FURTHER INVESTIGATIONS ON COMPONENTS OF SHIP RESISTANCE

FINAL REPORT

by

L. Landweber

This research was carried out under the
Naval Ship Systems Command
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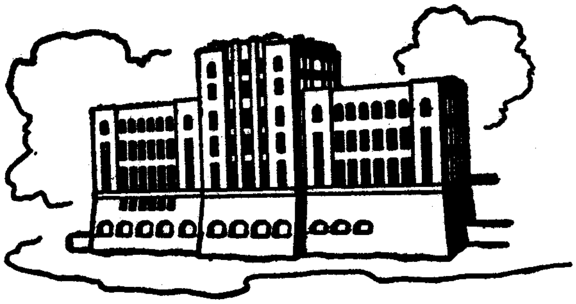

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Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa

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I. INTRODUCTION

This report summarizes the work accomplished at the Iowa Institute of Hydraulic Research, from 1 October 1973 to 1 October 1974, on problems of ship resistance, under Contract N00014-68-A-0916-0010 of the General Hydromechanics Research Program, administered by the Naval Ship Research and Development Center. As is indicated by the title, it may be considered as an addendum to the final report of almost the same title [1] in which the results of the previous ten years of research were described.

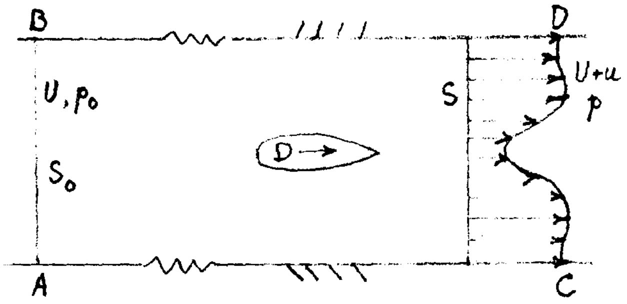
II. VISCOUS RESISTANCE

It was mentioned in Reference [1] that "a new and simpler expression for the viscous drag in terms of wake characteristics has been derived which yields the appreciable lower values required by the measurements". This work, concluded after the termination of the contract, has yielded a much more rigorous derivation of a viscous drag formula, with well-defined bounds for the approximations introduced. This will appear as Appendix 2 of the Report of the Resistance Committee of the International Towing Tank Conference. In order to make it available sooner, and to a wider audience, the derivation is also given here.

III. DERIVATION OF VISCOUS - DRAG FORMULA

Formulas for viscous-drag were derived in the paper "The Determination of the Viscous Drag of Submerged and Floating Bodies by Wake Surveys," by L. Landweber and J. Wu, Journal of Ship Research, June 1963.

A refinement of that derivation will now be presented.



The body shown is taken at the approximate center of a circular channel of large radius. The body is at rest in a uniform stream of velocity U in the positive x-direction. The disturbance velocity components in a rectangular (x,y,z) coordinate system are (u,v,w); p denotes the pressure.

We select a control surface consisting of the transverse sections AB, far ahead of the body, and CD, a moderate distance behind it, and the portion of the channel wall lying between these sections. Application of the momentum theorem to this control surface yields the expression for the body drag D,

$$D = \int_S \{p_o - p - \rho[(U + u)^2 - U^2]\} \, dS \tag{1}$$

in which the viscous stresses are neglected. If the wake is turbulent, Reynolds stresses will be present, but these can be taken into account more efficiently by averaging the resulting expression derived for the drag. Introducing the definitions of total head,

$$\rho g H_o = p_o + \tfrac{1}{2}\rho U^2, \quad \rho g H = p + \tfrac{1}{2}\rho[(U + u)^2 + v^2 = w^2] \tag{2}$$

we obtain

$$D = \int_S \{\rho g(H_o - H) - \frac{\rho}{2} [(U + u^2) - U^2 - v^2 - w^2]\} dS \tag{3}$$

We now consider a velocity field $(U + u_1, v_1, w_1)$ with pressure p_1, generated by a volume distribution of sources of strength μ in the interior of the outer surface T bounding the boundary layer and wake (BLW), such that $(u_1, v_1, w_1) \equiv (u,v,w)$ in the exterior of T. We may again apply the momentum theorem, to the flow within the same control surface generated by this distribution of so-called Betz sources, to obtain the expression for the force on the sources within the control volume,

$$D_s = -\frac{\rho}{2}\int_S [(U + u_1)^2 - U^2 - v_1^{\,2} - w_1^{\,2}]\, dS \qquad (4)$$

the term corresponding to the difference in heads vanishing since the field (u_1, v_1, w_1) is irrotational. Application of the Lagally theorem now gives

$$D_s = -4\pi\rho\int_{\mathcal{V}} \mu(U + u_1)\, d\tau \qquad (5)$$

But, since the original flow is divergenceless, we have, by the flux theorem, with A the area of S intersected by the wake,

$$-4\pi\rho\, U\int_{\mathcal{V}} \mu d\tau = -\rho U\int_A (u_1 - u)\, dS \qquad (6)$$

Since the total force on all the sources in BLW is zero, with $\mathcal{V}' + \mathcal{V} = \mathrm{BLW}$, and $\bar{u}_1$ a mean value of u_1 in $\mathcal{V}'$, we obtain

$$-4\pi\rho\int_{\mathcal{V}} \mu u_1 d\tau = 4\pi\rho\int_{\mathcal{V}'} \mu u_1 d\tau = 4\pi\rho\bar{u}_1\int_{\mathcal{V}'} \mu d\tau \qquad (7)$$

or, in terms of the wake flux Q and its relation to the drag,

$$D = \rho U Q \qquad (8)$$

$$-4\pi\rho\int_{\mathcal{V}} \mu u_1 d\tau = 4\pi\rho\bar{u}_1\, [\int_{\mathrm{BLW}} \mu d\tau - \int_{\mathcal{V}} \mu d\tau] = -\rho\bar{u}_1\int_A (u_1 - u) dS + \frac{\bar{u}_1}{U} D \qquad (9)$$

Hence, by (6) and (9), (5) becomes

$$D_s = -\rho\int_A (u_1 - u)(U + \bar{u}_1) dS + \frac{\bar{u}_1}{U} D \qquad (10)$$

Subtracting (4) from (3) and substituting for D_s from (10), and observing that the resulting integrand is nonzero only over the wake area A, we obtain the expression for the drag

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U}}\int_A [2g(H_o - H) + (u_1 - u)\ (u_1 + u - 2\bar{u}_1) + v^2 + w^2 - v_1^2 - w_1^2]\, dS \qquad (11)$$

In applying (11), total-head tubes which measure H_m, given by

$$\rho g H_m = p + \frac{\rho}{2}\, [(U + u)^2 + \lambda(v^2 + w^{\,2})],\ 0 < \lambda < 1 \qquad (12)$$

where λ is a calibration constant, and velocities

$$u_m = [\,\frac{2}{\rho}\,(H_m - p)]^{\frac{1}{2}} - U \qquad (13)$$

are used for H and u. In terms of H_m and u_m, (11) becomes

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U}} \int_A [2g(H_o - H_m) + (u_1 - u_m)(u_1 + u_m - 2\bar{u}_1) - v_1^2 - w_1^2 + \lambda(v^2 + w^2)]dS \qquad (14)$$

in which the small difference between u_m and u has been neglected.

When the wake is turbulent, the mean value of D, obtained by replacing (u,v,w) by (u + u', v + v', w + w') and averaging, where (u',v',w') denote the components of the turbulence velocity fluctuations, becomes

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U}} \int_A [2g(H_o - H_m) + (u_1 - u_m)(u_1 + u_m - 2\bar{u}_1) - v_1^2 - w_1^2 + \lambda(v^2 + w^2) - \overline{u'^2} + \lambda(\overline{v'^2} + \overline{w'^2})] \, dS \qquad (15)$$

where H_m and u_m now refer to their mean values. The Reynolds-stress terms combine into $(2\lambda-1)\overline{u'^2}$ for isotropic turbulence, and would be negligible for $\lambda = \frac{1}{2}$. Jin Wu's measurements (Ph.D. thesis, Univ. of Iowa, 1964) indicate that the turbulence stresses would contribute about two percent to the calculated drag with $\lambda = 0$, but the actual value was $\lambda = 0.5$, with which the turbulence terms become negligible. We shall assume that the turbulence stresses in (14) may be neglected.

A value of $\bar{u}_1$, a mean of u_1 in V' must be selected. According to its definition in (7), the mean is weighted by the value of the source strength μ, which, together with u_1, diminishes to zero as $x \to \infty$. This suggests that the values $\bar{u}_1 = 0$ and u_1 can be used to obtain lower and upper bounds for the drag formula, the "true" value lying closer to the upper bound given by $\bar{u}_1 = u_1$.

We shall also neglect the terms $- v_1^2 - w_1^2 + \lambda(v^2 + w^2)$ since these are small and partly cancel each other. With these approximatious, and D_1 and D_2 referring to the formulas for D when $\bar{u}_1 = 0$ and u_1 respectively, we obtain

$$D = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U}} \int_A [2g(H_o - H_m) + (u_1 - u_m)(u_1 + u_m - 2\bar{u}_1)] \, dS \qquad (16)$$

$$D_1 = \frac{\rho}{2} \int_A [2g(H_o - H_m) + u_1^{\,2} - u_m^{\,2}]\, dS \qquad (17)$$

$$D_2 = \frac{\rho/2}{1 - \frac{\bar{u}_1}{U}} \int_A [2g(H_o - H_m) - (u_1 - u_m)^2]\, dS \qquad (18)$$

with $D_1 < D < D_2$

and $D_2 - D < D - D_1$

Since u_1 is unknown, it is replaced by $u_E(z)$, the measured value of $u(y,z)$ at the wake boundary T. D_z then becomes

$$D_2 = \frac{\rho/2}{1 - \frac{\bar{u}_E}{U}} \int_A [2g(H_o - H_m) - (u_E - u_m)^2]\, dS \qquad (19)$$

IV. WAVE RESISTANCE

A method of determining the wave resistance of a ship model, employing several simultaneous longitudinal cuts of surface-wave profiles and accepting data from reflected waves in order to lengthen the usable record, a necessity for narrow tanks, was described in Reference [1]. A paper presenting the final version of this technique, by Tsai and Landweber [2], has been accepted for publication by the Journal of Ship Research, but has not yet appeared.

One of the important uncertainties in resolving resistance components is the interchange of energy between waves and the vorticity in the wake. Previous analytical and experimental work on this question is reviewed in a report by Swain and Landweber [3] on work conducted under the present contract. Gadd [4] had previously shown that vertically oriented vorticity in the boundary layer and wake of a vertical flat plate piercing the free surface generates negligible wave energy. To supplement his results, a flat plate in the shape of a toboggan, supported so as to skim horizontally over the water surface with only the bottom side wetted, was tested in the towing tank, and its wave resistance determined by the method of Reference [2]. The toboggan was designed so that its wetted area was of the same order of magnitude as that of a 10-foot ship model. It was found that its measured wave energy was only about one percent of that of a ship model. One interpretation of these results is not that vorticity cannot generate waves, but that the vorticity elements, in the distributions of vorticity which satisfy the nonslip condition on the generating body, produce waves which tend to be nullified by mutual cancellation.

Although vorticity may not generate waves, it has been shown that a wake can strongly affect the surface disturbance outside of it by refraction and relfection, the wave energy appearing to be nearly excluded from the wake region. For this reason, one would expect that, in a tank in which the wake width is an appreciable fraction of the tank width, the concentration of the waves in a narrower zone would result in larger magnitudes of the wave-amplitude spectrum derived from the longitudinal-cut records, as Savitsky has shown [5]. A similar effect has been found by introducing a turbulence-producing grid into the wake of a 10-foot, Series 60, 0.60-block model. The grid used was made of aluminum strips, 1/16-inch by 3/4-inch mesh. This was supported by piano wires two feet behind the stern of the model, with its top 3 inches below the water surface, so as to minimize its own wavemaking. The wave resistance, determined by the method of Reference [2], was considerably greater than that obtained without the grid, as is indicated by the values in the table.

F_n	0.20	0.24	0.28	0.31
C_w (no grid)	0.0001	0.0002	0.0011	0.0017
C_w (with grid)	0.0003	0.0009	0.0029	0.0025

Here $F_n = V/\sqrt{gL}$ denotes the Froude number and

$C_w = \frac{R_w}{\frac{1}{2}\rho S V^2}$ denotes the wave-resistance

coefficient, with S the wetted surface area of the ship model. The results in the table are tentative, and are included to show the status of the project when the contract was terminated.

Another unfinished project is a study of the reflection of ship waves by the walls of the towing tank. This was undertaken to investigate the accuracy of the assumption of perfect reflection made in analyzing the longitudinal-cut records. Very close to a wall, the amplitude of the surface disturbance would be very nearly doubled due to a perfect reflection. A comparison between longitudinal-cut records taken near a tank wall with a 10-foot Series-60 model, and at the corresponding lateral position in the tank with a 6-foot geometrically similar model has indicated that the doubling effect due to reflection is very nearly satisfied.

V. BLOCKAGE EFFECT

Additional work on the problem of correcting resistance data for tank-wall effects has appeared in a contribution by Landweber and Nakayama at the 17th ATTC [6] and an Appendix to the Report of the Resistance Committee of the 14th ITTC [7]. Reference [6] presented the results of an analytical study with empirical correlations to derive a simple and accurate formula for the velocity increment due to blockage for towing tanks of rectangular section and for models of various midship section areas and various prismatic coefficients. In Reference [7], this work was completed by including the effects of the tank walls on wave resistance and viscous pressure drag and a procedure for correction for all these effects was successfully applied to a set of model data. For a rational treatment of the viscous pressure drag, it was decided, after a study of the literature, that insufficient data are available for slender bodies with blunt sterns, such as ship forms, and consequently the blockage effect on pressures at the stern of such bodies is being investigated in a wind tunnel under other sponsorship.

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ABSTRACT

The accomplishments during the eleventh year of research on components of ship resistance, supplementing that reported in IIHR Report No. 162 on the first ten years, are summarized. These include the derivation of a more exact formula for calculating the viscous drag of a ship model from wake-survey measurements, a refinement of a procedure for determining wave resistance from surface-profile measurements, studies of the effect of the wake on wave-resistance measurements, and some contributions to the problem of correcting resistance measurements for the influence of tank boundaries.

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