EFFECT OF WAKE ON WAVE RESISTANCE OF A SHIP MODEL

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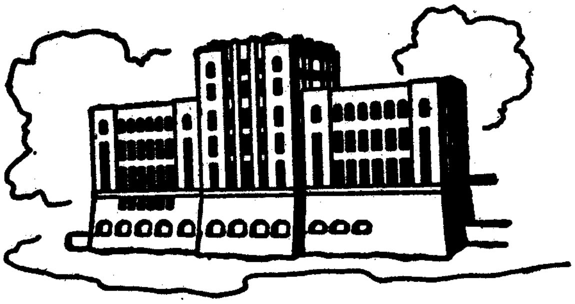

IIHR Report No. 180

Iowa Institute of Hydraulic Research
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ABSTRACT

For the purpose of resolving the question of the influence of its wake on the wavemaking resistance of a ship, the total, viscous and wavemaking resistance of a Series 60 ship model were measured with the wetted surface first smooth, and then rough. It was found that the wave resistance was significantly less with the rough surface, implying that viscous effects should not be neglected in the development of higher-order wave theory.

Since the wake-survey method was used to determine the viscous resistance, the opportunity was taken to compare the results with roughness with the values obtained by calculating the boundary layer on the rough "equivalent" body of revolution, with satisfactory agreement.

A long-period surge in the towing tank, of sufficient amplitude to affect the analysis of both the wake and surface-profile data, was detected. Procedures for correcting for this surge are indicated.

The sum of the viscous and wavemaking components is found to be less than the measured total resistance. It is concluded that the missing component is principally due to longitudinal vortices, the contribution of which to the viscous resistance is not detected in the present wake-survey procedure.

EFFECT OF WAKE ON WAVE RESISTANCE OF A SHIP MODEL

I. INTRODUCTION

It is customary to assume that the resistance of a ship hull, at a uniform speed, is the sum of viscous and wavemaking resistances, where the latter component is regarded as a function of the Froude number. This assumption, introduced by Froude a century ago, has remained unchallenged for years. Recent evidence, however, has shown that the assumption is not exact.

The dependence of the viscous resistance on the Froude number has been pointed out in several studies, Wu and Landweber [1], Tzou and Landweber [2], Townsin [3], and for the wave resistance on the Reynolds number, by Tatinclaux [4], Amfilokhiev and Conn [5].

Webster and Huang [6] and Chow [7] indicate the influence of the waves generated by the ship on the piezometric pressure gradient at the stern, and so on the characteristics of the boundary layer and the value of the viscous resistance. The same explanation is given ty Tzou [8] to justify the sinuous trend of the curve of viscous resistance versus Froude number [1].

The variation of the wave resistance with the Reynolds number seems to indicate its dependence on the viscosity of the fluid, contrary to the assumption of inviscidness usually employed in the study of the wavemaking of ships. Several studies have been carried out trying to take into account, in some way, the viscosity of the fluid, employing various models of the boundary layer and wake to study the influence of viscosity on the wavemaking.

Tatinclaux [4] used a vorticity distribution behind a semi-infinite strut, obtaining a contribution of the vorticity to the wave drag that may take either positive or negative values. Beck [9], using a U-shaped vortex sheet behind a slender body, obtained a positive wave-drag term from the vorticity, but with one term from the interaction between ship and wake-wave systems that could take either sign. Brard [10] derived an expression for the wave-drag that includes a term due to the wavemaking of the mean vorticity in the wake. According to him, the lower efficiency of the stern as a wavemaker compared with the bow is explained by the strong influence of the wake on the singularities modeling the stern.

The foregoing analytical arguments, which tend to show that the vorticity in the wake generates waves, are contradicted by Gadd's experiments [11], which indicate that vertically-oriented vorticity does not generate appreciable waves. Furthermore, the experiments of Swain and Landweber [12] at IIHR revealed the poor efficiency of horizontally-oriented vorticity as a wavemaker. Çalişal [13] and Emerson [14] have also found that the influence of the wake on wave-making is small in experiments in which the wake was reduced by Çalişal by sucking water at the stern, and by Emerson by adding drag-reducing polymer to the water.

Guilloton's method for the calculation of the wave resistance of ships [15], that has been shown by Noblesse [16] and Dagan [17] to be an inconsistent second-order approximation, shows that the results given by the Michell integral can be significantly improved by a higher-order approximation, according to the calculations carried out by Emerson [14] and Gadd [18]. Gadd indicates that good agreement with experiment is given by this inviscid model.

In most cases, when the experimentally determined values of viscous and wave resistances are added, one finds that their sum is appreciably less than the total. Since the discrepancy is larger for values of the Froude number at which the contribution of the wavemaking is rather small, the gap seems to be attributable to an error in the determination of the viscous resistance.

The purpose of this study is then two-fold: a) to determine the influence of viscosity, i.e., of the wake, on the wavemaking resistance. In contrast with the experiments of Çalişal [13] and Emerson [14], it appeared to be desirable to increase, rather than reduce, the wake; and (b) to analyze the wake-survey method for the evaluation of the viscous resistance.

Total, viscous and wave resistance of a ship model with and without roughness, were measured in the IIHR towing tank over a range of Froude numbers. The different characteristics of the boundary layers and wakes for the two cases should clarify the problem.

An analytical study of the influence of the roughness on the viscous resistance was also performed. This was accomplished by employing a body of revolution equivalent to the ship model. The method selected for the calculation of an exisymmetric boundary layer with a rough surface is described in the following section.

II. VISCOUS RESISTANCE OF A ROUGH, EQUIVALENT BODY OF REVOLUTION

A. Kind of Roughness. Three-dimensional roughness elements in the form of plastic pins were chosen. In determining their dimensions, two points must be taken into account. First, the size must not be so small that the pins lie inside the laminar sublayer because then the boundary layer would be unaffected by the roughness. On the other hand, it cannot be so big that it changes, in a significant way, the potential flow outside the boundary layer such that the wavemaking resistance would be affected. These two limitations indicate the necessity of estimating the boundary layer characteristics on the rough surface of the model.

B. Equivalent Body of Revolution. Recently, studies by Nakayama, Patel and Landweber [19], Gadd [20] and Granville [21] show that the measured viscous resistance of a double ship model is given, to a good approximation, by that computed for an equivalent body of revolution. This approach was considered suitable for the present purpose, and the equivalent body was selected as one having the same axial distribution of cross-sectional area.

Apart from the changes due to the surface roughness, the resistance of the equivalent body was calculated using the computer program developed by Nakayama and Patel [22] for the calculation of the viscous resistance of a streamlined body of revolution, placed axially in a uniform incompressible stream. In this program, the method developed by Landweber [23] is used for the potential flow calculation, and the method of Thwaites [24], as modified by Rott and Crabtree [25], was employed for the laminar boundary-layer development. Transition was fixed at the starting point of the roughness, assuming that the first row of pins acted as a turbulence stimulator. For the prediction of the drag coefficient, the Squire-Young drag formula was used.

C. Turbulent Boundary-Layer Calculation. Although many methods can be used to predict the development of turbulent boundary layers over smooth surfaces, unfortunately, corresponding published methods for rough surfaces are few. In the case of smooth surfaces, the different integral methods employ the momentum integral equation, and require a skin-friction relation and an auxiliary equation.

In the program cited earlier, a method by Patel [26] is used. In this method, a form of the momentum-integral equation due to Patel [27] is employed. The skin-friction relation is the friction law of Thompson [28], using the approximation of Head and Patel [29], and for the auxiliary equation, a modified form of the well-known entrainment equation of Head [30] was used.

We shall follow this method insofar as possible. It is quite clear we can keep the momentum equation, because it is independent of the roughness. A new skin-friction law is required, however, because the influence of the roughness on the skin friction is quite important. For the auxiliary equation, the entrainment hypothesis was postulated, depending upon the free-stream velocity, a length scale of the flow in the outer region of the boundary layer and the shape of the velocity profile in this region. This implies that the entrainment equation does not depend on the conditions in the wall region. Furthermore, in accordance with Moore's conclusion [31], the velocity distribution law in the outer region applies for both smooth or rough surfaces. All these considerations lead to the conclusion that the entrainment equation remains valid for rough surfaces.

Recently, a complete skin-friction law was presented by Dvorak [32] for the prediction of the skin-friction coefficient on smooth, transitionally-rough or fully-rough surfaces in zero, favorable or adverse pressure gradients.

According to Dvorak, the expression for the local skin-friction coefficient is given by

$$\sqrt{\frac{2}{c_f}} = 5.6 \log \frac{U\delta^*}{\nu} + 4.8 - \left(\frac{\Delta u}{u^*}\right)_{rough} + \left(\frac{\Delta u}{u^*}\right)_{press.} \tag{1}$$

where δ^* is the displacement thickness of the boundary layer, U is the velocity outside the boundary layer, c_f is the local surface resistance coefficient and u^* the shear velocity. The second term on the right represents the downward shift of the logarithmic velocity profile due to surface roughness. The last term corresponds to the effect of the pressure gradient.

Then, with the momentum equation by Patel, the entrainment equation of Head, and the skin-friction law due to Dvorak, we are able to calculate the characteristics of the boundary layer of the equivalent body of revolution.

As in all step-by-step calculation procedures, we must know the starting values of the calculation. Two ways are available. First as is suggested by Dvorak, experimental values downstream from transition may be used. Alternatively, we may take into account the additional momentum thickness due to the transition devices, plastic pins in the present case. Due to the limited data available for the rough case, the second method was used, as explained below.

Let us consider the initial row of roughness elements as a two-dimensional disturbance. We select two transverse sections close to the initial row, on its upstream and downstream sides, as is shown in Figure 1, and let these surfaces, together with the surface of the body and a solid wall far away from the body, serve as a control surface. Application of the momentum theorem then gives

$$R = \rho \int_0^Y (u_1^2 - u_2^2)\,dy \tag{2}$$

where R is the resistance per unit length due to the roughness and u_1 and u_2 are the velocities in the boundary layer upstream and downstream, respectively, of the disturbance. Using the two-dimensional definition of momentum and displacement thicknesses, the expression (2) becomes

$$R = \rho U^2(\theta_2 - \theta_1 + \delta_2^* - \delta_1^*) \tag{3}$$

where θ is the momentum thickness and δ^* the displacement thickness. Assuming the shape parameter $H_s = \delta^*/\theta$ is the same at both sections, we can write (3) as

$$R = \rho U^2(1 + H_s)(\theta_2 - \theta_1) \tag{4a}$$

or

$$R = \rho U^2(1 + H_s)\Delta\theta \tag{4b}$$

where R can be computed from the values of Todd's experiments [33].

We must point out that the final result is not sensitive to the particular selection of the initial values. This can be seen in Table I where values of the viscous drag coefficient are given for a determined size of roughness and widely varying initial values at a given Reynolds number, R_N

Table I

C_v for different initial values at $R_N = 2 \times 10^6$

$(\frac{\delta^*}{L} \times 10^5)_{turb.}$	$C_v \times 10^3$
14.2	9.64
27.6	9.72
49.7	9.99
101.1	10.38

III. AN IMPROVED DERIVATION OF THE VISCOUS-DRAG FORMULA

Since 1951, when Tulin [46] suggested a wake-survey method for the determination of the viscous drag as an extension of a method due to Betz [47], some improvements of this method have been introduced, as can be seen in [48,2,49].

Recently, a new refinement of this derivation has been presented by Landweber [50], in which the effects of turbulence in the wake and the flux of Betz sources have been considered.

The initial expression for the drag D of a body at rest in a uniform stream of velocity U_o in the positive x-direction, as given in [2], is

$$D = \int_{\Omega} \{p_o - p - \rho[(U_o + u)^2 - U_o^2]\}dS \tag{5}$$

where p_o is the pressure far upstream of the body, p the pressure in a section behind the body, U_o the free-stream velocity and u the disturbance velocity. Considerations of the distribution of the so-called Betz sources, application of the Lagally theorem and the relation between the drag and the wake flux Q, lead to the result

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U_o}} \int_{\Omega} [2g(H_o - H) + (u_1 - u)(u_1 + u - 2\bar{u}_1) + + v^2 + w^2 - v_1^2 - w_1^2]dS \tag{6}$$

where H_o is the undisturbed total head, H the total head in the wake, $\vec{u}_1$ (u_1, v_1, w_1) the disturbance velocity due to source distribution in the wake and $\bar{u}_1$ is a mean value of u_1 in the wake downstream of the transverse section Ω. This expression can be expressed in terms of measurable quantities as

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U_o}} \int_{\Omega} [2g(H_o - H_m) + (u_1 - u_m)(u_1 + u_m - 2\bar{u}_1) - - v_1^2 - w_1^2 + \beta(v^2 + w^2)]dS \tag{7}$$

where β is a pitot-tube calibration constant, and the subscript m denotes measurable quantities. If the wake is turbulent, replacing the velocity by $(\overrightarrow{u + u'})$ in (7) and averaging, yields

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U_o}} \int_\Omega [2g(H_o - H_m) + (u_1 - u_m)(u_1 + u_m - 2\bar{u}_1) - v_1^2 - w_1^2 + \beta(v^2 + w^2) - \overline{u'^2} + \beta(\overline{v'^2 + w'^2})] dS \qquad (8)$$

Neglecting the turbulence stresses, according to Wu[51], and also the terms $- v_1^2 - w_1^2 + \beta(v^2 + w^2)$, and replacing the unknown value of $\bar{u}_1$ by the velocity at the edge of the wake, finally we obtain the expression

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_e}{U_o}} \int_\Omega [2g(H_o - H_m) - (u_e - u_m)^2] dS \qquad (9)$$

where $\bar{u}_e$ is the mean value of the disturbance velocity at the edge of the wake.

IV. ANALYSIS OF ASSUMPTIONS IN THE CALCULATION OF WAVE RESISTANCE

Following Eggers [34] and Landweber and Tzou [35], the surface disturbance ζ and the wave resistance R_w assume the forms

$$\zeta = \sum_{m=o}^{\infty} (C_m \cos \omega_m x + S_m \sin \omega_m x) \cos \frac{2\pi m y}{b}$$

$$R_w = \tfrac{1}{4}\rho g b [C_o^2 + S_o^2 + \sum_{m=1}^{\infty} \frac{k_m}{k_o + k_m} (C_m^2 + S_m^2)] \qquad (10)$$

The wave resistance will then be known when the amplitude-spectrum coefficients C_m and S_m are determined. The details of the procedure to obtain these coefficients from the measured values of $\zeta(x)$ in (10) can be found in the studies by Moran and Landweber [36] and Tsai and Landweber [37].

The method of analysis yielding the former expressions is based upon the following assumptions:

1. The walls of the towing tank are vertical and smooth; the depth may be considered infinite.
2. The wavemaking associated with the linearized free-surface boundary condition may be used.
3. The near-field part of the surface disturbance contributes negligibly to measurements taken far enough downstream.
4. The fluid is inviscid.

The first assumption has already been studied experimentally in an unpublished work by Swain and Landweber by using models of different sizes, and the error due to this assumption was found to be negligible. The imperfections in the walls and the fact that they are not exactly vertical have an effect on the precision with which the position of the longitudinal cuts are measured. This effect has been studied by Tsai [38] by considering the influence of an error Δy in the lateral position of the wave probe, i.e. of the longitudinal cut.

As far as the finiteness of the depth is concerned, it can be seen in Lamb [39] that, when the depth exceeds half the wave-length, the characteristics of surface waves are sensibly the same as in the case of infinite depth. The relationship between the wave number ω and the wave-length λ is $\lambda = 2\pi/\omega$. Since the expression for ω_m in (10) is

$$\omega_m = \{\tfrac{1}{2}k_o[k_o + \sqrt{k_o^2 + (\tfrac{4\pi}{b}m)^2}]\}^{\frac{1}{2}} \tag{11}$$

where $k_o = g/U_o^2$, the largest value for λ will be that corresponding to m=o and to the largest velocity U_o. So, for $U_o = 6.3$ fps, m=0, and a depth of 10 ft., we get $\lambda = 7.75$ ft.; this verifies the validity of this assumption.

The second assumption implies that the surface slope in any direction is small, as well as the surface displacement and the disturbance velocities, in such a way that their products can be considered as second-order terms. All of these assumptions will be correct as long as the region we are considering is far enough from the ship for the disturbance velocities to be small and the wave characteristics such that the wave slopes are small, as will be the case.

About the third assumption, it has been found in [35] that the contribution of the near-field terms to the surface profile, and therefore to the wavemeking resistance, is negligible when the upstream truncation point of the recorded data is taken at least one model length behind the center of the model. The same result can be seen in [40] and [41].

For the fourth assumption, the question is whether the viscosity of the fluid affects the wave pattern of the ship model or, in other words, whether there is an influence of the presence of the wake on the waves behind the ship. The answer is probably affirmative, and, as an example, one can take the study by Peregrine [42] in which a reduction of the Kelvin angle of the diverging stern waves is concluded and a confirmation of this result by the observation of ship stern waves pointed out.

V. EXPERIMENTAL PROCEDURE

All experiments were performed in the IIHR towing tank that has been described in [43]. The ship model employed was a Series-60 geosim, with 0.60 block coefficient and a length, between perpendiculars, of 10 ft. Its waterline length was 10.17 ft., the displacement 273.3 lb. and the wetted surface area 17.64 sq. ft.

The experimental equipment and procedure used can be found in [38], where the details are presented and several references are cited for additional information. The differences introduced with respect to the reference [38] are listed below.

A. Total Resistance. Initially, the mechanical system used to tow the model introduced large fluctuations in the readings. This was due to speed oscillations in the cable-driven system of the carriage that originated such inertial forces in the model that, at low Froude number, they were of the same order as the resistance to be measured. These oscillations were of a high frequency, and in former experiments had been corrected by an electronic system with filters.

An analysis of the spring-mass system with the original system considered as a spring of strength k_1, and the strength of the inserted spring as of strength k_2, indicates that the amplitude a_1 recorded by the transducer is approximately given by

$$a_1 \doteq \frac{k_2 M \omega_o^2 a_o}{k_1 (k_2 - M\omega_o^2)} \doteq -\frac{k_2}{k_1} a_o \tag{12}$$

where a_o and ω_o are the amplitude and angular frequency of the carriage oscillation, and M the effective mass of the system, principally due to the model. The approximations in (12) assume that

$$k_2 << k_1, \quad k_2 << M\omega_o^2 \tag{13}$$

It is clear from (12) that the selected spring should be as weak as possible.

Hence the model was attached to the carriage by a spring. It was found that two springs can cover the entire range of speeds. In order to prevent the model from moving laterally, two guides were used, at the bow and at the stern, but the model was free to sink and trim.

Recorded readings with and without the spring showed a marked improvement of the system, and it was then possible to take readings at as low a Froude number as 0.09.

B. Viscous Resistance. Due to the small but important area between the highest measuring section and the free surface, a traversing mechanism, which transports a surface-profile probe, was used. Such a probe and traversing mechanism are described in [44].

Measurements were taken at the transverse plane 6 ft. behind the stern of the model at different speeds. At each speed, the pitot rake was set below the undisturbed water surface at 12 different depths.

All the interpolations and integrations have been carried out in the manner indicated by Landweber and Tzou [2].

In the course of a run, a small, gradual increase of the velocity was observed. The recorded values of the total head across the wake, measured sequentially from one side of the wake to the other, enable a corrected speed to be estimated by linear interpolation between the initial and final values of the total head at the two sides of the wake.

It was pointed out in [2] that the effect of the compressibility of the air is negligible in the system. It was found that the relative error in the reading, e_r, can be written as

$$e_r = \gamma \frac{\Delta l}{P} \tag{14}$$

where Δl is the change in the length of the air column between calibration and run. γ is the specific weight of the water and P the air pressure. An estimation of this error showed that it is not greater than 1 percent. Hence, the compressibility of the air can be considered negligible.

The presence of a long-period longitudinal surge in the tank was observed and will be discussed later. In order to minimize its effects, the rake measurements closer to the free surface and the recording of the transverse surface profile across the wake were made at intervals of 1 1/2 hours, which was required for the surge to decay.

C. Wave Resistance. In the formerly cited reference [38], the necessity of a dynamic calibration correction of the results is indicated. The dynamic calibration procedure is outlined in [38], in which it can be seen that the dynamic calibration data correspond to pure harmonic motion. Since the vertical capacitance wire used to measure the surface disturbance is not a linear system, the response curve of the capacitance wire to a frequency spectrum cannot be applied, by linear superposition, to correct a measured surface-profile input. Consequently, one mean coefficient for correcting from a static to a dynamic calibration was selected.

Schmidt's dynamic calibration data are shown in Figure 2 and Tsai's in Figure 3. The correction coefficient A/A_o, where A corresponds to the actual or dynamic amplitude and A_o to the static, is presented in Figure 4 as a function of A_o, instead of A, because the real situation corresponds to the path indicated in Figure 2; an actual, hence dynamic, amplitude generates a voltage output that is interpreted as another amplitude, since the computer program for the calculation uses the static calibration curve to interpret the data. The mean value $A/A_o = 1.15$ was selected as a dynamic correction factor. The final results were multiplied by this coefficient, squared, since the wave resistance is a function of the square of the wave amplitudes.

D. Roughness. Plastic pins were chosen as three-dimensional roughness elements in order to change the characteristics of the boundary layer and wake. A diameter of 1/8 in., height of 1/16 in. and a spacing of 3/4 in. were chosen. These were attached by means of two-sided adhesive paper strips, sufficiently thin to lie in the laminar sublayer. This gives a density, as defined by Bettermanns [45], of 11.45. The arrangement of the roughness elements can be seen in Figure 5.

E. Study of the Surge. In the course of the experiments, a long period surge was encountered. Several records of it,taken at different positions of the towing tank, showed a periodic variation with a very irregular shape that depended upon the location. The period T was always the same and equal to approximately 34 seconds. Since it is a shallow wave, its velocity of propagation c is given by

$$c = (gh)^{\frac{1}{2}} = 17.94 \text{ ft/sec.} \tag{15}$$

where the depth of the towing tank h has been taken as 10 ft. The wave-length λ is therefore

$$\lambda = cT = 609.96 \text{ ft.} \tag{16}$$

Hence, the wave-length is approximately equal to twice the length of the towing tank, a result that is consistent with the theory of waves in rectangular closed channels.

Since the wave will be reflected at the ends of the towing tank, let us assume that the end walls are vertical and study the reflection as the superposition of progressive waves traveling in opposite directions. Take the origin of coordinates at one end of the channel. A record of a progressive wave would give the surface elevation ζ_o at the origin of coordinates

$$\zeta_o = f(t) \tag{17}$$

Therefore, at a point of abscissa λ, the elevation ζ for the resulting wave would be given by

$$\zeta = f(t + \frac{x}{c}) + f(t - \frac{x}{c}) \tag{18}$$

where $c = \frac{\lambda}{T} = \sqrt{gh}$ is the velocity of wave propagation. The boundary condition at both ends of the channel,

$$\left.\frac{\partial\zeta}{\partial x}\right|_{x = o, L_o} = 0 \tag{19}$$

where $L_o = \frac{\lambda}{2}$ is the length of the channel, is clearly satisfied. If $f(t)$ is expressed as the Fourier series

$$f(t) = \sum_{n=o}^{\infty} A_n \sin \sigma_n t + B_n \cos \sigma_n t, \qquad \sigma_n = \frac{2\pi n}{T} \tag{20}$$

then, the expanded expression for ζ becomes

$$\zeta = A_o + 2\sum_{n=1}^{\infty} (A_n \cos \frac{n\pi t}{T} + B_n \sin \frac{n\pi t}{T}) \cos (\frac{\sigma_n x}{c}) \tag{21}$$

where the coefficients A_n and B_n will be given by

$$\begin{Bmatrix} A_n \\ B_n \end{Bmatrix} = \frac{1}{2T \cos \frac{\sigma_n x}{c}} \int_{-\frac{T}{2}}^{\frac{T}{2}} \zeta \begin{Bmatrix} \cos \\ \sin \end{Bmatrix} \frac{n\pi t}{T} \, dt \tag{22}$$

A harmonic analysis of a record picked up at any point of the towing tank allows us to determine the coefficients A_n and B_n and, therefore, to predict the surge at any other point, at any other instant.

If we take x=o in the expression (18), we have:

$$\zeta = 2f(t) \tag{23}$$

from which the surge at any point and instant can be predicted without the necessity of a harmonic analysis.

It was assumed at the beginning that the ends were vertical planes and that the depth was uniform. Actually, that is not exact. If it were so, the wave-surge profile should remain similar with time, with amplitudes decreasing due to damping. A slight progressive change of shape is observed instead, attributable to the conditions at the ends and at the bed of the towing tank. Nevertheless, if the record is picked up immediately before a run, the change in the shape will be negligible, and the results could be corrected for this effect. Taking the record at the end of the channel makes the method easier to apply, but the irregularities at the ends might make that method inapplicable, in which case the record should be taken at another point and the harmonic analysis applied.

The surge effect has been found in other towing tanks and a study of its influence on total resistance and propulsion tests can be seen in [54].

In the present case it will be seen that corrections for the surge in the surface-profile measurements were not required. If necessary, however, wave data could be corrected for the surge effect in the following manner. A record of the surge should be taken immediately before the run. Choose a time origin that could be taken at the first instant of the recorded surge, and an origin of coordinates that could be at one end of the towing tank. If t is the instant at which a longitudinal-cut data point is taken and x its position, the corrected ship-wave elevation ζ_c would be

$$\zeta_c = z - f(t + \frac{x}{c}) - f(t - \frac{x}{c}) \qquad (24)$$

where z is the uncorrected wave elevation. For the case where harmonic analysis is used, the corresponding expression should be employed.

Where viscous resistance is concerned, let us consider the effect of the surge on the static-pressure reading. Omitting the new correction factor, we can write the viscous-drag expression as

$$D_v = \gamma \int_\Omega [2\{(H_o - \frac{p_e}{\gamma})(H - \frac{p}{\gamma})\}^{\frac{1}{2}} - (H - \frac{p_e}{\gamma}) - (H - \frac{p}{\gamma})]\, dS \qquad (25)$$

where the subscript e denotes values at the edge of the wake. Differentiating equation (22) with respect to p gives

$$\frac{\partial D_v}{\partial p} = \int_\Omega [1 - \sqrt{\frac{H_o - \frac{p_e}{\gamma}}{H - \frac{p}{\gamma}}}]\, dS = \int_\Omega [1 - (1 + \frac{H_o - H - \frac{p_e}{\gamma} + \frac{p}{\gamma}}{H - \frac{p}{\gamma}})^{\frac{1}{2}}]\, dS \qquad (26a)$$

Neglecting the terms $\frac{p}{\gamma} - \frac{p_e}{\gamma}$ and assuming $\frac{H_o - H}{H - \frac{p}{\gamma}}$ small, we can write

$$\frac{\partial D_v}{\partial p} \doteqdot - \int_\Omega \frac{\Delta H}{u^2} g\, dS \doteqdot - \frac{\overline{\Delta H}}{\overline{u^2}} g\omega \qquad (26b)$$

where $\overline{\Delta H}$ is the mean value of the difference between the undisturbed total head and total head in the wake, $\overline{u^2}$ the mean value of the square of the velocity in the wake and Ω the area of the wake.

Assume a value of 27.5 for $\overline{u^2}$ and 0.070 for $\overline{\Delta H}$, at a speed of 5.5 fps. Then, an error of 0.01 ft. of water in p yields an error of about 4% in the viscous drag. Thus this error is appreciable and a correction is needed.

If p is the reading for the static pressure and ζ_s the surface elevation due to the surge at the point and time at which p is obtained, the corrected static pressure would be

$$p_e = p - \gamma\zeta_s \qquad (27)$$

VI. RESULTS AND DISCUSSION

A. Total Resistance Coefficients. Results for both the smooth and rough hull, can be seen in Figure 6. For the smooth case, the values are slightly smaller than Tsai's results, as can be expected, since turbulence was not stimulated in the present tests.

For the rough case, the trend of the curve is slightly different. The slope between the range of Froude numbers from 0.25 to 0.32 is milder than in the case of the smooth body. For values up to a Froude number of 0.25, the curve for the rough case shows a slightly rising trend. Since the wave-resistance coefficient is small in this range, this trend, apart from an undulating shape, must be attributed to that of the viscous resistance, as is verified in Figure 4.

B. Viscous Resistance Coefficients. These results are presented in Figure 7. For the smooth case, the results are similar to Tsai's, but the deviation from the values of $C_t - C_w$ is smaller in the present case. The differences introduced in the procedure are now considered. Due to the important effect of the area of integration, as is shown in [2], the bounds of this area were chosen, after the values of $H_o - H$ were known, at the points where this difference is nearly zero. Furthermore, it was found that the influence of the free surface is important and, if the free surface is taken at its undisturbed level, an error of about 10% may be introduced when the Froude number is 0.32. This is due to the large magnitudes of $H_o - H$ in that zone of integration.

The largest discrepancy between the values of viscous resistance and the curve $C_t - C_w$ is 24% at a Froude Number of 0.25, where a special behavior due to a secondary flow can be expected, as was pointed out by Tzou [52] and Chow [7]. These discrepancies cannot be explained by means of experimental errors, and could be due to an unknown component of the viscous resistance not taken into account by a wake survey, such as vortices generated by secondary flows.

The discrepancy between values of C_v and $C_t - C_w$ for the rough case is of the same order of magnitude as the smooth case. The difference is slightly smaller, which may be due to a reduction in vortex formation when the boundary layer is fully turbulent.

The results for the equivalent body of revolution, shown in the Figure 7, are independent of the Reynolds number, as can be expected for a fully-rough regime. The agreement of the results for the equivalent body of revolution with the mean of the measured values confirms the validity of the boundary-layer calculations for a roughened body.

C. Wave Resistance. The two curves of wave resistance for smooth and roughened hulls that are plotted in Figure 8 show a very strong influence of the roughness on the wavemaking. The difference reaches a maximum value of forty percent at about F = 0.30 and then decreases to about fourteen percent at F = 0.345. These results indicate a reduction of the wavemaking when the boundary layer and wake are thickened, in agreement with Baba's results quoted by Brard [10]. Physically, this effect could be explained by the reduction of the wavemaking of the stern due to the increased influence of the wake.

The curve for the smooth case without turbulence stimulation shows fairly good agreement with Tsai's results, for the hull with turbulence stimulators, at all Froude numbers but those between 0.285 and 0.32. In that range, the maximum difference is about ten percent. The comparison between the total resistance curves with and without turbulence stimulators shows a larger hump in that range for the former case. This is consistent with the difference in wave resistance between the two cases.

The observation of the wave pattern along the hull for the model without turbulence stimulators shows the same location of the wave crest as was found by Tzou [8] for the case with stimulation of turbulence, i.e. about 1.5 ft. towards the stern from the center of the model. The occurrence of separation near the free surface found by Tzou [8] and Chow [7] under similar circumstances appear to be present, then, for the two cases in question. This phenomenon is different from the secondary flow discussed in the previous section which mainly affects the viscous resistance at a slightly lower range of Froude numbers. The difference in turbulence intensity in the boundary layer, with and without turbulence stimulation, by affecting the location of the separation zone, is the probable cause of the aforementioned wave-resistance discrepancy.

Before each run, several readings were taken for the zero, and no appreciable variation was observed. This indicates that the surge in the towing tank was negligible for these tests. A more serious source of error is that the velocity of the carriage could be kept constant only with an accuracy of 0.05 fps. Since a mean value of the velocity was used in the analysis, the velocity variation should not affect the integrated result for the wave resistance by more than about one percent, although the squares of the wave amplitudes could be in error by 3 or 4 percent.

The dynamic calibration coefficient corrects the results by 32 percent. This correction is derived from an overall estimate of the influence of dynamic effects that depend on the amplitude and frequency of the recorded waves. Nevertheless, this factor is not expected to affect the comparison of results, since all data were treated in the same way.

Finally, the data include waves that have crossed the wake once. This fact has not been studied very deeply yet. According to Savitsky's results [53], not very strong viscous energy dissipation should be expected, but there is a distortion of the wave pattern. Therefore, no estimation of the effect of the waves crossing the wake can be made at the moment.

Although several sources of error have been pointed out, nevertheless, the magnitude of the reduction in wave resistance due to roughness is, by far, larger than the possible errors in the procedure.

VII. CONCLUSIONS

1) The discrepancy between the values of C_v and $C_t - C_w$ at low Froude numbers cannot be explained by means of experimental errors. This suggests the existence of an additional component of the viscous resistance, probably due to vortex formation.
2) The discrepancy is slightly smaller in the rough case where the regime is fully turbulent.
3) It is important to record the transverse surface profile across the

wake because of its influence on the definition of the area of integration. It was found that, at Froude numbers greater than 0.30, the error in the viscous drag can be about 10% if the transverse surface profile is not taken into account.

4) The validity of the boundary-layer calculation for the equivalent roughened body of revolution is confirmed.
5) The viscosity of the water has an appreciable influence on the wavemaking, and therefore, should be taken into account when a theoretical approach to the problem is attempted. This is probably because the presence of the boundary layer and wake reduces the wave resistance of a ship model.

It appears that wave resistance, calculated by means of a higher-order inviscid wave theory may improve the agreement with the measured "residuary" or surface-profile wave resistance, but that effects of viscosity must also be included in the development of a more exact mathematical model for computing the wave resistance of a ship form.

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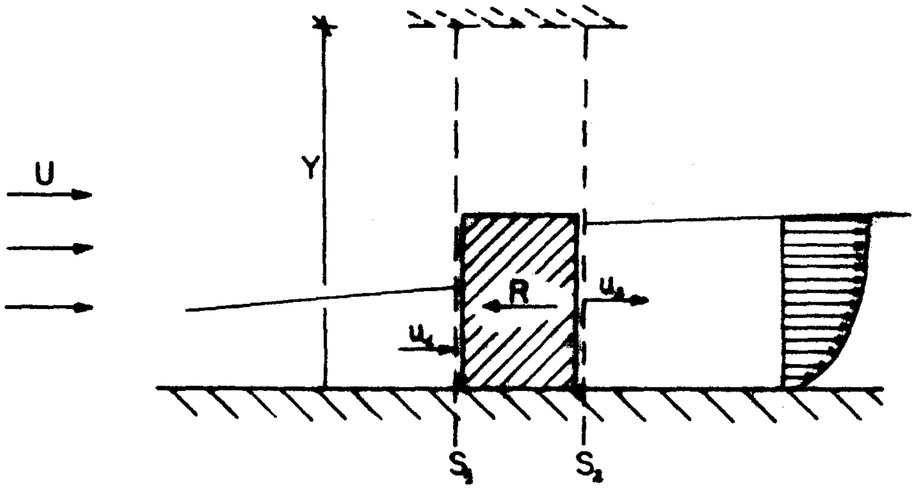

Figure 1 Control surface for initial values of the turbulent boundary layer

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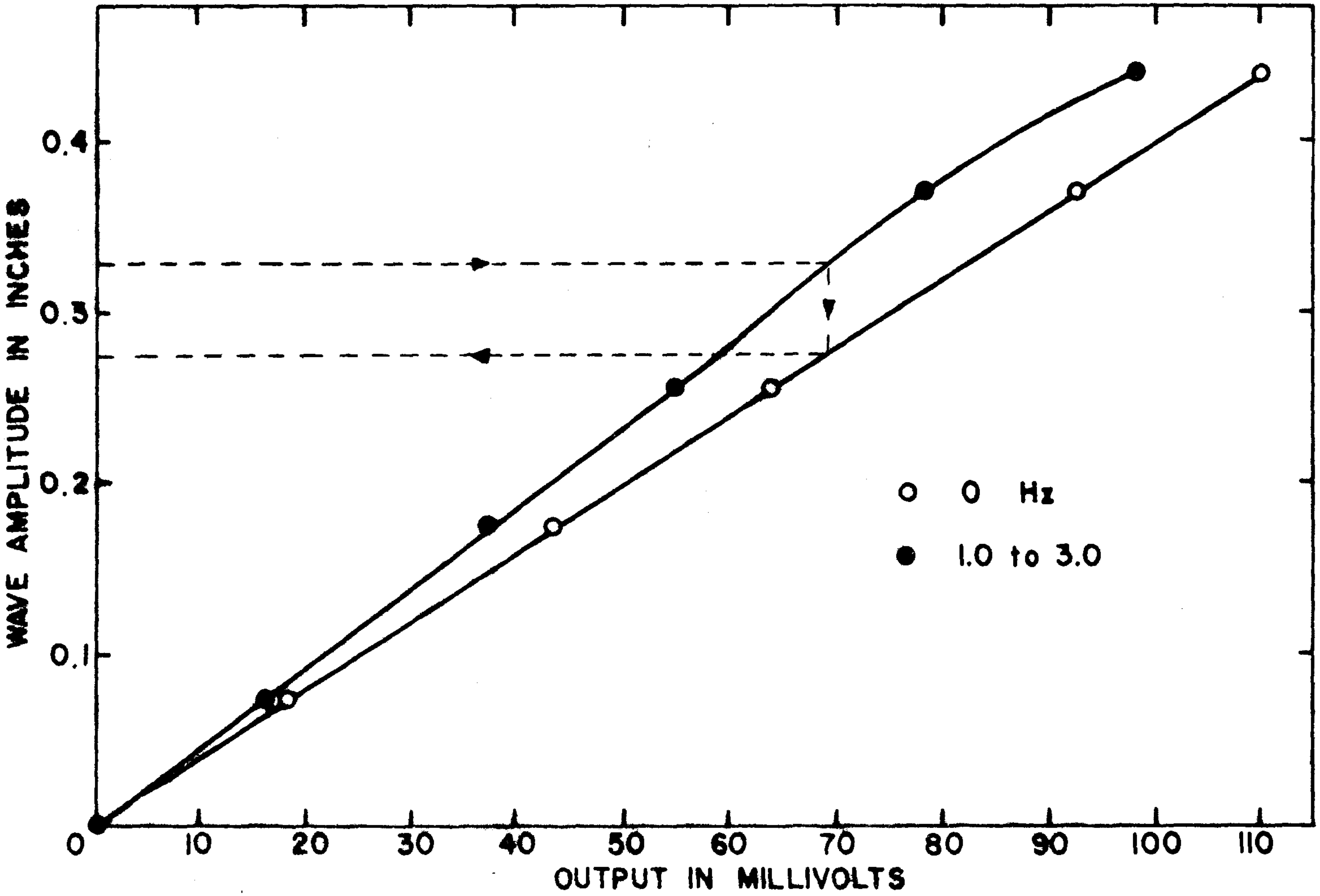

Figure 2 Schmidt's dynamic calibration data

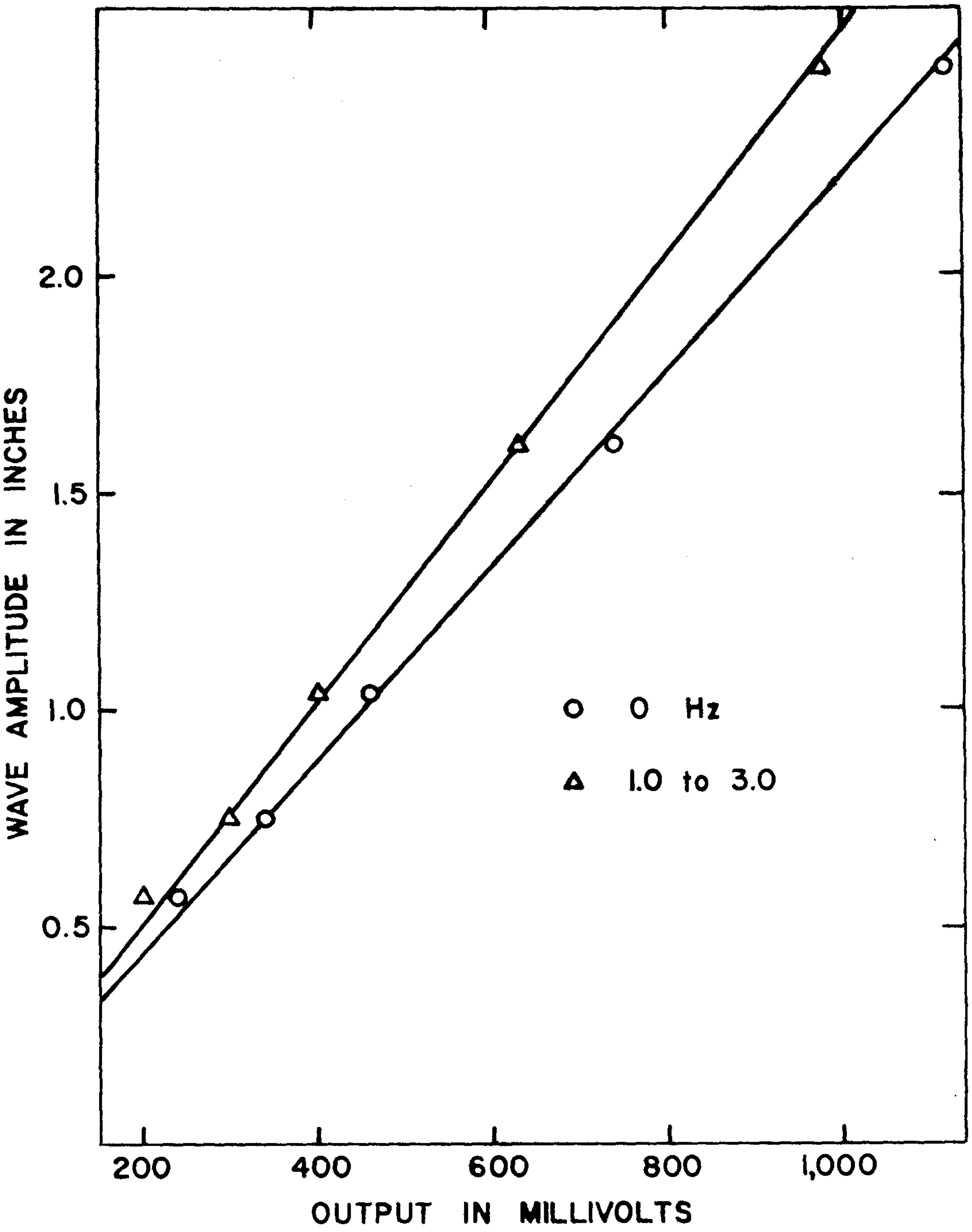

Figure 3 Tsai's dynamic calibration data

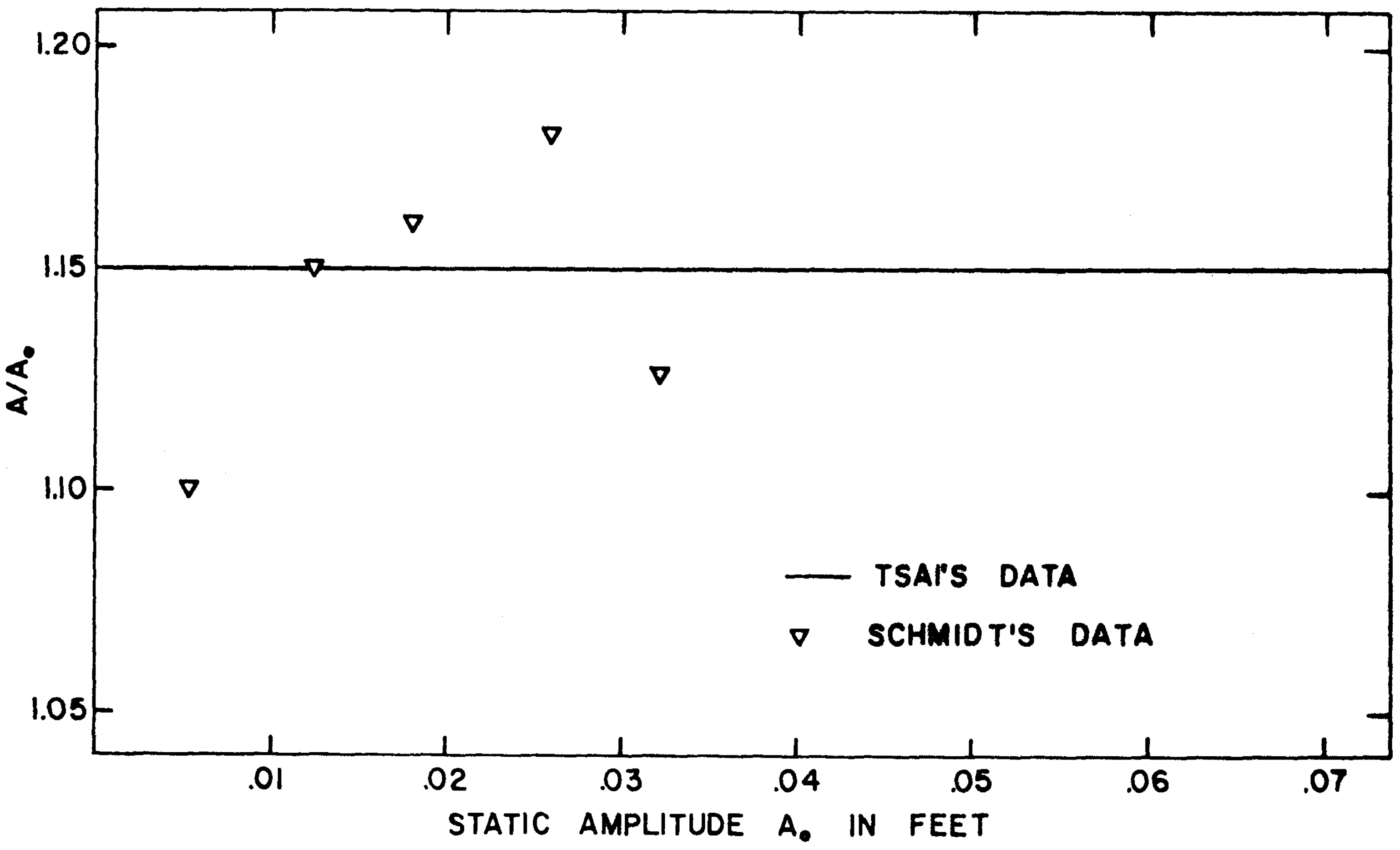

Figure 4 Correction coefficient A/A_0 vs. A_0

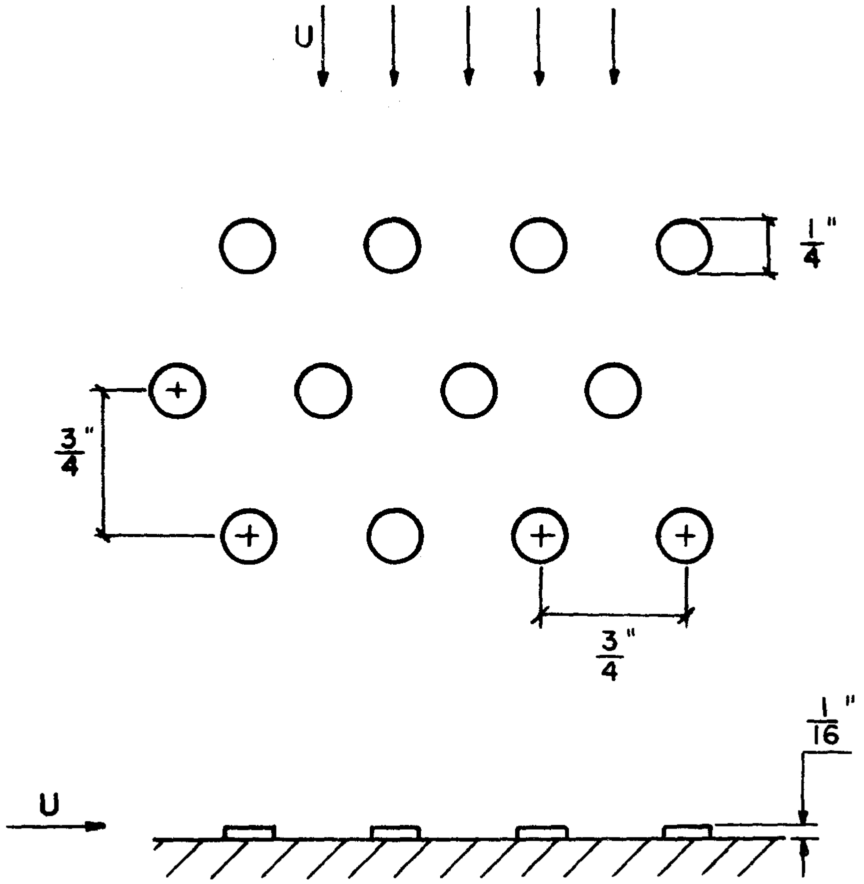

Figure 5 Arrangement of roughness elements

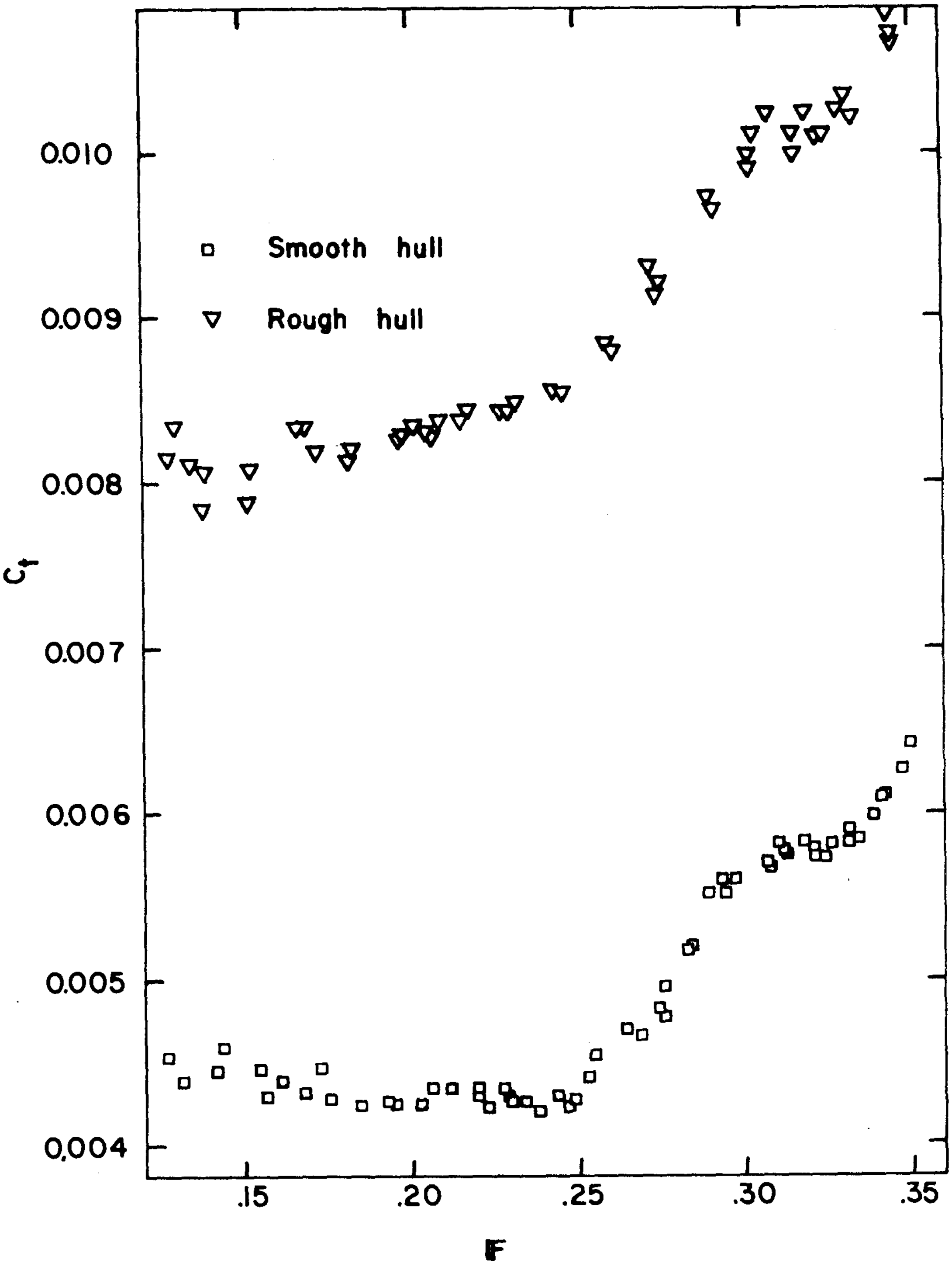

Figure 6 Total-resistance coefficient vs. 𝔽

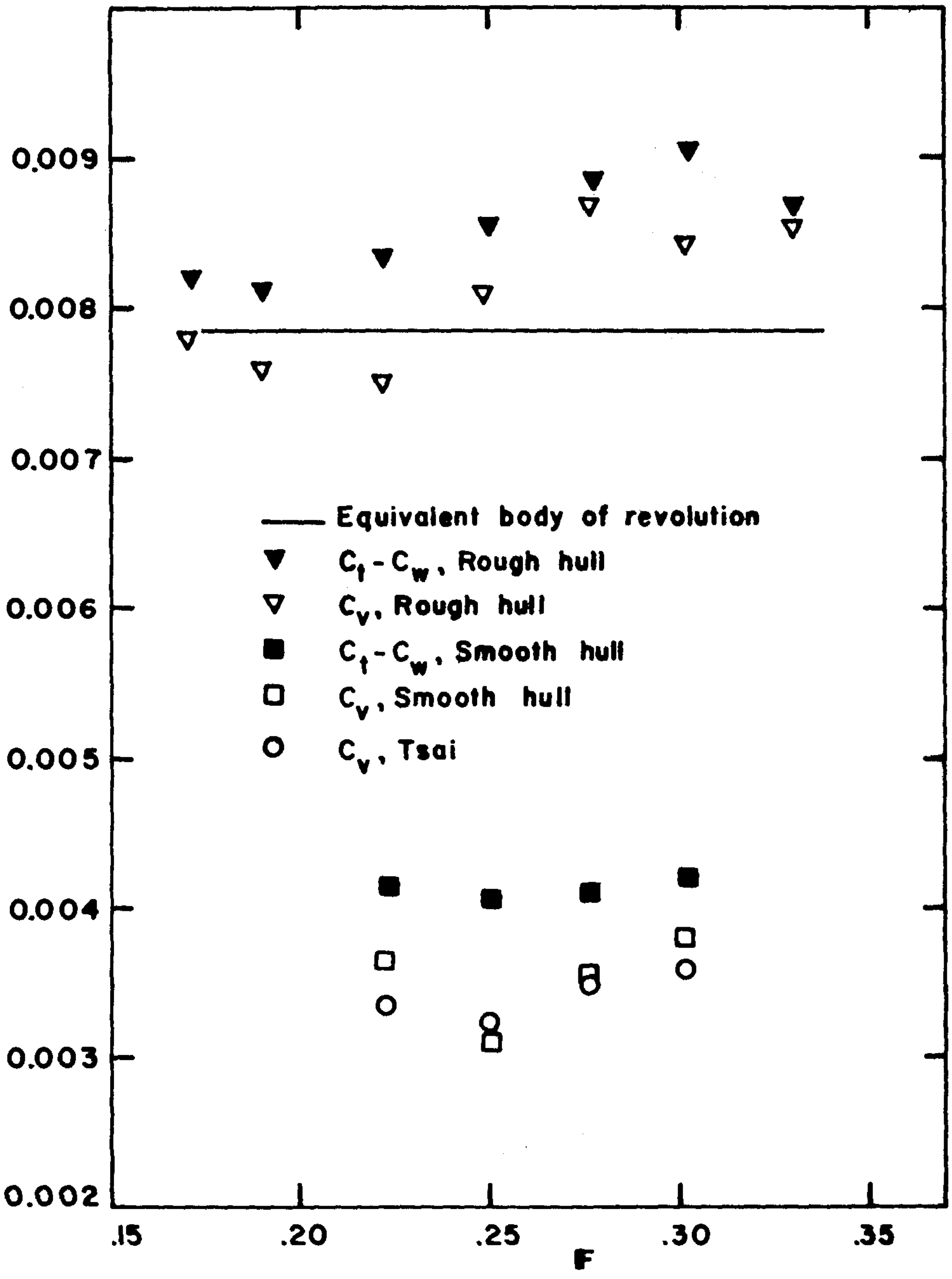

Figure 7 Viscous-resistance coefficient vs. $\mathbb{F}$

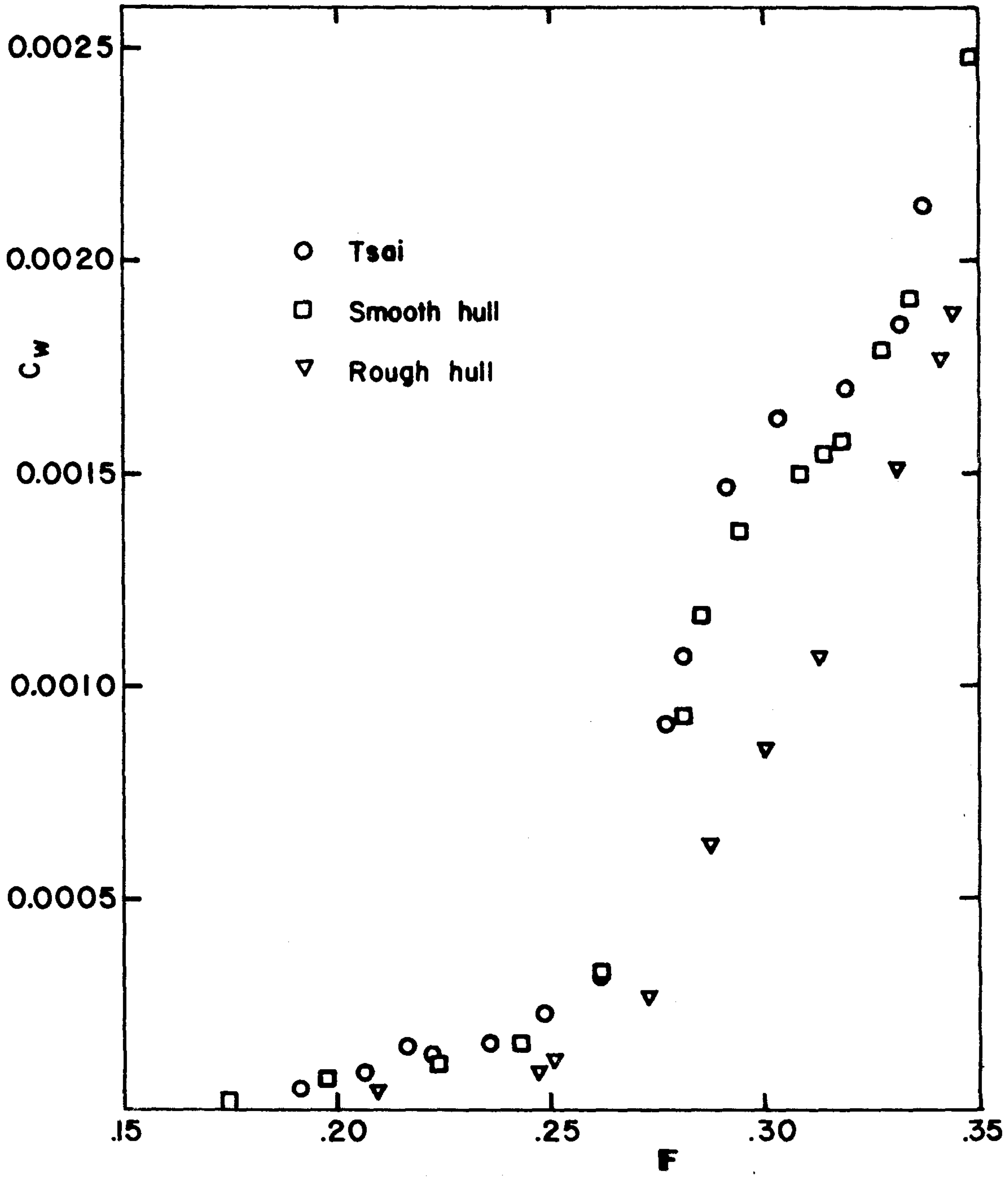

Figure 8 Wave-resistance coefficient vs. $\mathbb{F}$

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For the purpose of resolving the question of the influence of its wake on the wavemaking resistance of a ship, the total, viscous and wavemeking resistance of a Series 60 ship model were measured with the wetted surface first smooth, and then rough. It was found that the wave resistance was significantly less with the rough surface, implying that viscous effects should not be neglected in the development of higher-order wave theory.

Since the wake-survey method was used to determine the viscous resistance,

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the opportunity was taken to compare the results with roughness with the values obtained by calculating the boundary layer on the rough "equivalent" body of revolution, with satisfactory agreement.

A long-period surge in the towing tank, of sufficient amplitude to affect the analysis of both the wake and surface-profile data, was detected. Procedures for correcting for this surge are indicated.

The sum of the viscous and wavemaking components is found to be less than the measured total resistance. It is concluded that the missing component is principally due to longitudinal vortices, the contribution of which to the viscous resistance is not detected in the present wake-survey procedure.