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Stern Flap Application on Planing Hulls to Improve Resistance

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ABSTRACT

Drag is one of the main factors in improving fuel efficiency. Various study in regards to improve drag performance of a planing hull amongst them is a stern flap. The main parameters to design a stern flap are span length and angle of stern flap. The stern flap works by changing pressure distribution over the ship's bottom and creating a lift force on the stern transom part. This study aims to analyze the behavior of stern flap in variations of span length and angle of stern flap towards drag performance of Fridsma hull form. Finite Volume Method (FVM) and Reynolds-Averaged Navier - Stokes (RANS) are used to predict the hull resistance during simulations. Results show that shear drag is very sensitive towards the total drag value, proving that shear drag valued at least 60% of the total drag in each planing hull multi-phase characteristics phase. Stern flap with 58% of hull breadth span length installed at 0° is considered the most optimal, reducing 10.2% of total drag, followed by 18% displacement reduction. In conclusion, the stern flap effectively improves the Fridsma hull's total drag and its components on 0.89 < Fr < 1.89.

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NOMENCLATURE

y+	Boundary layer thickness	d_i	Vertex's displacement
L	Ship's length	n	Number of vertices
Re	Reynold's number	$subjc_j^2$	Basis constant
C_f	Friction coefficient	r_{ij}	Magnitude between two vertices
Δt	Time steps	λ_j	Expansion coefficient
U	Ship speed	α	Constant value
Fr	Froude number	Δ	Displacement
LCG	Longitudinal center of gravity	*B*	Breadth of the ship
VCG	Vertical center of gravity	T_{AP}	Draft of the ship
I_{yy}	Momen inertia at y axis	τ_o	Trim angle
I_{zz}	Momen inertia at z axis		

1. INTRODUCTION

Planing hull has very complex characteristics, especially during high-speed performance. Due to cost-related issues, the need to improve resistance performances of a planing hull emerges. Planing hulls have also been one of the most challenging problems for the naval architecture community as large hull motions complicate hydrodynamic calculations and hull optimization [1].

There has been a great deal of research towards saving devices to increase ship performance. Examples include microbubble injection method, stern wedges, tunnel stern, stern flap, and stepped hull. Yaakob [2]

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studied stern flap effect on a planing hull, resulting in 7.2% reductions in total drag.

Planing hulls are considered suitable to apply stern flap. That corresponds to the pressure drag value on the hull's bottom at a tangential angle between hulls and the water surface [3]. A boat or ship can be categorized as planing hull if its Froude Number values at (Fr) ≥ 1 – 1.2 [4]. Experimental research was conducted by Fridsma [5] using simple geometry to predict planing hull type. This research was then broadly used by researchers worldwide to perform numerical computational verifications. Studies on the mesh density of the Fridsma hull have been reported to ensure accurate results [6]. Recent research on Fridsma hull is concerned with hull modification. Spray strip application can reduce the deflection of the spray wash to reduce the wet surface on the hull. Recent research on Fridsma hull related to spray strip modification has been reported to reduce the deflection effect of spray wash. Using the CFD approach, spray strips on Fridsma hull can reduce the total drag [7].

In 2014, Ghadimi et al. [8] stated that a stern flap could reduce Effective Horsepower (EHP) values of a propulsion machine of a planing hull. Ghassemi et al. [9] used Savitsky equations to determine the stern flap usage efficient dimension. The optimal angle of stern flap depends on the size of the hull itself.

Technology development in numerical analysis has been one factor that encourages researchers to conduct numerical analysis-based studies. Numerical analysis of planing hull ships is considered less accurate than displacement hulls [10]. There are methods used in numerical analysis, such as Finite Volume Method (FVM), Finite Element Method (FEM), Finite Difference Method (FDM), and analytic-experiment [11]. Based on the literature mentioned above, the Finite Volume Method (FVM) is the most used method to solve fluid dynamics problems. Turbulence modeling is served in k-ε and Volume of Fluid (VOF) to represent the water and air phases. The RANSE method is used to calculate the turbulent free-surface flow around the stepped planing hull [12].

The present study aims to understand the effect of span length and angle of stern flap on total drag and its components in a planing hull, especially Fridsma hull form. Drag components such as trim, heave, and displacement provide good insight into stern flap effect on a planing hull. The results of our suggestion on ship drag components will increase the shear drag component. Stern flap application will reduce shear drag experienced by the hull.

The component studied is the ship's response to stern flap installation. Resistance components, shear resistance, and pressure resistance are shown in this study. Installation of stern flap causes resistance reduction, followed by heave, trim, and displacement.

This paper summarizes the effect of stern flap technology on ship resistance. The installation of a stern flap can change the flow of water underneath the transom area; therefore, resistance is reduced, and speed is increased. The principles behind the stern flap are the lift force and the pressure distribution change under the transom area. In addition, the stern flap tends to change the flow underneath the hull to be laminar flow. One of the approaches in stern flap study is CFD-based numerical simulation. This method is based on RANS principles to display turbulent flows. CFD approach is carried out by implementing finite volume method and calculated with morphing mesh method. Validation will then be based on Fridsma experimental study. This study aims to fill the gap of previous research in stern flap modeling in calm water conditions. By simulating stern flap installed planing hull with different span lengths and angle of stern flap. This study provides a better understanding of the changes in ship performances caused by stern flap.

This study explains the effect of the stern flap on ship dynamics, including heave and trim. The effect of span length and angle on the ship's performance will then be obtained. It is expected that the result of this study can help naval architects design planing hulls with lower resistance and higher fuel efficiency. These steps are carried out to achieve the global target of reducing fossil fuel emission rates.

2. MATERIALS AND METHOD

2.1. Fridsma Hull Form This research uses experimental data of Fridsma hull form as a benchmark and stern flap application. Experimental hull data used in the study is shown in Table 1 and Figure 1.

TABLE 1. Fridsma hull form main dimension [5]

Parameter	Unit	Value
L/B	-	5
L	m	1.143
B	m	0.229
T_{AP}	m	0.081
LCG from AP	m	0.457
VCG from keel	m	0.067
τ_o	Degree	1.569
Β	Degree	20
Δ	Kg	10.890
$I_{yy} = I_{zz}$	$Kg.m^2$	0.235

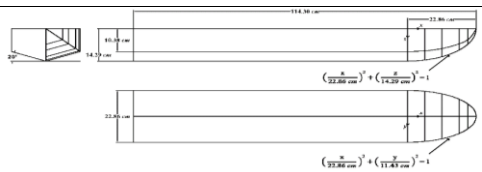


Figure 1. Fridsma hull form

2.2. Stern Flap

The present study will analyze the effect of span length and angle of stern flap on ship resistance. The visualization of stern flap configurations is shown in Figure 2.

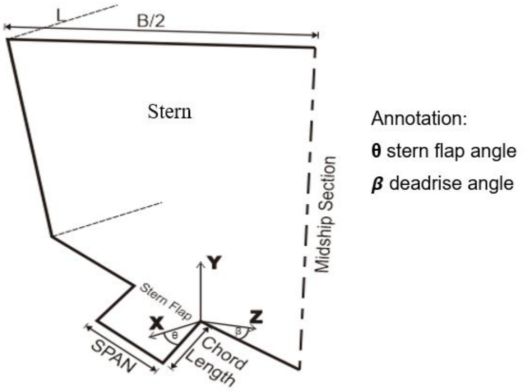


Figure 2. Stern flap parameter

Span length will be based on ship breadth (B), as shown in Figure 3. Stern flap are installed at three different angles; they are 0°, 5°, dan 7°.

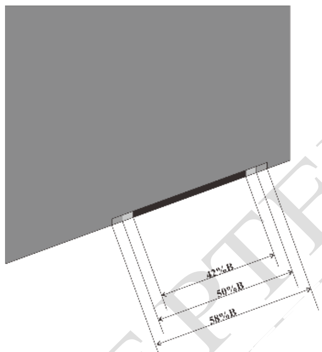


Figure 3. Configuration of stern flap

2.3. Numerical Modelling

This study represents fluid simulation using the star CCM code. The solver is based on FVM to discretize the Navier-Stokes equation and SIMPLE algorithm to couple the pressure and velocity equations. A SIMPLE type algorithm (Semi Implicit Method for Pressure Linked Equations) is also called a predictor-corrector approach, the non-linear governing equations are solved a poisson equation for pressure [13].

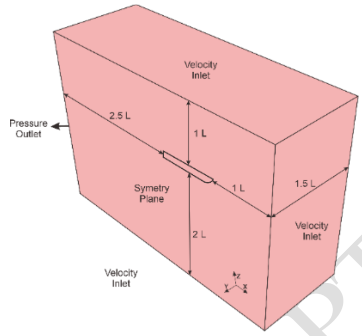


Figure 4. Fluid domain and boundary conditions

The Dynamic Fluid Body Interaction (DFBI) module is employed to solve the vessel's dynamic motion, which allows the solver to analyze hull movements under the influence of fluid forces and moments. There are two degrees of freedom in the heave and pitch directions. Visualization of the fluid domain and boundary conditions used during this study are shown in Figure 4. The setup is referred to the ITTC recommendation [14] and detailed information on the numerics used.

The quality of the mesh does affect the quality of the numerical results. In the mesh with sufficient fineness, it shows a better level of accuracy compared to the coarse mesh quality. Grid skewing and grid stretching important contributing factors to the loss in nominal accuracy of the solution. Local refinement is applied to a mapped mesh using feature edges, boundary regions, or volume shapes to maximize the accuracy.

This research explores the mesh density variations. This is carried out to give more details about the sensitive areas of physics characteristic definition around the hull. Mesh density will affect computation time; therefore, mesh density study is carried out with an expectation to increase the calculation's accuracy. Morphing mesh is used as the meshing method. Morphing meshworks based on interpolation between two shapes, morphing will need two model shapes consisting of the source shape and target shape, transformations can occur directly from the source shape towards the target shape. In this case, the whole ship hull can be transformed parametrically using the main dimension. Morphing mesh is convenient for relatively complex motions, while larger deformation requires new cells to be formed to maintain high-quality mesh. The morphing mesh method needs special treatment from the moving nodes to control the accuracy of derivative space and time-stepping scheme.

Morphing mesh and chimera grid (overset) are considered the most efficient meshing method in the numerical analysis of a planing hull [15]. Morphing mesh is more suitable to implement because it is more efficient in computation resources. The morphing grid method requires special treatment for moving cells to control the accuracy of the time-step scheme conducted during simulations. The locality of the B-spline coefficients and the parallelization scheme make this method more scalable for parallel computing, thereby potentially reducing computational costs [13]. Simulation using morphing grid mesh is carried out by interpolating specific fluid flow variables. Such interpolations are used to move cells from meshes using the Radial Basis Functions (RBF) method [16], a more detailed discussion of RBF can be seen in literature [17,18]. To be able to produce an interpolation field, it is necessary to solve system equations using control vertices and specific mesh displacements; for every i vertex, with d displacement, the equation is stated as :

$$d_i = \sum_{j=1}^{n} \lambda_j \sqrt{r_{ij}^2 + c_j^2 + \alpha} \qquad (1)$$

Computational domain and boundary conditions are defined based on ITTC Recommendations [14], as explained in Figure 4.

The present work investigates the use of the wall y+ as a guide in determining the right grid arrangement and corresponding turbulence models. Figure 5 shows the value of y+ between 60-70. Y+ wall functions are used to increase the accuracy of the simulations. Based on paractical guide line, the desired range of y+ value recommended between 45 - 60. Y+ value calculations based on ITTC are stated in equation (2) :

$$\frac{y}{L} = \frac{y^+}{R_e\sqrt{\frac{C_f}{2}}} \qquad (2)$$

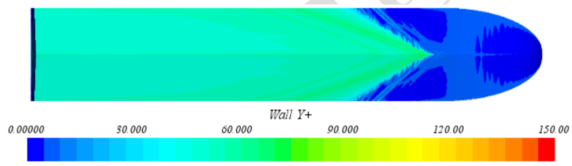


Figure 5. Y+ value at the bottom

Time-step is the time interval between iteration calculations in numerical simulations. The lower the time step, the more iteration calculations and the more time used in a simulation. Time-step used in the present study is 0,005 seconds. This study referred to the ITTC as an international standard that provides recommendations for predicting drag resistance using numerical and experimental methods [14] and referred to the user manual [13], shown in equation (3) :

$$\Delta t\ \text{ITTC} = 0.005 \sim 0.01\frac{L}{U} \qquad (3)$$

3. RESULTS AND DISCUSSION

3.1 Validation and Benchmark

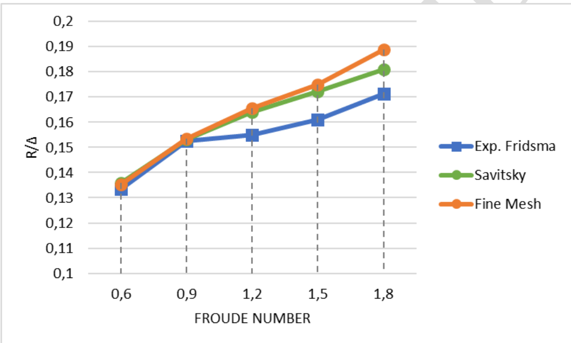
Previous research has studied mesh independency by using the same ship model [6]. Within those research, mesh independency characteristics are studied using five grid variations consisting of 0.48 M, 0.89 M, 1.44 M, 2.33 M, and 2.99 M, as shown in Figure 6. Froude Number 1.79 is simulated on each grid size. In that study, a high accuracy value of convergence was obtained on 2.33 M and 2.99 M grid sizes. However, the 2.99 M grid takes a relatively long time to finish each iteration calculation. Therefore, grid 2.33 M was chosen because the time is relatively shorter and shows good convergence values. The ideal mesh for numerical simulation of the stable planing problem is determined through a mesh analysis. The independency of the mesh resolution was verified using five grid meshes with cell numbers of 0.48 M, 0.89 M, 1.44 M, 2.33 M, and 2.99 M, respectively. Studies have been carried out on this topic to demonstrate the level of accuracy on high-speed vessel. A Froude value of 1.79 was used for mesh analysis. According to numerical simulation findings, the number of cells 2.3 M and 2.99 M have reliable outcomes. As a result, for the remainder of the CFD simulations, grid mesh 2.3 M was used.

Figure 6. Grid size

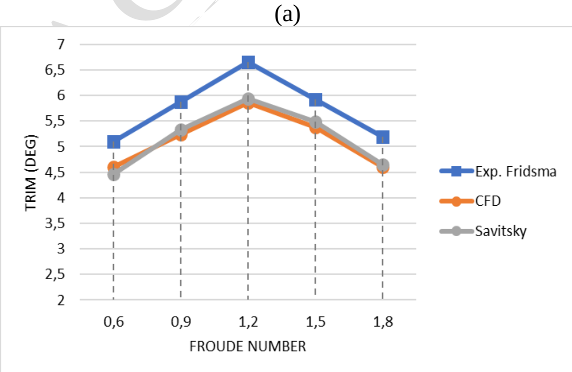
To validate the results of numerical simulations, Fridsma's experimental data with L/B = 5, LCG = 0.6L from AP is used. Simulations are conducted with 800 K-900 K meshes, mainly concentrated on the water surface and hull region to obtain more accurate results. Simulations are carried out with STAR CCM+ in deep and calm water conditions. Simulations will grant Y and Z axis motions freedom to obtain trim and sinkage results.

The numerical simulations of bare hull show a discrepancy between the obtained numerical and Fridsma's experimental data. This also occurred during studies conducted by Wheeler et al. [19]. What caused the discrepancy between experimental and computational studies is the difference between each hull's center of gravity.

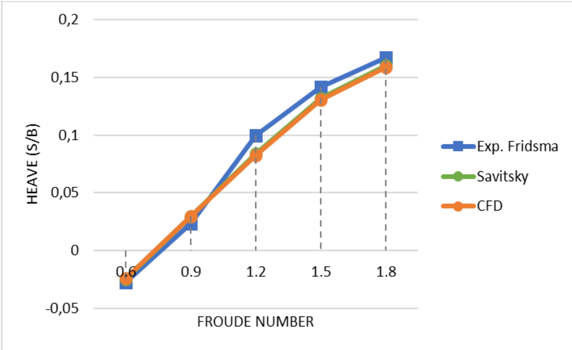
In this study, different Centre of Gravity (CG) positions might occur between experimental study and numerical simulations using CFD. This will cause a discrepancy between both results. However, the result shows a similar pattern between experimental data and the data obtained from numerical simulations, and the discrepancy is not that significant. Therefore, it is still considered acceptable. Our statements follow several studies carried out by Mousaviraad et al. [20]. It is stated that the change in location of CG causes a significant influence on resistance and trim values. They also changed the CG position to obtain better and more accurate results. A study carried out by Sukas et al. [1] also showed the CG position between the experimental and numerical simulation. In this study, the CG position is similar to experimental data, even though it shows a different CG position from experimental data when the ship is not moving.



(a)



(b)



(c)

Figure 7. Validation results for resistance, heave, and trim

Other than the difference between the presented model centre of gravity, Numerical Ventilation Problem (NVP) can cause such discrepancy, especially during high speed (Fr>1.0). A study regarding Numerical Ventilation Problem on Fridsma hull form with overset grid method carried out by Samuel [21] shows that during Fr 1.2 – 1.8, there is a significant inaccuracy of obtained numerical analysis results caused by Numerical Ventilation Problem.

The average discrepancy between experimental data and numerical analysis drag, dynamic trim, and heave was less than 9%, 4%, 10.5%, as explained in Figure 7; similar validation results between numerical and experimental methods. Studies also occurred in a study carried out by Nourghassemi [22]. He stated that such discrepancy is acceptable and that the presented model can predict the hydrodynamic performance of planing craft. Bakhtiari et al. [12] also obtained 10% average result errors and stated that such result shows good agreement with experimental results.

3.2 Results

Obtained numerical analysis on total drag for every Froude Number with shear drag and pressure drag as its components are shown in Figures 8,9, and 10.

The simulation results show a reduction in total drag and components from every flap model compared to bare hull in every Froude Number. One of the main factors in the total drag of a planing hull is hydrodynamic forces. During the high-speed phase, hydrodynamic forces that work during high-speed increase. Because of the increasing hydrodynamic forces, the ship's displacement also changes. Hydrodynamic forces also significantly affect the total resistance of a high-speed vessel. This is different from the ship's characteristics during the low-speed phase. During the low-speed phase, hydrostatic forces are more dominant than hydrodynamic forces; therefore, the change in displacement value is not significant.

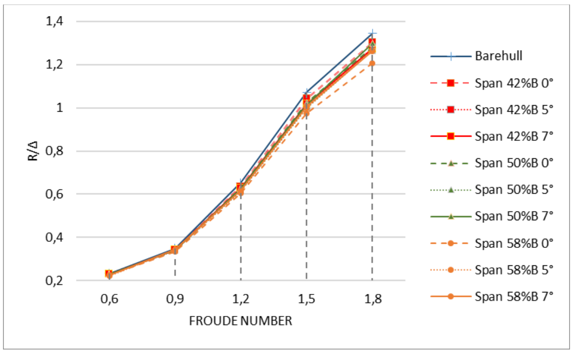


Figure 8. Total drag comparison

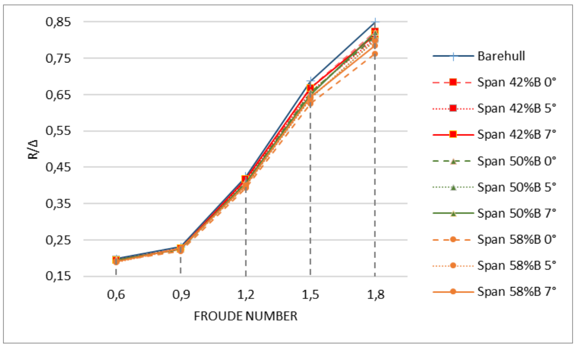


Figure 9. Shear drag comparison

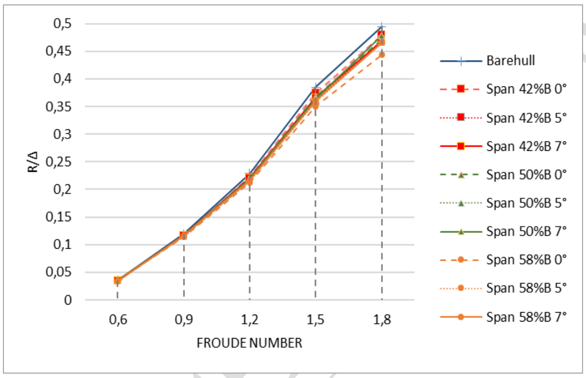


Figure 10. Pressure drag comparison

Figure 11 shows compositions of total drag in every phase of Fridsma hull form. Fr 0.6 represents the hull's displacement mode, Fr 0.9 represents the hump region or transitional phase between displacement and planing hull, and Fr 1.8 represents the full planing phase. Stern flap with 58%B span installed at 0° towards water surface shows 4.9% reduction in hump resistance. The result obtained from the simulation is similar to a study carried out by Zou et al. [23] on stern flap influence on double-stepped planing hull shows that stern flap played a positive role towards resistance reduction Fr < 3.94, reducing 4.9% on hump resistance.

There is a difference in R/Δ between validation and results of this study. Different R/Δ is because the benchmark uses constant displacement valued at 10,68 kg, while the present study calculates each displacement's differences in every Froude Number. Data regarding displacement changes in every model is shown in Figure 12. The drag results of each stern flap model are reduced by reducing displacement, one of the main components of drag calculations, especially in planing conditions. Changes in displacement values are caused by the hull's trim and heave value. Obtained trim angle predictions are shown in Figure 13. The obtained trim prediction shows that stern flap can significantly reduce trim experienced by Fridsma hull form. Besides trim, heave is also one of the main factors in calculating ship displacement. Figure 14 shows the heave predictions of each model.

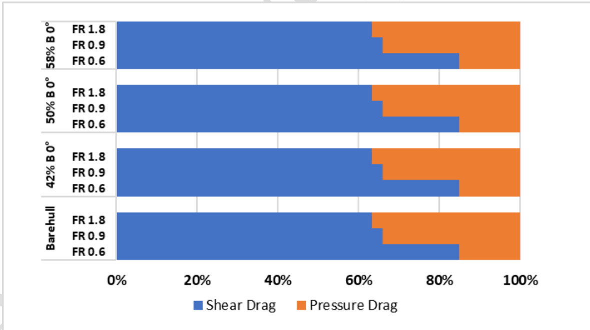


Figure 11. Total drag components

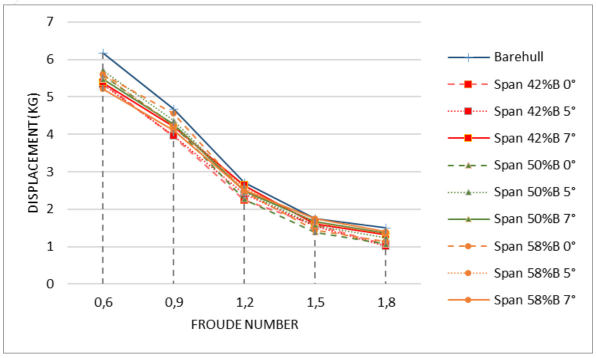


Figure 12. Displacement comparison

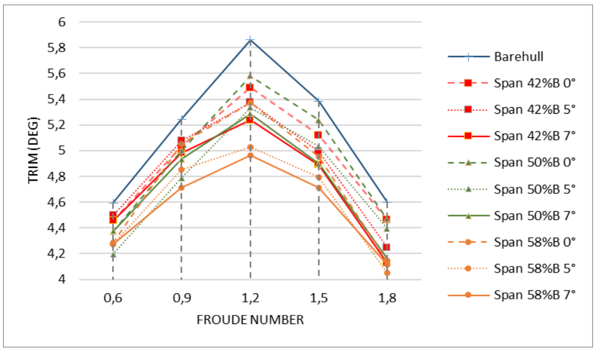


Figure 13. Trim angle comparison

Heave predictions also show significant heave reductions in each model compared to bare hull on Fr >

1. The study conducted by Zou et al. [23] showed similar results regarding trim angle and heave or sinkage reduction. The

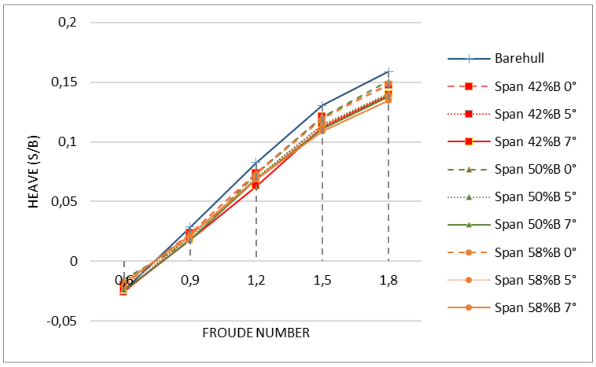


Figure 14. Heave comparison

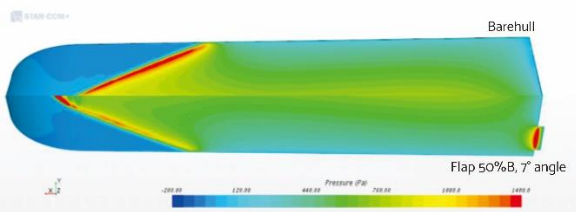


Figure 15. A Pressure Distribution Comparison Between Bare hull and Model with 50%B 7°

stern flap positively affects trim angle and sinkage in every observed Froude Number [23].

The stern flap will change the pressure distribution on hull's bottom. As observed in Figure 15, the part where stern flap is installed to the hull showed a high-pressure area, raising the stern and reducing the trim, and heave, which in return the total drag is reduced.

4. CONCLUSION

Simulation results show that stern flap application positively influences total drag on Fr 0.89 – 1.78 of Fridsma hull form. On top of that, obtained results showed that stern flap can improve the drag components experienced by Fridsma hull form, such as pressure drag and shear drag. Improvement in total drag and its components is followed by reducing displacement, with trim angle and heave value as its components. Flap with 58% of Hull Breadth as its span length shows the most optimal results compared to other flap models, reducing 10.2% of total drag and 18% displacement compared to bare hull.

5. ACKNOWLEDGEMENT

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Persian Abstract

چکیده

درگ یکی از عوامل اصلی در بهبود بهره وری سوخت است. مطالعات مختلف در رابطه با بهبود عملکرد درگ بدنه هواپیما در میان آنها یک فلپ استرن است. پارامترهای اصلی برای طراحی فلپ استرن طول دهانه و زاویه فلپ استرن می باشد. فلپ عقب با تغییر توزیع فشار در کف کشتی و ایجاد نیروی بالابر در قسمت گذرگاه عقب کار می کند. این مطالعه با هدف تجزیه و تحلیل رفتار فلپ استرن در تغییرات طول دهانه و زاویه فلپ استرن نسبت به عملکرد درگ فرم بدنه فریدما انجام شده است. روش حجم محدود (FVM) و رینولدز میانگین ناویر - استوکس (RANS) برای پیش‌بینی مقاومت بدنه در طول شبیه‌سازی استفاده می‌شود. نتایج نشان می‌دهد که کشش برشی نسبت به مقدار کشش کل بسیار حساس است، و ثابت می‌کند که پسا برشی حداقل ۶۰ درصد از کشش کل را در هر فاز ویژگی‌های چند فازی بدنه برنامه‌ریزی ارزش دارد. فلپ استرن با ۵۸٪ طول دهانه عرض بدنه نصب شده در ۰ درجه بهینه ترین در نظر گرفته می شود و ۱۰.۲٪ از کشش کل را کاهش می دهد و به دنبال آن ۱۸٪ کاهش جابجایی را به دنبال دارد. در نتیجه، فلپ عقب به طور موثر کشش کل بدنه Fridsma و اجزای آن را در ۱.۸۹> Fr > ۰.۸۹بهبود می بخشد.