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Experimental and numerical investigations on hydrodynamic and aerodynamic characteristics of the tunnel of planing trimaran

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ABSTRACT

The planing trimaran possesses distinctive hybrid hydrodynamic and aerodynamic performance due to the presence of tunnel. The research described in this paper was carried out based on the observation of wave characteristics of a planing trimaran model in towing tests, in which the resistance drops as soon as the wave surface separates from tunnel roof. In order to gain a deeper insight into the relationship between wave flow and forces in tunnel region, a comprehensive series of viscous CFD simulations considering free-surface and 2-DOF motion of the hull (heave and pitch) have been performed for the tested model at the volume based Froude numbers ranging from 3.16 to 5.87. The calculated results were validated by comparison with experimental data and showed good agreement. Numerical results of wave contours, longitudinal wave cuts and lifting force distributions at the calculated speeds were presented for the analysis of ventilation process in tunnel region and the corresponding variation of tunnel forces. It is found that, for the speeds higher than Froude number of 4.52, the aerodynamic forces provide major tunnel lift and mainly act on the straight section of the tunnel. And, therefore, numerical simulations of two modified models have also been performed for the analysis of influence of straight section length on the hydrodynamic and aerodynamic performance of planing trimaran.

1. Introduction

Planing trimaran is a newly developed tunnel type planing craft, it has exceptional resistance performance and extensive application prospect in both commercial and military purpose. Geometric features of this hull (see in Fig. 1) are quite different from those of conventional monohull, the hull body consists of a relative flat main hull in the middle and two slender demihulls arranged aside. The tunnel is surrounded by the mainhull and demihull, compared with the other drag-reducing configurations such as step, spray rail and stern flap which decrease drag by using hydrodynamic physical support, tunnel can create aerodynamic lift during high-speed forward motion and thus achieve a significant resistance reduction.

Since the aerodynamic forces partially sustain the vessel weight, the planing trimaran can be grouped under the definition of Aerodynamic Alleviated Marine Vehicle (AAMV) [1]. Normally, the most common AAMV is planing catamaran, which has been widely used in race boats. Planing catamaran has two planing sponsons acting as aerodynamic end plates of the central tunnel, therefore its tunnel could work like a ram wing and create additional aerodynamic forces to lift 30–80% of the total weight [2]. The planing trimaran, in plan view, has smaller tunnel area than catamaran and thus creates lower tunnel lift, often less than 30% of vessel weight [3].

In recent years, several studies on planing trimaran or some other tunnel type planing crafts have been carried out using numerical or experimental method. [4] compared several hydrodynamic analysis techniques for the planing hulls and chose a FVM based numerical method to study the drag reduction effect of tunnels [5], which were introduced at the bottom section of a planing monohull; a resistance reduction of ∼14% was reported at 60 knot. [6] numerically simulated the forward motion for a series of tunneled planing hulls with different tunnel aperture using the FLUENT software, their result showed that the small tunnel aperture could achieve more drag reduction at high Froude number. Ghassabzadeh and Ghassemi [7] developed a mathematical procedure to automatically generate the hull form of a planing tunnel vessel, they also utilized the FLUENT software coupled with dynamic mesh restructuring method to model 2-DOF motion of this vessel in calm water [8]. [9] conducted a series of model tests to investigate both resistance and sea keeping performance of a planing trimaran, steps were introduced to reduce resistance at high speed [10]. [11] experimentally and numerically studied the calm water performance of a planing trimaran as well, and found that the longitudinal location of gravity center and displacement had significant influence on the

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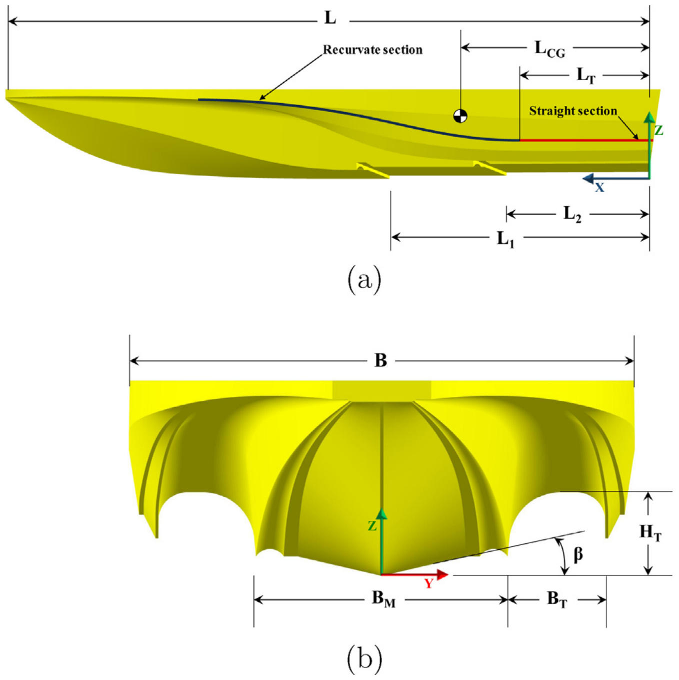

Fig. 1. Specification of the planing trimaran.

total resistance. [12] developed a numerical algorithm based on the finite volume discretization to simulate 3D nonlinear motion of a high-speed planing catamaran, this algorithm showed good capacities in dealing with complex hydrodynamic problems at high speed.

The aforementioned researches give an overall description of the tunnel type planning hull, including resistance, sea keeping and motion characteristics, however, relative few studies are focused on the internal flow of the tunnel which would directly determine the hydrodynamic and aerodynamic performance of planing trimaran. Therefore, in this article, the main objective is to analyze the flow characteristics in tunnel region under the influence of the distinctive configuration of planing trimaran. Considering the capacity in simulation of viscous flow with complex free-surface profile, the FVM based software CFX is employed to simulate the tunnel flow and the forward motion of planing trimaran in calm water.

The paper is organized as follows: at first, the hull configuration and towing tests in calm water are shown, experimental results of resistance, sinkage, trim angle and visible wave features are presented. A brief description of numerical method is then reported, followed by the description of numerical setup, mesh generation, mesh dependency analysis and validation of the numerical results. Subsequently, the relationships between tunnel forces and wave characteristics in planing mode are analyzed. Based on the numerical analysis, parameter studies on crucial tunnel configuration are performed.

2. Model test

2.1. Geometrical description of planing trimaran model

The hull geometry and tunnel configuration are shown in Fig. 1 (a) and (b), whereas the main characteristics are given in Table 1. It can been seen that the main hull is the major structure of planing trimaran and possesses the majority of volume of displacement; to improve the high-speed resistance performance, two steps are introduced on the main hull bottom. The demihulls are slender and only provide little buoyancy. The tunnel starts amidships and extends aft to the transom; using two circular surfaces, the tunnel roof is smoothly blended with the main hull and demihull. Longitudinally seeing, the tunnel consists of a recurvate section at front which has an inverse S shape, and a straight section in the rear; as it will be shown in the following numerical analysis, the straight section has significant influence on the hydrodynamic performance of tunnel.

Table 1
Main dimensions.

Main feature	Symbol	Value
Length overall (m)	L	2.5
Beam overall (m)	B	0.9
Main hull beam (m)	B_M	0.46
Tunnel beam (m)	B_T	0.125
Tunnel height (m)	H_T	0.175
Length of tunnel straight section (m)	L_T	0.625
Longitudinal location of fore step (m)	L_1	1
Longitudinal location of aft step (m)	L_2	0.55
Longitudinal center of gravity (m)	L_{CG}	0.7
Draft (m)	T	0.17
Deadrise angle (∘)	β	13
Displacement (kg)	Δ	125
Block coefficient of the main hull	C_B	0.585

2.2. Experimental setup

The planing trimaran model has been tested in the towing tank of China Special Vehicle Research Institute (also named No. 605 Research Institute, a subsidiary of AVIC), of which the main dimensions are 510 m × 6.5m × 6.8 m in length, width and depth, respectively. Fig. 2 shows a schematic view of the experimental setup, the tested model is attached to a carriage platform with two degrees of freedom (heave and pitch). During the towing tests, the resistance is measured by a dynamometer mounted on the carriage; the trim angle and sinkage are measured by an electric angle sensor and a cable-extension displacement sensor, which are mounted at the fore deck and gravity center of the hull, respectively; in addition, two cameras placed in front of and behind the hull body are used to record the wave-making characteristics. A detailed description of the experiments can be found in [3].

2.3. Experimental results

In this article, the volume based Froude number is used to represent the dimensionless velocity, which is defined as $Fr_\nabla = U/\sqrt{g\left(\nabla^{\frac{1}{3}}\right)}$, where U is the model velocity, g is the acceleration of gravity and ∇ is the volumetric displacement of the hull. The measured drag-to-weight ratio (R/Δ), trim angle and dimensionless sinkage (defined as $sinkage/3T$ to acquire a similar variation range with R/Δ) versus Froude number are summarized in Fig. 3. It can be seen that the hull body has evident bow-up trim at lower speeds, while, after entering planing mode, the hull body is lifted out of water and the bow gradually goes down with the increasing speed. The resistance curve has two humps, the first hump appears in the semi-displacement regime, it is mainly caused by the large trim angle; the second hump in the high-speed planing regime indicates that the resistance will decrease as the speed is increased, this is a representative resistance characteristic of the planing trimaran and directly influenced by the ventilation status in tunnel region.

Fig. 4 shows a series of wave snapshots of bow and stern regions at different speeds. In the front view, it can be seen that the main hull produces most of waves during forward motion, part of which are absorbed by the tunnel, while the rest propagate outside