Seakeeping and resistance analysis of 1200 GT passenger ship fitted with NACA 4412 stern foil using CFD method

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Abstract. Seakeeping performance is one of the requirements to ensure the convenience and safety of life at sea, especially for passenger ships. In this paper, the result of computational fluid dynamics (CFD) analyses concerning the effect of NACA 4412 stern foil to the improvement of seakeeping quality and resistance of 1200 GT passenger ship are presented. The fitting of stern foil has become a popular method for the improvement of ship design. Stern foil is hydrofoil attached to the transom of the vessel located at the stern part below the waterline. The analysis was developed on the conditions of regular and irregular head waves. The CFD computation on 8 variations of the stern foil position and attack angle has been carried out by using Numeca Fine/Marine. The study confirms that the ship resistance decrease by 3.6 % at the service speed of the ship. The improvement of heaving and pitching amplitudes, as well as heaving acceleration, are significant for the hull vane located at 50% of displacement draft and 1% of displacement length with the attack angle of -4°.

1. Introduction
Ship motion response to regular and irregular waves can be determined from motion analysis, namely maneuvering and seakeeping analysis. The maneuvering usually only considers the 3 degrees of freedom of ship motions in the horizontal plane area including surging, swaying and yawing. Seakeeping analysis concern about the 3 other motions including heaving, pitching and rolling. External excitation such as current, wind, and wave cause additional resistance and the 6 degrees of freedom of ship motion, as seen in Fig.1. The excessive amplitude and acceleration of the motion will cause motion sickness symptoms. The naval architect should consider the ability of the ship to be operated on various sea conditions by complying the requirement of seakeeping criteria. This paper provides the improvement seakeeping performance of 1200 GT passenger ship equipped with NACA 4412 stern foil.

The development of maritime technologies and its support, especially in ship designs has been achieved by the invention of Hull Vane®. It has been invented by Van Oossanen [1]. It is aimed to reduce ship motion and increase performance. Hull vane is a fixed hydrofoil located below the waterline that attached to the transom or stern of the vessel. The research shows there are 4 interrelated effects can be found on the hull vane, a thrust force, a trim correction, the reduction of waves, and the reduction of motions in waves. Based on basic the foil theory, a foil will generate decomposed force vectors, chordwise force and neutral force [2]. Those force will influence on ship motion.
Hull Vane® is one of the appendages fitted on the stern which has the potential to increase the ship’s resistance. Accordingly, its proper position and attack angle is necessary to be found out in order to ensure that the resistance of ship fitted with hull vane will improve the ship propulsion efficiency. The other study shows that hull vane can lead to a significant reduction in ship resistance [3].

2. Literature Review
Seakeeping performance of the vessel is dependent on heading angle of wave, the wave amplitude, and wave spectrum. The ship motions will cause the level of motion sickness incidence and the ship operability. The definition of seakeeping, response amplitude operator, wave spectrum, motion sickness incidence and operability of ship is described as below.

2.1. Seakeeping
The motions of ship considered in seakeeping analysis is divided into 3 motions. i.e. heaving, pitching, and rolling. The pitching response is more significant than the rolling response by considering that the longitudinal distance of the stern foil to the center line of the motion, the moment lever is significantly longer than that of the pitching motion. Figure 1 represents that heaving is the motions of a ship parallel to the vertical direction, Z axis. The heaving is the oscillation motion leading to vertically ship motion, up and down movement. Pitching is the oscillation motions of the ship rotating according to the lateral direction, the Y-axis. The pitching motion represented by the change of ship’s trim to the bow and stern. The pattern of the motions depends on the inertial load of the ship and hydrostatic load of the wave. The seakeeping criteria are presented in Table 1.

![Six Degrees of Ship Motions](image)

**Figure 1.** Six Degrees of Ship Motions.

**Table 1.** Seakeeping Criteria.

| No. | General Criteria |
|-----|------------------|
| 1.  | RMS Pitch ≤ 1.5° [8] |
| 2.  | RMS Heave Acceleration ≤ 0.1g (normal work for the crew) [9] |
| 3.  | 3° single amplitude average pitch [10] |
| 4.  | Significant heave acceleration ≤0.4g (no people working on deck) [10] |
| 5.  | Significant heave acceleration ≤0.2g (people working on deck) [10] |
2.2. **Respon Amplitude Operator (RAO)**

The motion of a floating vessel due to a passing hydrodynamic regular wave is called the RAO (Response Amplitude Operator), where RAO is the ratio between ship's amplitude of motions (either translation or rotation) to the amplitude of the wave at a particular frequency. RAO or often referred to as the Transfer Function because it is an instrument to transfer the external load (wave) in response to a structure. The general form of the RAO equation in the frequency function is as follows [4]:

\[
\text{Response} (\omega) = (\text{RAO})\eta(\omega)
\]  

where, \( \eta = \) wave amplitude, m, ft

The RAO for translational motion is a direct comparison between the amplitude of the ship's motions and the wave amplitude both in length units as shown by (2).

\[
\text{RAO} = \frac{z(t)}{\zeta_0} \text{ (m/m)}
\]  

RAO for rotational motion is the ratio between the amplitude of the rotational motion, in radians, to the wave inclination which is the multiplication of the wave number, \( kw = \omega^2 / g \) with wave amplitude as shown by (3).

\[
\text{RAO} = \frac{\theta_\phi}{kw\zeta_0} = \frac{\theta_\phi}{\left(\frac{g^2}{\omega^2}\right)\zeta_0} \text{ (rad/rad)}
\]  

Unfortunately, RAO can’t describe the ship’s response to the real state of the ocean because the waves are irregular. Response of ship motions to random wave can be described with response spectrum. The response spectrum is obtained by multiplying the wave spectrum, \( S_\zeta \) with RAO2 as seen in (4).

\[
S_\zeta(\omega) = \text{RAO}^2 \times S_\zeta(\omega)
\]  

2.3. **Wave Spectrum**

The JONSWAP wave spectrum [3] is used in this analysis. This spectrum is a refinement of the Pierson-Moscowits spectrum. The North Sea has extreme environmental conditions and is bordered by islands and continents which result in fetch in this area quite short but has large waves. So the Pierson-Moscowits equation is changed in the form of equation (5)

\[
S(\omega) = \alpha g^2 \omega^{-5} \exp \left[ -1.25 \left( \frac{\omega}{\omega_0} \right)^{-4} \right] \exp \left[ \frac{[\omega - \kappa_0]}{\sqrt{\alpha_0^2 - \omega^2}} \right]
\]  

where,

- \( \gamma \) is peakedness parameter = 3.3
- \( \tau \) is shape parameter = 0.07, if \( \omega \leq \omega_z \) = 0.09, if \( \omega > \omega_z \)
- \( \alpha \) = 0.076 \((x_0)^{0.22}\)
- \( \omega_0 \) = 0.00819 \text{ (when x is unknown)}
- \( x_0 \) = \( 2 \pi \left( \frac{g}{U\omega_0} \right) (x_0)^{-0.33} \)
- \( \omega_0^2 \) = \( gx/U\omega_0^3 \)
- \( \omega_0 \) = 0.161g/HS

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3. Methodology

The CFD analysis is handled by using Numeca Fine/Marine software. The related variables of wave height and period for the motion computation are derived from the data on the same condition of Java Sea shipping route. The results are ship response amplitude of heaving and pitching as well as the heaving acceleration and ship’s resistance. Seakeeping analysis is performed in this study by comparing the motion of the ship with hull vane and without the hull vane in regular waves. In addition, the seakeeping analysis of the ship equipped with the stern foil in irregular waves is developed to predict the probability of the ship motion not complying with the seakeeping criteria. The main dimension of 1200 GT passenger ship analyzed in this study is shown in Table 2 as below. The ship’s model is developed in Maxsurf Modeler. It has been verified by using key plan data and stability booklet. The precision of the model is 99.02% of displacement, 99.56% of the coefficient block, and 99.69% of the longitudinal center of buoyancy.

| No. | Dimensions                          | Passenger Ship |
|-----|-------------------------------------|----------------|
| 1   | Length overall (LOA), meters        | 62.8           |
| 2   | Length between perpendiculars (Lpp), meters | 57.36         |
| 3   | Breadth (B), meters                 | 12             |
| 4   | Height (H), meters                  | 4              |
| 5   | Draught (T), meters                 | 2.7            |
| 6   | Service speed (Vs), knots           | 12             |
| 7   | Displacement (Δ), tons              | 1318           |
| 8   | Gross Tonnage (GT), tons            | 1200           |

The stern foil models are designed referring to an embodiment of aft foil patented by Van Oossanen [1]. There are 8 models of the foil differing by foil’s reference point position and angle, horizontal position (x-axis), and vertical position (y-axis). The leading edge of foil is used as a reference point. The horizontal position is measured from the stern waterline intersection to the leading edge. The vertical position is measured from keel to the leading edge. The variation is presented in Table 3 as seen in Figure 2 and Figure 3.

| No. | Models | X-axis (m) | Y-axis (m) | Foil Angle (degree) |
|-----|--------|------------|------------|---------------------|
| 1   | 1A     | 0          | 1.030      | 0                   |
| 2   | 1B     | 0          | 1.538      | 0                   |
| 3   | 1C     | 0.588      | 1.030      | 0                   |
| 4   | 1D     | 0.588      | 1.538      | 0                   |
| 5   | 2A     | 0          | 1.030      | -4                  |
| 6   | 2B     | 0          | 1.538      | -4                  |
| 7   | 2C     | 0.588      | 1.030      | -4                  |
| 8   | 2D     | 0.588      | 1.538      | -4                  |
The meshing model of the ship fitted with the NACA 4412 stern foil is shown in Figure 4. The number of cell meshing of the model is 667461 cells selected by comparing the result on the trend of the motions by the number of cell meshing as shown in Figure 5.
Firstly, seakeeping analysis of root mean square (RMS) pitch, RMS heave, and RMS heave acceleration on a regular wave with height significant (Hs) of 1.8 meters at the Java Sea and zero up crossing wave period is 7s. The RMS value is calculated after the ship has reached steady motion. Secondly, JONSWAP wave spectrum is chosen to evaluate the acceptance of the ship’s motion according to the seakeeping criteria and to calculate the probability of the motions out of the criteria. The criteria are presented in Table 3. Finally, the mean value of ship resistance on the regular wave at the medium and full speed is simulated. The position of the ship in the computational domain is shown in Figure 6. The distances are 1.0 length overall (LOA) to the inlet, 3.0 LOA to the outlet, 1.5 LOA the bottom, 0.5 LOA to the top, and 1.5 LOA to both sides.

4. Results and Discussion

4.1. Motions on Regular Wave
The root mean square (RMS) motions at the condition of the regular head sea is shown in Fig. 4. The responses of 8 models compared to those of the model without Hull Vane® (NOHV) are presented in Table 3. The most reduction on the root means square (RMS) motions happen on model 2C. The RMS pitch is reduced by -10.75\%, the RMS heave by -6.96\% and the RMS heave acceleration by -7.32\%, as presented by Figure 7.
Table 3. Comparison Of Motions.

| Model | RMS Pitch (deg) | RMS Heave (m) | RMS Heave Acceleration (m/s²) |
|-------|-----------------|---------------|-------------------------------|
| NOHV  | 1.1078          | 0.3411        | 0.6823                        |
| 1A    | 1.0118          | 0.3298        | 0.6716                        |
| 1B    | 1.0275          | 0.3295        | 0.6689                        |
| 1C    | 0.9936          | 0.3244        | 0.6630                        |
| 1D    | 1.0067          | 0.3253        | 0.6625                        |
| 2A    | 1.0127          | 0.3272        | 0.6558                        |
| 2B    | 1.0226          | 0.3288        | 0.6582                        |
| 2C    | 0.9887          | 0.3174        | 0.6323                        |
| 2D    | 0.9987          | 0.3280        | 0.6558                        |

Figure 7. Pitch, Heave, and Heave Acceleration Responses to Regular Wave.

4.2. Resistance
The reduction of ship resistance fitted with the foil at the full speed of 12 knots is shown in Figure 8. The RMS resistance of ship using NOHV model is -68,157.41 N and 2C model is -65,672.91 N. The negative value of the X force shown in Figure 7 means the force against ship direction. The turbulent viscosity of the ship with stern foil 2C is presented in Figure 9.
4.3. Seakeeping Performance

Computation using an irregular wave of JONSWAP spectrum with height significant, $H_s$ of 1.8m, period, $T$ of 7s, and peakedness parameter, $\gamma = 2.5$ for model 2C results in RMS pitch of 0.8220 and RMS heave acceleration of 0.0416g. The response motions are presented in Figure 10. The probability of the motions comply with the criteria are presented in Table 7.
Figure 10. Pitch, Heave, and Heave Acceleration Responses to Irregular Wave.

Table 7. Probability of Complying The Criteria.

| No | Criteria                                      | Probability |
|----|-----------------------------------------------|-------------|
| 1  | RMS Pitch $\leq 1.5^\circ$                    | 76%         |
| 2  | RMS Heave Acceleration $\leq 0.1$ g           | 93.67%      |
| 3  | $3^\circ$ single amplitude average pitch      | 100%        |
| 4  | Significant heave acceleration $\leq 0.4$ g   | 100%        |
| 5  | Significant heave acceleration $\leq 0.2$ g   | 100%        |
5. Conclusion
Analysis of resistance and seakeeping of 1200 GT passenger ship using CFD computation based on responses to regular and irregular wave is concluded as below.

a) NACA 4412 stern foil fitted according to model 2C can reduce the resistance by 3.6% at the service speed.

b) The RMS pitch, heave and heave acceleration decrease up to 10.75%, 6.96%, and 7.325, respectively.

c) The probability of the ship fitted with the foil to comply with the seakeeping criteria is 76%.

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