUTPUT VARIABLES ARE REFERENCED TO THE GAMMA=2.0 TEST SECTION. INPUT IS AT ADDRESS 1 IN FORMAT 900 (TWO CARDS PER CASE). THE REQUIRED INPUT VARIABLES ARE

LI	SPAN LOAD-DISTRIBUTICN INDICATOR, LI=1 FOR UNIFORM LOADING, LI=2 FOR ELLIPTIC LOADING
ZETA1	SEMIHEIGHT OF GAMMA=2 SECTION DIVIDED BY HEIGHT OF AERODYNAMIC CENTER ABOVE FLOOR IN GAMMA=2 SECTION
ETA1	DISTANCE FROM AERODYNAMIC CENTER TO RIGHT-HAND WALL DIVIDED BY TUNNEL SEMIWIDTH
SIGMA	RATIO OF WING SPAN TO TUNNEL WIDTH
LAMBDA	WING SWEEP ANGLE, DEG
ALPHA	ANGLE OF ATTACK OF WING, DEG
ITAIL	NUMBER (0 TO 9) OF TAIL POSITIONS, PROPORTIONATELY INCREASED IN TAIL LENGTH AND HEIGHT, AT WHICH INTERFERENCE IS REQUIRED. USE SMALLEST LENGTH AND HEIGHT AS INPUT.
SIGMAT	RATIO OF TAIL SPAN TO TUNNEL WIDTH
TL	DISTANCE OF TAIL BEHIND AERODYNAMIC CENTER, NONDIMENSIONALIZED WITH RESPECT TO SEMIHEIGHT OF GAMMA=2 SECTION
TH	HEIGHT OF TAIL ABOVE AERODYNAMIC CENTER, NONDIMENSIONALIZED WITH RESPECT TO SEMIHEIGHT OF GAMMA=2 SECTION

THIS PROGRAM REQUIRES SUBROUTINE DLTAS (SEE APPENDIX G).

```
      PROGRAM WINDTUN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)            (E 1)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)              (E 2)
      DIMENSION XLE(10),XLOAD(10),XDELTA(28),C(8)                       (E 3)
      REAL LAMBDA                                                       (E 4)
      DATA (C(I),I=1,8)/20.,30.,40.,50.,60.,70.,80.,90./                (E 5)
      XLE(1)=XLE(10)=0.43579                                            (E 6)
```

```
      XLE(2)=XLE(9)=0.71422
      XLE(3)=XLE(8)=0.86603
      XLE(4)=XLE(7)=0.95394
      XLE(5)=XLE(6)=0.99499
    1 READ (5,900) LI,ZETA1,ETA1,SIGMA,LAMBDA,ALPHA,ITAIL,SIGMAT,TL,TH
      IF (EOF,5) 999,47
   47 AALP=ALPHA
      ALAM=LAMBDA
      ATL=TL
      ATH=TH
      AZETA=ZETA1
      RAD=0.0174532925199
      ALPHA=ALPHA*RAD
      LAMBDA=LAMBDA*RAD
      DO 101 K1=1,16
      IF (LI.EQ.1) GO TO 804
      IALPHA=8HELLIPTIC
      SUML=0.0126104
      DO 808 M2=1,10
  808 XLOAD(M2)=XLE(M2)
      GO TO 160
  804 SUML=0.01
      IALPHA=8HUNIFORM
      DO 809 M2=1,10
  809 XLOAD(M2)=1.0
  160 GAMMA=0.4+0.1*FLOAT(K1)
      AC=0.5*SIGMA*TAN(LAMBDA)*GAMMA
      IF (LI.NE.1)  AC=0.848*AC
      WRITE (6,901)  IALPHA,GAMMA,ETA1,SIGMA,AZETA,AALP,ALAM
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      CONST1=1.0
      DO 41 K=1,8
      DO 803 L1=1,28
      DELTA(L1)=0.
  803 XDELTA(L1)=0.
      IF (SIGMA.NE.0.) GO TO 811
      M7=N7=1
      XLOAD(1)=1.0
      SUML=1.
      GO TO 812
  811 IF (ETA1.NE.1.) GO TO 813
      M7=5
      N7=10
      CONST1=2.
      GO TO 812
  813 M7=N7=10
  812 ZETA1=AZETA/(1.0+AC*AZETA*SIN(ALPHA))
      ZETA1=2.0/(2.0+GAMMA*(1.0-ZETA1))
      DO 801 M1=1,M7
      DO 802  N1=1,N7
      XSTAR=(11.-2.*FLOAT(M1))/10.
      YSTAR=(2.*FLOAT(N1)-11.)/10.
      ZSTAR=(11.-2.*FLOAT(N1))/10.
```

```
      ETA=ETA1+YSTAR*SIGMA
      ZETA=ZETA1/(1.-ABS(YSTAR)*SIGMA*GAMMA*ZETA1*TAN(LAMBDA)*SIN(ALPHA)
     1)
      XOVERH=SIGMA*GAMMA*TAN(LAMBDA)*CCS(ALPHA)*(ABS(XSTAR)-ABS(ZSTAR))
      YOVERH=(FLOAT(M1)-FLOAT(N1))*SIGMA*GAMMA*(-.2)
      ZOVERH=SIGMA*GAMMA*TAN(LAMBDA)*SIN(ALPHA)*(ABS(ZSTAR)-ABS(XSTAR))
      CALL DLTAS (C(K))
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS ********************
      DO 805 L1=1,28
  805 XDELTA(L1)=XDELTA(L1)+(DELTA(L1)*XLOAD(N1))
  802 CONTINUE
  801 CONTINUE
      DO 807  L3=1,28
  807 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.)
      WRITE (6,149)  C(K)
      WRITE (6,150) (DELTA(I),I=1,25,4)
      WRITE (6,151) (DELTA(I),I=2,26,4)
      WRITE (6,152) (DELTA(I),I=3,27,4)
      WRITE (6,153) (DELTA(I),I=4,28,4)
      IF (SIGMA.EQ.0.) GO TO 822
      IF (C(K).EQ.90.) GO TO 820
      XS1=TAN(C(K)*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      CHIM=2.0*C(K)-90.
      XS2=TAN(CHIM*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      WRITE (6,120)  XS1,XS2
      GO TO 822
  820 WRITE (6,119)
  822 DO 814  L4=1,28
  814 XDELTA(L4)=0.
   41 CONTINUE
      IF (ITAIL.EQ.0)  GO TO 101
      SUML=0.031526
      IF (LI.EQ.1) SUML=0.025
      IF (SIGMAW.EQ.0..AND.SIGMAT.EQ.0.)  GO TO 450
      IF (SIGMAW.EQ.0..AND.SIGMAT.NE.0.)  GO TO 455
      IF (SIGMAW.NE.0..AND.SIGMAT.EQ.0.)  GO TO 460
      M7=4
      N7=10
      CONST1=1.0
      IF (ETA1.NE.1.)  GO TO 412
      M7=2
      CONST1=2.0
      GO TO 412
  450 M7=N7=1
      XLOAD(1)=1.0
      SUML=0.025
      CONST1=40.0
      GO TO 412
  455 M7=4
      N7=1
      XLOAD(1)=1.0
      SUML=0.025
      CONST1=10.0
      IF (ETA1.NE.1.)  GO TO 412
      M7=2
      CONST1=20.0
      GO TO 412
  460 M7=1
      N7=10
      CONST1=4.0
      IF (ETA1.NE.1.)  GO TO 412
```

```
      N7=5
      CONST1=8.0
  412 DO 420  ITL=1,ITAIL
      WRITE (6,901)  IALPHA,GAMMA,ETA1,SIGMA,AZETA,AALP,ALAM
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      DO 91  K=1,8
      TL=(ATL*FLOAT(ITL)*GAMMA/2.0)+AC
      TH=ATH*FLOAT(ITL)*GAMMA/2.0
      ZETA1=AZETA/(1.0+AC*AZETA*SIN(ALPHA))
      ZETA1=2.0/(2.0+GAMMA*(1.0-ZETA1))
      DO 400  L2=1,28
      XDELTA(L2)=0.
  400 DELTA(L2)=0.
      DO 401  M1=1,M7
      DO 402  N1=1,N7
      XSTAR=(2.*FLOAT(N1)-11.)/10.0
      YSTAR=(11.-2.*FLOAT(N1))/10.0
      ZSTAR=(5.-2.*FLOAT(M1))/4.0
      ETA=ETA1+XSTAR*SIGMA
      ZETA=ZETA1/(1.-ABS(YSTAR)*SIGMA*GAMMA*ZETA1*TAN(LAMBDA)*
     1      SIN(ALPHA))
      XOVERH=TL*COS(ALPHA)+TH*SIN(ALPHA)-SIGMA*GAMMA*TAN(LAMBDA)*
     1      COS(ALPHA)*ABS(YSTAR)
      YOVERH=ZSTAR*SIGMAT*GAMMA-YSTAR*SIGMA*GAMMA
      ZOVERH=TH*COS(ALPHA)-TL*SIN(ALPHA)+SIGMA*GAMMA*TAN(LAMBDA)*
     1      SIN(ALPHA)*ABS(YSTAR)
      CALL DLTAS   (C(K))
******************** SEE APPENDIX G FCR SUBROUTINE DLTAS ********************
      DO 405 L1=1,28
  405 XDELTA(L1)=XDELTA(L1)+(DELTA(L1)*XLOAD(N1))
  402 CONTINUE
  401 CONTINUE
      DO 407 L3=1,28
  407 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.C)
      TL=ATL*FLOAT(ITL)
      TH=ATH*FLOAT(ITL)
      WRITE (6,148)  C(K),SIGMAT,TL,TH
      WRITE (6,150)  (DELTA(I),I=1,25,4)
      WRITE (6,151)  (DELTA(I),I=2,26,4)
      WRITE (6,152)  (DELTA(I),I=3,27,4)
      WRITE (6,153)  (DELTA(I),I=4,28,4)
      DO 414  L4=1,28
  414 XDELTA(L4)=0.0
   91 CONTINUE
  420 CONTINUE
  101 CONTINUE
      GO TO 1
  119 FORMAT (5X*IMPINGEMENT DISTANCE IS INFINITE*)
  120 FORMAT (5X*IMPINGEMENT DISTANCE (SPANS) USING CHI (EFFECTIVE) IS*
     1F10.2,5X*USING CHI (MOMENTUM) IS*F10.2)
  148 FORMAT (//5H CHI=F5.1,5X*INTERFERENCE AT TAIL*5X*SIGMA(TAIL)=*
     1F6.3,5X*TL/H=*F7.3,5X*TH/H=*F7.3/)
  149 FORMAT (//5H CHI=F5.1,5X*INTERFERENCE AT WING*/)
```

```
  150 FORMAT (3X5H(W,L)7(F17.4))
  151 FORMAT (3X5H(U,L)7(F17.4))
  152 FORMAT (3X5H(W,D)7(F17.4))
  153 FORMAT (3X5H(U,D)7(F17.4))
  210 FORMAT (1X131(1H-))
  211 FORMAT (1X1HI11X1HI31X61HCORRECTICN FACTORS FOR CORRECTING FROM A
     1WIND TUNNEL WHICH IS25X1HI)
  212 FORMAT (1X1HI11X1HI117(1H-)1HI)
  213 FORMAT (1X1HI11X1HI16X1HI5X6HCLOSED5X1HI16X1HI2X12HCLOSED FLOOR2X1
     1HI6X4HOPEN6X1HI16X1HI5X6HCLOSED4X1HI)
  214 FORMAT (1X1HI3X5HDELTA3X1HI5X6HCLCSED5X1HI4X9HON BOTTOM3X1HI6X4HOP
     1EN6X1HI6X4HONLY6X1HI5X5HFLOOR6X1HI5X6HCLOSED5X1HI3X9HON BOTTOM3X1H
     2I)
  215 FORMAT (1X1HI11X1HI16X1HI6X4HONLY6X1HI16X18HI(GROUND EFFECT) I6X4H
     1ONLY6X1HI16X1HI6X4HCNLY5X1HI)
  216 FORMAT (1X1HI11X1HI84(1H-)1HI32(1H-)1HI)
  217 FORMAT (1X1HI11X1HI36X11HTO FREE AIR37X1HI8X16HTO GROUND EFFECT8X1
     1HI)
  218 FORMAT (1X131(1H-))
  900 FORMAT (I1,F9.3,4F10.3/I1,F9.3,2F10.3)
  901 FORMAT (1H1///26X*AVERAGE INTERFERENCE FOR SWEPT WING IN A VARIABL
     1E WIDTH-HEIGHT-RATIO CLOSED TUNNEL*//58XA8* LOADING*//
     236X*GAMMA =*F6.3,10X*ETA    =*F7.3,10X*SIGMA  =*F7.3//
     336X*ZETA  =*F6.3,10X*ALPHA =*F7.3,10X*LAMBDA =*F7.3//
     435X*ALL VALUES ARE REFERENCED TO THE HIGH-SPEED (GAMMA=2.0) SECTIO
     5N*/39X*ALL DIMENSIONS ARE MEASURED FROM THE AERODYNAMIC CENTER*//)
999   STOP
      END
```

APPENDIX F

FORTRAN PROGRAM FOR COMPUTING INTERFERENCE OVER ROTORS IN A VARIABLE WIDTH-HEIGHT-RATIO CLOSED TUNNEL

THIS PROGRAM WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS PROGRAM HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

NOTE THAT ALL INPUT AND OUTPUT VARIABLES ARE REFERENCED TO THE GAMMA=2.0 TEST SECTION. INPUT IS AT ADDRESS 1 IN FORMAT 900 (TWO CARDS PER CASE). THE REQUIRED INPUT VARIABLES ARE

LI	DISK-LOAD DISTRIBUTION INDICATOR, LI=1 FOR UNIFORM LOADING, LI=2 FOR TRIANGULAR LOADING
ZETA1	SEMIHEIGHT OF GAMMA=2 SECTION DIVIDED BY HEIGHT OF ROTOR CENTER ABOVE FLOOR IN GAMMA=2 SECTION
ETA1	DISTANCE FROM ROTOR CENTER TO RIGHT-HAND WALL DIVIDED BY TUNNEL SEMIWIDTH
SIGMA	RATIO OF ROTOR DIAMETER TO TUNNEL WIDTH
ALPHA	ANGLE OF ATTACK OF ROTOR TIP-PATH PLANE, DEG
ITAIL	NUMBER (0 TO 9) OF TAIL POSITIONS, PROPORTIONATELY INCREASED IN TAIL LENGTH AND HEIGHT, AT WHICH INTERFERENCE IS REQUIRED. USE SMALLEST LENGTH AND HEIGHT AS INPUT.
SIGMAT	RATIO OF TAIL SPAN TO TUNNEL WIDTH
TL	DISTANCE OF TAIL BEHIND ROTOR CENTER, NONDIMENSIONALIZED WITH RESPECT TO ROTOR RACIUS
TH	HEIGHT OF TAIL ABOVE ROTOR CENTER, NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS
ALPHAB	ANGLE OF ATTACK OF BODY CARRYING TAIL, DEG

THIS PROGRAM REQUIRES SUBROUTINE CLTAS (SEE APPENDIX G).

SINCE THE TAIL LOCATIONS ARE NONDIMENSIONALIZED WITH RESPECT TO ROTOR RADIUS, THIS PROGRAM CAN NOT ACCOMMODATE, AND WILL REJECT, TAIL INTERFERENCE CALCULATIONS FOR CASES INVOLVING SIGMA = 0, HOWEVER, THE INTERFERENCE AT THE CENTER OF LIFT WILL BE CALCULATED FOR SUCH CASES. TAIL INTERFERENCE FOR SUCH CASES CAN BE OBTAINED FROM THE CORRESPONDING PROGRAM FOR WINGS, SINCE, WHEN SIGMA IS ZERO, THE REPRESENTATION OF WINGS AND ROTORS IS IDENTICAL.

APPENDIX F

```
      PROGRAM WINDTUN(INPLT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)
      DIMENSION XDELTA(28),PSI(20),XLOAD(20),RUNIF(20),RTRIA(20),
     1    C(8)
      DATA (RUNIF(I),I=1,20)/4*0.2981,8*0.6255,8*0.8921/
      DATA (RTRIA(I),I=1,20)/4*0.4386,8*0.7296,8*0.9262/
      DATA (C(I),I=1,8)/20.,30.,40.,50.,60.,70.,80.,90./
      RAD=0.0174532925199
      PI=3.14159265358979
      PSI(1)=(PI/4.)
      PSI(2)=3.*PSI(1)
      PSI(3)=5.*PSI(1)
      PSI(4)=7.*PSI(1)
      PSI(5)=PSI(13)=(PI/8.)
      PSI(6)=PSI(14)=3.*PSI(5)
      PSI(7)=PSI(15)=5.*PSI(5)
      PSI(8)=PSI(16)=7.*PSI(5)
      PSI(9)=PSI(17)=9.*PSI(5)
      PSI(10)=PSI(18)=11.*PSI(5)
      PSI(11)=PSI(19)=13.*PSI(5)
      PSI(12)=PSI(20)=15.*PSI(5)
    1 READ (5,900)  LI,ZETA1,ETA1,SIGMA,ALPHA,ITAIL,SIGMAT,TL,TH,ALPHAB
      IF (EOF,5) 999,47
   47 AZETA=ZETA1
      ATL=TL
      ATH=TH
      ALPR=ALPHA
      ALPB=ALPHAB
      ALPHA=ALPR*RAD
      ALPHAB=ALPB*RAD
      IF (LI.EQ.1) GO TO 804
      IALPHA=10HTRIANGULAR
      DO 808 M2=1,20
  808 XLOAD(M2)=RTRIA(M2)
      GO TO 160
  804 IALPHA=10H UNIFORM
      DO 809 M2=1,20
  809 XLOAD(M2)=RUNIF(M2)
  160 DO 421  K1=1,16
      GAMMA=0.4+0.1*FLOAT(K1)
      WRITE (6,901)  IALPHA,GAMMA,SIGMA,ALPR,AZETA,SIGMAT,ALPB,ETA1
      WRITE (6,210)
      WRITE (6,211)
      WRITE (6,212)
      WRITE (6,213)
      WRITE (6,214)
      WRITE (6,215)
      WRITE (6,216)
      WRITE (6,217)
      WRITE (6,218)
      SUML=0.0025
      CONST1=1.
      DO 41  K=1,8
      DO 803 L1=1,28
      DELTA(L1)=0.
  803 XDELTA(L1)=0.
      M7=N7=20
      IF (SIGMA.NE.0.) GO TO 811
      N7=M7=1
```

```
      CONST1=400
      GO TO 812
  811 IF (ETA1.NE.1.)  GO TO 812
      CONST1=2.
  812 DO 801  M1=1,M7
      DO 802  N1=1,N7
  836 IF (ETA1.NE.1.)  GO TO 840
      IF (PSI(N1).GT.PI) GO TO 802
  840 ETA=ETA1-(XLOAD(N1)*SIGMA *SIN(PSI(N1)))
      ZETA1=2.0/(2.0+GAMMA*(1.0-AZETA))
      ZETA=1./((1./ZETA1)-(XLOAD(N1)*SIGMA *SIN(ALPHA)*COS(PSI(N1))*GAMM
     1A))
      XOVERH=SIGMA *GAMMA*COS(ALPHA)*(XLOAD(M1)*COS(PSI(M1))-XLOAD(N1)*C
     1OS(PSI(N1)))
      YOVERH=SIGMA *GAMMA*(XLOAD(M1)*SIN(PSI(M1))-XLOAD(N1)*SIN(PSI(N1))
     1)
      ZOVERH=-SIGMA *GAMMA*SIN(ALPHA)*(XLOAC(M1)*COS(PSI(M1))-XLOAD(N1)*
     1COS(PSI(N1)))
      CALL DLTAS  (C(K))
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS *********************
      DO 805 L1=1,28
  805 XDELTA(L1)=XDELTA(L1)+(DELTA(L1))
  802 CONTINUE
  801 CONTINUE
  835 DO 807  L3=1,28
  807 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.)
      WRITE (6,149) C(K)
      WRITE (6,150) (DELTA(I),I=1,25,4)
      WRITE (6,151) (DELTA(I),I=2,26,4)
      WRITE (6,152) (DELTA(I),I=3,27,4)
      WRITE (6,153) (DELTA(I),I=4,28,4)
      IF (SIGMA.EQ.0.)  GO TO 822
      IF (C(K).EQ.90.)  GO TO 820
      XS1=TAN(C(K)*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      CHIM=2.0*C(K)-90.
      XS2=TAN(CHIM*RAD)/(2.0*SIGMA*GAMMA*ZETA1)
      WRITE (6,120)  XS1,XS2
      GO TO 822
  820 WRITE (6,119)
  822 DO 814 L4=1,28
  814 XDELTA(L4)=0.
   41 CONTINUE
      IF (ITAIL.EQ.0)  GO TO 1
      IF (SIGMA.NE.0.) GO TO 400
      WRITE (6,901) IALPHA,GAMMA,SIGMA,ALPR,AZETA,SIGMAT,ALPB,ETA1
      WRITE (6,904)
      GO TO 1
  400 SUML=0.0125
      IF (SIGMAT.NE.0.)  GO TO 411
      M7=1
      CONST1=4.0
      GO TO 412
  411 IF (ETA1.NE.1.)  GO TO 413
      M7=2
      CONST1=2.0
      GO TO 412
  413 M7=4
      CONST1=1.0
  412 DO 420  ITL=1,ITAIL
      TL=ATL*FLOAT(ITL)
      TH=ATH*FLOAT(ITL)
```

```
      WRITE (6,901) IALPHA,GAMMA,SIGMA,ALPR,AZETA,SIGMAT,ALPB,ETA1       (F 120)
      WRITE (6,210)                                                      (F 121)
      WRITE (6,211)                                                      (F 122)
      WRITE (6,212)                                                      (F 123)
      WRITE (6,213)                                                      (F 124)
      WRITE (6,214)                                                      (F 125)
      WRITE (6,215)                                                      (F 126)
      WRITE (6,216)                                                      (F 127)
      WRITE (6,217)                                                      (F 128)
      WRITE (6,218)                                                      (F 129)
      DO 91 K=1,8                                                        (F 130)
  399 ZETA1=2.0/(2.0+GAMMA*(1.0-AZETA))                                  (F 131)
      DO 401  M1=1,M7                                                    (F 132)
      DO 402  N1=1,20                                                    (F 133)
      ETA=ETA1-(XLOAD(N1)*SIGMA*SIN(PSI(N1)))                            (F 134)
      ZETA=1./((1./ZETA1)-XLOAD(N1)*SIGMA*GAMMA*SIN(ALPHA)*COS(PSI(N1))) (F 135)
      XOVERH=SIGMA*GAMMA*((TL*COS(ALPHAB))+(TH*SIN(ALPHAB))-(XLOAD(N1)   (F 136)
     1     *COS(ALPHA)*COS(PSI(N1))))                                    (F 137)
      XM1=FLOAT(M1)                                                      (F 138)
      YOVERH=SIGMA*GAMMA*(-((2.*XM1-5.)/4.)*(SIGMAT/SIGMA)-(XLOAD(N1)    (F 139)
     1     *SIN(PSI(N1))))                                               (F 140)
      ZOVERH=SIGMA*GAMMA*((TH*COS(ALPHAB))-(TL*SIN(ALPHAB))+(XLOAD(N1)   (F 141)
     1     *SIN(ALPHA)*COS(PSI(N1))))                                    (F 142)
      CALL DLTAS  (C(K))                                                 (F 143)
******************** SEE APPENDIX G FOR SUBROUTINE DLTAS *********************
      DO 405 L1=1,28                                                     (F 144)
  405 XDELTA(L1)=XDELTA(L1)+DELTA(L1)                                    (F 145)
  402 CONTINUE                                                           (F 146)
  401 CONTINUE                                                           (F 147)
      DO 407 L3=1,28                                                     (F 148)
  407 DELTA(L3)=XDELTA(L3)*SUML*CONST1*(GAMMA/2.0)                       (F 149)
      WRITE (6,148) C(K),TL,TH                                           (F 150)
      WRITE (6,150) (DELTA(I),I=1,25,4)                                  (F 151)
      WRITE (6,151) (DELTA(I),I=2,26,4)                                  (F 152)
      WRITE (6,152) (DELTA(I),I=3,27,4)                                  (F 153)
      WRITE (6,153) (DELTA(I),I=4,28,4)                                  (F 154)
      DO 414 L4=1,28                                                     (F 155)
  414 XDELTA(L4)=0.0                                                     (F 156)
   91 CONTINUE                                                           (F 157)
  420 CONTINUE                                                           (F 158)
  421 CONTINUE                                                           (F 159)
      GO TO 1                                                            (F 160)
  119 FORMAT ( 5X*IMPINGEMENT DISTANCE IS INFINITE*)                     (F 161)
  120 FORMAT ( 5X*IMPINGEMENT DISTANCE (SPANS) USING CHI (EFFECTIVE) IS* (F 162)
     1F10.2,5X*USING CHI (MOMENTUM) IS*F10.2)                            (F 163)
  148 FORMAT (//5X*CHI =*F7.3,5X*INTERFERENCE AT TAIL*5X*TL/R =*F9.3,    (F 164)
     15X*TH/R =*F8.3/)                                                   (F 165)
  149 FORMAT (//5H CHI=F7.3,5X*INTERFERENCE AT ROTOR*/)                  (F 166)
  150 FORMAT (3X5H(W,L)7(F17.4))                                         (F 167)
  151 FORMAT (3X5H(U,L)7(F17.4))                                         (F 168)
  152 FORMAT (3X5H(W,D)7(F17.4))                                         (F 169)
  153 FORMAT (3X5H(U,D)7(F17.4))                                         (F 170)
  210 FORMAT (1X131(1H-))                                                (F 171)
  211 FORMAT (1X1HI11X1HI31X61HCORRECTICN FACTORS FOR CORRECTING FROM A  (F 172)
     1WIND TUNNEL WHICH IS25X1HI)                                        (F 173)
  212 FORMAT (1X1HI11X1HI117(1H-)1HI)                                    (F 174)
  213 FORMAT (1X1HI11X1HI16X1HI5X6HCLOSED5X1HI16X1HI2X12HCLOSED FLOOR2X1 (F 175)
     1HI6X4HOPEN6X1HI16X1HI5X6HCLOSED4X1HI)                              (F 176)
  214 FORMAT (1X1HI3X5HDELTA3X1HI5X6HCLCSED5X1HI4X9HON BOTTOM3X1HI6X4HOP (F 177)
     1EN6X1HI6X4HONLY6X1HI5X5HFLOOR6X1HI5X6HCLOSED5X1HI3X9HON BOTTOM3X1H (F 178)
     2I)                                                                 (F 179)
```

```
  215 FORMAT (1X1HI11X1HI16X1HI6X4HONLY6X1HI16X18HI(GROUND EFFECT) I6X4H (F 180)
     1ONLY6X1HI16X1HI6X4HCNLY5X1HI)                                     (F 181)
  216 FORMAT (1X1HI11X1HI84(1H-)1HI32(1H-)1HI)                          (F 182)
  217 FORMAT (1X1HI11X1HI36X11HTO FREE AIR37X1HI8X16HTO GROUND EFFECT8X1 (F 183)
     1HI)                                                               (F 184)
  218 FORMAT (1X131(1H-))                                               (F 185)
  900 FORMAT (I1,F9.3,3F10.3/I1,F9.3,3F10.3)                            (F 186)
  901 FORMAT (1H1   /42X*AVERAGE INTERFERENCE OVER A ROTOR OF FINITE SPA (F 187)
     1N*//43X*IN A VARIABLE WIDTH-HEIGHT-RATIO CLOSED TUNNEL*///42X,A10  (F 188)
     2* DISK LOADING*10X*GAMMA =*F6.3//30X*SIGMA(ROTOR) =*              (F 189)
     3F6.3,8X*ALPHA(ROTOR) =*F7.3,10X*ZETA =*F6.3//30X*SIGMA(TAIL)  =*  (F 190)
     4F6.3,8X*ALPHA(TAIL)  =*F7.3,10X*ETA  =*F6.3//35X*ALL VALUES ARE RE (F 191)
     5FERENCED TO THE HIGH-SPEED (GAMMA=2.0) SECTION*//)                (F 192)
  904 FORMAT (///40X*TAIL IS OMITTED - EQUATIONS ARE NOT VALID WHEN SIGM (F 193)
     1A(ROTOR) = 0.*///)                                                (F 194)
999     STOP                                                            (F 195)
        END                                                             (F 196)
```

APPENDIX G

SUBROUTINE DLTAS

THIS SUBROUTINE WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS SUBROUTINE HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

THIS SUBROUTINE IS REQUIRED BY THE PROGRAMS OF ALL PRECEEDING APPENDICES.

```
      SUBROUTINE DLTAS  (ANGL)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)
      DIMENSION V(3,9),ADEL(28)
      SC=SIN(ANGL*0.0174532925199)
      CC=COS(ANGL*0.0174532925199)
      Z6=ZETA*ZOVERH+1.
      Z8=-Z6
      Z7=Z8-1.
      DO 8 J1=1,28
    8 DELTA(J1)=0.
      DO 10 M=1,7
      DO 10 N=1,7
      IF (N.EQ.4.AND.M.EQ.4)  GO TO 10
      DO 11 J1=1,3
      DO 11 J2=1,9
   11 V(J1,J2)=0.
      DO 12 J1=1,28
   12 ADEL(J1)=0.
      AM=M-4
      AN=N-4
      X=ZETA*XOVERH
      Y=ZETA*(YOVERH-2.*AM*GAMMA+GAMMA*(1.-ETA)*(1.-(-1.)**M))
      Z=ZETA*(ZOVERH-4.*AN)
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,1)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      V(2,1)=-(X*Z)/(B*A*A*A)-(Z+A*CC)*(X-A*SC)/(B*B*A*A)
      V(3,1)=((Y*Y+Z*Z)/(B*A*A*A))-((X-A*SC)/(B*A))**2
      Z=-Z-2.
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,3)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      V(2,3)=-(X*Z)/(B*A*A*A)-(Z+A*CC)*(X-A*SC)/(B*B*A*A)
      V(3,3)=((Y*Y+Z*Z)/(B*A*A*A))-((X-A*SC)/(B*A))**2
      IF (ANGL.EQ.90.0)  GO TO 13
      X=X-(SC/CC)
      Z=-Z-1.
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,2)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
```

```
      V(2,2)=-(X*Z)/(B*A*A*A)-(Z+A*CC)*(X-A*SC)/(B*B*A*A)
      V(3,2)=((Y*Y+Z*Z)/(B*A*A*A))-((X-A*SC)/(B*A))**2
      B=A-X
      V(1,5)=((X*X+Y*Y)/(B*A*A*A))-(Z/(B*A))**2
      V(3,5)=X/(A*A*A)
      Z=-Z
      B=A+Z*CC-X*SC
      V(2,5)=Z/(A*A*A)
      V(1,4)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      V(2,4)=-(X*Z)/(B*A*A*A)-(Z+A*CC)*(X-A*SC)/(B*B*A*A)
      V(3,4)=((Y*Y+Z*Z)/(B*A*A*A))-((X-A*SC)/(B*A))**2
   13 ADEL(1)=V(1,1)-V(1,2)-V(1,3)+V(1,4)
      ADEL(2)=V(2,1)-V(2,2)+V(2,3)-V(2,4)
      ADEL(3)=V(2,1)-V(2,2)-V(2,3)+V(2,4)+2.*V(2,5)
      ADEL(4)=V(3,1)-V(3,2)+V(3,3)-V(3,4)+2.*V(3,5)
      ADEL(5)=((-1.)**(M+N))*ADEL(1)
      ADEL(6)=((-1.)**(M+N))*ADEL(2)
      ADEL(7)=((-1.)**(M+N))*ADEL(3)
      ADEL(8)=((-1.)**(M+N))*ADEL(4)
      ADEL(9)= ((-1.)**M)*(V(1,1)-V(1,2)+V(1,3)-V(1,4)+2.*V(1,5))
      ADEL(10)=((-1.)**M)*(V(2,1)-V(2,2)-V(2,3)+V(2,4)+2.*V(2,5))
      ADEL(11)=((-1.)**M)*(V(2,1)-V(2,2)+V(2,3)-V(2,4))
      ADEL(12)=((-1.)**M)*(V(3,1)-V(3,2)-V(3,3)+V(3,4))
      DO 14 J1=1,12
   14 DELTA(J1)=DELTA(J1)+ADEL(J1)
   10 CONTINUE
      DO 15 J1=1,8
   15 DELTA(J1+20)=DELTA(J1)
      X=ZETA*XOVERH
      Y=ZETA*YOVERH
      Z=Z7
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,7)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      V(2,7)=-(X*Z)/(B*A*A*A)-(Z+A*CC)*(X-A*SC)/(B*B*A*A)
      V(3,7)=((Y*Y+Z*Z)/(B*A*A*A))-((X-A*SC)/(B*A))**2
      IF (ANGL.EQ.90.0)  GO TO 16
      X=X-(SC/CC)
      Z=Z6
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,6)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      V(2,6)=-(X*Z)/(B*A*A*A)-(Z+A*CC)*(X-A*SC)/(B*B*A*A)
      V(3,6)=((Y*Y+Z*Z)/(B*A*A*A))-((X-A*SC)/(B*A))**2
      B=A-X
      V(1,9)=((X*X+Y*Y)/(B*A*A*A))-(Z/(B*A))**2
      V(2,9)=Z/(A*A*A)
      V(3,9)=X/(A*A*A)
      Z=Z8
      B=A+Z*CC-X*SC
      V(1,8)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      V(2,8)=-(X*Z)/(B*A*A*A)-(Z+A*CC)*(X-A*SC)/(B*B*A*A)
      V(3,8)=((Y*Y+Z*Z)/(B*A*A*A))-((X-A*SC)/(B*A))**2
   16 DELTA(13)=-V(1,6)-V(1,7)+V(1,8)
      DELTA(14)=-V(2,6)+V(2,7)-V(2,8)
      DELTA(15)=-V(2,6)-V(2,7)+V(2,8)+2.*V(2,9)
      DELTA(16)=-V(3,6)+V(3,7)-V(3,8)+2.*V(3,9)
      DELTA(17)=-V(1,6)+V(1,7)-V(1,8)+2.*V(1,9)
      DELTA(18)=DELTA(15)
      DELTA(19)=DELTA(14)
      DELTA(20)=-V(3,6)-V(3,7)+V(3,8)
      DO 17 J1=1,4
   17 DELTA(J1)=DELTA(J1)+DELTA(J1+12)
      DO 18 J1=5,12
   18 DELTA(J1)=DELTA(J1)+DELTA(J1+8)
      AMT=-2.*GAMMA*ZETA*ZETA/3.14159265358979
      DO 19 J1=1,28
   19 DELTA(J1)=AMT*DELTA(J1)
      RETURN
      END
```

APPENDIX H

SUBROUTINE VARLET

THIS SUBROUTINE WAS WRITTEN IN CDC FORTRAN, VERSION 2.1, TO RUN ON CDC 6000 SERIES COMPUTERS WITH THE SCOPE 3.0 OPERATING SYSTEM AND LIBRARY TAPE. MINOR MODIFICATIONS MAY BE REQUIRED PRIOR TO USE IN OTHER COMPUTERS. THIS SUBROUTINE HAS BEEN FOUND TO BE SATISFACTORY ON THE AFOREMENTIONED COMPUTERS WHICH CARRY THE EQUIVALENT OF APPROXIMATELY 15 DECIMAL DIGITS. COMPUTERS OF LESSER PRECISION MAY REQUIRE MODIFICATION TO DOUBLE PRECISION IN ORDER TO OBTAIN RESULTS OF EQUAL ACCURACY.

THIS SUBROUTINE IS REQUIRED BY THE PROGRAMS OF APPENDICES A, B, C, AND D.

```
      SUBROUTINE VARLET (ANGL)
      COMMON ZETA,ETA,GAMMA,XOVERH,YOVERH,ZOVERH,DELTA(28)
      DIMENSION V(1,9),ADEL(28)
      SC=SIN(ANGL*0.0174532925199)
      CC=COS(ANGL*0.0174532925199)
      Z6=ZETA*ZOVERH+1.
      Z8=-Z6
      Z7=Z8-1.
      DELTA(5)=0.0
      DO 20 M=1,7
      DO 20 N=1,7
      IF (N.EQ.4.AND.M.EQ.4) GO TO 20
      DO 22 J1=1,9
   22 V(1,J1)=0.
      ADEL(5)=0.
      AM=M-4
      AN=N-4
      X=ZETA*XOVERH
      Y=ZETA*(YOVERH-2.*AM*GAMMA+GAMMA*(1.-ETA)*(1.-(-1.)**M))
      Z=ZETA*(ZOVERH-4.*AN)
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,1)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      Z=-Z-2.
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,3)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      IF (ANGL.EQ.90.0)  GO TO 23
      X=X-(SC/CC)
      Z=-Z-1.
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,2)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      Z=-Z
      B=A+Z*CC-X*SC
      V(1,4)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
   23 ADEL(5)=((-1.)**(M+N))*(V(1,1)-V(1,2)-V(1,3)+V(1,4))
      DELTA(5)=DELTA(5)+ADEL(5)
   20 CONTINUE
      X=ZETA*XOVERH
```

```
      Y=ZETA*YOVERH
      Z=Z7
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,7)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      IF (ANGL.EQ.90.0)  GO TO 26
      X=X-(SC/CC)
      Z=Z6
      A=SQRT(X*X+Y*Y+Z*Z)
      B=A+Z*CC-X*SC
      V(1,6)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
      Z=Z8
      B=A+Z*CC-X*SC
      V(1,8)=((X*X+Y*Y)/(B*A*A*A))-((Z+A*CC)/(B*A))**2
   26 DELTA(5)=DELTA(5)-V(1,6)-V(1,7)+V(1,8)
      AMT=-2.*GAMMA*ZETA*ZETA/3.14159265358979
      DELTA(5)=DELTA(5)*AMT
      RETURN
      END
```

REFERENCES

1. Kuhn, Richard E.; and Naeseth, Rodger L.: Tunnel-Wall Effects Associated With VTOL-STOL Model Testing. AGARD Rep. 303, Mar. 1959.
2. Heyson, Harry H.: Jet-Boundary Corrections for Lifting Rotors Centered in Rectangular Wind Tunnels. NASA TR R-71, 1960.
3. Heyson, Harry H.: Wind-Tunnel Wall Interference and Ground Effect for VTOL-STOL Aircraft. J. Amer. Helicopter Soc., vol. 6, no. 1, Jan. 1961, pp. 1-9.
4. Heyson, Harry H.: Linearized Theory of Wind-Tunnel Jet-Boundary Corrections and Ground Effect for VTOL/STOL Aircraft. NASA TR R-124, 1962.
5. Lee, Jerry Louis: An Experimental Investigation of the Use of Test Section Inserts as a Device to Verify Theoretical Wall Corrections for a Lifting Rotor Centered in a Closed Rectangular Test Section. M.S. Thesis, Univ. of Washington, Aug. 20, 1964.
6. Davenport, Edwin E.; and Kuhn, Richard E.: Wind-Tunnel-Wall Effects and Scale Effects on a VTOL Configuration With a Fan Mounted in the Fuselage. NASA TN D-2560, 1965.
7. Grunwald, Kalman J.: Experimental Study of Wind-Tunnel Wall Effects and Wall Corrections for a General-Research V/STOL Tilt-Wing Model With Flap. NASA TN D-2887, 1965.
8. Staff of Powered-Lift Aerodynamics Section, NASA Langley Res. Center: Wall Effects and Scale Effects in V/STOL Model Testing. AIAA Aerodynamic Testing Conference, Mar. 1964, pp. 8-16.
9. Heyson, Harry H.; and Grunwald, Kalman J.: Wind-Tunnel Boundary Interference for V/STOL Testing. Conference on V/STOL and STOL Aircraft, NASA SP-116, 1966, pp. 409-434.
10. South, P.: Measurements of the Influence of Mixed Boundaries on the Aerodynamic Characteristics of a V/STOL Wind Tunnel Model. Fluid Dynamics of Rotor and Fan Supported Aircraft at Subsonic Speeds, AGARD CP No. 22, Sept. 1967, pp. 25-1 – 25-15.
11. Halliday, A. S.; Cox, D. K.; and Gregory, N.: An Experimental Investigation of Wind-Tunnel Constraint Effects on the Performance of Helicopter Rotors. NPL Aero Note 1054, Brit. A.R.C., Mar. 22, 1967.
12. Heyson, Harry H.: Use of Superposition in Digital Computers To Obtain Wind-Tunnel Interference Factors for Arbitrary Configurations, With Particular Reference to V/STOL Models. NASA TR R-302, 1969.

13. Theodorsen, Theodore: The Theory of Wind-Tunnel Wall Interference. NACA Rep. 410, 1931.

14. Silverstein, Abe; and Katzoff, S.: Experimental Investigation of Wind-Tunnel Interference on the Downwash Behind an Airfoil. NACA Rep. 609, 1937.

15. Davis, Don D., Jr.; and Moore, Dewey: Analytical Study of Blockage- and Lift-Interference Corrections for Slotted Tunnels Obtained by the Substitution of an Equivalent Homogeneous Boundary for the Discrete Slots. NACA RM L53E07b, 1953.

16. Bhateley, I. C.: A Theoretical Optimization of the Test-Section Geometry for the Proposed Boeing Low-Speed Wind Tunnel. D6-15023, Boeing Co., 1967.

17. Wright, Ray H.: Test Sections for Small Theoretical Wind-Tunnel-Boundary Interference on V/STOL Models. NASA TR R-286, 1968.

18. Heyson, Harry H.: Wind-Tunnel Wall Effects at Extreme Force Coefficients. International Congress on Subsonic Aeronautics. Ann. N.Y. Acad. Sci., vol. 154, art. 2, Nov. 22, 1968, pp. 1074-1093.

19. Templin, R. J.: Recent Trends in Low-Speed Wind-Tunnel Design and Techniques. International Congress on Subsonic Aeronautics. Ann. N.Y. Acad. Sci., vol. 154, art. 2, Nov. 22, 1968, pp. 1055-1073.

20. South, P.: Research on Reduction of Wall Effects in Low Speed Wind Tunnels. Nat. Res. Counc. Can. Quart. Bull., no. 1, 1968, pp. 57-77.

21. Katzoff, S.; Gardner, Clifford S.; Diesendruck, Leo; and Eisenstadt, Bertram J.: Linear Theory of Boundary Effects in Open Wind Tunnels With Finite Jet Lengths. NACA Rep. 976, 1950. (Supersedes NACA TN 1826.)

22. Kroeger, Richard A.; and Martin, Walter A.: The Streamline Matching Technique for V/STOL Wind Tunnel Wall Corrections. AIAA Paper No. 67-183, Jan. 1967.

23. Rae, William H., Jr.: Limits on Minimum-Speed V/STOL Wind-Tunnel Tests. J. Aircraft, vol. 4, no. 3, May-June 1967, pp. 249-254.

24. Shindo, Shojiro; and Rae, William H., Jr.: An Experimental Study of Alleviating the Limits on Minimum-Speed V/STOL Wind-Tunnel Tests. Rep. 68-1, Aeronaut. Lab., Univ. of Washington, Jan. 1968.

25. Turner, Thomas R.: Endless-Belt Technique for Ground Simulation.Conference on V/STOL and STOL Aircraft, NASA SP-116, 1966, pp. 435-446.

26. Heyson, Harry H.: Equations for the Application of Wind-Tunnel Wall Corrections to Pitching Moments Caused by the Tail of an Aircraft Model. NASA TN D-3738, 1966.

27. Heyson, Harry H.: Nomographic Solution of the Momentum Equation for VTOL-STOL Aircraft. NASA TN D-814, 1961. (Also available as "V-STOL Momentum Equation," Space/Aeronaut., vol. 38, no. 2, July 1962, pp. B-18 – B-20.)

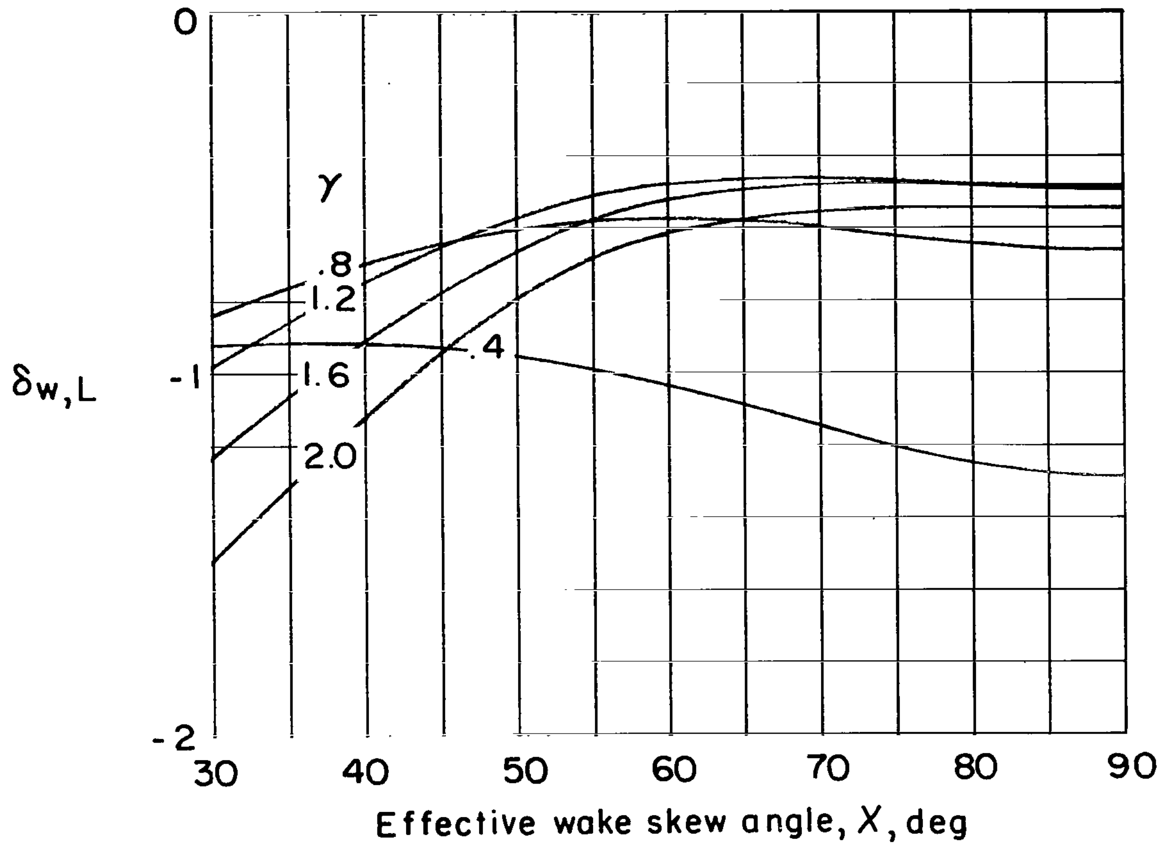
28. Hunter, George S.: V/STOL Push Requiring Tunnel Advances. Aviat. Week Space Technol., vol. 89, no. 2, July 8, 1968, pp. 39-51.

29. Jacobs, Eastman N.: Investigation of Air Flow in Open-Throat Wind Tunnels. NACA Rep. 322, 1929.

30. Schulz, G.; and Viehweger, G. (Barbara Crossland, trans.): The Low-Speed Wind Tunnel of the DVL in Porz-Wahn (Part II). Improvements and Developments in Properties and Equipment. Libr. Transl. No. 1224, Brit. R.A.E., Apr. 1967.

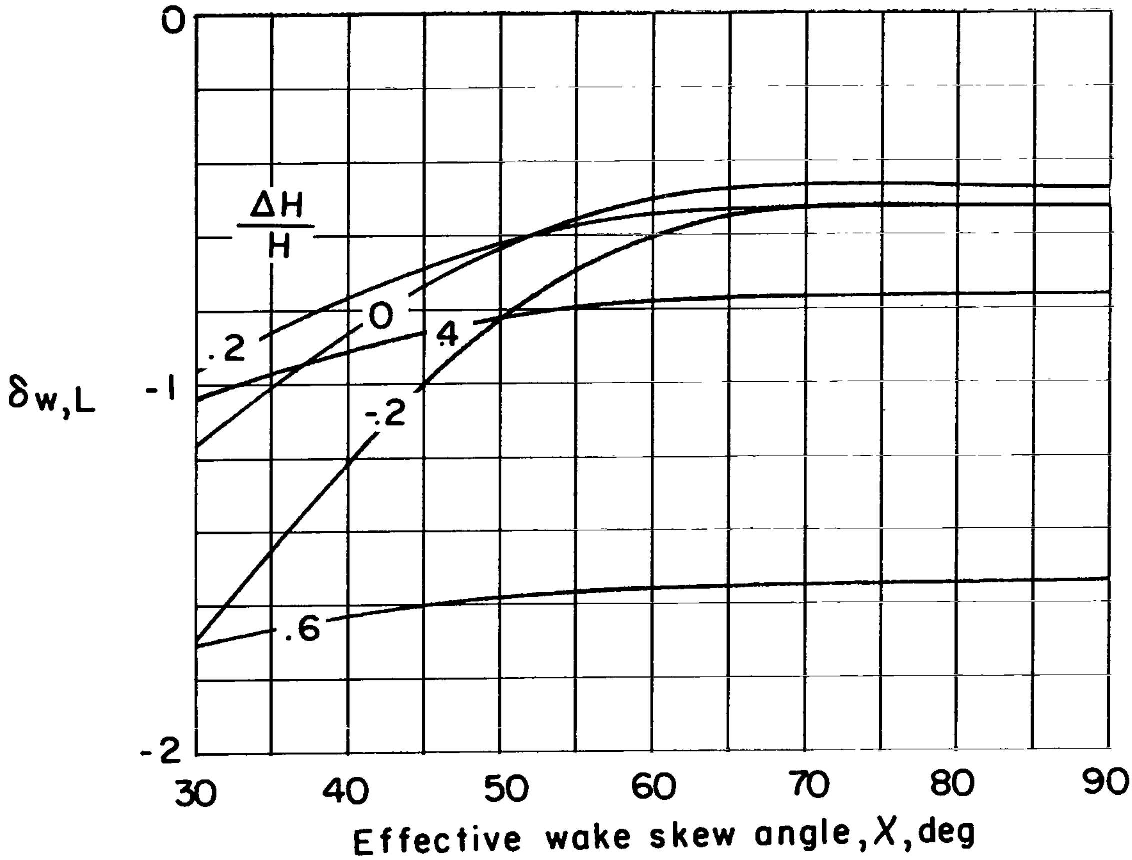
31. Prandtl, L.; and Tietjens, O. G. (J. P. Den Hartog, trans.): Applied Hydro- and Aeromechanics. Dover Pub., Inc., 1957, pp. 222-224.

32. Margason, Richard J.: The Path of a Jet Directed at Large Angles to a Subsonic Free Stream. M.S. Thesis, Virginia Polytech. Inst., 1968. (Also available as NASA TN D-4919.)



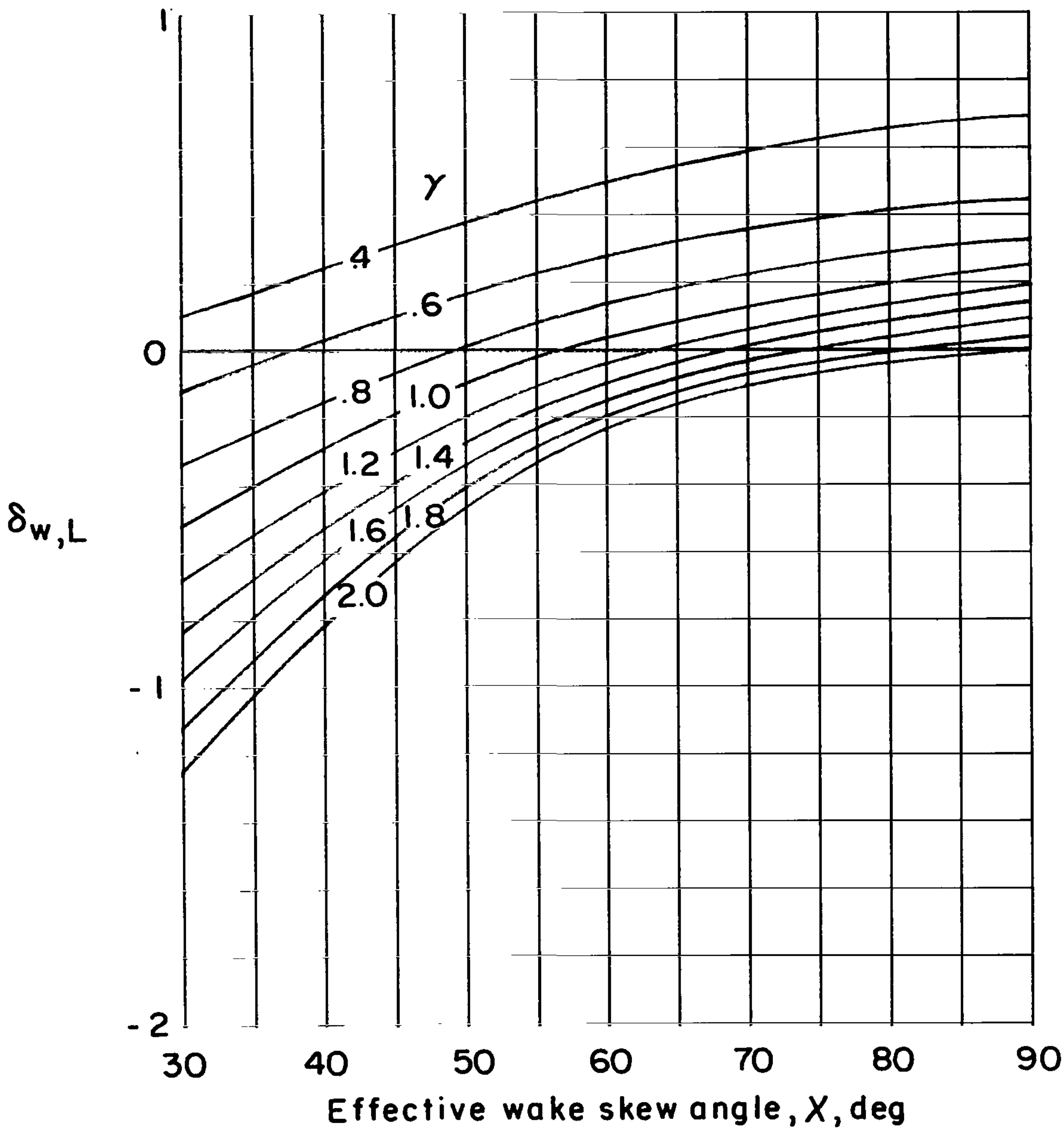
(a) Effect of γ. $\frac{\Delta H}{H} = 0$.

Figure 1.- Effect of variations in width-height ratio and model height on vertical interference due to lift for a vanishingly small model laterally centered in a closed tunnel.



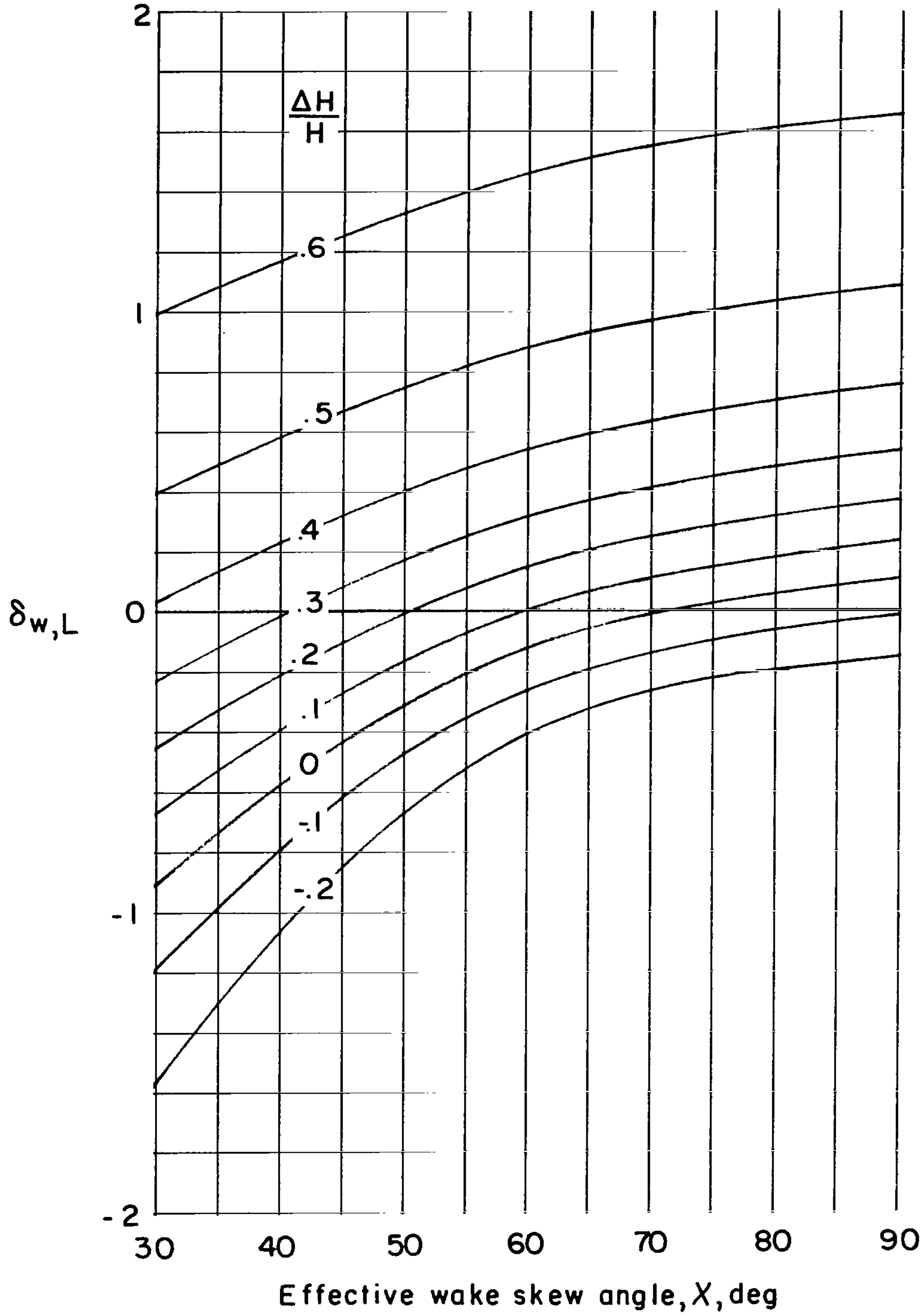
(b) Effect of model height. γ = 1.5.

Figure 1.- Concluded.



(a) Effect of γ. $\frac{\Delta H}{H} = 0$.

Figure 2.- Effect of variations in width-height ratio and model height on vertical interference due to lift for a vanishingly small model laterally centered in a closed-on-bottom-only tunnel.



(b) Effect of model height. $\gamma = 1.5$.

Figure 2.- Concluded.

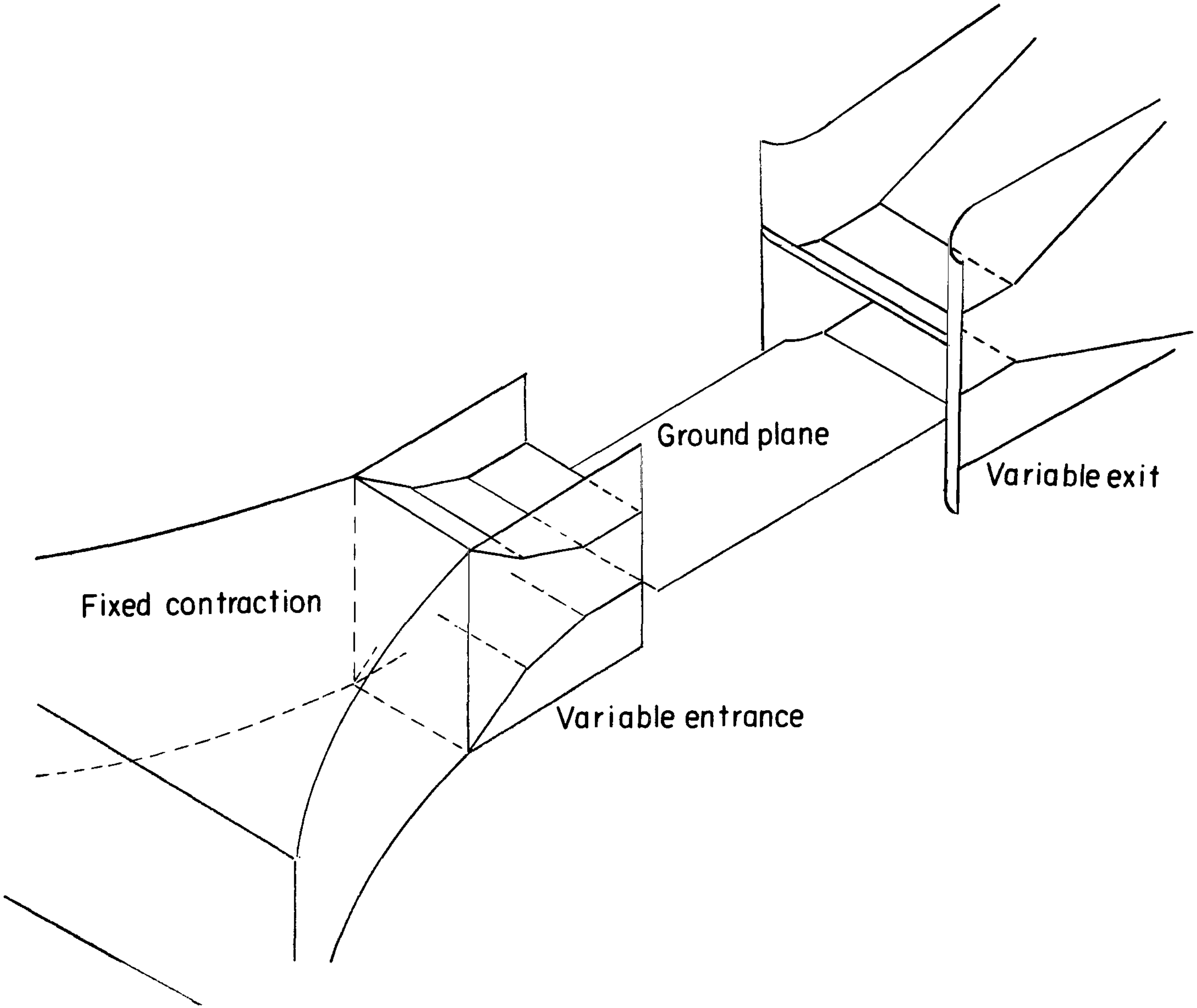


Figure 3.- Sketch of variable-geometry low-speed test section.

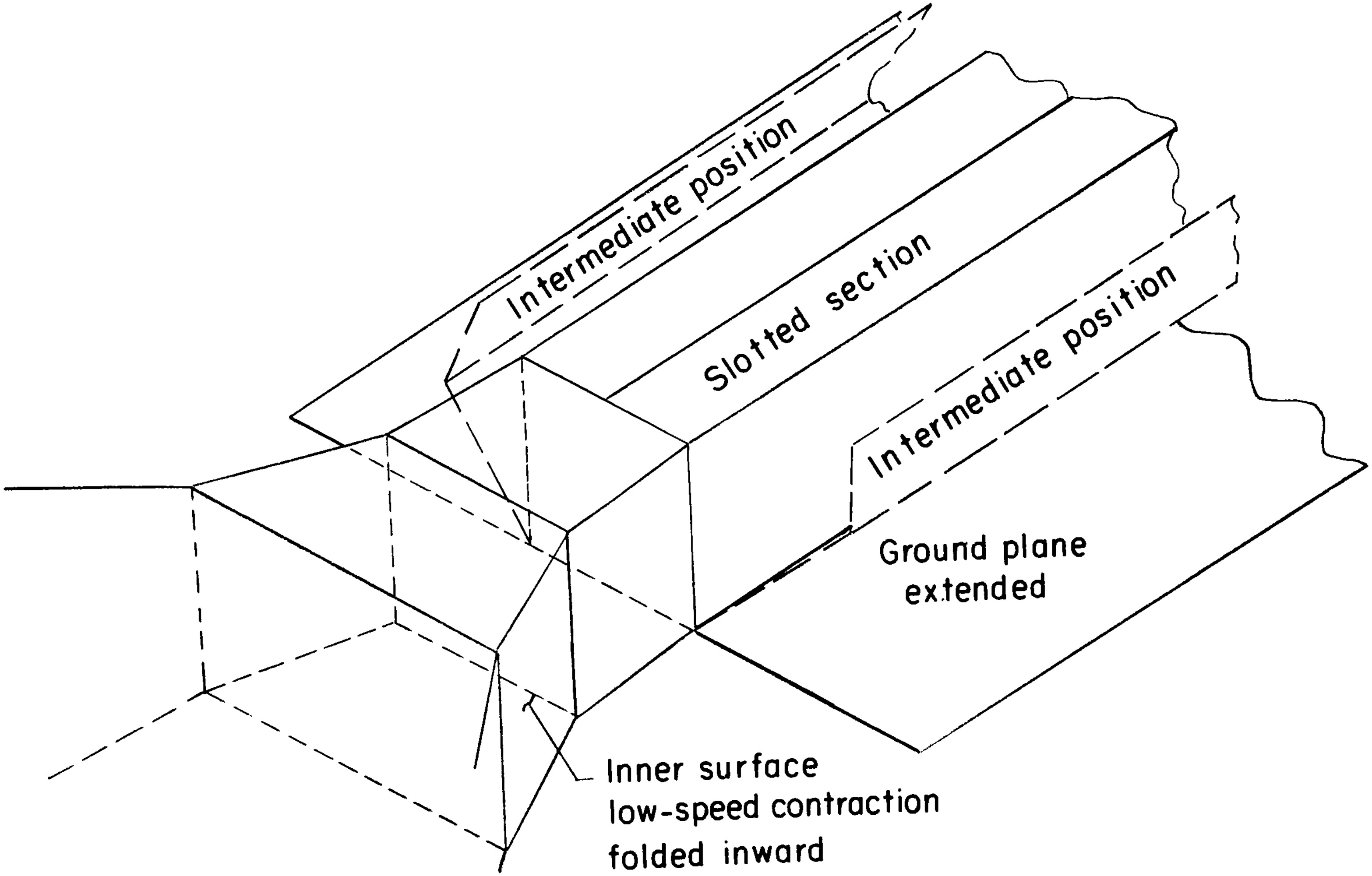
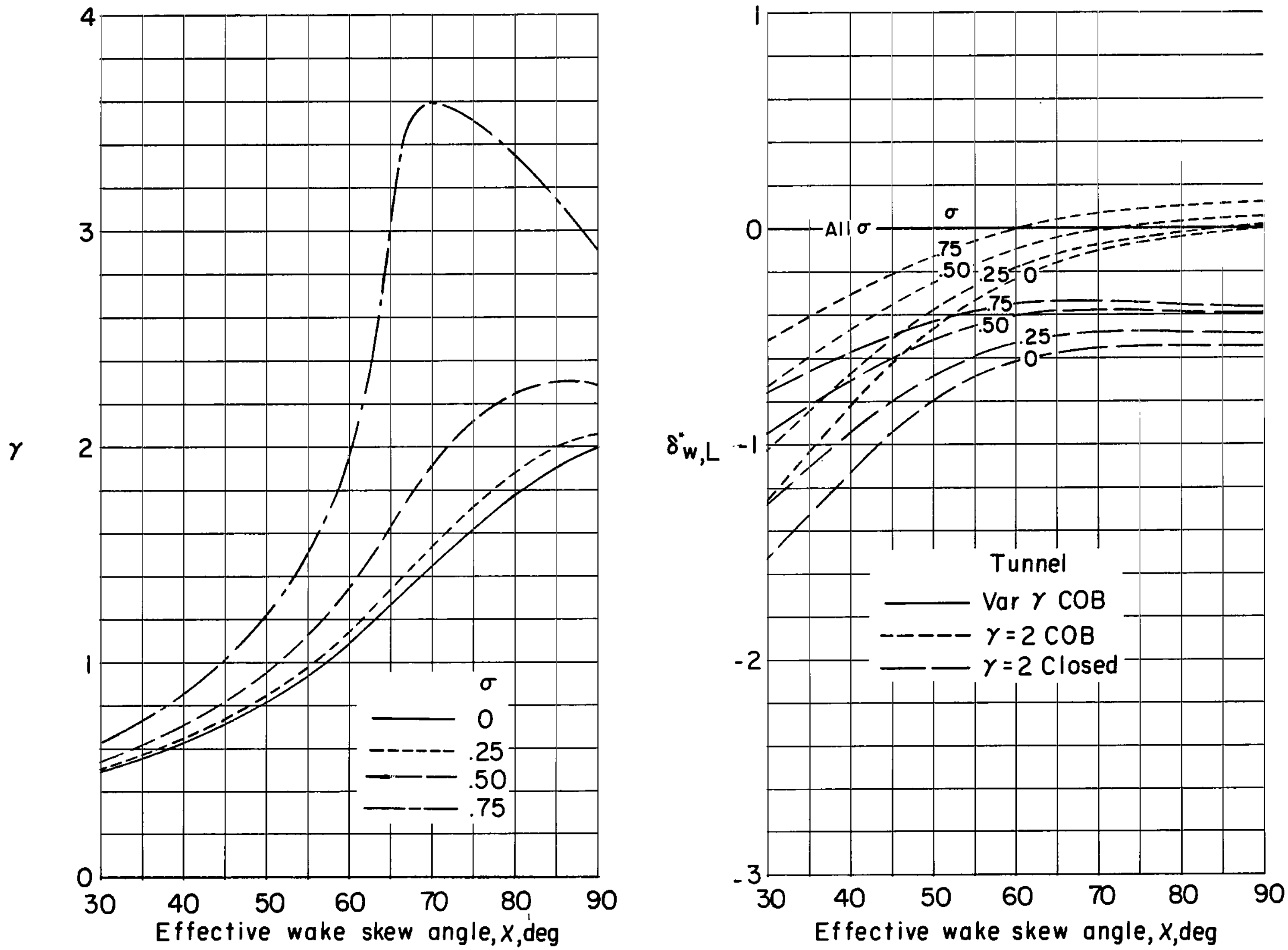


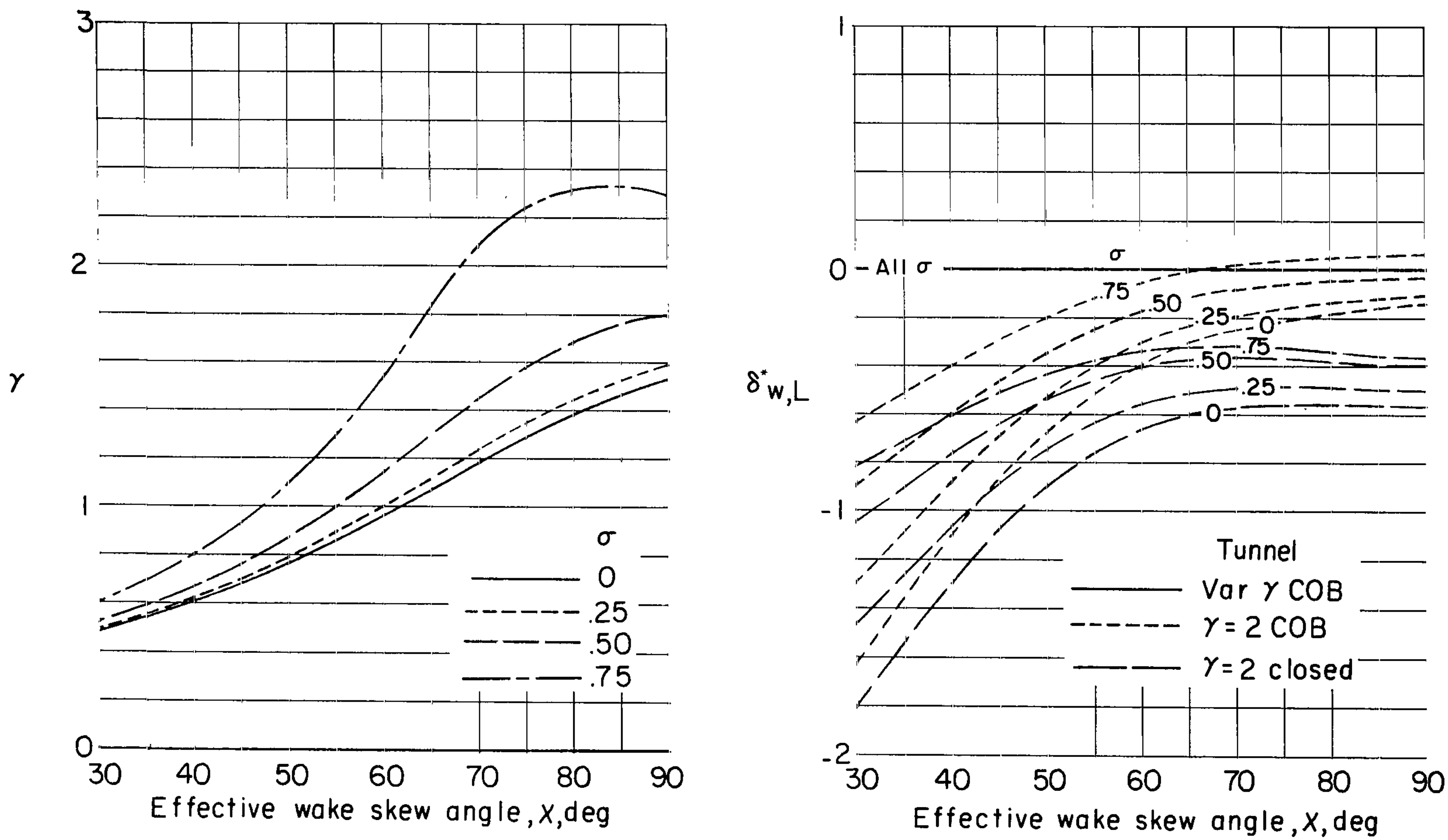
Figure 4.- Sketch of high-speed section showing one scheme for folding ground plane to form tunnel walls.



(a) Required width-height-ratio schedule for $\delta_{w,L} = 0$.

(b) Interference factors for variable and fixed width-height-ratio tunnels.

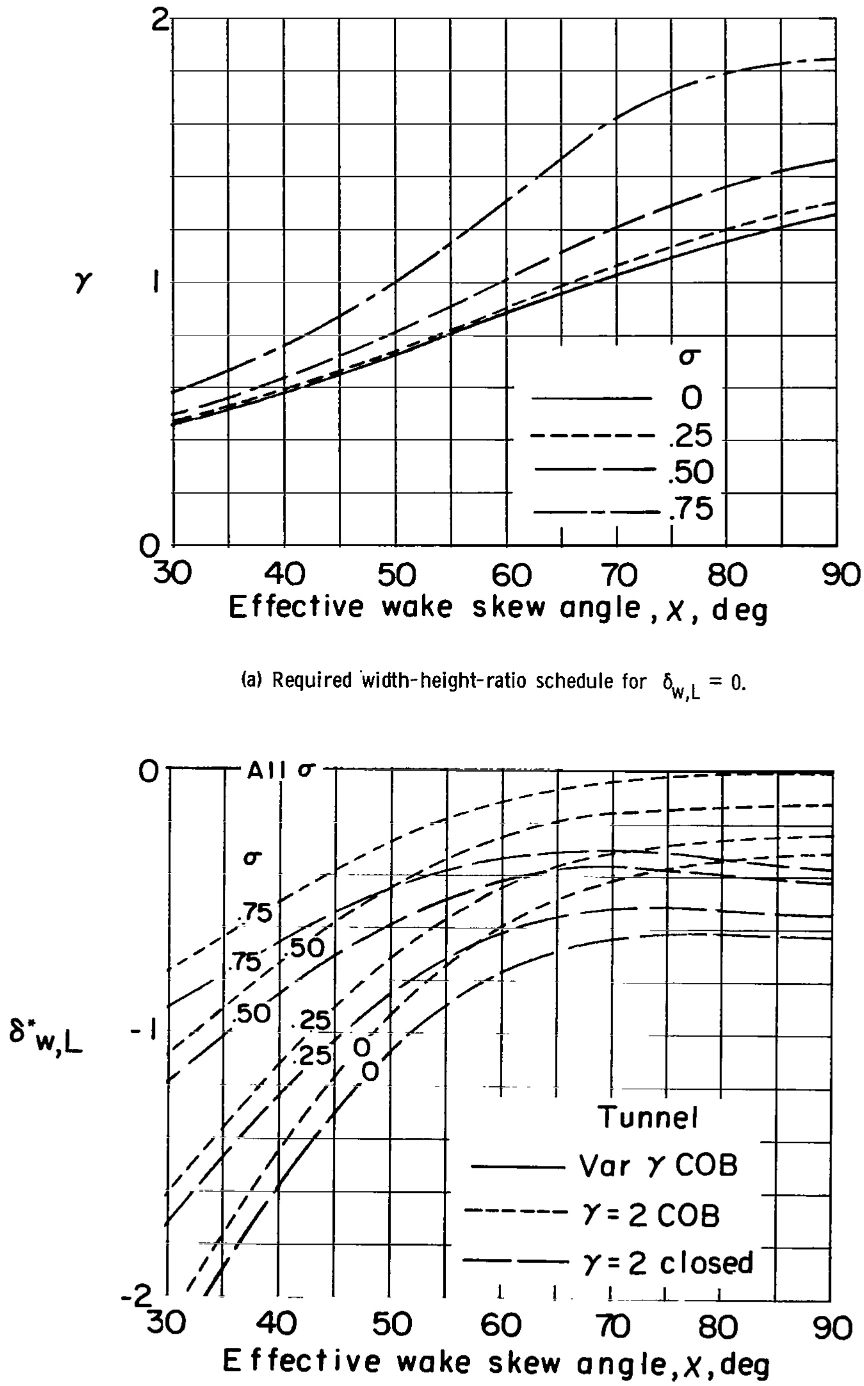
Figure 5.- Required schedule and comparison of interference factors for unswept wings centered in a variable width-height-ratio closed-on-bottom-only tunnel. $\alpha = 0^{0}$.



(a) Required width-height-ratio schedule for $\delta_{w,L} = 0$.

(b) Interference factors for variable and fixed width-height-ratio tunnels.

Figure 6.- Required schedule and comparison of interference factors for unswept wings, laterally centered, but 0.1 H^* below the centerline, in a variable width-height-ratio closed-on-bottom-only tunnel. $\alpha = 0^{\circ}$.



(a) Required width-height-ratio schedule for $\delta_{w,L} = 0$.

(b) Interference factors for variable and fixed width-height-ratio tunnels.

Figure 7.- Required schedule and comparison of interference factors for unswept wings, laterally centered, but 0.2 H* below the centerline, in a variable width-height-ratio closed-on-bottom-only tunnel. $\alpha = 0^0$.

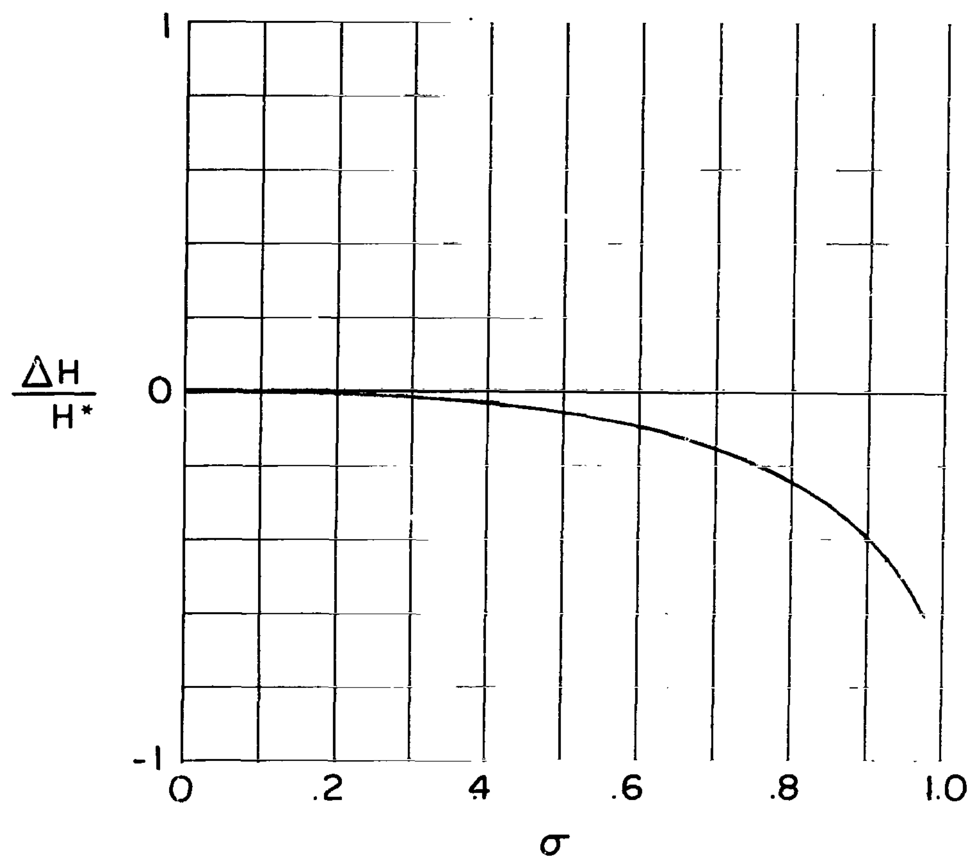


Figure 8.- Required model height to obtain $\delta_{w,L} = 0$ for unswept wings when $\gamma = 2.0$ and $\chi = 90^0$. Closed-on-bottom-only tunnel.

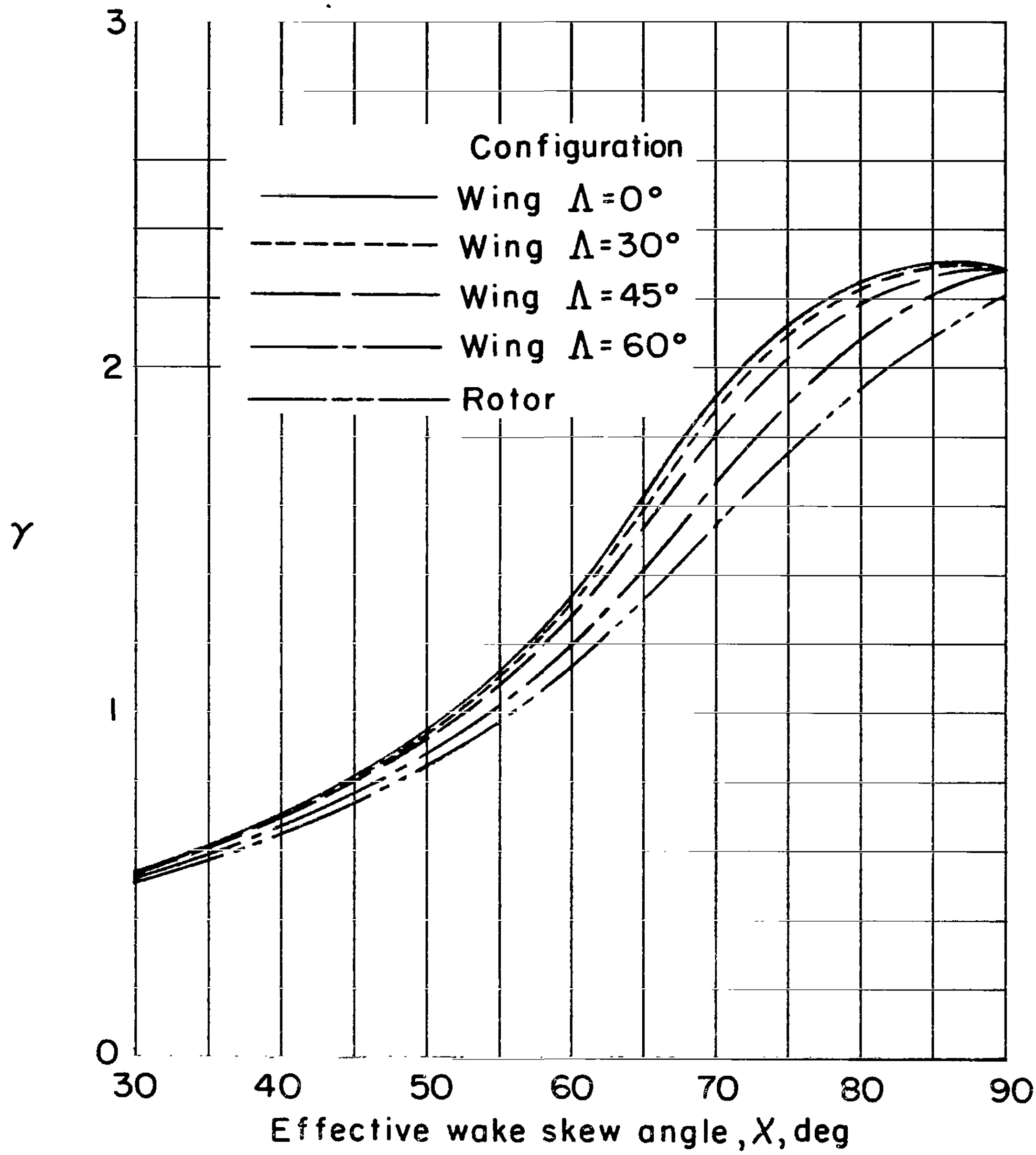


Figure 9.- Effect of model configuration on required schedule of width-height ratio for centered models in a variable width-height-ratio tunnel. $\sigma = 0.5$; $\alpha = 0^{\circ}$.

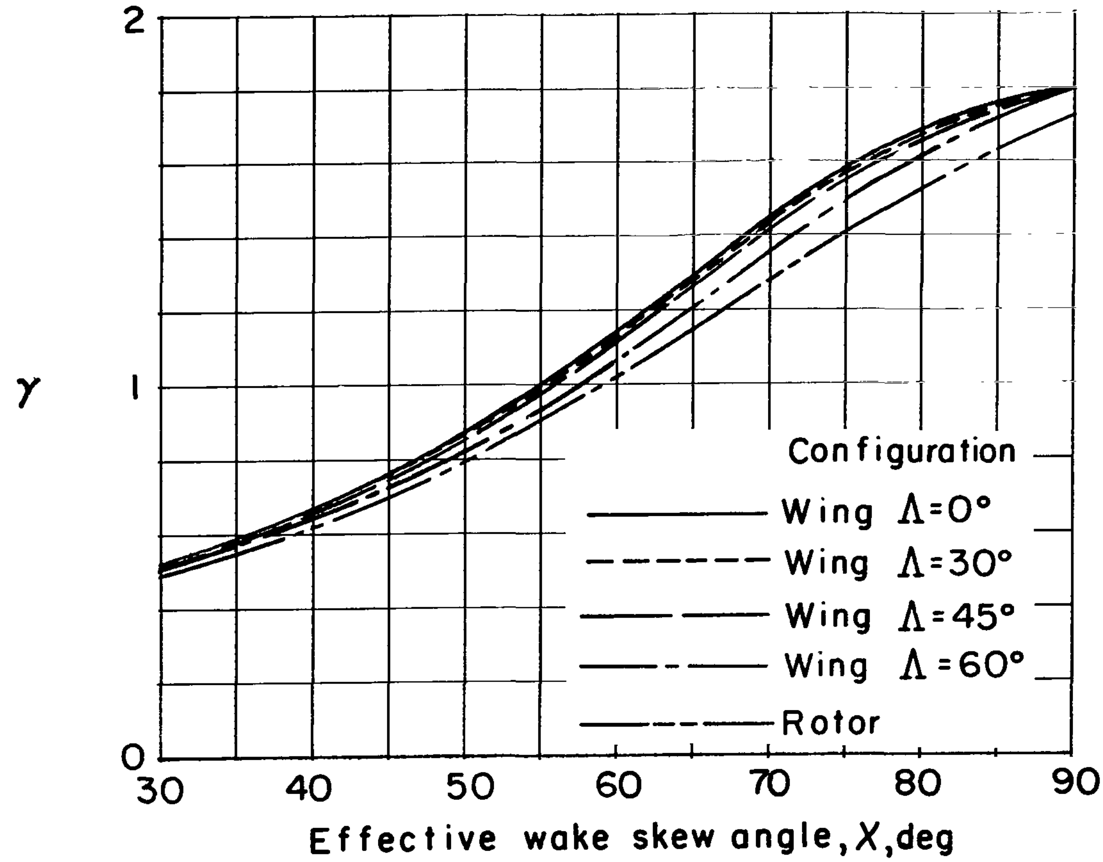


Figure 10.- Effect of model configuration on required schedule of width-height ratio for laterally centered models mounted 0.1 H^* below the centerline in variable width-height-ratio closed-on-bottom-only tunnel. $\sigma = 0.5$; $\alpha = 0^{\circ}$.

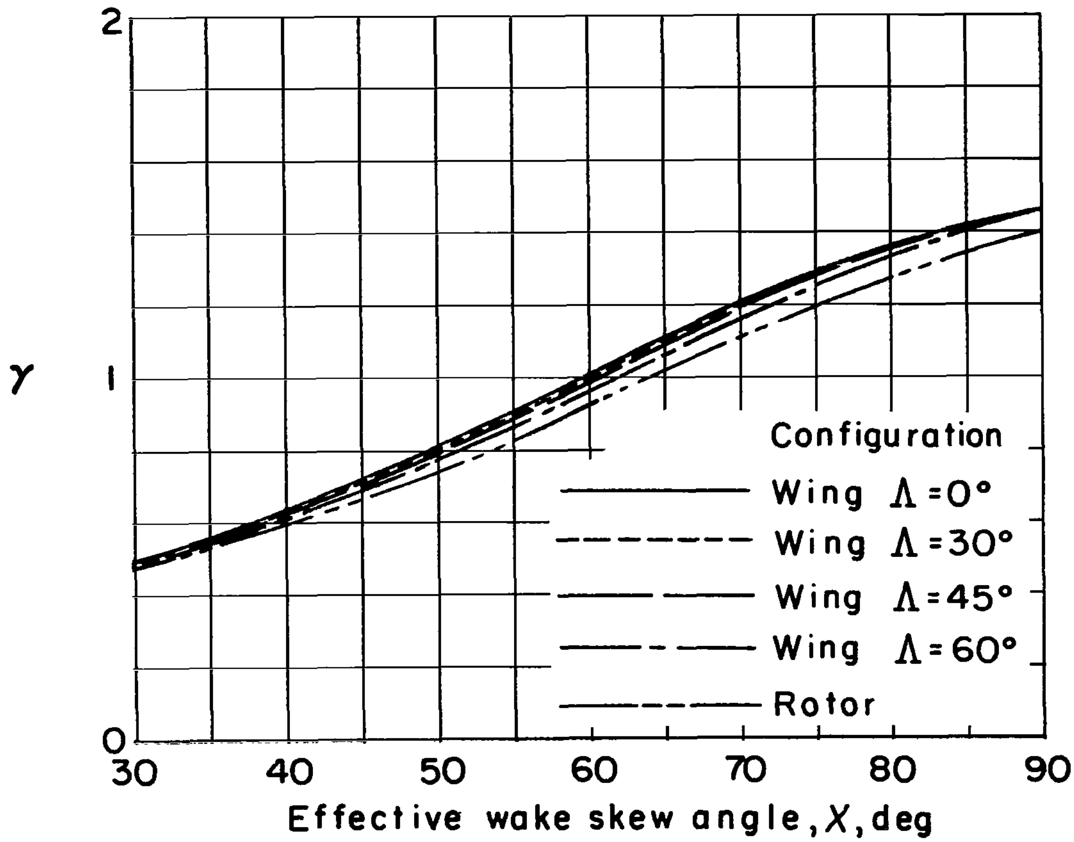
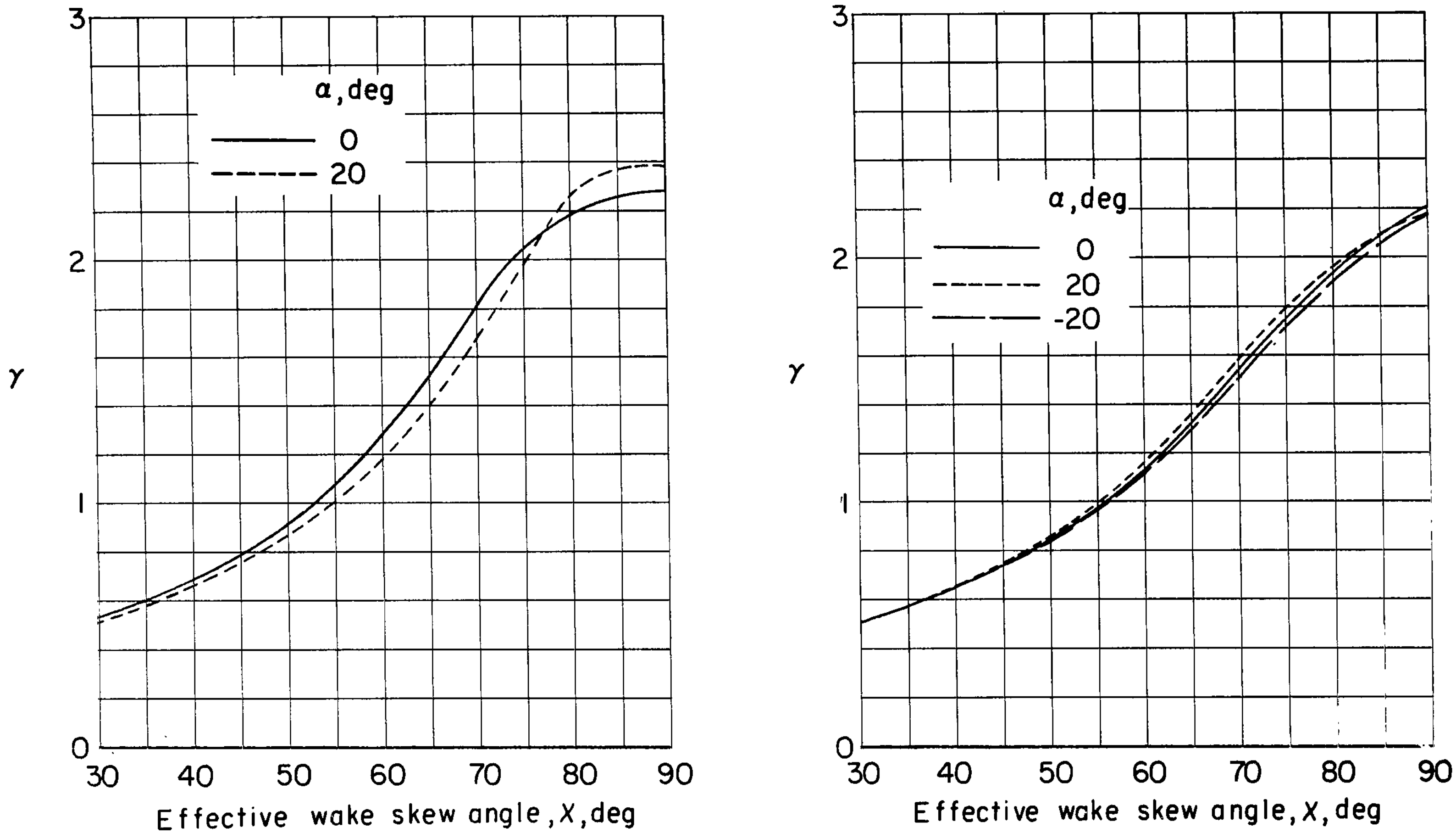


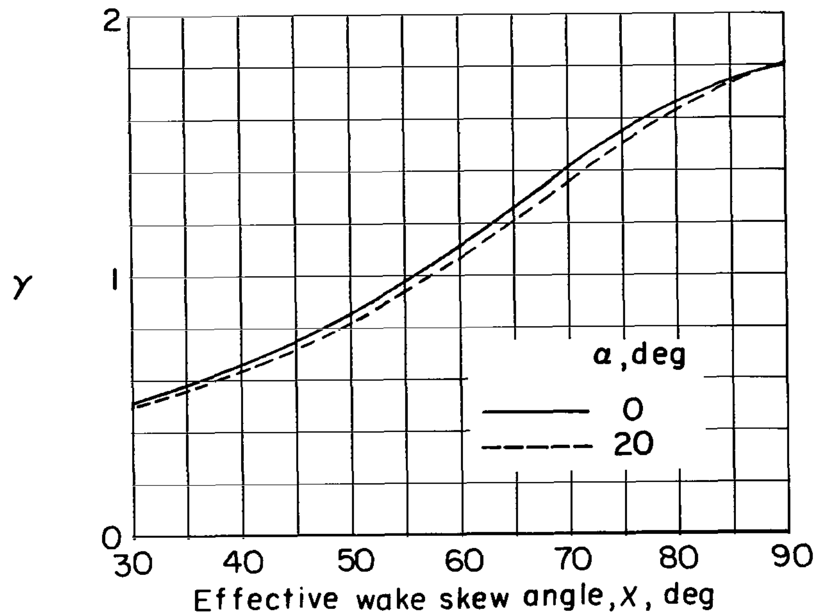
Figure 11.- Effect of model configuration on required schedule of width-height ratio for laterally centered models mounted 0.2 H^* below the centerline in a variable width-height-ratio closed-on-bottom-only tunnel. $\sigma = 0.5$; $\alpha = 0^0$.



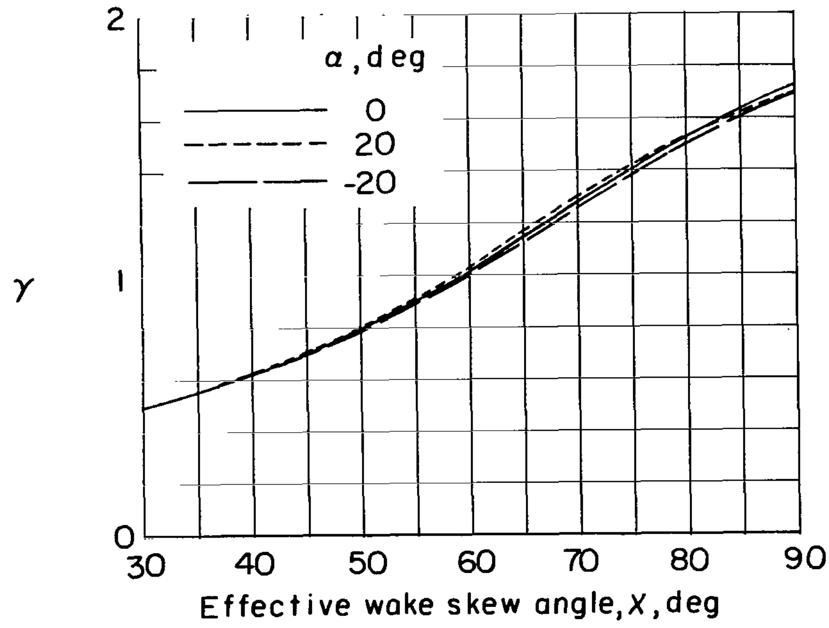
(a) Wing, $\Lambda = 45^{0}$.

(b) Rotor.

Figure 12.- Effect of angle of attack on required schedule for centered models in a variable width-height-ratio closed-on-bottom-only tunnel. $\sigma = 0.5$.

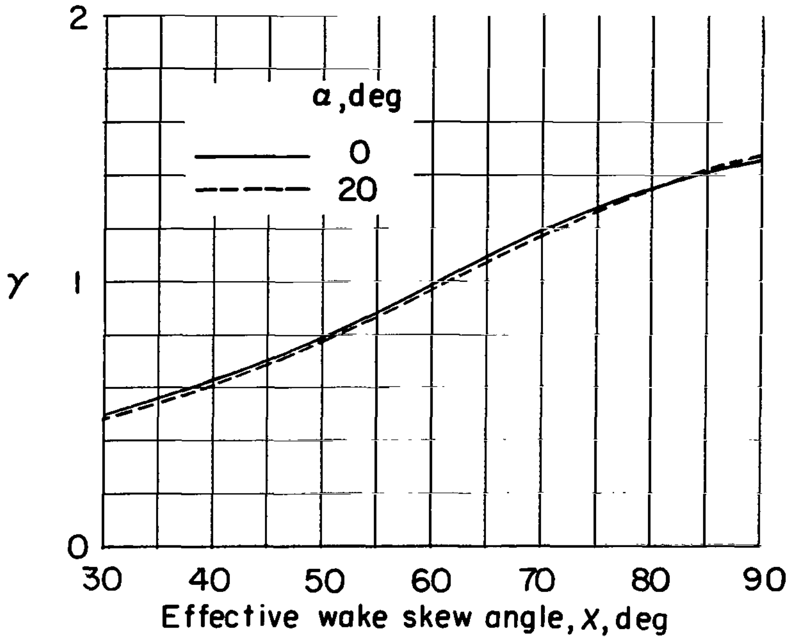


(a) Wing, Λ = 45°.

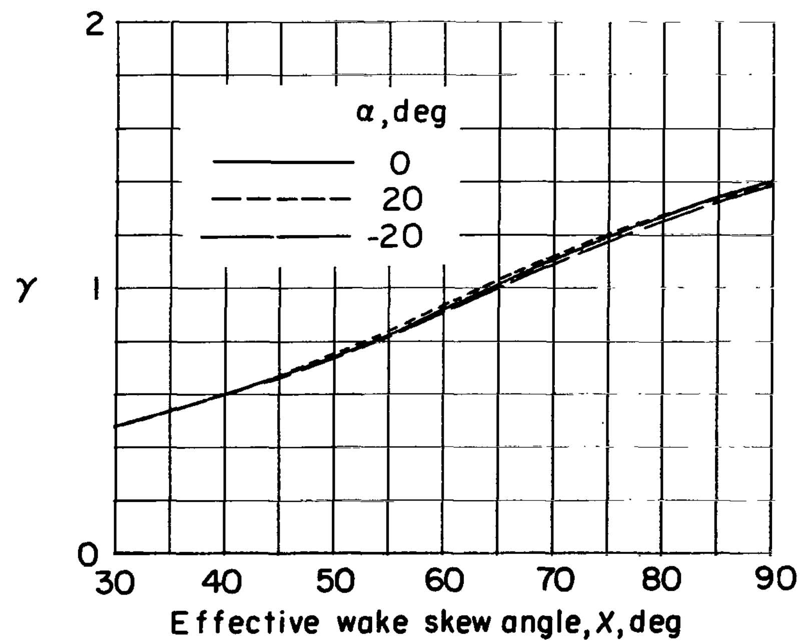


(b) Rotor.

Figure 13.- Effect of angle of attack on required schedule for laterally centered models mounted 0.1 H* below the centerline in a variable width-height-ratio closed-on-bottom-only tunnel. $\sigma = 0.5$.

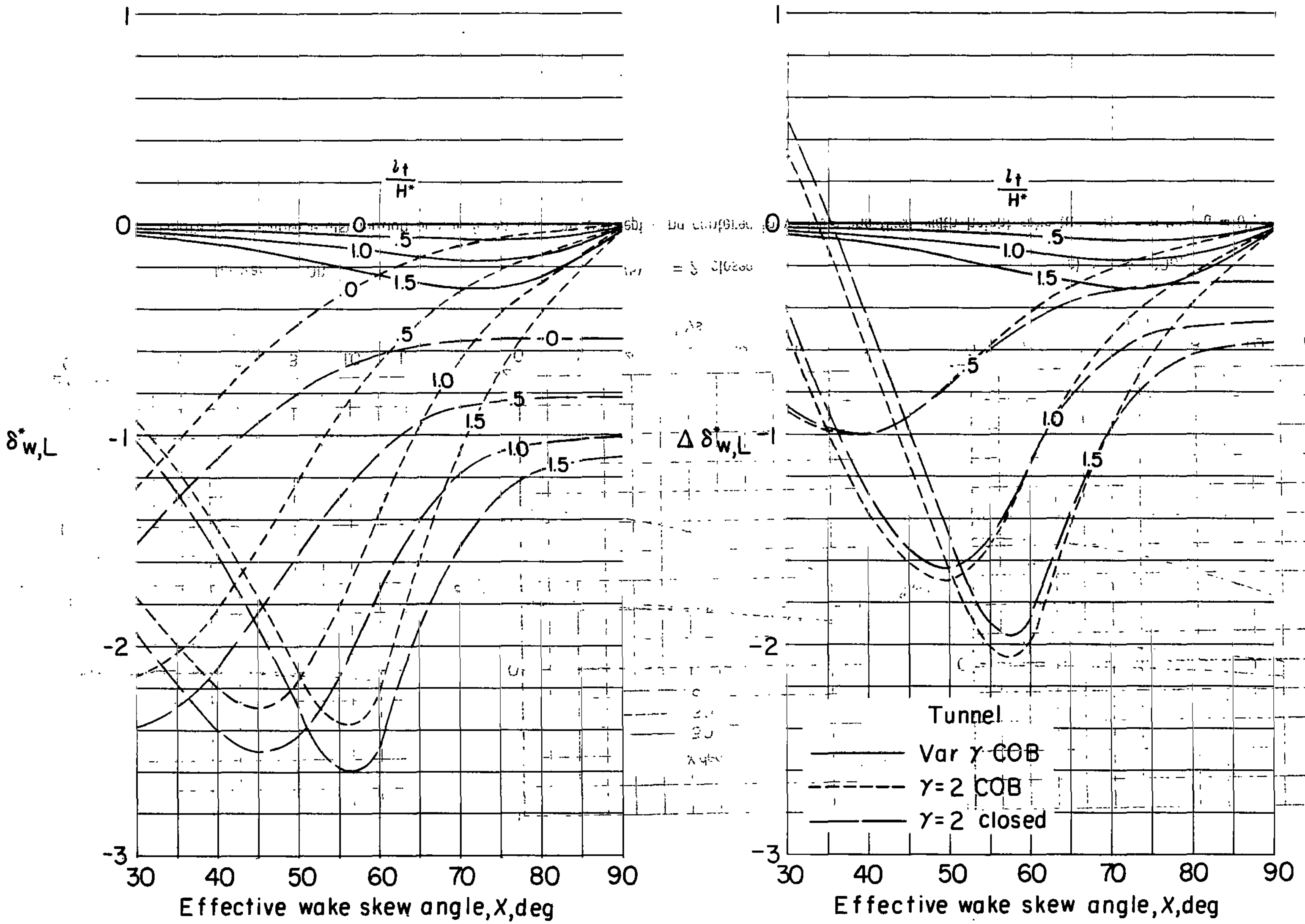


(a) Wing, $\Lambda = 45^{0}$.



(b) Rotor.

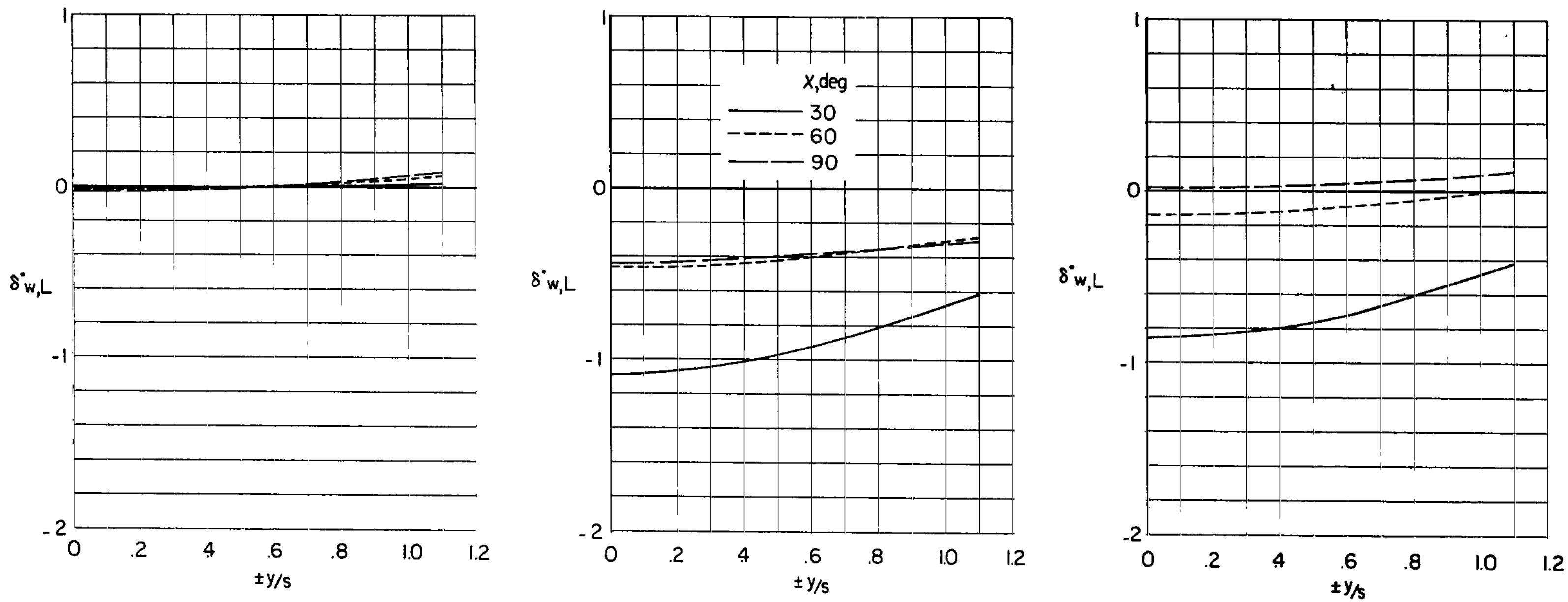
Figure 14.- Effect of angle of attack on required schedule for laterally centered models mounted 0.2 H* below the centerline in a variable width-height-ratio closed-on-bottom-only tunnel. $\sigma = 0.5$.



(a) Interference factors at wing and tail.

(b) Difference between interference factors at wing and tail.

Figure 15.- Interference factors at tail in both variable and fixed width-height-ratio tunnels for centered models. $\sigma = \sigma_t = 0$; $\alpha = 0^0$.

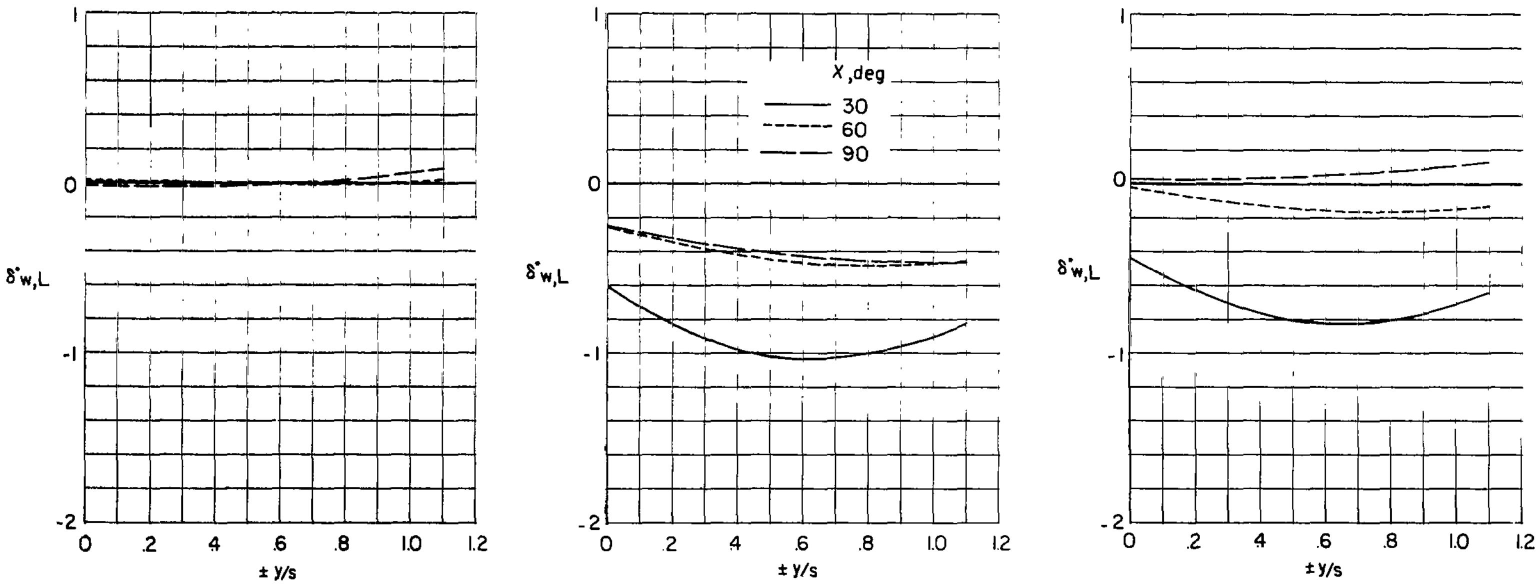


(a) Var γ COB.

(b) γ = 2 closed.

(c) γ = 2 COB.

Figure 16.- Spanwise distribution of interference for an unswept wing centered in variable and fixed width-height-ratio tunnels. $\sigma = 0.5$; $\alpha = 0^{0}$.



(a) Var γ COB.

(b) γ = 2 closed.

(c) γ = 2 COB.

Figure 17.- Spanwise distribution of interference for a wing with 45° of sweep centered in variable and fixed width-height-ratio tunnels. $\sigma = 0.5$; $\alpha = 0^{\circ}$.

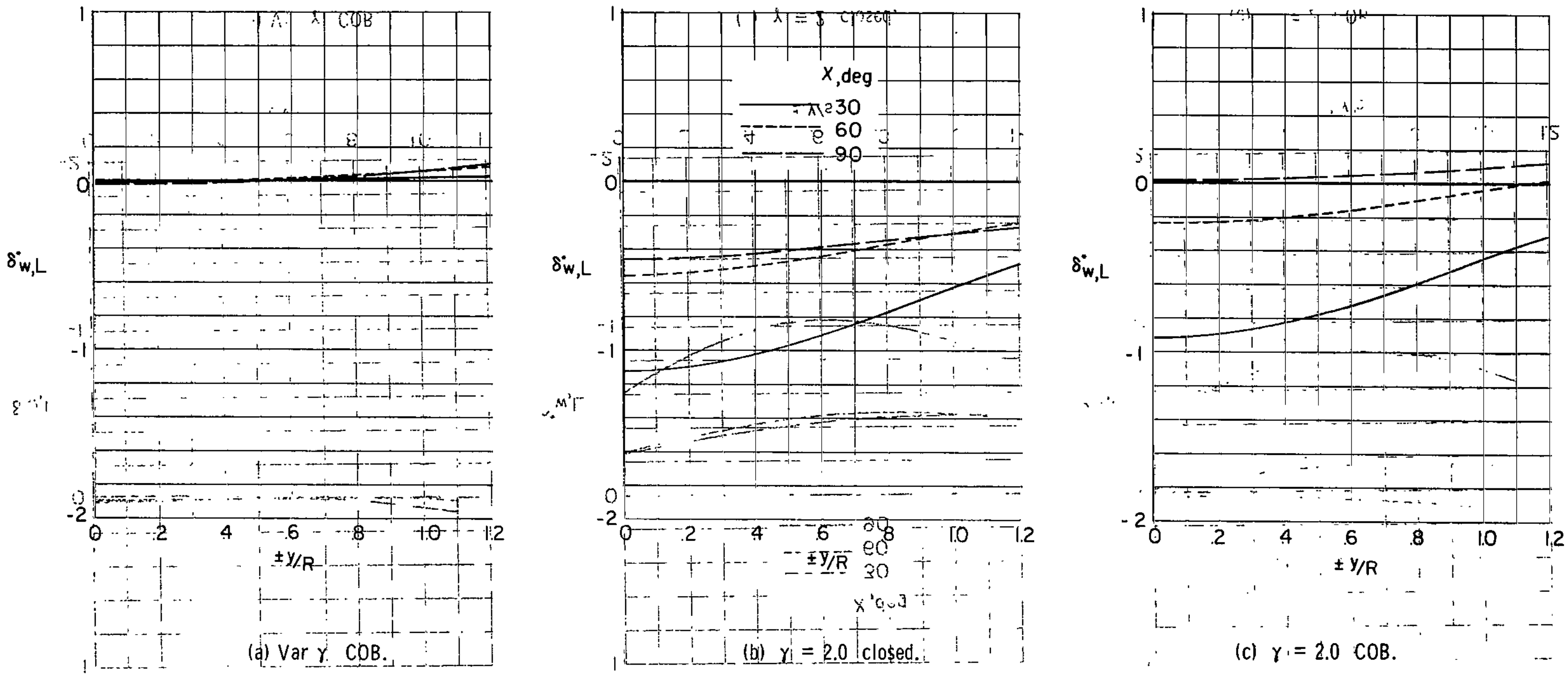
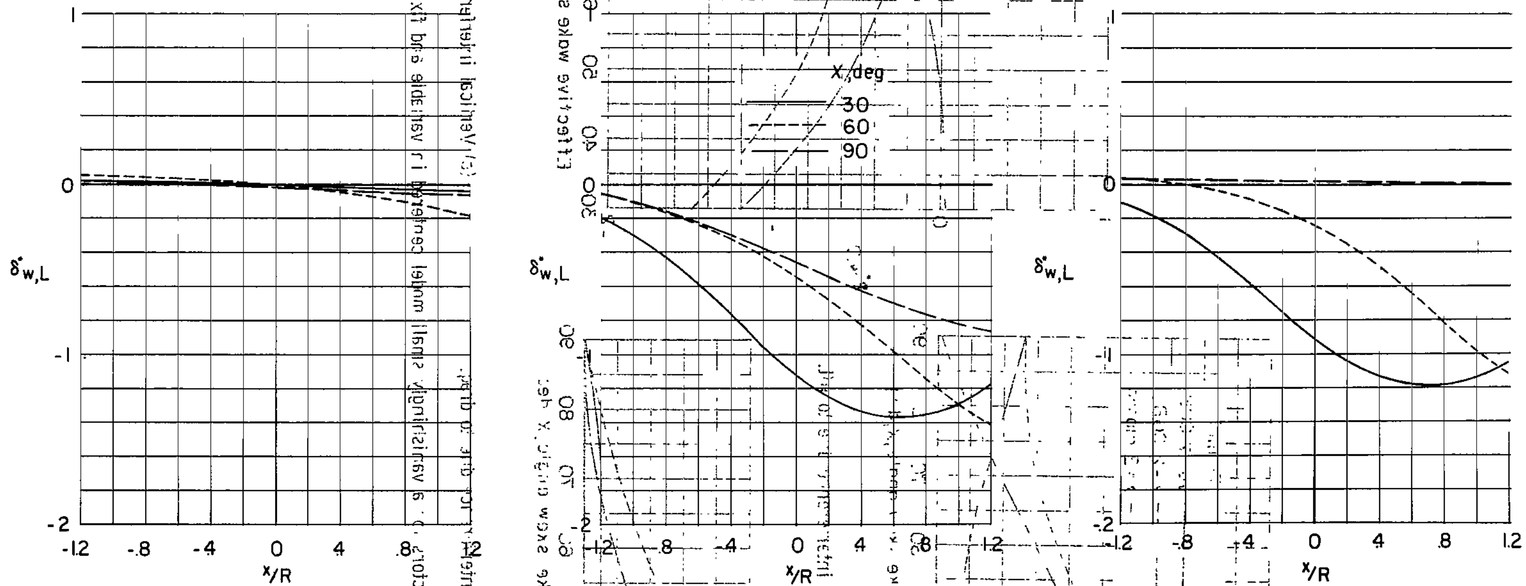
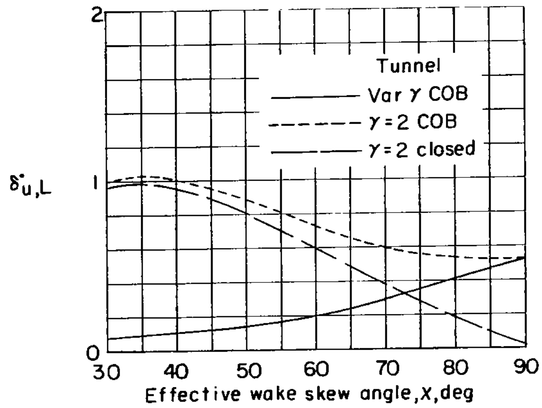


Figure 18.- Lateral distribution of interference over a rotor centered in variable and fixed width-height-ratio tunnels. $\sigma = 0.5$; $\alpha = 0^0$.

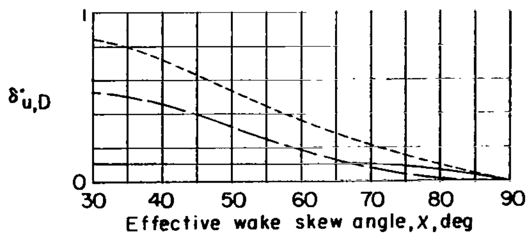


(a) Var γ COB. (b) γ = 2.0 closed. (c) γ = 2.0 COB.

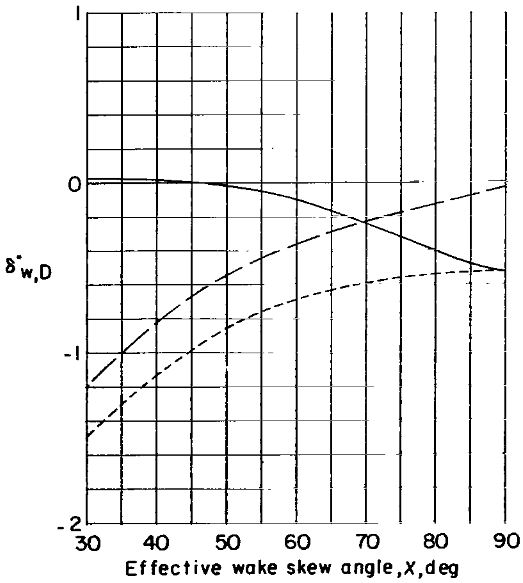
Figure 19.- Longitudinal distribution of interference over a rotor centered in variable and fixed width-height-ratio tunnels. $\sigma = 0.5$; $\alpha = 0^o$.



(a) Horizontal interference due to lift.



(b) Horizontal interference due to drag.



(c) Vertical interference due to drag.

Figure 20.- Residual interference factors for a vanishingly small model centered in variable and fixed width-height-ratio tunnels.

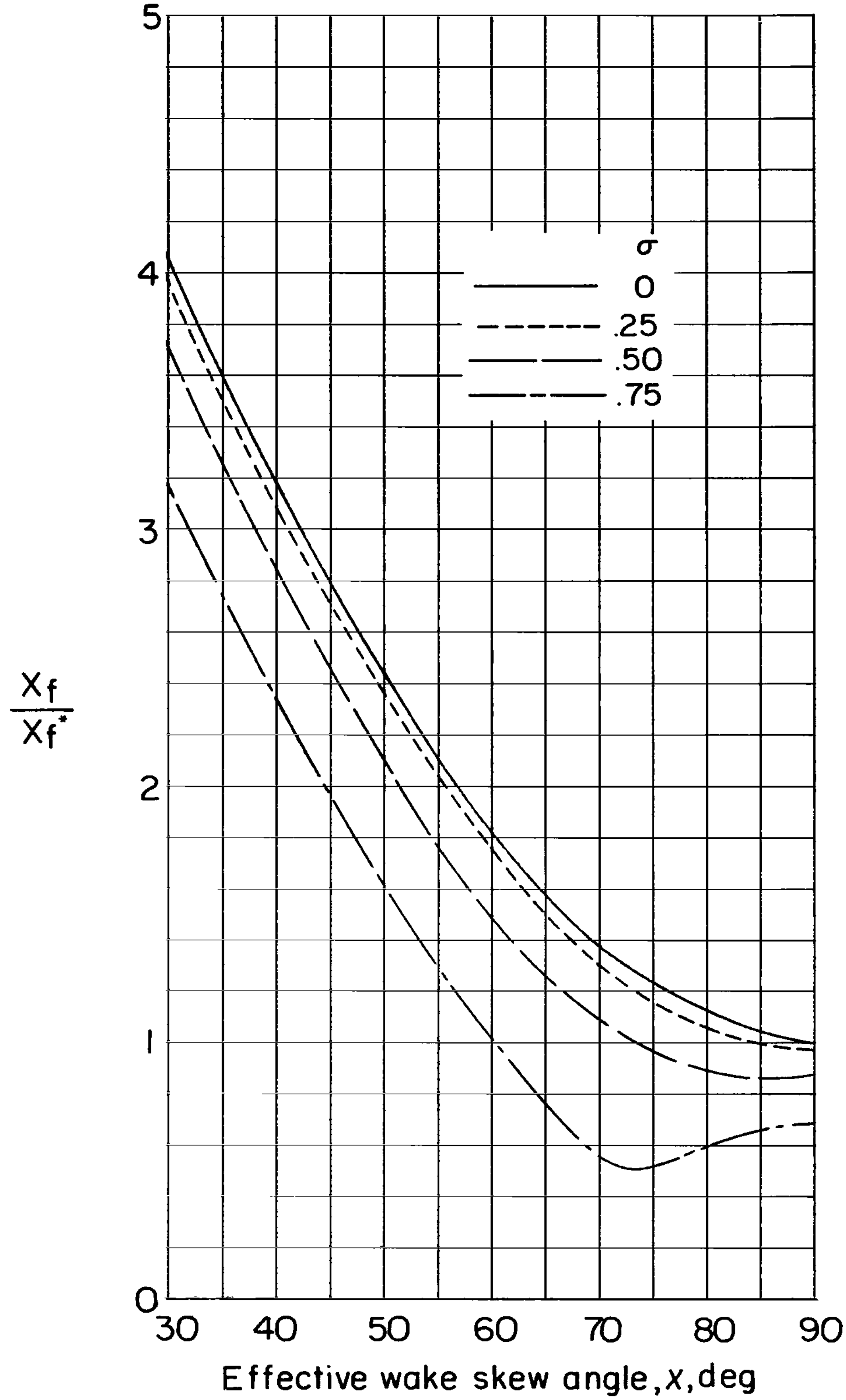
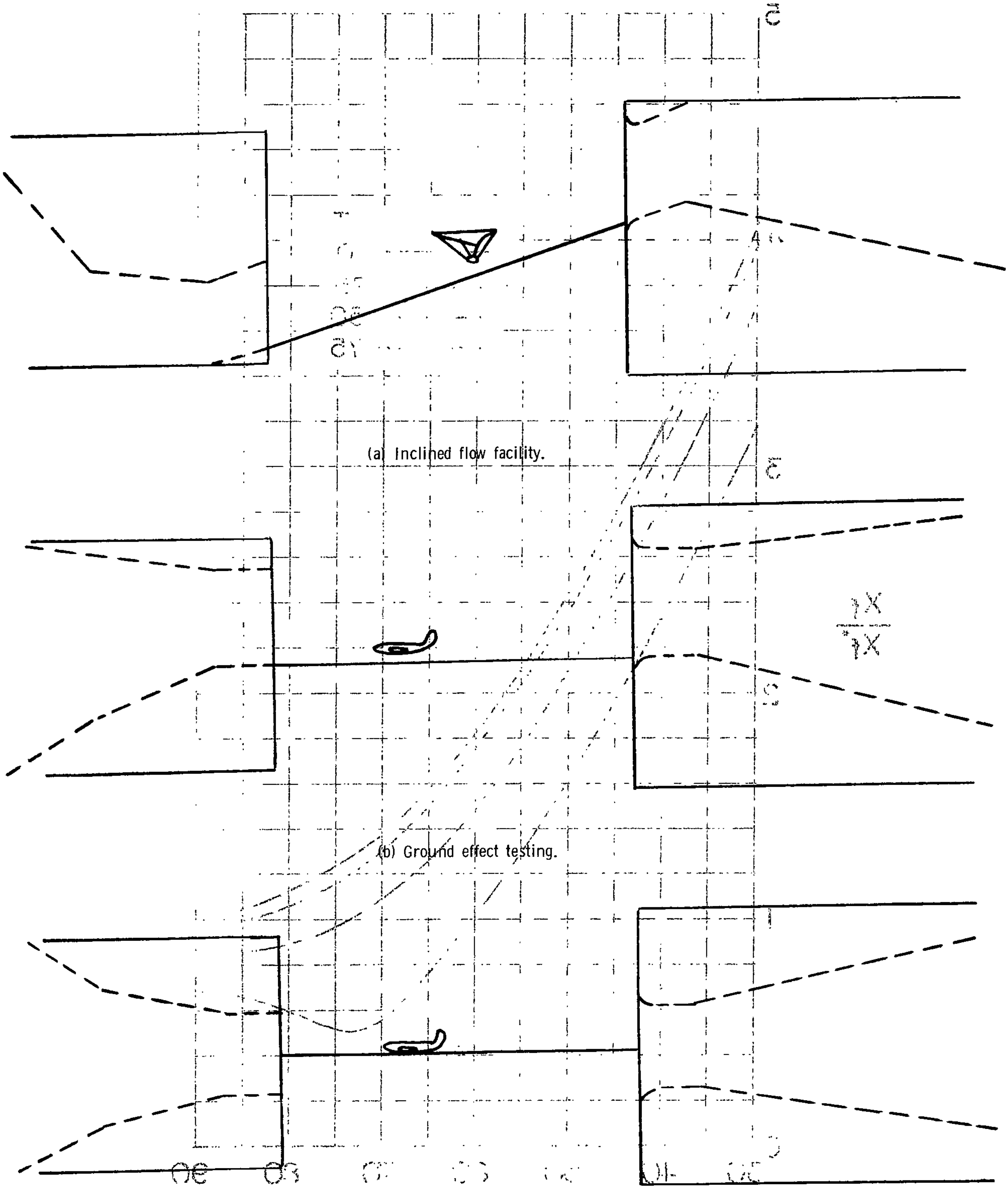


Figure 21.- Relative recirculation for unswept wings centered in a variable width-height-ratio closed-on-bottom-only tunnel.



(a) Inclined flow facility.

(b) Ground effect testing.

(c) Convenient work height.

Figure 22.- Additional advantages of variable-geometry wind tunnel.

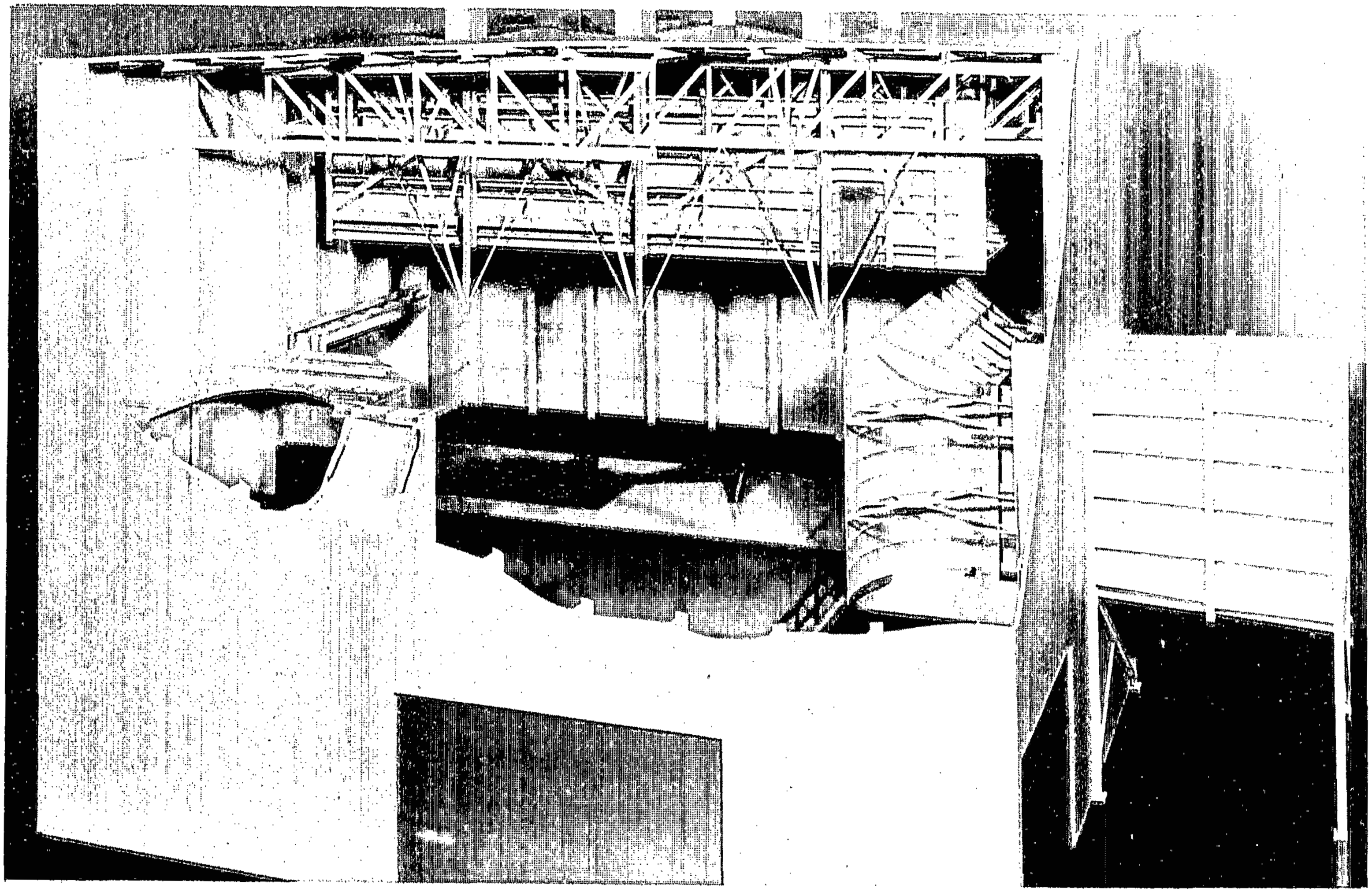
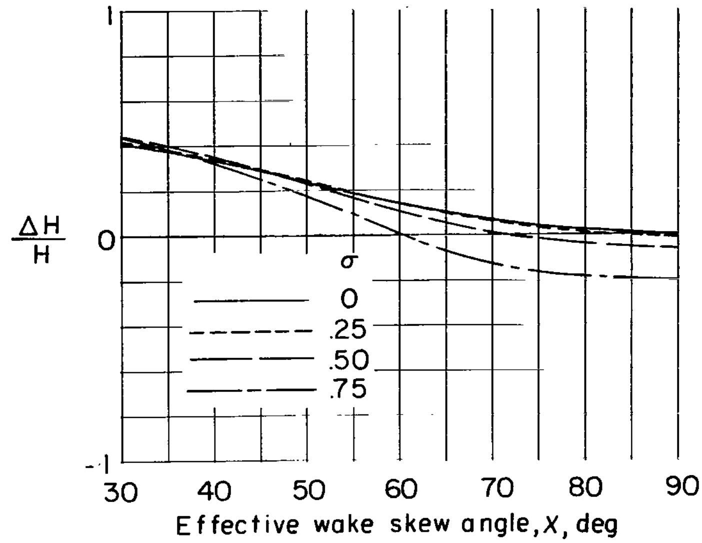
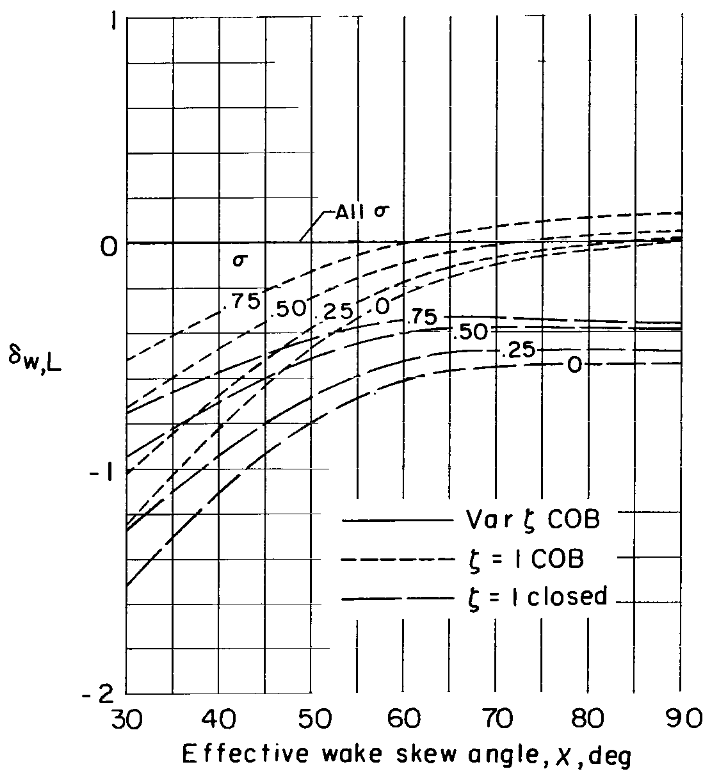


Figure 23.- Model of variable model-height closed-on-bottom-only test section. L-67-10 000

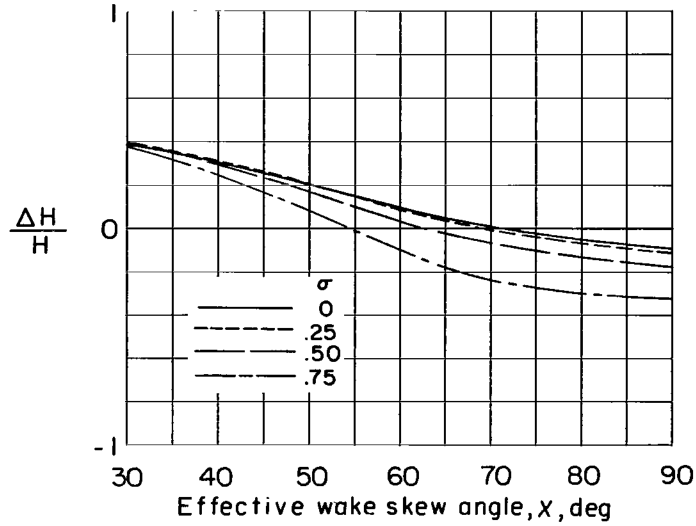


(a) Required schedule for $\delta_{w,L} = 0$.

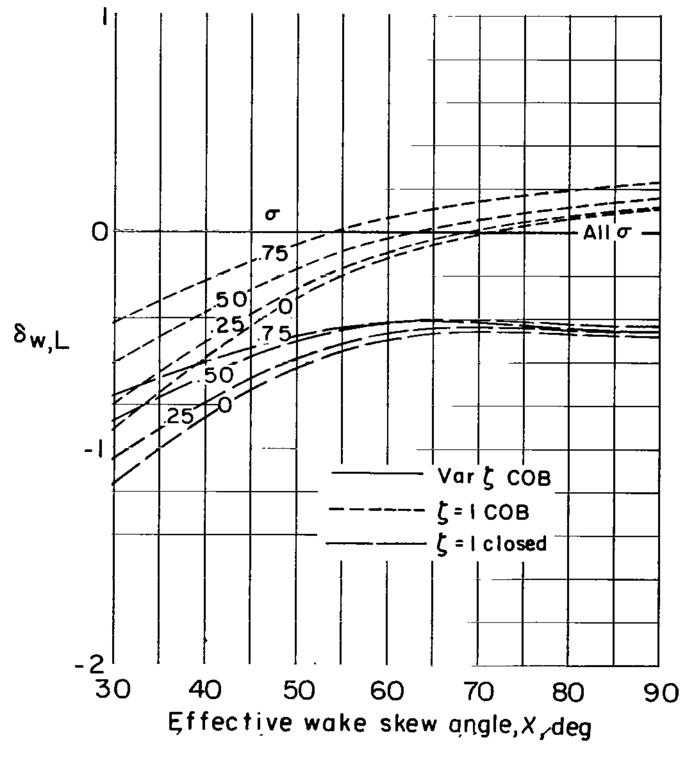


(b) Interference factors for variable and fixed model height tunnels.

Figure 24.- Required schedule and comparison of interference factors for unswept wings in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 2.0.

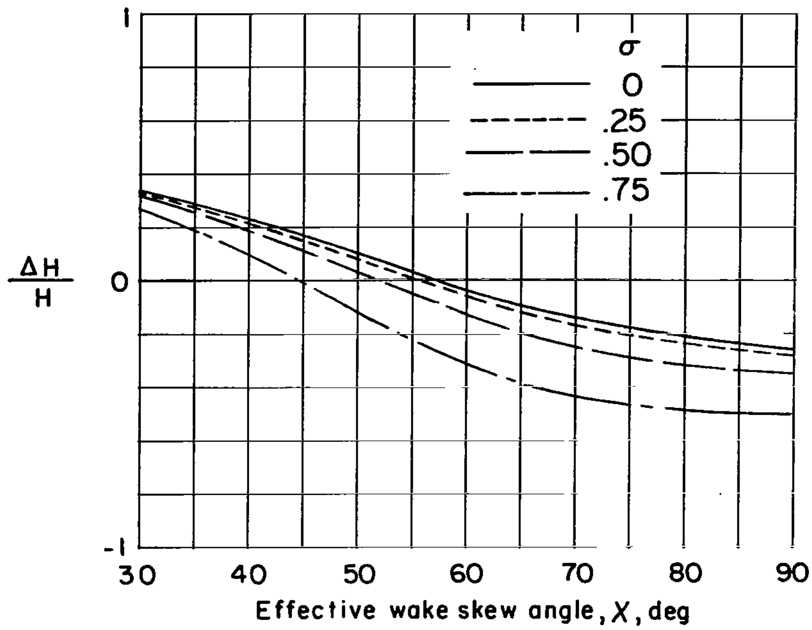


(a) Required schedule for $\delta_{w,L} = 0$.

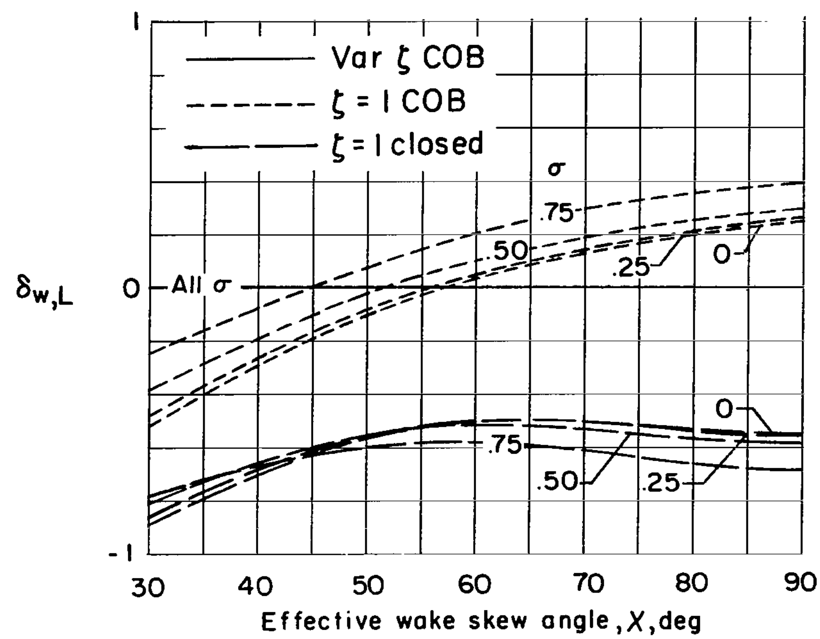


(b) Interference factors for variable and fixed model-height tunnels.

Figure 25.- Required schedule and comparison of interference factors for unswept wings in a variable model height closed-on-bottom-only tunnel having a width-height ratio of 1.5.

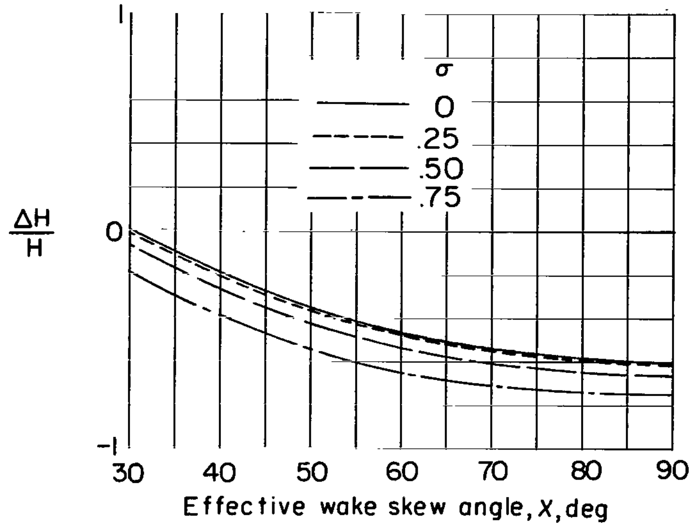


(a) Required schedule for $\delta_{w,L} = 0$.

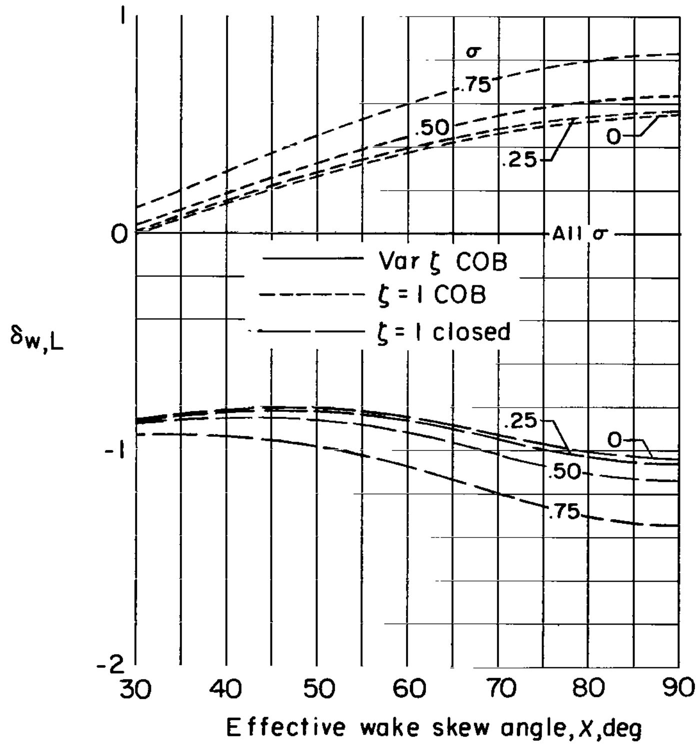


(b) Interference factors for variable and fixed model-height tunnels.

Figure 26.- Required schedule and comparison of interference factors for unswept wings in a variable model height closed-on-bottom-only tunnel having a width-height ratio of 1.0.

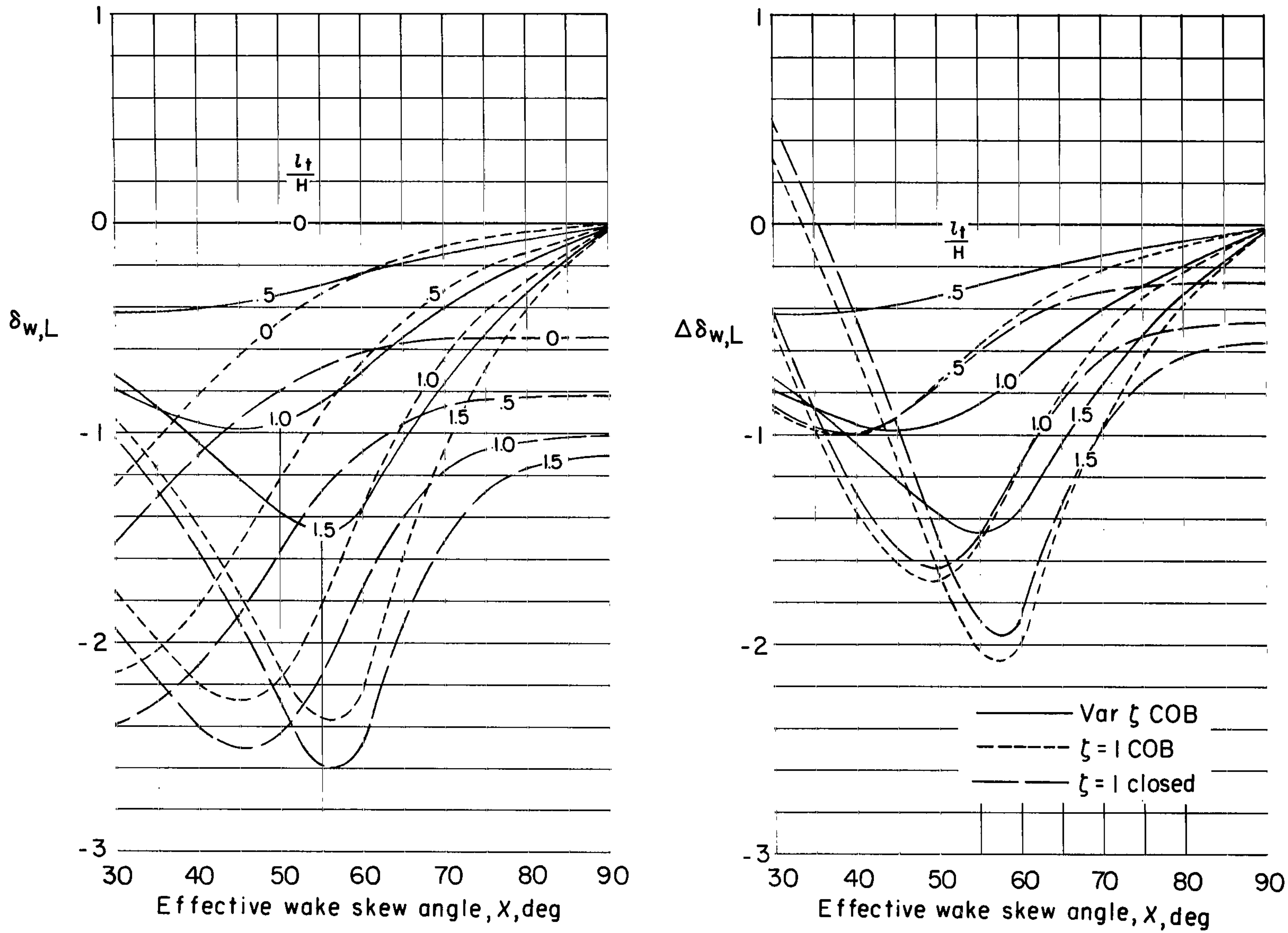


(a) Required schedule for $\delta_{w,L} = 0$.



(b) Interference factors for variable and fixed model-height tunnels.

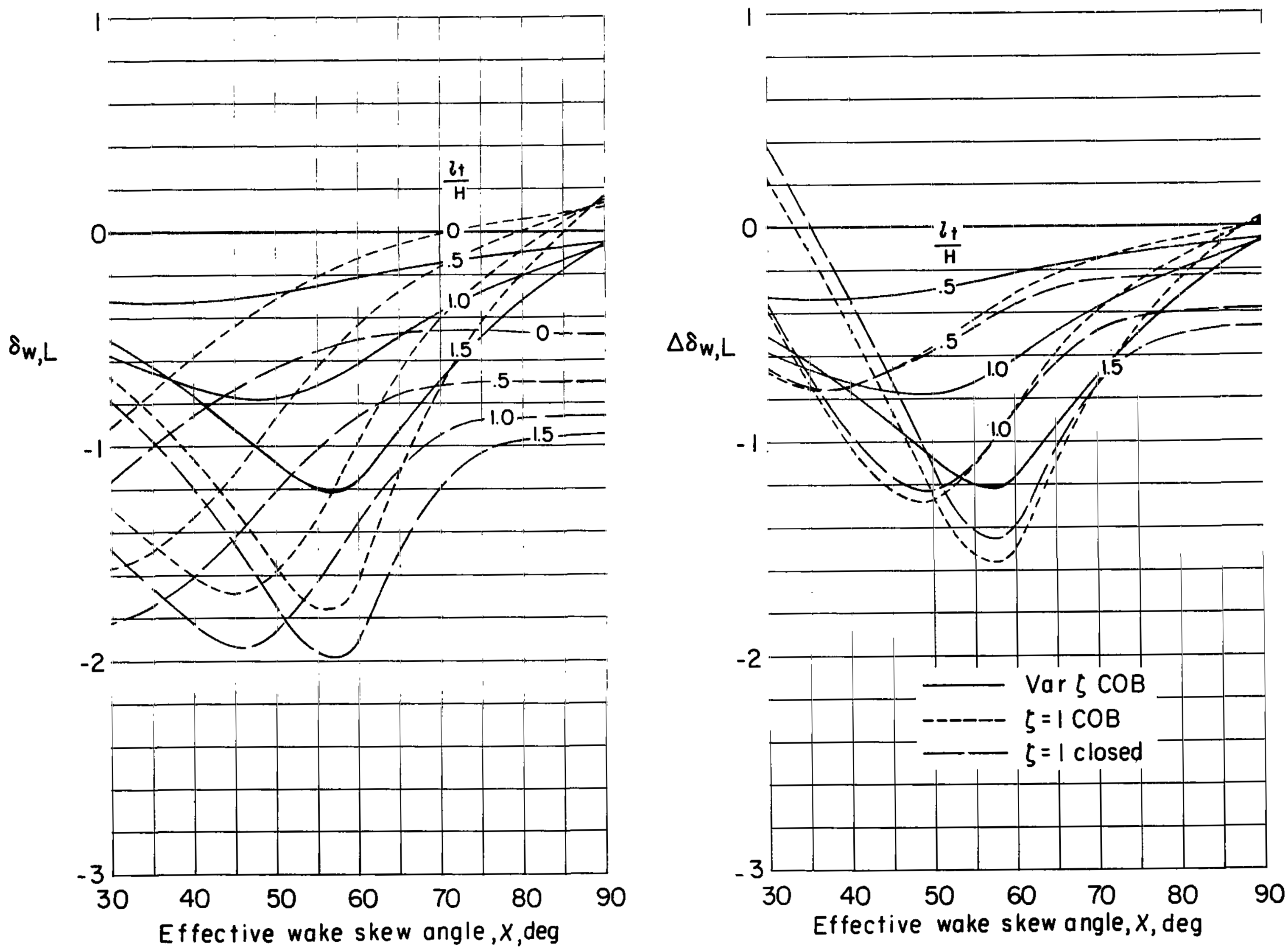
Figure 27.- Required schedule and comparison of interference factors for unswept wings in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 0.5.



(a) Interference factors at wing and tail.

(b) Difference in interference at wing and tail.

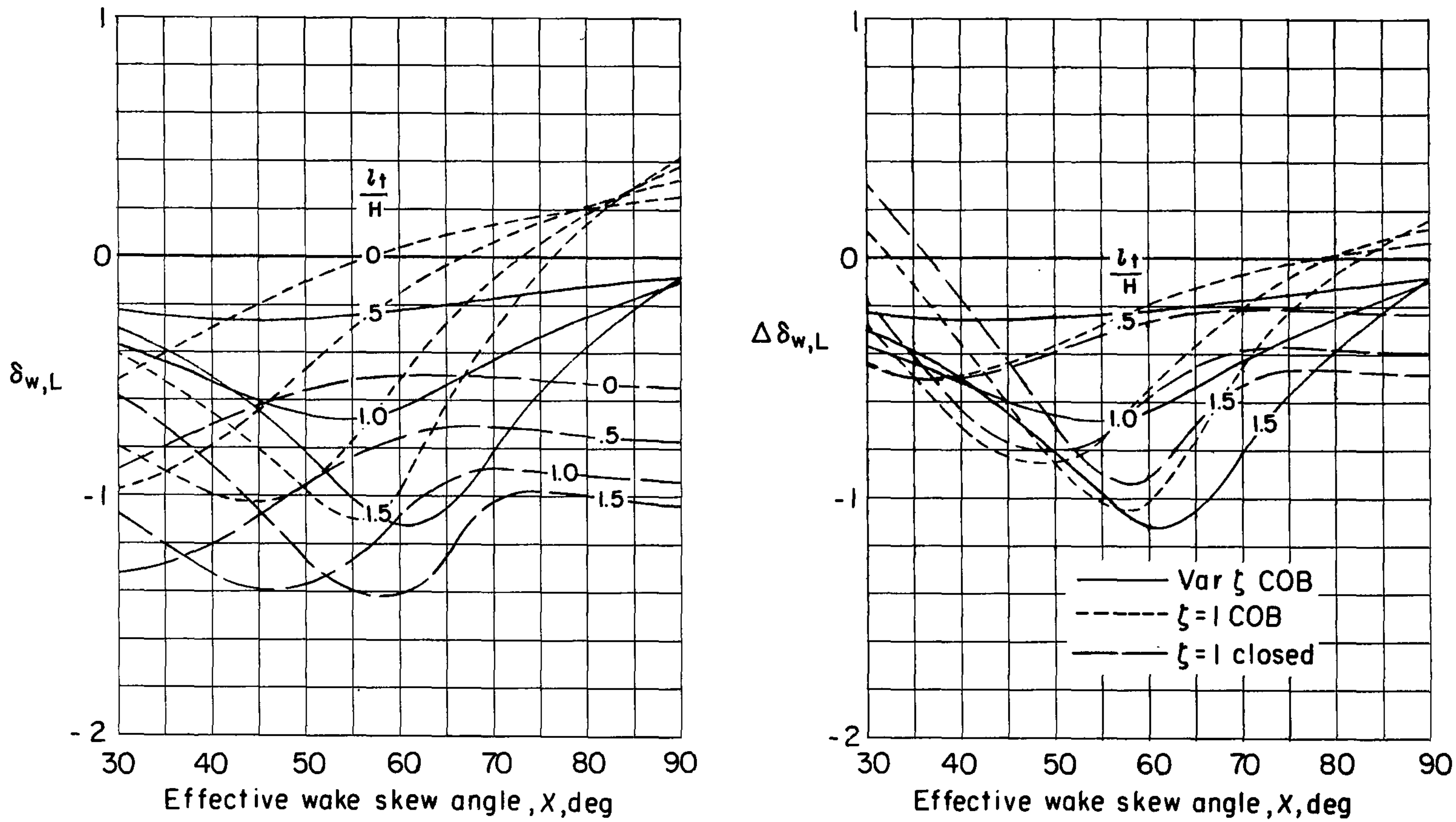
Figure 28.- Interference factors at tail in both variable and fixed model-height tunnels. $\gamma = 2.0$; $\sigma = \sigma_t = 0$; $\alpha = 0^0$.



(a) Interference factors at wing and tail.

(b) Difference in interference at wing and tail.

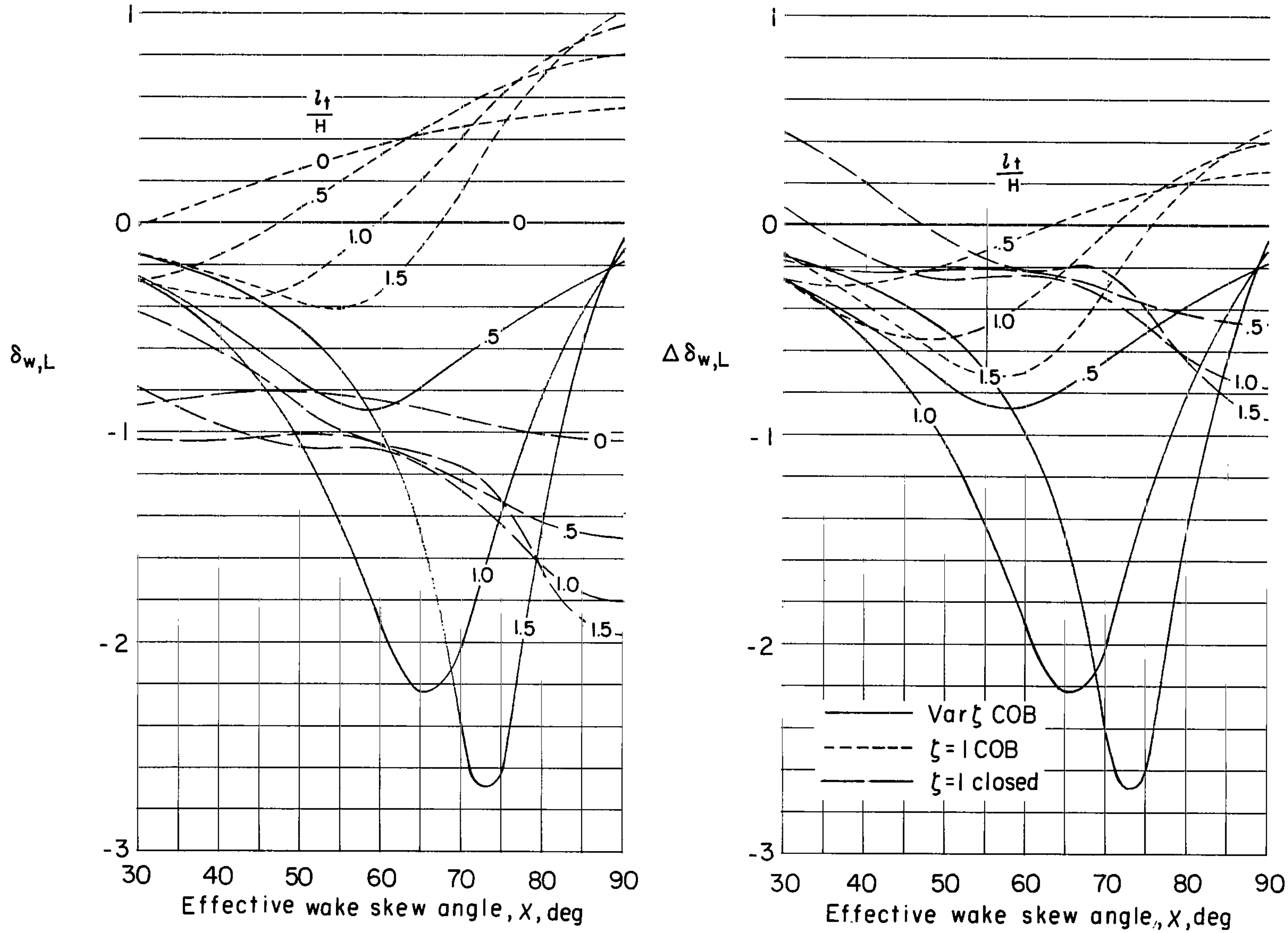
Figure 29.- Interference factors at tail in both variable and fixed model-height tunnels. $\gamma = 1.5$; $\sigma = \sigma_t = 0$; $\alpha = 0^{0}$.



(a) Interference factors at wing and tail.

(b) Difference in interference at wing and tail.

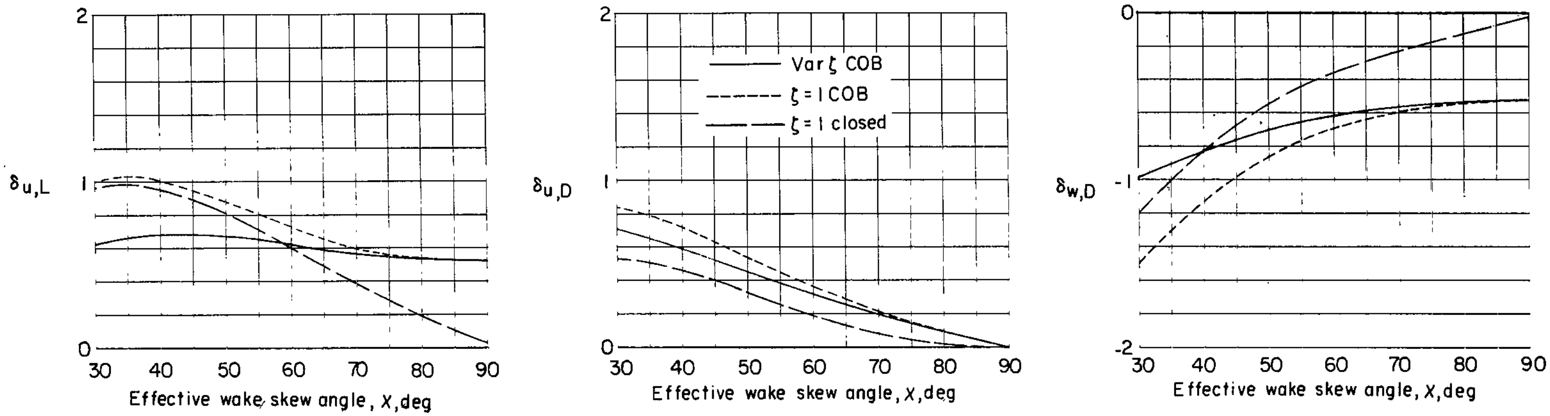
Figure 30.- Interference factors at tail in both variable and fixed model-height tunnels. γ = 1.0; $\sigma = \sigma_t = 0$; $\alpha = 0^{0}$.



(a) Interference factors at wing and tail.

(b) Difference in interference at wing and tail.

Figure 31.- Interference factors at tail in both variable and fixed model-height tunnels. $\gamma = 0.5$; $\sigma = \sigma_t = 0$; $\alpha = 0^0$.

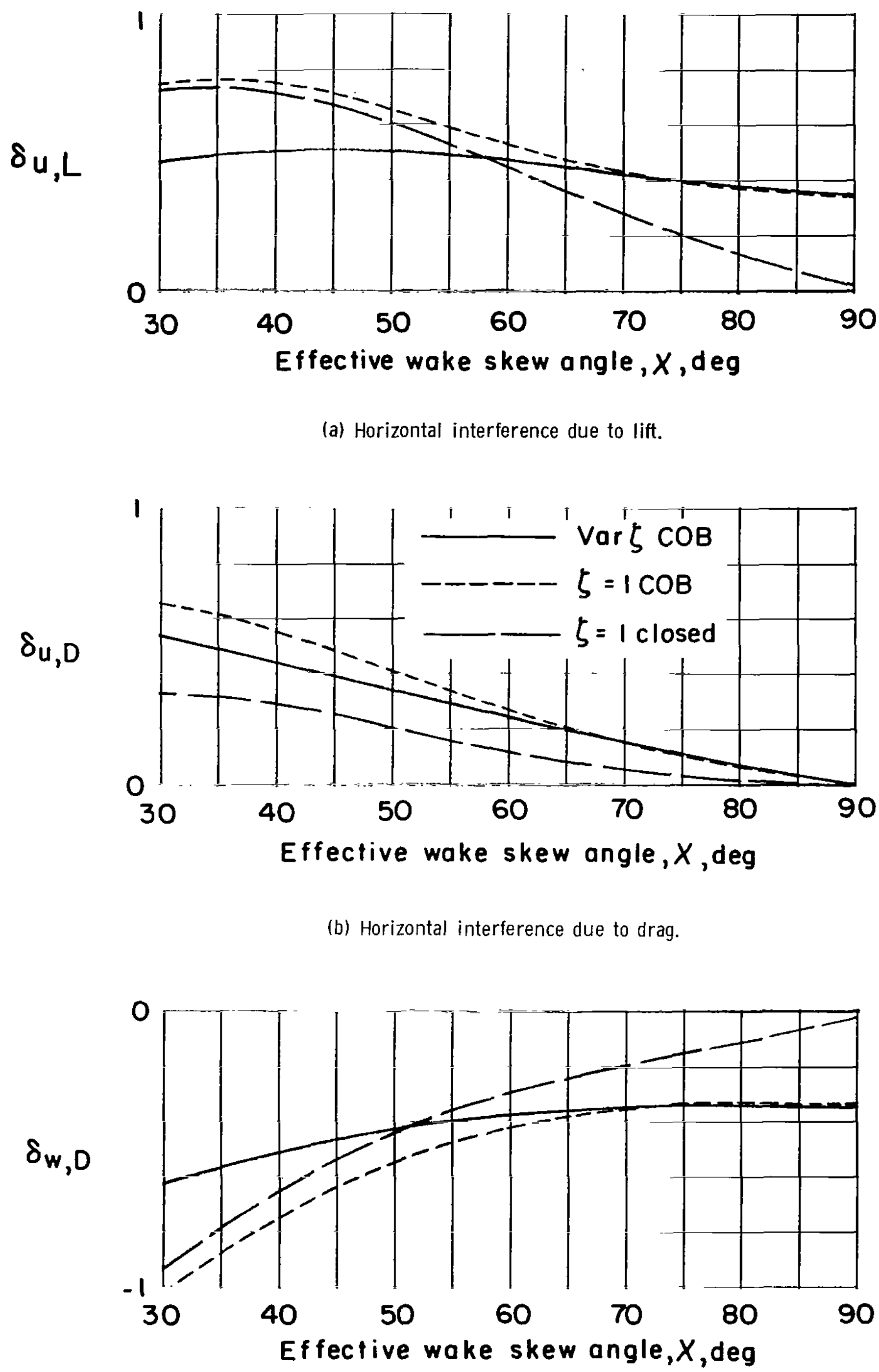


(a) Horizontal interference due to lift.

(b) Horizontal interference due to drag.

(c) Vertical interference due to drag.

Figure 32.- Residual interference factors for a vanishingly small model in variable and fixed model-height tunnels having a width-height ratio of 2.0.

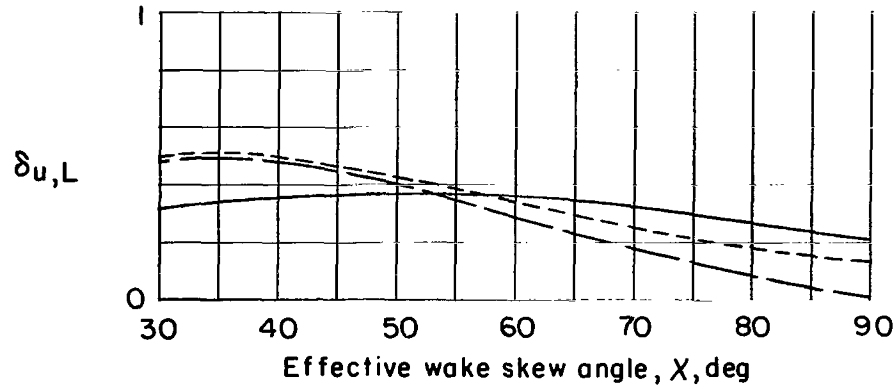


(a) Horizontal interference due to lift.

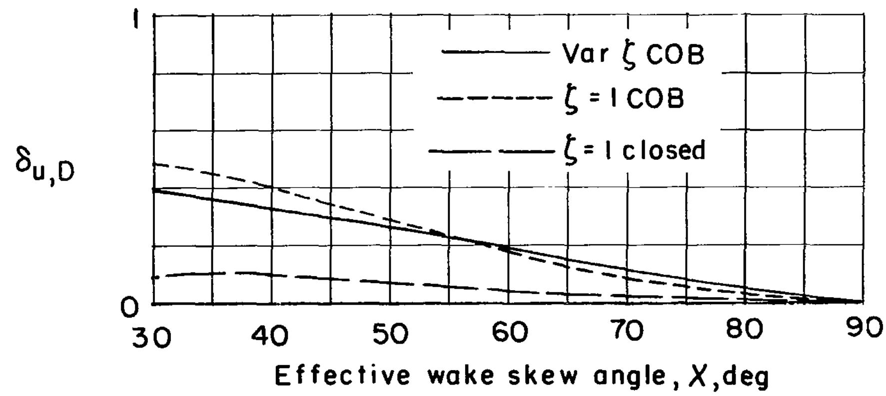
(b) Horizontal interference due to drag.

(c) Vertical interference due to drag.

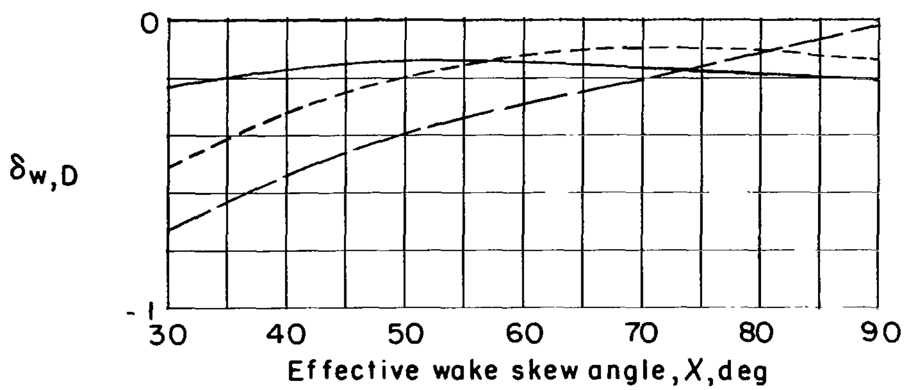
Figure 33.- Residual interference factors for a vanishingly small model in variable and fixed model-height tunnels having a width-height ratio of 1.5.



(a) Horizontal interference due to lift.

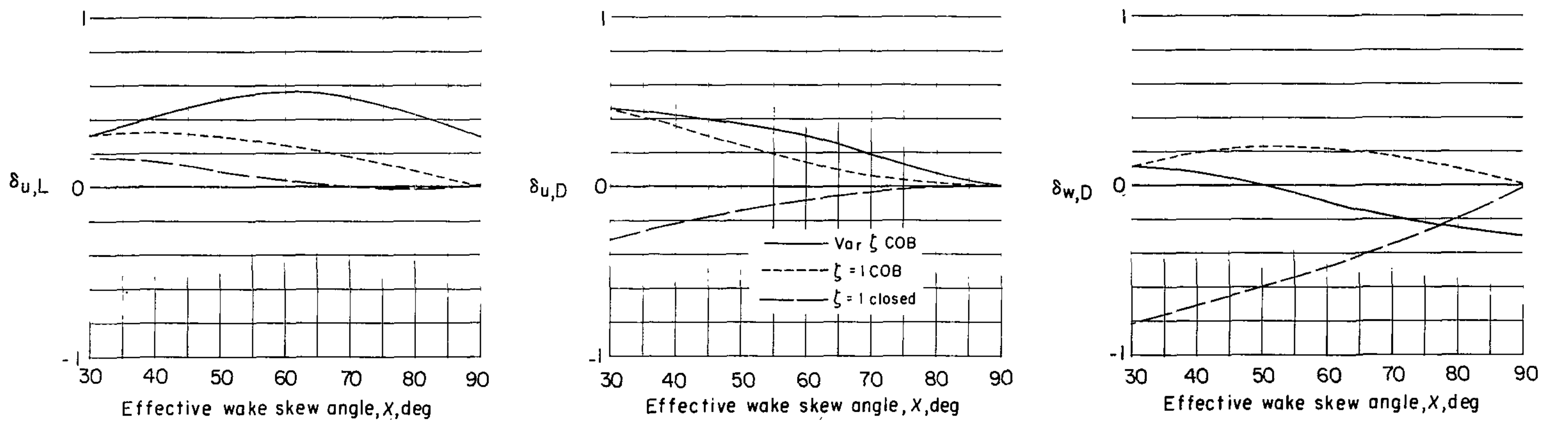


(b) Horizontal interference due to drag.



(c) Vertical interference due to drag.

Figure 34.- Residual interference factors for a vanishingly small model in variable and fixed model-height tunnels having a width-height ratio of 1.0.



(a) Horizontal interference due to lift. (b) Horizontal interference due to drag. (c) Vertical interference due to drag.

Figure 35.- Residual interference factors for a vanishingly small model in variable and fixed model-height tunnels having a width-height ratio of 0.5.

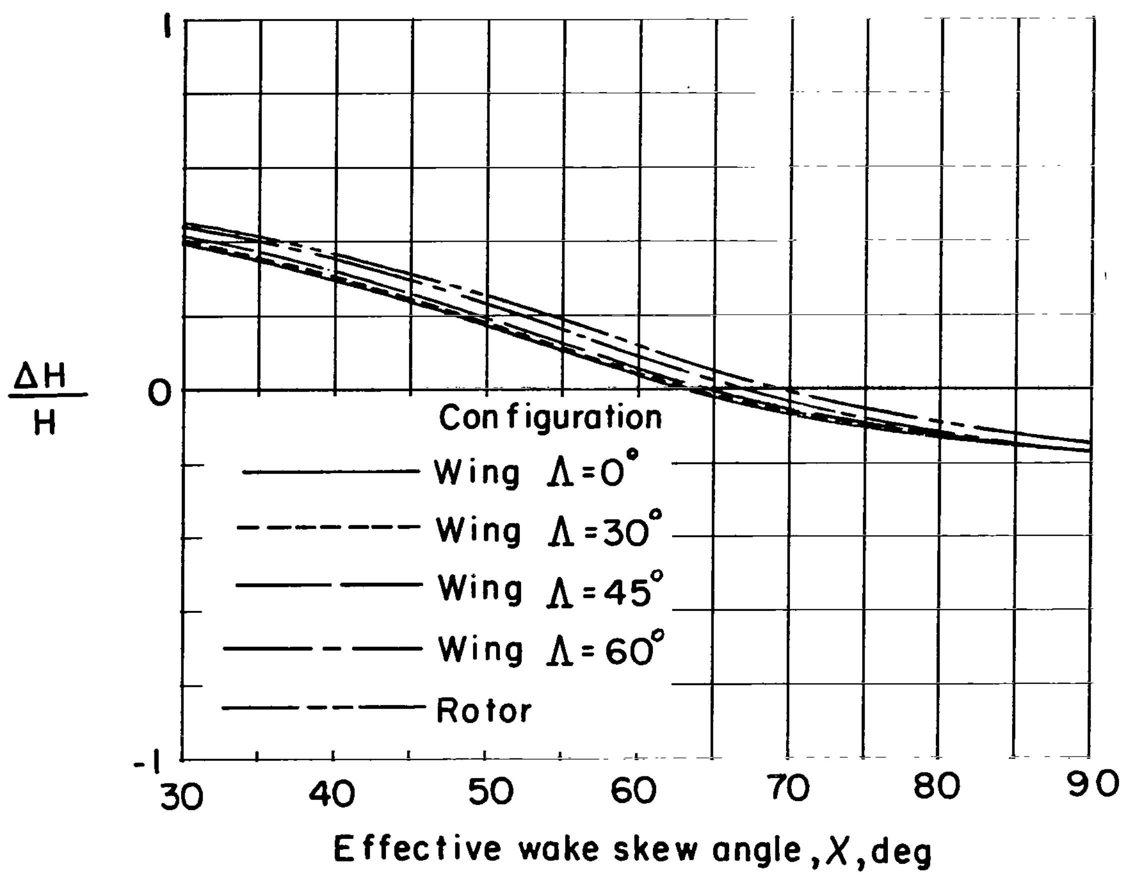
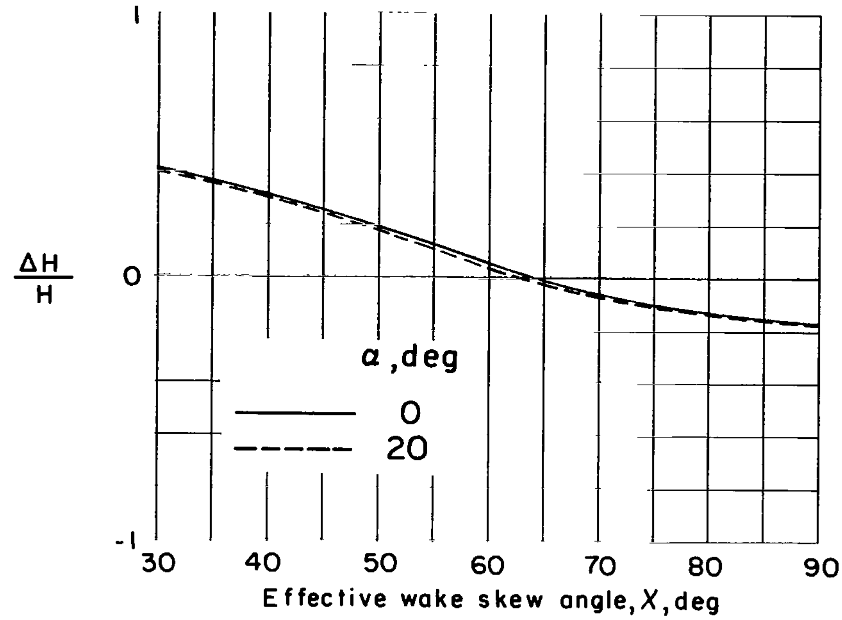
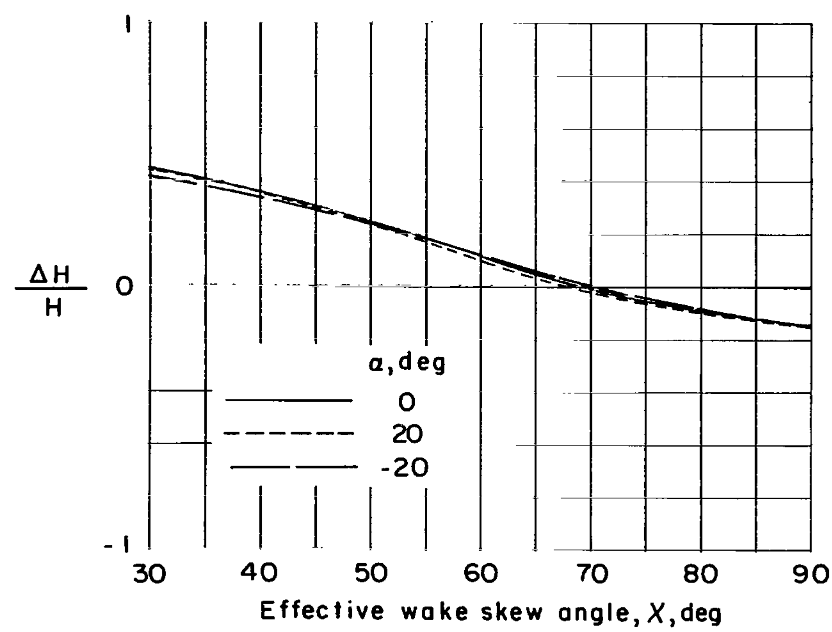


Figure 36.- Effect of model configuration on required schedule of model height for models in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 1.5. $\sigma = 0.5$; $\alpha = 0^{\circ}$.



(a) Wing, $\Lambda = 45^{o}$.



(b) Rotor.

Figure 37.- Effect of angle of attack on required schedule of model height for models in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 1.5. $\sigma = 0.5$.

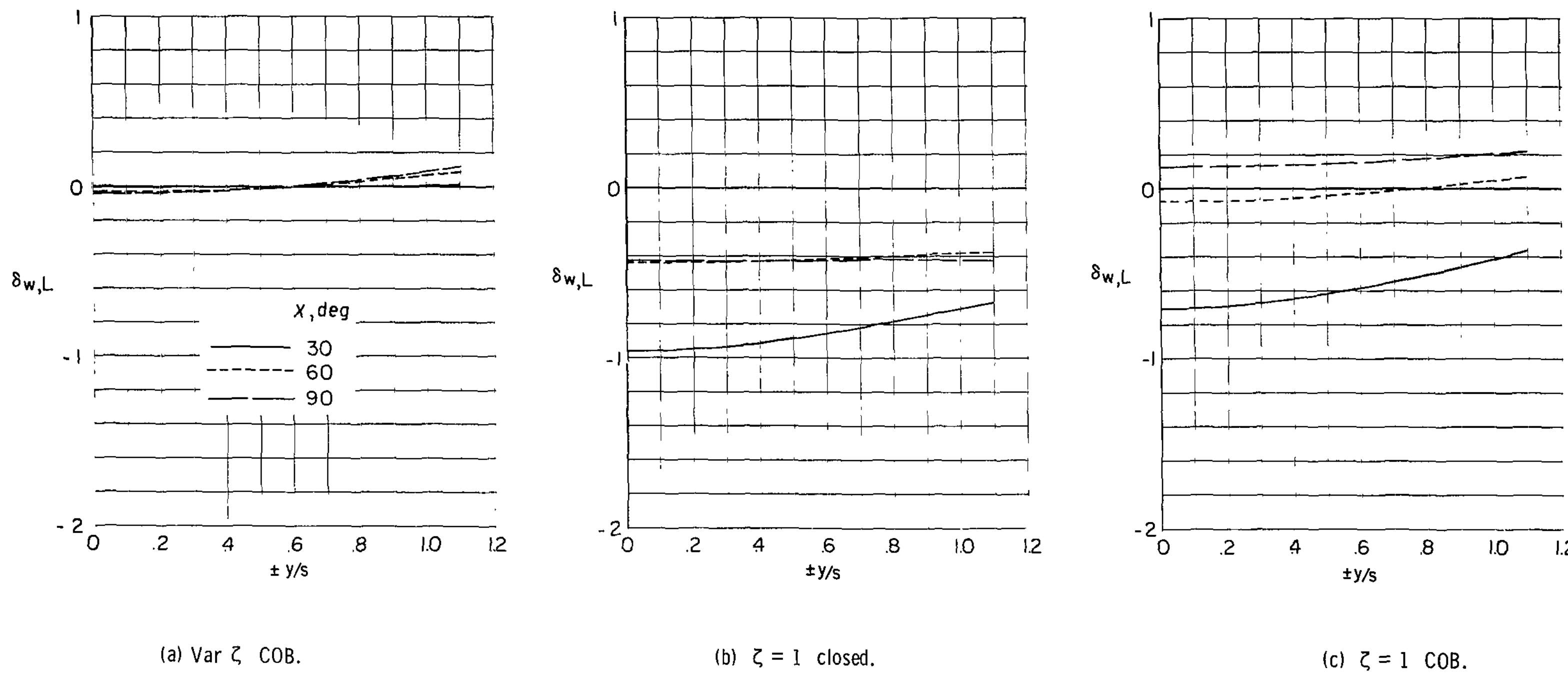
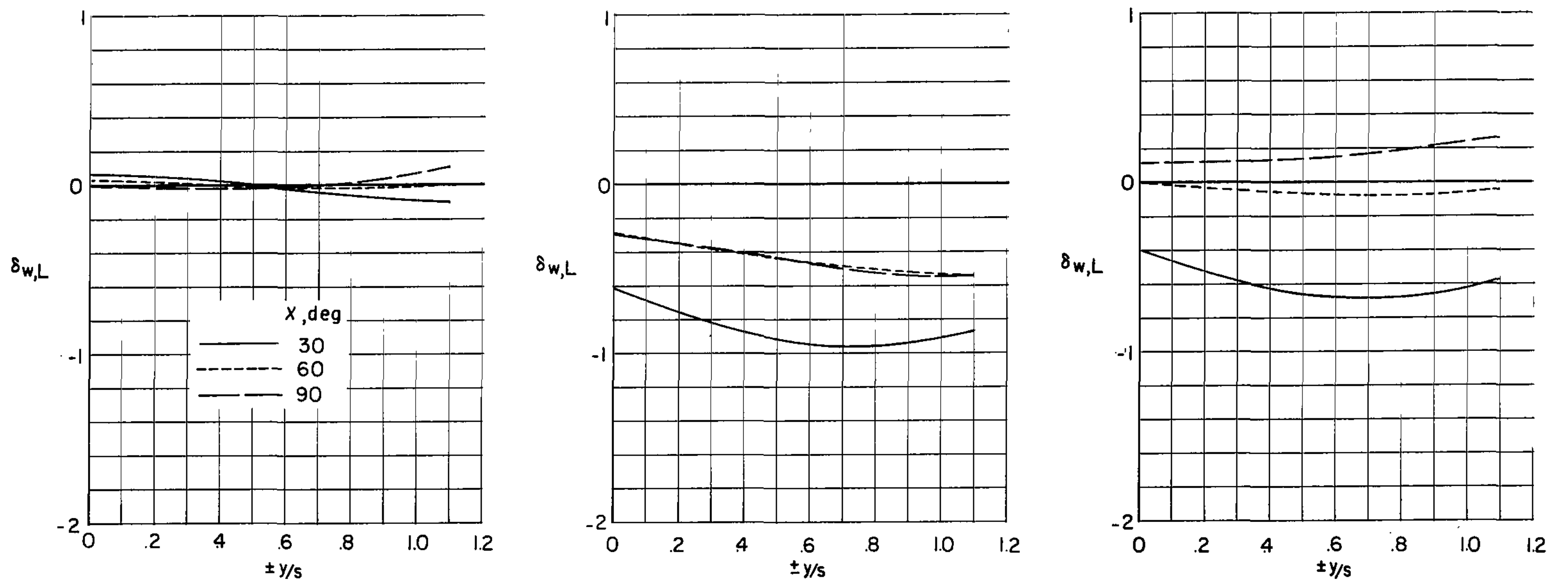
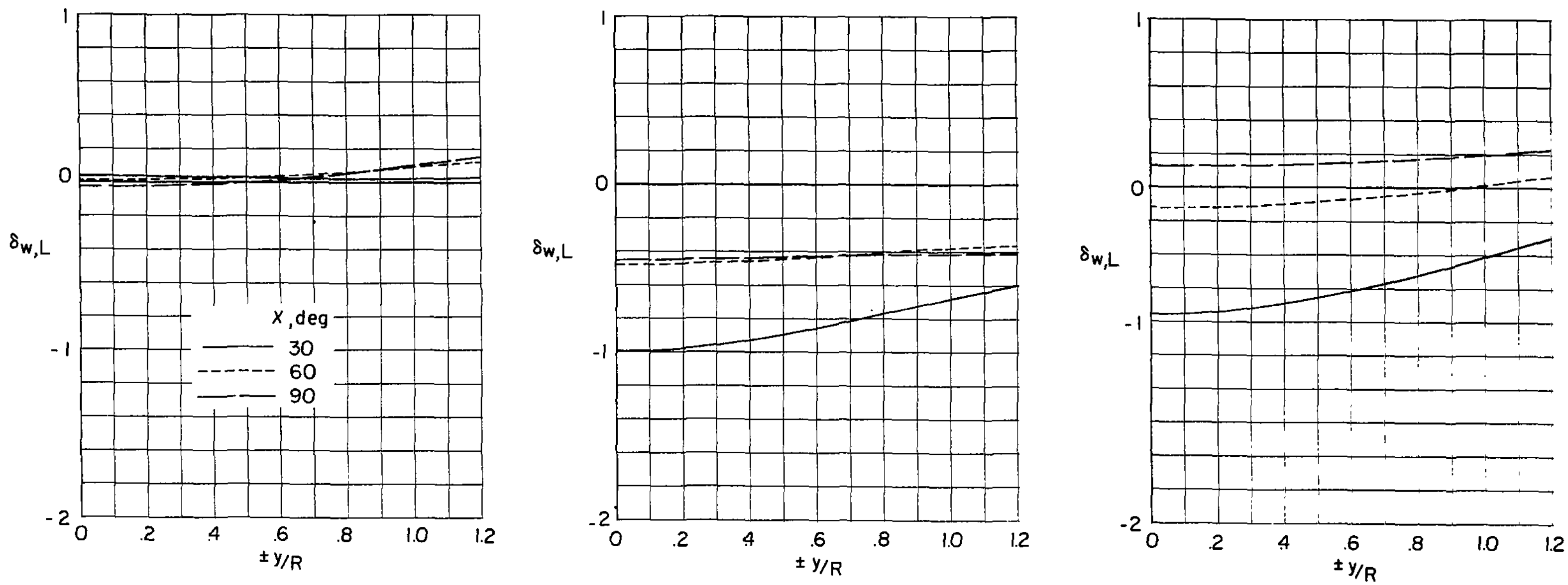


Figure 38.- Spanwise distribution of interference over an unswept wing in variable and fixed model-height closed-on-bottom-only tunnels having a width-height ratio of 1.5. $\sigma = 0.5$; $\alpha = 0^{0}$.



(a) Var ζ COB. (b) $\zeta = 1$ closed. (c) $\zeta = 1$ COB.

Figure 39.- Spanwise distribution of interference over a wing with 45^0 of sweep in variable and fixed model-height closed-on-bottom-only tunnels having a width-height ratio of 1.5. $\sigma = 0.5$; $\alpha = 0^0$.

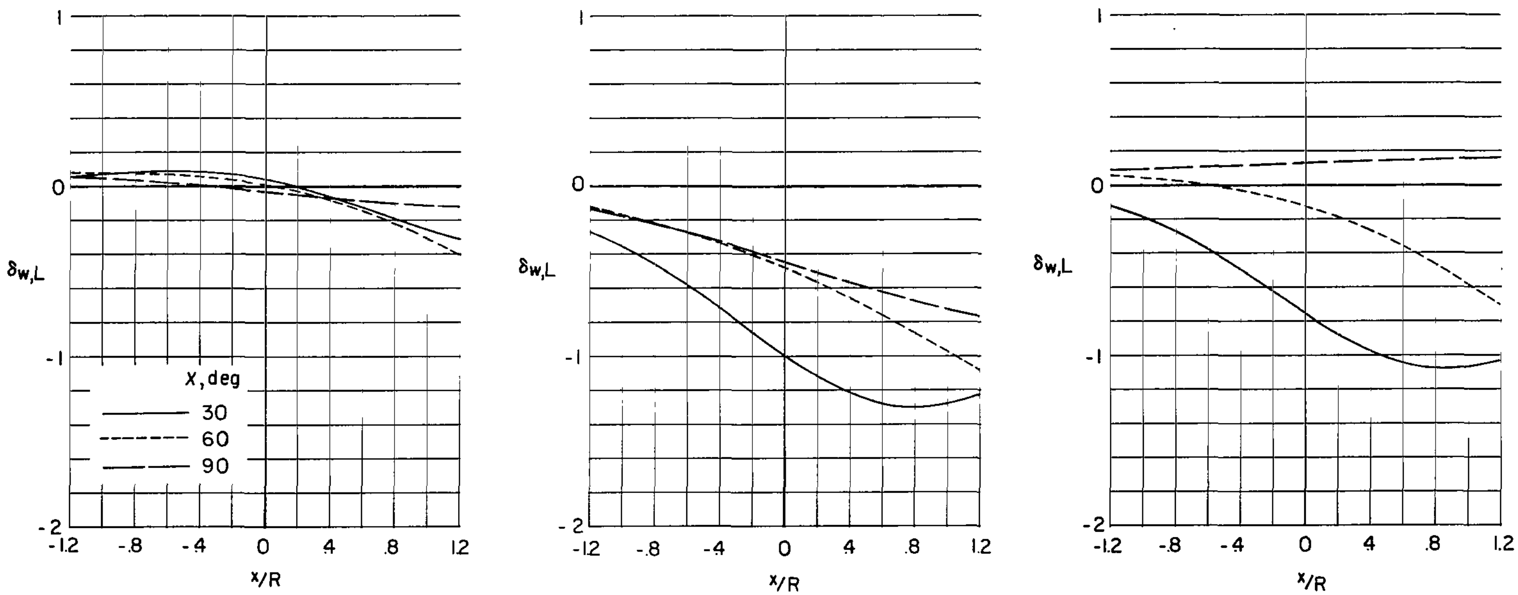


(a) Var ζ COB.

(b) $\zeta = 1$ closed.

(c) $\zeta = 1$ COB.

Figure 40.- Lateral distribution of interference over a rotor in variable and fixed model-height closed-on-bottom-only tunnels having a width-height ratio of 1.5. $\sigma = 0.5$; $\alpha = 0^0$.

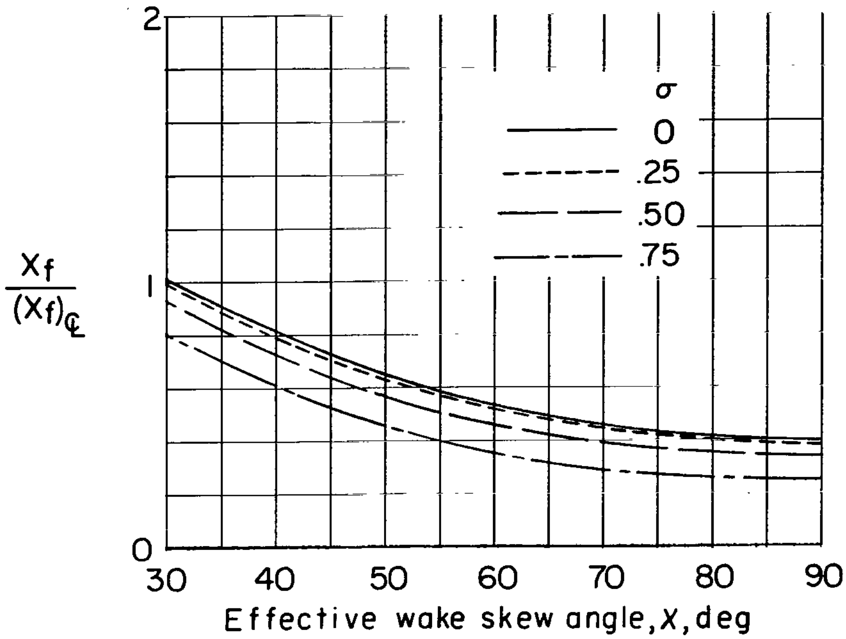


(a) Var ζ COB.

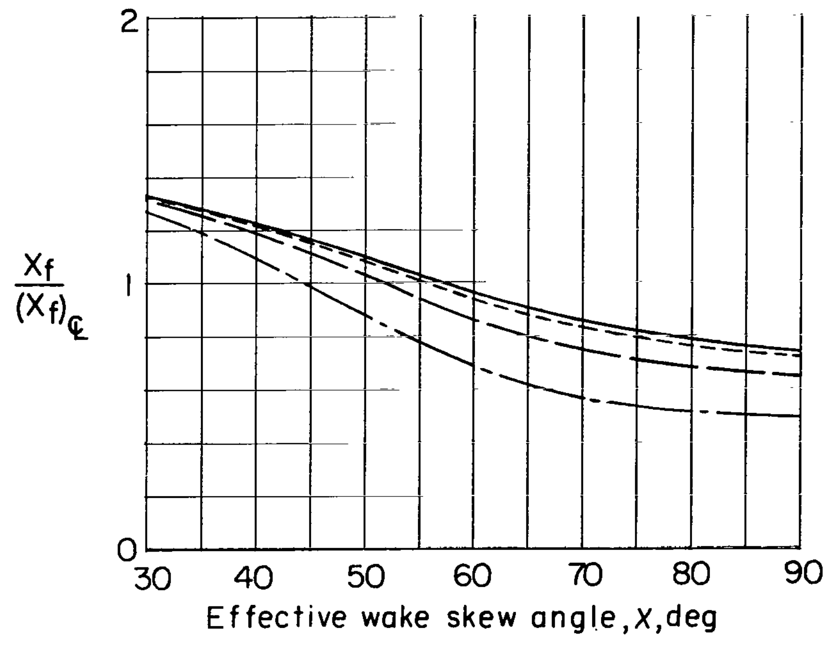
(b) $\zeta = 1$ closed.

(c) $\zeta = 1$ COB.

Figure 41.- Longitudinal distribution of interference over a rotor in variable and fixed model-height closed-on-bottom-only tunnels having a width-height ratio of 1.5. $\sigma = 0.5$; $\alpha = 0^{0}$.

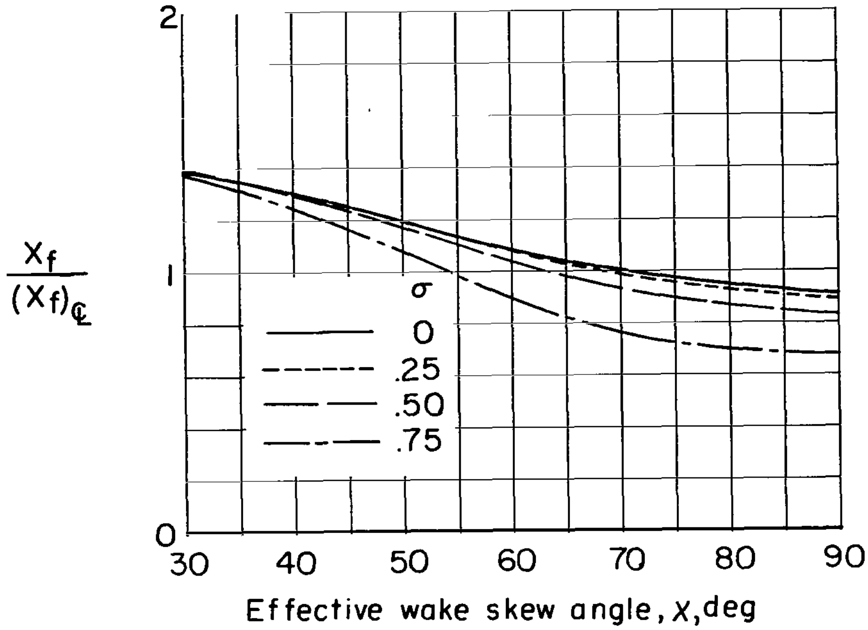


(a) γ = 0.5.

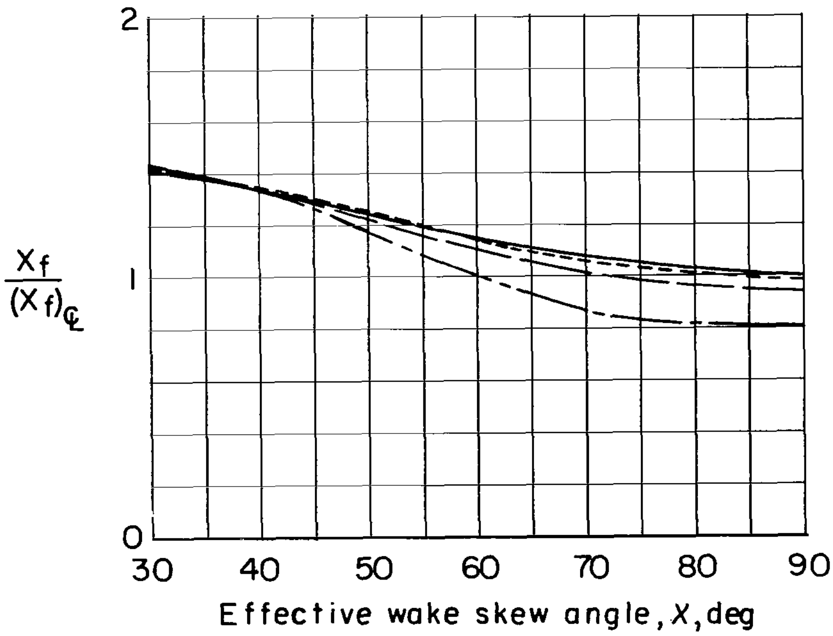


(b) γ = 1.0.

Figure 42.- Relative recirculation in variable model-height closed-on-bottom-only tunnels compared to fixed model-height tunnels of the same width-height ratio. Unswept wings; $\alpha = 0^{0}$.

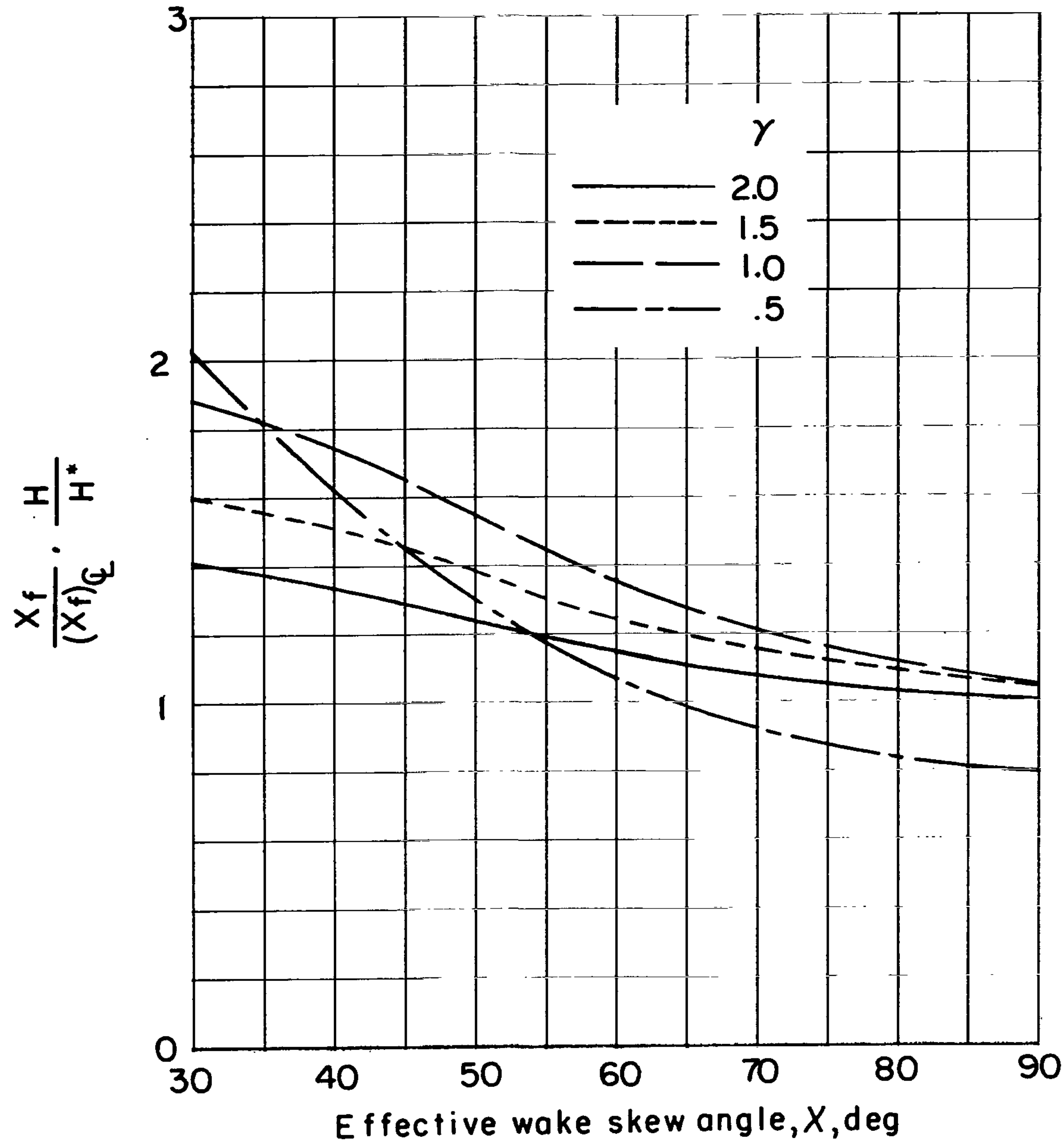


(c) $\gamma = 1.5$.



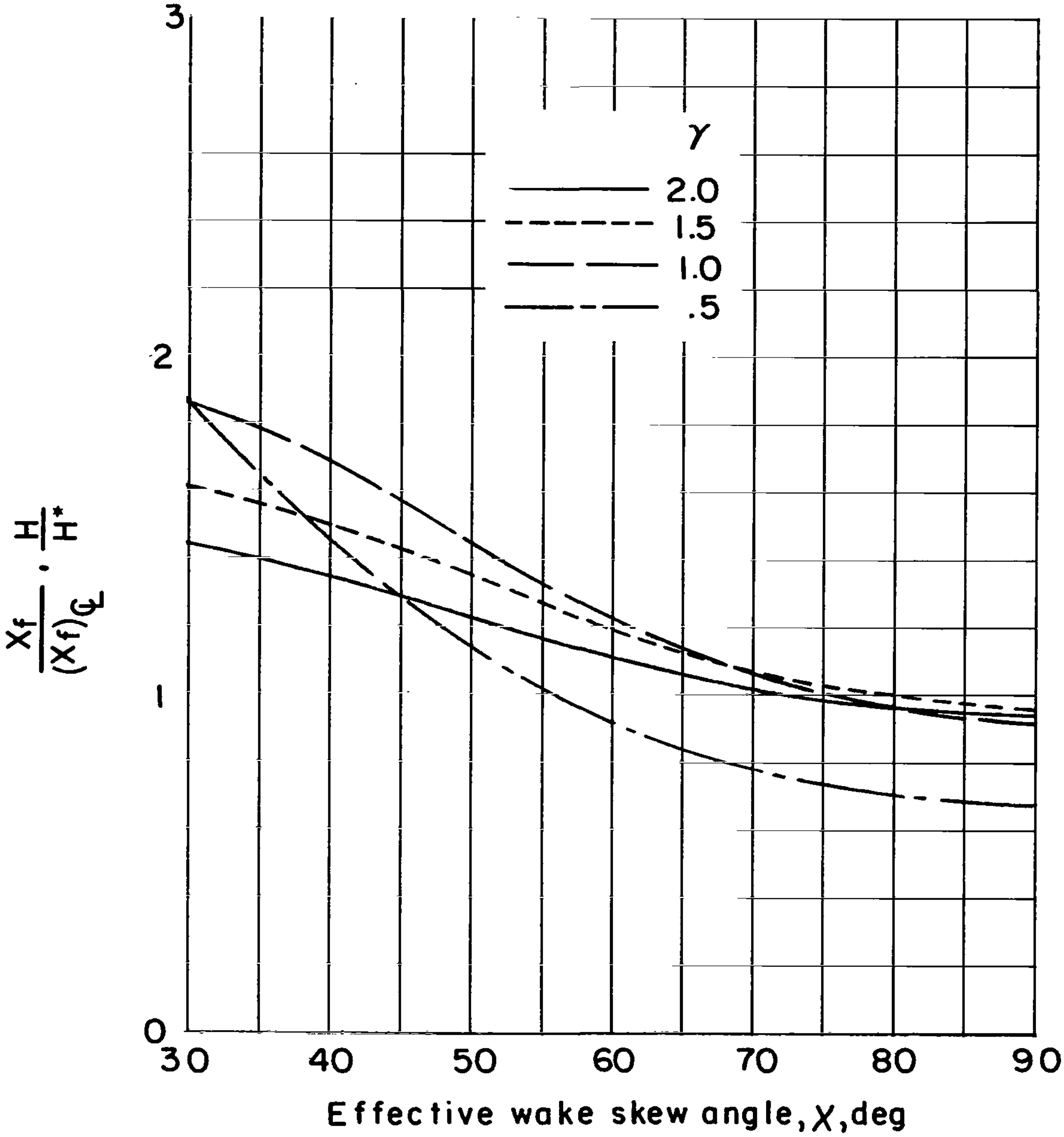
(d) $\gamma = 2.0$.

Figure 42.- Concluded.



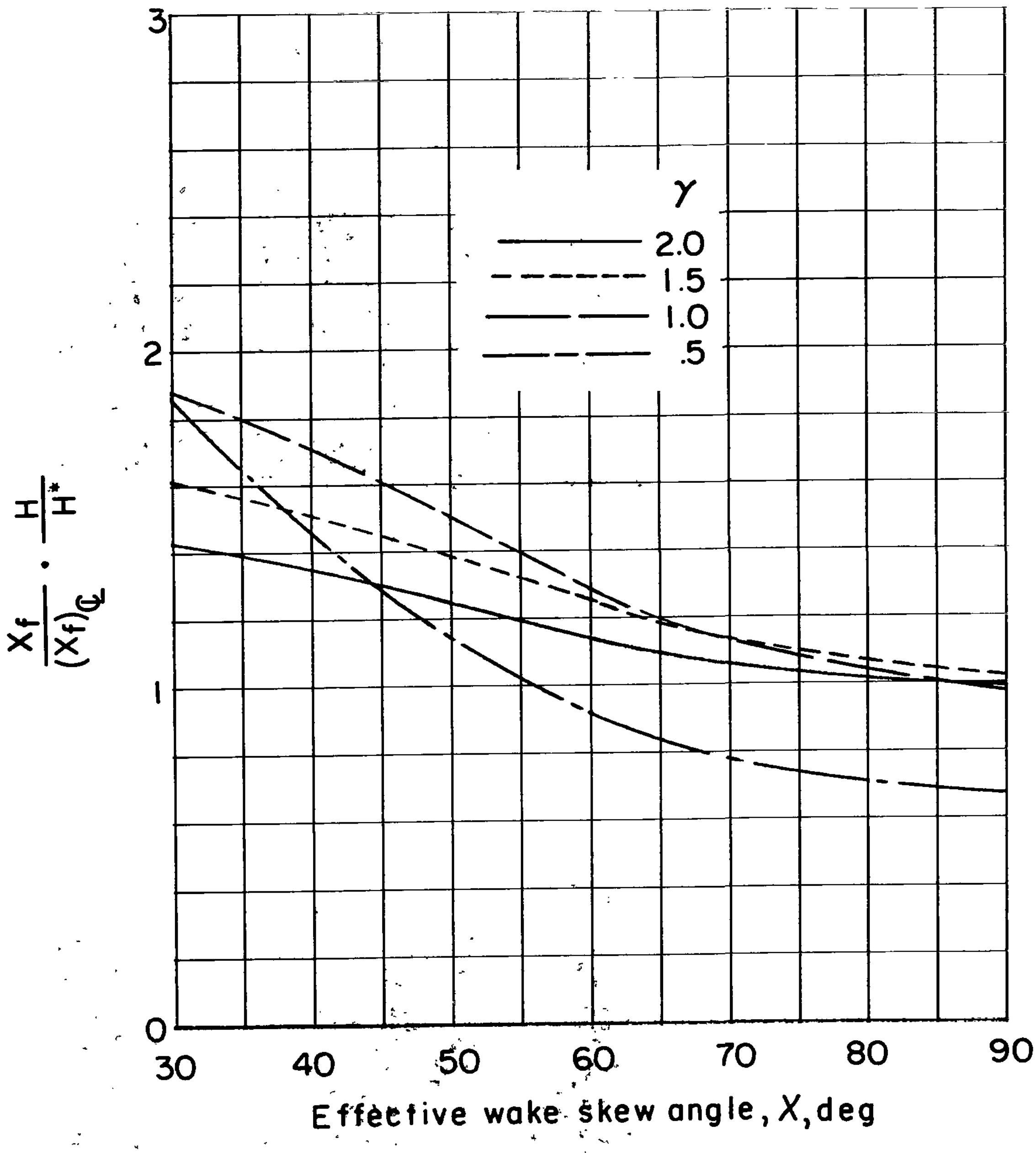
(a) σ = 0.

Figure 43.- Relative recirculation of equal-area variable model-height closed-on-bottom-only tunnels. Reference tunnel has a width-height ratio of 2.0. Unswept wings; α = 0°.



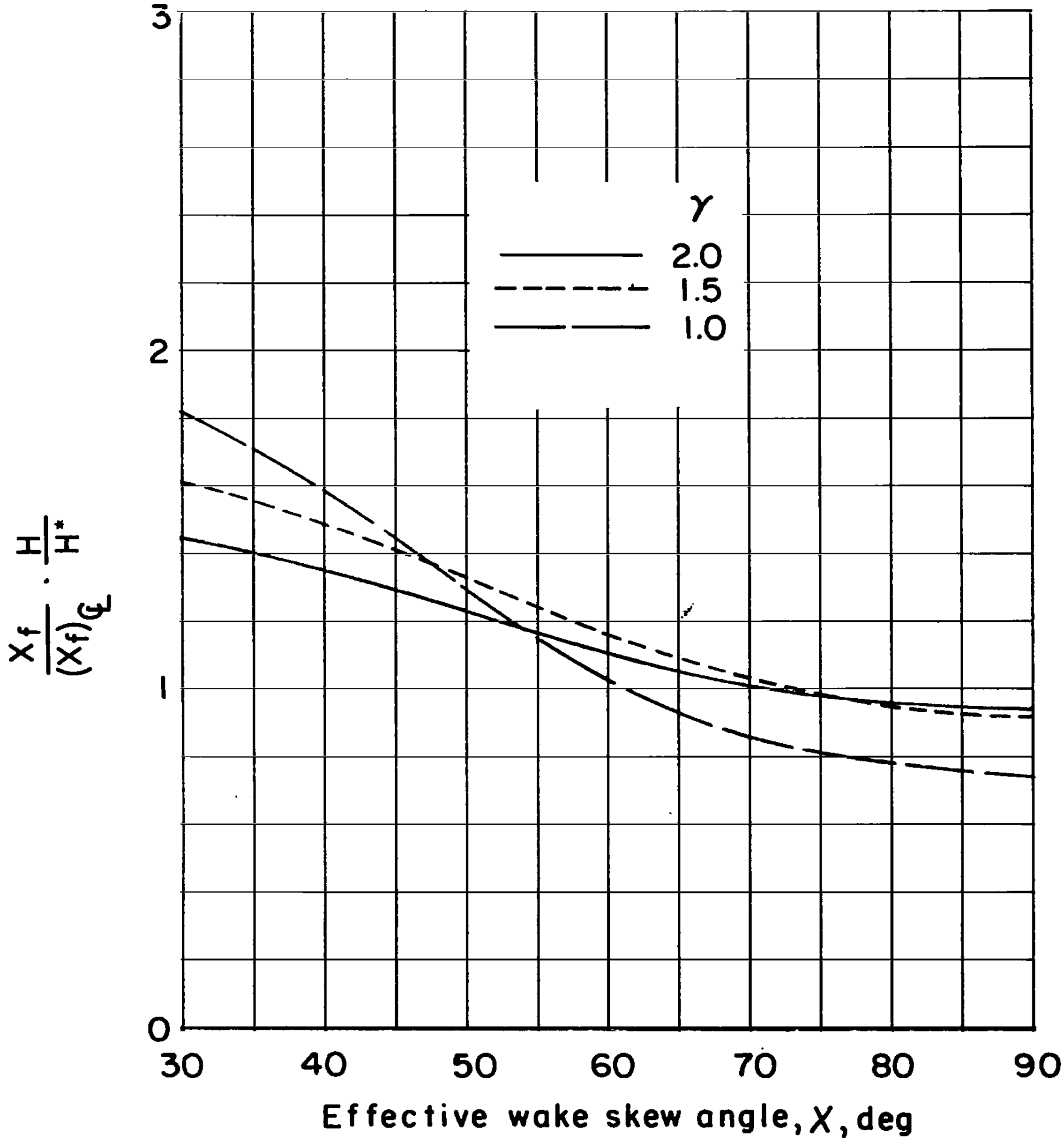
(b) $\sigma = 0.5$.

Figure 43.- Concluded.



(a) $\sigma^* = 0.25$.

Figure 44.- Relative recirculation for fixed physical span unswept wings in equal-area variable model-height closed-on-bottom-only tunnels. Reference tunnel has a width-height ratio of 2.0; $\alpha = 0^0$.



(b) $\sigma^* = 0.5$.

Figure 44.- Concluded.

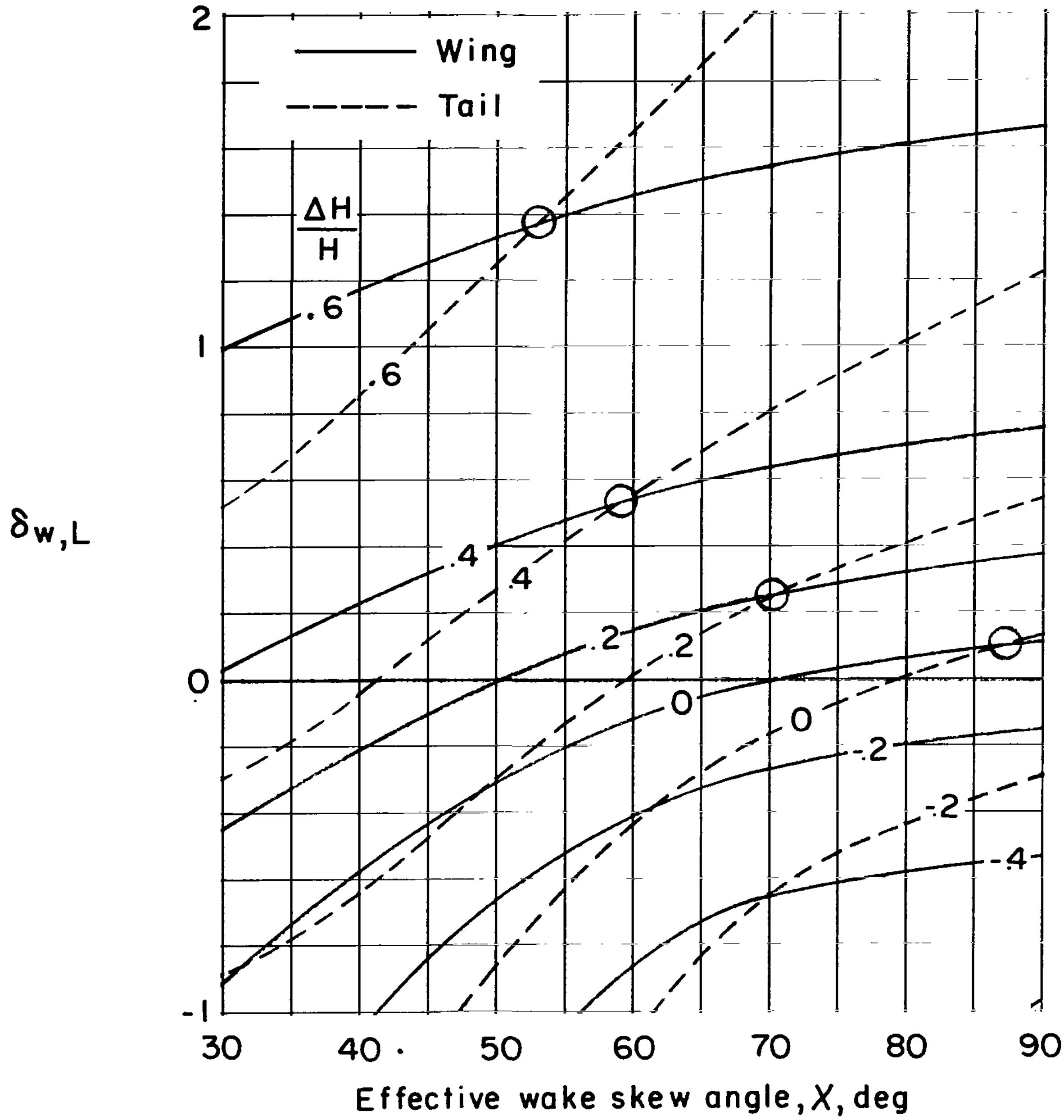
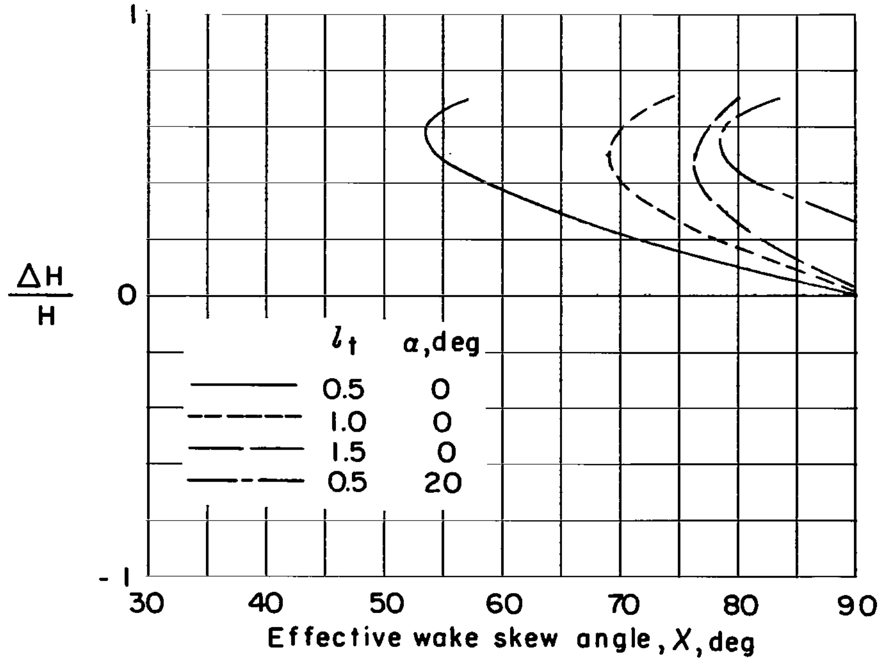
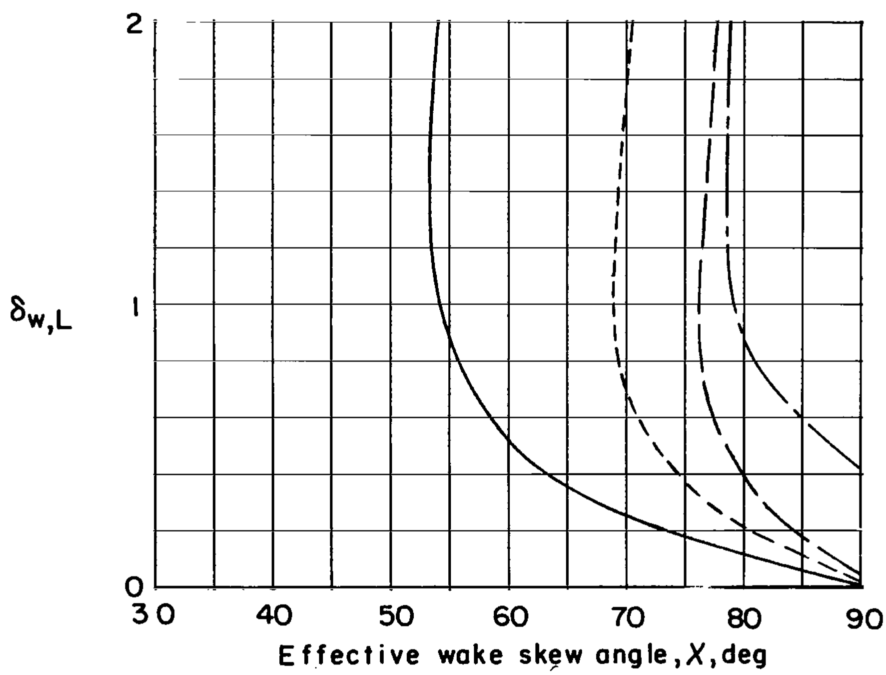


Figure 45.- Illustration of graphical procedure for determining required schedule to reduce $\Delta\delta_{w,L}$ to zero in a variable model-height closed-on-bottom-only tunnel. $\gamma = 1.5$; $\sigma = \sigma_t = 0$; $\alpha = 0^0$; $\frac{l_t}{H} = 0.5$.

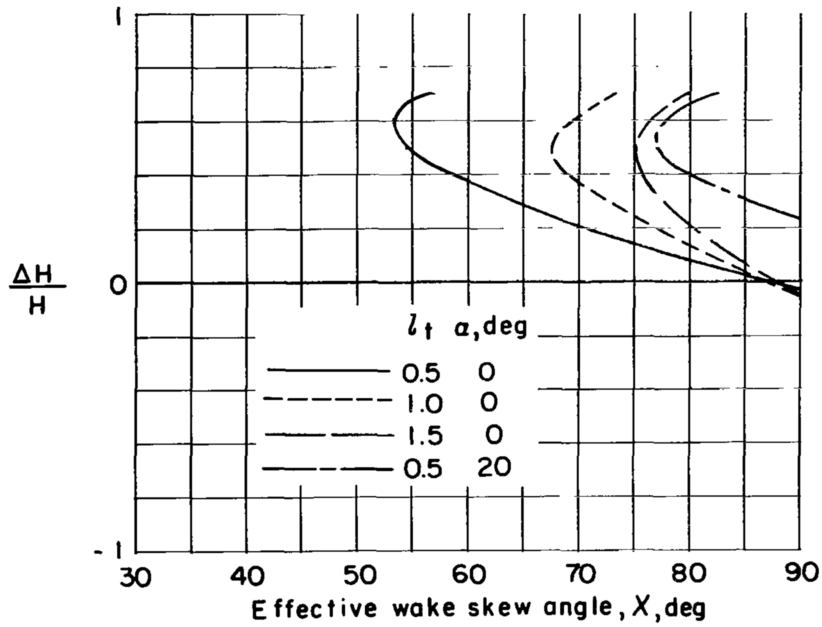


(a) Required schedule for $\Delta\delta_{w,L} = 0$.

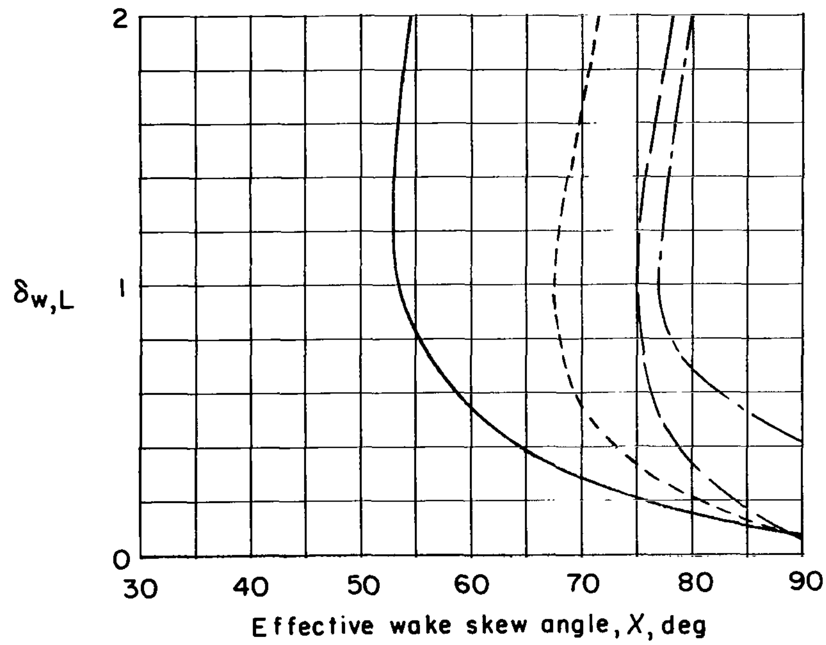


(b) Interference factors.

Figure 46.- Required schedule and resultant interference factors to reduce $\Delta\delta_{w,L}$ to zero in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 2.0. $\sigma = \sigma_t = 0$.

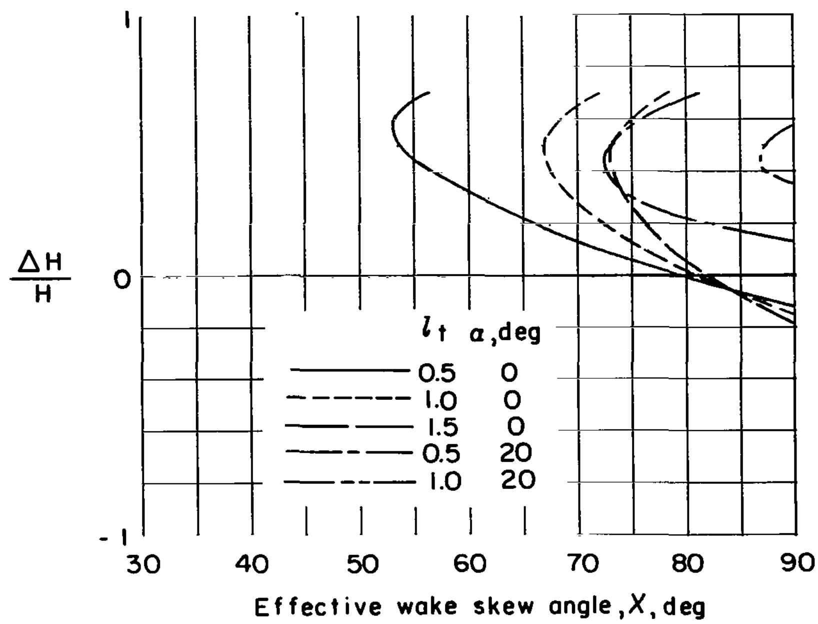


(a) Required schedule for $\Delta\delta_{w,L} = 0$.

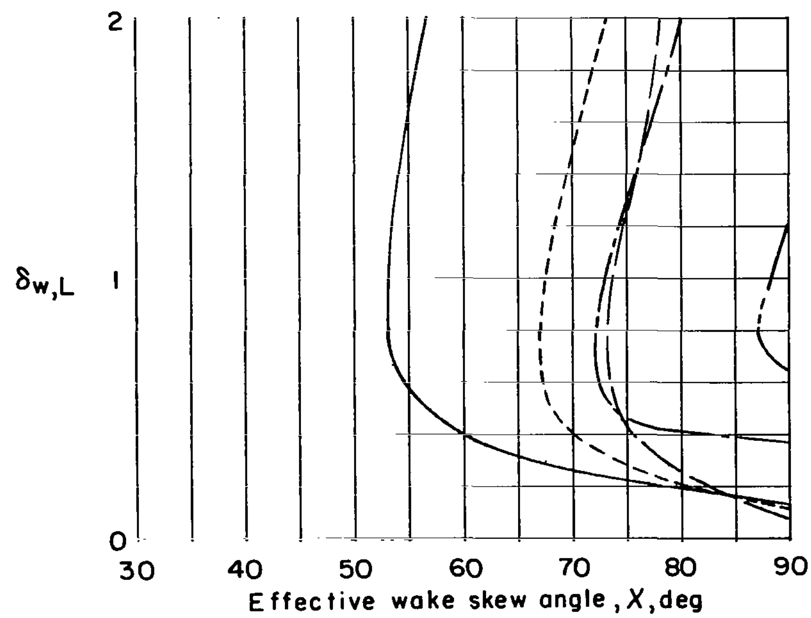


(b) Interference factors.

Figure 47.- Required schedule and resultant interference factors to reduce $\Delta\delta_{w,L}$ to zero in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 1.5. $\sigma = \sigma_t = 0$.

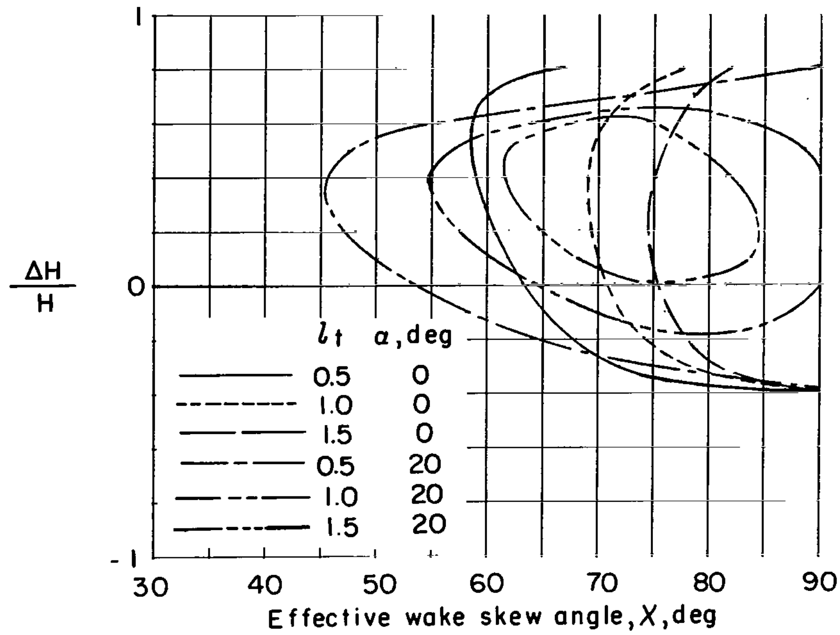


(a) Required schedule for $\Delta\delta_{w,L} = 0$.

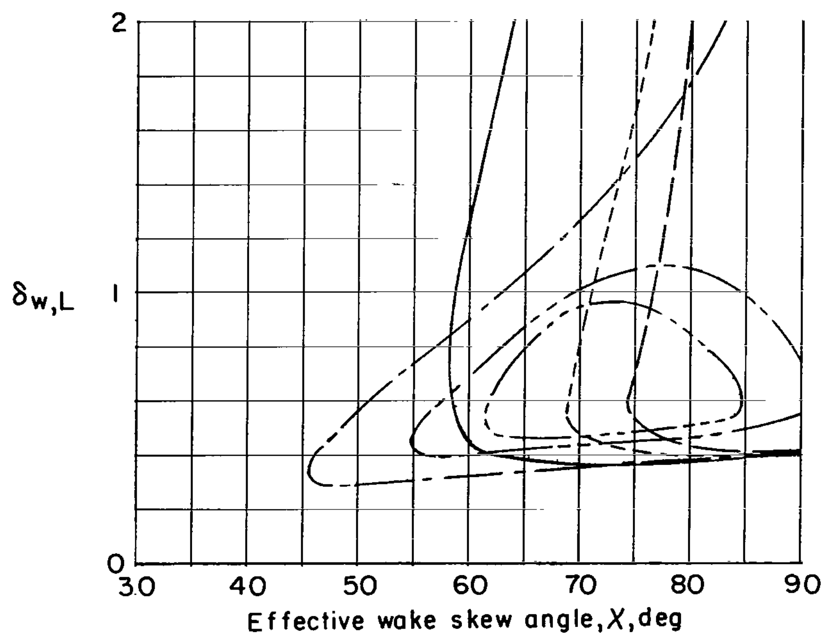


(b) Interference factors.

Figure 48.- Required schedule and resultant interference factors to reduce $\Delta\delta_{w,L}$ to zero in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 1.0. $\sigma = \sigma_t = 0$.

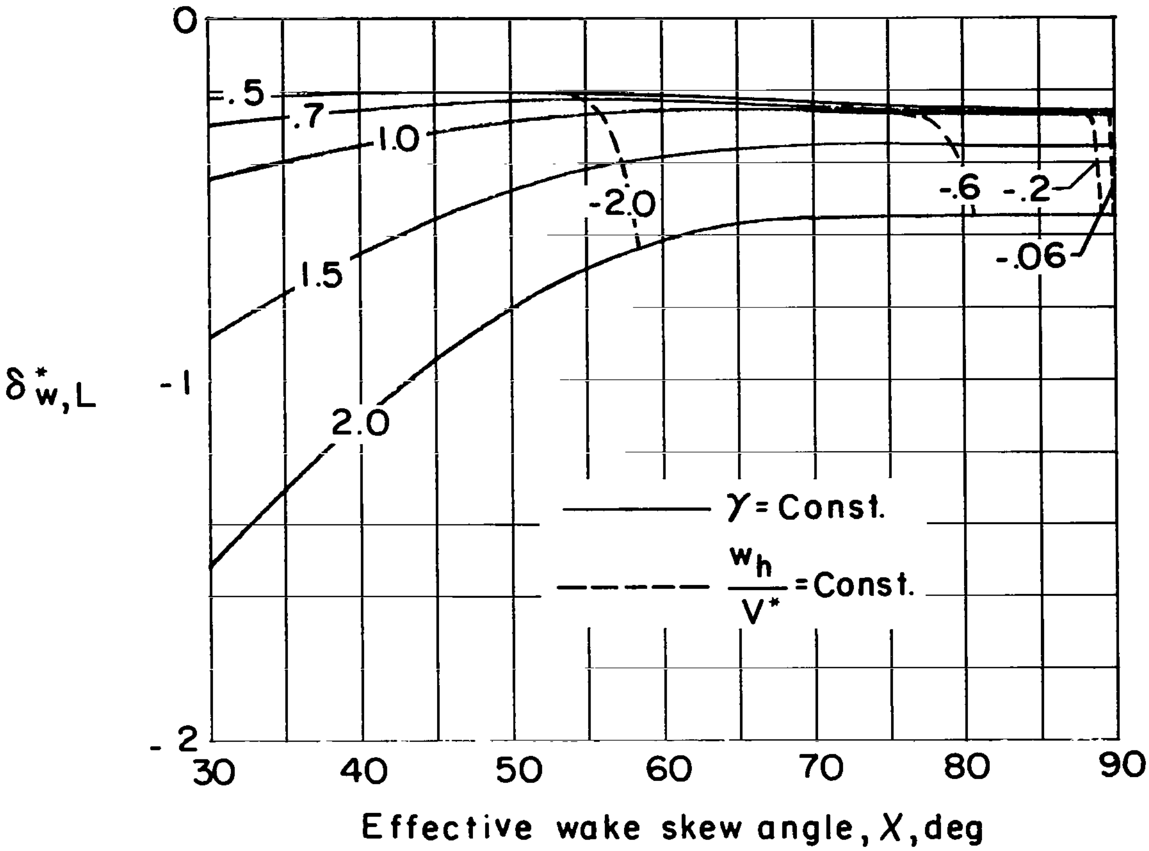


(a) Required schedule for $\Delta\delta_{w,L} = 0$.



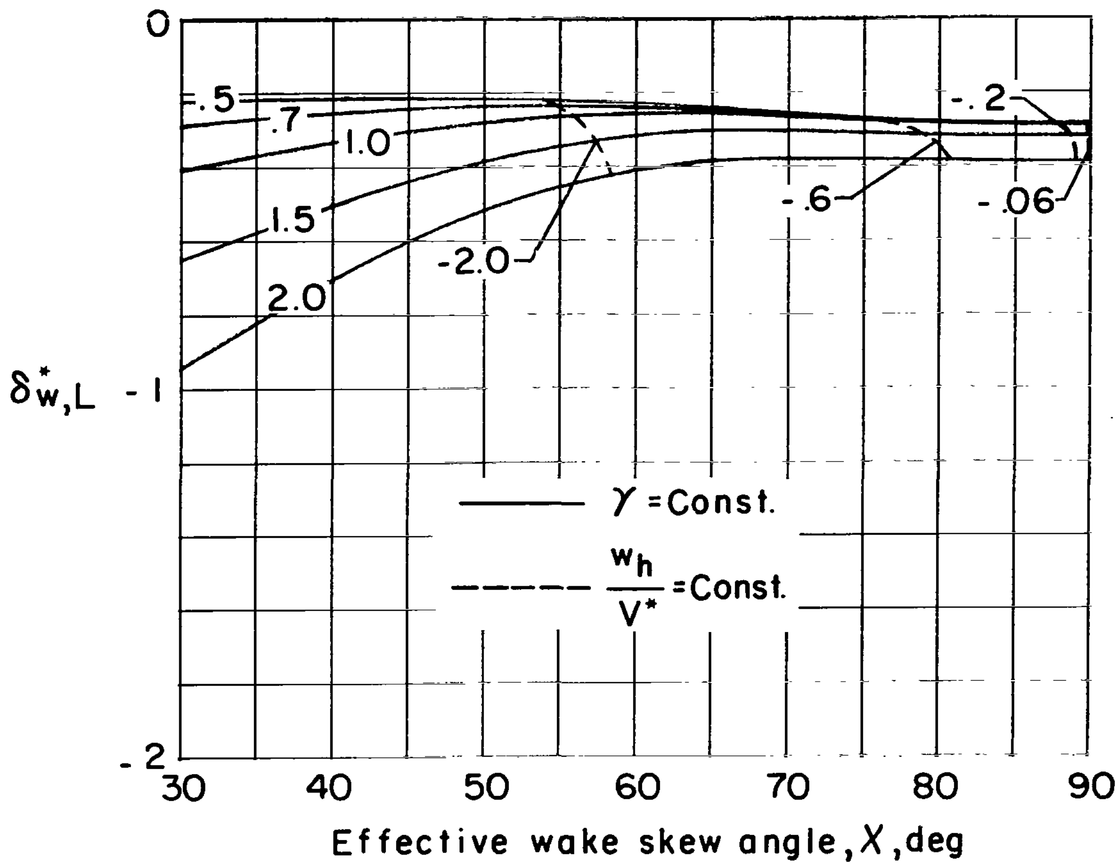
(b) Interference factors.

Figure 49.- Required schedule and resultant interference factors to reduce $\Delta\delta_{w,L}$ to zero in a variable model-height closed-on-bottom-only tunnel having a width-height ratio of 0.5. $\sigma = \sigma_t = 0$.



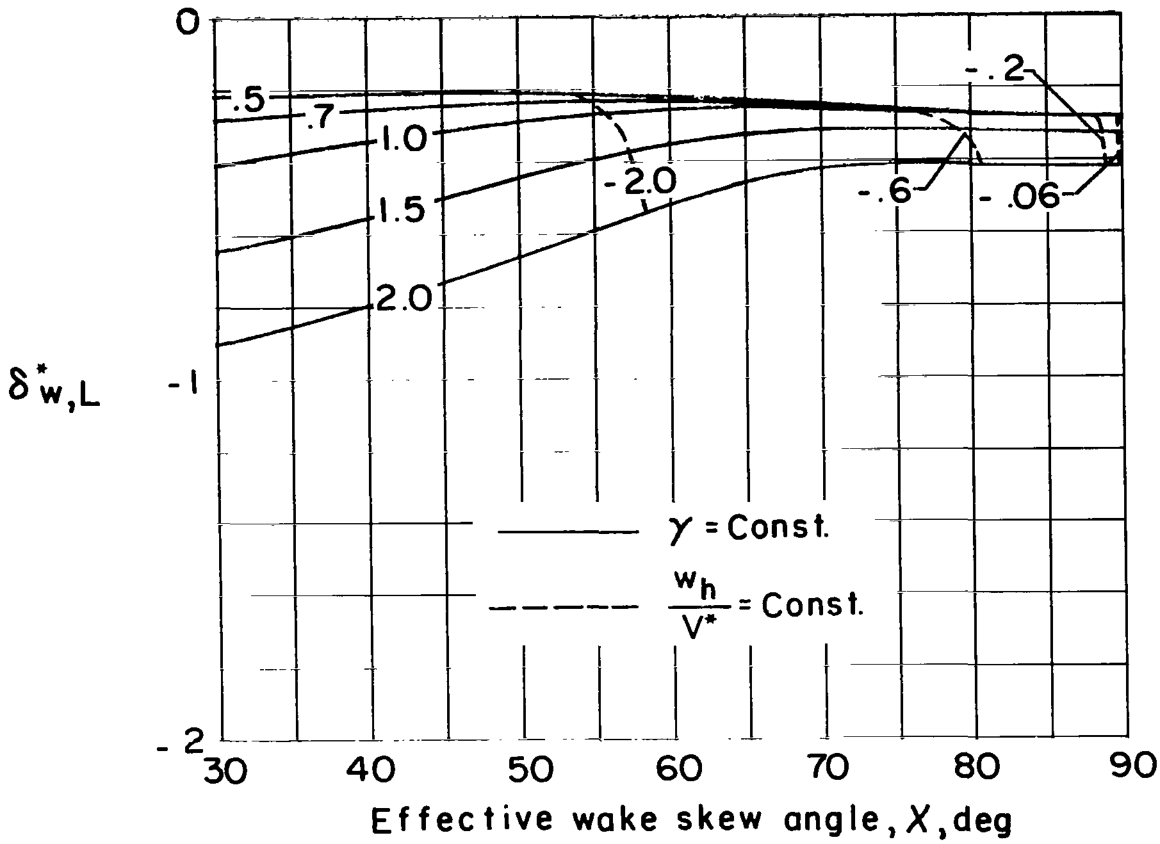
(a) $\sigma = 0$.

Figure 50.- Interference factors in a variable width-height-ratio closed tunnel.



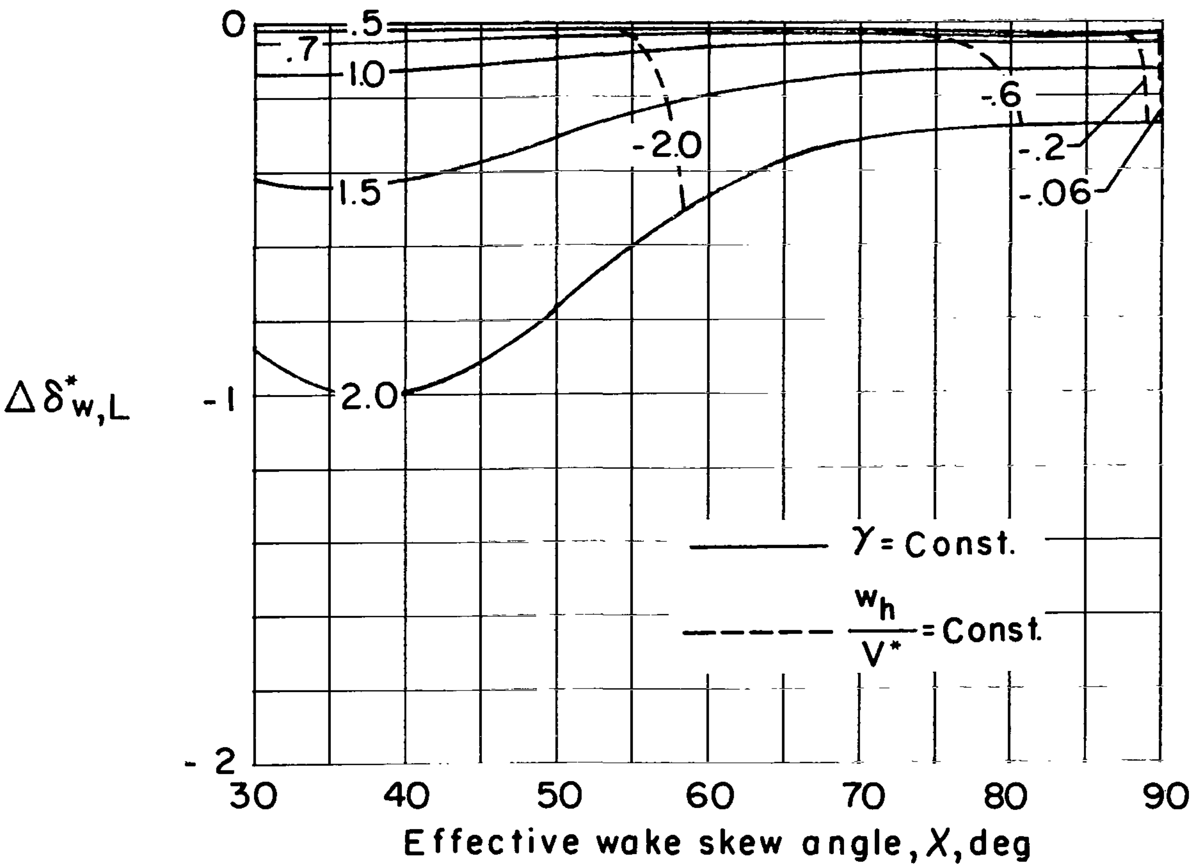
(b) Wing, $\sigma = 0.5$.

Figure 50.- Continued.



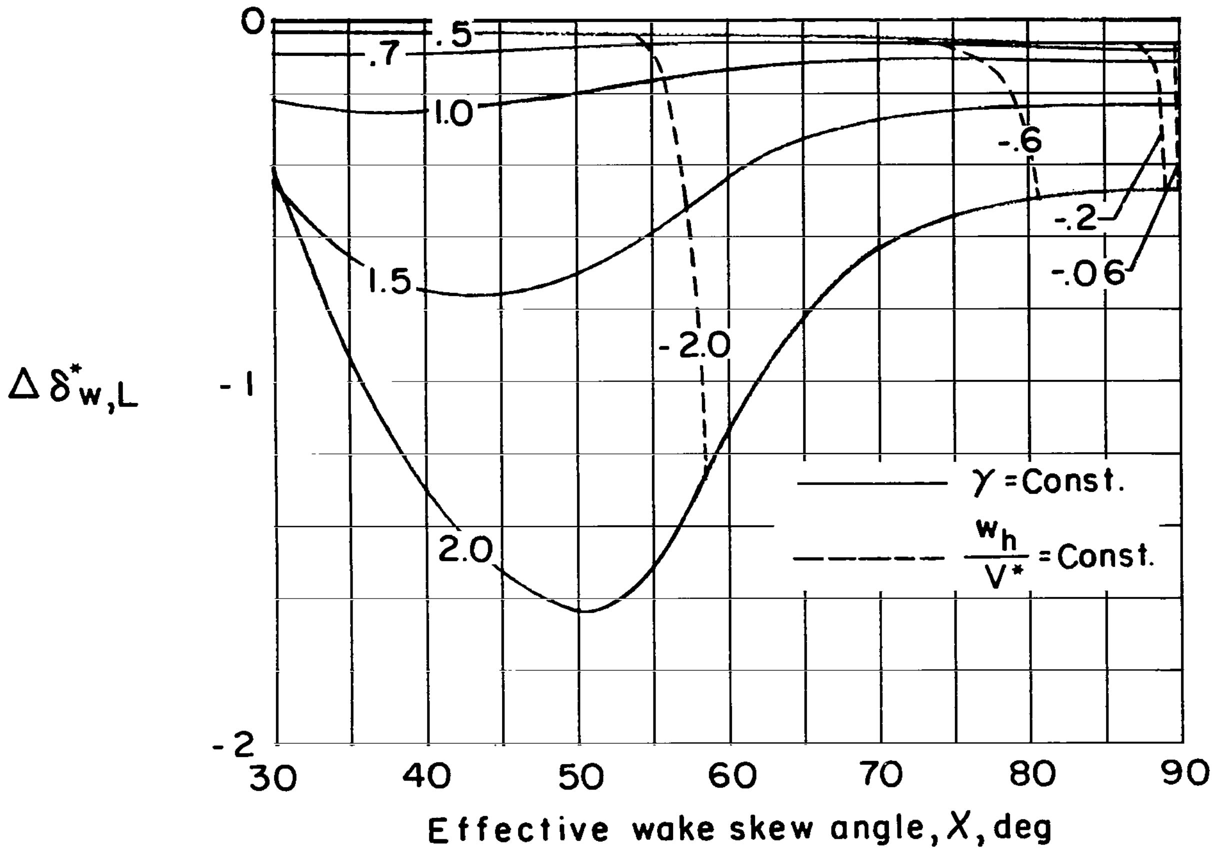
(c) Rotor, $\sigma = 0.5$.

Figure 50.- Concluded.



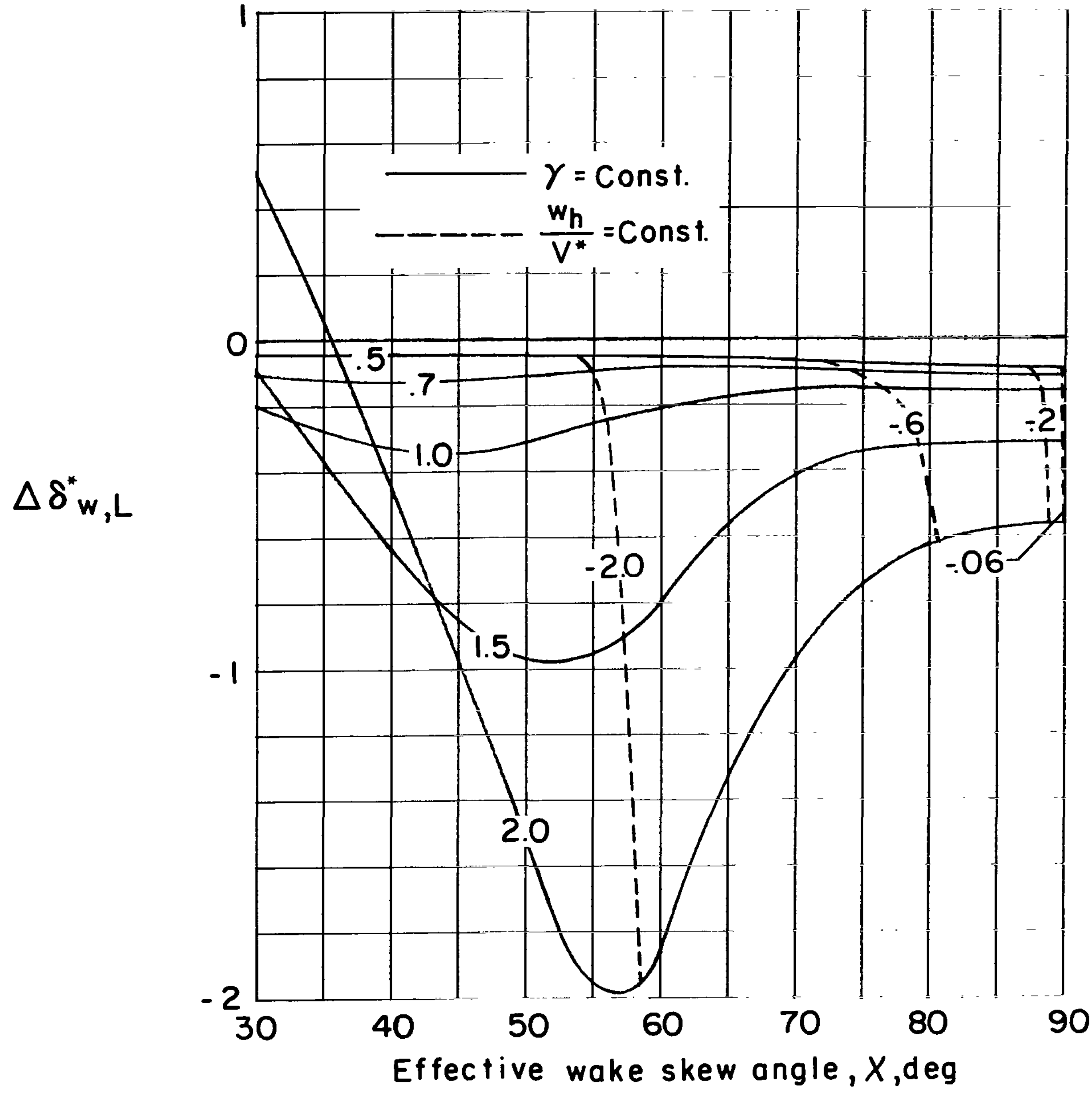
(a) $\frac{l_t}{H^*} = 0.5.$

Figure 51.- Difference in interference factors at wing and tail in a variable width-height-ratio closed tunnel. $\sigma = \sigma_t = 0$; $\alpha = 0^o$.



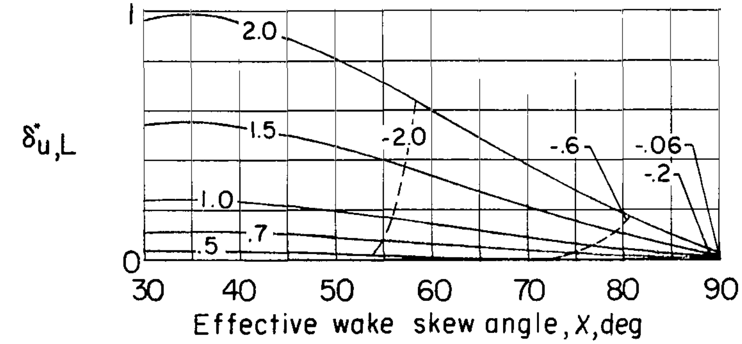
(b) $\frac{l_t}{H^*} = 1.0.$

Figure 51.- Continued.

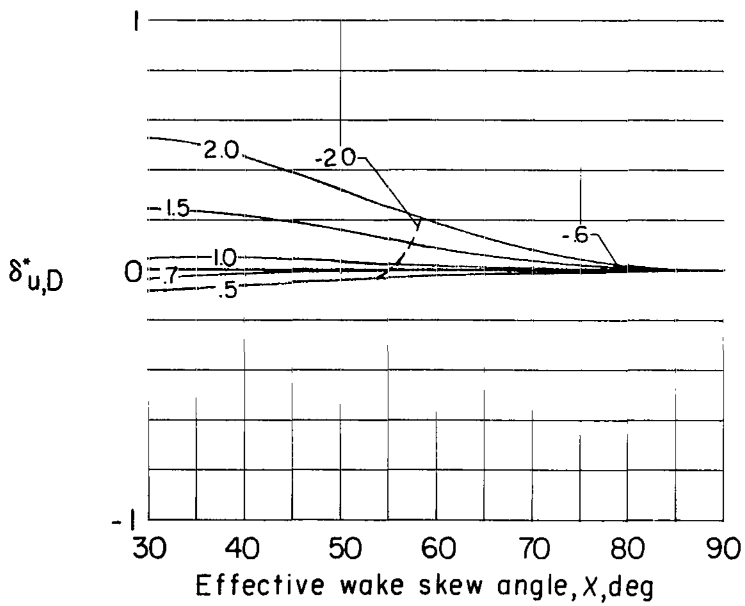


(c) $\frac{l_t}{H^*} = 1.5.$

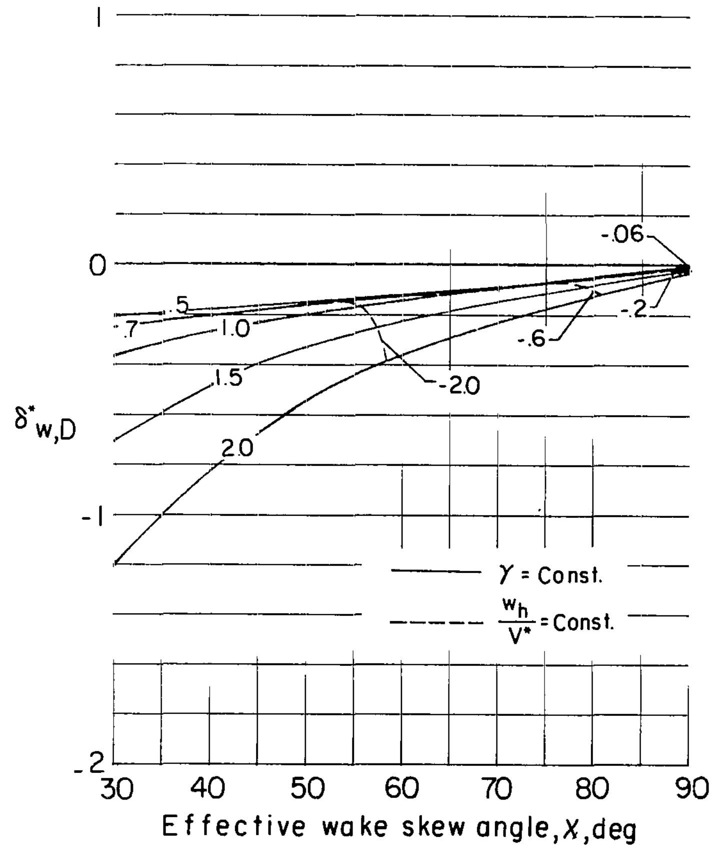
Figure 51.- Concluded.



(a) Horizontal interference due to lift.

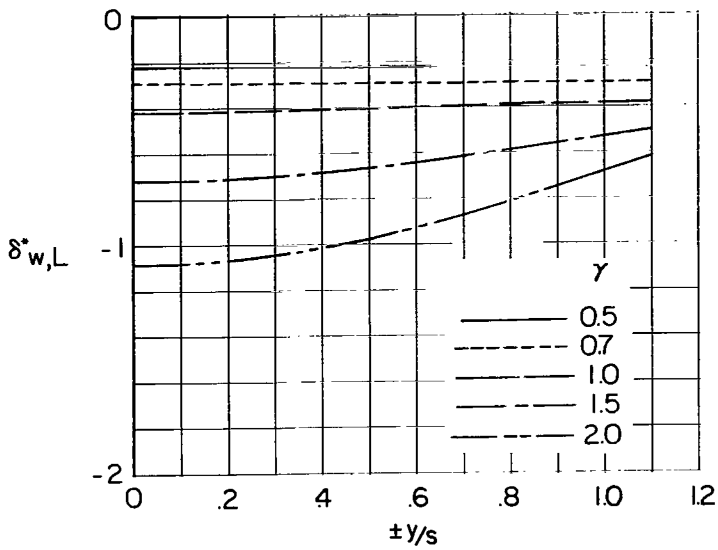


(b) Horizontal interference due to drag.

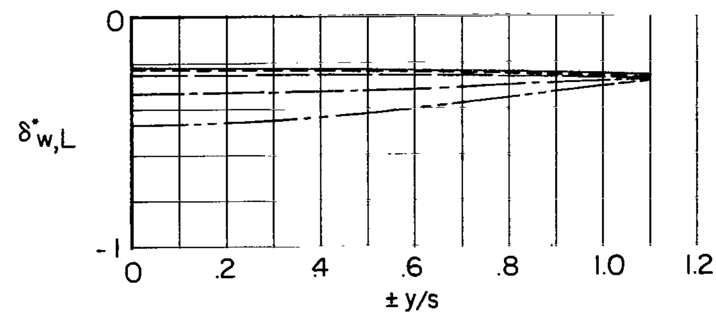


(c) Vertical interference due to drag.

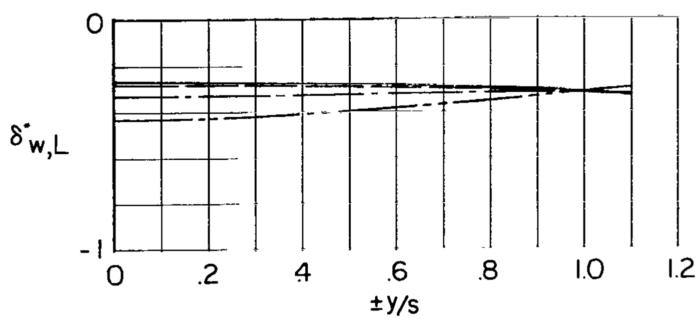
Figure 52.- Residual interference factors for a vanishingly small model centered in a variable width-height-ratio closed tunnel.



(a) $\chi = 30^0$.

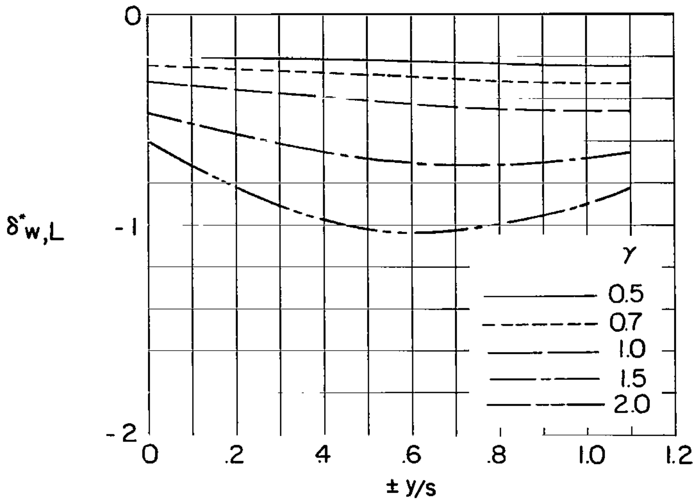


(b) $\chi = 60^0$.

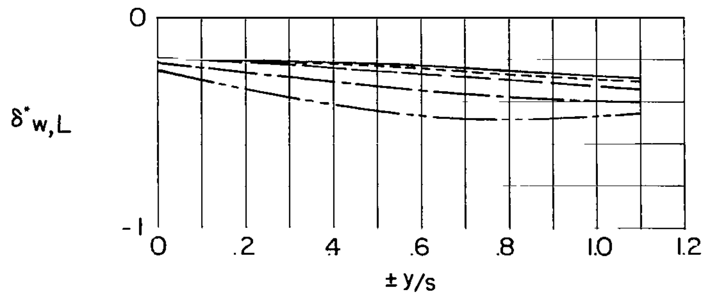


(c) $\chi = 90^0$.

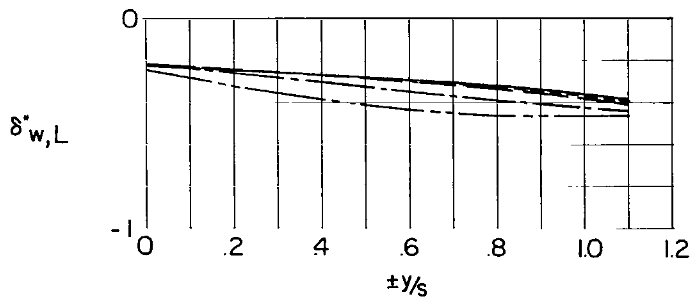
Figure 53.- Spanwise distribution of interference over an unswept wing centered in a variable width-height-ratio closed tunnel. $\sigma = 0.5$; $\alpha = 0^0$.



(a) $\chi = 30^0$.

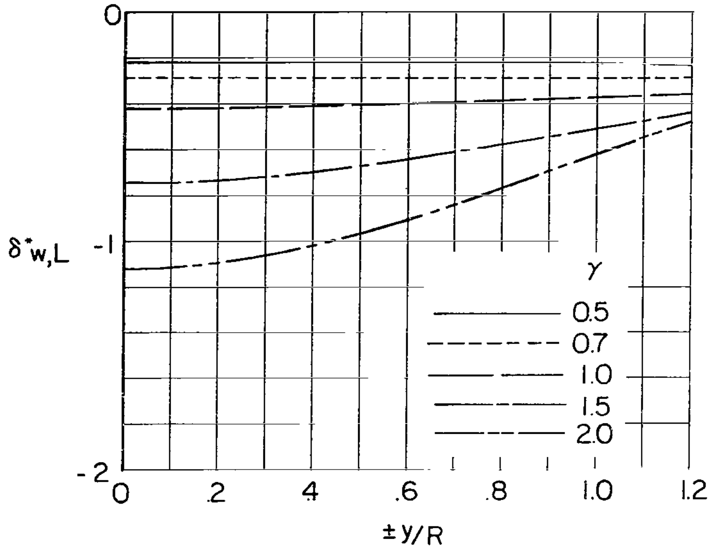


(b) $\chi = 60^0$.

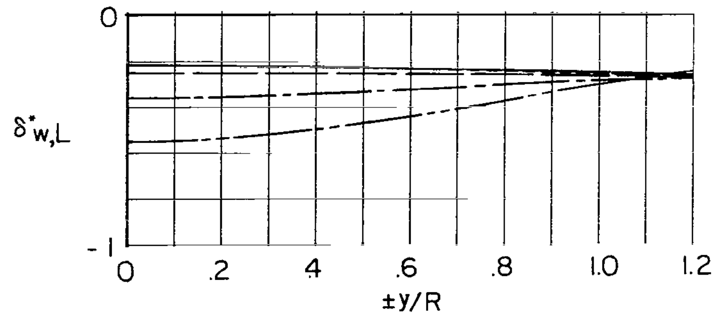


(c) $\chi = 90^0$.

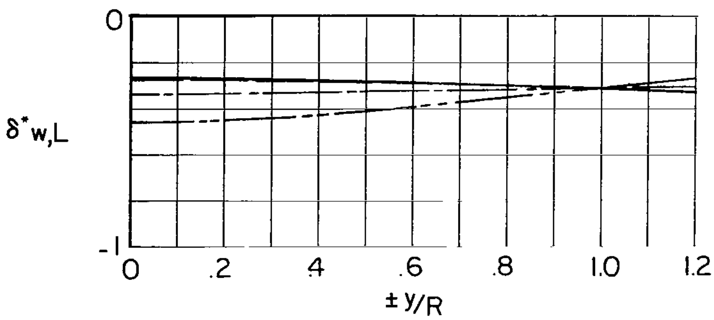
Figure 54.- Spanwise distribution of interference over a wing with 45^0 of sweep centered in a variable width-height-ratio closed tunnel. $\sigma = 0.5$; $\alpha = 0^0$.



(a) $\chi = 30^0$.

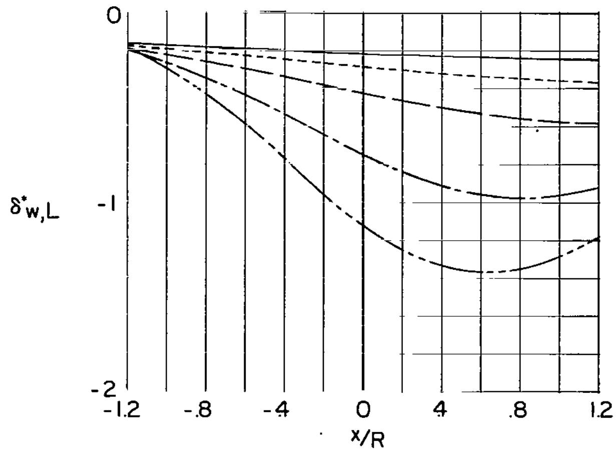


(b) $\chi = 60^0$.

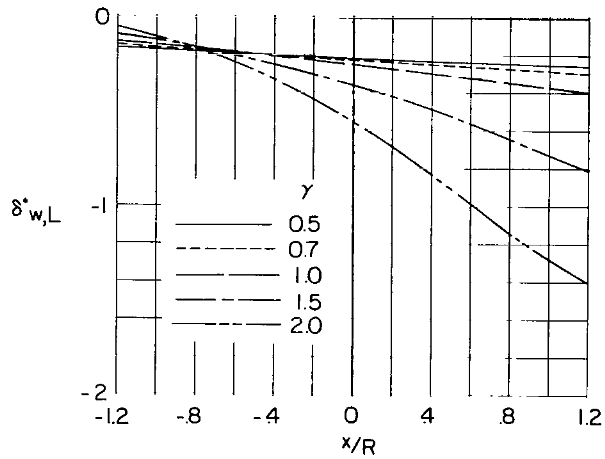


(c) $\chi = 90^0$.

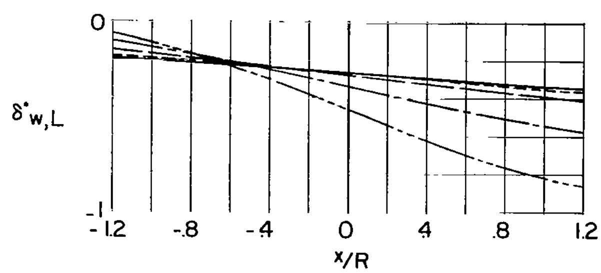
Figure 55.- Lateral distribution of interference over a rotor centered in a variable width-height-ratio closed tunnel. $\sigma = 0.5$; $\alpha = 0^0$.



(a) $\chi = 30^0$.

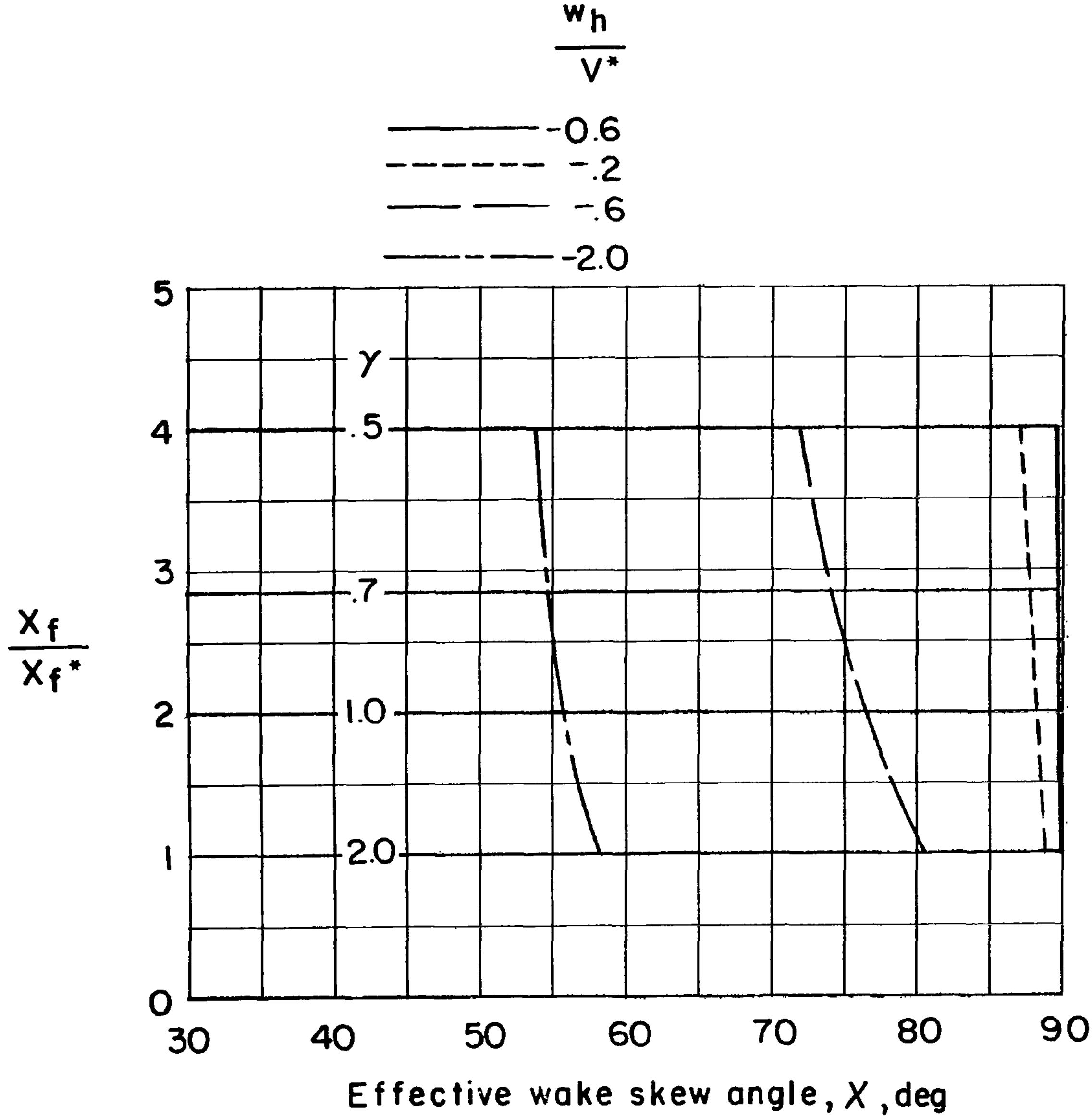


(b) $\chi = 60^0$.



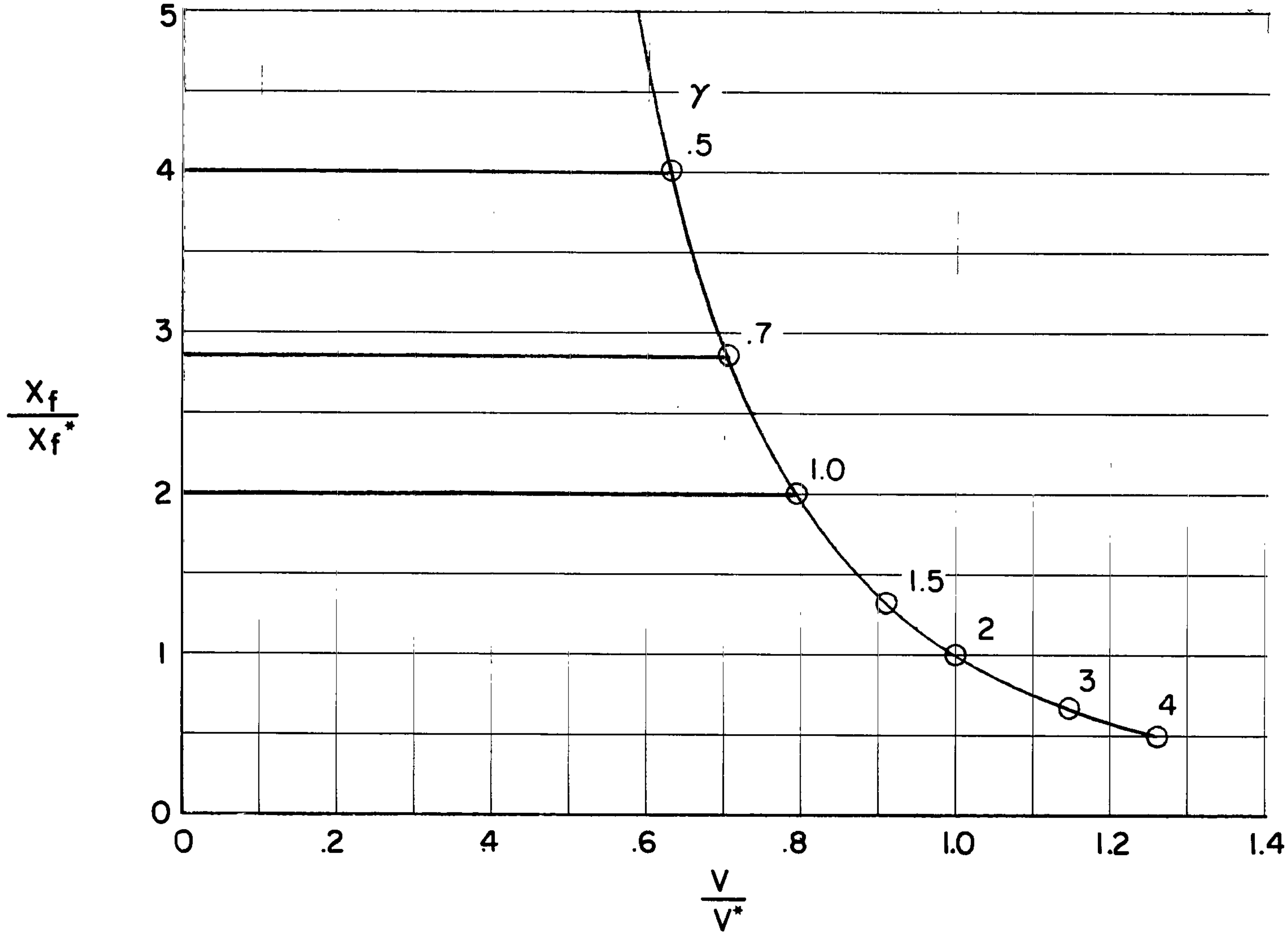
(c) $\chi = 90^0$.

Figure 56.- Longitudinal distribution of interference factors over a rotor centered in a variable width-height-ratio closed tunnel. $\sigma = 0.5$; $\alpha = 0^0$.



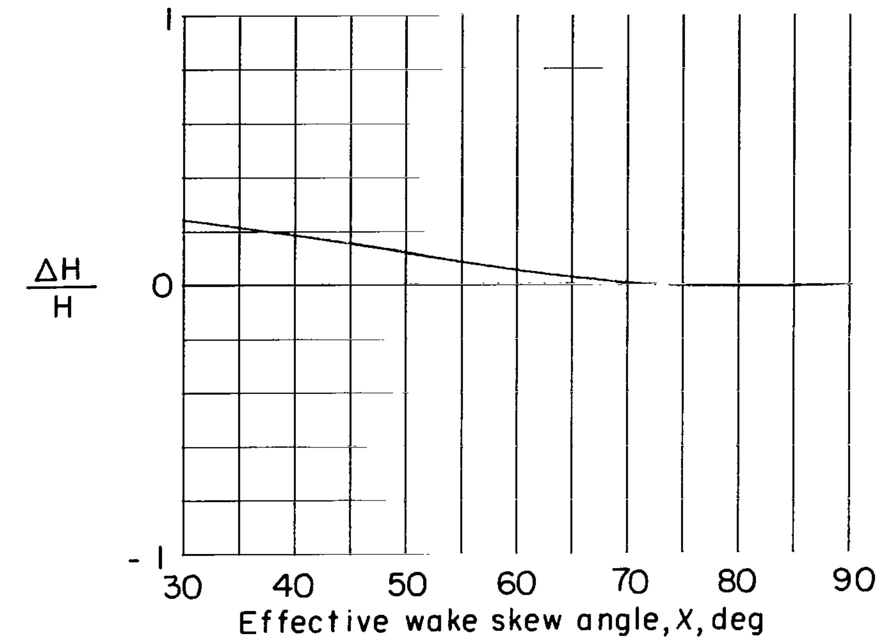
(a) As a function of χ.

Figure 57.- Relative recirculation in a variable width-height-ratio closed tunnel.

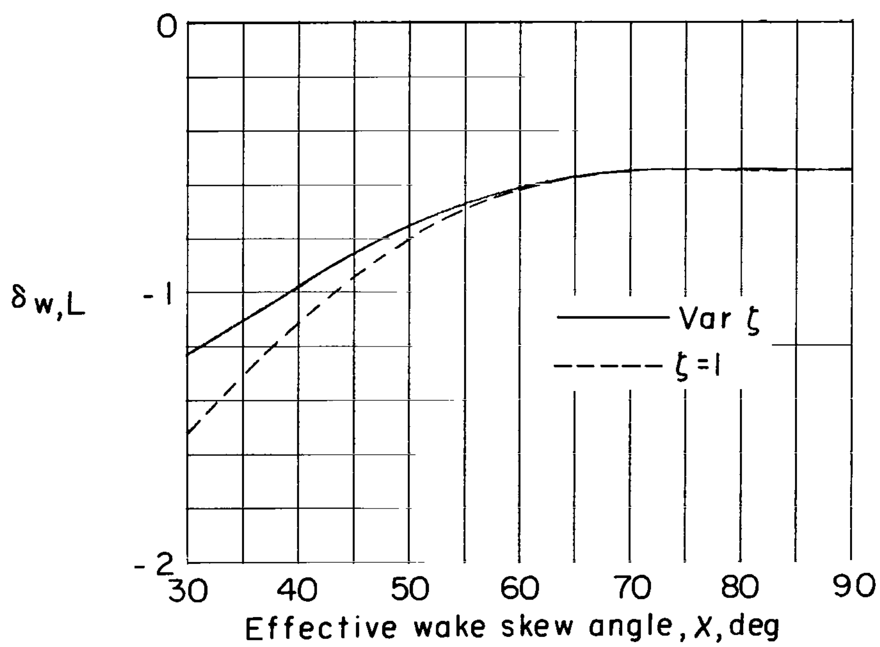


(b) As a function of V/V*.

Figure 57.- Concluded.

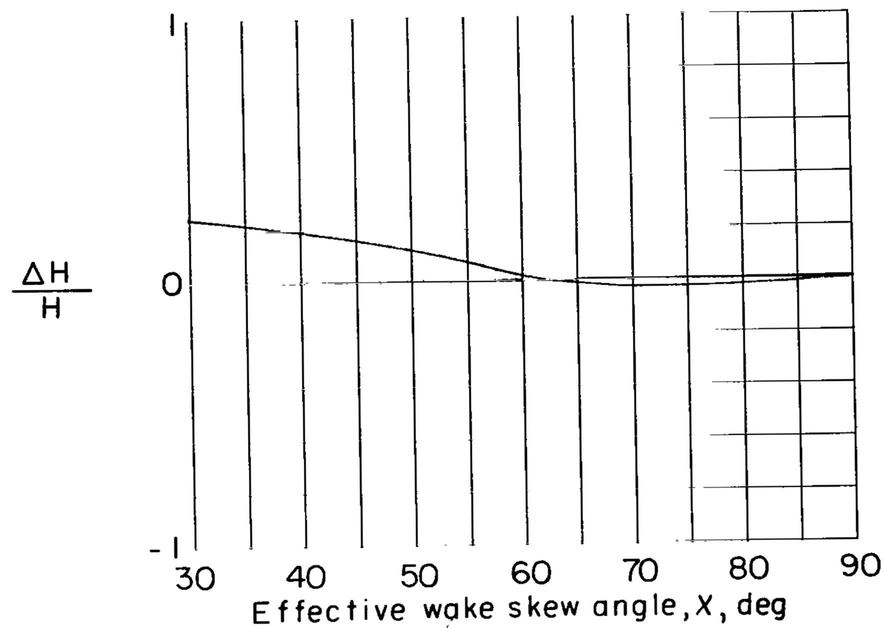


(a) Schedule for minimum $\delta_{w,L}$.

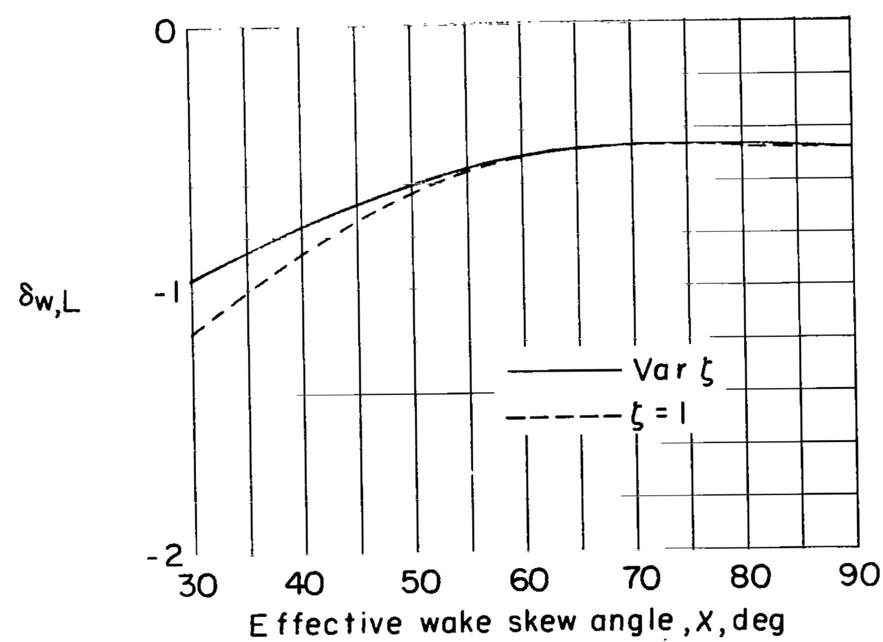


(b) Interference factors for variable and fixed ζ tunnels.

Figure 58.- Required schedule for minimum interference and a comparison of interference factors in a variable model-height closed tunnel. $\gamma = 2.0$; $\sigma = 0$.

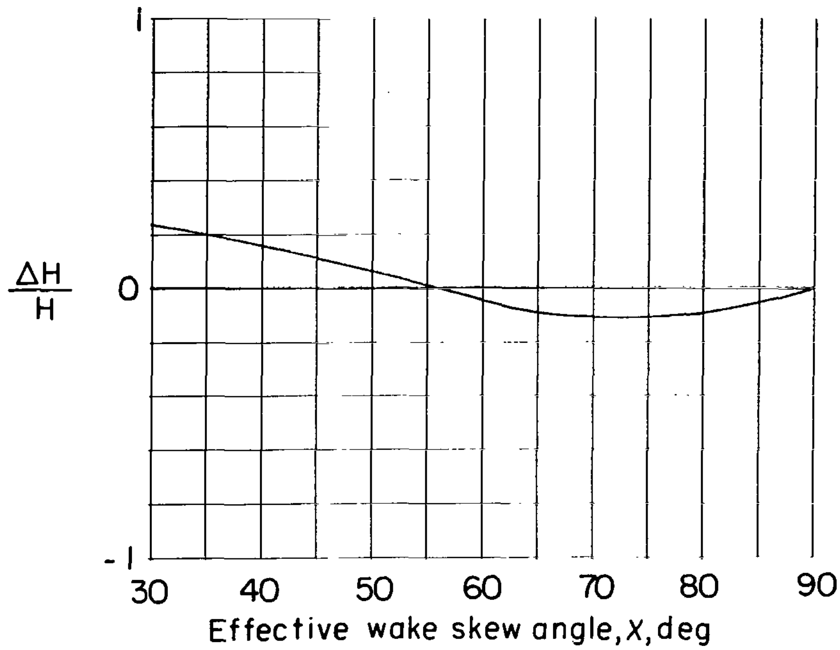


(a) Schedule for minimum $\delta_{w,L}$.

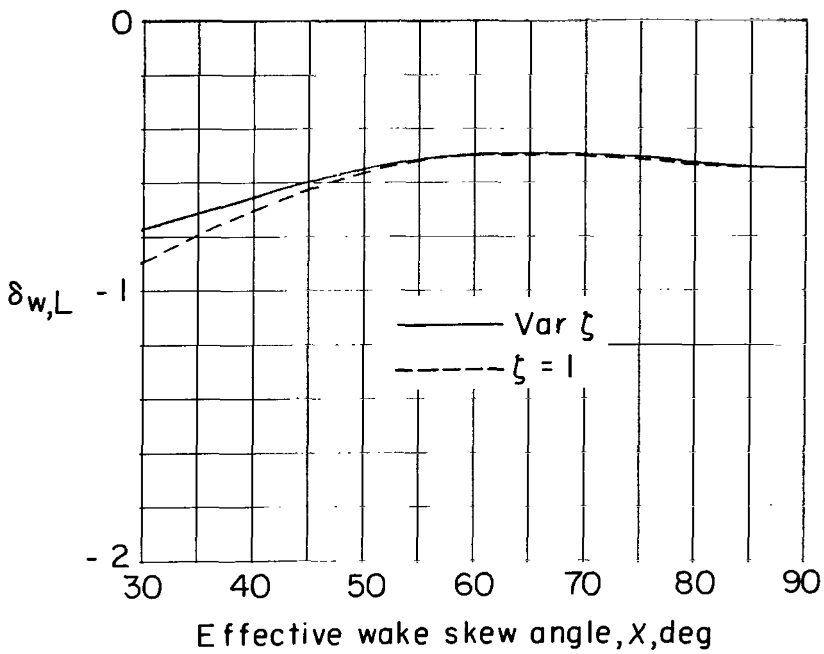


(b) Interference factors for variable and fixed ζ tunnels.

Figure 59.- Required schedule for minimum interference and a comparison of interference factors in a variable model-height closed tunnel. $\gamma = 1.5$; $\sigma = 0$.

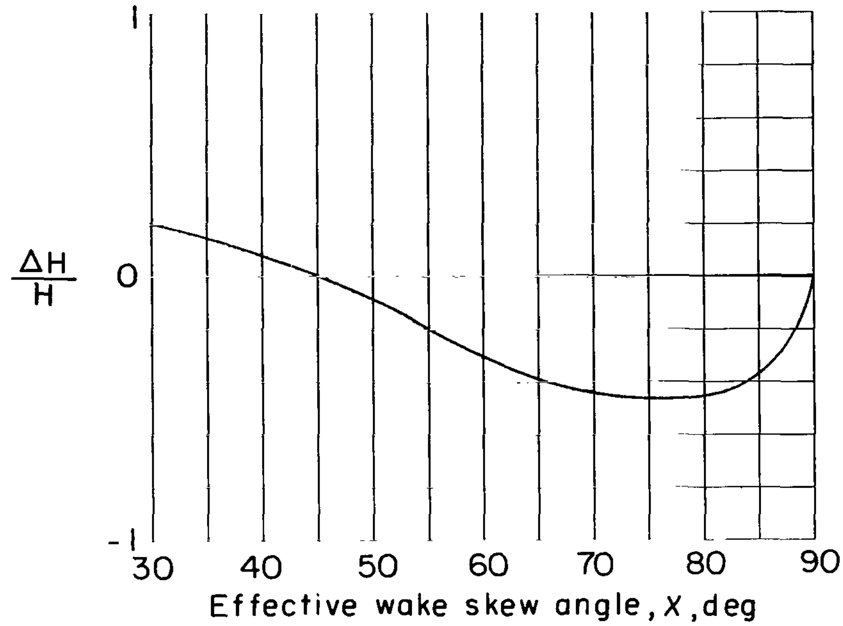


(a) Required schedule for minimum $\delta_{w,L}$.

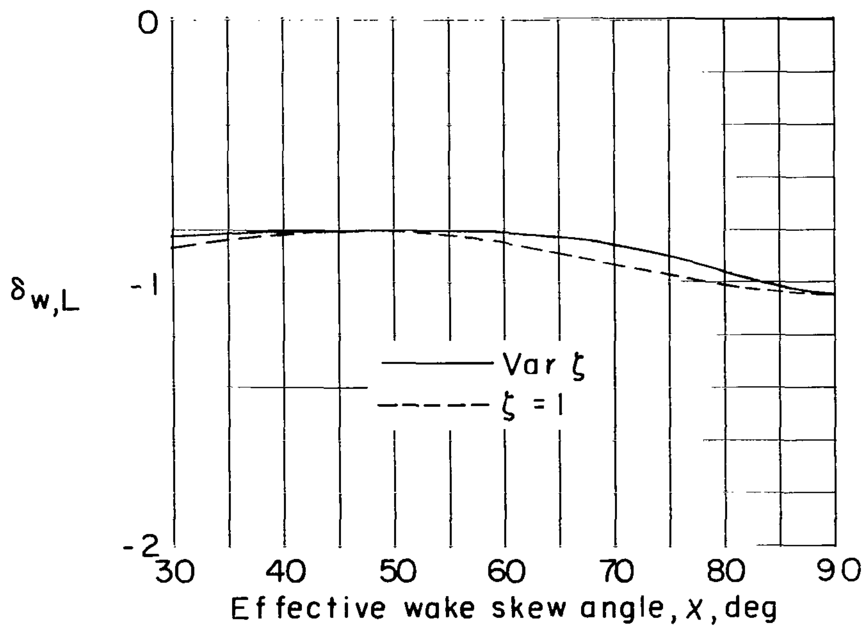


(b) Interference factors for variable and fixed ζ tunnels.

Figure 60.- Required schedule for minimum interference and a comparison of interference factors in a variable model-height closed tunnel. $\gamma = 1.0$; $\sigma = 0$.



(a) Required schedule for minimum $\delta_{w,L}$.



(b) Interference factors for variable and fixed ζ tunnels.

Figure 61.- Required schedule for minimum interference and a comparison of interference factors in a variable model-height closed tunnel. $\gamma = 0.5$; $\sigma = 0$.

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