

RANSE Simulation of High-speed Planning Craft in Regular Waves

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Abstract: This paper presents a study on the numerical simulation of planing crafts sailing in regular waves. This allows an accurate estimate of the seas keeping performance of the high speed craft. The simulation set in six-degree of freedom motions is based on the Reynolds averaged Navier Stokes equations volume of fluid (RANSE VOF) solver. The trimming mesh technique and integral dynamic mesh method are used to guarantee the good accuracy of the hydrodynamic force and high efficiency of the numerical simulation. Incident head waves, oblique waves and beam waves are generated in the simulation with three different velocities ($Fn=1.0, 1.5, 2.0$). The motions and sea keeping performance of the planing craft with waves coming from different directions are indicated in the flow solver. The ship designer placed an emphasis on the effects of waves on sailing amplitude and pressure distribution of planing craft in the configuration of building high speed crafts.

Keywords: planing craft; RANSE VOF solver; high-speed planning craft; hydrodynamic performance; regular waves

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1 Introduction

The designing of crafts with characteristics of high-speed traits have become a widely used mechanism by many for achieving good performances. Due to the high-speed, slamming, wave-piercing and spray characters the traditional method for ship hydrodynamic performance estimating is not the most suitable for designing crafts. In recent years, the computational fluid dynamics (CFD) technique has proved to be accurate and robust for hydrodynamic calculation of high-speed planing hulls.

The hydrodynamic characteristics of planing surfaces were first studied through experiments on a large systematic series of tests made between 1940 and 1960 at the towing tank of NACA in Langley and at Davidson laboratory (Chambliss and Boyd, 1953). On the basis of these tests, a number of interpretation of the results have been made and several methods were developed for the estimation of hydrodynamic forces on planing surfaces of simple geometrical shapes. The most widely diffused method proposed is by Savitsky (1964) which account for the experimental results solving more of a general hydrodynamic problem of fast hull running in steady condition in a pure planing regime. Zhao *et al.* (1997) present a 2.5D method based on potential theory calculations of the hydrodynamic lifts of planing crafts. Sun and Faltinsen (2007) conducted research on sea keeping performance on planing crafts using a 2.5D method. Katayama also applied a very

small model on the research on the hydrodynamic character of planning crafts (Katayama *et al.*, 1999, 2000, 2001, 2002a, 2002b). Azcueta *et al.* (2001, 2002, 2003) used commercial software COMET to numerically simulate a high speed planning vessel ($Fn=4$). Qiu, *et al.* used 2-D and 3-D methods to compute the slamming force on a planing hull and comparison between 3D and 2D Solutions. The planning crafts suffer significant wave load and impact force when they sail in waves at high-speed. Some of the peculiar issues to keep in mind in the planing of crafts are the violent motions that occur in severe seas such as jumping from wave crest and falling down to wave surface. During the motion of the planing crafts the change in the ship's running attitude, due to the pressure field around the hull is quite significant and effects influence the performance greatly.

This paper uses the commercial codes STAR-CCM+ to have simulations of planing craft sailing in waves coming from different directions (Star-CCM+ User guide, 2008). Based on the study, this paper has validated the accuracy of the numerical simulation of Katayama's planing craft model sailing in head waves. The effects of different wave directions and speeds on planning crafts are proposed. The motions and hydrodynamic performance of the planing craft in different speeds are calculated in the flow solver. The effects of waves on planing craft are presented to give a reference for the ship designer.

2 Calculation model

2.1 The body-motion module

Two orthogonal Cartesian reference systems (RS) are used: one fixed the earth-(dynamic fasten), the other fixed on the planing vessel (moving fasten), the origin of the moving

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coordinate at the ship's centre of gravity G , G_x , G_y , G_z respectively stand for intersecting lines passing the waterline plane, the cross profile and the longitudinal section. Assuming the quality of the water glider is m , the speed for the center of gravity G is $V(u, v, w)$, angular velocity is $\Omega(p, q, r)$, the force is $F(x, y, z)$, the torque that force to the center of gravity is $M(L, M, N)$.

The quality heart movement theorem and the momentum torque theorem relative to the quality heart are:

$$\begin{aligned}\frac{d\mathbf{B}}{dt} &= \mathbf{F} \\ \frac{d\mathbf{K}}{dt} &= \mathbf{M}\end{aligned}\quad (1)$$

In the formula, (2) \mathbf{B} is the momentum, \mathbf{K} is the momentum torque relative to the quality heart G . the dynamic fastens is as such:

$$\begin{aligned}\frac{d\tilde{\mathbf{B}}}{dt} + \Omega \times \mathbf{B} &= \mathbf{F}, \\ \frac{d\tilde{\mathbf{K}}}{dt} + \Omega \times \mathbf{K} + \mathbf{V} \times \mathbf{B} &= \mathbf{M}\end{aligned}\quad (2)$$

The formula (3) namely the planing vessel's six degrees of freedom equation of motion.

$$\begin{aligned}m(\dot{u} + qw - rv) &= X \\ m(\dot{v} + ru - pw) &= Y \\ m(\dot{w} + pv - qu) &= Z \\ I_x \dot{p} + (I_z - I_y)qr &= L \\ I_y \dot{q} + (I_x - I_z)rp &= M \\ I_z \dot{r} + (I_y - I_x)pq &= N\end{aligned}\quad (3)$$

The formula (3) is the planing vessel's six degrees of freedom equation of motion. In the simulation of this paper, waves come from different directions. 3 DOF (degree of freedom) is set free in the simulation of planing craft sailing in incident head waves, and 4 DOF is set free in the oblique waves and beam waves. The formula (3) is simplified from 6 formulas to 3 or 4.

2.2 The numerical wave generation

The incident waves are generated at the inlet flow boundary by imposing the instantaneous wave elevation and orbital velocities according to the linear wave theory. The orbital velocities of the wave are thus superimposed to the mean flow velocity. Three wave parameters are set at the beginning of a simulation: the wave amplitude- a , the wave length- λ and wave direction. The wave velocities satisfy the formula:

$$\omega^2 = gkh2ka, U = a\omega \sin(kx - \omega t)e^{kz} \quad (4)$$

ω is circle frequency, g is gravity acceleration, U is wave velocity and k is wave number. In this paper, the waves come from three different directions: head wave, oblique head wave with a 30 degree angle of the ship velocity direction and the beam wave (with a 90 degree angle of the ship velocity direction) $\lambda=1.5L_m$, L_m is the length of hull. And the steepness

(h/λ) is 1/40, h is wave height.

Fig. 1 shows the hull in the three different waves. In the single-grid strategy used in these simulations, the computational domain moves as a whole relative to this plane. Since the free surface can leave the computational domain in any place, even capsize upside down would be possible in the numerical simulation.

The deformation of the free surface is computed with an interface-capturing scheme of VOF type, which has proven to be well suited for flows involving breaking waves, sprays, hull shapes with flat stern overhangs and section flare. In this method the solution domain covers both the water and air region around the hull and both fluids are considered as one effective fluid with variable properties.

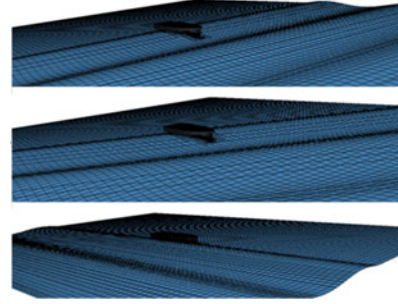


Fig.1 The free surface mesh of planing craft in different waves

3 Calculation methods

3.1 RANSE equation

The simulations used 3-D incompressible Reynolds Averaged Navier Stokes equation based on finite volume method (2004) is applied:

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) &= 0, \\ \frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) &= -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial u_i}{\partial x_j} - \overline{\rho u_i' u_j'} \right) + S_i \\ (i, j &= 1, 2, 3)\end{aligned}\quad (5)$$

The solution method in STAR-CCM+ is of finite volume type. The integration in space is of second order, based on midpoint rule integration and linear interpolation. The method is fully implicit. SIMPLE arithmetic was applied and $k-\omega$ *sst* two equations turbulence model was used in the simulation. The time step was set with 0.005-0.0005s depending on the sailing speeds.

3.2 The numerical mesh

The trimming mesh technique is developed in recent years with the development of computer. Since the trimming mesh is generated easily and have high quality with the complex surface, many CFD researchers pay attention to this kind of mesh. The STAR-CCM+ codes contain this function of

trimming mesh generation.

In order to keep lower central processing unit (CPU) time and have a good accuracy, the researcher used the commercial code STAR-CCM+ to generate trimming mesh for the simulation of high-speed planing crafts. The trimming mesh was generated automatically by computer spends large random access memory; however, this method provides a much less mesh number compared with the traditional unstructured mesh.

Figure 2 displays the trimming mesh of the planing craft model in the whole calculation zone for simulation. The length of the model is 2.75 m, and the breadth is 0.78 m. The zone near the liquid-air surface is concentrated to capture the wave surface accurately. The number of the control volumes for the whole hull is controlled about 300 000.

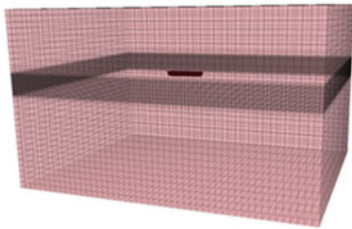


Fig. 2 Trimming mesh of the planing craft generated in STAR-CCM+

3.3 The validation of the numerical method

The research indicates very few methods are used to validate sea keeping performances of planing crafts and there are also many difficulties with the model experiments. The numerical simulation results in this paper are not available for validation.. However, the researcher has selected the Katayama's model experiment and validated the accuracy and feasibility of this numerical method in an anterior paper. The validated results are provided within the research paper.

The figures 3 gives the model lines of Katayama's planing craft and figure 4, provides the heave motion and pitch angle comparison of calculation results and experiment data. Therefore the simulation results in this paper are considered credible for reference.

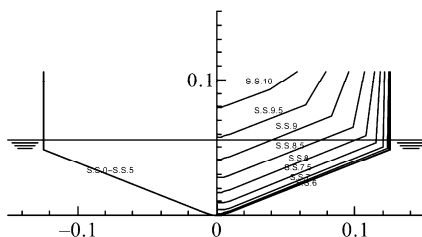


Fig. 3 Planing craft lines of the sea keeping experiment model

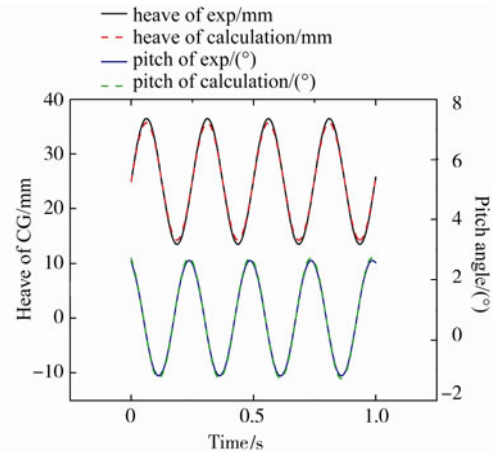


Fig. 4 Comparison of experiment data and numerical data of sailing attitude in waves

4 Results and discussion

In order to keep the planing craft sailing in the waves at given speeds, the drags of the hull running in calm water are calculated first. Following this procedure the wave simulation begins and previously calculated forces remain the same in calm water for consistency throughout the simulation. The steepness of the wave simulation is on a small scale and therefore, the induced increased drag component will not be studied. As a result sailing speed will remain close to the given speed with a little amplitude oscillation.

4.1 sailing upwind in head waves

First, the planing craft is set in incident head waves in three different velocities ($Fn=1.0, 2.0$ and 3.0). 3DOF are set free: Surge, heave and pitch. The motions and hydrodynamic forces are calculated in the simulation procedure.

Figs. 5 and 6 show the computed heave motions and pitch angles in the 3DOF for the last 2 seconds of the three speed simulations. The motions of planing craft have been steady after 3 seconds. In the first few seconds simulation time the motions are irregular, since the waves have to build up first and the hull is set in an unbalanced position and pitch angle. In the simulation ($Fn=1,2$), the heave motions and pitch angle are regular after several seconds. The difference is that planing craft moves up to one wave length in one circle in case 1 ($Fn=1$), but undergo two wave length in one circle in case 2 ($Fn=2$). When ship speed reach to 15.6 m/s in case3 ($Fn=3$), that the motion of the hull is absolutely irregular, but vibrates in a little region. Figure 5 and 6 also show that with the rise of the speed the oscillation of the heave and pitch is smaller according with the fact of ship character.

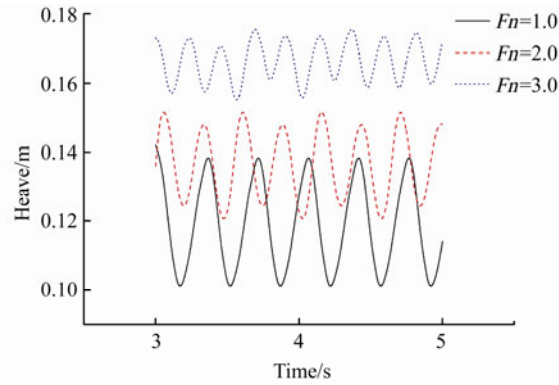


Fig. 5 Heave motions of planing craft with different speeds in head waves

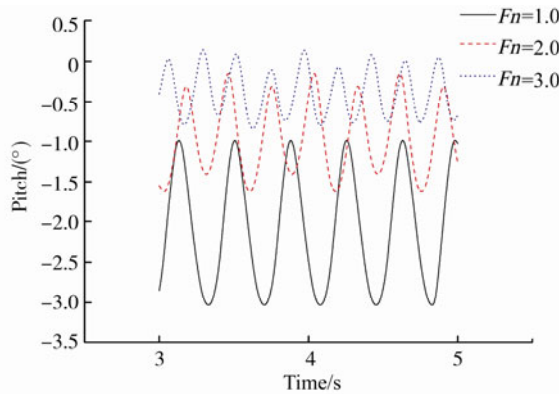


Fig. 6 Pitch angles of planing craft with different speeds in head waves

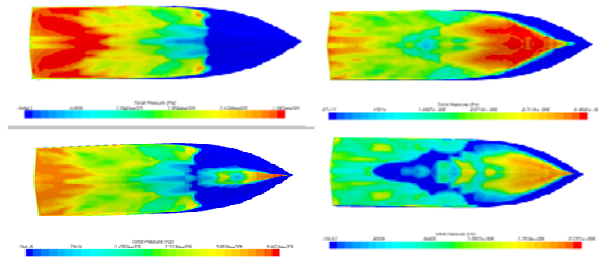


Fig. 7 Total pressure distribution of planing craft with $Fn=3.0$ in head waves

Fig. 7 shows the pressure distributions of the bottom of the planing craft sailing in different positions in the head waves in case 1 ($Fn=1$). The researcher could refer to the pressure results to guarantee the strength of the hull. Benefiting from the RANSE VOF solver, the simulation can provide ship designer's various kinds of data for reference in the optimization procedure of the hull.

As a result of the high-speed and spray characteristics of the planing craft, the simulation needs adequate control volumes around the surface of the two phases of the mixture, and the time step should not take much to satisfy the wall functions. The CPU time needed for computing the 5 seconds simulation time is about 10 hours in STAR-CCM+ with 4 Intel Core Q8400(2.66GHz) processors.

4.2 sailing in oblique waves

For these simulations the parameters of the waves are the same as before in 4.1 except for the direction of the wave transmission. Since the flow field is no longer symmetrical, 4 DOF are set free: Surge, heave, roll, and pitch. The waves come obliquely at an angle of 30° from the bow.

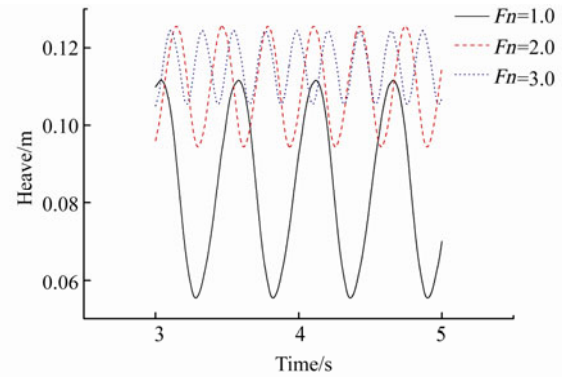


Fig. 8 Heave motions of planing craft with different speeds in oblique waves

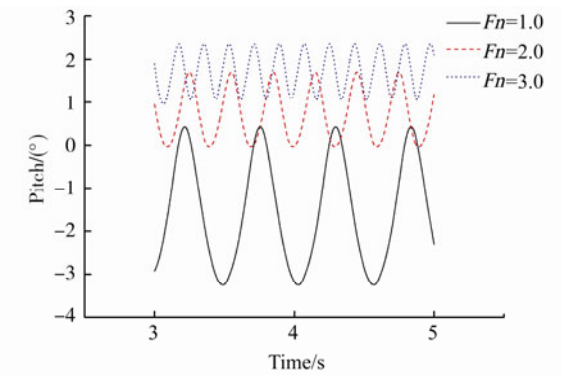


Fig. 9 Pitch angles of planing craft with different speeds in oblique waves

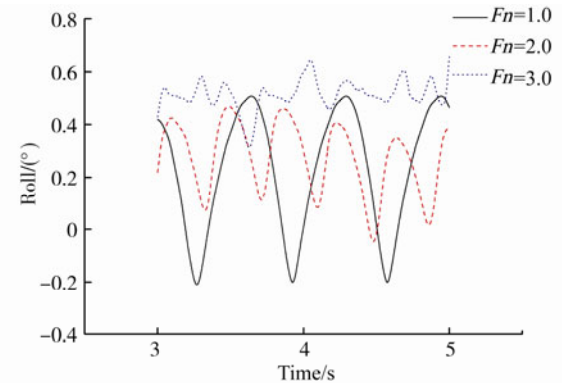


Fig. 10 Roll angles of planing craft with different speeds in oblique waves

Figs. 8-10 show the heave, pitch and roll motions of planing craft in oblique wave with three different speeds. Compared with results in head waves without oblique angle, the heave motions and pitch in oblique waves angle remain regular in $Fn=3$. The 30° angle of the waves coming direction reduces

the impact of the wave influence on the craft because of the relative speed of the hull and wave is smaller and the wave length becomes larger. However the oblique waves induce irregular roll angles plotted in the figure 10. The roll angles oscillate in little period. As the speed increases the oscillation becomes smaller.

Figure 11 shows pressure distribution of the craft's bottom in case 4 ($Fn=1.0$). The oblique head waves cause asymmetrical dynamic pressure could be clarified in the scalar.

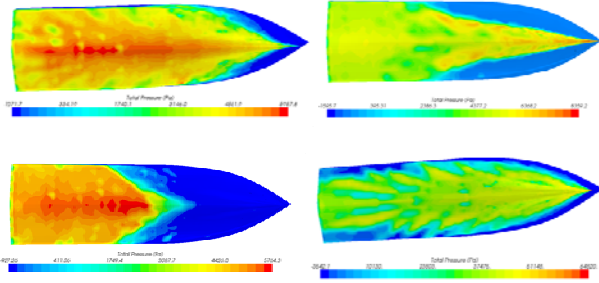


Fig. 11 Total pressure distribution of planing craft with $Fn=3.0$ in oblique waves

4.3 Reaching in beam waves

The last example presented here is for planing craft in the same sailing attitude and with the same wave parameters as the previous study, but in waves coming from the port beam. Also 4 DOF are set free: Heave, surge, roll and pitch. The simulation also runs in three different $Fn=1.0$, 2.0 and 3.0. The influence of speed on transverse stability of in the beam waves is considered here.

Figs. 12-14 indicate the heave, pitch and roll motion curves of planing craft in beam waves over 4 seconds. The heave motions are regular in three speeds and change little with different speeds. The pitch angles are irregular and decrease with increasing speed, but vary in little oscillations. The roll angles in this wave don't show the stability losing in high speed. In three cases, the roll oscillations are approximate.

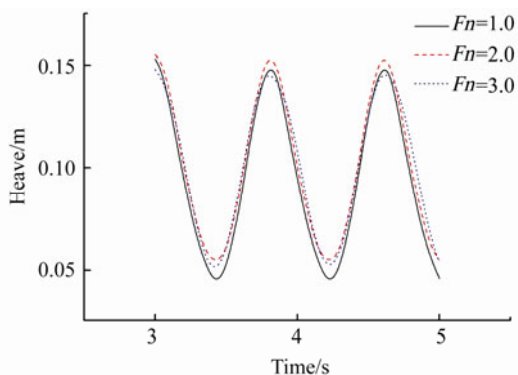


Fig. 12 Heave motions of planing craft with different speeds in beam waves

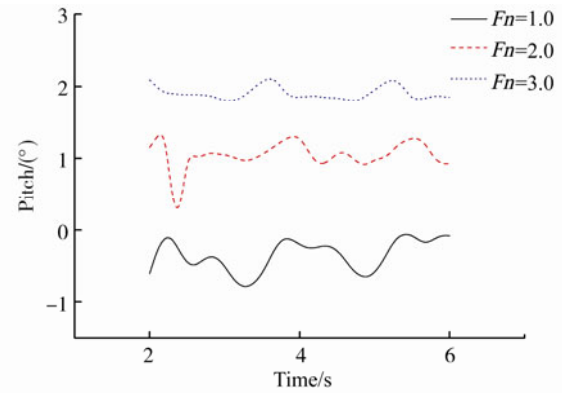


Fig. 13 Pitch angles of planing craft with different speeds in beam waves

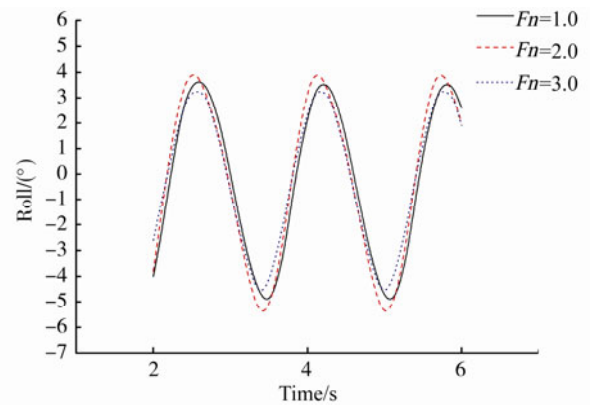


Fig. 14 Roll angles of planing craft with different speeds in beam waves

5 Conclusions

The RANSE simulations presented here have been applied to optimize hull shapes and provide designer's with a reference of the planing craft sailing in waves. The model experiment is able to validate in planing craft design today. The simulations provided a reference in the initial stage of ship designs before the model experiments. The accuracy of these numerical simulations has been proven in previous studies.

More research study on the enhancement of free-surface computations will need to be conducted in the future. Evidence has shown the free-surface deformation of the wave oscillation and reflection at the boundaries has been the main reason for the scattered results in the research and poor analysis of data. As a result, validation with a model or full-scale measurement still remains of the essence.

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