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UNIVERSITY OF WASHINGTON
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SUMMARY

A new method of calculating the wind tunnel wall induced interference factors has been developed. The tunnel walls are represented by a vortex lattice of strength sufficient to satisfy the boundary conditions at the wall. The vortex lattice is then used to calculate the interference velocities at any point in the wind tunnel. The resulting interference factors agree with the classical results that are available for square and circular tunnels. Calculations are also presented for a rectangular tunnel, and they can be made to closely approximate a tunnel of any cross-section.

INTRODUCTION

Current interest in V/STOL aircraft has resulted in a renewed interest in the problems of the wind tunnel measurement of their characteristics. Among the problems of critical importance is that of calculating the interference velocities due to the presence of the tunnel walls, particularly the longitudinal distribution of the

interference because of its large effect on the measured pitching moment. Classical methods of computing these interference velocities are inadequate for V/STOL models that characteristically produce large downwash, and so a new method is required to handle this case. In this report a new method of representing the tunnel walls is developed which should be applicable to the large downwash case, and it is tested by being applied to the limiting case of small downwash in order to compare results with classical theory.

The classical solutions have depended upon the assumption of a proper set of images outside the tunnel, of the vortex flow inside the tunnel, such that the walls become streamlines. Unfortunately, no proper image system has been found for any tunnel except the rectangular cross-sections. Prandtl (Ref. 1) has presented a solution for the circular wind tunnel with an undeflected wake which gives correct values of upwash at the wing. Glauert (Ref. 2) has solved the rectangular wind tunnel problem, including the effects downstream, i.e., at the tail location. Others (Refs. 3 to 9) have extended it to include other tunnel shapes. Lotz (Ref. 10) has offered a solution for the upwash interference for circular and elliptical tunnels which will yield results at downstream locations as well as at the wing. In Lotz's solution, an image system is used which is valid at the wing and far downstream, and an additional potential function is assumed in infinite series form which is required to cancel the remaining normal velocities

at the wall, also expressed in series form. To the degree that these series do not completely converge before being truncated, this solution is an approximation.

The object of this work is to present an alternate method of representing the tunnel walls which would be applicable to a tunnel of any arbitrary cross-section and which could be extended to handle the large downwash case. It is hypothesized that the tunnel walls might be represented by a network of vortex lines whose magnitude and direction are just sufficient to prevent flow through a set of control points on the walls. The approach is similar to that of approximate lifting surface theory.

This paper presents the mathematical development of the theory. The results of sample calculations for the interference factors and the distribution of interference over the longitudinal and lateral axes are presented for uniformly loaded wings of various spans in a variety of wind tunnels. The wind tunnel configurations include square, rectangular and circular cross-sections. These results are then compared, where possible, with prior work which have obtained corresponding values by other theoretical treatments.

SYMBOLS

b	Wing vortex span
c	Wind tunnel cross-section area
C_L	Wing lift coefficient

$h_{(\ )}$	Normal distance to a point p from a line containing a vortex segment identified by subscript
$h_{(\ )(\ )}$	Normal distance to a point p from a plane containing vortex segments identified by subscript
H	Height of wind tunnel
$\bar{i},\bar{j},\bar{k}$	Unit vectors in the directions X, Y, Z
L,G	Dimensions of rectangular vortex ring (Fig. 3)
$\bar{n}$	Unit vector normal to vortex ring
$R_{(\ )}$	Vector from point (X,Y,Z) to end of a vortex vector $\bar{S}$ indicated by subscript
$R_{(\ )_{(\ )}}$	Magnitude of component of vector $R_{(\ )}$ indicated by second subscript
s	Wing area
$\bar{S}$	Vector representing a vortex segment of strength Γ and length S
$S_{(\ )}$	Component of $\bar{S}$ indicated by subscript
$\bar{v}$	Unit vector in the direction of the total velocity vector at a point
$\bar{V}$	Velocity induced at a point
w	Vertical component of wall-induced interference velocity
W	Width of wind tunnel
$\bar{W}$	Vector representing a wing bound vortex of strength Γ_w
X,Y,Z	Cartesian coordinate of a point (see Fig. 1)
β	Angles defining direction to a point from the end of a vortex segment (Fig. 2)
Γ	Circulation strength of a vortex
δ	Tunnel-wall-induced interference factor

STATEMENT OF PROBLEM

The problem is to find that distribution of vorticity lying in the tunnel walls which will prevent any flow through the wall due to the action of a lifting system in the wind tunnel. The lifting surface is assumed to be uniformly loaded and is represented by a simple horseshoe vortex with the trailing pair undeflected. In principle, any desired distribution of lift could be built up of such simple elements.

The walls are represented by a tubular vortex sheet of finite length composed of a network of circumferential and longitudinal vortices having equal spacing (Fig. 1). Helmholtz' theorem that a vortex filament can neither end nor begin in the flow is satisfied most readily by constructing the network of square vortex rings lying wholly within the plane of the walls. Each such square has a vortex strength Γ_i, and each side is coincident with the side of the neighboring square. Thus, the strength of any segment is the sum of the strengths of the two adjoining squares. The boundary condition that the wall must be impervious to flow is satisfied at a control point in the center of each square. This results in a set of simultaneous equations, one written for each control point, in which the unknowns are the Γ_i.

A large number of equations results if the tube is very long, thus some judgment is required in choosing the geometric arrangement. The use of square vortex rings requires a tunnel of constant cross-section. One notes that for a wing mounted in the center

of the tunnel, lateral symmetry always exists; and if the wake is undeflected, vertical symmetry also exists, thus reducing the number of unknowns. The trailing edge of the finite length tube which represents the long tunnel requires a slightly different treatment. At a far downstream section only longitudinal vorticity should exist. This is represented by elongating the last ring of squares by a large amount, while keeping the control point at the same location with respect to the last circumferential station. Figure 1 shows the arrangement for a rectangular tunnel with filleted corners.

SETUP OF THE EQUATIONS

A right-hand axis system is established with the X-axis on the longitudinal centerline of the tunnel, positive downstream. The Y-axis is taken positive upward and the Z-axis positive to the right side of the tube facing downstream.

Since the surface of the tunnel is to be made of square elements, its cross-section is a polygon of equal segments arranged to approximate any desired shape. In this development the cross-section will be assumed to be symmetrical about the X,Y plane.

In general, the velocity induced at any point p (Fig. 2) due to a vortex segment may be written:

$$\bar{V} = \frac{\Gamma}{4\pi h} \quad (\cos \beta_1 + \cos \beta_2) \ \bar{v} \qquad (1)$$

The terms required are written as follows:

$$\cos \beta_1 + \cos \beta_2 = \frac{R_1+R_2}{2R_1R_2S} \left[S^2 - (R_1-R_2)^2 \right]$$

$$\bar{v} = \frac{\bar{R}_1 \times \bar{S}}{|\bar{R}_1 \times \bar{S}|} = \frac{\begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ R_{1_x} & R_{1_y} & R_{1_z} \\ S_x & S_y & S_z \end{vmatrix}}{R_1 S \sin \beta_1}$$

$$\text{But } \sin \beta_1 = \frac{h}{R_1}$$

$$\bar{v} = \frac{\left(R_{1_y} S_z - R_{1_z} S_y\right) \bar{i}}{Sh} - \frac{\left(R_{1_x} S_z - R_{1_z} S_x\right) \bar{j}}{Sh} + \frac{\left(R_{1_x} S_y - R_{1_y} S_x\right) \bar{k}}{Sh}$$

Finally, the velocity induced at a point due to a vortex segment is:

$$\frac{\bar{V}}{\Gamma/4\pi h} = \frac{R_1+R_2}{2R_1R_2S^2h} \left[S^2-(R_1-R_2)^2 \right] \left[\left(R_{1_y} S_z - R_{1_z} S_y \right) \bar{i} \right. \qquad (2)$$

$$\left. + \left(R_{1_z} S_x - R_{1_x} S_z \right) \bar{j} \quad + \left(R_{1_x} S_y - R_{1_y} S_x \right) \bar{k} \right]$$

One could then add the contributions of all four sides of a vortex square, but it is more convenient to take advantage of the lateral symmetry and sum the effects due to a pair of symmetrically located vortex squares of the same strength. The arrangement is shown in Figure 3 and the following equation results:

$$\frac{\bar{V}}{\Gamma/8\pi L} = h_{AB}\left\{\frac{R_{NA}+R_{NB}}{h_{N_1}^2 R_{NA}R_{NB}}\left[L^2-(R_{NA}-R_{NB})^2\right] - \frac{R_{MA}+R_{MB}}{h_{M_1}^2 R_{MA}R_{MB}}\left[L^2-(R_{MA}-R_{MB})^2\right]\right\}\bar{i}$$

$$+ h_{DC}\left\{\frac{R_{ND}+R_{NC}}{h_{N_2}^2 R_{ND}R_{NC}}\left[L^2-(R_{ND}-R_{NC})^2\right] - \frac{R_{MD}+R_{MC}}{h_{M_2}^2 R_{MD}R_{MC}}\left[L^2-(R_{MD}-R_{MC})^2\right]\right\}\bar{i} \qquad (3)$$

$$+ \cos\Phi_B\left\{\frac{R_{NA}+R_{NB}}{h_{N_1}^2 R_{NA}R_{NB}}\left[L^2-(R_{NA}-R_{NB})^2\right] + \frac{R_{ND}+R_{NC}}{h_{N_2}^2 R_{ND}R_{NC}}\left[L^2-(R_{ND}-R_{NC})^2\right]\right\}(X_N-X)\,\bar{j}$$

$$+ \cos\Phi_B\left\{\frac{R_{MA}+R_{MB}}{h_{M_1}^2 R_{MA}R_{MB}}\left[L^2-(R_{MA}-R_{MB})^2\right] + \frac{R_{MD}+R_{MC}}{h_{M_2}^2 R_{MD}R_{MC}}\left[L^2-(R_{MC}-R_{MB})^2\right]\right\}(X_M-X)\,\bar{j}$$

$$+\left\{\frac{R_{MA}+R_{NA}}{h_A^2\,R_{MA}R_{NA}}\left[L^2-(R_{MA}-R_{NA})^2\right](Z-Z_A)+\frac{R_{NB}+R_{MB}}{h_B^2\,R_{NB}R_{MB}}\left[L^2-(R_{MB}-R_{NB})^2\right](Z_B-Z)\right\}\bar{j}$$

$$+\left\{\frac{R_{NC}+R_{MC}}{h_C^2\,R_{NC}R_{MC}}\left[L^2-(R_{NC}-R_{MC})^2\right](Z_C-Z)+\frac{R_{ND}+R_{MD}}{h_D^2\,R_{ND}R_{MD}}\left[L^2-(R_{ND}-R_{MD})^2\right](Z-Z_D)\right\}\bar{j}$$

$$+\sin\Phi_B\left\{\frac{R_{NA}+R_{NB}}{h_{N_1}^2\,R_{NA}R_{NB}}\left[L^2-(R_{NA}-R_{NB})^2\right]-\frac{R_{NC}+R_{ND}}{h_{N_2}^2\,R_{NC}R_{ND}}\left[L^2-(R_{NC}-R_{ND})^2\right]\right\}(X_N-X)\;\bar{k}$$

$$+\sin\Phi_B\left\{\frac{R_{MC}+R_{MD}}{h_{M_2}^2\,R_{MC}R_{MD}}\left[L^2-(R_{MC}-R_{MD})^2\right]-\frac{R_{MA}+R_{MB}}{h_{M_1}^2\,R_{MA}R_{MB}}\left[L^2-(R_{MA}-R_{MB})^2\right]\right\}(X_M-X)\;\bar{k}$$

$$+\left\{\frac{R_{NA}+R_{MA}}{h_A^2\,R_{NA}R_{MA}}\left[L^2-(R_{NA}-R_{MA})^2\right]-\frac{R_{NC}+R_{MC}}{h_C^2\,R_{NC}R_{MC}}\left[L^2-(R_{NC}-R_{MC})^2\right]\right\}(Y_A-Y)\;\bar{k}$$

$$+\left\{\frac{R_{ND}+R_{MD}}{h_D^2\,R_{ND}R_{MD}}\left[L^2-(R_{ND}-R_{MD})^2\right]-\frac{R_{NB}+R_{MB}}{h_B^2\,R_{NB}R_{MB}}\left[L^2-(R_{NB}-R_{MB})^2\right]\right\}(Y_B-Y)\;\bar{k}$$

Similarly, the velocity induced at point p by a simple horseshoe vortex located in the center of the tunnel is derived from Figure 4 using eq. (1). Summing the contributions from the three segments yields:

$$\frac{\bar{V}}{\Gamma_w/8\pi b} = -\frac{R_{W1}+R_{W2}}{h_b^2 R_{W1}R_{W2}}\left[b^2 - (R_{W1}-R_{W2})^2\right] R_{W1_y}\,\bar{i} \qquad (4)$$

$$+\left\{\frac{2b}{h_2^2}\left(1+\frac{X-X_w}{R_{W2}}\right)R_{W2_z} - \frac{2b}{h_1^2}\left(1+\frac{X-X_w}{R_{W1}}\right)R_{W1_z}\right.$$

$$\left. + \frac{R_{W1}+R_{W2}}{h_b^2 R_{W1}R_{W2}}\left[b^2 - (R_{W1}-R_{W2})^2\right] R_{W1_x}\right\}\bar{j}$$

$$+\left\{\frac{2b}{h_1^2}\left(1+\frac{X-X_w}{R_{W1}}\right)R_{W1_y} - \frac{2b}{h_2^2}\left(1+\frac{X-X_w}{R_{W2}}\right)R_{W2_y}\right\}\bar{k}$$

The boundary condition is expressed at each control point by writing $\bar{V}.\bar{n} = 0$ where $\bar{n}$ is the unit outer normal to the surface at that point.

$$\bar{n} = \frac{\bar{i} \times (\bar{R}_1 - \bar{R}_2)}{|\bar{i} \times (\bar{R}_1 - \bar{R}_2)|}$$

Thus there is a set of N equations, one for each control point. Because of the right and left symmetry and vertical symmetry, there are N/4 unknown Γ_i. An electronic computer is used to solve the matrix for the Γ_i.

Once the Γ_i are known, the induced velocity due to the walls can be calculated at any point in the tunnel by the use of eq. (3) summed over all the vortex rings in the tunnel walls. The interference is expressed as an angle whose tangent is the vertical component of interference velocity divided by the tunnel wind speed. Results are expressed in terms of the classical interference factor δ, defined by the equation:

$$\Delta\alpha = \delta \frac{S}{C} C_L$$

The factor is computed in terms of wing circulation and vortex span

$$\delta = \frac{w\ c}{2b\ \Gamma_w}$$

Results are presented graphically to show the longitudinal variation of the factor δ for different wing spans in a variety of tunnels.

RESULTS OF CALCULATIONS

Results of calculations made for three representative tunnel shapes are presented in the form of graphs of the wall interference factor δ. Values of δ were calculated at points along the tunnel centerline from the wing location downstream for several values of wing vortex span. These are presented for a circular, a square, and a 3:5 rectangular tunnel in Figures 5, 6, and 7. The average value of this interference factor over the vortex span of the uniformly loaded wing was also calculated and is shown as a function of vortex span for each of these tunnels along with the centerline values in Figure 8.

COMPARISON OF RESULTS WITH CLASSICAL WORK

Square Tunnel

Very little previous work exists which can be used for a check on the accuracy or convergence of the present method. Prandtl's concept of an infinite array of images of the wing located outside the tunnel is applicable only to rectangular (including square) tunnels and has been applied by Silverstein & White in Reference 9. Results are presented there for square and 2:1 rectangular tunnels; only the square tunnel results are used for comparison, since 2:1 tunnels are not common.

The number of line segments, each corresponding to the side of a vortex square, to be used to adequately represent the square

tunnel cross-section was determined by making a series of calculations with increasing numbers of segments. Figure 9 shows the results of using 12, 16, and 20 segments to make up the periphery of the square cross-section. The results for 16 and 20 segments differ only slightly and correspond very closely to the data taken from Reference 9. The excellent agreement shown indicates that 16 segments are enough to represent satisfactorily the square cross-section tunnel.

Circular Tunnel

In the case of the circular tunnel, no exact solution is available for the downstream interference factors, so two approximate results are compared with the new calculations in Figure 10. The treatment presented by Lotz (Ref. 10) would be exact except that the numerical values depend upon the point at which an infinite series in truncated. Reference 10 gives no indication of the accuracy expected in its numerical values. The result taken from Silverstein & White (Ref. 9) was arrived at by following their suggestion that the downstream interference factors for the circular tunnel be taken as the same as for the square tunnel of the same area.

Four different approximations to the circular tunnel were used for this calculation. Two regular polygons having 12 or 16 sides were used for the cross-section shape; each was rotated so that either points or flats of the polygon were at the top and side centerline. All four calculations yielded the same curve, with

values within one-tenth of one percent. Thus, it is concluded that a 12-sided polygon is adequate to represent the circular tunnel.

Length Effect

The effect of length of the tunnel to be used in calculations was explored for the circular tunnel. A twelve-sided polygon was used in the calculation, with the model vortex span equal to 0.4 of the tunnel diameter. It is evident from Figure 11 that a length-to-diameter ratio of 3 or 4 is ample for convergence. The reason for this may be seen in an examination of the distribution of the wall vorticity. The bound vortex of the wing requires some circumferential vorticity in the walls, but only in the region quite near to the wing. Longitudinal vorticity is not required far upstream, and far downstream only longitudinal filaments exist to control the trailing pair from the wing. By using the artifice of a very long last ring, the proper conditions are met far downstream, and the vortex lattice need only be long enough to provide the circumferential vorticity needed in the immediate vicinity of the wing. In fact, all the vorticity in the circumferential rings is quickly transferred to the longitudinal filaments.

Figure 12 shows the wall vortex strengths taken from calculations made for circular tunnels of various lengths. The circumferential vorticity strengths were taken at the floor near the center of the tunnel where they are the strongest; the longitudinal vortex filament strength is that along the side wall at model height. It is evident that the details of the distribution are not strongly

affected by the presence or absence of tunnel walls more than about one diameter up or downstream from the wing.

CONCLUSIONS

A new method of calculating the tunnel-induced interference velocities has been developed which depends on the representation of the walls by a network of square vortex rings.

The method may be used to represent any tunnel cross-section by using an equivalent polygon of equal length sides and having the same cross-section area.

The method yields interference factors that agree with classical theory where that is available.

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FIGURES

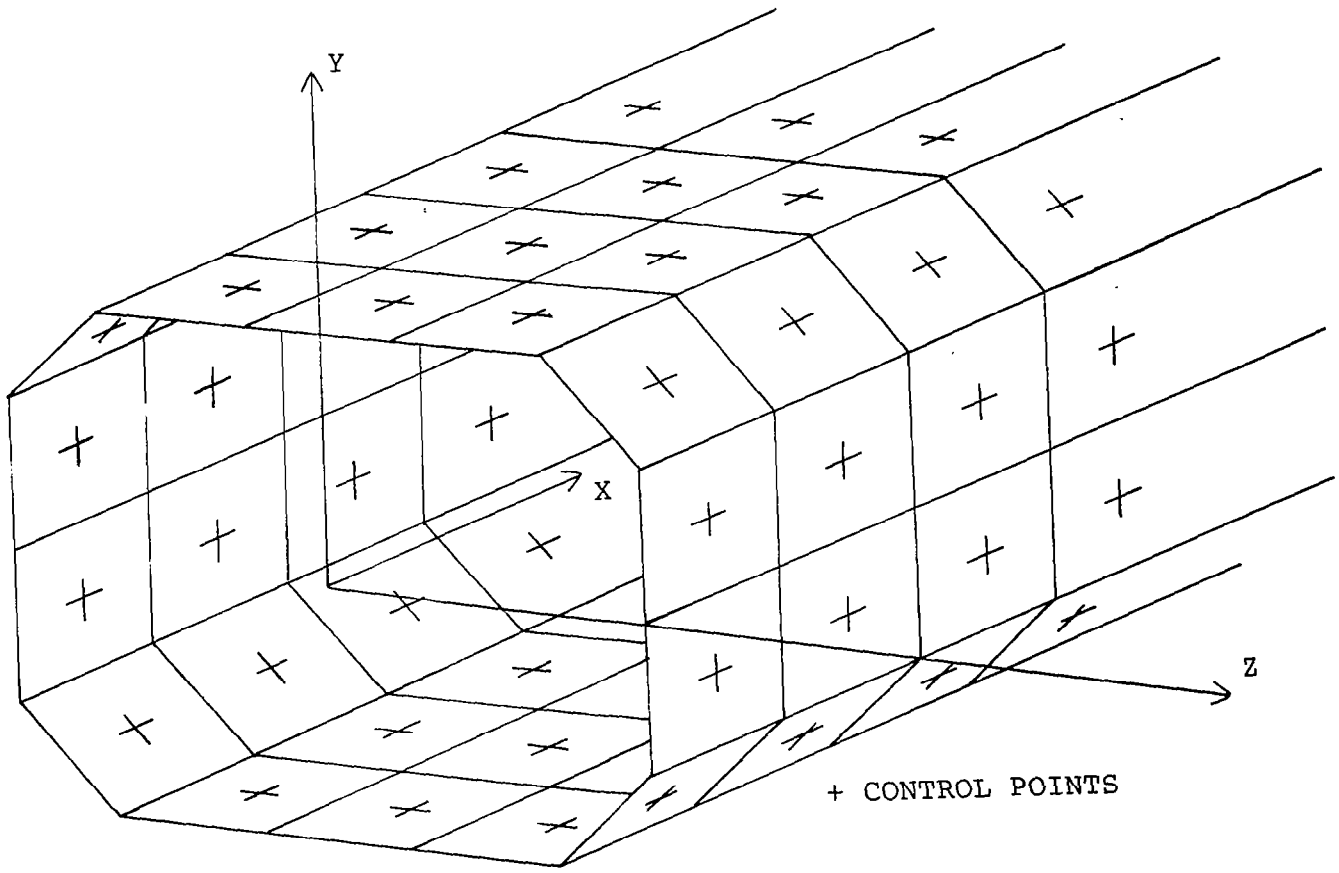


FIGURE 1

REPRESENTATION OF A RECTANGULAR TUNNEL WITH CORNER FILLETS

BY A VORTEX LATTICE OF SQUARE VORTEX RINGS LYING IN THE TUNNEL WALLS

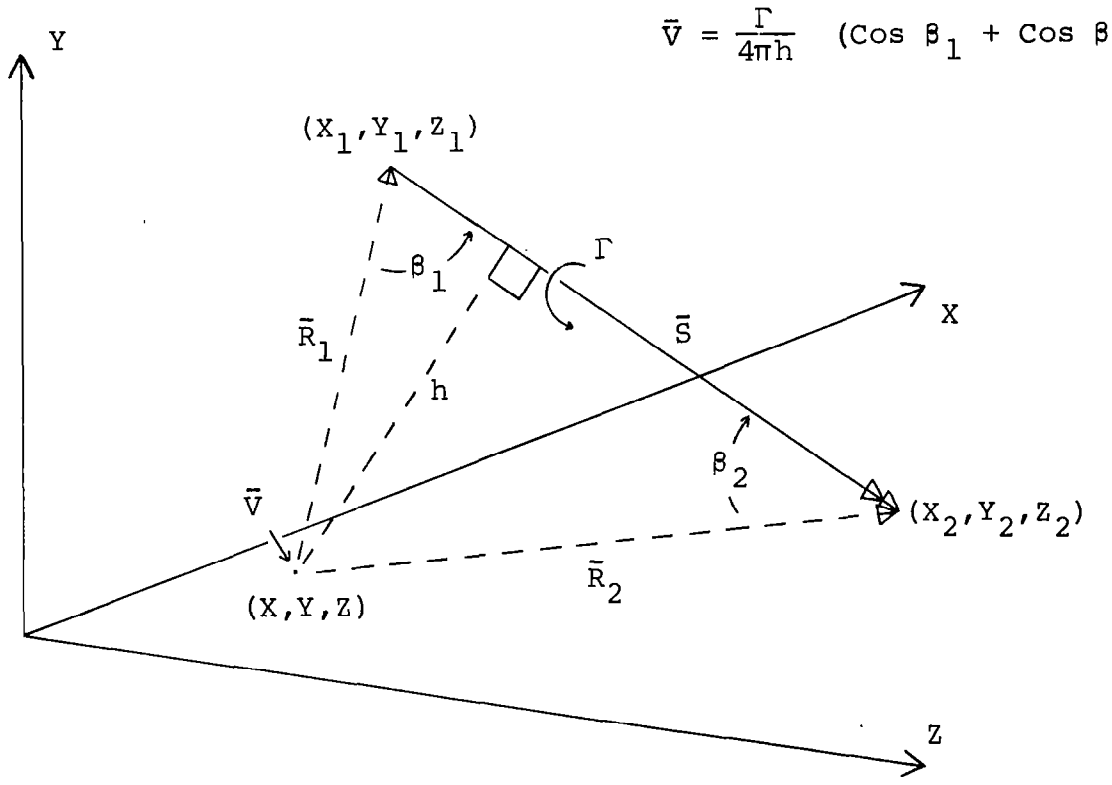


FIGURE 2

VELOCITY INDUCED AT A POINT BY AN ARBITRARILY ORIENTED VORTEX SEGMENT

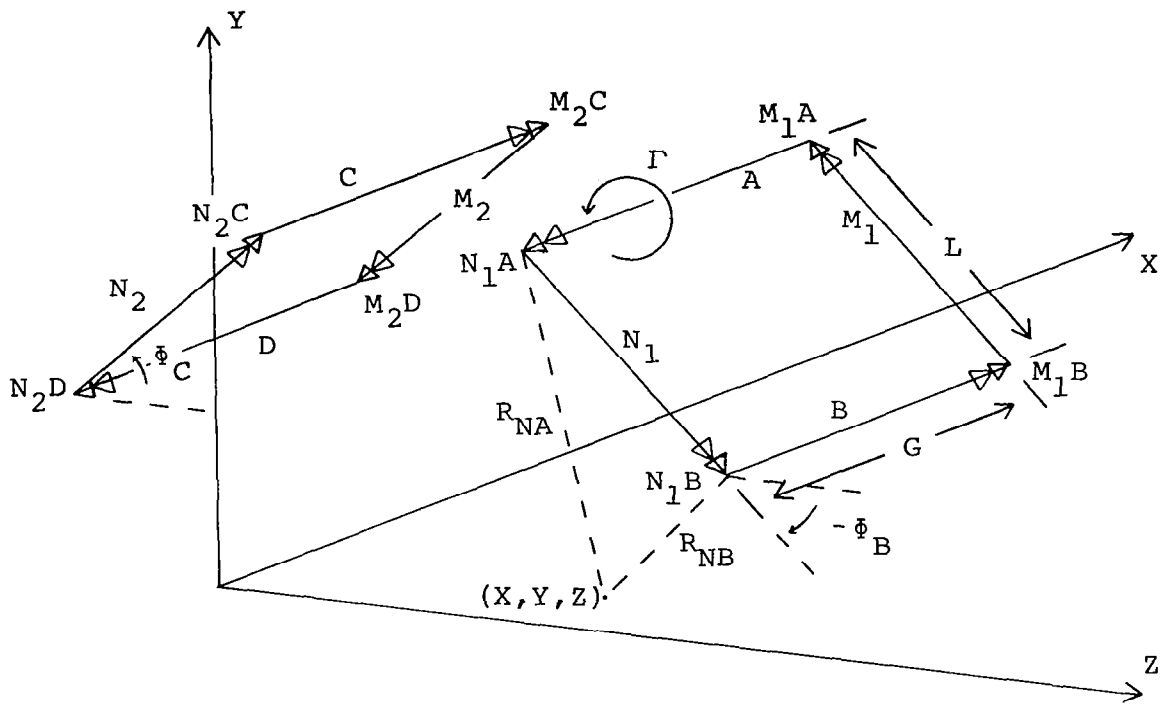


FIGURE 3

DEFINITION OF ANGLES AND DISTANCES FOR A PAIR OF VORTEX SQUARES ORIENTED SYMMETRICALLY ABOUT THE X,Y PLANE

(ELEMENTS A, B, C, & D ARE PARALLEL TO THE X-AXIS)

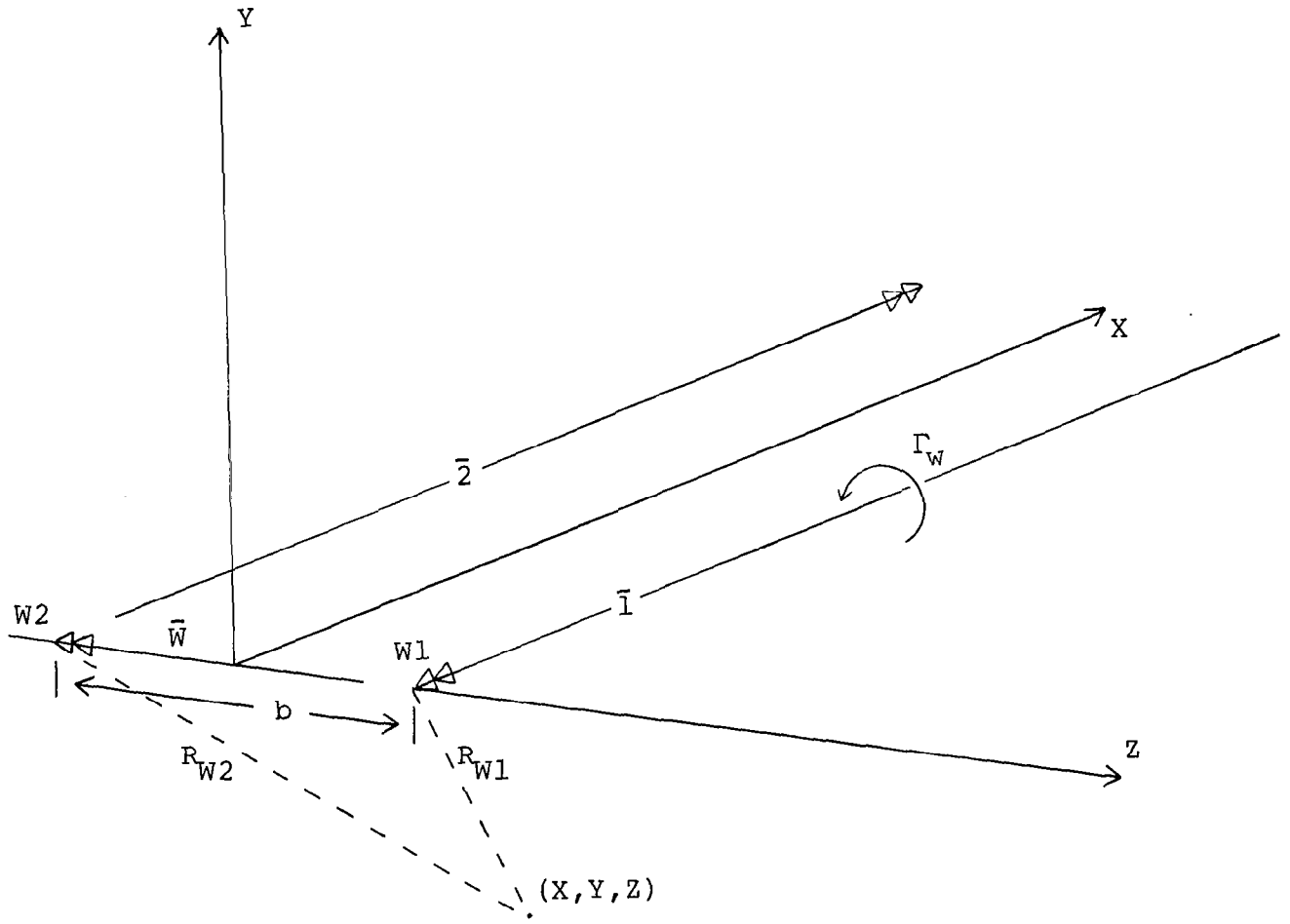


FIGURE 4

DEFINITION OF DISTANCES FOR A HORSESHOE VORTEX

REPRESENTING A WING LOCATED WITH ITS MIDSPAN AT THE ORIGIN OF COORDINATES

WALL INTERFERENCE FACTORS

FOR A CIRCULAR WIND TUNNEL

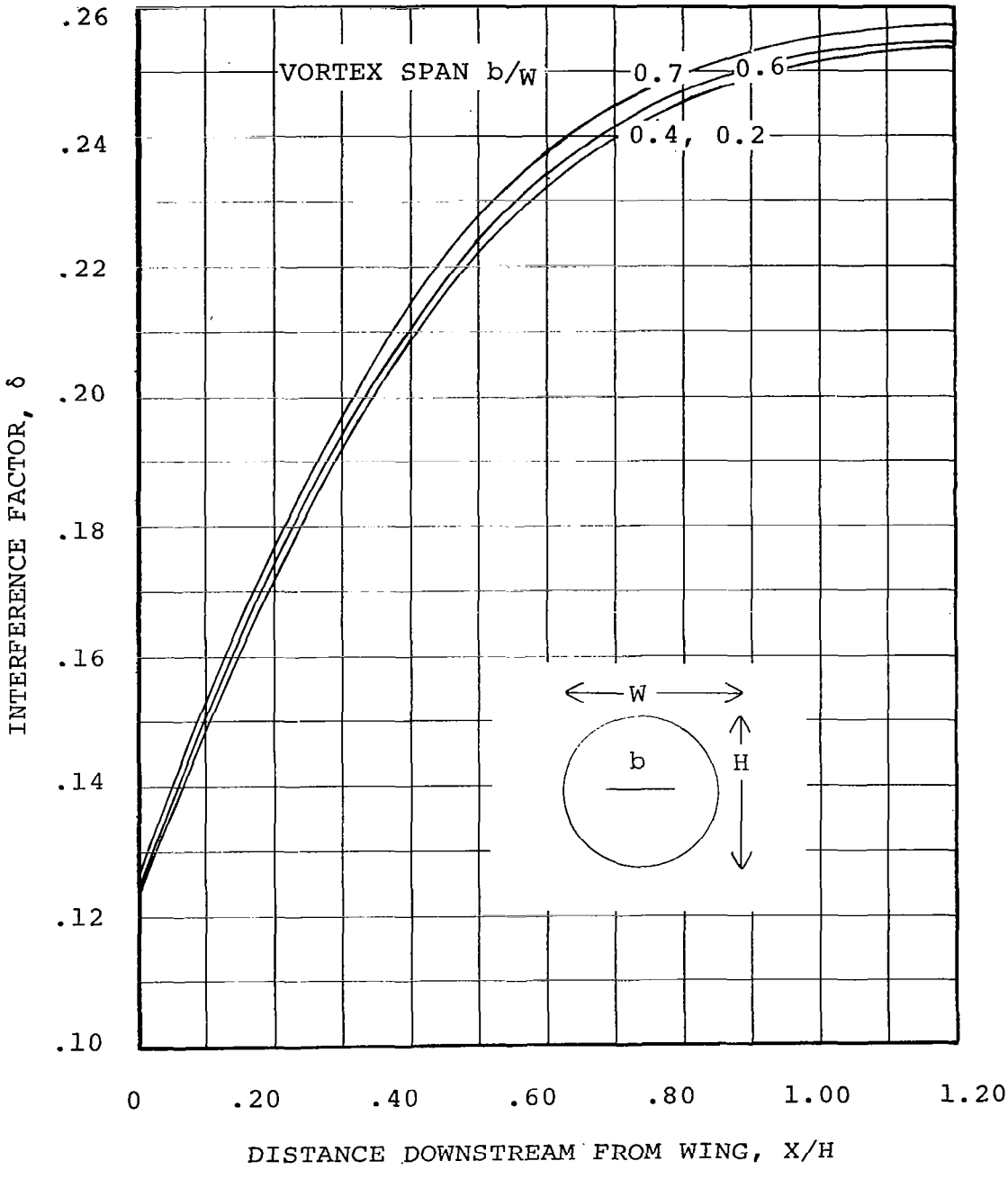


FIGURE 5

WALL INTERFERENCE FACTORS

FOR A SQUARE WIND TUNNEL

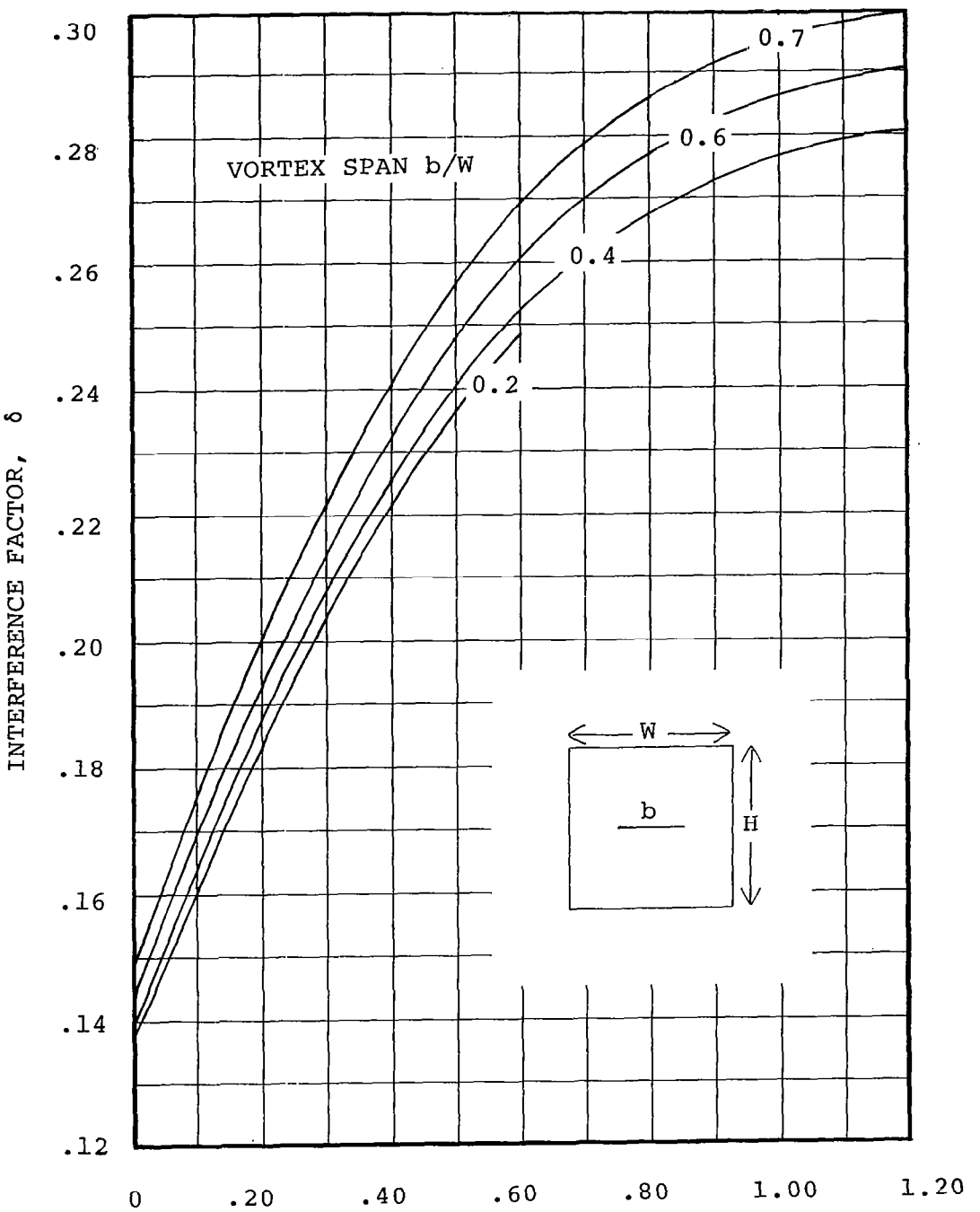


FIGURE 6

WALL INTERFERENCE FACTORS

FOR A 3:5 RECTANGULAR WIND TUNNEL

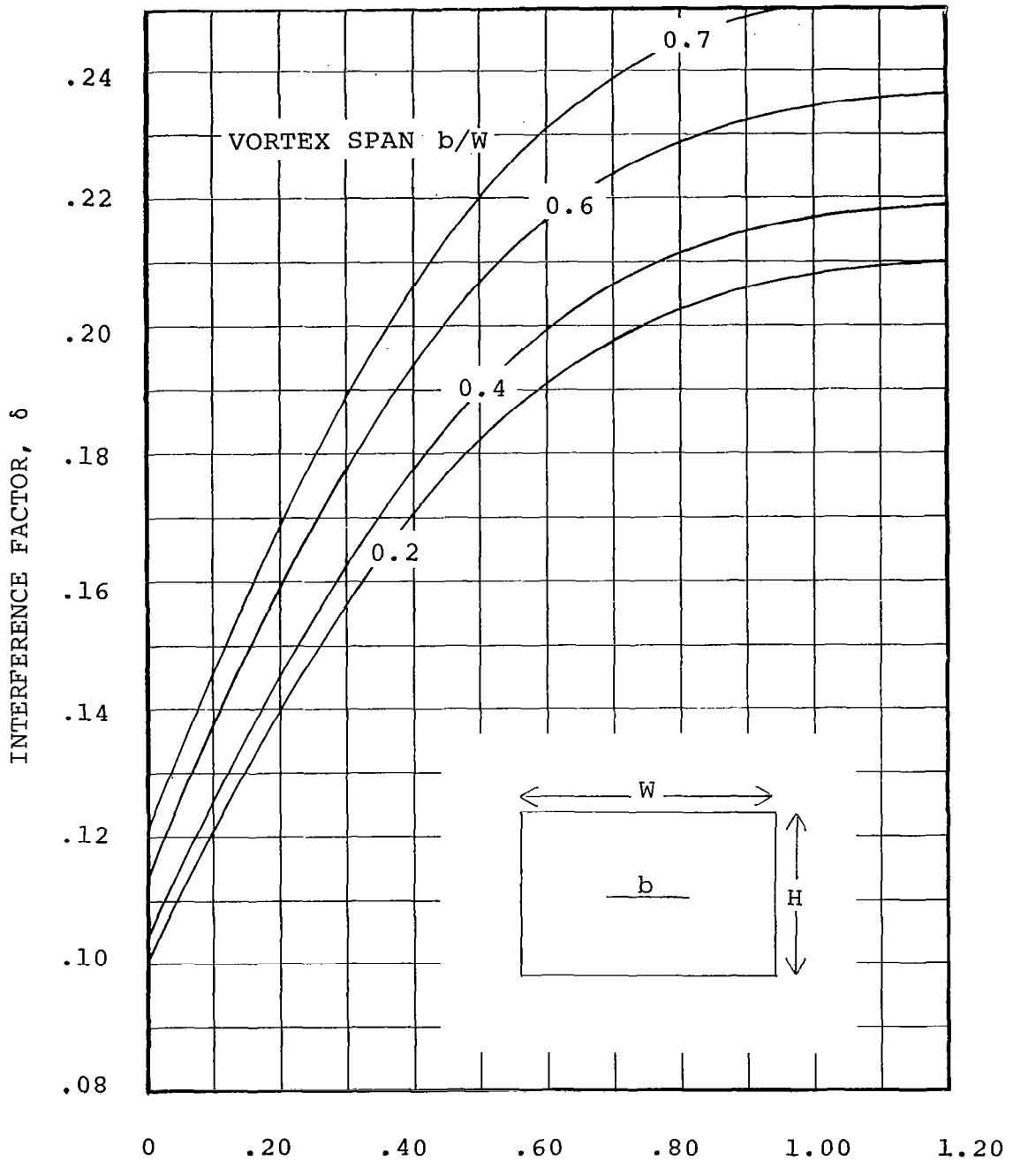
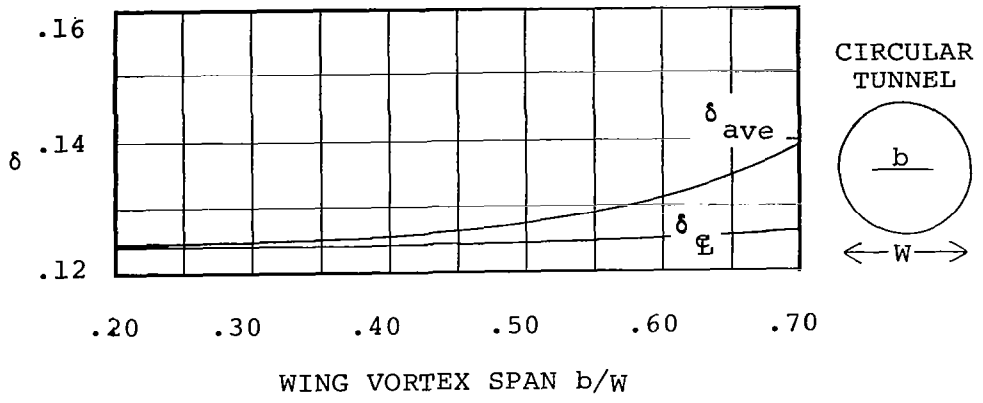
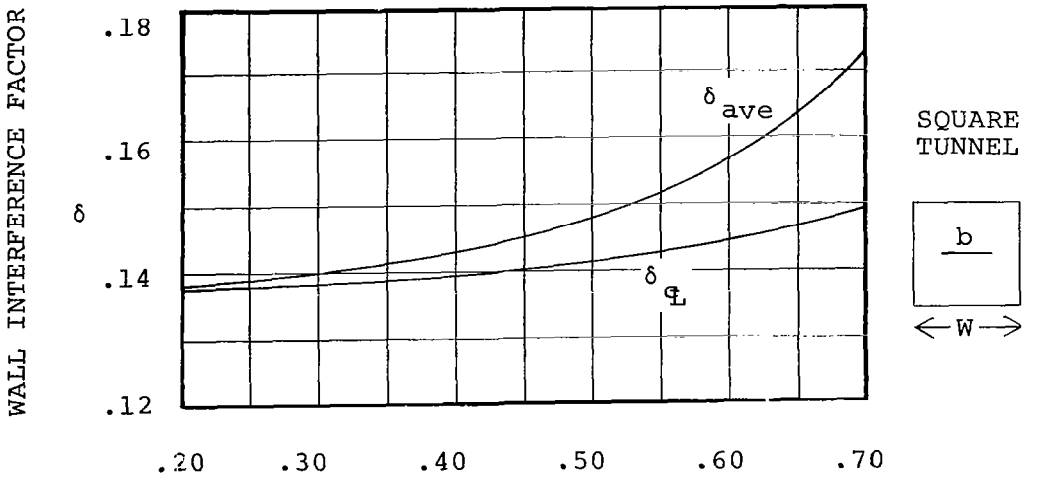


FIGURE 7

EFFECT OF WING SPAN ON AVERAGE INTERFERENCE FACTOR

AND THE CENTERLINE INTERFERENCE FACTOR AT THE WING





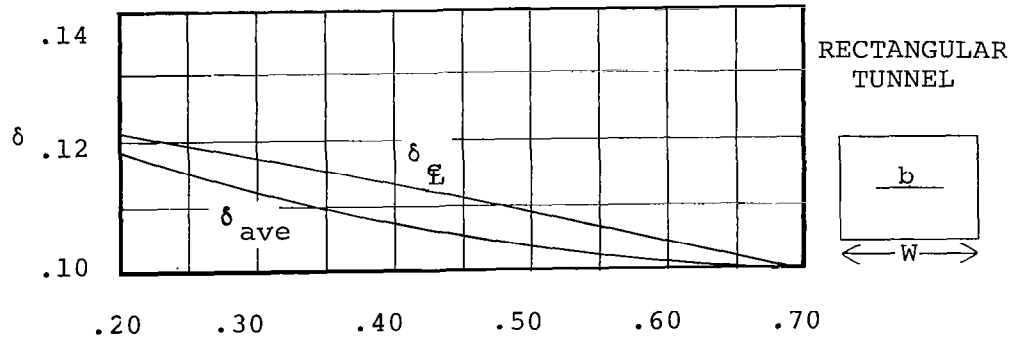


FIGURE 8

COMPARISON OF INTERFERENCE FACTORS

WITH CLASSICAL VALUES FOR A SQUARE TUNNEL

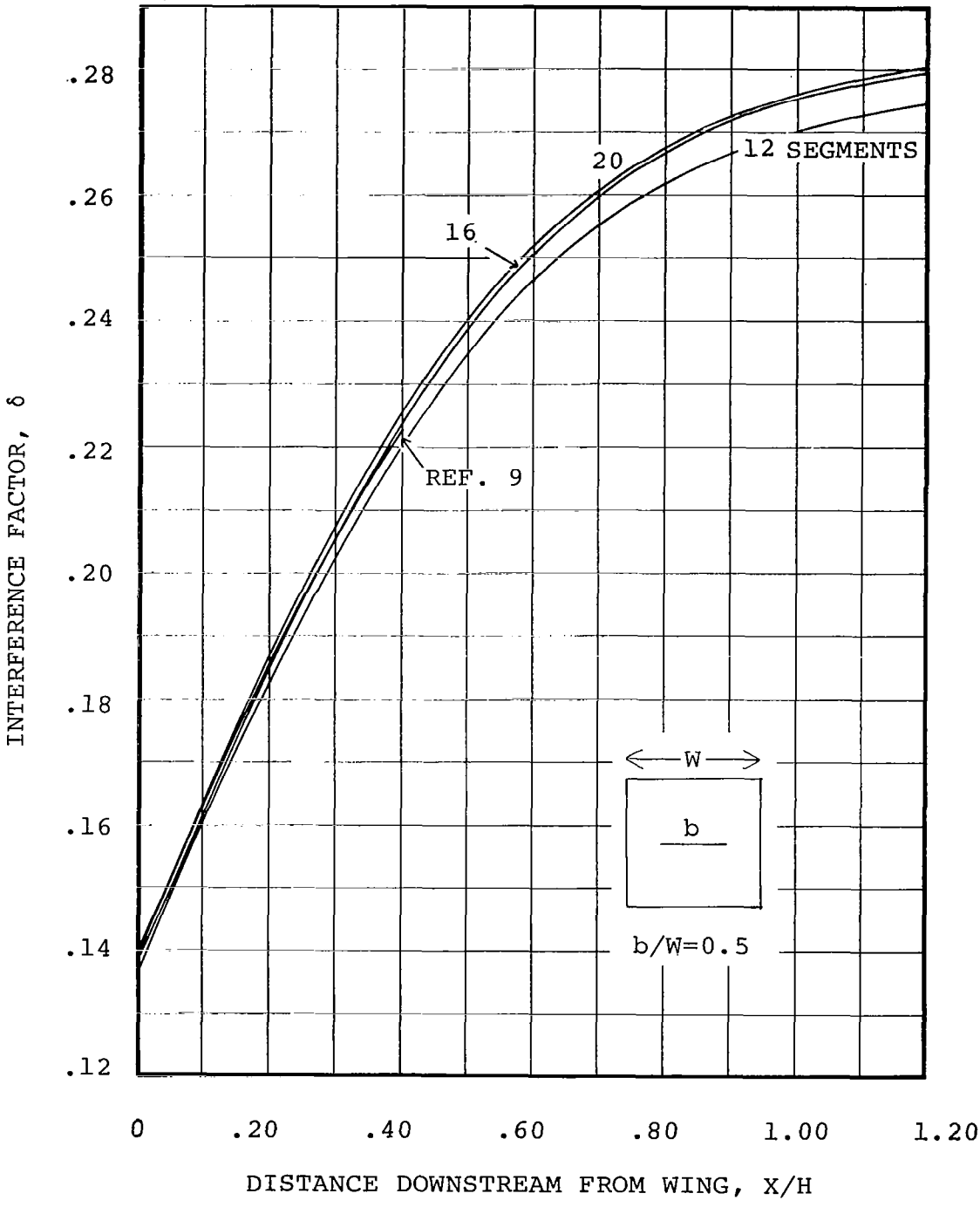


FIGURE 9

COMPARISON OF INTERFERENCE FACTORS

WITH CLASSICAL VALUES FOR A CIRCULAR TUNNEL

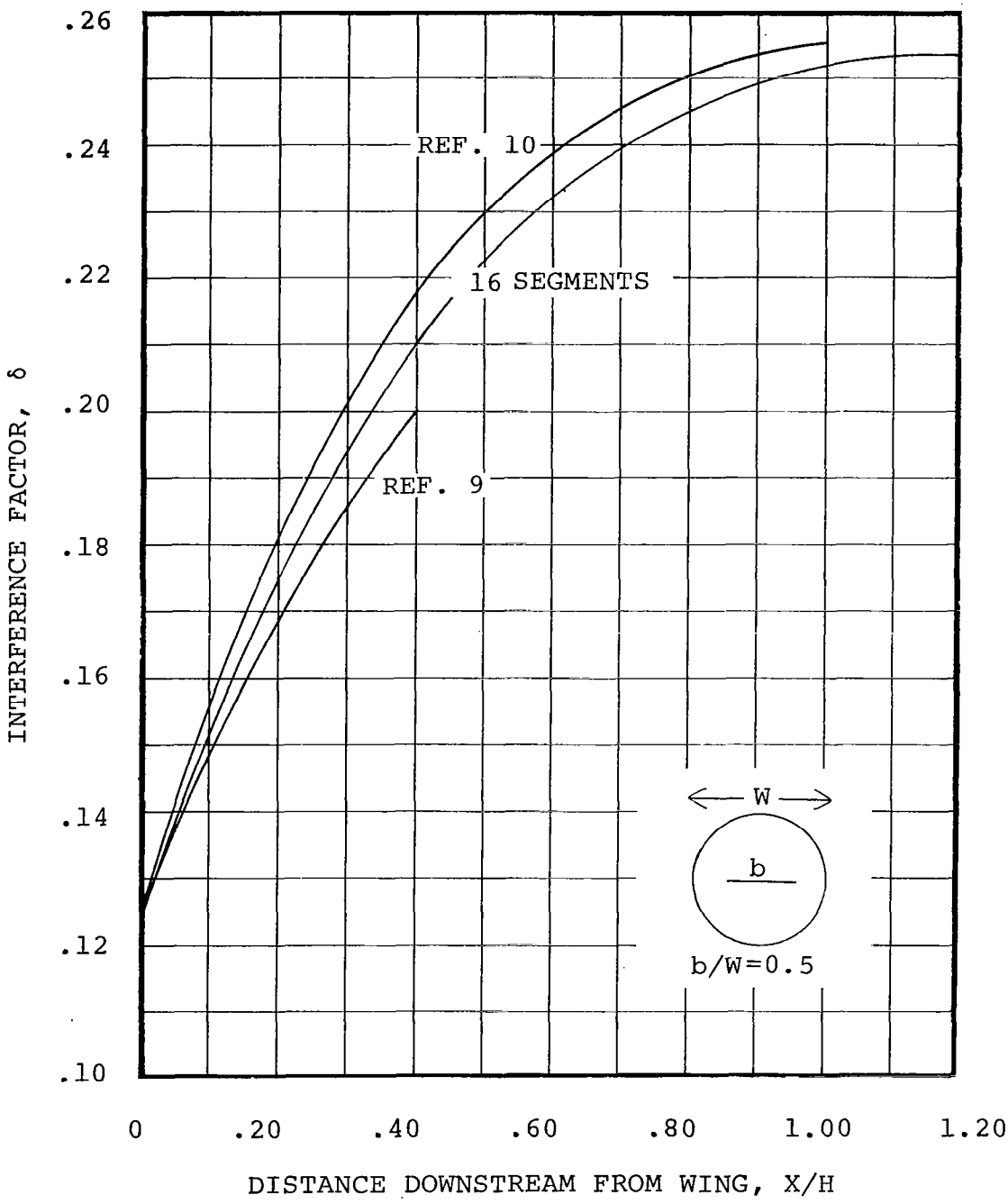


FIGURE 10

EFFECT OF TUNNEL LENGTH ON INTERFERENCE FACTORS

FOR A CIRCULAR TUNNEL

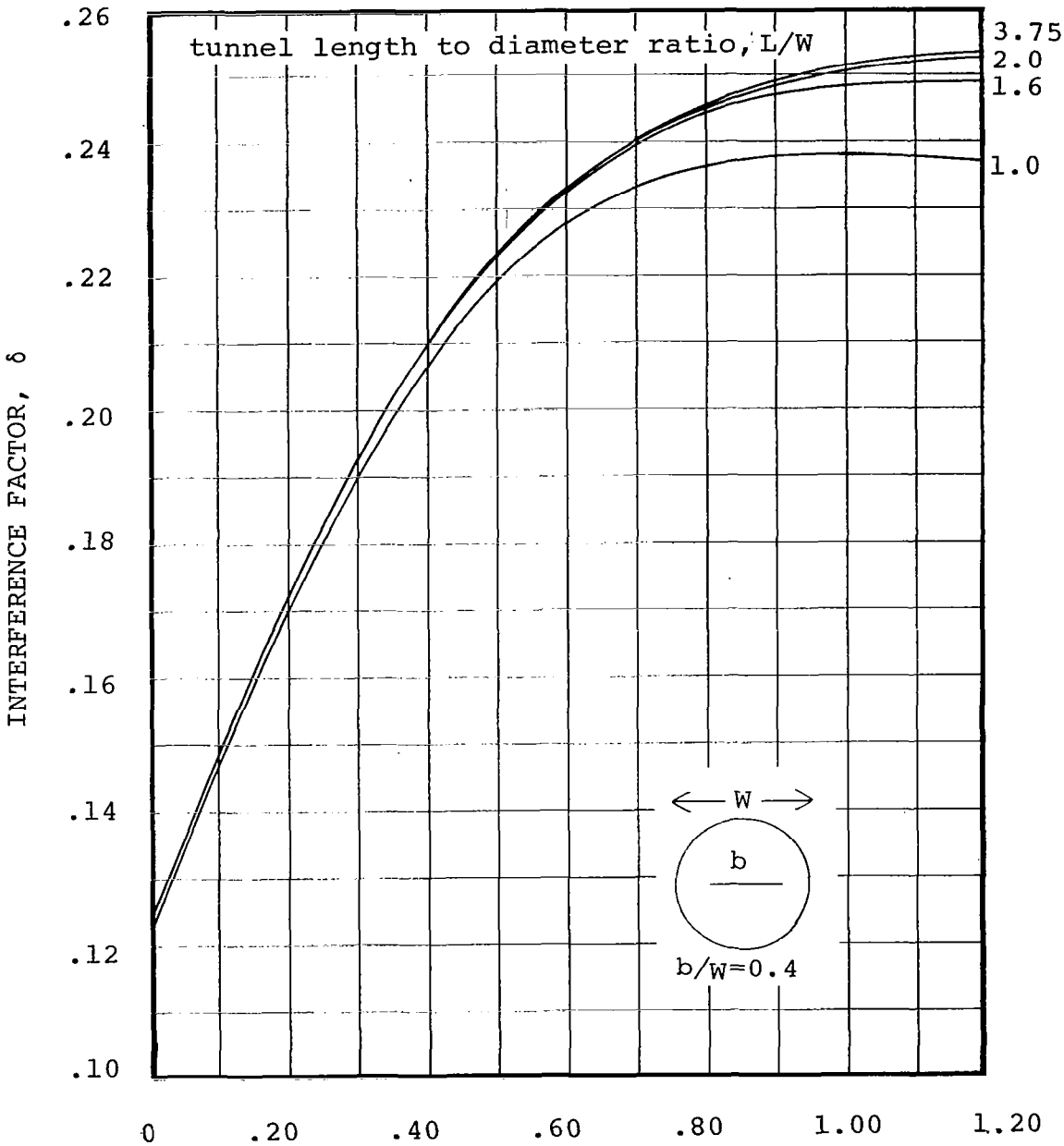
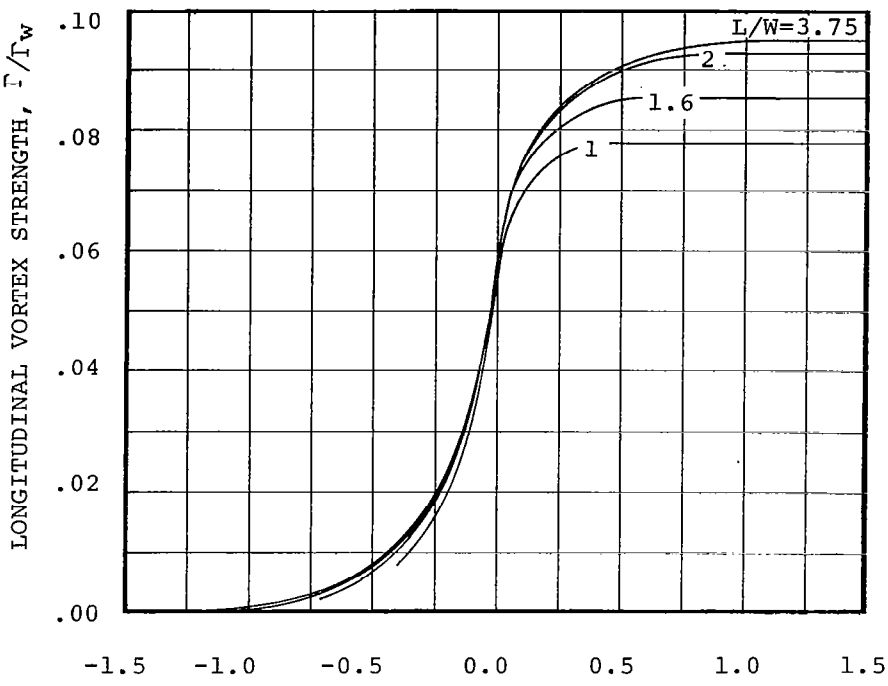


FIGURE 11

EFFECT OF TUNNEL LENGTH ON WALL VORTICITY DISTRIBUTION

FOR A CIRCULAR TUNNEL



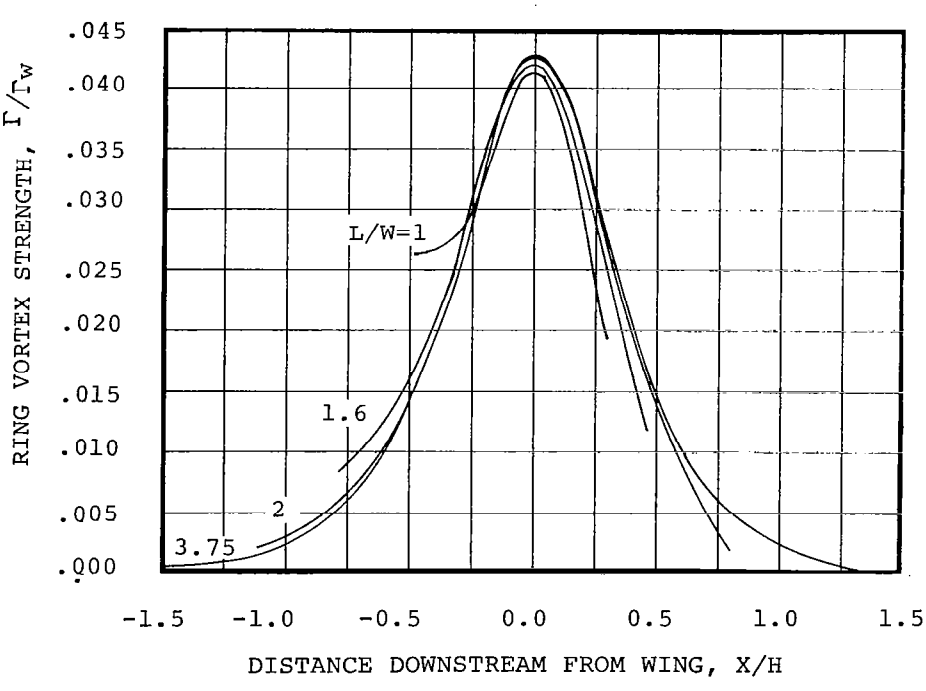


FIGURE 12

NASA-Langley, 1967 — 12 CR-845

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