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Hydrodynamic Optimization of a Patrol Vessel: Evaluating Stern Foil Configurations on Resistance and Seakeeping via CFD

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Abstract**—** The operational efficiency and safety of patrol vessels critically depend on minimizing hydrodynamic resistance and enhancing seakeeping performance. This study explores the effect of stern foils with different NACA airfoil sections on a patrol vessel. Employing Computational Fluid Dynamics (CFD), we assessed water resistance in calm conditions and seakeeping traits in regular head seas. Based on the results obtained, the total resistance value (RT) without stern foil shows a value of 202,112 N. Findings show that stern foils lead to a considerable reduction in total resistance, with the NACA 2412 profile achieving the greatest reduction at 14.85%, followed by NACA 64-212 (14.70%) and NACA 4412 (11.67%) at 20 knots and Fn 0.418. Additionally, seakeeping assessments revealed a significant mitigation of pitch and heave motions across all foil designs, notably a marked decrease in pitch Response Amplitude Operator (RAO) at the dominant frequency of 0.13 Hz. This work provides significant contributions to the optimization of patrol vessel design through advanced hydrodynamic additions, contributing to better fuel economy and greater operational stability in challenging maritime environments.

*Keywords***—** Patrol Vessel, Stern Foil, CFD, Resistance, Seakeeping, NACA Airfoil

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I. INTRODUCTION

Globally, the maritime industry continues to face increasing demands for energy efficiency and environmental sustainability [1]. These demands are reinforced by international regulations such as the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) established by the International Maritime Organization (IMO) [2]. In this context, reducing fuel consumption and greenhouse gas emissions has become a top priority in ship design and operations. One significant approach to achieve these objectives is through the hydrodynamic optimization of vessels, particularly for patrol boats that often require high speed and good maneuverability in various sea conditions [3, 4].

Patrol vessels, as a type of ship with specific operational characteristics, require an optimized hull design to balance speed, stability, and seaworthiness. These vessels often operate at high speeds, where hydrodynamic drag becomes particularly dominant. This increased drag not only reduces fuel efficiency but also affects the ship's seakeeping performance, which is crucial for crew comfort, operational sustainability, and mission reliability [5, 6]. Therefore, efforts to reduce drag and enhance seakeeping in patrol vessels constitute a vital research area.

Various energy-saving technologies have been adopted, including hull shape optimization, the use of anti-fouling coatings, and the installation of hydrodynamic appendages [1]. Among various appendages, the application of hydrofoils has garnered significant attention as a potential solution for reducing drag and improving seakeeping performance [7, 8]. Hydrofoils are devices designed to generate lift force when moving through water, analogous to the functioning of an aircraft wing in the air [9]. With strategic placement, hydrofoils can reduce the wetted surface area of the hull interacting with water, thereby decreasing frictional resistance, and alter the wave pattern generated by the vessel, consequently mitigating wave resistance [1, 2]. Furthermore, hydrofoils can also contribute to enhanced longitudinal stability and reduced pitching and heaving motions of the vessel in a seaway [10, 11].

The NACA (National Advisory Committee for Aeronautics) airfoil series are standard profiles widely employed in hydrofoil design due to their well-established and documented aerodynamic characteristics. Airfoils such as NACA 64-212, NACA 4412, and NACA 2412 exhibit distinct lift-drag curve characteristics, making them attractive candidates for evaluation in the context of patrol boat hydrodynamic optimization. This evaluation is crucial for identifying

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the most suitable profile for the specific operating conditions of patrol boats, which generally involve high speeds and dynamic motions at sea [12].

The Computational Fluid Dynamics (CFD) methodology has become a highly effective and efficient tool in ship hydrodynamics design and optimization [13, 14]. CFD enables the simulation of fluid flow around ship hulls and appendages with a high level of detail, predicting total resistance, propulsive performance, and seakeeping response without the need for costly and time-consuming physical testing [15, 16]. CFD's capability to model the interaction between the ship hull and hydrofoils, including free surface effects and the generated wave patterns, makes it an ideal choice for this research [17, 18]. Previous studies have demonstrated the successful application of CFD in evaluating Hull Vane® and other foils for reducing resistance and improving seakeeping on various vessel types [3, 4, 8].

However, despite extensive research on hydrofoils and hull vanes for drag reduction and seakeeping enhancement, several gaps remain to be addressed. Firstly, most studies have concentrated on specific vessel types (e.g., crew boats, catamarans, flat-bottomed vessels) or single appendage designs. There is a lack of systematic comparative studies that analyze various NACA hydrofoil profiles (such as NACA 64-212, NACA 4412, and NACA 2412) on a specific vessel type like patrol boats. Patrol boats possess unique design characteristics and operational requirements, including the necessity for robust seakeeping performance across diverse sea states and the capability to maintain high speeds. While they did focus on patrol boats, their scope was limited to the application of stern foils under full load conditions, without a comparative analysis of diverse foil profiles [4]. Second, although several studies have investigated seakeeping performance, a comprehensive evaluation of how different hydrofoil profiles simultaneously affect total resistance and seakeeping parameters (heave, pitch, and vertical acceleration) on patrol vessels remains limited [5, 11]. The interaction between foil profiles, mounting positions, and vessel speed can lead to complex effects on both performance aspects. For instance, it was found that hydrofoils can effectively reduce heave and pitch motions as well as added wave resistance but also noted conditions where hydrofoils could lead to excessive resistance increases [7]. This indicates the necessity for in-depth analysis for each configuration. Third, while CFD has been validated as a reliable tool, there is still a need for studies that specifically optimize hydrofoil designs for patrol vessels, considering various operational conditions. Existing studies tend to focus on CFD model validation or the evaluation of one or two configurations, rather than a systematic comparison of several standard profiles that have already proven effective in aerodynamics. This gap indicates that there is no clear guidance yet on which NACA hydrofoil profiles are most optimal for patrol vessels in terms of drag reduction and improved seakeeping.

Addressing this gap will significantly contribute to the design of more efficient and stable patrol vessels, in line with global efforts towards maritime sustainability. This research will fill this void by conducting a comparative evaluation of NACA 64-212, NACA 4412, and NACA 2412 hydrofoil profiles on patrol vessels using CFD simulations, which simultaneously analyze drag and seakeeping performance.

II. METHOD

The methodology employed in this study involved a combination of numerical modeling and CFD simulations to evaluate the hydrodynamic performance of a patrol vessel with different stern foil configurations. The process included hull model creation, stern foil design, CFD setup, and analysis of results. A representative patrol vessel hull form was selected as the baseline for this study. The principal dimensions and hull characteristics were obtained from existing literature and design data. The hull form was created using commercial CAD software, ensuring accurate representation of the geometry. The hull model was then imported into the CFD software for further processing [19]. The baseline vessel model was based on the patrol vessels, with key dimensions provided in Table 1.

Total resistance (R_T) was calculated by integrating pressure and viscous forces over the hull surface. The resistance coefficient (C_T) was derived using the ITTC standard [20, 21, 22]. Comparisons were made between the baseline vessel and configurations with stern foils. The total resistance coefficient per ITTC non-dimensional standard can be calculated using formula 1.

$$C_T = \frac{R_T}{\frac{1}{2}\rho S V^2} \tag{1}$$

Where CT is the Total Resistance Coefficient, RT is the Total Resistance in kN, S is the Wetted Surface Area in m², and V is the Ship Speed in m/s.

Three stern foil configurations were designed, each employing a different NACA airfoil: NACA 64-212, NACA 4412, and NACA 2412, as shown in Figure 1 [23]. The foils were designed with a fixed chord length and span, and their position and angle of attack were optimized based on preliminary simulations and existing literature [24]. In this simulation, the value of the angle of attack is 0° with a single foil. Seakeeping refers to a vessel's ability to operate in waves. Key performance indicators include heave, pitch, and roll motions. Reducing these motions is critical for crew comfort, safety, and operational effectiveness. The seakeeping performance is evaluated by analyzing the response amplitude operators (RAO) for heave and pitch motions in regular waves [25].

Seakeeping analysis was conducted via frequency-domain analysis based on the ITTC method to evaluate the vessel's dynamic responses. The environmental parameters were set to Sea State 4, characterized by a significant wave height (Hs) of 1.875 m, a peak period (Tp) of 6 s, a wave angular frequency (□) of 0.1667 Hz, a peak frequency (□p) of 1.047 Rad/s, a gravitational acceleration (g) of 9.81 m/s², heading seas (□) of 180°, and a Pierson-Moskowitz wave spectrum value (S□) of 1.8886 m².s. Through this approach, the Response Amplitude Operators (RAO) for both heave and pitch motions were successfully calculated to assess the seakeeping performance.

TABLE 1.
PRINCIPAL DIMENSION OF THE SHIP

Parameter	Symbol	Full Scale	Units
Length of Overall	Loa	70	m
Length of Perpendicularity	LPP	62	m
Beam	B	10	m
Depth	H	6	m
Draft	T	3	m
Froude Number	Fn	0.416	Knots
Maximum Speed	V	20	Knots

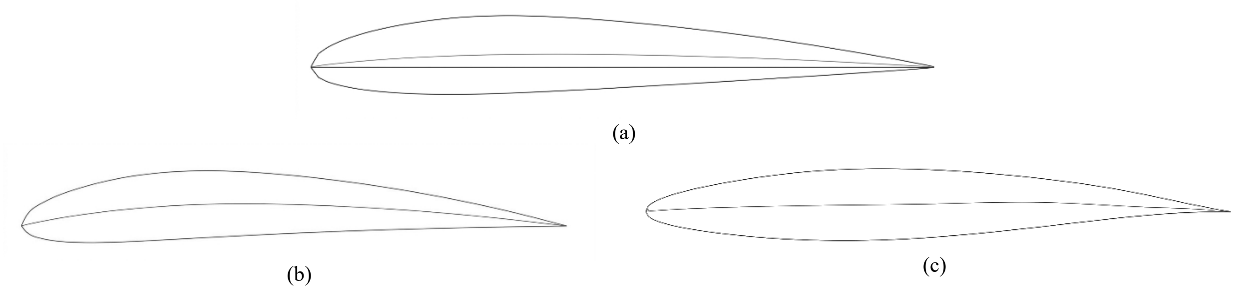

Figure 1. (a) NACA 2412, (b) NACA 4412, and (c) NACA 64-212.

CFD simulations are based on the RANS equations, which are used to model the turbulent flow around the vessel and its appendages [13]. The simulations involve solving the conservation equations for mass and momentum, along with a turbulence model, such as the k-ω SST model, to close the equations. The free surface is modeled using the volume of fluid (VOF) method to capture the wave patterns [26, 27]. The general form of the Navier-Stokes equations can be described in formulas 2 and 3.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i \rho u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial\left(-\rho\overline{u_i' u_j'}\right)}{\partial x_j} \quad (2)$$

$$\overline{-u'_i u'_j} = V_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \quad (3)$$

where the indices i and j represent the horizontal and vertical directions. The average velocity components are denoted as u_1 and u_2. The Reynolds stress is represented by u'_i. u' describes the effect of velocity fluctuations on turbulent flow, where u'_i is the velocity component that changes with time. Meanwhile, P represents the dynamic pressure and ρ indicates the fluid density.

Then, determining boundary conditions is a crucial step in the hydrodynamic simulation process, particularly in the analysis of flow around a ship's hull and stern foil. Boundary conditions are necessary to define the fluid domain, flow direction, and interaction between the ship's surface and the fluid so that the simulation results can represent real-world operating conditions. The upstream (inlet) section is placed at a distance of 3 Lpp from the bow, while the downstream (outlet) is at 1 Lpp from the stern so that the flow exiting the domain does not affect the main analysis zone.

Afterward, the meshing process is a crucial step in CFD simulations because mesh quality determines the accuracy of numerical calculations, especially in areas with high velocity and pressure gradients. This study uses a polyhedral/cut-cell-based unstructured mesh to accommodate the complex hull shape while maintaining the stability of the numerical calculations. Two types of simulations were conducted: simulation resistance and seakeeping in regular and irregular head seas. Mathematically, the surface elevation of regular and irregular waves can be written in formulas 3 and 4 [28]:

$$\zeta(x,t) = \zeta_0 \cos(kx - \omega t) \quad (4)$$

$$\zeta(t) = \sum_{i=1}^{N} \zeta_{0i} \cos(\omega_i t + \phi_i) \quad (5)$$

Where ζ_0 is the wave amplitude (m), (k) is the wave number (rad/m), ω is the angular frequency (rad/s), x is the coordinate of the direction of wave propagation (m), (t) is the time (s), and (ϕ_i) is the random phase which is assumed to be uniformly distributed between 0 - 2π.

For the calm water simulations, the vessel was advanced at various speeds to obtain the resistance curves for each stern foil configuration. The simulations were performed for one Froude number to assess the performance across different operating speeds [29]. For the seakeeping simulations, regular head waves were generated, and the vessel's heave and pitch motions were analyzed. The wave parameters, such as wave height and wavelength, were selected based on representative sea states. The simulations were performed for a range of wave frequencies to obtain the RAO for heave and pitch motions [25].

The simulation results were analyzed to determine the resistance, wave patterns, and seakeeping performance of each stern foil configuration. The resistance curves were compared to identify the configuration with the lowest resistance at different speeds. The wave patterns were visualized to understand the impact of the foils on wave generation. The RAOs for heave and pitch motions were computed to evaluate the seakeeping performance. The results were compared to the baseline hull without stern foils to quantify the improvements achieved by each configuration [30]. Statistical analysis was performed to determine the significance of the observed differences.

The CFD simulations were validated by comparing the results with numerical calculations and published literature. The comparison ensured the accuracy and reliability of the CFD simulations [26]. Discrepancies between the simulation results and numerical calculation were carefully investigated, and appropriate measures, such as mesh refinement and turbulence model selection, were implemented to minimize errors.

III. Results and Discussion

Comparison of total resistance (RT) values for patrol vessels at a speed of 20 knots (Fn=0.418) without Stern Foil simulated using CFD and empirical calculations. The empirical calculation results produce a total resistance (RT) value of 203.769 N, while the CFD simulation results show a value of 202.112 N. The difference between the two is only 0.82%, indicating a very good level of consistency between the empirical method and numerical simulation. This low error illustrates that the mesh configuration, simulation domain, and boundary conditions have been well defined so that they are able to represent hydrodynamic conditions accurately.

Furthermore, simulation results using several NACA profiles showed variations in drag values. The NACA 64-212 profile produced a drag of 172.408 N, the NACA 4412 profile 178.530 N, and the NACA 2412 profile 172.103 N. Compared to the empirical drag results, the use of a stern foil with the NACA 64-212 profile reduced drag by 14.697%, the NACA 4412 profile by 11.668%, and the NACA 2412 profile by 14.848%.

These results conclude that the use of stern foil significantly reduced ship drag. The NACA 2412 profile performed best with the largest percentage drag reduction, followed by the NACA 64-212 and NACA 4412 profiles. This drag reduction has the potential to improve ship operational efficiency, particularly in terms of energy savings and improved hydrodynamic performance at the operating speeds examined.

Visualization of the pressure distribution and water flow patterns around the hull under various conditions shows varying hydrodynamic characteristics at an angle of attack of 0 degrees. In the bottom condition without foils (Figure 2.a), high pressure is formed at the bow due to the bow wave formation phenomenon, while low pressure occurs at the stern due to flow acceleration, confirming the stability of the pressure gradient typical of a fine hull form.

The application of stern foils provides significant flow modification: the NACA 64-212 profile (Figure 2.b) is able to direct the flow, stabilize the low-pressure zone, and reduce flow separation and surface waves. In contrast, the use of the NACA 4412 profile at a speed of 20 knots (Figure 2.c) shows less optimal effectiveness compared to the other profiles because it still leaves a relatively high bow wave and turbulence pattern behind the hull. The best hydrodynamic performance is demonstrated by the NACA 2412 profile (Figure 2.d), where the flow around the stern becomes much more stable and the flow separation under the stern almost completely disappears, indicating the superior ability of the foils to distribute pressure evenly and minimize the total ship's drag.

Simulation results show that installing a stern foil on patrol vessels significantly reduces total drag at an operating speed of 20 knots. A vessel without a stern foil has a total drag of 202.112 N, while using a stern foil reduces drag by up to 14.8%, with the lowest drag value being achieved on the NACA 2412 profile.

Resistance reduction is also attributed to the lift force generated by the foil, which lifts the hull, reducing the wetted area and frictional resistance, as well as altering the wave pattern to decrease wave-making resistance [2, 4]. This drag reduction occurs due to reduced stern sinkage and stern trim, thereby reducing the wave-making resistance and pressure resistance components. These results are consistent with studies on the Holland-class patrol vessels, which showed a drag reduction of approximately 15.3% (CFD prediction) and were validated in sea trials with a peak efficiency/resistance reduction of approximately 16% at 17.5 knots [31].

Another study shows that a foil system can reduce total resistance by up to 32% at a Froude number (Fr) service speed of 1.24 [1]. Furthermore, the addition of hydrofoils can reduce total resistance by up to 17.822% at Fr 0.670 on high-speed vessels [28]. So, using a foil on the stern of a medium-speed vessel can reduce total drag by up to 10–15% under certain conditions, particularly when the foil is positioned optimally relative to the waterline. The range of drag reduction is consistent with the results of this study, which shows that stern foil effectively increases the hydrodynamic efficiency of patrol vessels [8].

Then, the seakeeping analysis in this study was conducted based on the ITTC method with the Pierson–Moskowitz spectrum. The parameters used include wave characteristics, geometric and operational parameters of the ship, and the ship's dynamic response expressed in the Response Amplitude Operator (RAO). The RAO analysis was conducted to determine the characteristics of the ship's dynamic response, especially pitch and heave movements, due to wave excitation with varying frequencies. The results of the RAO analysis of ships without stern foils and ships equipped with stern foils using several variations of the NACA profile, namely NACA 64-212, NACA 2412, and NACA 4412 under regular and irregular wave conditions, are shown in Figure 3.

Response Amplitude Operator (RAO) in Figure 3 for the pitch (a) and heave (b) motions of the ship under regular wave conditions against frequency (Hz), by comparing the condition without a foil and the use of three different types of foils (NACA 64-212, NACA 2412, and NACA 4412). In the pitch motion, the highest response value occurs at a frequency of around 0.13 Hz, where the condition without foil produces the largest peak RAO value (approaching 2.8 deg/m), while the addition of foil successfully reduces the amplitude of the motion significantly. Meanwhile, in the heave motion, the maximum response value approaches 1 m/m at very low frequencies (0 to 0.05 Hz) and decreases drastically as the frequency increases, with variations in foil types showing a trend of decreasing response that are almost similar to each other.

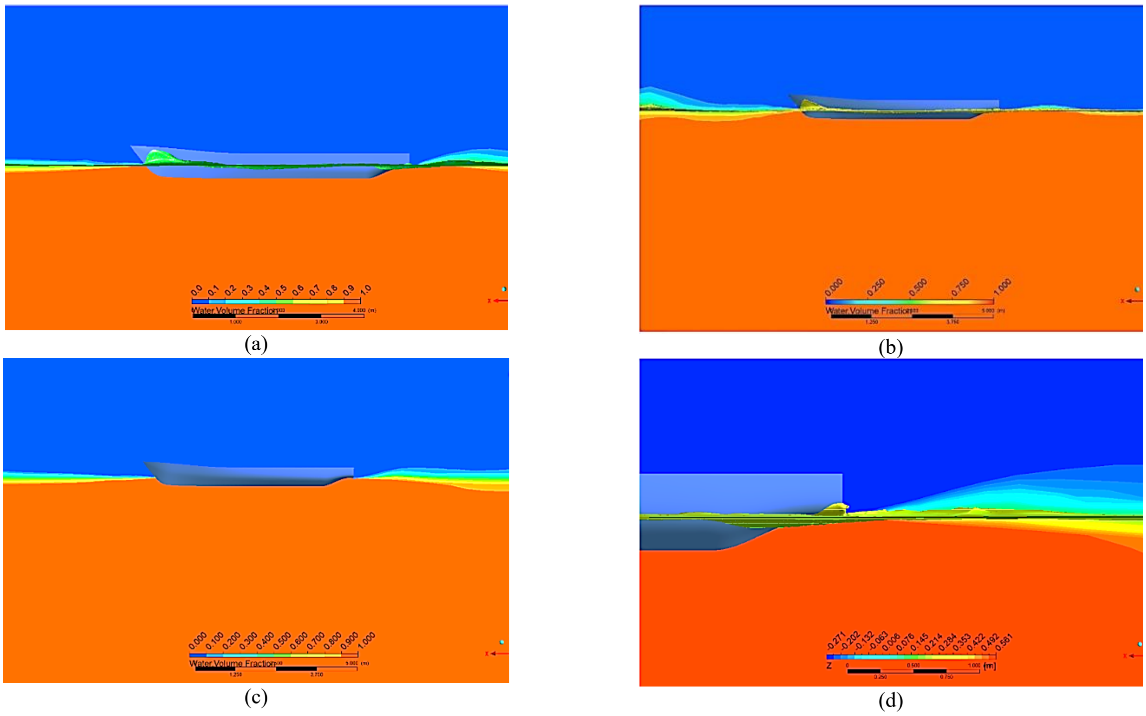

Figure 2. (a) Flow Visualization without NACA; (b) Flow Visualization with NACA 64-212; (c) Flow Visualization with NACA 4412; (d) Flow Visualization with NACA 2412

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Then Figure 3 presents the Response Amplitude Operator (RAO) for the pitch motion (c) and heave motion (d) of the ship in irregular wave conditions by comparing variations without foil and the use of three types of foils (NACA 64-212, NACA 2412, and NACA 4412) in the frequency range up to 1 Hz. In the pitch motion, the RAO value reaches its highest peak of around 2.8 deg/m at a frequency of around 0.13 Hz for the condition without foil, where the addition of the three types of foils is proven to be effective in reducing the response amplitude value. Meanwhile, in the heave motion, the highest RAO value is in the low-frequency range approaching 0.1 Hz with a maximum value of around 0.82 deg/m, which then immediately experiences a drastic decrease to near zero as the frequency increases above 0.2 Hz in all variations of ship conditions.

The comparison shows consistency of the pattern in pitch motion, where both datasets display a stable peak amplitude response near 2.8 deg/m at a frequency of 0.13 Hz, but there is a significant anomaly in the heave motion, which experiences a change in units from dimensional ratio (m/m) to angular units (deg/m) and a decrease in the peak value from 1.0 to 0.82, although this latest graph presents more comprehensive data with an expanded frequency range up to 1.0 Hz. The RAO analysis results show that the installation of stern foil is able to reduce the ship's pitch response significantly, both in regular and irregular wave conditions. The maximum pitch RAO value occurs at a frequency of around 0.1667 Hz, which coincides with the dominant frequency of the Pierson–Moskowitz spectrum. The condition of the ship without stern foil produces the highest pitch RAO value. The use of stern foil shows a decrease in the amplitude of the pitch movement around the peak frequency. This is in line with previous research, which states that additional hydrodynamic devices at the stern are able to reduce pitch movement by controlling the dynamic moment due to waves and can streamline the pitch amplitude characteristics by 20 – 25% [32].

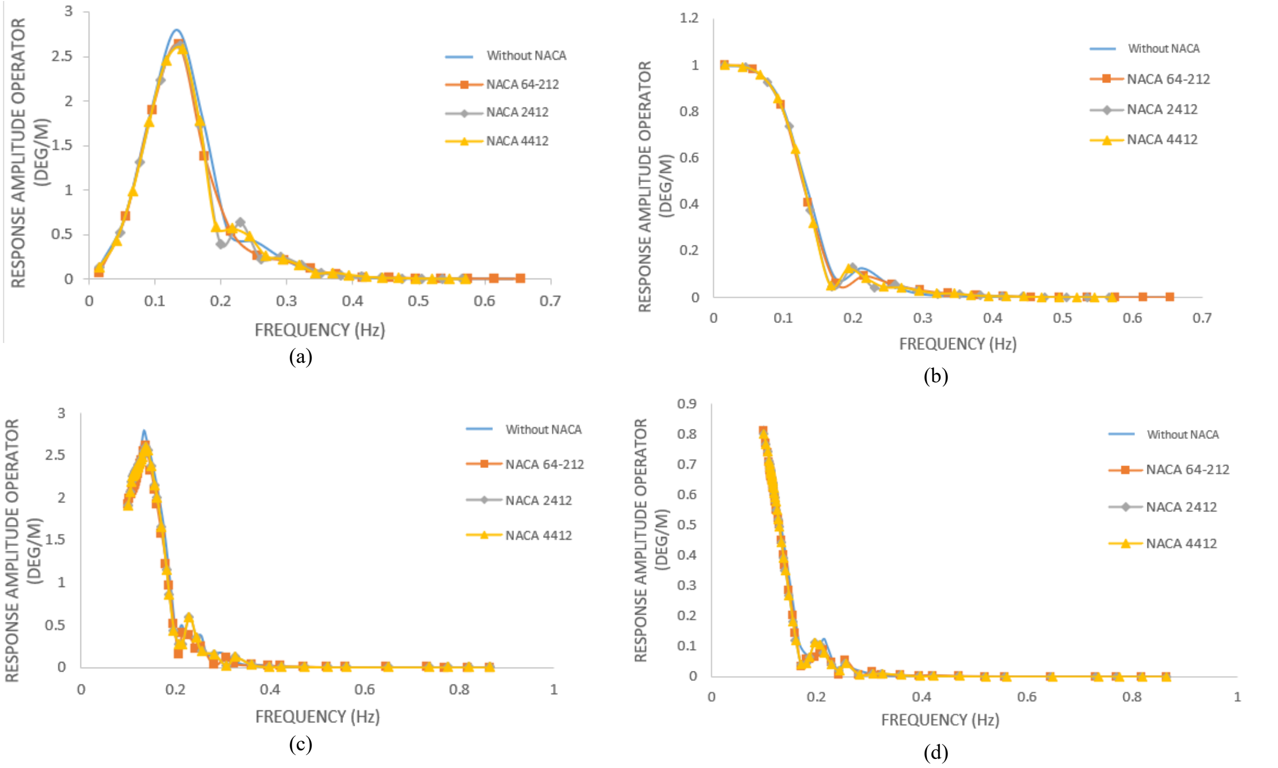

Figure 3. (a) Pitch - RAO Value in Regular Wave Conditions; (b) Heave - RAO Value in Regular Wave Conditions; (c) Pitch - RAO Value in Irregular Wave Conditions; (d) Heave - RAO Value in Irregular Wave Conditions.

Meanwhile, the RAO heave results show that the installation of stern foil has a significant effect on the amplitude of the ship's heave motion. The RAO heave value is relatively high at low frequencies and decreases sharply as the wave frequency increases for all configurations. This result is in accordance with Bhattacharyya's theory which states that the heave motion is more influenced by the displacement and waterplane area of the ship than additional devices at the stern [33]. Other research states that the application of stern foil can reduce the amplitude of the ship's heave by 15-20% [32].

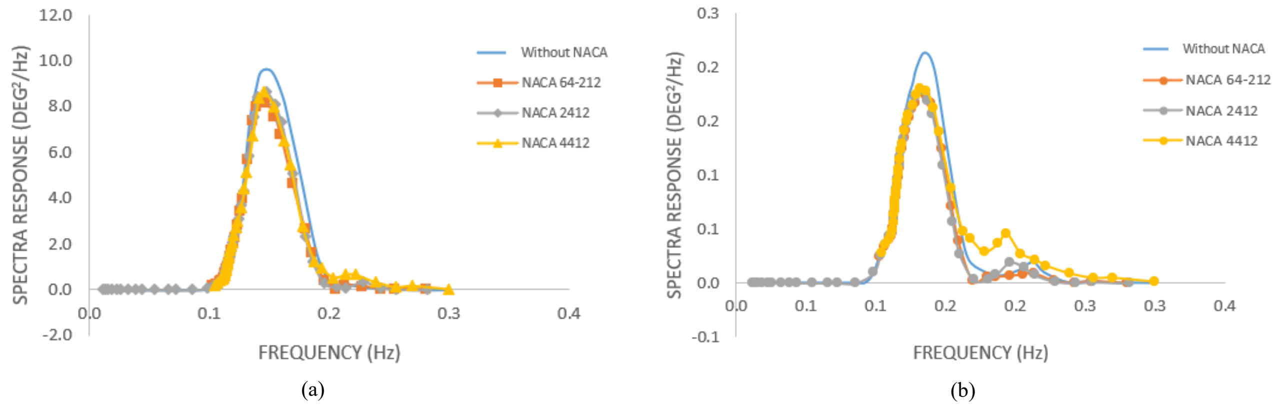

Figure 4. (a) Pitch Spectrum Response; (b) Heave Spectrum Response

Then the comparison of the response spectrum of pitch and heave motion of patrol vessels for conditions without a stern foil and with stern foil variations NACA 64-212, 2412, and 4412. Figure 4 shows the relationship between wave frequency and the magnitude of the ship's pitch response energy. It can be seen that the pitch spectrum response reaches a peak in the frequency range of around 0.14 Hz, which indicates the dominant frequency of the ship's pitch and heave motion response. The condition without stern foil produces the highest spectrum peak value, while the use of stern foil is able to reduce the peak value of the spectrum response. Among the variations of stern foil profiles, the NACA 64-212 and NACA 4412 profiles show a more significant decrease in the pitch spectrum response compared to the NACA 2412 profile. This indicates that the installation of stern foil is effective in reducing the energy of the ship's pitch response at the dominant wave frequency.

The results of this study indicate that all NACA foil configurations have the potential to reduce ship motion. This is reinforced by previous research that found that the Hull Vane can reduce heave response by up to 18.9% and pitch response by up to 20.4% at a speed of 22 knots in sea state 4 [8]. Other studies have also reported that NACA-type stern foils are capable of significantly increasing heaving and pitching amplitudes, as well as heaving acceleration [5]. Furthermore, NACA-type stern foils are also known for their ability to generate significant lift at specific angles of attack, which can be used to control trim and dampen vertical motion [10]. This suggests that the addition of foils can have a substantial positive impact on the longitudinal stability of a ship, making it more comfortable and safer to operate [34].

The integration of these two aspects is crucial. The most optimal configuration may not be the one with the greatest individual resistance reduction or the greatest individual seakeeping increase, but rather the one that offers the best overall performance. If NACA 2412 provides excellent resistance reduction but slightly increases the tendency for proposing at a certain speed, then its benefits might be offset by stability and seakeeping issues. Conversely, NACA 64-212 and NACA 4412, offering moderate resistance reduction but substantial seakeeping improvements, might be better choices for patrol vessels.

IV. Conclusion

Based on the research objective to evaluate the influence of stern foil configurations on the hydrodynamic resistance and seakeeping performance of a patrol vessel, CFD simulations have demonstrated that the addition of stern foils successfully enhanced the vessel's efficiency and stability significantly compared to the initial condition without foils, which exhibited a total resistance value RT of 202.112 N. In terms of reducing resistance at a speed of 20 knots, the NACA 2412 profile yielded the best performance, achieving the largest reduction of 14.85%, followed by NACA 64-212 at 14.70%, and NACA 4412 at 11.67%. Meanwhile, from a seakeeping perspective, all foil designs proved effective in mitigating vessel motion energy by significantly reducing pitch motion amplitude at the dominant frequency of 0.13 Hz and damping heave motions. Consequently, the NACA 64-212 profile is concluded to be the most optimal configuration, as it is capable of providing the best balance between fuel consumption savings and operational stability of the vessel in challenging marine environments.

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