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Model tests on resistance and seakeeping performance of wave-piercing high-speed vessel with spray rails

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Abstract

The resistance and seakeeping performance of a high-speed monohull vessel were investigated through a series of model tests in a towing tank. The hull had a slender wave-piercing bow, round bilge, and small deadrise angle on stern. Tests on the bare hull in calm water were first conducted and tests on spray rails followed. The spray rails were designed to control the flow direction and induce a hydrodynamic lift force on the hull bottom to reduce trim angle and increase rise of the hull. The maximum trim of the bare hull was 4.65° at the designed speed, but the spray rails at optimum location reduced trim by 0.97°. The ship motion in head seas was examined after the calm water tests. Attaching the rails on the optimum location effectively reduced the pitch and heave motion responses. The vertical acceleration at the fore perpendicular reduced by 11.3%. The effective power in full scale was extrapolated from the model test results and it was revealed that the spray rails did not have any negative effects on the resistance performance of the hull, while they effectively stabilized the vessel in calm water and waves.

Keywords: Wave-piercing bow; High-speed vessel; Model test; Seakeeping

1. Introduction

High-speed vessels are designed to reach a relatively high speed with limited motor power. Therefore, various hull designs and appendages have been applied to reduce the wave-making resistance and the wetted surface area. Among them, the planing hull is one of the most widely used. This planing hull is designed to reduce the drag force by raising the hull, utilizing the hydrodynamic pressure at the bottom of the ship. As the hull is not equipped with prominent appendages such as hydrofoils, the hull shape is relatively simple; design, manufacturing, and maintenance of the planing hull are easier than those of other types of high speed vessels. The planing hull employs a wide bottom area to obtain sufficient lift force to raise the hull; thus, strong resonances in pitch and heave motions develop periodically in response to waves because of the wide bottom. Because strong vertical resonance motion and the slamming impact can damage the hull and harm passengers, it is important in the design stage of the planing hull to analyze and minimize the impact of the hull in waves.

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List of symbols

A	Wave amplitude $A = H/2$ (m)
B	Maximum Breadth of the ship (m)
C_R	Residual resistance coefficient
Fr_V	Volumetric Froude number $Fr = V_A/\sqrt{G\nabla^{\frac{1}{3}}}$
G	Gravitational acceleration (9.8 m/s^2)
H	Wave height (m)
k	Wave number $k = 2\pi/\lambda$
L_{PP}	Length between perpendiculars (m)
Rn	Reynolds number based on the length between perpendiculars $Rn = \rho L_{PP} V_A/\mu$
T	Draft of the ship (m)
V_A	Ship advance speed (m/s)
∇	Ship displacement (m^3)
λ	Wave length (m)
μ	Dynamic viscosity of water ($kg/m\cdot s$)
ρ	Density of water (kg/m^3)

Grigoropoulos and Chalkias (2010) used the Rankine source panel method to analyze the motion of a planing craft in waves. They developed a method to estimate the vertical acceleration of the bow and proposed an improved design of a double-chine planing hull. The modified hull was more prismatic than the original and the vertical acceleration of the bow in waves was reduced by 25.9%. Sun and Faltinsen (2011) used the boundary element method to analyze the planing hull motion in waves and the vertical acceleration of the bow with wave condition variations. The analysis method was applied to various speeds and loading conditions; these researchers reported that the magnitude of the sharp vertical acceleration peaks at the resonant wave encounter frequency ranged from 2 G to 7 G, according to the ship configuration variations.

In addition to the above numerical approaches, studies on the seakeeping performance of the planing hull were also implemented through model tests. Kim et al. (2013) conducted model tests for three different types of planing hull designs in calm water and in head seas to measure and compare the bow vertical acceleration. They found that the vertical acceleration of the bow and the motion response to waves could be reduced by applying the wave-piercing bow design. Begovic et al. (2014) performed seakeeping model tests of planing hull designs with various deadrise angles, and they reported a decrease in the vertical acceleration of the bow by introducing large deadrise angle to the hull bottom.

Dynamic stability of planing hull is an important topic in design, as well as vertical acceleration of the bow. Previous experimental and mathematical studies on transversal stability have reported that transverse stability of planing hulls is very sensitive to their bottom design and attitude in planing (Lewandowski, 1997; Katayama et al., 2007). To insure suitable dynamic stability and maneuverability, small deadrise angle is recommended, but it results in increasing vertical acceleration of the bow, as described above. It is hard to satisfy both of seakeeping and maneuverability of planing hull, thus a different hull shape has been developed and tested to overcome the limitations of planing hulls design.

A slender hull with wave-piercing bow has been suggested as an alternative. Wave-piercing bow was shaped like a sharp axe blade, to provide small displacement on the bow (Kim et al., 2013). Thus, the displacement of the ship is concentrated near the stern; the Center of Gravity (CG) is also located near the stern. Previous studies on wave-piercing bow have revealed that this configuration reduces motion and added resistance of the hull in waves.

Keuning et al. (2001) applied a wave-piercing bow to a fast patrol boat and analyzed its motion in waves by applying the non-linear strip theory. The results were compared with those for the original hull to indicate that the hull with a wave-piercing bow reduced the vertical acceleration of the bow. Moreover, it was reported that the application of the wave-piercing bow resulted in the decrease of the trim in running (Keuning et al., 2002).

When a wave-piercing bow is used in a high-speed vessel, the breath of the bow decreases; L_{PP}/B of the ship increases and the transverse stability reduced in wave-piercing vessels. Hence, the wave-piercing bow has been mainly applied to catamarans, which have good transversal stability. By introducing wave-piercing bow to a catamaran, it was reported that the slamming impacts of the bow diminishes (Lavroff et al., 2013).

Herein, a high-speed monohull with a wave-piercing bow was designed and tested to assess its resistance and seakeeping performance. As its design principle was different from that of planing hulls, which have been used for high speed vessels most frequently, the resistance and seakeeping characteristics were expected to be dissimilar to those of planing hulls. Moreover, spray rails with location variations were also tested in calm water and head seas conditions. Appendages similar to spray rails in this study have been applied to planing hulls to reduce trim in running and longitudinal and transverse stability (Yousefi et al., 2013; Larsson et al., 2014). As the optimal location of spray rails varies with the hull geometry and flow stagnation line (Clement, 1964), spray rails with various locations were tested in calm water first, and the optimal spray rails which minimize the running trim and resistance at the design speed were chosen. The hull with optimal spray rails were also tested in head seas. These model test results provided estimates of the vertical acceleration of the bow and its full-scale effective power in head seas.

This paper is organized as follows. The next section explains the experimental model, facility, measurement system, and conditions. The following section details the experimental results and discussion, wherein the first subsection covers the resistance test results in calm water for the bare hull and spray rails and the second subsection describes the seakeeping test results in head seas. The last section summarizes the conclusions and future work of this study.