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MOTION CONTROL IN WAVES OF A 140M SES

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ABSTRACT

This paper introduces the air cushion pressure control of the 140m Techno Super Liner (TSL), which Mitsui Engineering & Shipbuilding Co., Ltd. (MES) has constructed. TSL is an air-supported catamaran ship, which contains pressurized air between rigid side hulls. The ship dynamic performance is investigated through simulations, for the first, which is based on 3DOF motion (Heave/Pitch/Roll) and air cushion dynamics. It was performed for both model and full scale in various wave headings. The scale effect is discussed through simulation results. Then, the results of towing model tests in both regular and irregular waves are described. The model is equipped with lift fans and all the tests are carried out under the on/cushion conditions. The results of model scale simulations and model tests are compared and verified. With these results from the simulations and model tests, the design of the air cushion control system is discussed in terms of the fan stability and ship vertical accelerations. The basic concept of air-vent louver control is presented. As for the sea trial of the ship, it was successfully completed on October 12, 2005. Some of her splendid performances were demonstrated. A brief introduction of the trial is also presented in this paper.

KEY WORDS

Motion Simulations, Model Tests, Scale Effect, Ride Control System, Air Suction

INTRODUCTION

In 2005, the new huge TSL was constructed as a cargo and passenger liner, and whose route was 1000km far away across the open sea.[1)] Her photograph is given in Fig.1 and the outline is given in Table 1.

Figure 1 140m huge TSL

The TSL is categorized into Surface Effect Ship (SES) and it has an aluminum catamaran-type hull form which contains an air cushion with flexible structures called seals at the fore and aft ends of the air cushion. Pressurized air is supplied into the cushion by eight lift fans and is retained by rigid side-hulls and the flexible seals. Fig.2 shows a perspective view of the hull form of the TSL without seals.

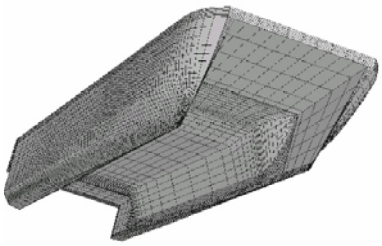

Figure 2 Perspective view of the hull form of the TSL

The major part of the ship weight is supported by the excess air cushion pressure, with the rest of its weight supported by the buoyancy of the side-hulls. The ratio of the weight supported by air-cushion system to the total weight is called cushion borne ratio. The lifted condition is called on/cushion, while the condition where it is fully in displacement mode is called off/cushion. Fig.3 illustrates these two conditions.

Table 1 Outline specification of the TSL

Length over all	140.00 m
Length of design waterline	126.83 m
Breadth, mld.	29.80 m
Depth, mld.	10.50 m
Draft, mld. (Off cushion) (On cushion)	5.00 m 2.34 m
Gross tonnage	13,923 t
Dead weight	925 t
Maximum cargo payload	210 t
Maximum passenger number	740 p
Trial Maximum Speed	42.8 knot
Endurance	2,500 km
Propulsion machinery (2G/T & 2W/J)	
Maximum continuous output	25,180 kW/unit
G/T : gas turbine (GE LM2500+)×2	
W/J : water-jet (Rolls Royce 235S2)×2	
Lift machinery (4D/E & 8L/F)	
Maximum continuous output	4,000 kW/unit
D/E : diesel engine (Niigata 16V20FX)×4	
L/F : lift fan (centrifugal type fan)×8	
ETC (4B/T & RCS)	
B/T : bow thruster (Nakashima 5blade CPP)×4	
RCS : air vent louvers (MES) fin stabilizer (MDI)	

*RCS means ride control system

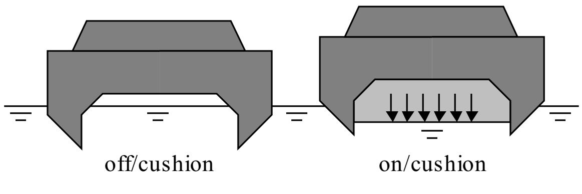

Figure 3 Conditions of on/cushion and off/cushion

Practical applications of SES have been so far limited to relatively small craft such as fast patrol craft, military craft, passenger craft, and so on. The length of these craft is around 40 meters and the cushion borne ratio is about 80%. Some of the main challenges related to hydrodynamics of such small SES are discussed by Steen[2].

Whereas, the developed TSL is far larger than those craft, in fact, it has the length of 140 meters indeed. It is necessary to make the hull size large to some extent to cope with a longer voyage because of its large scale of the necessary accommodation, machinery, and dead weight including round-trip fuel oil. Besides, it is preferable to make the ship length long enough to achieve the tough seaworthiness in a seaway.

Fig.4 shows the frequency distribution of the wave height on the route of the TSL. The significant wave height of 5m is the worst intended conditions [4] of the TSL.

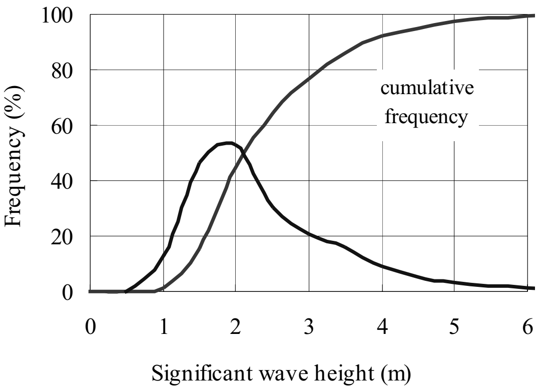

Figure 4 Frequency of the wave height on the route

SES is known to offer a better seaworthiness in heavy sea states compared with conventional catamarans, which often experience wet-deck slamming. However, shallow draft causes air suction to the water-jets and air leakage from the cushion in some cases. Besides, in low and moderate sea states, there are said to be such discomfort due to high-frequency vertical accelerations caused by resonant oscillation of the air pressure in the cushion. [2) 3)]

As a result of these considerations on typical features of SES, the TSL has been developed according to the concept of huge SES with the moderate speed and moderate cushion borne ratio. In fact, the speed range in terms of Froude number Fn is around 0.55 and its cushion borne ratio is about 70%. This new concept of the TSL has rather different effects on the hydrodynamics compared with the traditional fast small SES. Some of those dynamic features of the TSL were investigated through simulations and model experiments.

MOTION SIMULATIONS AND MODEL TESTS

Mathematical models in motion simulations

As for the mathematical model adopted in motion simulations presented here, coupled equations of motion (Heave/Pitch/Roll) and uniform cushion pressure are solved numerically with an aid of strip theory. The ship is assumed to be advancing in regular sea waves in any oblique direction. Equations of motion (Surge/Sway/Yaw) and the spatially varying pressure are not taken into account. In the air cushion thermodynamics, adiabatic process is assumed. The volumetric airflow into the air cushion is given by linearization of the fan characteristic curve about the ship equilibrium operating point. The ride control system (RCS) of a pair of roll fin stabilizers and variable air vent louvers are taken into account. More explanation in detail is given by Sorensen 3) and Kaplan 5).

Model experiments in regular waves

The tests were conducted in regular head waves at a certain forward speed (corresponding to 34.2 knots), and in beam regular waves at rest condition. The lift fans were carefully adjusted to set a correct cushion pressure before towing. A set of motion, acceleration, and cushion pressure was measured. The test results are introduced in the following subsection with the simulation results. Fig.5 shows a photograph of the model advancing in head waves.

Figure 5 The model test in regular head sea

Motion simulations in model scale

As stated by Kaplan et al. 5), the natural frequency and damping of the heave-pressure mode of SES motion dynamics are not in accordance with the Froude's law of comparison. They are relatively higher in the model case than what would be indicated by the Froude scaling. This is the reason why it is difficult to predict the full-scale performance from the data obtained by model experiments according to the Froude scaling. To cope with this difficulty, it is necessary to validate the observed model data by means of simulation results for the same conditions, using the appropriate model scale parameters, and then to get the full-scale prediction with full-scale parameters by means of simulation.

A comparison between heave response amplitude operator (RAO) obtained by the simulation and the one from the model test is shown in Fig.6. The ship is advancing in head regular waves at corresponding ship speed of 34.2 knots (Fn=0.5). Similar comparisons for pitch, accelerations, and cushion pressure are also shown in Fig.7 through 9. All the simulation results are based on model scale parameters, but do not take any RCS into account.

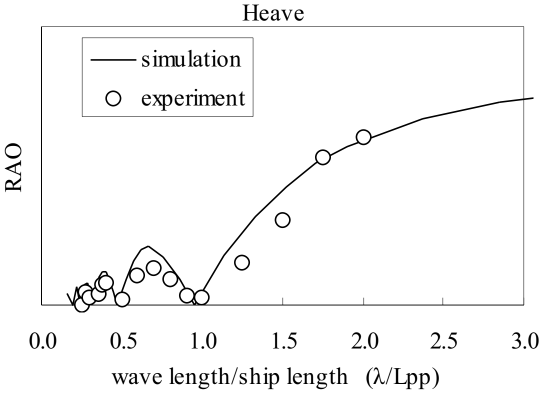

Figure 6 Heave RAO in head sea (Fn=0.5)

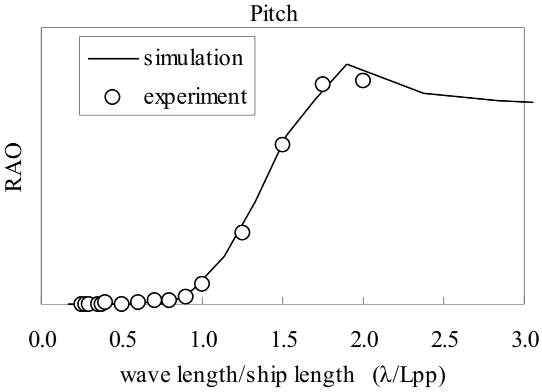

Figure 7 Pitch RAO in head sea (Fn=0.5)

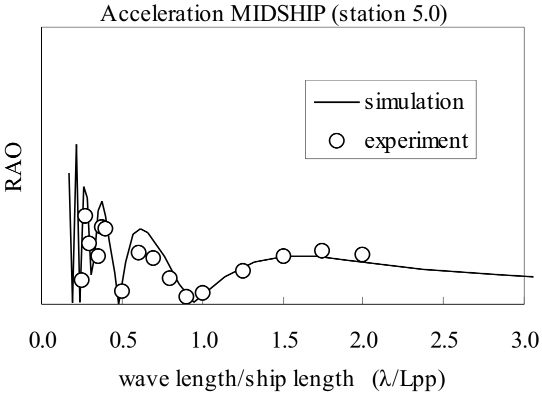

Figure 8 MIDSHIP acceleration RAO in head sea (Fn=0.5)

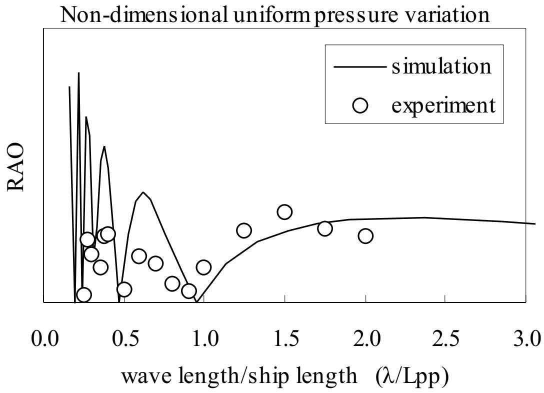

Figure 9 Non-dimensional uniform pressure variation RAO in head sea (Fn=0.5)

Although some exaggerated humps in simulation results are recognized around 0.4 and 0.7 of λ/Lpp, the simulation results are in good agreement with the experimental ones for the most part. Such humps are caused by wave volume-pumping phenomena, and some of the linearizing assumptions might induce an exaggerative estimation in these λ/Lpp regions.

As long as the model scale parameters, the simulation is valid on the whole.

Full –scale motion simulations

It is advisable to recognize the scale effect stated above by means of the simulation before full-scale prediction. Fig.10 shows a comparison between heave response amplitude operators (RAO) obtained by the full-scale simulation and the one by the model-scale simulation. The ship is advancing in head regular waves at corresponding speed of 34.2 knots (Fn=0.5). A simple RCS of the air vent louver is taken into account in the full-scale simulation to avoid a serious resonance in the pressurized air cushion. Fig.10 also shows typical sea spectra of significant wave height of 3m and 4m to illustrate the power density distribution of the irregular sea states.

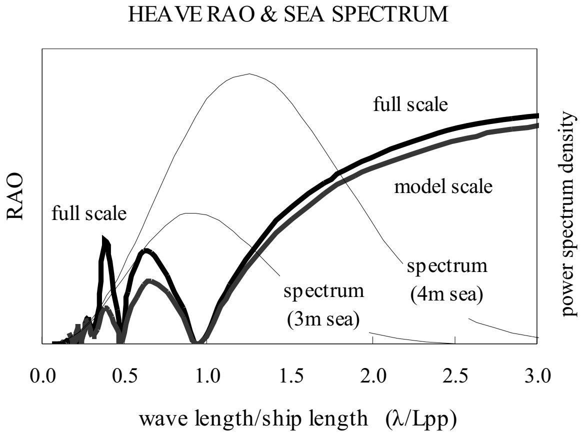

Figure 10 Heave RAO in head sea of model-scale and full-scale, with the typical sea spectra

A sharp peak is recognized around 0.4 of λ/Lpp in the full-scale simulation result. This is caused mainly by the resonance with the natural frequency in the pressurized air cushion and the lower damping of the heave-pressure mode. The natural frequency of the uniform air cushion pressure is about 0.5Hz, which induces certain vertical accelerations in the high frequency region. This phenomenon is not recognized in the model tests. This is the reason why it is important to validate motion simulations in design of huge SES.

Ride control systems (RCS)

The TSL has two ride control systems; a louver system for air cushion pressure fluctuation control and a fin stabilizer system for roll motion control.

Fig.11 shows the photograph of the fore louver system.

Figure 11 Photograph of the fore louver system

The louver opens or shuts the air vent automatically according to the information from pressure sensors to reduce the pressure variation. This control system is effective to reduce the heave motion and vertical accelerations mainly caused by the resonance of the cushion pressure at high frequency region. Fig.12 shows the vertical acceleration obtained by simulation and sea trial at the head sea. It has been made clear that the vertical accelerations with RCS/ON are about 20% lower than those with RCS/OFF.

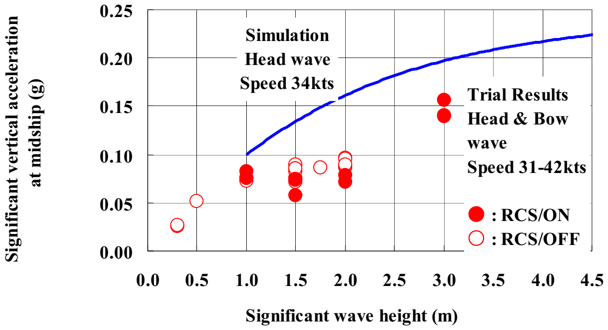

Figure 12 Vertical accelerations (single amplitude) obtained by the simulation and sea trial of the TSL

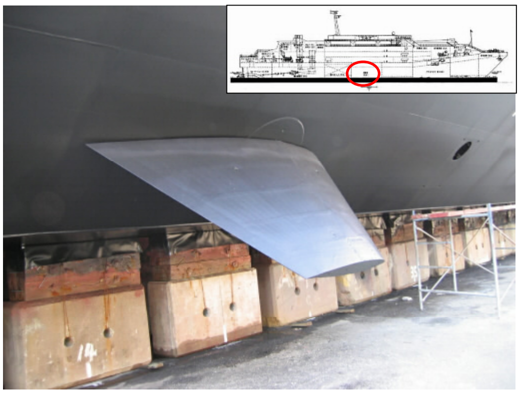

Figure 13 Photograph of the fin stabilizer system

In addition, the TSL has one pair of the fin stabilizer to damp the roll motion. Fig.13 shows the photograph of the fin stabilizer system. Fig.14 shows the simulation results of the significant roll angle in beam sea with RCS/ON and RCS/OFF. The TSL is assumed to be advancing at 34.2 knots .The fin stabilizer system with advancing at high speed is very effective to reduce roll motion, so the horizontal accelerations are also reduced.

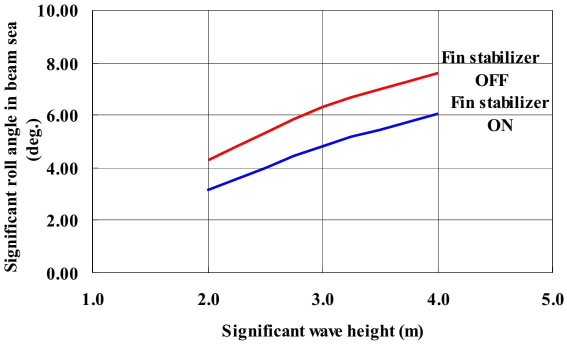

Figure 14 Significant roll angle (single amplitude) in beam sea (34.2 knots)

AIR SUCTION TO WATER-JETS AND DESIGN OF THE INELT SHAPE

Air suction to water-jets

In the design about seakeeping performance, it is important to consider prevention of the air suction to water-jets in waves if the design draft is shallow like SES. The air suction often occurs when the water-jet inlet is close or above the sea surface[2)].

The reason why the air suction is serious is that this phenomenon often leads to torque fluctuation or main engine trip.

Design of the inlet shape and model tests

One of the effective countermeasures to prevent the air suction is to design appropriate inlet shape for wave condition. In the design of TSL, scoop-type inlet was developed to cope with this matter. Fig.15 shows the model of scoop-type inlet with conventional flush-type inlet.

The water-jets with scoop-type inlet draw deeper water than ones with flush-type inlet, so it is hard to suck up air with water. The added resistance due to protuberance by the inlet is also smaller than pod-type inlet.

Figure 15 Model of the flush-type inlet (above) and scoop-type inlet (below)

The model self-propulsion tests were carried out to investigate flow rate fluctuation in waves. In these tests, pressure at water-jet outlet was measured and the flow rate was calculated from the pressure. Eye observation around inlet and outlet is also effective to grasp this phenomenon. Fig.16 shows an example of the flow rate fluctuation with scoop-type inlet and flush-type inlet for comparison, where the TSL is advancing in head irregular waves ($H_{1/3}$=3.0m) at corresponding ship speed of 34.2knots (Fn=0.5).

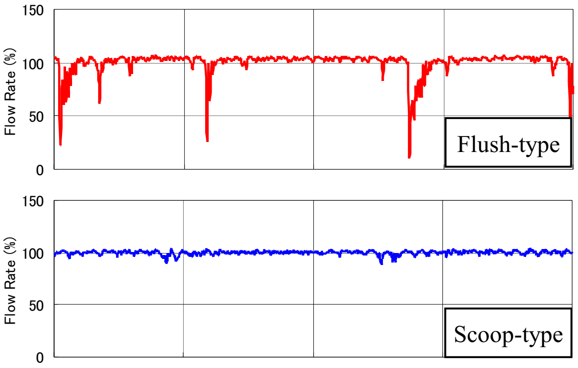

Figure 16 An example of the flow rate fluctuation with flush-type inlet (above) and scoop-type inlet (below) in head irregular waves (34.2knots, $H_{1/3}$=3.0m)

It has been made clear that the large-scale air suctions found with flush-type inlet doesn't occur with scoop-type inlet. A simple simulation about main engine revolution was also carried out with scoop-type inlet. The torque fluctuation was assumed to be in proportion to the flow rate fluctuation. An example of the simulation result is given in Fig.17, where the TSL is advancing in head irregular waves ($H_{1/3}$=3.5m).

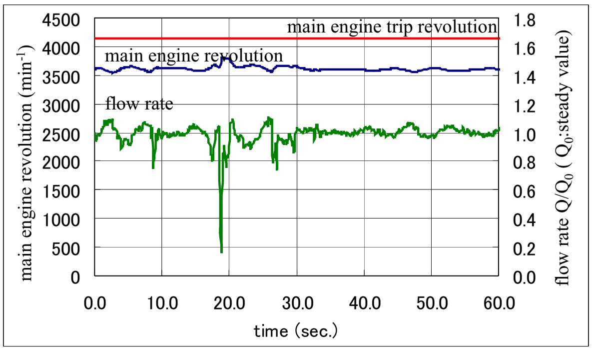

Figure 17 An example of the main engine revolution and water-jet torque fluctuation in waves

The main engine revolution sometimes rises up corresponding to the water-jets torque deduction, but it is confirmed that the extent rise is low enough to avoid the trip phenomena.

In addition, the louver opening condition is also controlled to reduce the cushion borne ratio in waves. It makes the ship draft and water jet immersion deeper. This control is effective to not only the prevention of air suction but also the reduction of acceleration caused by the leakage of cushion air.

BRIEF REVIEW OF THE TRIAL RESULTS

MES successfully completed a sea trial of the 140m TSL on October 12, 2005. The sea trial has made it clear that the performance of the TSL exceeds design requirements in many respects. Especially, the speed of 42.8 knots (about 80km/h) was confirmed at the 92% MCO in spite of sea condition with the wave height of 2 meters.

As for the dynamic performance, it has been made clear that the significant vertical acceleration is below the estimated one and the maximum horizontal acceleration is far below the safety level 1 defined by 2000 HSC code in all conditions encountered in the sea trial. .

CONCLUSIONS

The TSL was developed according to the concept of huge SES with moderate speed and cushion borne ratio, to achieve the tough seaworthiness for the long voyage. This new concept of the TSL has various unique dynamic features and they were investigated through simulations and model experiments.

As for the full-scale performance prediction, it is necessary to depend on not only model testing but also simulation because of the lack of applicability of Froude scaling. In terms of the model scale parameters, the present simulation is successfully verified being compared to the model test results.

It is only the well valid simulation that predicts the full-scale dynamic performance of the TSL. The simulation has made it clear that the vertical accelerations in the high frequency region are prominent when advancing in head waves.

The model test and simulation about air suction to the water-jet in waves were also carried out and effective scoop-type inlet was developed.

These investigations played an important part in realization of such a large TSL.

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