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Experimental Evaluation for Hydrodynamic Performance of a Hybrid Supported Type Fast Craft

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Abstract

This paper deals with the sea trial results of a fast craft with the hybrid supported type hull form, waterjet propulsion system and motion control system. The hybrid-type container ship operable in the sea with a wave height of 6 m, a speed of 50 knots and a payload of 1,500 tons were designed. A 1/8 scale 10 m-long test craft was constructed and tested in open seas. The hydrodynamic performance such as speed, turning, motion control in waves and waterjet thrust was analyzed.

Keywords: hybrid full form, waterjet, motion control, sea trial

1 Introduction

It is well-known that there are limitations to air transport in respect to volume, and to marine transport in respect to speed. Comparing with the convenient land and fast air transportations, the marine transportation has advantages of mass, low-priced and long-range transport. If the fast freight ship is developed, it will play an important role as a marine transportation and new demand by the new fast marine transport system will be occurred. The fast freight ship, designed to carry more cargo than aircrafts and to move cargo more quickly than container ships, is being considered. Since the container ships in the next century are expected to become larger and faster, it is necessary to develop a reliable fast container ship with a speed of up to 50 knots and a payload of 1,000 tons and more. Since the feasibility study on the development of the fast freight ship was carried out by Yang et al(1991), interest in high speed ships by Korean shipbuilders increased. Thereafter the development of a fast freight ship was initiated by Yang et al(1992) and the conceptual design of the hybrid supported type container ship was carried out(Yang et al 1997). The designed ship is operable in the wave height of 6 m with the speed of 50 knots and a payload of 1,500 tons and is supported by buoyancy and foil lifting force charged 50%of her weight each. For the validation of the designed ship, a 1/8 scaled 10 m long test craft was constructed and its hydrodynamic performance was analyzed through a series of sea trial tests.

2 Design of a fast container ship

The governing equations are the incompressible RANS equations which describe the conservation of mass and momentum and can be written in the Cartesian tensor notation as follows.

2.1 Dimensions of fast container ship

The requirements were decided as follows:

- Payload capacity: Considering the size (250-500 TEU) of container feeders for short-distance sea routes, the payload of the fast freight ship was decided to be 200 TEU (1,500 tons) or more.
- Endurance range: In general, the fuel consumption and the fuel portion in the deadweight of the fast freight ships is higher than the conventional ships. The endurance range of the fast freight ship was decided to be 720 nautical miles considering the distances between sea ports of interest in the East Asian region such as Pusan, Inchon, Shanghai, Hongkong, Vladivostock, Yokohama.
- Principal dimensions: Since the reach of the crane in the container ports covers generally 13-15 TEU, the breadth of the fast freight ship was to be 37.2 m for loading 13 TEU transversely. In case of 2 tiers, the ship has to load 8 TEU longitudinally. The length of the fast freight ship was to be 80 m.
- Displacement: The lightweight is estimated to be 2,300 tons consisting of the weight of the hull, outfittings, engines and electrical parts. The cargo weight is to be 1,500 tons assuming 7.5 tons/TEU. The deadweight is estimated to be 2,200 tons consisting of the cargo, fuel, provisions, drinking water, etc. Therefore the full load displacement is 4,500 tons.

In summary, the general requirements are that the endurance limit for sea route is 720 nautical miles; the maximum speed is 50 knots; and the number of containers to be carried should be as many as possible or 200 TEU. The principal particulars are to arrange 200 TEU by 13 rows × 8 bays × 2 tiers as presented in Table 1.

2.2 Conceptual design of hybrid hull form

For hybrid supported hull form a combination of buoyancy and dynamic lift was chosen. The hybrid hull form consists of upper and lower hulls. The catamaran type upper hull has a wide deck area for loading cargos easily and minimizing instability due to the loss of lifting force caused by trouble of the ship motion control system. The lower hull consists of a submerged body of revolution and foils. The static buoyancy by the submerged hull and the hydrodynamic lift by the main foils support half-and-half the weight of the hybrid hull form. The lower hull is connected to the forward V-type strut and the afterward I-type strut which are attached to the upper hull as shown in Figure 1.

For the designed hybrid hull form two gas turbines as main engines and two large-powered waterjets are selected. The waterjet propulsion system consists of pod-type inlets and axial flow-type pumps. The pod-type waterjet propulsion system mostly applied in hydrofoil ships has the

Table 1: Principal particulars of KRISO hybrid fast container ship

Length, Upper Hull	80.0m
Lower Hull	85.0m
Breadth	37.2m
Depth	16.5m
Draft, Hull borne	12.5m
Foil borne	8.5m
Max. Speed	50knots
Cruising Range	720 n.miles
Payload	1,500ton
Container Load Capacity	200TEU

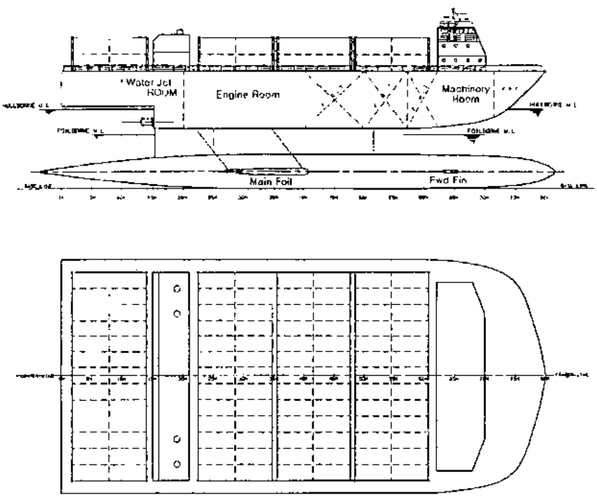

Figure 1: General arrangement of the 80m fast container ship

inlet located at the end of the strut, through which fluid is intaked. The sea water is sucked in through the waterjet inlets of the main foils and pumped to the waterjet propulsion units on the upper hull. The inclined side struts are structurally connected to the main foils. This system shows higher propulsive efficiency by dynamic water pressure, but larger resistance due to struts and pods. The waterjet propulsion system is designed considering the pump type, inlet type, nozzle shape, and impeller as an integrated system.

The operational mode of this ship is divided into two parts: hull-borne mode and foil-borne mode. The change of these two modes should be as smooth as possible to keep stable operational condition. The ship floats by the buoyant force from both hulls at the hull-borne mode. The upper hull fully emerges out of the water at the foil-borne mode, and half of her weight is supported by the lifting force from lifting foils and fins attached to the lower hull. Since this type of ship has a center strut, she has enough hydrodynamic force for the directional stability during the hull-borne mode. However, she loses directional stability due to the reductions of the submerged strut area

Table 2: Principal particulars of hybrid test craft "NARAE"

Length, Overall	11.0650m	Depth from B.L.	3.700m	Main Foil,Span	1.675m
Breadth	4.650m	K.L	1.600m	Chord	4.650m
Lower Hull, Length	10.625m	Draft,Hull-borne	2.530m	Forward Fin, Span	0.800m
Diameter	0.700m	Foil-borne	1.500m	Chord	0.500m

and hydrodynamic force during the foil-borne mode. Therefore the active control is indispensable. A pair of foils with flaps and a pair of forward fins for the control system are shown in Figure 1.

3 Hybrid supported type test craft

3.1 Scale of test craft

The construction of a scaled test craft and its sea trial test were planned in order to validate the hydrodynamic performance of the test craft and to predict the full-scale performance of the hybrid-type fast container ship. If the model is smaller, it is very difficult to accommodate the necessary test equipment within the model displacement and to carry out the test. If the model is larger, the construction is expensive. After due consideration of the test craft's dimension and displacement, the scale ratio of the test craft was decided to be 1/8 for sufficient hydrodynamic performance. The principal particulars of the test craft are shown in Table 2.

3.2 Construction of a hybrid test craft

The test craft consists of an upper catamaran and a lower submerged body of revolution. The upper and lower hulls are connected by 5 struts: V-type two forward struts, I-type one afterward strut and two inclined side struts. The section of NACA 0016 was applied to all struts connections between the upper and lower hulls. The inclined side struts strengthen the connections between foils and the upper hull. The inlets are located on the ends of both main foils, from which suction ducts inside the inclined side struts are passed through to the waterjet propulsion units.
Main propulsion systems are:

- main engine: diesel engine (brake power 272 kW $\times$ 2,800 rpm $\times$2 sets)
- reduction gear : reduction ratio 1/1.408
- propulsor: waterjet (input power 240 kW$\times$1,989 rpm$\times$2 sets)

The ship motion control system is composed of a controller in the steering room, a hydraulic unit in the engine room and the lifting planes. The hydraulic unit includes a hydraulic tank, hydraulic pump, accumulator, manifold, actuator, hydraulic filter and cooler. The lifting planes are two forward fins and two afterward flaps of main foils, which are hydraulically controlled by four actuators. The main foils of the NACA 4412 section with 2 degrees of incident angle were employed to support 50% of hull weight with lifting force. The forward fins of the NACA 0012 section and the flaps of the foils were engaged to control pitch motion of a craft. Figure 2 shows the photograph of a test craft after construction. The general arrangement of "Narae" is shown in Figure 3.

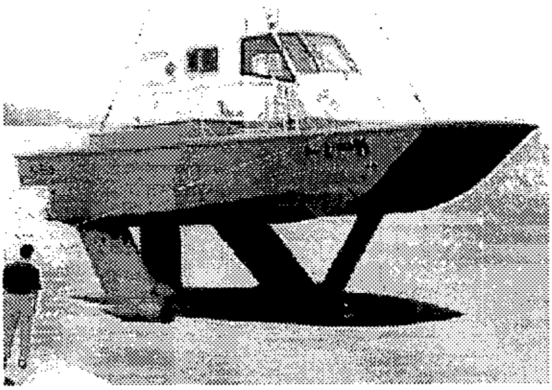

Figure 2: Photograph of 10m class hybrid test craft "Narae"

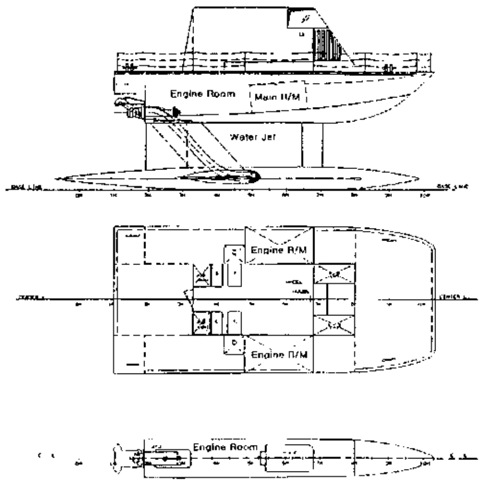

Figure 3: General arrangement of hybrid test craft "Narae"

3.3 Evaluation of hydrodynamic performance by sea trials

The sea trials were carried out in the southern inland sea of the Korean peninsular over a period of 3 months from August to November in 1997. The test craft in the foil-borne mode is obtained by taking off the craft by 1.0 m from the hull-borne draft of 2.53 m.

(1) Lightweight and center of gravity by the inclining test

The actual weight of the hybrid test craft is 9.2 tons, which is increased by 250 kg compared with estimated weight. The longitudinal center of gravity is 0.46 m afterward the midship, which is forwarded by 1.5 cm from the estimated value. The vertical center of gravity is 2.74 m above the baseline, which is higher by 4 cm than the estimated height.

(2) Performance of motion control system

The performance tests of the motion control system were carried out in open seas and covered the take-off, turning and motion control in waves(Kim et al 1998). The heave displacement is measured by three types of sensors: capacity-type wave probe, pressure sensor and ultrasonic height sensor. The pitch and roll are measured by 2-axis vertical reference gyro. A rate-gyro is used to measure yaw rate. GPS is used to get the advancing speed of the craft.

(a) Take-off trial
Figure 4 is a measured time history of motions during the take-off trial with the initial pitch angle of 1.5 degrees and the take-off height was 1.0 m. Additional pitch angle of 0.5 degrees was introduced to get a sufficient lift at the take-off stage. It shows that the overall characteristics of tracking control are satisfactory during take-off, cruising and landing.

(b) Turning trial

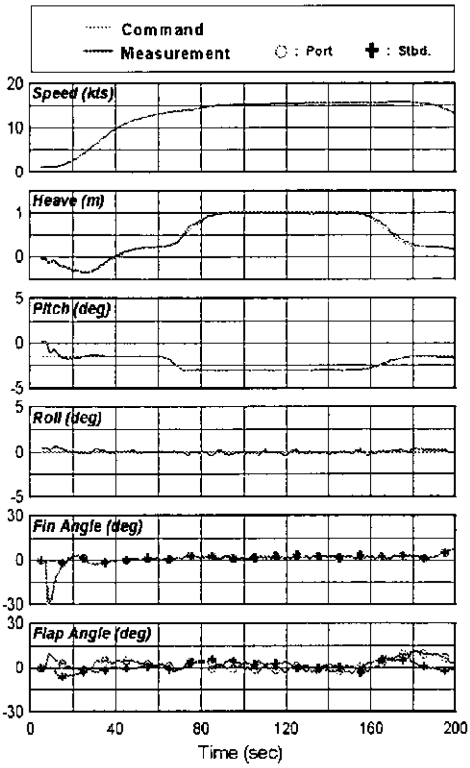

Figure 4: Time history of motion during take-off trial

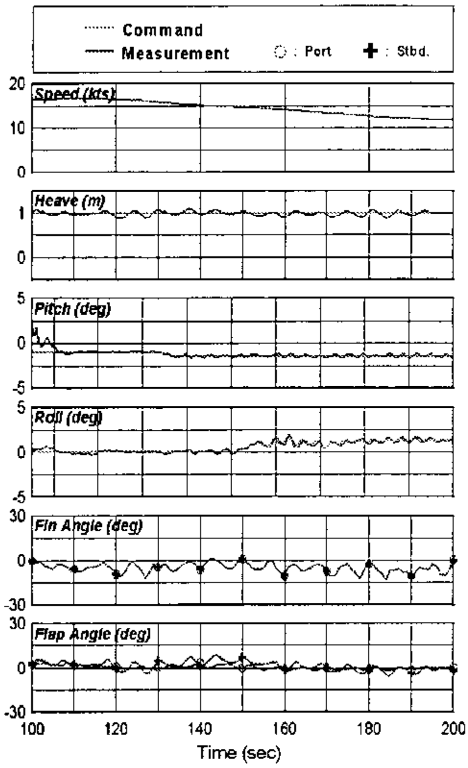

Figure 5: Time history of steady turning trial

Figure 5 is obtained from a steady starboard turning test with the bucket angle of starboard 8 degrees. The initial pitch angle was 1.5 degrees and additional pitch angle of 0.5 degrees was introduced. It shows the starboard heeled turning and the decreasing speed and that the banking-turn scheme worked well. Figure 6 shows the turning trajectories with and without a drift correction. This drift is mainly due to a strong current in the area where the trial test was performed. The tactical diameter is about 260 m, and the ratio of the tactical diameter to the craft length is 23.5. This value is relatively high since it represents the tactical diameter under the foil-borne mode.

(c) Motion control test in waves// Figure 7 shows a measured time history of the motion in waves such as heave, pitch and roll by the motion control system. The significant wave height was about 0.6 m. It shows large amplitudes of heave and pitch before the motion control system is applied

(3) Performance of waterjet propulsion system

The waterjet performance was tested at sea for the first time in Korea with the following measurements such as waterjet velocity, mean pressure of the duct, torque and thrust of impeller, revolution of impeller shaft and craft speed(Ahn et al 1998). The measurement diagram of waterjet propulsion system is shown in Figure 8. The strain gauges were attached on the impeller axis at inner part of the duct for torque and thrust measurements. The measured torque and thrust in the sea

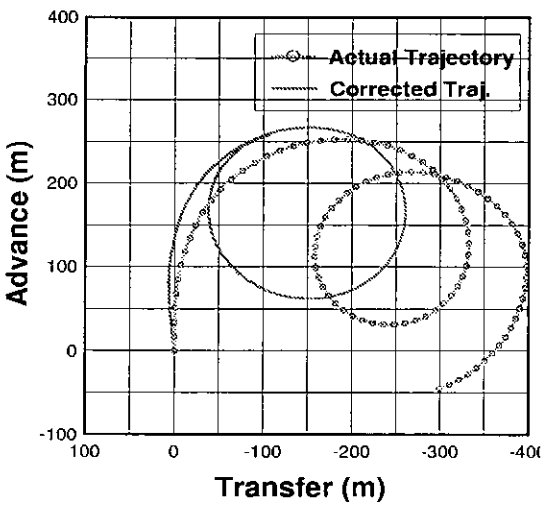

Figure 6: Turning trajectories with drift correction

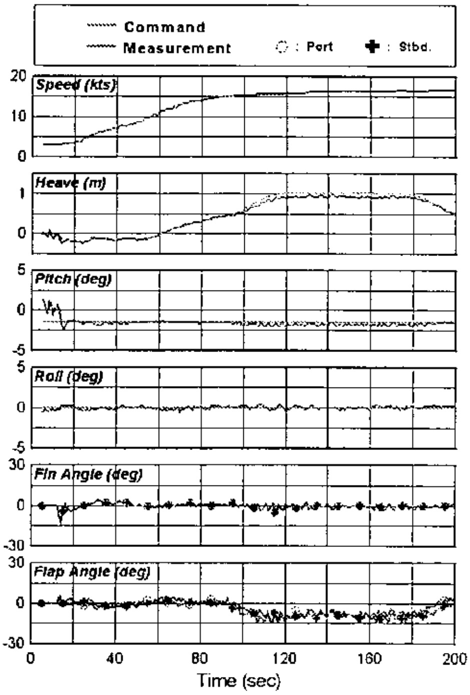

Figure 7: Time history of motion in waves

trial test are shown in Figures 9 and 10, where h represents the take-off height, and I and II denote the roundtrip directions of the test craft. The torque and thrust are linearly related to the impeller rotational speed regardless to the take-off heights and the directions.

The jet velocity($V_j = \sqrt{2(P_{total} - P_{static})/\rho}$) is measured by the Pitot tube installed behind the jet nozzle and connected to a differential pressure transducer. Figure 11 shows the jet velocity of x-axial direction measured at the position of $0.5r_n$ (r_n : nozzle radius) from the center of the waterjet nozzle. The flow rate at the nozzle section(Q_j) is calculated using the jet velocity. The jet velocity shows the similar trend to the torque and thrust. However, while the jet velocity has first-order linear relation to the impeller rotation, the torque and thrust have linear relation above second-order.

The water head by the impeller and the diffuser (H) is obtained from mean pressures which are measured at D-section (front of the impeller), C-section (between the impeller and the diffuser), and B-section (rear of the diffuser) in Figure 8. There are 4 pressure holes at D-section and 7 pressure holes at B- and C- sections to obtain more accurate mean pressure. Pressure holes at each section are connected to strain-gauge type pressure transducers. The impeller/diffuser efficiency(η_P) is calculated from the water head and the supply power as follows:

$$\eta_P = \frac{J_Q}{2\pi}\frac{K_H}{K_Q} \tag{1}$$

where $J_Q(= Q_j/nD^3)$ denotes the flow rate coefficient, $K_H(= H/n^2D^2)$ the head coefficient, $K_Q(= Q/\rho n^2D^5)$ the torque coefficient. Q denotes the impeller torque, n the revolution of the impeller shaft and D the impeller diameter and r fluid density. Figures 12 and 13 show the impeller

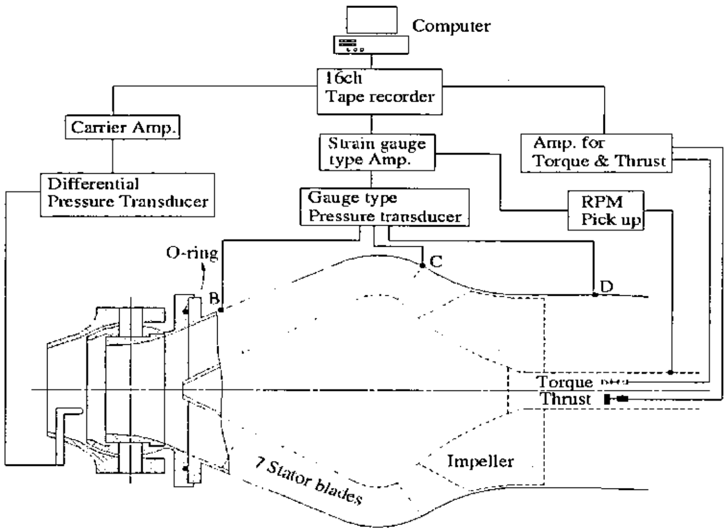

Figure 8: Measurement diagram of "Narae" waterjet propulsion system

efficiency (η_P) and the jet efficiency (η_J) for the test craft, respectively. The jet efficiency (η_J) is defined as follows:

$$\eta_J = \frac{2IVR(1-IVR)}{1+\xi_j-(1-\xi_{in})IVR^2+2g\triangle h/V_J^2} \tag{2}$$

where IVR denotes inlet velocity ratio(V_S/V_J), δh the distance from water surface to the center of the impeller axis, and ξ_{in} and ξ_j the water head loss coefficients between the duct inlet and the impeller and between the diffuser and the nozzle, respectively. The three scalar momentum equations given in (14) can be written as follows.

$$\xi_{in} = \frac{P_{in}-P_{pi}+1/2\rho(V_{in}^2-V_{pi}^2)-\rho g\triangle h}{1/2\rho V_{in}^2} \tag{3}$$

$$\xi_j = \frac{P_{po}-P_{atm}+1/2\rho(V_{po}^2-V_J^2)}{1/2\rho V_J^2} \tag{4}$$

where P_{in}: mean pressure at the duct inlet, P_{pi}: mean pressure at the front of the impeller (D-section), P_{po}: mean pressure at the rear of the impeller (B-section), P_{atm}: atmospheric pressure, V_{in}: mean velocity at the duct inlet, V_{pi}: mean velocity at the front of the impeller (D-section), V_{po}: mean velocity at the rear of the impeller (B-section), V_J: jet velocity, V_S: craft speed.

The effective power (P_E) can be obtained from the measured torque and the quasi-propulsive efficiency(η_D). The quasi-propulsive efficiency is defined as follows:

$$\eta_D = \eta_P\eta_J\eta_H \tag{5}$$

where the thrust deduction fraction (t) and the wake fraction (w) must be considered to calculate the hull efficiency($\eta_H = (1-t)/(1-w)$). The thrust deduction fraction means the difference in

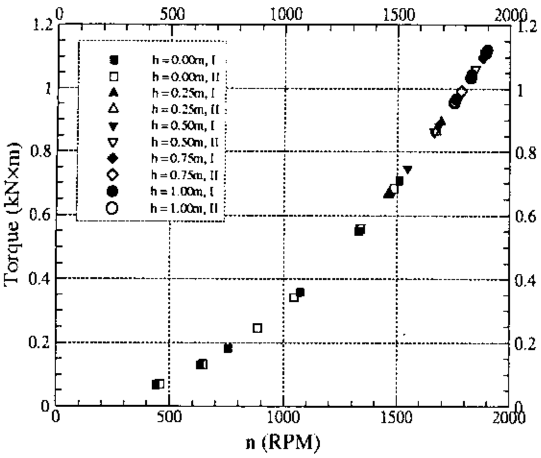

Figure 9: Torque

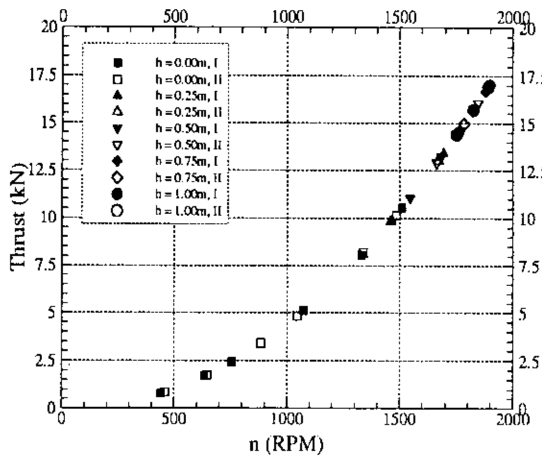

Figure 10: Thrust

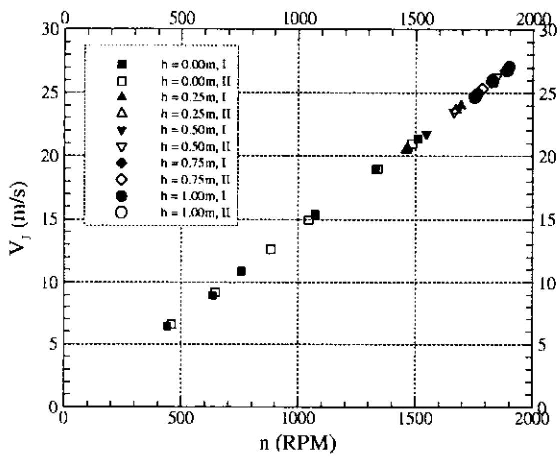

Figure 11: Jet velocity

the resistance between the condition in which a duct inlet is closed and the condition in which an impeller is operated. However, it is very difficult to get this thrust deduction fraction of the pod-type waterjet propulsion ship experimentally. Moreover, it is more difficult to get it in the sea-trial test since there are the resistance increments due to waves, flap operation for hull take-off, surface roughness and pressure energy increase between diffuser and nozzle. In this study, considering the self-propulsion test result of the model ship with a flush-type waterjet propulsion system and various resistance increments, the thrust deduction fraction is assumed to be 0.2(Kim et al 1995). However, the wake fraction is neglected. Figure 14 shows the quasi-propulsive efficiency for the test craft. The quasi-propulsive efficiency is about 0.315 at the speed of 15 knots assuming the thrust deduction factor is 0.2. Figure 15 shows the effective power ($P_E = 2\pi n Q \eta_D$) calculated from the torque measurement and the quasi-propulsive efficiency.

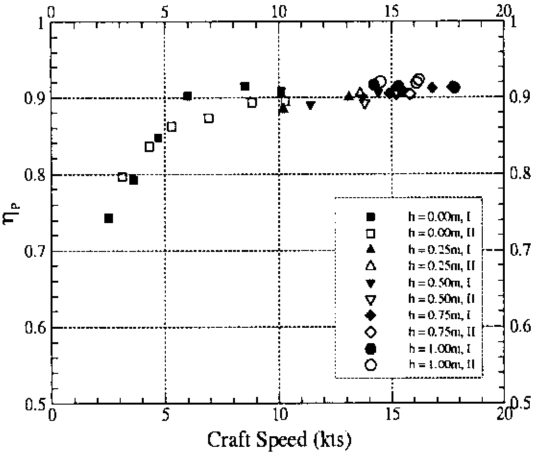

Figure 12: Impeller/diffuser efficiency

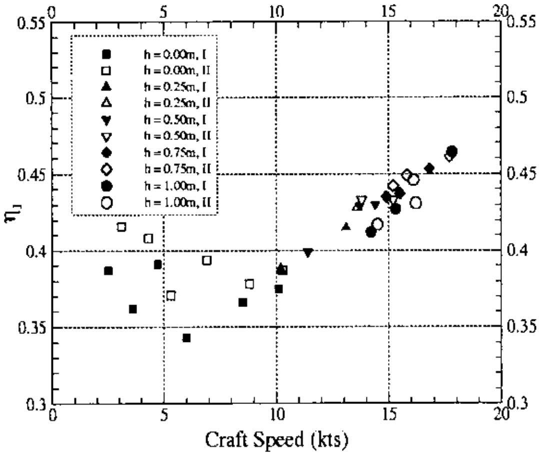

Figure 13: Jet efficiency

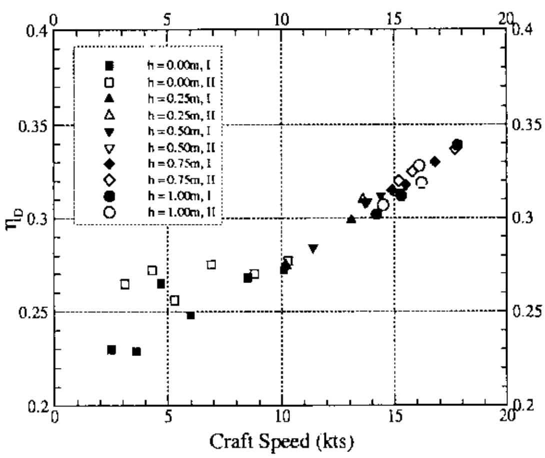

Figure 14: Quasi-propulsive efficiency

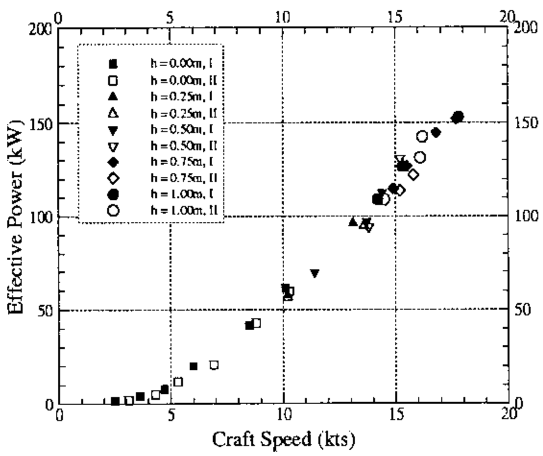

Figure 15: Effective power

(4) Speed

A speed test was carried out at the same time with the performance test of waterjet to measure the craft's speed, rpm of propulsion shaft, torque and thrust of waterjet. The performance of the test craft at the speed of 17.7 knots (corresponding to 50 knots in full scale ship) is as follows: η_D = 0.34, P_E = 151 kW, and P_D = 443 kW The maximum speed of the hybrid test craft is about 19 knots, where η_D =0.35, P_E =171 kW, and P_D =489 kW.

4 Concluding remarks

The hydrodynamic performance of a hybrid type test craft with the motion control system and the waterjet was experimentally investigated. The sea trials covered the take-off test, turning test, motion control test in waves and the torque and thrust measurements. It is made clear that the motion control can be done effectively by changing the angles of fins and foils. The control can make the craft taken off as expected even in waves. The propulsive performance of waterjet was also analyzed by measuring the mean pressure of duct, thrust and torque of impeller and waterjet velocity. As a general conclusion, this study demonstrated the possibility of the hybrid type fast ship and established the core technology for the development of the hybrid type fast ship.

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