N76-28172

REPORT ON THE STATUS OF A SLOTTED WIND-TUNNEL WALL REPRESENTATION USING THE VORTEX-LATTICE TECHNIQUE*

Fred L. Heltsley
ARO, Inc.

SUMMARY

A combined analytical/experimental program for development of an improved slotted wind-tunnel wall representation is described. The effort is presently being conducted at the Arnold Engineering Development Center (AEDC) and is scheduled for completion in 1977. The vortex-lattice technique which is being used as the primary analytical tool for representing both the wind-tunnel and the lifting model is discussed. Comparisons of results obtained to date with available data are presented. Included also is a brief description of the experimental effort to be conducted in conjunction with the analytical development.

INTRODUCTION

The literature contains numerous examples of the application of vortex-lattice theory to the modeling of closed wall wind tunnels (refs. 1 through 3). Interference factors provided by the vortex lattice method correlate well with values computed using various analytical techniques. Considerably less work, however, has been directed toward the vortex-lattice simulation of tunnels with partially open walls, in particular those with slots (refs. 2 and 3). In addition, comparisons of the resulting interference factors with those generated by analytical methods are limited to cases involving extremely simplified wall configurations and equally simple test vehicle geometries since analytical solutions are not available for the more complex models. This paper describes a program presently underway at the AEDC which is intended to provide a more useful vortex-lattice ventilated wind-tunnel model by accounting for the viscous effects

*The work reported herein is sponsored by NASA/Ames Research Center and was conducted by the Arnold Engineering Development Center, Air Force Systems Command. Research results were obtained by personnel of ARO, Inc., Contract Operator at AEDC. Further reproduction is authorized to satisfy needs of the U.S. Government.

9

associated with flow through and/or across the slots (ref. 4). Similar studies have been conducted to develop representations of several aerodynamic configurations (refs. 5 through 9). Many of the resulting models are capable of generating the effects of complex real flow phenomena such as separated wakes and jet exhausts although most of the simulations are strongly dependent upon empirical information. The intent of the present effort is to develop an improved mathematical wind-tunnel wall formulation by supplementing an in-depth analytical study with appropriate experimentation.

SYMBOLS

$\hat{B}_i$	unit normal vector at the ith control point, negative away from the boundary on the inner surface
$\hat{b}_i$	unit normal vector at the ith control point
C	tunnel cross-sectional area
C^*	reference tunnel area
$\vec{C}_{ij}$	influence of the jth singularity on the ith control point
C_L	lift coefficient
C_p	pressure coefficient
$d\ell$	length of a vortex line
$\vec{K}_i$	singularity density at the ith control point
N	number of singularities
P	wall
$\hat{p}_i$	unit vector parallel to the boundary at the ith control point
S	wing area

u_∞	free-stream velocity
$\vec{v}_i$	velocity induced at the ith control point in the vortex sheet
$\vec{v}_i^*$	velocity induced at the ith control point on the inner surface of the vortex sheet
$\vec{v}_i^{**}$	velocity induced at the ith control point on the outer surface of the vortex sheet
$\vec{v}_\infty$	free-stream velocity
Δv	velocity jump across the vortex sheet
W	local downwash velocity
X	nondimensionalized distance from model along center line
x/c	nondimensionalized chord length
α	angle of attack
Γ_j	strength of the jth singularity
δ	lift interference factor
δ^*	normalized lift interference factor
λ	ratio of tunnel height to tunnel width
τ	ratio of wing span to tunnel span

ANALYTICAL STUDY

Vortex-Lattice Technique

The analytical work has been directed toward representing both the wind-tunnel walls and the lifting model. The vortex-lattice technique was chosen as the primary tool since the method can be extended to simulate extremely complex aerodynamic geometries without changing the basic solution scheme. Reference 10 describes a digital program (PFP) which has been developed at the Arnold Engineering Development Center for potential flow analysis using vortex-lattice theory. The computation procedure involves definition of the model geometry and boundary conditions, calculation of the influence coefficient matrix, and solution of the resulting set of linear equations for the strengths of the individual vortex filaments. Once the singularity strengths are known, velocities can be determined anywhere in the flow field, including the model surfaces. In addition, the program is capable of computing lift forces, pressure coefficients, and streamlines. Routines are also available for generating three-view, isometric, and perspective plots of both the model input geometry and computed streamlines and velocity vectors.

Solid Surface Simulation

The PFP has been used extensively at the AEDC for aerodynamic analyses involving solid boundaries (refs. 5, 6, 8, and 10). These cases involved the classical form of the vortex lattice equation:

$$\vec{v}_i \cdot \hat{b}_i = \vec{v}_\infty \cdot \hat{b}_i + \sum_{j=1}^{N} \Gamma_j \, (\vec{C}_{ij} \cdot \hat{b}_i) \qquad (1)$$

Application of the solid-wall boundary condition, $\vec{v}_i \cdot \hat{b}_i = 0$, forces the components of velocity perpendicular to the surface to vanish and permits solution of the resulting N linear homogeneous equations.

The technique has been used to compute lift interference in a closed wall wind tunnel. A simple example is illustrated in figure 1. The resulting interference levels averaged along the span at each axial location are shown in figure 2. Included also in the plot are interference distributions for several other tunnel cross sections along with corresponding analytical results due to Kraft (ref. 12).

Slotted Wall Simulation

Extension of the method to represent tunnels with partially open walls is somewhat more difficult due to the added complexity of applying the constant-pressure boundary condition in the slots. This requires that the tangential component of velocity on the interior surface of the vortex sheet which represents the free jet boundary must vanish. It can be shown that the continuity in the tangential component of velocity across the vortex sheet is equal to the local vortex density, i.e., $K = d\Gamma/d\ell$. Since equation (1) is expressed in terms of the velocity directly on the sheet, only half of the velocity jump must be accounted for. Modification of equation (1) yields

$$\vec{V}_i^* \cdot \hat{p}_i = \vec{V} \cdot \hat{p}_i + \sum_{j=1}^{N} {}_j (\vec{C}_{ij} \cdot \hat{p}_i) + (\tfrac{1}{2}\vec{K}_i \times \hat{B}_i) \cdot \hat{p}_i \quad (2)$$

The nomenclature used in equations (1) and (2) is illustrated in figure 3.

A vortex-lattice model of a slotted wall tunnel is presented in figure 4 to demonstrate the application of both types of boundary conditions. The wall interference distribution computed for the configuration show in figure 5. In addition, distributions for a closed tunnel and a tunnel with open upper and lower walls and closed side walls are shown. Theoretical data due to Kraft (ref. 12) and vortex-lattice results computed by Bhateley (ref. 2) for similar configurations are included for comparison. Two basic rules of thumb to be followed in the construction of a model such as the one in figure 4 should be noted here. These are (1) the edge of each slot should coincide with a vortex filament and (2) the vortex grid and the control points should be positioned by the same function. In the present case, the slot configuration has been conveniently selected so that a uniform spacing satisfies both rules. Situations in which the slots are narrow relative to the width of the solid wall panels are somewhat more difficult to handle. Two primary alternatives exist. A uniform spacing which is at least as narrow as the slots can be used for both the slots and the solid wall panels. This may result, however, in a prohibitive number of singularities. An alternate solution is to select a nonuniform spacing. The use of a cosine function has been found to yield good tip definition when representing finite wings. A similar technique, illustrated in figure 6, has been used by the author. In addition to reducing the number of singularities required, the scheme provides excellent mutual slot/panel edge definition.

Lifting Model

The experimental model used during this study to provide lift interference measurements is shown in figure 7. The wing assembly consists of a 32.0 in. (81.28 cm) span x 9.0 in. (22.86 cm) chord NACA 63A006 airfoil with a minimum blockage circular centerbody. A similar half-scale assembly is mounted aft of and above the wing to provide tail surface measurements. A vortex-lattice representation of the lifting model is presented in figure 8. Since the PFP is capable of assuming symmetry, definition of only one-half of the model is required. Pressure coefficient distributions over a two-dimensional version of the wing model are shown in figures 9 and 10 to illustrate the effects of grid spacing and angle of attack, respectively. In all cases, a precisely computed cosine (cosine) function was used to determine both the vortex and the control point locations. An attempt to interpolate between previously obtained "as built" coordinates proved to be unsuccessful due to the extreme sensitivity to the lack of measurement precision. Finally, good results were achieved by generating slope continuous smoothing functions to define the surface.

Details of the leading and trailing edges of the lattice wing model are shown in figure 11. It should be noted that the trailing edge was not closed but was allowed to "leak" in both the two- and three-dimensional models since the tips of the three-dimensional wing were closed with lattice plates.

A less detailed vortex-lattice representation of the lifting model is under development which will require a significantly smaller number of singularities. The new model will be utilized in order to reduce the computer time required during the development of the tunnel wall model. Later, the detailed vortex lattice lifting model will be recalled to provide the necessary precision for correlation of analytical and experimental interference results.

EXPERIMENTAL PROGRAM

Wind-Tunnel Description

The AEDC Low Speed Wind Tunnel (V/STOL) shown in figure 12 will be used to provide experimental interference data. The tunnel has a test section 45.0 in. (114.3 cm) wide and 36.0 in. (91.44 cm) high and is capable of generating velocities from near zero to 250 ft/sec (76.2 m/sec). The solid test section walls can easily be replaced with selected slotted walls to provide wall flow relief. Figure 13 is a schematic of the lifting model installed in the V/STOL tunnel. The installation shown permits an angle-of-attack variation from 6° to 16° about the pitch center.

Interference Free Data

Only a limited amount of suitable interference free data are available for the lifting model since a majority of the previous tests has been conducted at high Mach numbers. Plans are presently underway to obtain the necessary additional interference free data for the lower Mach numbers.

CONCLUDING REMARKS

The vortex-lattice technique has been successfully used to represent solid surfaces for both the wind-tunnel walls and the lifting model. Correlation with available interference free experimental data and analytical results were excellent. In addition, the free jet boundary condition has been applied to simulate the flow in the tunnel wall slots. Good agreement was obtained with existing analytical predictions. Development of both vortex-lattice models is continuing.

Preparation for the experimental program is underway and testing will begin in the near future.

REFERENCES

1. Joppa, Robert G. "Wind Tunnel Interference Factors for High-Lift Wings in Closed Wind Tunnels." NASA CR-2191, February 1973.

2. Bhateley, I. C. "A Theoretical Optimization of the Test-Section Geometry for the Proposed Boeing Low-Speed Wind Tunnel." Boeing Report D6-15023, February 1967.

3. Wasserstrom, E., Borovik, Y., Hazandvsky, D., and Rom, J. "Calculation of Lift Interference Corrections Due to Wind-Tunnel Test-Section Boundaries by the Vortex-Lattice Method." T.A.E. Report No. 124, Technion-Israel Institute of Technology, Haifa, Israel, April 1971.

4. Keller, J. D. "Numerical Calculation of Boundary-Induced Interference in Slotted or Perforated Wind Tunnels Including Viscous Effects in Slots." NASA TN D-6871, August 1972.

5. Parker, R. L., Jr. and Heltsley, F. L. "Simulation of a High Disc Loading Free Propeller in a Cross Flow by the Vortex-Lattice Method." AEDC-TR-72-139, November 1972.

6. Heltsley, F. L. and Parker, R. L., Jr. "Application of the Vortex Lattice Method to Represent a Jet Exhausting from a Flat Plate Into a Crossflowing Stream." AEDC-TR-73-57, June 1973.

7. Rubbert, P. E., et al. "A General Method for Determining the Aerodynamic Characteristics of Fan-in-Wing Configurations." Vol. 1 and 2, USAAVLABS TR-67-61A, December 1967.

8. Palko, R. L. "Full-Scale Inlet/Engine Testing at High Maneuvering Angles at Transonic Velocities." AIAA Paper No. 72-1026, September 1972.

9. Maskew, B. "Calculation of the Three-Dimensional Potential Flow Around Lifting Non-Planar Wings and Wing-Bodies Using a Surface Distribution of Quadrilateral Vortex-Rings." Loughborough University of Technology, Report TT 7009, September 1970.

10. Todd, D. C. and Palko, R. L. "The AEDC Three-Dimensional, Potential Flow Computer Program, Vol. I and II." AEDC-TR-75-75.

11. Kraft, E. M. and Lo, C. F. "A General Solution for Lift Interference in Rectangular Ventilated Wind Tunels." AIAA Paper No. 73-209, January 1973.

12. Kraft, E. M. "Upwash Interference on a Symmetrical Wing in a Rectangular Wall Wind Tunnel: Part I - Development of Theory." AEDC-TR-72-187, March 1973.

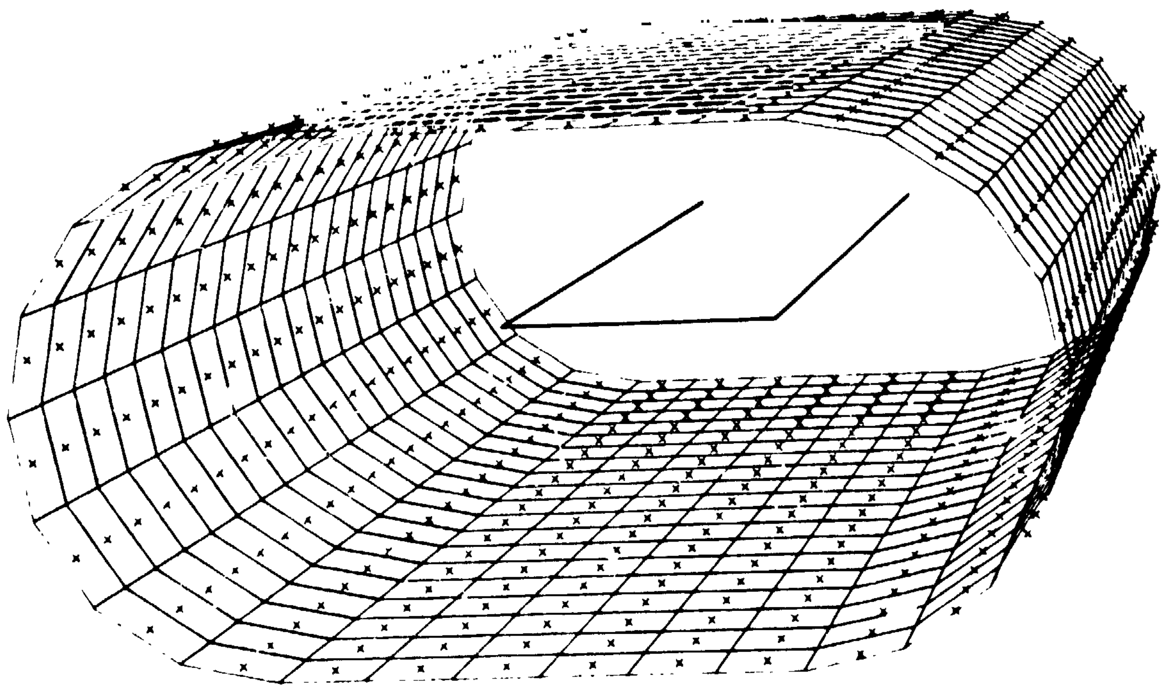


Figure 1.- Vortex-lattice representation of the NASA Ames flat oval tunnel.

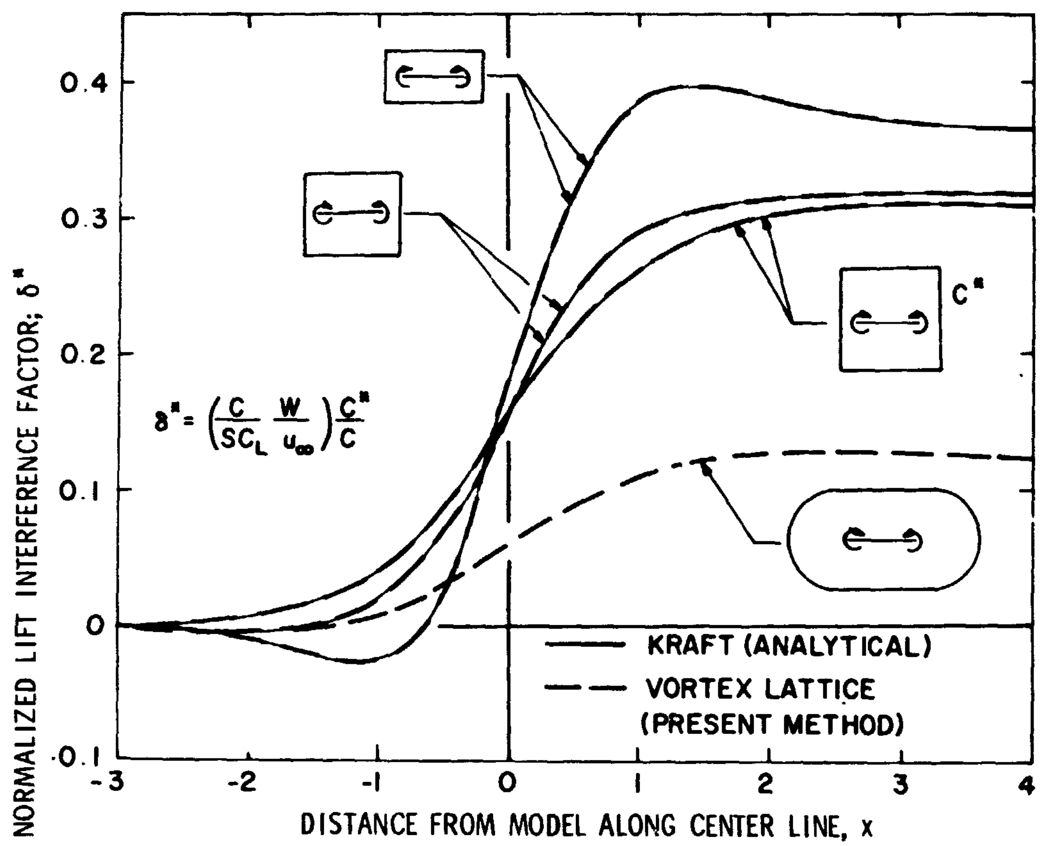
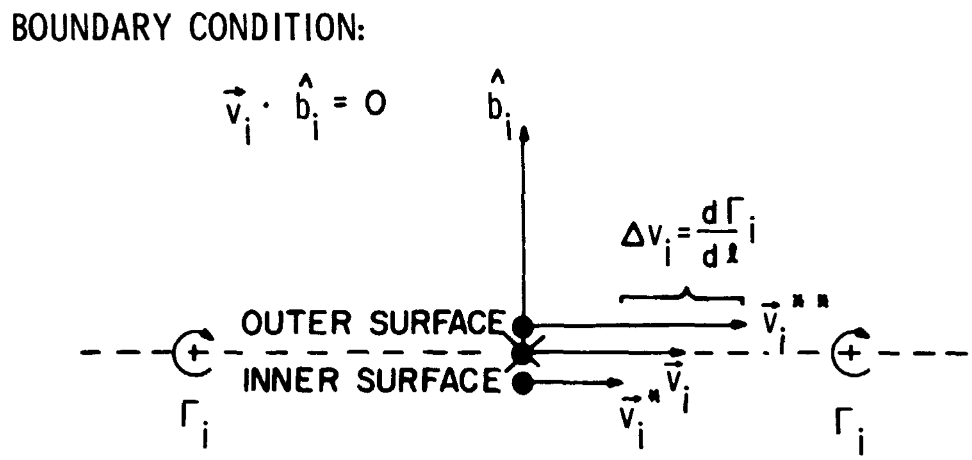
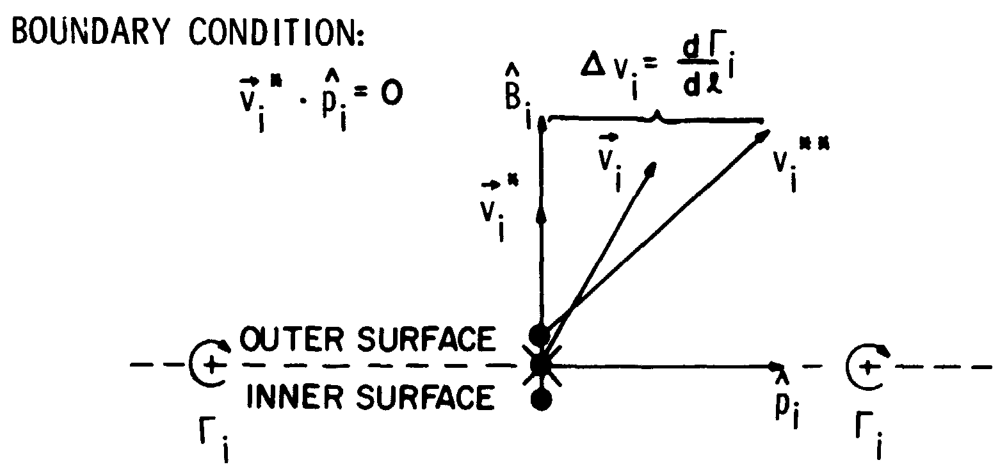


Figure 2.- Comparison of theoretical wall interference results for several tunnel cross sections.



CLOSED WALL BOUNDARY



FREE JET BOUNDARY

Figure 3.- Vortex-lattice boundary condition nomenclature.

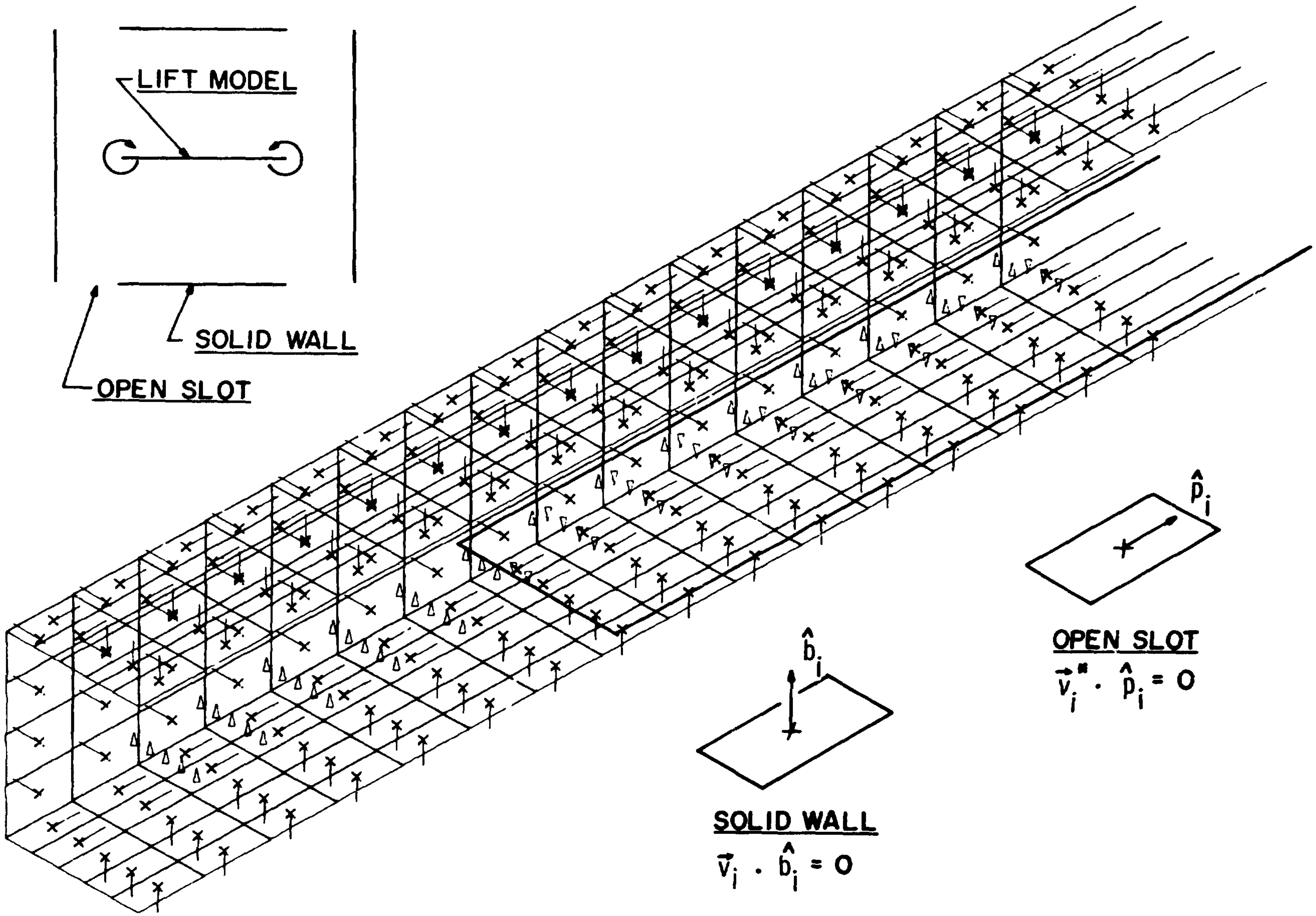


Figure 4.- Basic vortex-lattice wind tunnel model.

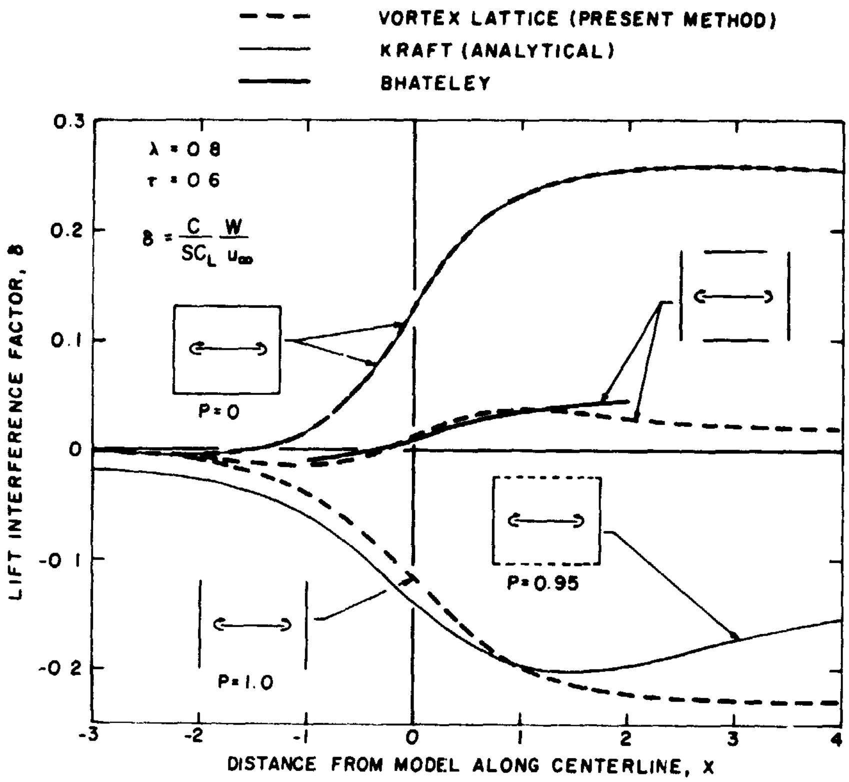
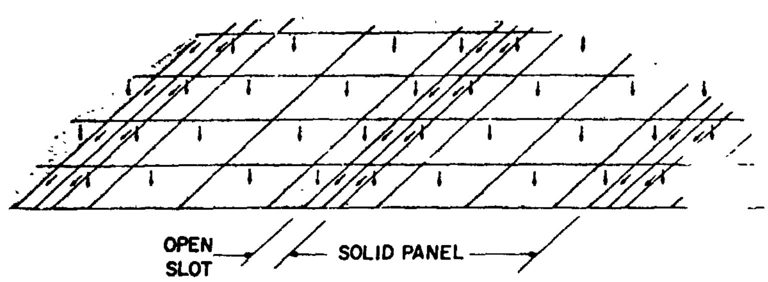


Figure 5.- Comparison of present data with other techniques for several tunnel configurations.



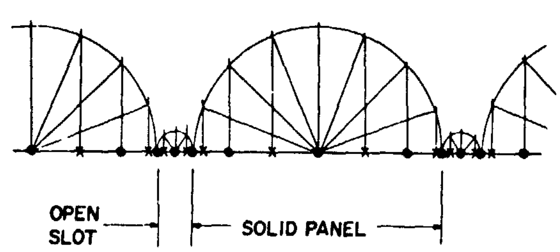


Figure 6.- Cosine spa 'ng details.

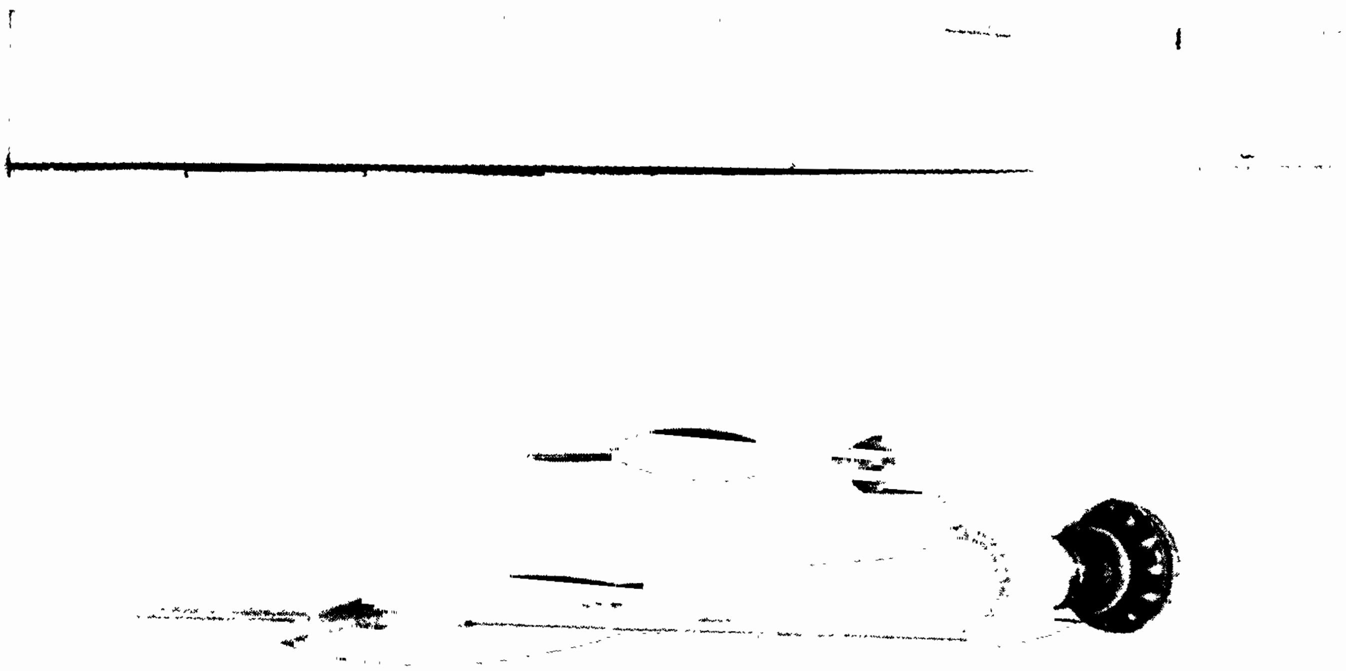


Figure 7.- Experimental lifting model.

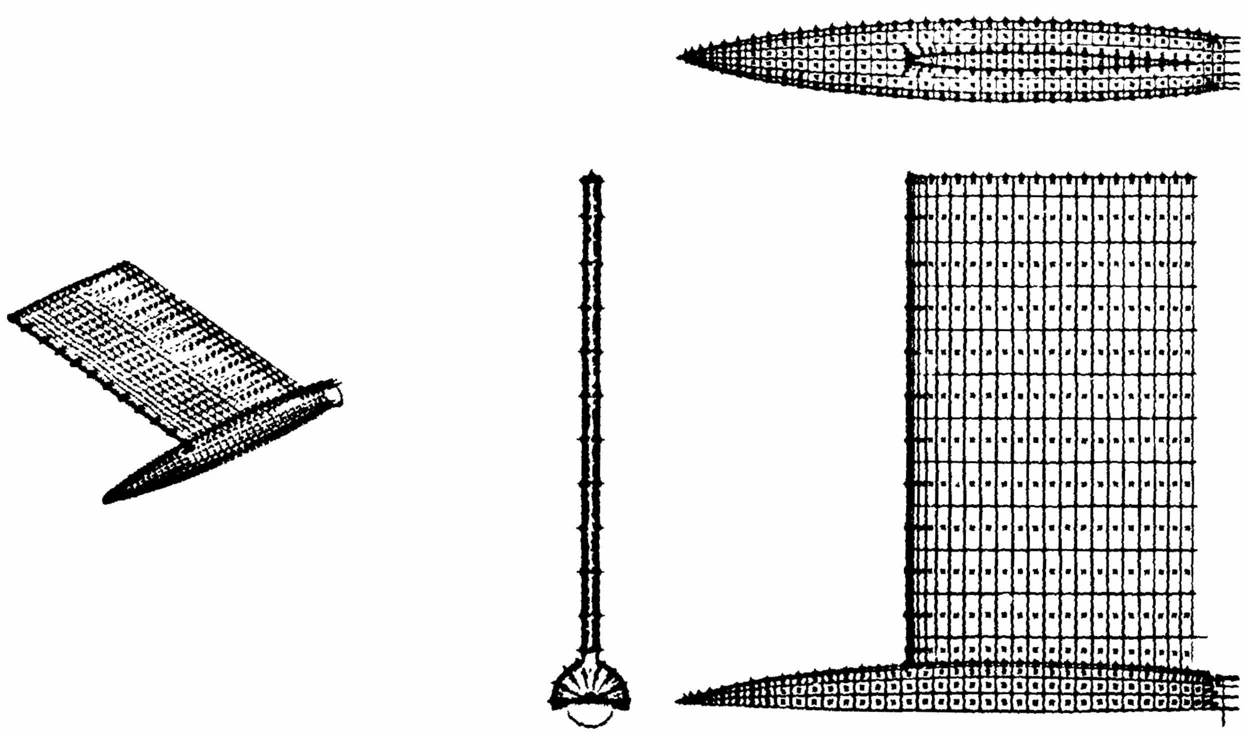


Figure 8.- Detailed vortex-lattice representation of the lifting model.

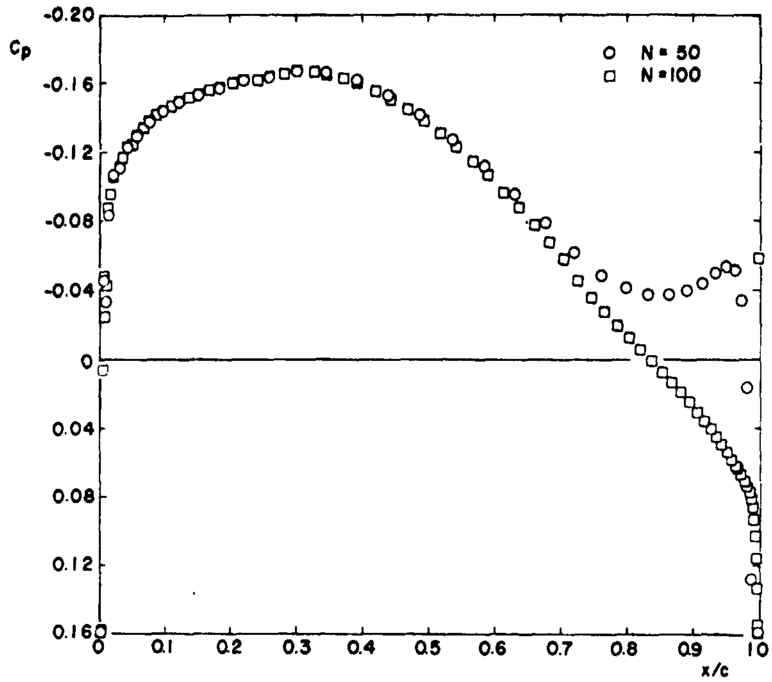


Figure 9.- Effect of vortex spacing.

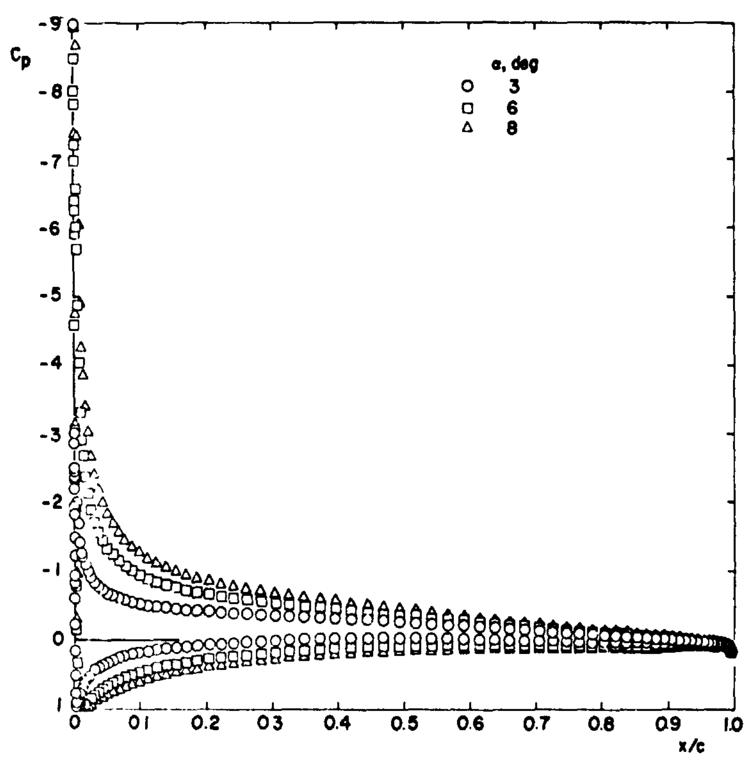


Figure 10.- Wing pressure coefficient versus angle of attack.

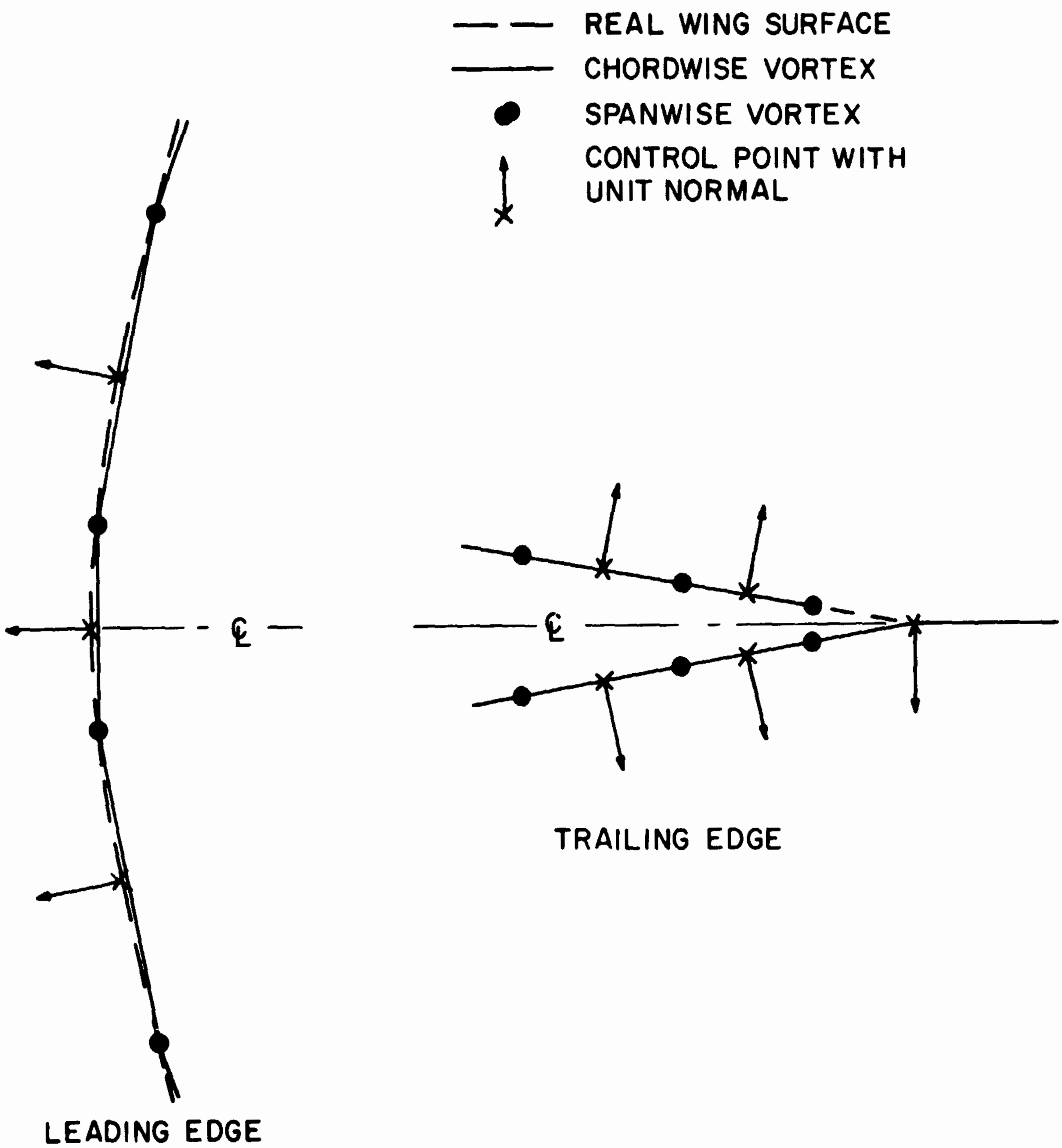


Figure 11.- Wing lattice details.

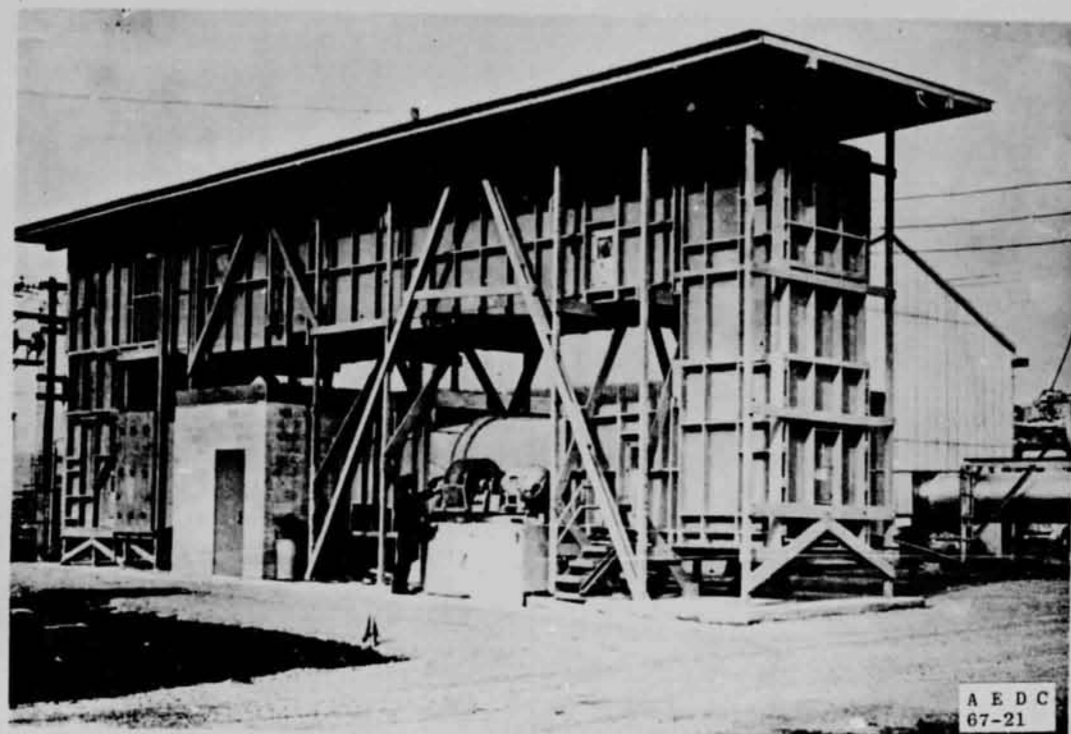


Figure 12.- AEDC low speed wind tunnel (V/STOL).

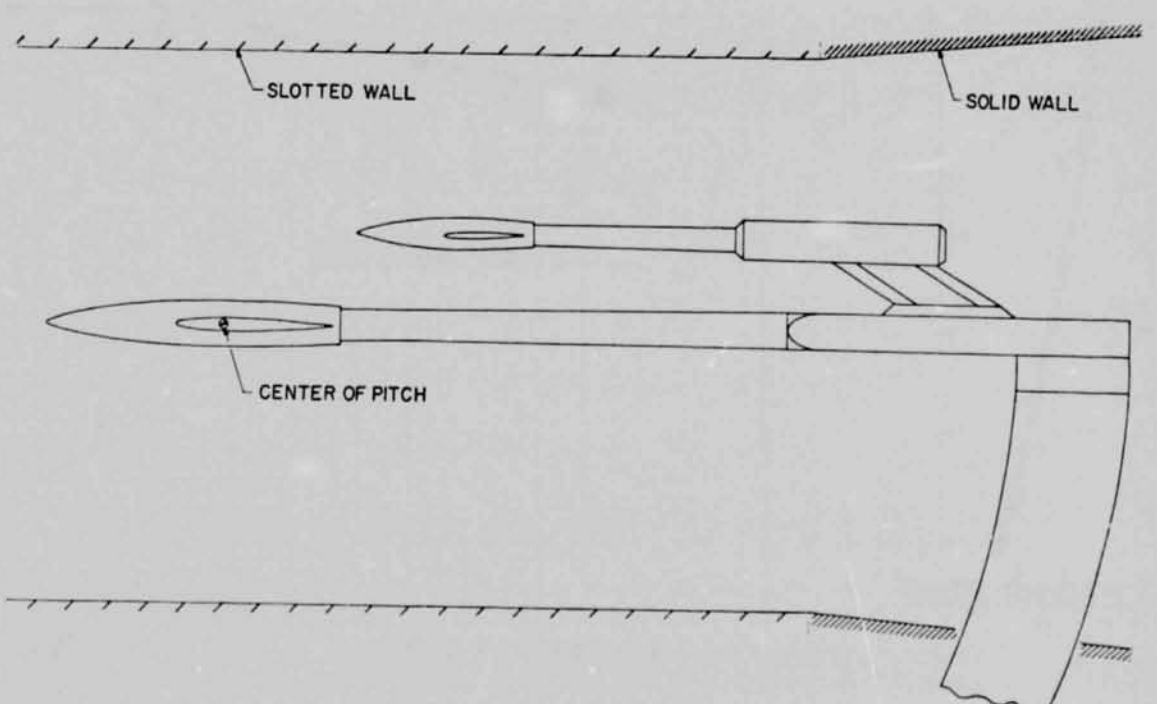


Figure 13.- Lifting model installed in the AEDC low speed wind tunnel (V/STOL).