Engineering Notes

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A Comparative Study of the Aerodynamics and Hydrodynamics of a Tunnel Boat Hull

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Introduction

OVER the past decade, the design and construction of the outboard raceboat hull has changed considerably. These changes have introduced higher speeds, smoother rides, and better handling to the sport. In an effort to gain insight into this enhanced performance, some preliminary fluid-flow experiments were performed on a scale model of a Molinari tunnel boat. The model used was a toy Molinari tunnel boat manufactured by K&B, a division of Aurora Products Corporation.

The preliminary fluid-flow measurements taken during the course of this study can be classified as follows:

1) A wind-tunnel study of the aerodynamic characteristics of the hull.

2) A tow tank study of the hydrodynamic characteristics of the hull.

Results of the Aerodynamic Study

The first phase of the aerodynamic study involved the measurement of the aerodynamic drag force on the boat model. The measurements were made with a Scot Aviation Corporation force-moment indicator in the controlled fluid environment of one of the low-speed wind tunnels at the Ohio State University. The flow characteristics and calibrations of this wind-tunnel facility are discussed by Daugherty and Velkoff.[1] In an effort to model the effect of the water surface, a flat plate was mounted beneath the model in the wind tunnel. The results of these tests are shown in Fig. 1, where the aerodynamic drag coefficient based on projected area C_D is plotted as a function of the aerodynamic Reynolds number based on length Re. Drag measurements were taken at two angles of attack or trim angles: $\alpha = 0.0$ and 6.2 deg. The maximum absolute error in these measurements was $\pm 4.0\%$.

Static pressure taps were drilled on the upper and lower decks of the hull. The results of these measurements are presented in Fig. 2 where the local aerodynamic pressure coefficient C_p is plotted as a function of the dimensionless space parameter Z/L for both deck surfaces. These results are corrected for the effect of tunnel blockage by the method of Allen & Vincenti.[2] Here, Z is the distance from the leading edge of the hull and L is the total length. Also in this figure, the net resultant of these two curves is shown, a quantity related to the lift distribution due to pressure forces on the hull. The net resultant was found by subtracting the pressure distribution on the top deck from that of the bottom deck. The maximum absolute error in these measurements was $\pm 11\%$.

The final phase of the aerodynamic investigation was a flow visualization study of the airstream on the upper deck. These experiments were performed by observing the motion of pieces of fine thread taped to the deck in strategic locations. Some typical results are shown in Fig. 3.

Results of the Hydrodynamic Study

Measurements of the total hydrodynamic drag force for fixed trim angle and waterline were conducted in the small tow-tank facility of the U.S. Naval Academy. For a more detailed discussion of this facility see Ref. 3. The total hydrodynamic drag coefficient based on wetted area C_T was then computed for each of these measurements. The residual drag coefficient C_R was subsequently calculated using the suggestion of Refs. 4 and 5. That is,

$$C_R = C_T - C_F$$

where the hydrodynamic skin friction coefficient C_F was computed from the Prandtl-Schlichting formula,[6] modified to account for the effect of the trim angle,

$$C_F = \left[\frac{0.455}{(lg_{10} Re_w)^{2.58}} - \frac{1700}{Re_w} \right] \cos\alpha$$

These results are summarized in Fig. 4. Re_w is the Reynolds number based on wetted length measured along the bottom surface of the hull.

The error in the computation of the residual drag coefficient was a relatively weak function of the trim angle, but inversely proportional to the square of the Froude number.

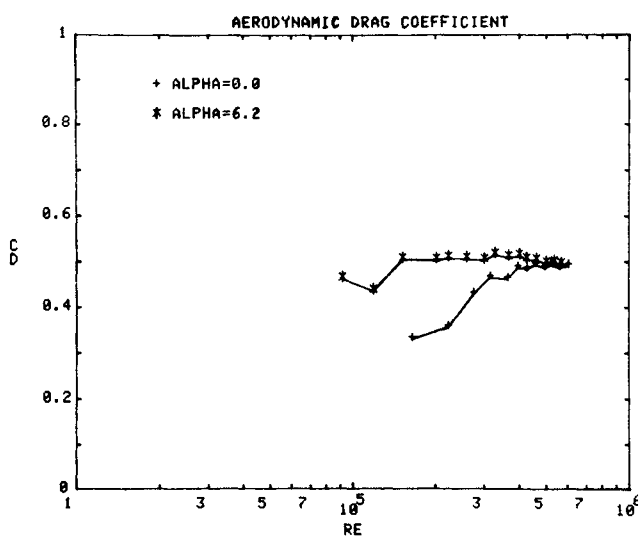

Fig. 1 Aerodynamic drag coefficient based on projected area as function of Reynolds number based on boat length.

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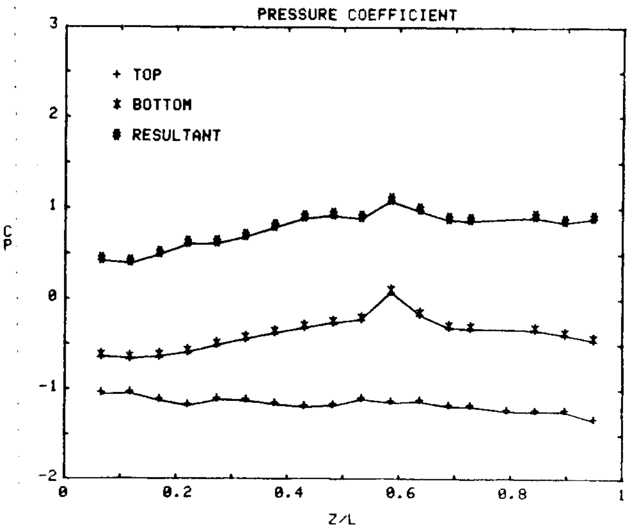

Fig. 2 Dimensionless pressure distribution on upper and lower decks and the net resultant curve, $Re = 1.16 \times 10^6$ and $\alpha = 0.0$ deg.

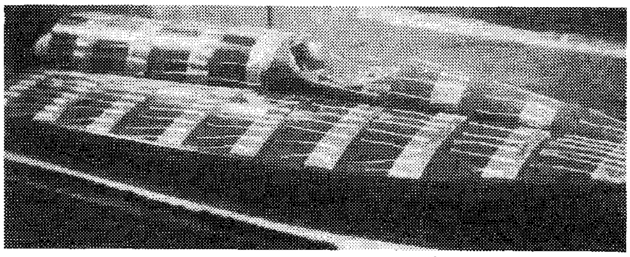

Fig. 3 Flow visualization, $Re = 1.16 \times 10^6$ and $\alpha = 0.0$ deg.

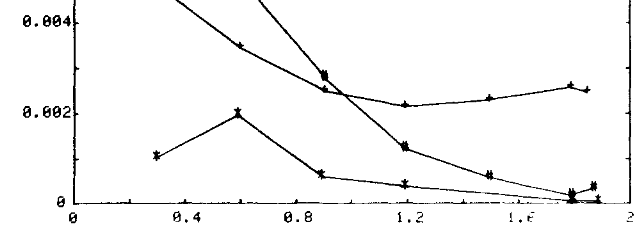

Fig. 4 Residual drag coefficient as a function of Froude number based on boat length.

For example, at $\alpha = 0.0$ deg and $Fr = 0.32$, the absolute error in C_R was ± 0.002 ($\pm 42.6\%$). However, at $\alpha = 0.0$ deg and $Fr = 7.90$, the error was only ± 0.0006 ($\pm 2.4\%$). Consequently, the experimental errors were reasonable for most of the data presented in Fig. 4. Only at the lower values of Fr were the errors of any consequence, and these values of Fr were considerably lower than those corresponding to the normal operating speed of the hull.

Conclusions

In Fig. 1, the aerodynamic drag coefficient was shown to increase as angle of attack was increased for the lower range of Reynolds numbers encountered in this study. However, for Reynolds numbers greater than 4×10^5, C_D was fairly independent of the angle of attack.

In Fig. 4, the residual drag coefficient was shown to decrease as the Froude number was increased. Data are shown in this figure for three trim angles. At $\alpha = 0.0$ deg, the hull generated a detectable bow wave, as indicated by the more conventional shaped curve. However, at the higher trim angle, C_R was reduced considerably at Froude numbers greater than about 1.0. This change in the trend of the data at the higher trim angles is an indication that the hull was planing, with negligible drag from sources other than skin friction. This effect is even more pronounced at higher trim angles, as indicated by the $\alpha = 6.2$ deg curve.

With the results of Figs. 1 and 4, it is possible to make some comment on the relative importance of the aerodynamic drag force, F_A, with respect to the hydrodynamic drag force, F_w, for the full-scale hull. Performing these calculations for a boat speed of 100 mph at $\alpha = 3.0$ deg results in $F_A / F_w = 0.11$. Thus, the aerodynamic drag force is of the order of 11% of the hydrodynamic force for these conditions. Note that in performing these calculations it was necessary to extrapolate Fig. 1 to a Reynolds number of 1.83×10^7. Also, no attempt was made to compute the hydrodynamic drag to the lower unit of the outboard engine.

The full-scale power requirement for a boat speed of 100 mph was found to be of the order of 600 hp. This figure is somewhat higher than what was actually required to power this particular hull design, while it was competitive on the racing circuit.[7] This discrepancy is probably due to an erroneous setting of the waterline during the tow-tank test. The waterline setting of the model was estimated based on the first author's observation of the full-scale craft during its active campaign years.

Figure 2 shows that pressures on the top and bottom decks were, for the most part, less than atmospheric. Furthermore, the pressures on the upper deck were less than those on the lower deck. Consequently, there was a net positive lift force due to pressure. From the resultant curve, it was possible to calculate the center of lift due to the pressure stresses. This value was determined to be approximately 58% from the leading edge.

The pressure coefficient, C_p, for the lower deck surface was negative over most of the length. Therefore, the air velocity in the "tunnel" portion of the hull was generally greater than the velocity of the freestream. Further, the trend in C_p was to increase from fore to aft. Thus, there was a general deceleration or "packing" of the air inside the tunnel. As seen from Fig. 2, this packing effect served to increase the total aerodynamic lift of the boat.

Figure 3 shows that the flow near the leading edge was separated with a periodic vortex shedding, as indicated by the motion of the threads attached to the upper deck. Also, the flow directly behind the driver, as well as the flow over the motor, was separated. Further, the flow over the rear decks tended to be deflected to the sides.

Closures

Because of problems with scaling, the range of Reynolds numbers and Froude numbers encountered in this preliminary study are too low for direct design application. In fact, data are presently being collected on larger models in an effort to make the range of Reynolds and Froude numbers more realistic. However, when compared with similar data of different boat designs on a relative basis, this information can be invaluable. In addition, the results of the flow visualization study suggest that the drag and stability of this particular hull design can be improved significantly e.g., eliminate the regions of separation by streamlining. For a more detailed discussion of the experimental apparatus and the flow visualization study see Ref. 8.

Acknowledgments

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