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Evaluation of Resistance Performance of a Racing Boat using Unmanned High-speed Towing Carriage

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Abstract

A light-weight cantilever type towing carriage was devised and installed in the towing tank at Seoul National University. Wireless measurement devices were also provided for appropriate data acquisition during high-speed towing tests. With the new carriage system, a series of model tests were performed to investigate the hydrodynamic characteristics of the racing boat in the towing tank and the resistance test results had sufficient accuracy so that they could be used in the development of a high speed planning hull.

Keywords: high-speed towing carriage, wireless measurement, racing boat, resistance

1 Introduction

Adoption of the five-day work system in a week and steady growth in the Korean economy in recent decades has nourished the popularity of the marine leisure business. Among the marine leisure sports, motorboat racing has been introduced to the public as a leisure sport. This new competing sport game has rapidly been loved by spectators as the most exciting form of aquatic competition. Six skillful motorboat racers participate in this enthusiastic competing game. In this competition, spectators may purchase racing tickets and record their predicted winners.

In 2002, the Seoul Olympic Sports Promotion Foundation of Korea(SOSFO) developed a racing boat to help promote the domestic marine industry and equipment industries for aquatic sports, relatively delayed behind other sports-related industries. Furthermore, SOSFO continued to raise the localization rate and upgrade the racing boat to induce spectator interest in motor boat racing.

The maximum towing speed of the towing carriage at Seoul National University (SNU) is 3.5 m/sec, and the length of model is usually taken 3 meters to provide a space for the measuring instruments on displacement type vessels. Under these limited test conditions, the model length of a high-speed motor boat had to be reduced far below the recommended conventional model size or the towing speed had to be increased up to a hardly accessible high speed to reach the required Froude number. To accommodate the requirement for the high speed model test, a new unmanned high-speed towing carriage with remote measuring technique was devised and installed in the SNU towing tank.

A high-speed motor boat to be used for boat racing was tested by the high speed towing carriage to evaluate resistance. A wooden model of the racing boat was constructed and experiments were performed by captive test procedure. The resistance performances of the racing boat are introduced in this report.

2 High-speed towing carriage & experimental setup

2.1 High-speed towing carriage

The speed limitation of the towing carriage makes the model impractically small for keeping the similitude law of Froude in the desired test condition, and sometimes it is hard to get reliable measurements on hull attitudes and hydrodynamic forces, especially for tests of a planing hull in the high speed region. The light-weight high-speed towing carriage could be a solution to overcome the difficulties in experimental evaluation of high-speed vehicles.

A light-weight cantilever type towing carriage system has been considered in the design stage appropriate for acceleration applicable for the SNU towing tank (Kim 2002). The schematic diagram of the high-speed carriage installed in the towing tank is introduced in Figure 1 and the truss structure in Figure 2. Extruded aluminum profiles, A6NO1S-T5, have been used as major structural members of the carriage to reduce weight and to assure the convenience in manufacturing.

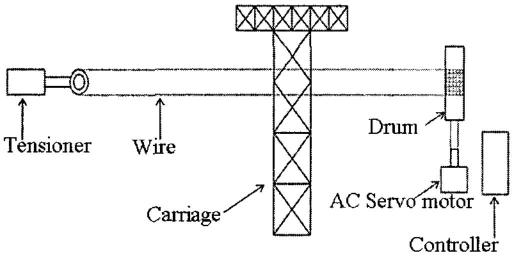

Figure 1: Schematic diagram of towing carriage system

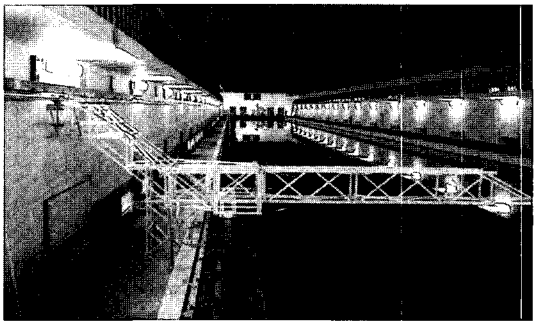

Figure 2: Truss structure of carriage

Structural weight of the towing carriage was estimated to be 60 kg. The total weight of the system will go up to 230 kg if the weight of a typical model and measuring instruments are included. The structural safety of the carriage system at the maximum acceleration was evaluated by a computer program. Structural member No.450 and No.458 shown in Figure 3 sustained the maximum stress; however, the stress level was less than 25% of the yielding stress throughout the time history of the whole period of tests, proving that the members had sufficiently reliable strength. The structure had enough structural strength so that the carriage weight could be optimized if necessary.

The new cantilever type carriage uses the rail of the conventional towing carriage. An additional guide rail to support the high speed carriage is installed on the side wall of the towing tank building. The guide rail is assembled with a machined stainless steel tube SCH-40 to guide the carriage.

The carriage is towed by the wire wound around a drum connected to the AC servomotor and suffers from surge velocity components caused by the springing deformation of the wire rope. The phenomenon is profound both in the encoder signals of the carriage and integrated output of the accelerometer mounted on the carriage.

The speed of the carriage was measured during its acceleration and deceleration, and during operation in a prescribed test speed. The measured time history of carriage operations is shown in Figure 4.

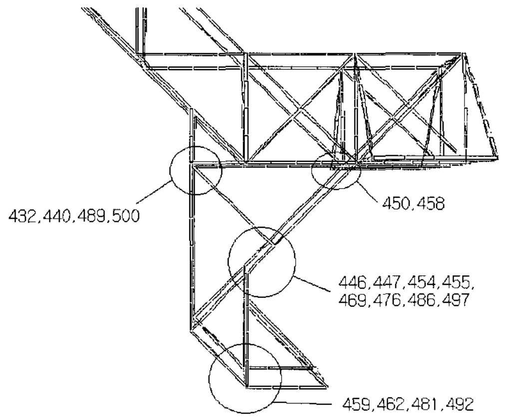

Figure 3: Analysis of structural safety

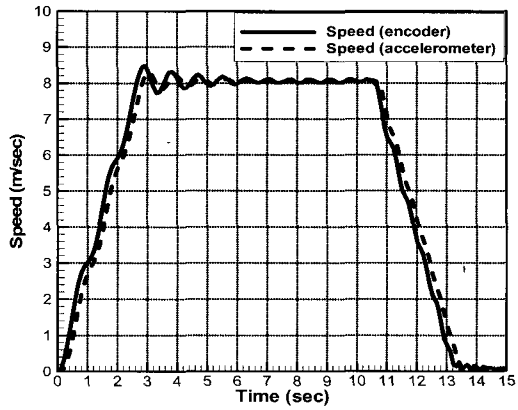

Figure 4: Time history of carriage speed

In the time history shown in Figure 4, the velocity measured from the accelerometer is expressed by a dotted line. The surge velocity of 250mm/sec amplitude and 0.8 sec of period is overlaid on the prescribed control speed of the towing carriage in the acceleration stage, and the oscillation components rapidly diminish. This surge velocity should be inherited by the springing elastic deformation of the driving wire rope for carriage. The slight phase shift in the solid line and dotted line may be caused by the elastic deformation of the towing carriage itself during the tests. Comparison of the deviations showed that speed fluctuation is more important for maintaining accuracies in carriage speeds than structural deformations. To reduce the speed fluctuation effectively, pneumatic damper was selected and installed at the joint of carriage structure connected to wire rope. As a result, the surge in carriage speed was reduced remarkably especially in the acceleration and deceleration regions, and the stable speed region suitable for measurement has been enlarged with this damper system.

2.2 Experimental setup

To predict the resistance characteristic of a high-speed boat by model experiments, force components of the model and hull attitude should be measured when the model is towed at a prescribed speed. In principle, the model's speed is identical to that of the carriage and can be found from the encoder signal of the carriage. However, structural oscillation and/or slip of the encoder wheel attached on the rail may give faulty signals. By taking the integrated signal of the accelerometer as the towing speed, the accuracy of the towing speed could be ensured.

The forces acting on the model are measured by the multi component load cell. The accuracy of the load cell exclusively designed for the model test can be improved by decomposing the interferences among force components from the influence matrix obtained through calibration tests of load cell. The vertical movement of the towing carriage itself could influence the lift force if the model is fixed on the carriage. Thus, vertical displacements of the carriage at the rod restraining the model have to be monitored during the tests.

The signals transmitted from the load cell, encoder, accelerometer, etc. are collected with a data acquisition system. Amplifiers are specifically designed to be accommodated in a limited space and with reduced weight as light as possible. The signals from the amplifiers are digitized through an AD/DA board installed in a laptop computer with a system controller. The controller is connected to the host computer in the main control room through wireless LAN cards. The total system is operable with rechargeable DC power sources on the carriage. The system enables real time monitoring of measured signals such as force components Fx, Fz, My and Mz; vertical displacement, speed and acceleration of the carriage; and trim angle, etc. by the host computer system, where the data are statistically processed in real time. The schematic diagram of the measuring system is shown in Figure 5.

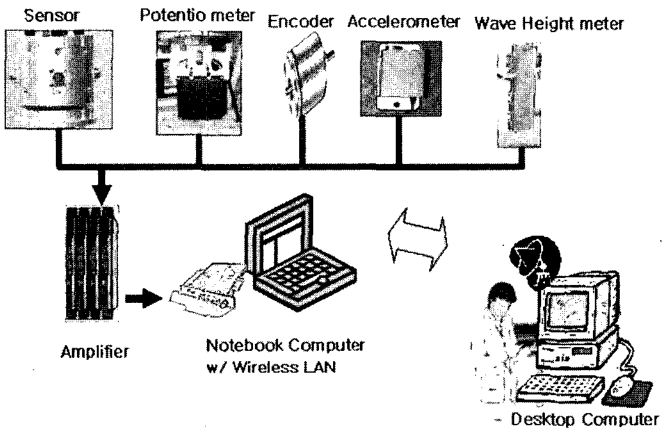

Figure 5: Schematic presentation of wireless measuring system.

3 Resistance tests for racing boat

3.1 Test Procedures

To ensure measuring time necessary for reliable data collection, the towing carriage has to be stabilized at a constant test speed long enough after reaching the set speed. It is, however, not always possible since the remaining travel distances may not always be sufficient, especially if the carriage has to run fast. In such situation, the attitude of the model may not converge to the steady state before reaching the end of the towing tank.

In the captive model test, the forces acting on the model fixed to the carriage are measured. The measured data are utilized in predicting the attitude for the next iterative hull attitude by compensating the unbalanced lift and bending moment component. The procedure is repeated until the hull attitude converges to zero lift and moment. This time-consuming experimental procedure has been used to evaluate the resistance performance of a small model of a high-speed planing hull.

Hayashita(1995) proposed a two-rod-system to measure hydrodynamic forces acting on a high-speed vessel. In the system, the rod installed on the bow side rises by a stepping motor if a vertical force component is detected by the two component load cell located between the model and the rod. The rod installed on the stern side behaves alike in the vertical direction while it allows lateral displacement with freely sliding gimbals. However, this two rod system requires careful alignment to avoid mechanical interference between the rods and hence a new measuring system in which a single rod installed at the center of a model to avoid the interference was devised in the present research.

The force acting on a planing boat at the free running condition has following schematic relation.

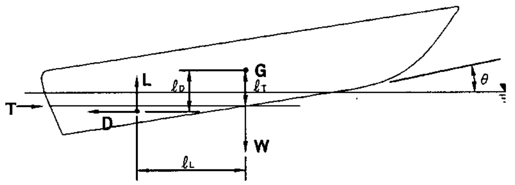

Figure 6: Force diagram in free running condition

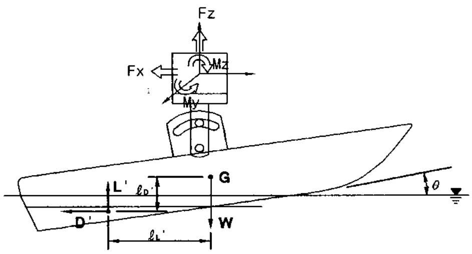

Figure 7: Captive model test condition.

In Figure 6, T, D, L and W are thrust, drag, lift and weight, respectively. These forces satisfy the equilibrium condition both in the lateral and vertical directions as given in the following relation while the moment should be balanced around the center of gravity G.

$$T - D = 0 \qquad (1)$$

$$L - W = 0 \qquad (2)$$

$$T \cdot l_T - L \cdot l_L - D \cdot l_D = 0 \qquad (3)$$

In the captive test, the forces acting on a model satisfies the equilibrium condition with the measured forces at the load cell. The lift acting on model; L', drag; D' and the displacement weight of model; W are expressed in the free body diagram Figure 7. These forces should satisfy the equilibrium condition in lateral and vertical directions along with the moment balance about G.

$$F_x - D' = 0 \qquad (4)$$

$$L' - W - F_z = 0 \qquad (5)$$

$$M_y - L' \cdot l_{L'} - D' \cdot l_{D'} = 0 \qquad (6)$$

If a boat is propelled steadily as shown in Figure 6, the hydrodynamic force acting on the boat must be identical to those shown in Figure 7, and hence the force components have to satisfy following relations.

$$T - F_x = 0 \quad \text{at} \quad D = D' \qquad (7)$$

$$F_z = 0 \quad \text{at} \quad L = L' \qquad (8)$$

$$T \cdot L_T + M_y = 0 \quad \text{at} \quad -L \cdot l_L - D \cdot l_D = -L' \cdot l_{L'} - D' \cdot l_{D'} = 0 \qquad (9)$$

The force components Fx, Fz, My can be measured by a three-component load cell in a captive condition. The trim and sinkage are prefixed as an installation of the model to the measuring device in accordance with the prescribed hull attitudes. Thus, the hull attitude of successive iterative test should be determined from the force equilibrium condition by the above relation. With the measured force components, free running hull attitude of the model could be more precisely estimated and this information can be adopted for the successive hull attitude for the next iterative approach to free running attitude. Usually, three or four iterative tests suffice in converging hull attitude and resistance.

3.2 Resistance Characteristics of the Racing boat

For validation of the new wireless measuring technique, a series of model tests in the captive condition was conducted for a semi-planing hull form on the unmanned high-speed towing carriage. The hull form was chosen since it was a test model in a cooperative research program of KTTC, the Korea Towing Tank Conference(1995). The validation test results confidently suggested the application of the present method of wireless measuring technique using unmanned high-speed towing carriage for the towing tests of high-speed marine vehicles(Shin et al 2004).
Since the present test facility was validated to be dependable, the high-speed racing boat for boat racing can be tested at the unmanned high-speed towing carriage with the proposed wireless measuring technique. The principal particulars of the designed hull are tabulated in Table 1, and the lines of the hull form are expressed in Figure 8.

Table 1: Principal particulars of model ship

Designation		Unit	Full scale	Model
Length overall		m	2.90	0.725
Breadth		m	1.32	0.330
Wetted surface area		m^2	2.03	0.127
Weight	Light ship	kg	116	1.813
	Full load	kg	186	2.906

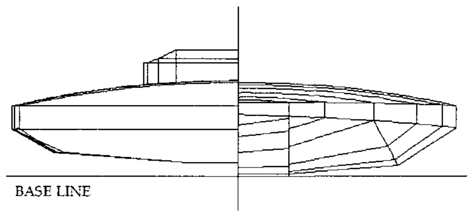

Figure 8: Lines of the racing boat

It is generally believed that the shifting of the riding position of a motorboat racer has a great influence on the resistance performance of a racing boat. The payload of the boat consists of the fuel and weight of the boat racer, both totaling to approximately 70 kg. The racer's body weight is approximately equivalent to one third of the full load displacement when estimated from the data given in Table 1. Thus, a slight attitude change of the boat racer varies the boat speed in a race, as observed in a typical video recording given in Figure 9.

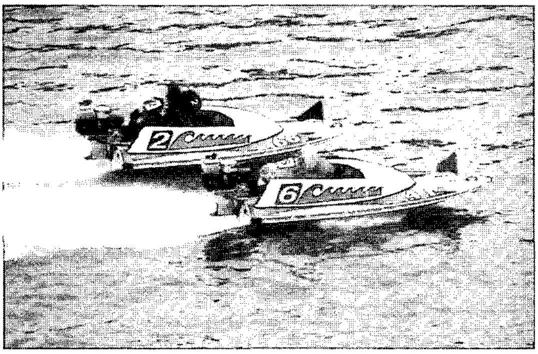

Figure 9: Attitude of boat racer in competition

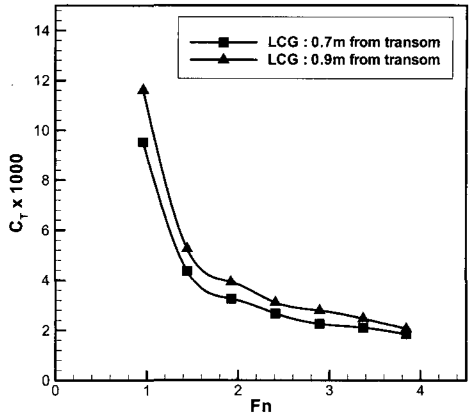

Figure 10: Curves of resistance coefficients

To investigate the influence of the shift of the longitudinal center of gravity upon resistance, two longitudinal centers of gravity at the full load condition were chosen. One of these centers is 0.7m from a transom, which could be estimated when the racer shifts his weight extremely to the rear, and the other center 0.9m, estimated from the extreme forward shifted attitude. The model ship was towed at the position of the center of gravity for each test condition. The maximum speed of the racing boat was 40knots, and the towing tests were performed iteratively in accordance with the prescribed captive test method at speeds equivalent to 10, 15, 20, 25, 30, 35 and 40knots.

The total resistances were measured at the converged free running condition after a series of iterative captive test. The results are expressed in non-dimensional form in Figure 10. From the finally converged free running hull attitude, the trim was measured and is shown in Figure 11 and the sinkage is expressed in Figure 12. The effective horse power of the racing boat was derived from the measured resistance data and is shown in Figure 13. The curves of the total resistance coefficient, CT, given in Figure 10, show that resistance coefficients changes abruptly in the low speed region. Over this low speed region, the resistance coefficient decreases rapidly until the speed reaches to Fn=2, but the decreasing tendency moderated at speeds above Fn=2. The boat seems to have less resistance when the longitudinal center of gravity shifted to the rear, as shown in this Figure 10 than that when the longitudinal center of gravity shifted forward. Thus, the boat racer would have a better chance of winning if the racer shifts his/her body extremely to the rear under an allowable limit.

The trim angle of the racing boat also varies abruptly in the low speed region. The trim apparently reaches over 10 degree near the boat speed equivalent to Fn=1.0 as observed in Figure 11. Over that speed, the trim of the boat rapidly reduces until the boat speed reach to Fn=2.0 and after that, the trim angle approach to a stable 2 degree. In case of trim, the forward shifted boat racer's attitude is more effective in approaching the stable hull attitude.

A racing boat rises mainly in the low speed region less than Fn=1 with rise of hull as shown Figure 12. The racing boat begins to gradually approach a stable planing attitude over this region of low speed. In this test, the hull rose more rapidly when the longitudinal center of gravity was located toward the rear of the racing boat. As expected, the shifted LCG toward the rear induced larger initial trim and faster rise of hull than the front.

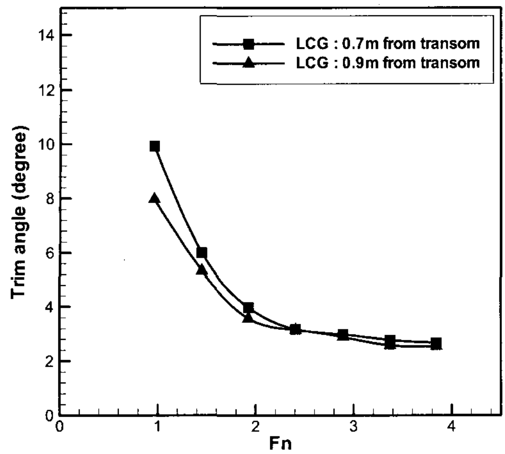

Figure 11: Curves of trim

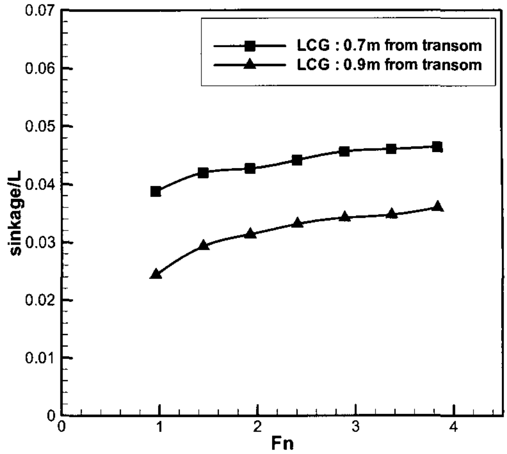

Figure 12: Curves of sinkage

From the above experimental results, the effective horse power of the racing boat was estimated, as shown in Figure 13. From this figure, we can easily imagine that faster speed could be obtained when the boat racer shifts his body weight toward the rear of the boat in allowable limits. However, the racer must be trained to drive the boat at an awkward boat riding attitude to win the game.

In actual competition, 5% of the displacement is adopted as a handicap weight to compensate the weight difference. To investigate the effect of the handicap weight, an additional resistance test was conducted with the total weight of 195kg in a full scale boat The test results obtained when the longitudinal center of gravity was located on 0.7 m from transom are expressed in Figure 14. As expected, the total resistance coefficient increases with the increase of displacement. But the trim angle and sinkage are almost the same for both conditions.

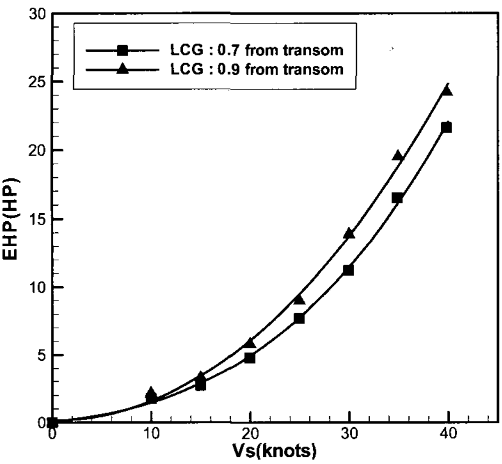

Figure 13: Curves of EHP

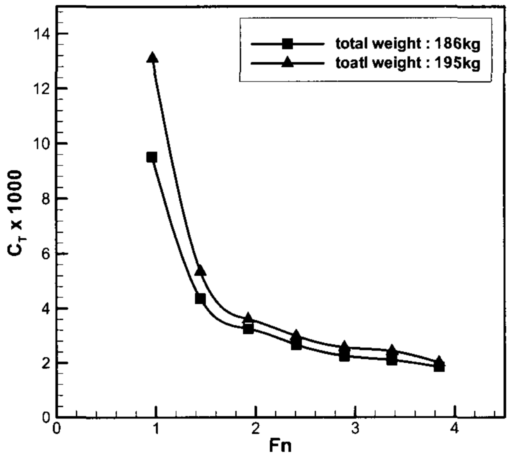

Figure 14: Curves of Resistance Coefficients

Two-cycle out board gasoline engine have been developed exclusively for this racing boat. The Korean Society of Ship Inspection and Technology(KST) have tested this engine for official inspection. The authorized performance curve of the engine is introduced in Figure 15.

For the propulsion of the racing boat, a stoke propeller, supplied by the engine maker, have been adopted as the official propeller of the racing game. The propeller performance is introduced in Figure 16.

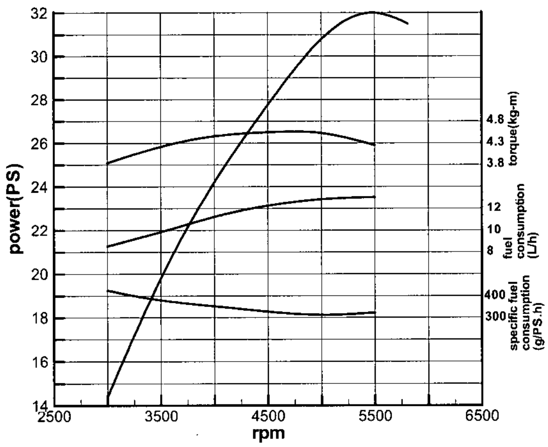

Figure 15: Engine performance curve

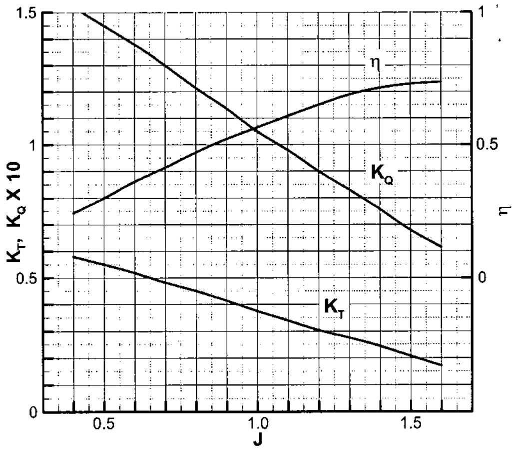

Figure 16: Propeller performance

When the racing boat is approaching the finish line at a full speed, only a small portion of bottom area near the transom comes in contacts with water, as shown in the video recording in Figure 17.

In this high speed planing condition, the propulsive efficiency could be replaced by the propeller efficiency. Thus, the delivered horse power could be expressed as shown in Figure 17. When the boat is approaching to finish line at maximum engine power, the boat speed was detected at 40.17 knots. This point quantitatively coincided with the estimated delivered horse power as marked on Figure 18. The racing boat was developed based on the designer's intuition and repeated revisions by an expert in manufacturing without any experimental confirmation of the hull's hydrodynamic performances. However, the boat gives enough performance to excite the spectators' enthusiasm especially when the boats are competing in an actual boat race. The resistance performance was successfully evaluated with the unmanned high speed towing carriage at SNU.

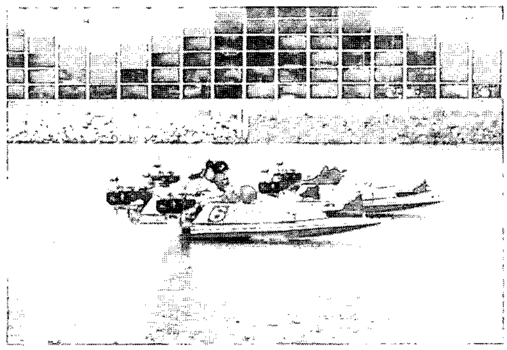

Figure 17: Hull Attitude near Goal Line

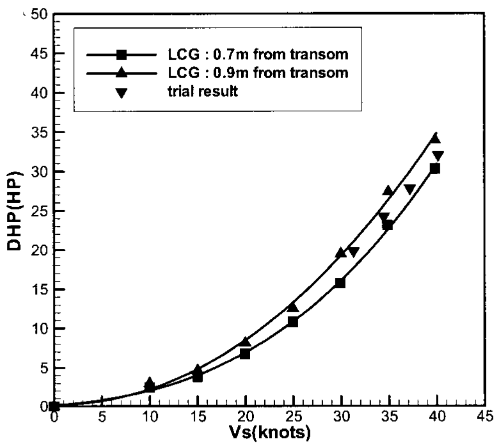

Figure 18: Delivered power and trial result

4 Concluding Remarks

The resistance performance of a high-speed boat was evaluated from the hydrodynamic forces measured at high speeds, practically impossible to attain in an ordinary towing tank. Fortunately, Seoul National University devised a new unmanned lightweight high speed towing carriage that could be accelerated up to 15 m/sec. In addition, a wireless measuring system adequate for the carriage was implemented.

The wireless remote measurement system was validated carefully through a series of benchmark tests of the semi planing hull used in a cooperative research program of KTTC. Validation procedure confirmed that the present captive model test technique with an unmanned high-speed towing carriage was qualitatively and quantitatively accurate.

The high-speed towing carriage with a wireless control system was used to develop a racing boat using an iterative captive model test method. The results showed that the effects of the center of gravity and the increase of displacement on resistance were very important for a race. These results can be very useful for both racing boat designers and racers.

Acknowledgements

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