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Comparison of numerical solution and semi-empirical formulas to predict the effects of important design parameters on porpoising region of a planing vessel

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ABSTRACT

Stability of the marine vessels in different conditions is one of the most important problems in the design of a planing vessel. In this research, the effects of some important design parameters (mass, longitudinal center of mass, deadrise angle, and length) of DTMB 62 model 4667-1 planing hull on the drag and also on the longitudinal dynamic stability (porpoising) are investigated in the velocity range of 2.12–8.486 m/s in calm water. In this paper, both numerical simulation of Reynolds Average Naiver Stokes (RANS) equations and semi-empirical formulas of Savitsky are used to analyze the motion of a 4667 planing vessel in calm water with two degrees of freedom (2DOF). For this purpose a finite volume, ANSYS-FLUENT, code is used to solve the Navier-Stokes equations for the simulation of the flow field around the vessel. In addition, an explicit VOF scheme and SST- Kω model is used with dynamic mesh scheme to capture the interface of a two-phase flow and to model the turbulence respectively, in 2DOF model (heave and pitch). Also, the results of both methods are compared with each other. According to the present results, changing the aspect ratio of the vessel and also the longitudinal center of gravity have the most effect on the porpoising region.

1. Introduction

The possibility of achieving a higher speed in marine vessels was prepared by introducing planing hulls since the early years of 20th century. In high speed planing vessels, weight of the craft is balanced with the hydrodynamic forces instead of the buoyancy force [1,2]. The trim angle and the drag force increase with increasing speed in the displacement and semi-displacement modes of motion. In planing regime of motion the draft of the vessel is reduced compared with the semi-displacement regime. Assume the trust line has passed through the center of gravity, therefore the center of hydrodynamic forces on the hull moves backward and the trim angle and the distance between the center of gravity and the center of hydrodynamic forces is reduced until balancing between the torques is satisfied. Because of the reduction in wave drag, a hump can be seen in the planing hull drag curve at the time of transition from displacement regime to planing mode. It should be noted that the drag force increase[s] continuously with increasing the speed [3]. Also higher speeds make some structural limits and also can increase the possibility of instability. One of the important modes of instability is longitudinal dynamic instability (porpoising). This instability is a self- excitation phenomenon due to the different signs of the coupling restoring coefficients between heave and pitch motions. Porpoising happens more at high speeds. When the planing vessel is in instability region, the bow gets up and falls down in the water continuously with a constant or increasing amplitude and it can cause some damages if it is not prevented [4].

So far, a lot of research were done using empirical equations and also experimental methods in order to identify the trim range of porpoising phenomenon. Some equations were provided by the researchers in terms of speed and geometric characteristics of some planing vessels to specify the critical trim angle. Savitsky et al. [5] provided hydrodynamic characteristics of prismatic planing hull. They suggested some semi-empirical equations for motion of planing vessels. Also they determined the trim range of porpoising phenomenon based on the different deadrise angles. These equations still are used because of their high accuracy. Katayama and Ikeda [6–8] investigated the effect of hydrodynamic non-linear forces on the range of porpoising phenomenon. They compared the results of porpoising obtained by nonlinear and linear simulations with each other and also with experimental results. They concluded that the accuracy of linear method reduces at high speeds. Also,

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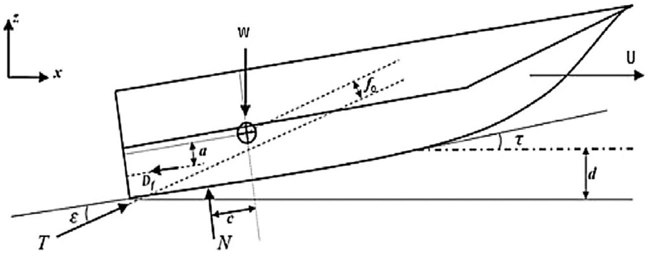

Fig. 1. The forces acting on the planing vessel [15].

they showed that this phenomenon is a self- excitation due to different signs of restoration coefficients in both heave and pitch couples at high speeds. Furthermore, Katayama [9] showed that planing vessels fluctuate (screws, heave and roll) when they turn at high speeds, which is known as transverse porpoising. Celano [10] determined a formula by analyzing five different planing hulls data for deducing the range of critical trim angle to stay away from porpoising phenomenon. Milton [11] used the added mass concept, empirical equations and Ruth-Hurwitz method to investigate the important factors in porpoising phenomenon. He concluded that the effect of surge on porpoising is small with analyzing the combination of screw, surge, and heave motions. Milton also investigated the effect of deadrise angle, velocity coefficient (Cv = 2–5), and gyration radius on porpoising phenomenon.

Recently some numerical methods are used to investigate the drag of planing vessels, but most of them are used with a fixed trim angle and fixed draft conditions for lowering the time consumed. But a fixed model is not a proper method for investigating the instabilities like porpoising, since porposing is an unsteady fluctuating phenomenon. Hailong et al. [12] calculated the forces acting on a catamaran planing vessel at speeds between 10–40 knots by solving the RANS equations. Yamin et al. [13] investigated the forces acting on a boat hull at speeds range of 8–10 m/s by solving the RANS equations in free to trim conditions. They assumed that the boat has two degrees of freedom (heave and pitch). Ghassabzadeh and Ghassemi [14] used FLUENT software to calculate the trim angle and the forces acting on a multi-hull tunnel vessel at speeds range of 0–20 m/s.

In this paper, the effects of some important design parameters (mass, center of mass, length, and deadrise angle) of a 4667 planing vessel on the drag force and the longitudinal dynamic stability (porpoising) are investigated using the ANSYS-FlUENT software and also with semi-empirical equations of Savitsky and the results are compared with each other in calm water.

2. Governing equations and the Savitsky semi-empirical method

In this research, both numerical simulation of RANS equations and the Savitsky method are used to analyze the motion of a 4667 planing vessel in calm water with two degrees of freedom (2DOF). Fig. 1 shows the forces that act on the vessel and should be balanced in order to have a trim condition.

In Fig. 1, f_0, a, and c are distances of trust line to center of gravity (COG), frictional drag line to chine, and planing hull normal hydrodynamic force position to COG respectively. The effects of f_0, a, and c are negligible, therefore, general force balance equations can be written in the form of Eqs. (1) and (2).

$$X : T\cos(\varepsilon+\tau) - D_f\cos(\tau) - N\sin(\tau) = 0 \tag{1}$$

$$Y : T\sin(\varepsilon+\tau) - D_f\sin(\tau) + N\cos(\tau) - W = 0 \tag{2}$$

where τ is the angle between the keel and horizontal axis (trim angle) and ε is the angle between the trust line and the trim angle. Also T, N, D_f, and W are trust, hydrodynamic normal force to the planing hull, drag force on the hull along the trim angle, and weight of the vessel respectively.

Table 1
The geometric characteristics of 4667 planing vessel.

Geometric characteristics	L0 (m)	Lcg (m)	B (m)	β	M (kg)	ε
Values	2.44	1.094	0.597	14.5	100.29	10

where L0, Lcg, B, β, M, ε are length, center of gravity from the transom, width, deadrise angle, mass, and trust line angle of planing vessel respectively.

Also, in order to solve the RANS equations, the continuity and momentum equations in incompressible flow are used as in Eqs. (3) and (4) respectively [16]:

$$\operatorname{div}\left(\vec{v}\right) = \nabla\cdot\vec{v} = 0.0 \tag{3}$$

$$\frac{\partial\vec{V}}{\partial t} + \left(\vec{V}.\vec{\nabla}\right)\vec{V} = \frac{1}{\rho}\vec{\nabla}.\sigma + \vec{g} \tag{4}$$

where σ is stress tensor and is equal to:

$$\sigma_{ij} = -p\delta_{ij} + 2(\mu+\mu_t)S_{ij} \tag{5}$$

where p, S, μ, V, ρ and δ_{ij} are static pressure, strain tensor rate, dynamic viscosity, fluid velocity, fluid density and Kronecker delta function respectively. Also, μ_t is turbulence viscosity which should be calculated with the SST-Kω model.

Note that the dynamic condition, i.e., continuity of pressure at the interface is automatically implemented. The kinematic condition, which states that the interface is convected with the fluid, can be expressed in terms of volume fraction φ as follows [17]:

$$\frac{D\varphi}{Dt} = \partial_t\varphi + \left(\vec{V}.\vec{\nabla}\right)\varphi = 0.0 \tag{6}$$

In the VOF method, the interface is described implicitly, and the data structure that represents the interface is the fraction φ of each cell that is filled with a reference phase, say phase 1. The scalar field φ is often referred to as the color function. The magnitude of φ in the cells cut by the free surface is between 0 and 1 ($0<\varphi<1$) and away from it is either zero or one.

μ and ρ at any cell (denoted by ij) can be computed using φ by taking a simple volume average over the cell:

$$\rho_{ij} = \varphi_{ij}\rho_L + \left(1-\varphi_{ij}\right)\rho_a \tag{7}$$

$$\mu_{ij} = \varphi_{ij}\mu_L + \left(1-\varphi_{ij}\right)\mu_a \tag{8}$$

The rigid body motion equations are specified as Eqs. (9) and (10).

$$m.\dot{w} = X_z \tag{9}$$

$$I_y.\dot{q} = N_y \tag{10}$$

where X_z, N_y are the force and moment in z and y respectively and I_i shows the moment of inertia. Also, $\dot{w}and\dot{q}$ are z direction acceleration and angular acceleration around y-axis respectively. The right hand sides of these equations are hydrodynamic forces and moments which can be obtained from the pressure distribution on the body and the shear stresses along the body surface by solving the RANS equations.

Furthermore, planing vessel attitude can be investigated by semi-empirical methods such as the Savitsky method using the force balance equations and the Savitsky formulations [5].

The Savitsky formula can be used in the range $Fn_L \geq 0.9$ [5]. Also, ITTC method can be used to calculate the friction force.

The possibility of entrance of the planing vessel into porpoising range will increase by increasing the speed. Porposing is a self-excitation phenomenon but after starting, it will be continued due