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A METHOD OF WAKE PRODUCTION IN WATER TUNNELS

by

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HYDROMECHANICS LABORATORY

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ABSTRACT

A procedure for producing prescribed, arbitrary longitudinal velocity distributions in water tunnels, by arrangements of wire screens, is outlined. A theory for flow past nonuniform screens is summarized and experimental results are presented, along with a description of the method of screen fabrication. The predicted and measured velocity distributions are found to be in good agreement.

INTRODUCTION

During the past two years a method has been developed at the David Taylor Model Basin for producing prescribed nonuniform axial velocity distributions in closed jet water tunnels. Since the ITTC Cavitation Committee, during this period, has been evaluating existing methods for producing such flows for propeller testing, and since the results of the work at DTMB have not yet been published, it is believed that a summary of the work to date would be of interest to the delegates to the ITTC.

The wake producer consists of a grid of screens of various mesh sizes, having known resistances, which are arranged in a predetermined pattern on a support screen to yield a prescribed velocity distribution. The distribution of screen resistance is based on a theory for flow past grids of nonuniform properties and the trial-and-error system is eliminated. Following, an outline of the theory is presented, the method of fabrication of the grids is given, and some experimental results are shown.

THEORY

The formulation is presented for steady, moderately sheared, three-dimensional flow past a wire grid of arbitrary resistance distribution which is placed normal to the axis of a duct of arbitrary but constant cross-section. The formulation is an extension to those given by Owen and Zienkiewicz[1] and Elder[2] for weakly sheared, two-dimensional flow past wire grids. Unlike

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[1] References are listed on page 6.

these previous formulations, however, it is not required that the departures from uniformity of velocity and resistance be small. The velocity far upstream of the screen is assumed uniform and downstream of the grid it is assumed that streamline deflections are sufficiently small so that vorticity may be taken constant along streamlines. Far upstream and far downstream the static pressure is taken to be uniform and the nonaxial velocity components are taken to be zero. It is found by experiment that upstream and downstream of a grid these conditions are reached within a distance roughly equal to the lateral dimensions of the grid. Viscosity is neglected except in the immediate vicinity of the grid and the grid is considered as a surface of hydrodynamic discontinuity. At the grid the effect of viscosity produces a static pressure drop across the grid and locally deflects streamlines. The local pressure drop is defined by a nondimensional resistance coefficient, K, which is based on the local velocity normal to the grid, w_o;

$$K = \frac{\Delta p}{\frac{1}{2} \rho w_o^2} \qquad [1]$$

The discontinuity in lateral velocity at the grid is defined by a refraction coefficient, α, where

$$\alpha = \frac{\text{local nonaxial velocity component immediately downstream of grid}}{\text{local nonaxial velocity component immediately upstream of grid}}, \qquad [2]$$

and is related to resistance coefficient[3] by

$$\alpha = 1.1 \ (1 + K)^{-\frac{1}{2}} \qquad [3]$$

Denoting the axial velocity far downstream of the grid by $w_{+\infty}$, a linearized equation of motion may be written in the form,

$$K \frac{d}{dK} w_o + \frac{1}{2} w_o + \frac{d}{dK} w_{+\infty} = 0 \qquad [4]$$

To relate the axial velocity at the grid, w_o, to the axial velocity far downstream, $w_{+\infty}$, a perturbation velocity potential is defined and the perturbation velocities are superimposed on the flows far upstream and far downstream. Using the boundary conditions at the grid, namely:

(a) the continuity of axial flow across the grid, and (b) the discontinuity in nonaxial velocity across the grid as given in equation [2], one obtains,

$$w_o = \frac{1}{1 + \alpha} \left(w_{+\infty} + \alpha w_{-\infty} \right) \qquad [5]$$

which for the special case of continuity of nonaxial flow across the grid ($\alpha = 1$) yields the expression obtained in the "actuator disk problem," where the axial velocity at the grid is the average of those far upstream and far downstream of the grid.

The equation of motion [3] is then solved by substitution of equations [3] and [5], and after considerable manipulation the resulting relation between resistance coefficient and velocity distribution is given by,

$$w' = 1 - N \frac{(1 + \chi)}{(1 + \chi^3)^{\frac{2}{3}}} \left[\frac{1/6 + \chi^3}{\chi^2} - \gamma_o \right] \qquad [6]$$

where,

$$w' = w_{+\infty} / w_{-\infty}$$

$$\chi = (1 + K)^{\frac{1}{2}}$$

$N = 1.00 \rightarrow 1.02$, based on average K

$$\gamma_o = \frac{\int_\sigma \frac{1 + \chi}{(1 + \chi^3)^{\frac{2}{3}}} \cdot \frac{1/6 + \chi^3}{\chi^2} \, d\sigma}{\int_\sigma \frac{1 + \chi}{(1 + \chi^3)^{\frac{2}{3}}} \, d\sigma}$$

where, $d\sigma$ is an increment of area on the grid.

Equation [6] is plotted in Figure 1 for a range of γ_o values taking $N = 1.02$. For the design of a given grid γ_o would be determined by first selecting a screen having minimum K to produce the highest velocity desired. Substitution of w'_{max} and K_{min} into Equation [6] would then allow γ_o to be determined and, for the complete design of the grid, the distribution of K could then be determined from Equation [6] or Figure 1 for a prescribed distribution of velocity, w'. It should be noted that w' is nondimensionalized on the basis of the average flow velocity in the duct;

therefore, ship wakes nondimensionalized on ship speed must be adjusted accordingly in using Figure 1 or Equation [6].

FABRICATION OF GRID

The grids are constructed by arranging screens of various mesh sizes in carefully fitted patterns on a single support screen of low resistance coefficient. All screens used are of the square mesh, plain weave variety and made of stainless steel wire. The support screen used is a 16 x 16 wires per square inch mesh with a 0.009-inch wire diameter and a 0.267 solidity ratio. The resistance coefficient of each screen combination was calculated from Equation [1] using water tunnel measurements of pressure drop and flow velocity across the screens, and in Figure 2 the experimental resistance coefficients for thirty-six screen combinations are plotted versus solidity ratio, s, of the overlay screen. Also shown is an estimated resistance coefficient curve which is based in part on the work of Weighardt,[4] and is given by the formula,

$$K = 0.78 \frac{s}{(1 - s)^2} + K_s \qquad [7]$$

where,

$K_s = 0.41$ = resistance coefficient of support screen.

For the Reynolds number range, $600 < R_e < 5000$, (based on the overlay screen geometry) the change in resistance coefficient was found to be small. It was also found that changes in the orientation of the wires of one screen relative to the other had a negligible effect on resistance coefficient. The scatter of the experimental results in Figure 2 can probably be attributed to departures of screen geometry from nominal dimensions, and dirt or scale which would occasionally collect on the screens. In designing wake producing grids, in all cases the experimentally measured resistance coefficients were used, rather than those determined by Equation [7].

The fabrication of the wake producer grids requires great care in order that the various screens making up the grid are accurately pieced together. The method of fabrication which has finally been adopted is as follows:

A. The required screen pattern is drawn on a 1/8-inch thick aluminum sheet and the pieces are cut out using a 1/64-inch thick band saw blade. A number of 1/8-inch diameter holes are then drilled in each pattern.

B. The required overlay screens are then glued to the aluminum patterns and are cut to size using the band saw.

C. The support screen is stretched and permanently attached to a stainless steel frame; the aluminum-plus-screen patterns are laid out on the support screen. Through each hole the overlay and support screen wires are then spot welded together.

D. Solvent is applied to the glue and the aluminum patterns are removed. Final welding of the screens is then completed.

Two grids which have been fabricated in this way are shown in Figure 3.

EXPERIMENTAL RESULTS

The wake experiments were performed in a 12-inch diameter lucite duct which was inserted into the open jet test section of the David Taylor Model Basin 12-inch water tunnel. Two grids were designed according to Equation [6] to produce wakes which would adequately check the theoretical results and which were representative of those wakes of interest in propeller testing. The grids constructed are shown in Figure 3 and the measured and predicted wake distributions are shown in Figures 4 and 5.

The first grid was designed to produce a circumferentially varying sinusoidal velocity distribution as given by the formula,

$$w' = 1 + \frac{(r/R)^2}{2} \sin 2\theta$$

where,

r/R = nondimensional duct radius.

Velocity measurements were taken one duct diameter downstream of the grid ($z/R = 2.0$) where the static pressure was found to be uniform and no significant change was measured in the velocity distribution at $z/R = 3.0$, the furthest position downstream of the grid investigated. The maximum deviation of theory from experiment amounts to about 3 percent of the mean velocity.

The second grid was designed to produce the axial velocity distribution in the wake of a single-screw surface ship. The predicted velocity distribution has been calculated from Equation [6], but because of the great nonuniformity of the velocity distribution a streamline deflection correction, based on continuity considerations, had to be made to the theoretical result. In Figure 5 the corrected theoretical curve is shown as a stepwise distribution of velocity in order to accentuate the stepwise nature of the resistance distribution of the screens. The measured velocity distribution is plotted in Figure 5 for three axial positions downstream of the grid, $z/R = 0.5$, 2.0, and 3.0. The static pressure did not become uniform until a position nearly one duct diameter downstream of the grid ($z/R = 2.0$). Further downstream of this position the experimental results indicate that in areas of large velocity gradient the axial velocities tend to equalize. As would be expected, then, the calculated and measured velocities are in best agreement for the $z/R = 2.0$ position (indicated by the dashed line in Figure 5) where the static pressure has become uniform and where the decay of the high velocity gradients has not yet begun.

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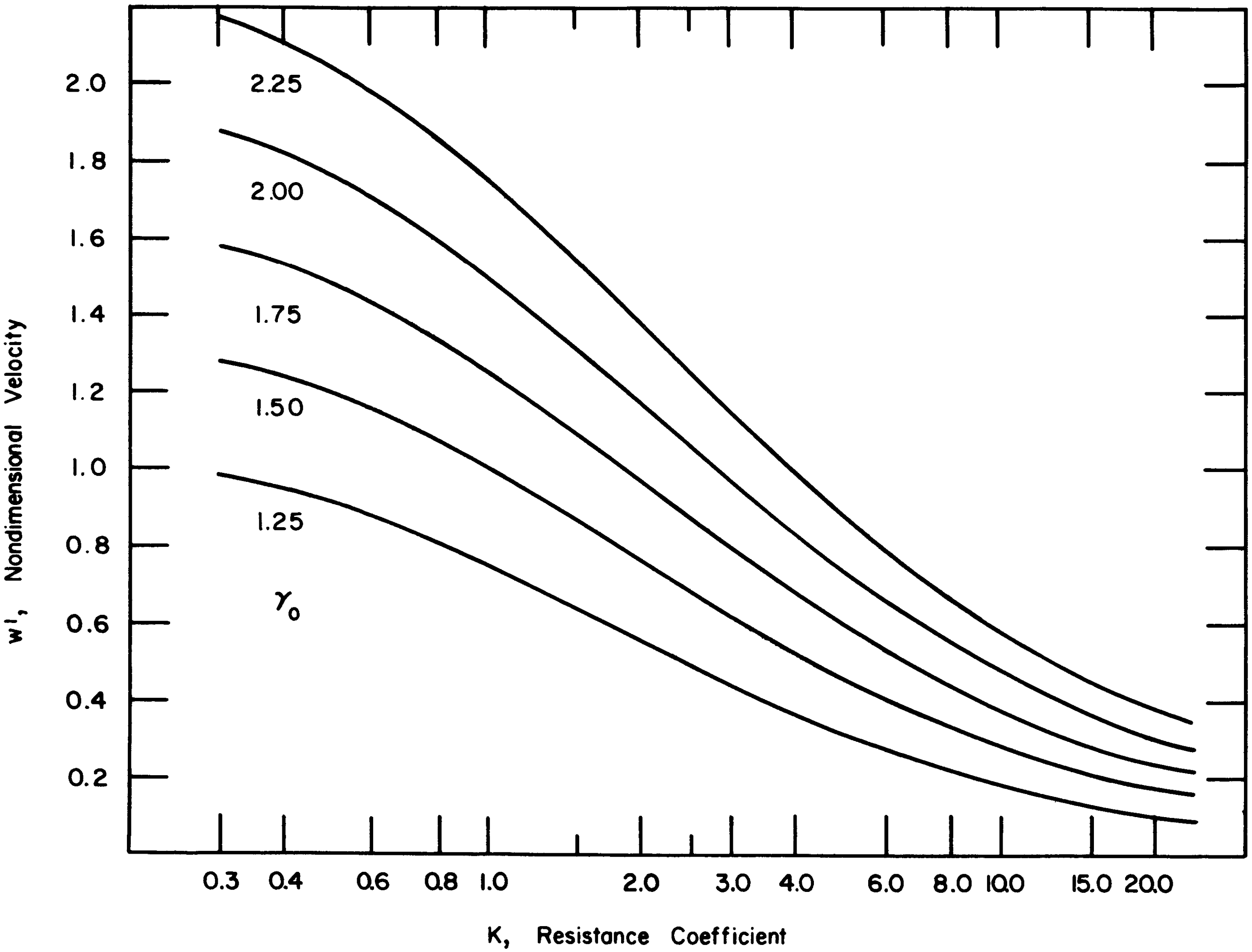

Figure 1 - Plot of Equation [6], Giving Relationship Between K and w' for a Range of γ_0

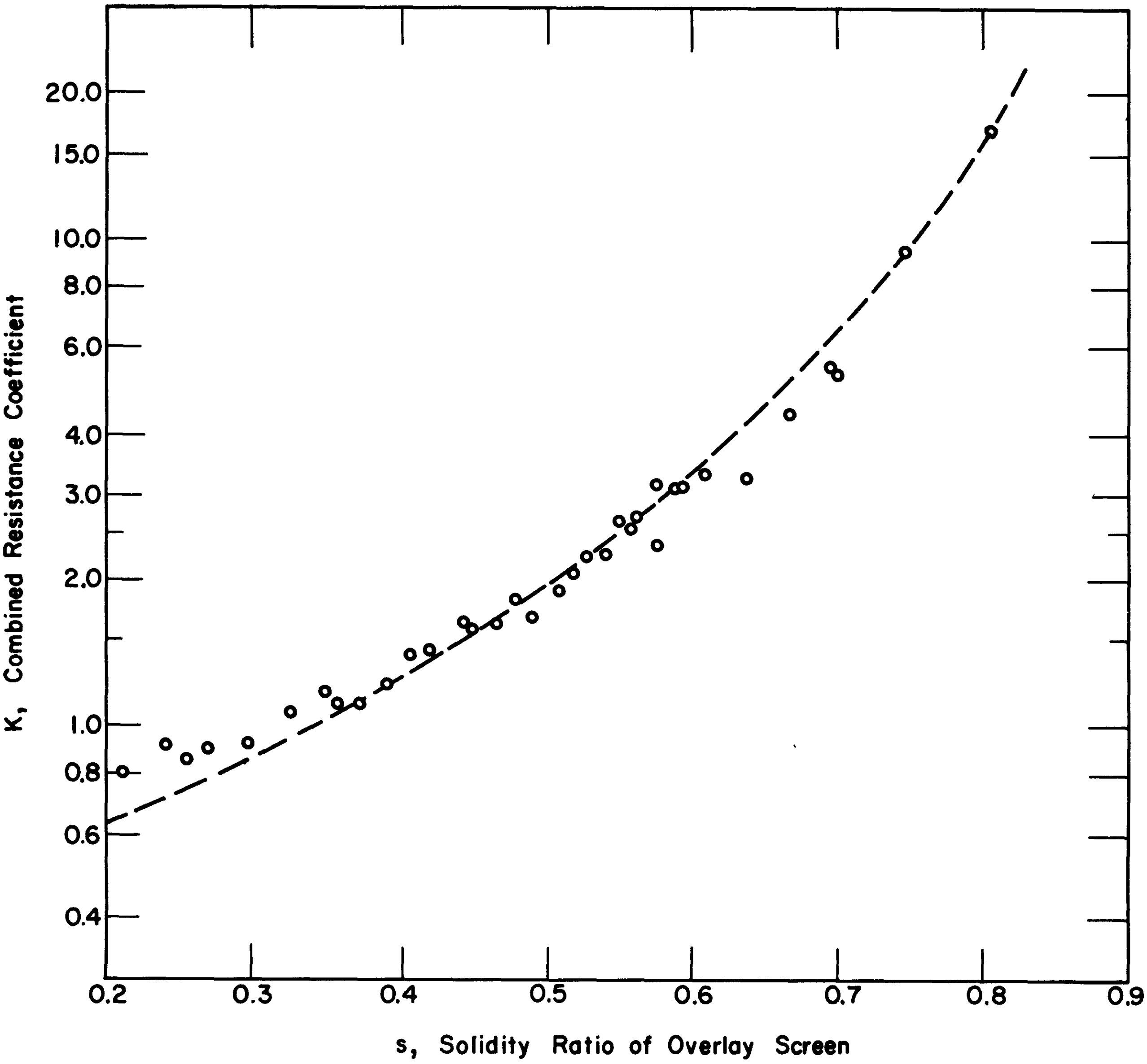

Figure 2 - Plot of Experimentally and Theoretically Determined Relationship Between K and s, for Screens in Combination with a 16 x 16 x 0.009" Support Screen

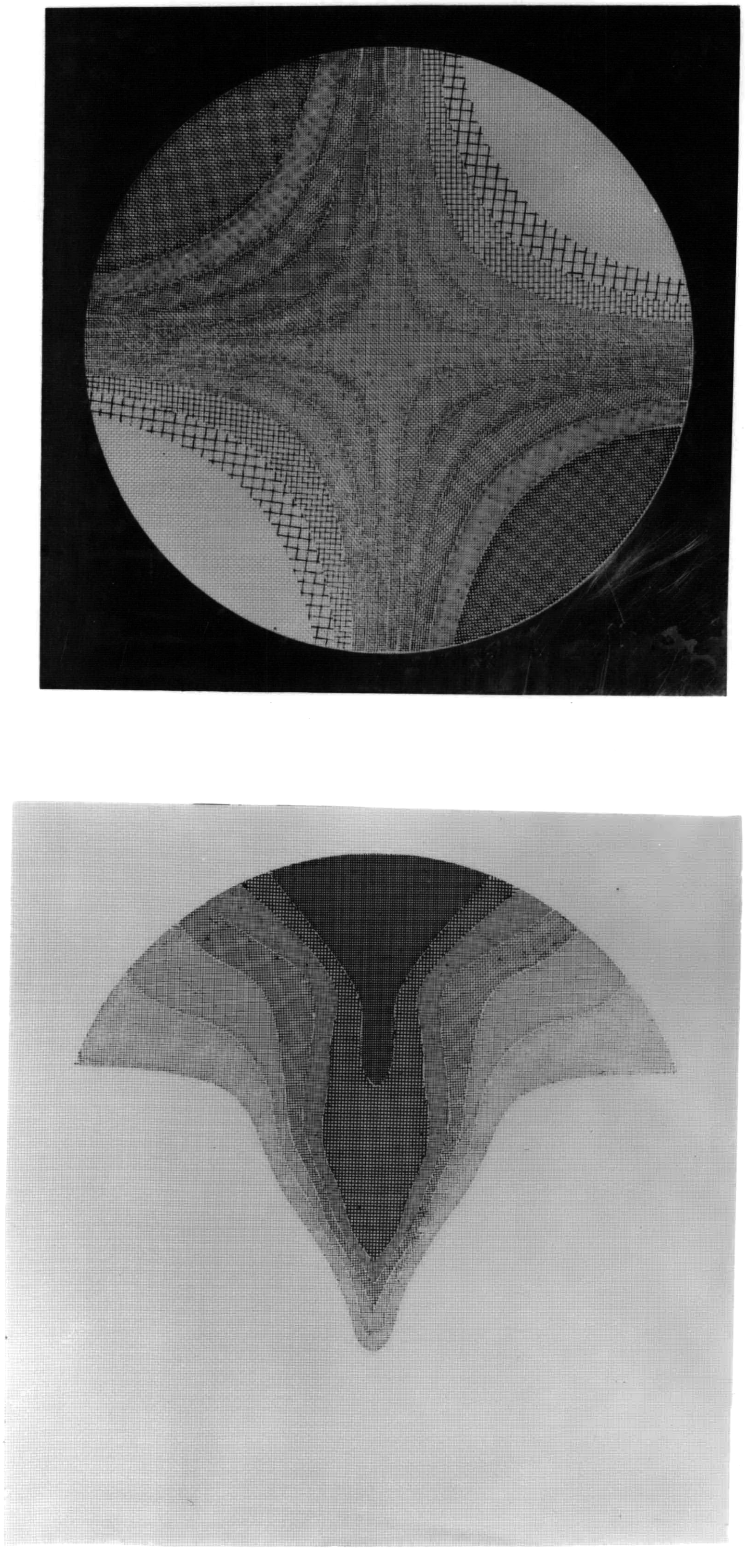

Figure 3 - Photographs of the Grids Constructed to Produce a Sinusoidal Velocity Distribution and the Axial Velocity Distribution in the Wake of a Single-Screw Surface Ship

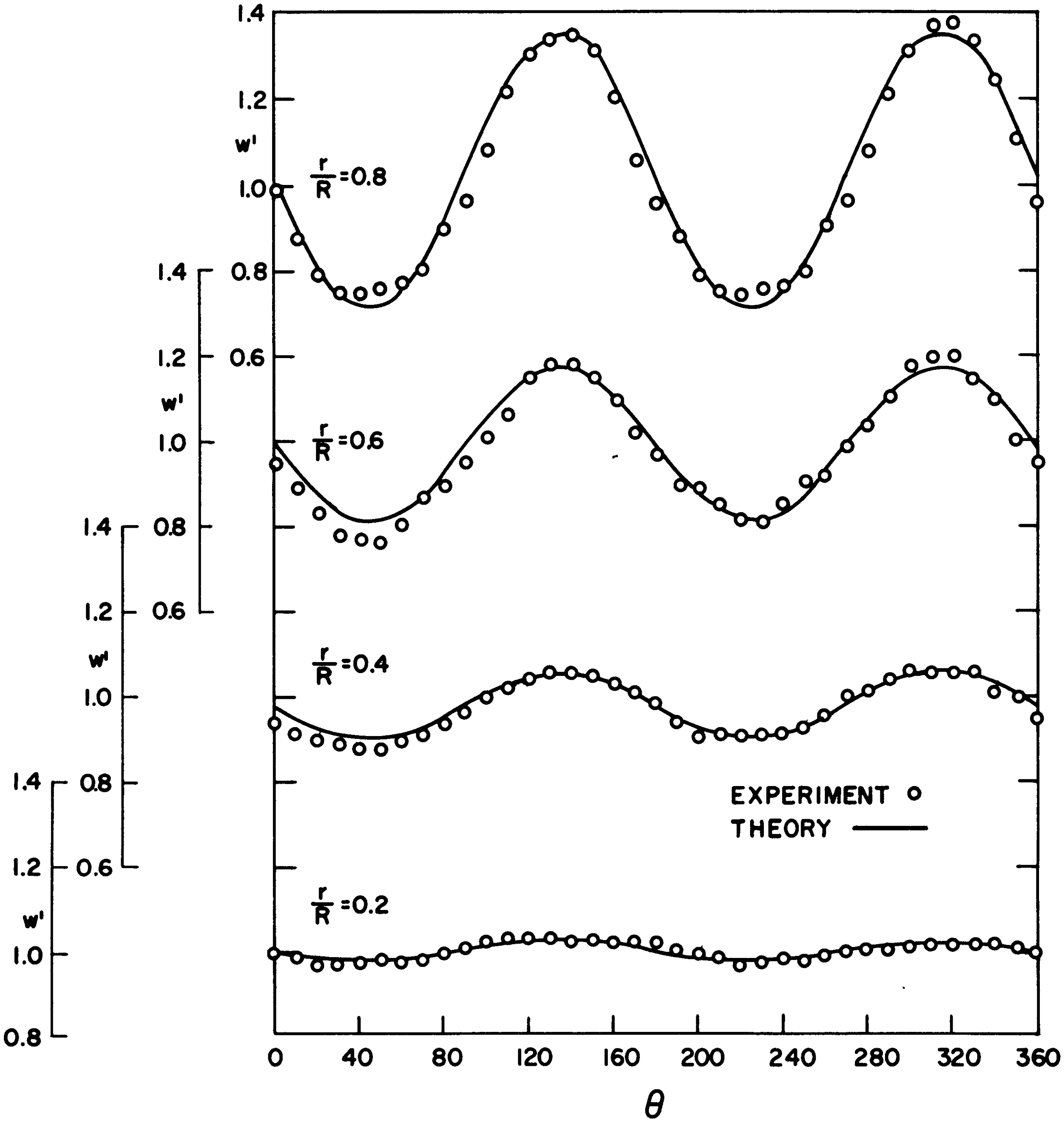

Figure 4. Measured and Calculated Velocities for Grid Designed to Produce a Sinusoidal Velocity Distribution

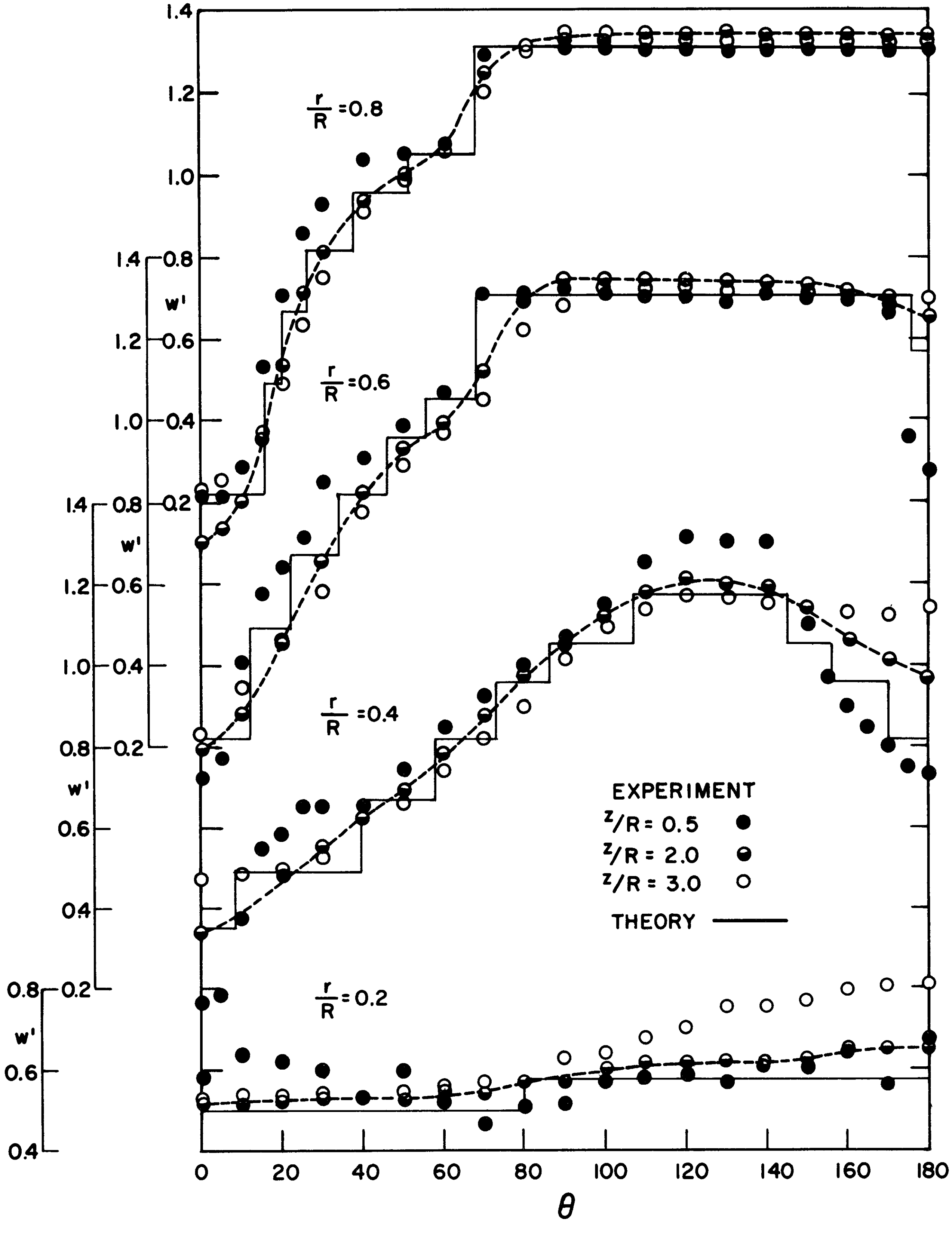

Figure 5 Measured and Calculated Velocities for the Grid Designed to Produce the Axial Velocity Distribution in the Wake of a Single – Screw Surface Ship.

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