STUDY OF TOTAL AND VISCOSOUS RESISTANCE FOR THE WIGLEY PARABOLIC SHIP FORM

by

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Sponsored by

Office of Naval Research
Contract No. N00014-82-K-0069

IIHR Report No. 261
Iowa Institute of Hydraulic Research
The University of Iowa
Iowa City, Iowa 52242

April 1983
ABSTRACT

Total resistances of the Wigley parabolic ship model with both free and fixed conditions were measured. Viscous resistances of the same model in the fixed condition were measured by the wake-survey method. The differences between total and viscous resistances for the fixed condition are compared with the residuary resistance and the wave resistance derived by the wave-pattern analysis. The wake-survey measurements were automated with transient-time control between successive tubes, sampling-time control, and simultaneous sampling of pressure and model speed by using a scanivalve and an HP-1000 minicomputer. Correction methods of the total-head readings and the flow velocities in the wake for variations of the model velocity were introduced. The experimental results show that the form-factor procedure gives a good estimate of the viscous resistance of the Wigley hull due to its low block coefficient. The total-resistance coefficients of the free and fixed conditions show a similar oscillatory variation with Froude number, but the values with the free condition are greater than those with the fixed condition.

ACKNOWLEDGEMENT

The author is indebted to Professor Louis Landweber for his continuous guidance and encouragement throughout the course of this study. Special thanks are extended to Mr. Ali Shahshahan for his assistance throughout the experiment.

This study was sponsored by the Office of Naval Research, Department of the Navy under Contract No. N00014-82-K-0069 (NR-062-183).
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<th>Description</th>
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<tbody>
<tr>
<td>B</td>
<td>beam at midship of the model</td>
</tr>
<tr>
<td>c</td>
<td>phase speed of the surge</td>
</tr>
<tr>
<td>$C_B$</td>
<td>block coefficient, $V/LBH$</td>
</tr>
<tr>
<td>$C_f$</td>
<td>frictional-resistance coefficient derived from flat plate</td>
</tr>
<tr>
<td>$C_t$</td>
<td>total-resistance coefficient, $R_t/\frac{1}{2} \rho U_0^2 S$</td>
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<td>$C_v$</td>
<td>viscous-resistance coefficient, $R_v/\frac{1}{2} \rho U_0^2 S$</td>
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<td>$C_{vw}$</td>
<td>viscous-resistance coefficient derived from wake-survey measurements</td>
</tr>
<tr>
<td>$C_w$</td>
<td>wave-resistance coefficient, $R_w/\frac{1}{2} \rho U_0^2 S$</td>
</tr>
<tr>
<td>$C_{wpd}$</td>
<td>wave-resistance coefficient derived from a wave-pattern analysis</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Froude number, $U_0/\sqrt{gL}$</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration of gravity</td>
</tr>
<tr>
<td>$h$</td>
<td>undisturbed depth of the towing tank</td>
</tr>
<tr>
<td>$H$</td>
<td>draft of the model</td>
</tr>
<tr>
<td>$H_0$</td>
<td>undisturbed total head</td>
</tr>
<tr>
<td>$H_m$</td>
<td>measured total head in the wake</td>
</tr>
<tr>
<td>$H_m'$</td>
<td>uncorrected measured total head in the wake</td>
</tr>
<tr>
<td>$k$</td>
<td>form factor</td>
</tr>
<tr>
<td>$L$</td>
<td>length of the model</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure in the wake</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number, $U_0 L/\nu$</td>
</tr>
<tr>
<td>$R_t$</td>
<td>total resistance</td>
</tr>
<tr>
<td>$R_v$</td>
<td>viscous resistance</td>
</tr>
<tr>
<td>$R_w$</td>
<td>wave resistance</td>
</tr>
</tbody>
</table>
S  wetted-surface area of the ship model
T  period of the surge
U_0  velocity of the uniform stream
u_e  disturbed velocity at the edge of the wake
\bar{u}_e  mean of the values of u_e
u_m  measured flow velocity in the wake
u'_m  uncorrected measured flow velocity in the wake
V  displaced volume
V'_c  mean value of V'_c over the measuring section
V''_c  carriage speed corresponding to H'_m
\lambda  wave length
\nu  kinematic viscosity of water
\rho  mass density of water
\omega  area of the wake at the measurement section
CHAPTER I
INTRODUCTION

1. Review of Pertinent Literature

The Froude method was based on the assumption that the total resistance of both ship and model can be split into two components, one the frictional resistance and the other the residual resistance, which is essentially the wave resistance and the resistance due to eddies and vorticity. The frictional resistance was assumed to be sensibly equal to the resistance of a rectangular plate of the same length and wetted surface as the hull of the ship or the model. The residual resistance, the difference between the total resistance and frictional resistance, is then scaled according to the Froude law. The weaknesses of this method, explained in [1], are:

1) The effect of hull form, which plays an important role in flow separation, pressure drag, and generation of vorticity and wake, is neglected.
2) The effect of viscosity on wavemaking, and of wavemaking on viscous resistance are ignored.

It is now well known that the frictional-resistance coefficient $C_f$ derived from a flat plate is not the same as that of the hull and, furthermore, that $C_f$ is only a part of the viscous-resistance coefficient $C_v$. In order to improve the Froude method, it has been suggested that the ratio

$$1 + k = \frac{C_v}{C_f}$$

(1)

is independent of the Reynolds number $Re$ and Froude number $Fr$, where $k$ is the form factor and $C_f$ may be represented by the Schoenherr flat-plate friction formula

$$\frac{0.242}{\sqrt{C_f}} = \log_{10} (Re \cdot C_f).$$

(2)
In its Report to the 14th I.T.T.C. (Ottawa, 1975), the Resistance Committee defined the components of resistance. The viscous resistance is defined as the component associated with the expenditure of energy in generating vorticity, vorticities (eddies) and turbulence. The wave resistance is defined as the component associated with the expenditure of energy in generating gravity waves. Except for interference effects, these two resistances obey the Reech-Froude law,

\[ C_t(\text{Fr}, \text{Re}) = C_v(\text{Re}) + C_w(\text{Fr}) \]  

where \( C_t \), a function of \( \text{Re} \) and \( \text{Fr} \), is the total-resistance coefficient and \( C_w \) the wave-resistance coefficient of the model. Applying the form-factor hypothesis, the total resistance of the model would then be given by

\[ C_t = (1 + k) \ C_f + C_w \]  

which is an important improvement over Froude's method. The theoretical reason for preferring the form-factor procedure to the Froude method is that, at low Froude numbers where \( C_w \) must become negligible, it is known that \( C_t \) does not become equal to the flat-plate friction coefficient, which the Schoenherr line is intended to represent.

When \( k \) is known, \( C_v \) is obtained from the definition (1), and then \( C_w \) is given by (3). One way of determining \( k \) utilizes experimental data at very low Froude numbers, where \( C_w \) is negligibly small in comparison with \( C_v \). Unfortunately, the viscous resistance at low speeds is also small and the value of \( C_t \) at that speed may be inaccurate. Moreover, at low speeds, that is at low Reynolds numbers, the uncertain extent of laminar flow on the model may introduce another source of error. The form-factor procedure also involves the assumption that \( k \) is independent of Froude number, which is contradicted by many wake-survey measurements on models, even on models with a moderate block coefficient (0.6, for example) as can be seen in Tzou [2] and Tsai [1]. Nevertheless, in the present study, this form-factor procedure is one of the methods
utilized, since it represents an important improvement over the Froude method.

In order to determine the functions representing the variation of viscous and wave resistances with Froude number, it is necessary to measure, in addition to the total resistance, either the viscous or wave-pattern resistance. The wave-pattern analysis by the longitudinal-cut method requires no special runs and can be automated. The wake-survey measurements may also be automated, but they require special runs and cannot be introduced in current practice as easily as the wave-pattern analysis. Both are necessary, however, since wave resistance and the viscous resistance do not obey the same laws of similarity and there exist causes of systematic errors such that the sum of $C_{VW}$ and $C_{WP}$ is less than $C_t$, where $C_{VW}$ denotes the viscous-resistance coefficient derived from wake-survey measurements, and $C_{WP}$ the wave-resistance coefficient derived from a wave-pattern analysis. Causes of errors affecting the estimates of these two components still exist as shown in Tsai and Landweber [1, 3] and Moreno, Perez-Rojas and Landweber [4, 5, 6], but experience shows that in many cases they should not be overemphasized. The discrepancy between the $C_t-C_{VW}$ and $C_{WP}$ curves, and the self-consistency of both sets of curves, strongly suggest the existence of errors and the necessity of improvements in the estimates of these two components. The error may come from the experimental procedures, the assumptions, or missing terms in estimating both resistances. The experimental error seems to be small due to the self-consistency between the results obtained for both resistances. It was suggested in [6] that the viscosity of the water has an appreciable influence on the wavemaking, and therefore, should be taken into account for computing the wave resistance of a ship form, and that there exists an additional component of the viscous resistance, probably due to vortex formation.

In this study, the viscous resistances of the Wigley parabolic ship model were measured by the wake-survey method. Since no experimental data for the viscous resistance are available with this model restrained
in both trim and sinkage, the differences between total and viscous resistances are compared with the wave resistance derived by wave-pattern analysis.

2. Viscous-Resistance Formula

In 1951, Tulin [7] proposed a method for evaluating the viscous resistance of a ship form by means of a wake survey, an extension of a method due to Betz [8]. Some improvements of this method have been introduced, as can be seen in [2, 9, 10]. A recent refinement of this derivation has been presented by Landweber [11], in which the effects of turbulence in the wake and the flux of Betz sources have been considered. A formula for calculating the viscous resistance of a ship model from measurements in the wake, derived in [11], is

\[
R_v = \frac{\rho}{\bar{u}_\infty} \int \left[ 2g (H_o - H_m) - (u_e - u_m)^2 \right] \omega dS
\]

(5)

where
- \(H_m\) is measured total head in the wake
- \(H_o\) is the undisturbed total head
- \(\rho\) is the mass density of water
- \(g\) is the acceleration of gravity
- \(\omega\) is the area of the wake at the measurement section
- \(u_m\) is the measured longitudinal component of velocity in the wake
- \(u_e\) is the value of \(u_m\) at the edge of the wake
- \(\bar{u}_e\) is the mean of the values of \(u_e\)
- \(U_o\) is the velocity of the uniform stream
- \(R_v\) is the viscous resistance.

In order to apply this formula, it is necessary to measure \(H_m\) and \(u_m\).
CHAPTER II
EXPERIMENTAL EQUIPMENT AND PROCEDURE

1. Equipment

All experiments were performed in the IIHR towing tank which has been described in [12]. The tank is 91.44-m long, 3.048-m wide and 3.14-m deep. The ship model employed in this study was a Wigley parabolic ship model with 0.444 block coefficient $C_B$, a length of 3.048 m and the wetted surface area of 1.381 m$^2$. The Wigley parabolic hull is characterized by sharp edges at the bow, stern and keel. It is a mathematical form defined by

$$|y| = \frac{B}{2} \left[ 1 - \left( \frac{2x}{L} \right)^2 \right] \left[ 1 - \left( \frac{z}{H} \right)^2 \right]$$

in the $(x,y,z)$ coordinate system with increasing values of $x$ in the direction opposite to the ship's forward motion, $z$ vertically upward, and the origin at the undisturbed level of the free surface. Here $L$ is the length of the model, $B$ is the beam at midship and $H$ is the draft. For the selected form, the parametric values are $B/L = 0.1000$ and $H/L = 0.0625$. For turbulence stimulation along the hull, a row of studs of 3.2-mm diameter, 1.6-mm height and 9.5-mm spacing was fitted on the model at 15.2 cm, 5 percent of the model length from the bow. The model was attached to the towing-tank carriage and towed at constant speed. With the towing arrangement used, the model was restrained in both trim and sinkage for the total and viscous-resistance measurements in the fixed condition. For the total-resistance measurements in the free condition, two guides at the bow and stern were used in order to prevent the model from moving laterally, but the model was free to sink and trim.
The pitot rake and the traversing-probe mechanism were set on the trailer 3.05 m behind the stern of the ship model. The pitot rake consists of a horizontal array of pitot tubes, extending from a wooden board of streamlined form, 15.2-cm wide, 3.05-cm thick, and 1.30-m long. It contains 17 total-head tubes and 18 piezometric-head tubes, mounted alternately at a spacing of 3.05 cm. The tips of the total-head tubes lie in the same transverse section as the side holes of the piezometric-head tubes. Each piezometric-head tube has six 0.4-mm-diameter side holes around the circumference of a tube. Also four total-head tubes, two near each wall, mounted at a level of 0.762 m below the undisturbed water surface, were towed to measure the undisturbed total head outside the wake. For measuring the surface profile across the measuring section, a commercial "ceroc" wire with a ceramic-heavy teflon coating was mounted on the traversing mechanism which transports the probe across the tank during a test run, as described in [13].

2. Data Acquisition System

The data acquisition system for the carriage speed, and the total head and pressure in the wake, consists of a 48-terminal scanivalve, a ±0.021-kg/cm² pressure transducer, a scanco CCLR2/S2 solenoid controller, IIHR scanivalve positioning circuit, an Analog-to-Digital converter subsystem, and an HP-1000 E-series minicomputer, as shown in Figure 1. This is a more sophisticated computerized-system than that previously used with the IBM 1801 computer [1,2,5,14]. The transient time and sampling time are controlled by the computer. All the acquired data are stored for later analysis. The carriage velocity and the pressure data are sampled simultaneously by this system. The computer is programmed so as to control the sequence of positions of the scanivalve and the duration of the stay at a particular opening in the course of a run. While at an opening, the computer program instructs the computer to delay sampling data until a transient (to be discussed in a later section) has decayed, and then commands the A/D converter to take a desired number of samples in a given time. A generator linearly
Figure 1. Data-Acquisition System for the Carriage speed, Total Head and Static Head in the Wake.
converts carriage speed to frequency which is then converted to voltage. The pressures from the pitot tubes are converted to voltages by a pressure transducer and amplified by a voltage amplifier. The A/D converter samples these two voltage signals simultaneously. Then the data are read and stored by the computer. With the present system, only one operator is needed to conduct wake-survey measurements. With the previous equipment it was necessary to have a second operator stationed at the computer, in communication with each other through an intercom. The sampling program is listed in the Appendix. This program can be used for wake-survey measurements with the HP-1000 minicomputer with some modifications in the input data, such as the number of pitot tubes used, the arrangement of pitot tubes, etc.

The total resistance were measured by the same procedure as in [1, 5]. The surface profile across the measuring section was measured by the same procedure as in [1], except that now the HP-1000 minicomputer was used. The acquired data were confirmed by means of point gages, and the discrepancy between two methods was at most ±0.9 mm.

3. Experimental Techniques
A. Technique of Viscous-Resistance Measurement

More care is needed when the scanivalve is used with water than with air, due to the high humidity. Compressed air was used to clean the scanivalve head. The whole system, including scanivalve and tubing connecting the scanivalve and the pitot tubes, was checked by applying and removing pressure. Pressure is applied by lowering the scanivalve level after closing the header retaining ring, and removed by raising it. When the header of the scanivalve is closed at any fixed level, the voltage reading of the pressure transducer is the same as that of the open header. Then pressure is applied by lowering the scanivalve to another level, at which the voltage reading for the pressure should hold constant. Continuous dropping of the reading at the new level indicates that the pressure is leaking somewhere in the system. A sudden drop indicates that a tube is disconnected and a slow rise indicates that the
hole in the scanivalve is not completely open. No change in the voltage reading when the scanivalve is lowered, indicates that the hole in the scanivalve is closed. Every hole was checked in this way before starting and during data acquisition. This step was found to be very important because sometimes the hole was closed and it was difficult to recognize this from the acquired data.

Before using the pressure transducer, a preliminary warming time of 30 minutes was found to be necessary. Air was used in the tubing above the free surface to transmit the pressure to the transducer. The transducer used is ±0.021 kg/cm² which is more sensitive than that used previously [1,2,5]. This pressure range is enough for the velocity measurements up to Fr = 0.37. The A/D converter of the HP-1000 can read ±10 volts and it is recommended that this entire range be used to reduce cable noise at low voltage caused by the long cable length of 210 m connecting the pressure transducer and the A/D converter. For this reason, a gain of 500 was used to magnify the low voltage from the pressure transducer. Cable noise was found to affect the measured pressures by ±0.63x10⁻⁵ kg/cm². The transducer was calibrated by lowering the scanivalve to various levels from the base level in increments of 3.048 cm. The voltage was linear with the pressure, with a correlation coefficient 0.99995 and this linearity indicates that the compressibility of the air in the tubing is negligible.

For tests in the towing tank, a time interval of 15 minutes between runs was found to be necessary. To be sure that the water was at rest, dye was emitted at the measuring depth. By observing this dye, it was found that the water was still moving after one hour. It is not convenient however to wait this long. After the carriage returned to the starting position, the water becomes calm quickly, but the rate decreases with time. The free surface appears motionless after 5 to 7 minutes, but the water may still be in motion below the free surface. It was found that the water velocity was 1.5 cm/s after 2 minutes, 0.3 cm/s after 10 minutes, and 0.24 cm/s after 15 minutes. A waiting time of 15 minutes was used in this experiment. This gives an error of less
than 0.1 percent in the measured velocity. Dye was used to observe the water drift before each run.

The carriage-speed measurement is important because all the data in the towing tank are based on this speed. A generator linearly converts carriage speed to frequency which is then converted to voltage for sampling by A/D converter. The carriage speed was calibrated by measuring the time to pass a fixed distance and sampling the voltage signal simultaneously. The voltage was linear with the carriage speed, with a correlation coefficient 0.9998. One hour of preliminary warming time for the carriage driving motor and the mechanical parts was found to be necessary. During a carriage run, the speed fluctuates in the range ±0.006 m/s and increases 0.009 m/s during the run. This variation is significant at the low Froude numbers, and hence the total-head readings were corrected by using the instantaneous carriage-speed data which were sampled simultaneously with the pressures.

B. Sampling Technique

The voltage signals of the carriage speed and the pressures were sampled simultaneously by employing two channels of the A/D converter of the HP-1000 computer. Reduction of sampling time is important in order to reduce the total number of runs. The voltage of the carriage speed is sampled easily because the signal does not change much. For the pressure measurement, two possible sequences were considered. The total pressure and the static pressure can be sampled alternately or separately. The alternate sampling has the advantage that air leakage in the system can be recognized easily. The separate sampling has the very attractive advantage that the electrical transient time caused by the sudden voltage difference from a total-head to a static-head tube can be reduced due to the small pressure differences between successive tubes. The separate sampling method was used in this experiment because the smaller transient time reduced the total number of runs. The wake width of the Wigley ship model was found to be narrow, less than 0.3 m at 3.05 m behind the stern, so that the sampling was done with 11 total-
head tubes, 12 static-head tubes, and 4 undisturbed total-head tubes at a width of 0.61 m. Transient times, determined from preliminary experiments, are 0.2 sec between successive total-head tubes outside the wake region, 0.6 sec between successive total-head tubes in the wake region, 1.2 sec between total-head tubes and static-head tubes, and 0.2 sec between successive static-head tubes. The sampling time of 0.5 sec was used at each tube and it was increased to 1.0 sec in the wake region which gives the most contribution to viscous resistance calculation. Pressure leakage could be detected by plotting the sampled data after completing the experiment. The data could be sampled in 23 sec during a run. Two runs were required for Froude numbers greater than 0.25. The computer reads 200 simultaneous samples of the carriage velocity and pressure from each tube and stores the data for use in later analysis and graphics. A null point was measured before a run and subtracted from the acquired data. The null point could be set at a sufficiently high voltage to reduce cable noise.

4. Study of the Surge

The effect of a long-period surge in the towing tank on the total and static-pressure reading was studied. The period "T" was measured as 33 sec. Since it is a long and infinitesimal wave, its phase speed "c" is given by

\[ c = \sqrt{gh} = 5.55 \text{ m/s} \]  

(7)

where the undisturbed depth of the towing tank "h" has been taken as 3.14 m. The wave length \( \lambda \) will be, therefore

\[ \lambda = cT = 183 \text{ m} \]  

(8)

which is twice the length of the towing tank. A further theoretical analysis is given in [4].
For this experiment, the surge effect was studied under the actual conditions by employing a piezometric tube and a pressure transducer. The static pressures of the disturbed water were sampled at time intervals of one second for one hour after a run and converted to the water head at the various Froude numbers. Samples at the measuring and starting points in the towing tank between 10 and 20 minutes after a run are plotted in Figure 2. At the measuring point, which is in the middle of the towing tank, two superimposed wave patterns were detected. A small crest was observed between two large crests, but only the large crests were used to determine the period or wave length. This can be explained as an effect of the reflection at the end walls of the towing tank. It is interesting that the amplitude of the small crest becomes larger and that of the big one becomes smaller, until, after about 30 minutes, the two amplitudes become nearly equal. At the starting point, which is near the end wall of the towing tank, only one wave-pattern was detected. This can be explained by the fact that the reflected wave at the near wall dominates the other wave from the far wall.

The maximum amplitudes decrease with time due to damping, as shown in Figure 3. The amplitudes at the measuring point decrease more rapidly than those at the starting point. A suggested explanation is that, because of the interaction between the small and large wave crests, the amplitude decreases rapidly. After a run at Fr = .25, the maximum amplitude is less than 0.6 mm after 15 minutes and 0.4 mm after 30 minutes. After 1 hour, it becomes too small to detect because of the cable-noise error of ±0.06 mm in the amplitude measurements.

The viscous-resistance expression derived in [6] is

\[
\frac{\partial R_v}{\partial \rho} \frac{\delta z}{\omega} = \int \frac{H_0 - H_m}{u_m^2} g \, dS \, \frac{\delta z}{\omega} - \frac{\Delta H}{u_m^2} g \, \omega
\]

(9)

where \(\Delta H\) is the mean value of the difference between the undisturbed total head and total head in the wake, \(u_m^2\) the mean value of the square of the velocity in the wake, \(p\) the pressure in the wake, and \(\omega\) the area
Figure 2. Samples of the Surge at the Measuring and Starting Points.
Figure 3. Surge Decay with Time.
of the wake. By employing this expression, the possible maximum error due to the long-period surge was less than 0.5 percent in the viscous resistance and the corrections for the surge in this experiment were not considered.

5. Data Analysis

The calculation of the viscous resistance was carried out in the manner indicated by Landweber and Tzau [2], with some slight differences. Although the model velocity was not exactly constant through a run, it was assumed that the flow in the wake behind stern is steady, but the measured wake characteristics correspond to the instantaneous model velocity due to the rigid connection between the pitot rake and the carriage. For this reason, the total head and the flow velocity were corrected to the mean carriage speed of a run. These corrected values were also corrected to the mean carriage speed of a complete traverse of the wake section. The total-head readings were corrected as

$$H_m = \left(\frac{V}{V_c}\right)^2 H'_m$$

(10)

where $V'_c$ is the carriage speed corresponding to the measured value of $H'_m$, and $V_c$ is the mean value of $V'_c$ for the traverse over the measuring section. The flow velocity in the wake was corrected as

$$u_m = u'_m - (V'_c - V_c)$$

(11)

where $u'_m$ is the uncorrected measured flow velocity. For this study, the total-head readings and the flow velocities were corrected at most 1.4 and 2.8 percent of their values respectively.

Since the total-head tubes and the piezometric-head tubes were mounted alternately, a cubic interpolating spline function was used for determining the interpolated values of the piezometric head at the locations of the total-head tubes. For evaluating the viscous-
resistance integral, the values of the total head \(H_m\) and the velocity \(u_m\) were interpolated for additional locations at intervals of 1.52 cm both horizontally and vertically at the measuring section of the wake, and Simpson's one-third rule was utilized as the quadrature formula.

The results of the transverse surface profile, measured at 3.05 m behind the stern and used to evaluate the viscous-resistance integral, are shown in Figure 4.

In order to know the variation of the viscous-resistance coefficient with Froude number, the obtained data were corrected to the standard temperature 18.3°C at which the total resistances were measured, under the Reech-Froude assumption that \(C_v\) is a function of \(Re\). This temperature correction is essential since the kinematic viscosity \(\nu\) varies with temperature, approximately 2.5 percent per degree C for water, and the viscous resistances are obtained at the different water-temperatures. For this study, the temperature correction was at most 1 percent of the values of the viscous resistance.
Figure 4. Surface Profiles at 3.05 m behind Stern.
--- --- : undisturbed water level

Fr = 0.260

Fr = 0.284

Fr = 0.302

Fr = 0.319

Fr = 0.342

Wave Height (cm)

Y(cm)

Figure 4. (continued)
CHAPTER III
DISCUSSION OF RESULTS

1. Fixed Condition

Total and viscous-resistance coefficients are shown against Reynolds number and compared with the Schoenherr line of the flat plate in Figure 5. The sinuous trend of the viscous-resistance coefficient with Reynolds number is seen to have much less amplitude than was found for the series-60 model by Tzou [2] and Tsai [1]. This suggests that the form-factor procedure may give good agreement with experimental results. This is probably a consequence of the slenderness of the Wigley ship model.

The total-resistance coefficients have been compared in Figure 6 with the other experimental results; those for a 4-m model tested at the Ship Research Institute of Japan (SRI), and 2.5-m model tested at the University of Tokyo (U.T.). Here $C_t$ from SRI and U.T. were corrected to a standard temperature of 18.3°C, and the $C_t$ of Iowa was fitted by a smooth curve by comparing the experimental results from the three tanks. Then the residuary resistance $C_w$ from the three tanks were calculated by using the form-factor formula (4) with $k = 0.100$ for Iowa, $k = 0.065$ for SRI and $k = 0.050$ for U.T. These were selected so as to obtain the best agreement between the $C_w$'s of the three tanks.

The viscous-resistance coefficients have been corrected to a standard temperature of 18.3°C, and then plotted against Froude number in Figure 7. The viscous-resistance coefficient shows a hump at Froude number of 0.24, and two hollows at Froude numbers of 0.22 and 0.32, in contrast with the monotonically decreasing trend assumed in the form-factor procedure. This suggests that the viscous resistance is affected by the wave resistance; thus its coefficient is a function of not only Reynolds number, but also Froude number, although this dependence seems to be small in this case.
Figure 5. Variation of Total and Viscous-Resistance Coefficients with Reynolds Number. (Fixed Condition).
Figure 6. Comparison of $C_t$'s and $C_w$'s vs. Froude Number. (Fixed Condition)

Temperature = 18.3°C

- $C_t$, Iowa (L = 3.048 m)
- $C_t$, SRI (L = 4.0 m)
- $C_t$, U.T. (L = 2.5 m)
- $C_w$, Iowa (k = 0.10)
- $C_w$, SRI (k = 0.065)
- $C_w$, U.T. (k = 0.05)
Figure 7. Variation of Viscous-Resistance Coefficient with Froude Number.
(Fixed Condition)

Temperature = 18.3°C

\( C_{MW} \), Iowa
\( C_{F} \) (Schoenherr)
The wave-resistance coefficients obtained by subtracting the viscous resistance of the wake-survey measurements from the total resistance, $C_t - C_{vw}$, are compared in Figure 8 with the residuary resistance $C_w$ from the three tanks. $C_t - C_{vw}$ are seen to be in good agreement with $C_w$. The discrepancies between $C_t - C_{vw}$ and $C_w$ of Iowa are less than 7 percent at Froude numbers greater than 0.23. The largest discrepancy of 20 percent occurs in the range $0.21 < Fr < 0.22$ in which $C_t - C_{vw}$ has a hump. This is less than 3 percent of the total or viscous-resistance coefficients, that is about the same order as the experimental error. Generally speaking, $C_t - C_{vw}$ is greater than $C_w$ at Froude numbers less than 0.23. $C_t - C_{vw}$ is also compared with the experimental results for $C_{wp}$ from SRI and U.T., where $C_{wp}$ was obtained by wave analysis of longitudinal-cut data. $C_t - C_{vw}$ and $C_{wp}$ are in good agreement at Froude numbers in the range $0.24 < Fr < 0.34$, with discrepancies of less than 12 percent of $C_w$, or 3 percent of $C_t$ or $C_{vw}$, which may be attributed partly to experimental error and partly to the assumptions made in determining $C_t$, $C_{vw}$ and $C_{wp}$. The large discrepancy of 35 percent occurs in the range $0.21 < Fr < 0.22$. This is 5 percent of the total or viscous-resistance coefficients. At Froude numbers less than 0.27, the viscous resistance is more than 80 percent of the total resistance, and its effect dominates the flow characteristics. One would expect that, in this range, $C_t - C_{vw}$ derived from wake-survey measurements would be more reliable than the $C_{wp}$ derived from wave-pattern analysis, since $C_{wp}$ is derived from measurements of small quantities, and the influence of the wake on the waves behind the ship may be significant. At low Froude numbers or Reynolds numbers, the wake is wider and the boundary layer is thicker than at higher Froude numbers, thus the effect of wake and boundary layer becomes relatively more important. At Froude numbers greater than 0.34, the discrepancies between $C_t - C_{vw}$ and $C_{wp}$ become large again. $C_{wp}$ is seen to be significantly smaller than $C_t - C_{vw}$ or $C_w$. This is believed to be due to the assumption made in the wave-pattern analysis of the linearized free-surface boundary condition.
Figure 8. Comparison of $C_t$, $C_w$, and $C_{wp}$ vs. Froude Number. (Fixed Condition)
Table 1. Values of $C_t$, $C_{vw}$, $C_t-C_{vw}$ and $C_w$ with Froude Number.
(Fixed Condition, Temperature = 18.3°C)

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The values of $C_t$, $C_{vw}$, $C_t-C_{vw}$ and $C_w$, read from the curves in Figs. 6,7,8, are tabulated against Froude number in Table 1.

2. Free Condition

The Iowa total resistance coefficients, plotted against Froude number, are compared with the other experimental results in Figure 9; those for a 4-m model tested at the SRI, a 2.5-m model tested at the U.T., and a 6-m model tested at the Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI). Here the $C_t$'s from SRI, U.T. and IHI were corrected to a standard temperature of 13.3°C. These show a similar oscillatory variation with Froude number. The data from all four tanks show a significant hump and hollow in the ranges $0.31 < Fr < 0.32$ and $0.34 < Fr < 0.35$, respectively. The $C_t$'s from SRI and IHI which used larger models than the others, show additional humps at Froude numbers 0.21 and 0.25, and hollows at Froude numbers 0.22 and 0.27. The values of $C_t$ from Iowa are tabulated against Froude number in Table 2.

The Iowa total resistance coefficient for the fixed condition was also corrected to the standard temperature of 13.3°C and plotted in Figure 9 for comparison with results for the free condition.

This comparison shows that the humps and hollows for both cases occur at the same Froude numbers but the values of $C_t$ with the free condition are greater than those with the fixed condition, by about 1 to 4 percent for Froude numbers less than 0.28, and 4 to 10 percent for Froude numbers greater than 0.28.
Table 2. Values of $C_t$ with Froude Number.
(Free Condition, Temperature = 13.3°C)

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CHAPTER IV
SUMMARY AND CONCLUSIONS

The most useful purpose served by the present study is the collection of the viscous resistance for the Wigley parabolic ship model, restrained in both trim and sinkage. These data can serve as the basis for further theoretical studies of the Wigley hull. In view of this, the experimental results are presented in the form of a table in the Appendix.

The major conclusions of this study are as follows:

1) Experimental results for the total-resistance coefficients of the Wigley parabolic hull restrained in both trim and sinkage, its viscous-resistance coefficients obtained by means of wake-survey measurements, and the wave-resistance coefficients obtained from these data are shown in Table 1.

2) $C_t - C_{vw}$ and $C_{wp}$ are in good agreement at Froude numbers in the range $0.24 < Fr < 0.34$. The discrepancies between $C_t - C_{vw}$ and $C_{wp}$ outside of this range may be attributed to errors and assumptions made in determining $C_{wp}$, i.e., measurements of small quantities and the effect of wake at lower Froude numbers, and the linearized free-surface boundary condition at higher Froude numbers.

3) The viscous-resistance coefficient is weakly dependent upon the Froude number.

4) The form-factor procedure gives a good estimate of the viscous resistance of the Wigley hull due to its low block coefficient.

5) New techniques for wake-survey measurements have been introduced, employing the HP-1000 E-series minicomputer, with transient-time control and simultaneous sampling of pressure and carriage speed. The last is important since it enables corrections to be made for
variations of the model velocity, as proposed in equations (10) and (11).

6) Experimental results for the total-resistance coefficients in the free condition are shown in Table 2.

7) The comparison of the total-resistance coefficients between free and fixed conditions shows that the humps and hollows for both cases occur at the same Froude numbers, but the values with the free condition are greater than those with the fixed condition with the increment increasing to about 10 percent at the largest Froude number of 0.4.
BIBLIOGRAPHY


APPENDIX
LISTINGS OF SAMPLING PROGRAM USED IN WAKE-SURVEY MEASUREMENTS

&\text{WAKE T=00004 IS ON CR00022 USING 00044 BLKS R=0000}

0001 FTMXX.L
0002 $FILES(0,1)
0003 PROGRAM INPUT
0004 C
0006 C --- This program is used for the WAKE-SERVEY MEASUREMENTS with
0007 C --- HP-1000 minicomputer and A/D Converter directly and for the other
0008 C --- measurements related with SCANIVALVE with minor modifications.
0009 C --- Programmed to sample CARRIAGE SPEED (called VELOCITY after) and
0010 C --- PRESSURE from 2 channels of A/D Converter simultaneously, so
0011 C --- velocity and pressure should be converted to voltages (see Fig.1).
0012 C --- The range of -10 to +10 volts can be read by A/D Converter.
0013 C --- Sampling rate of 200 samples/sec is recommended.
0014 C --- High priority is required to avoid the interruption during runs.
0015 C --- The obtained data from the first run are stored in two files named
0016 C --- 'AVER01:SC:22' for the average values (REAL) at each tubes and
0017 C --- 'INST01:SC:22' for the instantaneous values (INTEGER), and
0018 C --- the number 01 of these names is increased by 1 for the next run.
0019 C --- After this program stops, all files to be stored should be renamed
0020 C --- for the permanent storage.
0021 C --- Following variables are to be specified.
0022 C --- NTUBE : number of pitot tube (0-47)
0023 C --- NSST : assumed same as the scanivalve-position number
0024 C --- NTDS : starting number of static-head tube
0025 C --- NTDS : starting number of total-head tube to be sampled for
0026 C --- double period in the wake
0027 C --- NTDS : ending number of total-head tube to be sampled for
0028 C --- double period in the wake
0029 C --- VSLOP : slope of calibration curve of velocity
0030 C --- VSLOP : slope of calibration curve of velocity
0031 C --- VCONS : constant of calibration curve of velocity
0032 C --- VCONS : constant of calibration curve of velocity
0033 C --- Note: Carriage Velocity should be calibrated for each series
0034 C --- of experiments to determine VSLOP & VCONS for input data.
0035 C --- VSLOP=1 & VCONS=1 gives voltage itself for calibration.
0036 C --- Followings are examples for the input data.
0037 C
0038 DATA NTUBE,NSST,NTDS,NTDE/27,16,7,9/
0039 DATA VSLOP,VCONS/4.95331,-0.5511/
0040 C
0041  10  WRITE(1,20)
0042  20  FORMAT(1X,"CHECK A/D CONVERTER, PITOT TUBES & SCANIVALVE!!!")
0043  */1X,"ARE YOU READY FOR SAMPLING ???"
0044  */1X,"TYPE 'YES' OR 'NO' ",'
0045  40  READ(1,30) MESS
0046  50  FORMAT(1A2)
0047  60  IF(MESS.EQ.2HYE) GO TO 40
0048  61  IF(MESS.EQ.2HND) GO TO 999
0049  62  IF(MESS.NE.2HYE .AND. MESS.NE.2HND) GO TO 10
0050  70  CONTINUE
0051  C
0052  80  WRITE(1,60)
0053  90  FORMAT(1X,"WANT TO KEEP INSTANTANEOUS DATA ???")
0054  */1X,"TYPE 'YES' OR 'NO' ",'
0055  100 READ(1,30) MESS
0056  110 IF(MESS.NE.2HYE .AND. MESS.NE.2HND) GO TO 50
0057  C
0058  120 NDATA=NBLK#NTUBE
0059  DO 110 NRUN=1,20
0060  130 WRITE(1,80)
0061  140 FORMAT(1X,"WANT TO RUN THE MODEL ???")
0062  */1X,"TYPE 'YES' OR 'NO' ",'
0063  150 READ(1,30) MESSR
0064  160 IF(MESSR.EQ.2HYE) GO TO 90
0065  161 IF(MESSR.EQ.2HND) GO TO 120
0066  162 IF(MESSR.NE.2HYE .AND. MESSR.NE.2HND) GO TO 70
0067  170 CONTINUE
0068  C
0069  180 CALL MAIN(NTUBE,NSST,NTDS,NTDE,VSLP,VCNS,NBLK,NDATA,NRUN,MESK)
0070  C
0071  190 WRITE(1,100)
0072  200 FORMAT(1X,"WAIT FOR 15 MINUTES BEFORE ANOTHER RUN !!!")
0073  210 CONTINUE
0074  220 WRITE(1,130)
0075  230 FORMAT(1X,"!!! RENAME THE VALUABLE FILES !!!!!!")
0076  240 STOP
0077  END
0078  C
0079  C
0080  C
0081  C --- This subroutine is used to execute the wake-survey measurements.
0082  C
0083  DO DOUBLE PRECISION SUM1,SUM2
0084  DIMENSION NQDF(125),IDATA(6000),SAMP(125)
0085  DIMENSION PRES(48),VEL0(48),PSAMP(48),VSAMP(48),PHNULL(48)
0086  DIMENSION NAME(6)
0087  C
0088  DO 190 IREPT=1,2
0089  IF(IREPT .GE. 2) GO TO 20
0090  WRITE(1,10)
0091  WRITE(1,10)
0092  10 FORMAT("' THIS RUN IS FOR THE NULL POINT MEASUREMENT "")
0093         ITIME=1
0094         GO TO 40
0095   20      WRITE(1,30)
0096   30      FORMAT(/1X,"HOW MANY TIMES FOR THIS RUN ?")
0097      #/1X,"GIVE THE ITIME : ",')
0098      READ(1,*) ITIME
0099      IF(ITIME.EQ.0) GO TO 20
0100   40      ITEMS=0
0101      IONES=0
0102      IGO=(NTU-1)/ITIME
0103      IFIRST=1
0104      ILAST=IFIRST+IGO
0105      MT=0
0106   C
0107      DO 120 II=1,ITIME
0108       IF(IREPL.GE.2) WRITE(1,50)
0109      50      FORMAT(/1X,"!!! RUN THE MODEL !!!")
0110       WRITE(1,60)
0111      60      FORMAT(/1X,"*** WHEN YOU ARE READY, HIT RETURN KEY ***","",")
0112     READ(1,*) GOON
0113   C
0114   C --- SAMPLING
0115      DO 80 I=IFIRST,ILAST
0116       MT=MT+1
0117      IONES=IONES+1
0118     IF(IONES.GT.9) ITEMS=ITEMS+1
0119     IF(IONES.GT.9) IONES=0
0120   C
0121      CALL JUSCN(ITEMS,IONES)
0122   C
0123      IBUF=200
0124     IF(MT.GE.NTDS .AND. MT.LE.NTDE) IBUF=400
0125      IRAN=20
0126     IF(MT.GE.NTDS .AND. MT.LE.NTDE) IRAN=-60
0127      IF(MT.EQ.NS) IRAN=-100
0128   C
0129      CALL SAMPL(IBUF,IRAN,NBUF)
0130   C
0131      JSTOR=125*(MT-1)
0132     DO 70 J=1,JSTOR
0133      IFDATA(JSTOR)=NBUF(J)
0134    70      CONTINUE
0135   C
0136   C --- DISPLAY SOME VALUES OBTAINED FROM LAST RUN
0137      WRITE(1,90)
0138    90      FORMAT(/1X,"DATA ACQUIRED AT THIS STAGE")
0140      MDISV=125*(IFIRST-1)-110
0141      MDISP=125*(IFIRST-1)-50
0142     DO 100 I=IFIRST,ILAST
0143      MDISV=MDISV+125
0144      MDISP=MDISP+125
VSAMP(I)=FLOAT(IAND(IDATA(MDISP),177776B))#3.05176E-4
PSAMP(I)=FLOAT(IAND(IDATA(MDISP),177776B))#3.05176E-4
VSAMP(I)=VSAMP(I)#VS+VC
WRITE(1,110) (VSAMP(I),I=IFIRST,ILAST)
WRITE(1,110) (PSAMP(I),I=IFIRST,ILAST)
FORMAT(7F10.3)
IFIRST=ILAST+1
ILAST=IFIRST+16
IF(ILAST.GT.NTU) ILAST=NTU
CONTINUE
C
--- At this stage, one complete set of data for one carriage speed
--- is contained in 'DATA'. DATA can be split into blocks.
--- Each blocks contain 125 integer data from each tubes, 1-25 for
--- velocity, 26-125 for pressure. They can be converted to voltage,
--- velocity or pressure and stored in files as shown below.
C
--- CALCULATE PRESSURE & VELOCITY FOR EACH TUBE
DO 170 NT=1,NTU
MN=MN*(NT-1)
DO 160 MN=1,NB
MN=MN+1
MBUF(MN)=DATA(MN)
DO 160 ML=1,NB
SAMP(ML)=FLOAT(IAND(MBUF(ML),177776B))#3.05176E-4
SUM1=0.
SUM2=0.
DO 150 K=1,25
SUM1=SUM1+SAMP(K)
DO 160 NT=1,NTU
VELO(NT)=SUM1/25.#VS+VC
PRESS(NT)=SUM2/100.
CONTINUE
IF(IREPT.GE.2) GO TO 190
DO 180 NT=1,NTU
PNULL(NT)=PRESS(NT)
CONTINUE
DO 200 NT=1,NTU
PRESS(NT)=PRESS(NT)-PNULL(NT)
C
--- CALCULATE CARRIAGE VELOCITY : AVERAGE, MAX & MIN FOR EACH RUN.
VELS=0.
VMAX=VELO(1)
VMIN=VELO(1)
DO 210 II=1,NTU
VELS=VELS+VELO(II)
IF(VELO(II).GT.VMAX) VMAX=VELO(II)
IF(VELO(II).LT.VMIN) VMIN=VELO(II)
CONTINUE
VAVG=VELS/NTU
WRITE(1,220) VAVG,VMAX,VMIN
0198 FORMAT(/1X,"--- THE LAST CARRIAGE VELOCITY DATA ---/
0199 *3X,"AVG=",F10.5," MAX= ",F10.5," MIN= ",F10.5"
0200 C
0201 C --- STORE THE OBTAINED DATA IN FILES.
0202 ENCODE(12,230,NAME) NRUN
0203 C 230 FORMAT(‘AVER’,12.2,’-SC:22’)
0204 OPEN(88,IOSTAT=105,ERR=998,FILE=NAME,ACCESS=’SE’,
0205 *STATUS=’UNKNOWN’)
0206 WRITE(1,300) NAME
0207 WRITE(88,240) VAVG,VMAX,VMIN
0208 240 FORMAT(/1X,"*** CARRIAGE VELO. ***
0209 *AVG=",F8.5," FPS MAX=",F8.5," MIN=",F8.5/
0210 *5X,"ENT DEPTH : 
0211 DO 250 IN=1,NTU
0212 250 WRITE(88,260) IN,VELO(IN),PRESS(IN)
0213 260 FORMAT(I10,2F10.5
0214 WRITE(1,110) (VELO(IN),IN=1,NTU)
0215 WRITE(1,110) (PRESS(IN),IN=1,NTU)
0216 CLOSE(88)
0217 C
0218 IF(MESK.NE.2KYE) GO TO 290
0219 ENCODE(12,270,NAME) NRUN
0220 270 FORMAT(‘INST’,12.2,’-SC:22’)
0221 OPEN(89,IOSTAT=105,ERR=998,FILE=NAME,ACCESS=’SE’,
0222 *STATUS=’UNKNOWN’)
0223 WRITE(1,300) NAME
0224 WRITE(89,280) (IDATA(J),J=1,ND)
0225 280 FORMAT(I108)
0226 CLOSE(89)
0227 290 CONTINUE
0228 300 FORMAT(/1X,"MAKING FILE ",A2,’ : WAIT !!!")
0229 GO TO 999
0230 C
0231 C --- OUTPUT ERROR IN OPEN OR READ,OUTPUT TO PRECONNECTED TERMINAL
0232 990 WRITE(1,994) IOS
0233 994 FORMAT(*ERROR ENCOUNTERED=",I6)
0234 999 RETURN
0235 END
0236 C
0237 C
0238 C SUBROUTINE SAMPL(IBFL,IITRAN,NBUF)
0239 C
0240 C --- This subroutine executes the transient-time control and sampling
0241 C --- ( 200 or 400 samples ). Integer data read from A/D Converter are
0242 C --- rearranged and stored NBUF(125). NBUF(1-25) contains velocity
0243 C --- data and NBUF(26-125) contains pressure data. The waiting time
0244 C --- before sampling is ABS(IITRAN)%10 milli-seconds.
0245 C --- Channel ‘0’ is for velocity and ‘1’ for pressure.
0246 C
0247 DIMENSION NBUF(125),IBUF(400),ICBUF(3)
0248 DATA ICBUF/300000,0,1/
ICNWD=011700B
ICNWD=ICNWD+7
CALL EXEC(12,0,1,0,ITRAN)
CALL EXEC(1,ICNWD,IBUF,IBUFL,ICBUF,3)
IPSKIP=2
IF(IBUFL.NE.200) IPSKIP=4
IVSKIP=IPSKIP+4
KV=0
DO 10 IV=3,IBUFL,IVSKIP
KV=KV+1
10 NBUF(KV)=IBUF(IV)
KP=25
DO 20 IP=2,IBUFL,IPSKIP
KP=KP+1
20 NBUF(KP)=IBUF(IP)
RETURN
END
SUBROUTINE JUSCM(ITEMS,IONS)
--- This Subroutine is used change the SCANIVALUE Position.
--- Description of parameters
ITEMS : Tens digit of hole number to be positioned.
On return, this is Tens digit positioned.
IONS : Ones digit of hole number to be positioned.
On return, this is Ones digit positioned.
--- Remarks
1) Hole number can be from 00 to 47.
2) Program should not tell the circuit to go to the hole that it is already at.
ITEM=ITEMS
IHUNS=1
ITEM=ITEMS+8
IHUNS=ISHFT(IHUNS,8)
ITEM=ISHFT(ITEMS,4)
IVALUE=IOR(IHUNS,ITEMS)
IVALUE=IOR(IVALUE,IONS)
IVALUE=NOT(IVALUE)
CALL EXEC(2,64+46,IVALUE,1)
ITEMS=ITEM
RETURN
END