Development of Fully Submerged Hydrofoil Catamarans

A diesel driven fully submerged hydrofoil catamaran has been completed. She is a newly developed passenger ferry with the speed of 40 knots and passenger capacity of 341 and now in commercial service on the Oki Islands route in Shimane Prefecture. Her technical features are as follows: (1) Catamaran hull brings hydrofoils with bigger span and small hull resistance in take-off condition and relatively soft wave impact in rough seas because of greater dead rise of the bottom than the mono-hull type. (2) Tandem foil configuration where fore and aft hydrofoils are exactly the same shape brings higher aspect ratio with high lift to drag ratio in comparison with the canard foil configuration on existing craft. (3) Automatic ride control system keeps foil-borne condition stable. (4) Her propulsion system consists of 4 sets of light weighted high-speed diesel engines and 2 sets of newly-developed light weighted water-jet propulsors.

1. Introduction

Recently, there has been increasing demand for high-speed passenger craft that are well adapted to sea conditions so as to provide a smooth and comfortable ride in waves. While there are various kinds of high-speed craft are operating in Japan, it is not easy to obtain a comfortable ride while keeping high speed performance in waves. After surveying various concepts of high-speed craft, the authors concluded that a fully submerged hydrofoil is a promising answer to such demands when the requirement of good comfort is crucial.

For existing fully submerged hydrofoils, there are other demands from the side of operators including improvement of economic performance and increase in passenger capacity. Existing craft of this type have passenger capacities of up to 280 people and are powered by gas turbine engines for which initial and maintenance costs are very high, while high-speed diesel engines which are most popular as propulsion units of high-speed craft have never been adopted to this type of craft because of their heavy weight.

Considering such backgrounds, the authors decided to develop a diesel driven fully submerged large hydrofoil catamaran, the "Mitsubishi Super-Shuttle 400." In order to increase passenger capacity, a catamaran hull configuration is adopted, and economic performance is improved by saving construction and maintenance costs, while newly developed high-speed diesel engines are installed as her main source of propulsion instead of the gas turbine engines usually used for this type of craft. A water-jet propulsion system was also newly developed to match the engine.

The construction of the first Super-Shuttle 400, named the "Rainbow," began in February, 1992 and sea trials started in October of the same year. After a series of sea trials and operational training carried out over a period of about six months, she was delivered to her owner, Oki Shinko Inc. in March,1993. Then, the craft began daily services as a passenger ferry running between Oki Islands and Honshu island (Japanese mainland) on April 1, 1993 under the operation of Oki Steam Ship Inc.

2. Design concept

In the design and construction of a hydrofoil craft, the apparent and most urgent task is saving weight. For that, not only the total power plant including diesel engines but also the hull structure, foil system, water-jet propulsion and every component of the craft are designed to be as light-weight as possible.

In addition to this, the design of the foil system and hull form were carefully carried out to minimize resistance, because resistance of a fully submerged hydrofoil during the take-off process is usually higher than that of a surface piercing hydrofoil. As a result, this craft has a different configuration compared with those of existing fully submerged hydrofoils. The design highlights of the craft are summarized below.

(1) Although the newly-developed engines have a low weight to power output ratio, they are inherently and significantly heavier than gas turbine engines having the same power output. To compensate for the weight penalty imposed by the adoption of diesel engines, hydrofoils with a greater aspect ratio and consequently higher lift to drag ratio are used. It is one merit of adopting a catamaran hull which allows the use of hydrofoils with bigger spans than mono-hulls.

(2) Other merits that can be realized through use of a catamaran hull include the following. Because the demi-hull of a catamaran can be thinner than a mono-hull, wave-making resistance of the hull during the take-off process is smaller than that for a mono-hull. Wave impact on the bottom which is likely to occur in rough weather is relatively soft, because the greater dead rise of the bottom can be adopted for catamaran demi-hulls compared with mono-hulls.

(3) Existing fully submerged hydrofoils usually adopt a canard foil configuration, which is a combination of a small forward foil and a full span large aft foil, because gas-turbine engines and water-jet pumps are installed close to the aft end of the craft, and therefore the center of gravity is in the aft. In the case of this craft, two aligned diesel engines are installed along the centerline of each demi-hull to obtain the required propulsive power. As a result, the center of gravity moves forward close to midship, and a tandem foil configuration is adopted where fore and aft hydrofoils are exactly the same shape.

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Mitsubishi Heavy Industries, Ltd.
Table 1 Principal particulars of the Mitsubishi Super-Shuttle 400

<table>
<thead>
<tr>
<th></th>
<th>Length overall</th>
<th>Beam overall</th>
<th>Depth molded</th>
<th>Design hull-borne draft</th>
<th>Design foil-borne draft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>33.24 m</td>
<td>13.20 m</td>
<td>4.20 m</td>
<td>4.50 m</td>
<td>2.10 m</td>
</tr>
<tr>
<td>Gross tonnage (Japanese)</td>
<td>302 tons</td>
<td>46 tons</td>
<td>341 people</td>
<td>4 people</td>
<td>App. 35 tons</td>
</tr>
</tbody>
</table>

Principal particulars of the craft are listed in Table 1. A photo of the “Rainbow” while in foil-borne condition and a shot during launching are shown in Figs. 1 and 2, respectively. The general arrangement of the vessel is shown in Fig. 3.

3. Hull structure and foil system

Safe and reliable structure and weight savings are the main goals being sought in the structural design. These two aims are contradictory in a sense, and careful design studies were carried out for hull structures as well as foil systems in order to find an appropriate compromise between them.

3.1 Hull structures

Extensive stress analyses were conducted using three-dimensional finite element method in order to design the structure with minimum weight and sufficient strength. Careful design by such analysis was performed for the connecting structures between the hull and forward struts in particular so as to distribute the concentrated supporting force on the struts into elements of the hull structure. Because the fore and aft propulsion engines and generator engine are set inside each demi-hull, significant areas of the upper deck must be covered by removable plates for the purpose of taking the engines out of the hull during maintenance and repair. Special attention was paid to maintaining the required bending strength of the hull by the remaining part of the deck. Aluminum honey-comb plates are used for these removable plates so as to minimize their weight.
3.2 Measures against noise and vibration

As the noise level of diesel engines is higher than that of gas turbine engines, it is an important task to proof the passenger cabins against noise and vibration from the engine rooms as much as possible. A series of numerical calculations were carried out to estimate the relation between the noise level in the passenger cabins and necessary weight of the soundproof system. The following measures were taken on the basis of these results.

1. Thick sheets of rock wool were placed between the upper deck plate and the overlay flooring.
2. All ceilings and walls were finished with newly developed aluminum honey-comb panels.
3. Upper deck cabin windows were finished with double plates of glass.

As a result, a maximum noise level of 76 dB(A) was attained in the cabins.

3.3 Foil system

The foil system of this craft consists of fore and aft foils (12.8 m in span length) and two pairs of supporting struts. Fore and aft foils have exactly the same shape. Motion control flaps and rudder flaps are fitted to the trailing edges of the foils and fore struts, respectively. The fore and aft foils and fore struts are made of precipitation-hardening corrosion resistance stainless steel of 15-5 PH, and they are designed to have considerable amount of follow space inside in order to minimize weight. The motion control flaps are made of solid titanium alloy.

In the structural design of the foils and struts, extensive stress analyses were conducted using a three-dimensional finite element method. A finite element model of the fore foil and strut is shown in Fig. 4.

The manufacturing process of the foil structure consists of rough shaping of solid billets, assembly of the parts by welding, heat treatment and final machining. To retain high strength, toughness and corrosion resistance in sea water for 15-5 PH welded joints, a new process of heat treatment was used as described below through an extensive test program using a 1/2 scale model.

Solution heat treatment: 790°C × 3 hr
Aging (precipitation hardening): 570°C × 4 hr

In the heat treatment process, the foil was placed in a stainless steel muffle and many thermocouples were attached to control the temperature constant over the span length of the foil. The mechanical properties of 15-5 PH before and after welding and heat treatment are listed in Table 2. As can be seen in the Table, the base metal and welded parts have higher absorbed energy after welding and heat treatment than the base plate while retaining sufficient yield strength.

After heat treatment, the foil was machined to the outer molded line, and further all external surfaces were polished to improve hydrodynamic performance. The aft struts, which are fabricated of aluminum alloy, have built-in structures of water-jet inlets and ducts.

4. Propulsion system

The propulsion system consists of four high-speed diesel engines and two water-jet propulsors which are divided into two groups. Two diesel engines are installed in each demi-hull of the catamaran to power each water-jet propulsor set on the respective transoms of the hull.

4.1 High-speed diesel engine

A high-speed S16 R-MTK-S diesel engine was newly developed based on MHI's widely used SR-series of diesel engines. An extensive test program was formulated and
Table 3  Particulars of S 16 R-MTK-S

<table>
<thead>
<tr>
<th>Type of engine</th>
<th>V type, 4-Cycle, Direct injection, Turbo-charged, Inter-cooled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cylinders</td>
<td>16</td>
</tr>
<tr>
<td>Bore</td>
<td>170 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>180 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>85.4 l</td>
</tr>
<tr>
<td>Output (MCR)</td>
<td>2 100 kW</td>
</tr>
<tr>
<td>Speed (MCR)</td>
<td>2 000 rpm</td>
</tr>
<tr>
<td>Weight (Dry)</td>
<td>5 500 kg</td>
</tr>
</tbody>
</table>

Table 4  Specification of water-Jet propulsion unit

<table>
<thead>
<tr>
<th>Pump type</th>
<th>Special axial flow (double cascade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input power (max.)</td>
<td>5 500 PS</td>
</tr>
<tr>
<td>Input speed</td>
<td>1 022 rpm</td>
</tr>
<tr>
<td>Direction of rotation</td>
<td>Counterclockwise view from the stern</td>
</tr>
<tr>
<td>Diameter of impeller</td>
<td>814 mm</td>
</tr>
<tr>
<td>Reversing &amp; steering system</td>
<td>Fixed louvre type</td>
</tr>
<tr>
<td>Weight</td>
<td>2.2 t</td>
</tr>
</tbody>
</table>

Fig. 5  Double cascade type impeller
Six forward blades and twelve rear blades are shaped by machining of a block of 15-5 PH.

various refinements in design were made in order to increase power output and reduce total weight. As a result, the engine has achieved the lowest level of weight to power output ratio as a marine use diesel engine at 2.6 kg/kW. The particulars of the engine are listed in Table 3.

The aft engine is set above the propeller shaft with a forward rake and is connected to the shaft through a conical type reduction gear, while the fore engine is set aligned with the shaft and connected by a regular parallel type reduction gear.

4.2 Water-jet propulsion

A MWJ-5000A water-jet propulsion was also newly developed to match the propulsion engine. The specifications of the MWJ-5000A water-jet propulsion unit are listed in Table 4.

In order to accelerate the craft during the take-off process at relatively low speed, high suction performance is required at the low suction head, while high efficiency is required during high speed corresponding to service conditions while foiltborne. These two requirements usually contradict each other, and a double cascade axial flow type impeller has been specially designed to resolve them. Six forward blades keep high suction performance at lower speed, while twelve rear blades assure high efficiency during high speed. A photo of the double cascade type impeller is shown in Fig. 5.

Detailed structural design of the impeller was made using a finite element method, and the external forces on the blades of impeller were estimated on the basis of the results of performance tests using a model of the impeller. The impeller is manufactured of 15-5 PH stainless steel in order to realize savings in weight.

The inlet duct is an important part of a water-jet propulsion system, and special attention was paid to optimizing the total performance of the water-jet system. Performance of the inlet duct was verified by model tests in a wind tunnel and cavitation tunnel. Thrust characteristics of the water-jet system composed of the propulsor and the inlet duct are shown in Fig. 6, and are compared with those when an ordinarily designed impeller is used. As shown in Fig. 6, thrust limit due to cavitation becomes higher by use of this double cascade impeller. This means that a sufficient thrust margin during the
take-off process is obtained.

5. Automatic ride control system

As this craft is categorized as a fully submerged hydrofoil which is unstable during her foil-borne condition without an automatic motion control system, the development of a suitable control system is a major task. Arrangement of the motion control system known as the APF (Auto Pilot on Foils) system is shown in Fig. 7. The APF system consists of feedback sensors, electronic components, hydraulic components and flap mechanisms.

5.1 Design process

The concept design of the system was mainly carried out on the basis of studies of published references, and was developed through a series of calculations by a newly-developed calculation program designed to estimate hydrodynamic coefficients and simulate non-linear ship motions. Model tests are considered to be indispensable to confirm the concept design and verify the simulation program as well as the designed control system. The two series of model tests were planned and conducted. They consist of

1. Free running tests using a small radio-controlled model with a simplified motion control system, in order to investigate the basic requirements of the control system for the craft and to check over-all behavior of the model; and
2. Take-off and landing simulations by controlling a larger scaled model in the towing tank, in order to verify the simulation program and the designed control system.

The results of these model tests were reflected in the design of the control system and improvements made to the simulation program.

Fig. 8 shows the variation of relative bow height during the take-off process obtained by the time-domain simulation program. Model test results obtained by a take-off simulation in the towing tank are also plotted in Fig. 7 and compared with the calculated values. Simulation results agree with the measured ones fairly well, thereby confirming the reliability of the simulation program.

Physical simulations using a towing tank model and numerical simulation by the program were carried out for several settings of the control system. The obtained results were analyzed, and the design of the control system was modified and improved accordingly. The development of the control system was completed prior to the commencement of sea trials where final adjustments to the system were performed.

5.2 Feedback sensors

In order to maintain necessary redundancy of the automatic ride control system for safety, two sets of feedback sensors are mounted. The sensors utilized are listed in Table 5. Each of the two sensor boxes installed on the upper deck at midship contains a vertical gyro, roll–pitch–yaw rate gyro and a heave velocity sensor. Four heave accelerometers are installed on the upper deck above four struts. Two ultra-sonic type height sensors are fixed at the fore end of the inner hull bottom, while electro-magnetic logs are installed on the forward bottom of starboard and port side pods on the forward foil.

Two sets of sensors usually run concurrently, and the average values of the signals from the two sensors are used as feedback signals. When a sensor has failed, it is automatically cut-off from the control system and the signal from the other sensor is used. Information concerning the failure is displayed on the monitor panel.

5.3 Electronic components

Electronic components consist of two digital computers, control and monitor panels and a sequencer. They are powered by 24 volt DC batteries to assure that steady control can be continued even in the case of a black-out in the electric power supply. Usually the two computers carry out the same calculations receiving the same feedback signals, but the calculated commands regarding flap angles done by only one computer are transmitted to the hydraulic servo system. When the computer on duty happens to fail, the output lines are automatically switched by the sequencer to the other computer, and information concerning the failure is displayed on the monitor panel.

5.4 Hydraulic components and flap mechanisms

After conducting a comparative study of various types of flap control mechanisms, a type was selected in which hydraulic servo actuators are installed in water, just next to flaps. Mechanisms to transmit the movement of the actuator to the flap were designed and kept to a minimum. Long-term endurance tests were then performed for various type of seals in order to select a seal system for the actuator which can assure sufficient reliability in sea water.

Four hydraulic actuators are installed, one each in four

Table 5 List of sensors

<table>
<thead>
<tr>
<th>Motion component</th>
<th>Type of sensor</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>Vertical gyro</td>
<td>2</td>
</tr>
<tr>
<td>Roll</td>
<td>Vertical gyro</td>
<td>2</td>
</tr>
<tr>
<td>Pitch rate</td>
<td>Rate gyro</td>
<td>2</td>
</tr>
<tr>
<td>Roll rate</td>
<td>Rate gyro</td>
<td>2</td>
</tr>
<tr>
<td>Yaw rate</td>
<td>Rate gyro</td>
<td>2</td>
</tr>
<tr>
<td>Heave velocity</td>
<td>Heave sensor</td>
<td>2</td>
</tr>
<tr>
<td>Relative height</td>
<td>Ultra-sonic type</td>
<td>2</td>
</tr>
<tr>
<td>Heave acceleration</td>
<td>Accelerometer</td>
<td>4</td>
</tr>
<tr>
<td>Advance speed</td>
<td>Electro-magnetic log</td>
<td>2</td>
</tr>
</tbody>
</table>
pods located at the intersections of the foils and struts; fore and aft and starboard and port sides. Each fore and aft foil has twelve component flaps. Each hydraulic actuator activates six component flaps located on the starboard and port side of the actuator.

6. Sea trials

The construction of the "Rainbow" was completed at the beginning of October, 1992, and sea trials were begun on October 15 starting with the adjustment of the main engines and automatic control system. Soon after the normal operation of the various systems on board were confirmed towards the end of October, the craft succeeded in taking off with an engine output of only 75% MCR, and a stable foil-borne state was obtained. With this success, various tests and adjustments of the system during high-speed could be started ahead of schedule. In November, the "Rainbow" recorded her maximum speed of 45.4 knots during overload output of the main engines. Adjustments to banked turn control were repeated, and very smooth turning was finally obtained. Because the "Rainbow" can continue foil-borne running at relatively low thrust, she can use a water-jet steering system as well as vertical flap rudders for maneuvering, and the effects of rudder ventilation can be minimized. The results of hard-over turning tests while in a foil-borne state are shown in Fig. 9. The diameter of the turning circle is less than 400 m.

From December, trials were repeated in waves with prepared sets of control gains, and the motion characteristics of the craft were measured. From the results analyzed, a few sets of control gains were selected for practical use. In total, 36 sea trials were carried out for about five months until the end of February, 1993, and the validity of the design was confirmed through various measurements, such as stresses on the hull structure and foil system, as well as noise and vibration in the cabins and engine rooms.

On March 5, the "Rainbow" was transferred from the Shimonoseki Shipyard to the area of Oki Islands, and more than 20 practice operations were carried out until the beginning of her commercial services. Final adjustments to the automatic control system were made at the site of real operation.

7. Conclusions and acknowledgement

This paper summarizes the outline of a fully submerged hydrofoil catamaran called the "Mitsubishi Super-Shuttle 400." She is probably the first craft of this type developed solely for commercial use.

The craft has started regular service on April 1, 1993. The number of passengers in 1993 has increased to about twice that of the previous year when the conventional high-speed monohull vessel was in operation, as she has large passenger capacity of 341 people and can reach high speeds of around 40 knots while maintaining good comfort in waves. Although the "Rainbow" has been operating successfully so far, she is the first prototype of the "Mitsubishi Super-Shuttle 400," and her operation record is only about two years old including sea trials. The authors would like to watch her operation and take every possible means to improve the performance of the craft.

In conclusion, the authors wish to express their sincere gratitude to Mr. Masahira Okada, the president of Oki Shinko, Inc., and Mr. Teruo Taguro, the chairman of the board of Oki Steam Ship, Inc., as well as the members of Shimane Prefecture and seven towns and villages of the Oki Islands; Saigo, Fuse, Goka, Tsuma, Ama, Nishinosima and Chibu. They also wish to express their deep appreciation to Professor Takeo Koyama of the University of Tokyo, Professor Emeritus Michio Nakato and Professor Kazuhiro Mori of Hiroshima University, and Professor Takeshi Takahashi of Kurume National College of Technology for their kind guidance during the development of the "Mitsubishi Super-Shuttle 400."

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