Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 50(4) (2018) 291-294
DOI: 10.22060/mej.2016.788

Investigation of Step Sweep-Forward Angle Effects on the Hydrodynamic Performance of a Planning hull

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ABSTRACT: One of the most effective methods to diminish the drag of the planning craft is using step at the bottom of the hull. Stepped hull causes to reduce the wet area and as a results reduce the drag. Shape of the step may be designed in a straight line through the entire width of the hull or it may be V-shape with a forward or backward sweep angle. In this paper, the effect of step sweep-forward angle on the hydrodynamic performance of a planning chine hull vessel is investigated by finite volume method. Reynolds-Averaged Navier-Stokes equations with standard k-ε turbulence model coupled with volume of fluid equations are solved in order to simulate transient turbulent surface flow around the hull with the help of Ansys CFX software. In order to predict the craft motions, equations of rigid body motions for two degrees of freedom are coupled with fluid flow governing equations. To validate presented numerical model, first the numerical results are compared with available experimental data and then obtained numerical results at different speeds and step angles are presented and discussed. The results show that the sweep-forward step angle up to 10 degrees have an insignificant effect on dynamic trim and sinkage, but its effect on the reduction of drag is significant.

Review History:

Received: 5 May 2016
Revised: 15 August 2016
Accepted: 23 October 2016
Available Online: 9 November 2016

Keywords:

Stepped planning craft
Step sweep-forward angle
Drag
Wake profile

1- Introduction

In recent decades, researchers have done many attempts to reduce drag and as a result to increase the speed of planning vessels through changing hull form. Among these methods, using the step at bottom of hull is known as one of the most effective ones. Steps may be designed in a straight line through the entire width of the hull (which this type of step is less common nowadays) or may be V-shape with a forward or backward swept angle (Fig. 1). The idea behind a stepped hull is to reduce wet surface by allowing the hull to plane on two or three small wet planning surfaces rather than large one.

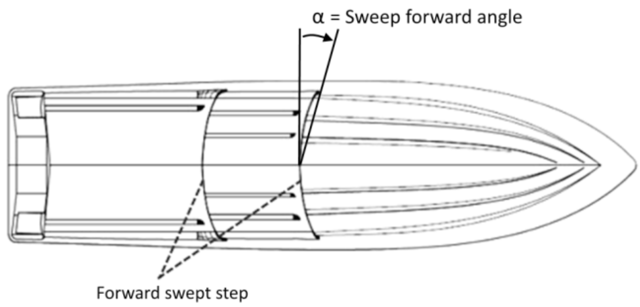

Fig. 1. A view of planning hull bottom with two forward swept steps

More recently, due to the market needs and in order to gain more efficiency by the stepped planning hull, much effort has been devoted to explore it numerically and experimentally. In 2010, Savitsky and Morabito [1] presented a mathematical model to define the stern wake profile of prismatic planning hulls by doing extensive model tests. In the same year, Taunton et al. [2] studied series of high speed hard chine planning hulls experimentally, with and without step. Garland and Maki [3], in 2012, investigated the performance of a stepped planning hull by numerical simulation of non-linear flow on a 2D body. In 2014, Veysi et al. [4] simulated a hard chine planning hull, in two cases of with and without step, by numerical method in calm water, and studied the effects of step on hydrodynamic performance of planning hull.

In this paper, the effects of step sweep forward angle on hydrodynamic performance of a hard chine planning hull are investigated by numerical Finite Volume Method (FVM). For this purpose, transient turbulent free surface flow around the hull is simulated by using Reynolds-Averaged Navier-Stokes (RANS) equations with standard k-ε turbulence model coupled with Volume Of Fluid (VOF) equations with the help of Ansys CFX software. First, the numerical results obtained for zero step angle are compared with experimental data. Then, the calculated numerical results are presented for four different Step sweep forward angles, and the effects of this angle on hydrodynamic performance are discussed.

2- Methodology

2- 1- Governing equations

The RANS equations, after relating Reynolds stresses to velocity gradients, are obtained as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_j\right)=0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{x_j}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+g_i \tag{2}$$

where, u, p and g are velocity, pressure and gravity. μ_{eff} is effective viscosity and is defined as:

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$$\mu_{eff} = \mu + \mu_t \tag{3}$$

$$\mu_t = c_\mu \rho \frac{k^2}{\varepsilon} \tag{4}$$

where k is turbulence kinetic energy and ε is turbulence dissipation rate, which are calculated from the following transport equations:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j k\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + p_k - \rho\varepsilon \tag{5}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j \varepsilon\right) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1} p_k - C_{\varepsilon 2}\rho\varepsilon) \tag{6}$$

Here, the VOF model is used to calculate the free surface shape.
In addition, the equations of motion in two degrees of freedom (heave and pitch) are solve to calculate hull motions in time.

2- 2- Solution domain and boundary conditions

The present study is carried out on a hard chine stepped planning vessel model, named C1, which have been tested at the University of Southampton [2].
Solution domain with applied boundary conditions are shown in Fig. 2.

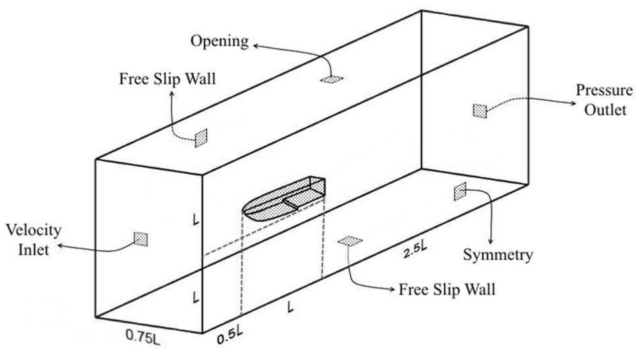


Fig. 2. Solution domain and boundary conditions

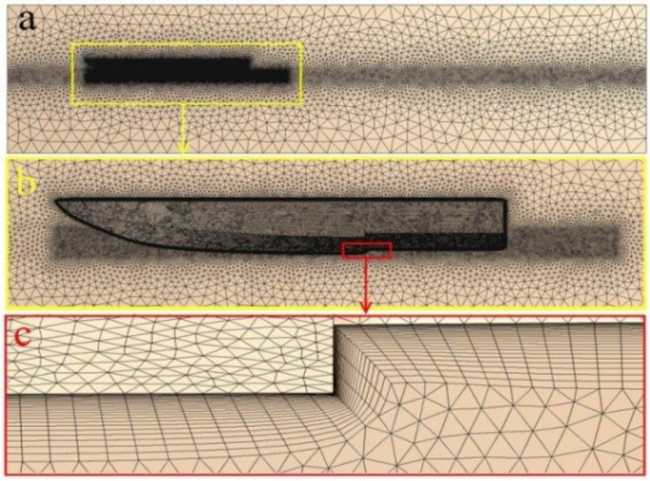


Fig. 3. Computational grid around the hull a) full domain, b) near field domain, c) step region

2- 3- Domain discretization

An unstructured mesh including tetrahedral cells is used to discrete the domain. The number of inflation layers inside the boundary layer is about 20 with y^+=50. The computational grid is illustrated in Fig. 3.

2- 4- Validation of numerical model

In this section, the numerical results obtained for zero-degree angle of step are presented and validated against experimental results [14]. The experimental and numerical values are given in Table 1 including the computational errors. The average errors for wet keel length (L_k), wetted chine length (L_c), dynamic sinkage (Z_v), dynamic trim (Θ_v), and drag force are 10.7%, 6.3%, 12.1%, 29.5%, 9.5%, respectively.

3- Results

The changes in drag force due to sweep-forward step angle variations for Froude numbers of 1.89 and 3.34 are shown in Fig. 4. It is obvious that the drag reduces with step angle at Froude number of 1.89. The minimum drag occurs at step angle of 10 degrees (a reduction of 3.5% relative to zero-angle step). Also, For Froude number of 3.34, the minimum drag occurs at step angle of 6 degrees (a reduction of 9.5% relative to zero-angle step).

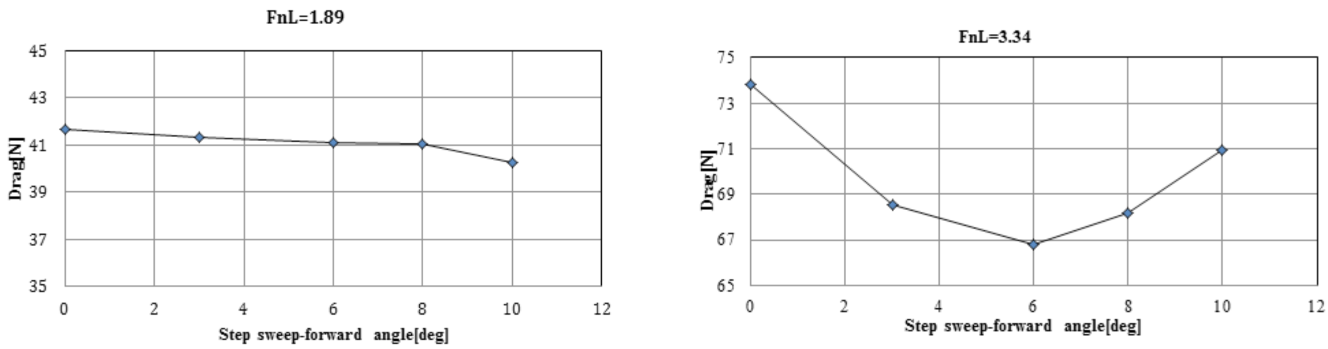
4- Conclusions

The effects of step forward swept angle on hydrodynamic performance of a hard chine planning hull was numerically studied. The following conclusions can be given:

- Based on good agreement achieved between numerical and experimental results, it is concluded that the numerical model presented in this study can be used as an

Table 1. Comparison between numerical and experimental results at different Froude numbers

	FnL =1.14			*FnL* =1.89			*FnL* =2.61			*FnL* =3.34		
	Exp.	CFD	Error%	Exp.	CFD	Error%	Exp.	CFD	Error%	Exp.	CFD	Error%
L_k (m)	1.5	1.45	3.33	1.4	1.31	6.42	1.31	1.1	16.03	1.27	1.05	17.32
L_c (m)	1.1	1.23	11.81	0.82	0.75	8.5	0.68	0.67	1.47	0.6	0.58	3.33
Z_v (m)	0.02	0.023	15	0.04	0.047	7.5	0.05	0.056	12	0.05	0.043	13
Θ_v [deg]	2.34	1.65	29.27	2.6	3.14	20.76	2.22	3.31	49.09	1.93	2.31	19
Drag (N)	35.6	31.2	12.35	44.36	41.19	7.14	51.25	48.19	5.75	65.97	73.82	12.62



(a) (b)

Fig. 4. Variations of drag force with step angle at Froude number of 1.89 and 3.34

accurate model to predict the hydrodynamic performance of hard chine stepped planning hulls.

- The sweep-forward step angle up to 10 degrees have an insignificant effect on dynamic trim and sinkage.
- The effects of step forward swept angle on drag is relatively significant, and the angle of step corresponding to minimum drag is dependent on Froude number value.

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Please cite this article using:

H.Nourghasemi, H. Ghassemi, M. Bakhtiari, M. Sayehbani, Investigation of Step Sweep-Forward Angle Effects on the Hydrodynamic Performance of a Planning hull, *Amirkabir J. Mech. Eng.*, 50(4) (2018) 903-912.

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