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Noise-Reducing Ship Propeller Design

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Abstract: Propellers, as the core of ship propulsion systems, significantly impact vessel speed, fuel efficiency, and overall performance. Achieving a balance between hydrodynamic efficiency, cavitation reduction, and noise minimization remains a significant challenge in traditional propeller design. These methods often focus on optimizing individual performance parameters while neglecting the interplay between them, resulting in suboptimal outcomes. This paper introduces a novel multi-objective integrated design theory for propellers, aiming to overcome these limitations. Leveraging advanced computational fluid dynamics (CFD) and optimization algorithms, this methodology simultaneously optimizes hydrodynamic performance, cavitation resistance, and noise reduction characteristics. The paper explores various noise suppression techniques, emphasizing the importance of blade shape optimization, surface treatments, and cavitation control strategies. Additionally, it highlights the role of material selection and structural optimization in achieving noise reduction goals. By adopting this integrated design, the paper aims to optimize propeller performance, enhance fuel efficiency, reduce noise emissions, and promote sustainable maritime transportation.

Keywords: Propeller Design, Multi-Objective Integrated Design Theory, Hydrodynamic Performance, Cavitation Resistance, Noise Suppression

1. Introduction

In the realm of marine engineering, the propeller, as the heart of the propulsion system, plays a crucial role in determining a vessel's speed, fuel efficiency, and overall performance. Amidst the booming growth and technological advancements in the global shipbuilding industry, propeller design has evolved to meet stricter and more varied demands, aligning with the ethos of green shipping. Compared to renewable energy technologies, such as solar and wind power, propeller optimization incurs lower costs and is easier to integrate into existing ship systems [1]. By optimizing the hull shape, using anti-corrosion coatings, and adopting air lubrication technologies, hull resistance can be effectively reduced, leading to decreased fuel consumption and emissions [2]. This evolution transcends mere enhancements in propulsion efficiency, aiming for greater energy efficiency, and also addresses critical issues such as minimizing cavitation—a phenomenon that causes bubble formation—and curbing noise emissions, both of which are vital in modern propeller design [3].

The pursuit of high hydrodynamic performance and the minimization of cavitation in propeller design are crucial for enhancing fuel efficiency in shipping, which, in turn, significantly reduces atmospheric pollution from maritime activities. A propeller optimized for high hydrodynamic performance can more effectively translate engine power into propulsion, thus conserving fuel. This approach not only reduces operational costs for shipping companies but also curtails the emission of greenhouse gases and other harmful pollutants, aligning with contemporary environmental protection and energy conservation mandates and supporting the growth of eco-friendly maritime transportation. The design and development of low-noise propellers also play a vital role in enhancing the stealth capabilities of naval vessels and safeguarding the delicate marine ecosystem. However, crafting marine propellers is a complex and demanding task that involves balancing multiple objectives. It requires a nuanced approach to optimizing hydrodynamic efficiency for faster ship movement, minimizing cavitation to prevent performance degradation and material erosion, and reducing noise levels to ensure the propeller operates within acceptable noise standards under various conditions. Traditional propeller design methodologies often struggle to achieve this delicate balance, with improvements in one area sometimes coming at the expense of others, creating a challenge that limits the advancement and application of propeller design technologies. Their relationship is as mentioned in the Figure 1.

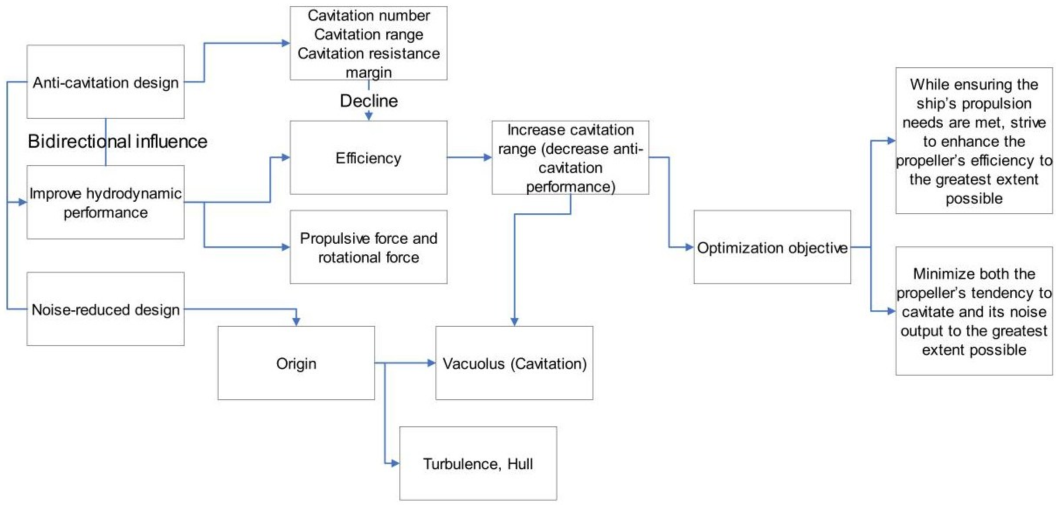

Figure 1: The relationship between cavitation number, cavitation resistance, efficiency, and propulsion force in optimizing ship propulsion systems

The propeller model, a key component of power conversion systems, encompasses a range of types, including fixed pitch, variable pitch, reverse rotation, and water jet propulsion. The design process involves the meticulous matching of diameter, pitch, blade count, and efficiency to cater to various fluid dynamics and load requirements. CFD enables flexible and controlled deformation of the blade shape by manipulating control points within a defined domain [4]. Fluid dynamics principles guide the optimization of blade shape and angle, while materials science ensures resilience and performance in challenging environments. As technology evolves, propeller models are increasingly incorporating smart, efficient, and eco-friendly concepts. Through the integration of sensors and advanced control systems, these models can automatically adjust and enhance energy efficiency while also reducing noise levels and emissions.

In contemporary naval architecture, the minimization of noise generation has emerged as a critical aspect of propeller technology innovation. The significance of noise reduction extends beyond the immediate implications for the crew's working conditions and overall well-being; prolonged exposure to high noise levels can lead to irreversible auditory damage among the crew. Furthermore, excessive noise pollution has the potential to disrupt the natural behaviors of marine fauna, thereby compromising the delicate ecological equilibrium of marine ecosystems [5].

Despite the continuous progression in propeller design technology, conventional methodologies have revealed notable constraints when confronted with the challenge of simultaneously fulfilling the interconnected performance criteria of efficient thrust generation, cavitation suppression, and noise minimization. These methodologies tend to focus excessively on the optimization of individual performance parameters, without adequately addressing the intricate and nuanced equilibrium and interplay among the various performance attributes. Consequently, the resulting designs often fall short of meeting the rigorous comprehensive performance standards required for modern naval vessels. To propel the technological advancement of propeller systems, there is an urgent need to embrace novel integrated design philosophies that aim for the holistic optimization of all performance metrics, thereby catalyzing a comprehensive renovation and advancement in propeller design methodologies. The process of propeller design mention in the figure 2. Propeller design: Hydrodynamic prediction & optimization.

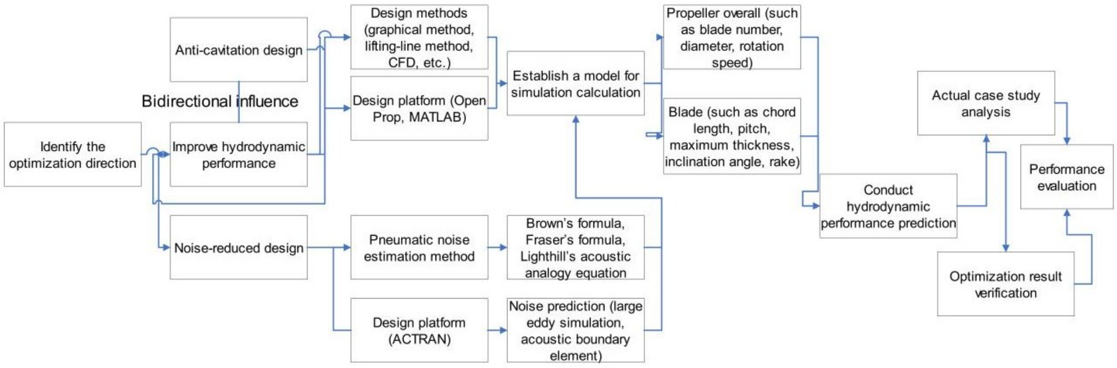

Figure 2: The process of hydrodynamic performance prediction and optimization for a propeller design

2. Analysis of propeller noise

2.1. Main sources of propeller noise

In the field of marine acoustics, the characterization of propeller noise is generally divided into two distinct categories: cavitation noise and non-cavitation noise, as extensively documented in the literature [6]. At higher operational speeds, cavitation noise becomes the predominant acoustic feature, highlighting its critical role in the high-speed performance of marine propellers.

In contrast, studies of non-cavitating propellers have shown that the tip vortex is the primary source of noise when the propeller operates in a uniform flow field. Additionally, propellers generate noise at the trailing edge, leading edge, and hub, each contributing to the complex acoustic signature of the propeller. The relationship between boundary layer thickness and trailing edge thickness plays a crucial role in this context, influencing the overall noise profile.

This intricate interplay of fluid dynamics not only shapes the propeller's acoustic signature but is also significantly intensified by fluid-structure interactions, leading to increased noise levels. At higher speeds, propeller cavitation becomes a major contributing factor to the overall noise spectrum [6].

Addressing the noise issue in propeller navigation requires a targeted approach to mitigate its fundamental cause: the onset of cavitation during operation. To reduce noise, an integrated design strategy must prioritize anti-cavitation principles, ensuring a more efficient and acoustically optimized marine propulsion system. This analysis aims to provide a comprehensive examination of these factors, offering insights into the challenges and potential strategies for mitigating propeller noise in marine applications.

2.2. Overview of propeller cavitation

The diameter of the propeller significantly affects the operational state of the blades and the velocity distribution of the water flow around them, greatly influencing the occurrence of cavitation [7]. Additionally, cavitation bubbles can cause material erosion on the blade surface, leading to issues that affect the propeller's service life and decrease its hydrodynamic performance. Anti-cavitation design has long been a critical challenge in the shipbuilding industry. Several factors influence propeller performance, including pitch ratio, camber ratio, disk area ratio, skew, rake, and blade profile.

Numerous anti-cavitation techniques exist, with a common approach involving the study of one variable at a time. For example, increasing the skew angle within a specific range can effectively reduce the area covered by cavitation bubbles. However, this adjustment shifts the outer radius of the bubbles, increasing the length of cavitation at the outer radius [8]. Large eddy simulations of the propeller, combined with the FW-H acoustic analogy method, were used to estimate the noise generated by cavitation. The findings indicate that while the method can identify low-frequency noise within the flow, it does not effectively address high-frequency noise resulting from small-scale flow interactions.

3. The multi-objective integrated design theory for propellers

Marine propellers, as the cornerstone of a ship's propulsion system, must be designed not only for efficient hydrodynamic performance but also with consideration for cavitation resistance and low-noise operation. The effective functioning of propellers is vital for swift ship navigation, while their resistance to cavitation is crucial for ensuring longevity and safety. Of paramount importance is the design of low-noise propellers, which are invaluable for enhancing ship stealth, minimizing underwater noise radiation, and safeguarding the marine ecosystem. The development of a multi-objective integrated design theory for propellers is thus critically needed. This paper leverages fluid dynamics, cavitation theory, and acoustic principles, incorporating state-of-the-art computational fluid dynamics (CFD) and optimization algorithms to achieve a holistic optimization of hydrodynamic performance, cavitation resistance, and low-noise characteristics [9]. Through this integrated approach, the paper aims to transcend the constraints of traditional designs, achieving substantial enhancements in propeller efficiency, durability, and noise reduction, thereby charting new territories in the evolution of ship propulsion systems.

Efforts to reduce noise through propeller design have already been given high priority, due to the significant impact of propeller noise on marine life and the well-being of the crew. The process of designing low-noise propellers is comprehensive, beginning with a thorough analysis of requirements and goal setting. It is essential to clearly define the scenarios in which the propeller will be used and to establish key performance indicators, such as thrust, efficiency, operating speed, and noise level. During the preliminary design phase, fundamental geometric parameters, such as diameter, blade count, pitch ratio, and blade angle, are generally determined. The design or selection of blade shapes that meet low-noise requirements, including airfoil shape and thickness distribution, is carefully considered, along with the structural layout of the blade. The process then moves to the stage of numerical simulation and optimization, where computational fluid dynamics (CFD) software is used for flow field analysis, predicting hydrodynamic characteristics. Acoustic simulations are conducted in conjunction with CFD results to predict noise characteristics. Based on these simulations, the geometric parameters of the propeller are optimized. A prototype is then constructed and undergoes water tunnel and noise testing to validate the design's effectiveness [10]. By comparing experimental data with simulation results, a detailed analysis is performed, leading to redesigns aimed at achieving superior low-noise performance. Finally, validation tests in real or simulated environments are

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conducted, applying the low-noise propeller to actual products and establishing a quality control system for continuous improvements.

4. Integrated design methods for anti-cavitation and low-noise propellers

Both anti-cavitation and noise suppression design methodologies involve a series of interconnected steps and share common optimization goals. They both strive to improve the propeller's performance and reliability through optimizing its geometric parameters, such as pitch ratio, camber ratio, disk area ratio, skew, rake, and blade profile. In anti-cavitation design, a common strategy is to adjust a single variable, such as skew angle, to reduce cavitation area, although this may cause cavitation to shift toward the outer radius. This approach is similar to the selection and optimization of blade shapes in low-noise design, with both aiming to enhance hydrodynamic characteristics. During the numerical simulation and optimization stage, both methods depend on computational fluid dynamics (CFD) software for flow field analysis, predicting dynamic characteristics and informing design iterations. Additionally, both include the fabrication of prototypes, water tunnel tests, and noise testing to verify the design's effectiveness. A thorough analysis of data is performed by comparing experimental results with simulation outcomes, guiding the redesign process. Ultimately, both methodologies emphasize applying verified designs to actual products, conducting final tests in real or simulated environments, and establishing a quality control system to support continuous improvement and performance enhancement.

4.1. Hydrodynamic and cavitation noise reduction technology

Optimizing blade shape is the primary approach to reducing hydrodynamic noise. This involves adjusting the geometric configuration of the propeller blades by adopting asymmetric blade profiles and optimizing parameters like blade chord length and thickness distribution. A well-designed blade shape can significantly reduce the formation and vortex shedding, thereby lowering noise levels. Additionally, blade surface treatment technologies are crucial for further reducing noise. By applying special coatings or textures to the blade surface, such treatments alter the interaction between the blade and the water, reducing friction and vortex generation, consequently lowering noise. For instance, microstructure designs inspired by biomimetic concepts, which mimic the drag-reducing effect of fish skin, have been shown to be effective in reducing hydrodynamic noise.

To mitigate cavitation noise, the primary strategy involves optimizing the inlet and outlet angles of the blades and the load distribution across the blade surface, effectively preventing or minimizing the progression of cavitation. Utilizing materials with high resistance to cavitation and enhancing the surface smoothness of the blades also contribute to the reduction of cavitation noise. To further enhance noise control, cavitation monitoring and control technologies are implemented. These technologies utilize advanced sensors to monitor the propeller's cavitation state in real-time and make adjustments to its operating parameters, such as rotation speed and pitch, through a control system. This enables active control of cavitation noise.

4.2. The role of materials and optimized design in noise reduction

Material and structural optimization are key approaches to noise reduction in propellers. By selecting high-performance materials and optimizing structural design, this method can effectively decrease the noise produced by the propeller during operation.

Utilizing high-strength, high-toughness materials enhances the propeller's durability and minimizes noise from material fatigue. For example, composites known for their superior mechanical properties and corrosion resistance are widely used in propeller manufacturing. Using composites strengthens the propeller and contributes significantly to noise reduction [11].

Designing to reduce structural vibration is an effective way to decrease propeller noise. Utilizing embedded vibration dampers or damping materials absorbs and suppresses vibrational energy, thereby reducing noise levels. For example, optimizing the way blades are connected and enhancing structural damping has demonstrated significant effectiveness in vibration and noise reduction [3]. Moreover, refining the geometric shape and structural arrangement of the blades is another effective approach to further minimize vibration and noise.

Lightweight design is an effective strategy for reducing propeller noise. By decreasing the propeller's mass and inertia, it helps lower vibration and noise levels during operation. This design approach includes both material selection and structural optimization. Techniques such as using hollow blades and refining blade cross-sections can lighten the propeller without compromising its strength and rigidity, ultimately contributing to noise reduction.

4.3. Reducing noise by controlling cavitation

Cavitation, a primary source of noise in propellers, plays a crucial role in determining the overall noise level. Therefore, effective control of cavitation is essential for noise reduction.

Designing blades with specific shapes is an effective way to control cavitation, a major noise contributor in propellers. For instance, increasing the radius of the blade's leading edge helps minimize cavitation bubble formation, thereby reducing noise. Adjusting the chord length distribution and twist angle not only improves the propeller's resistance to cavitation but also enhances its overall efficiency [3].

Continuously monitoring the propeller's cavitation status and adjusting its operational parameters as needed can further reduce noise levels. Modern propeller designs frequently incorporate sophisticated sensors and monitoring systems to detect cavitation in real time. Analyzing this data allows for immediate adjustments to the propeller's speed and load, effectively mitigating cavitation-induced noise [12].

Applying anti-cavitation coatings is a practical approach to enhance the blade surface's resistance to cavitation, thereby minimizing cavitation-related noise. These coatings increase the surface roughness of the blades, discouraging the formation and expansion of cavitation bubbles, thus contributing to noise reduction [13]. Moreover, these coatings not only mitigate cavitation but also bolster the blades' resistance to corrosion, thereby prolonging their lifespan. Numerous anti-cavitation coating materials have been successfully integrated into propeller designs, demonstrating their effectiveness and practicality.

5. Propeller-related models

5.1. Advancements in propeller design: leveraging CFD and FVM

As global ship engineering progresses, the focus on propeller research intensifies. Numerical simulation methods used for propeller analysis offer benefits such as low cost, short turnaround times, and the ability to simulate a range of parameters under real-world conditions. As a result, these methods have led to the widespread adoption of Computational Fluid Dynamics (CFD) and the Finite Volume Method (FVM) in propeller design. This section emphasizes the efficient construction of propeller models to validate the effectiveness of these designs.

To understand the noise generated by a propeller during operation, it is essential to know its rotational speed, number of blades, and blade pitch angle as it operates underwater, and to examine how these factors affect noise output. Research in this field predominantly relies on the OpenProp methodology. When a propeller generates thrust and moves through water, the multiple reference frame model can only analyze its steady-state hydrodynamic performance, not its actual movement. Therefore, a sliding mesh model is required for calculations. This model not only simulates the

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propeller's true rotational motion but also enables the study of its unsteady hydrodynamic characteristics.

OpenProp excels in propeller blade design, offering an optimal balance between high hydrodynamic efficiency and superior cavitation resistance. Its ease of use in predicting the hydrodynamic performance curves of the designed blades surpasses that of other software combinations [3].

This paper introduces a novel integrated design approach for ship propellers, focusing on hydrodynamics, cavitation, and low noise. It utilizes the open-source software OpenProp and optimization algorithms. The method aims to enhance and balance overall propeller performance by optimizing its geometry and integrating advanced materials and technologies. The paper begins by surveying current propeller design methods and the challenges they face. It then delves into the theoretical underpinnings and technical implementation of the proposed integrated design method. Through case studies, the paper demonstrates the feasibility and effectiveness of the method. The research not only contributes new perspectives and references to propeller design but also establishes a robust foundation for the future advancement and application of ship propulsion systems.

The process of integrating propeller design is complex, with various factors influencing each other, making it challenging to achieve the desired results. Common propeller design methods include the graphical method, the lifting-line theory, and the surface panel method. In the design process focused on suppressing cavitation in propellers, adjustments to the propeller's structure and design parameters are made to achieve this goal, thereby improving the propeller's hydrodynamic performance. The optimized design is analyzed to identify the best solution. Regarding noise, during the operation of a propeller, the inflow conditions through the blades constantly change, leading to dynamic variations in the forces acting on the blade surfaces. Due to the non-uniform distribution of inflow, the propeller experiences forces with clear periodicity. This periodic force, determined by the propeller's blade frequency (the product of its rotational speed and the number of blades), manifests as a series of discrete spectral lines [14]. Furthermore, cavitation can produce significant noise, which is influenced by the blade frequency. Hence, during the design process, noise reduction strategies can be incorporated into the considerations for cavitation suppression. This approach reduces unnecessary workload. Given the complexity of multi-objective optimization, this paper utilizes OpenProp for relevant data simulations to achieve optimization results.

5.2. Fluid-structure interaction analysis

The fluid-structure interaction model serves as a comprehensive tool for evaluating the propeller's hydrodynamic and structural performance, accomplished through the seamless integration of Computational Fluid Dynamics (CFD) hydrodynamic calculations and finite element analysis solutions. Initially, a precise solid model of the propeller is crafted, setting the stage for detailed analysis. Within the CFX software environment, an array of calculation parameters is meticulously defined, ensuring accuracy and reliability in the subsequent simulations.

Using the CFD finite element method, a thorough calculation and analysis of the propeller's key performance indicators are conducted. This includes evaluating the thrust coefficient, torque coefficient, open water efficiency, and the distribution of blade pressure across various advance speeds. Through this process, the trends and variations in these hydrodynamic parameters are observed and documented, providing valuable insights into the propeller's operational characteristics.

Building on this foundation, the analysis extends to structural integrity and dynamic behavior. Using the advanced capabilities of the Workbench platform, the fluid-structure interaction approach is applied to explore the propeller's structural strength and vibration characteristics. This comprehensive analysis ensures a complete understanding of the propeller's performance, covering both its hydrodynamic efficiency and structural robustness. It also facilitates the design and optimization of superior propulsion systems.

6. Conclusion

In the realm of marine propulsion, propeller design requires a holistic approach that harmonizes hydrodynamic efficiency, cavitation resistance, and noise suppression. This study highlights the limitations of traditional design methodologies, which often prioritize individual performance metrics over overall system optimization. By integrating advanced computational tools such as Computational Fluid Dynamics (CFD), Finite Volume Method (FVM), and optimization algorithms, the proposed integrated design framework demonstrates significant potential in balancing competing objectives. Key findings show that optimizing geometric parameters—including blade shape, pitch ratio, skew angle, and chord length distribution—can effectively reduce cavitation, mitigate hydrodynamic noise, and maintain high propulsion efficiency.

The adoption of innovative materials, such as composites and anti-cavitation coatings, further enhances propeller durability and noise reduction. Structural optimization, including vibration-damping techniques and lightweight designs, helps minimize operational noise and extend service life. These advancements align with the principles of green shipping by reducing fuel consumption, greenhouse gas emissions, and underwater noise pollution, thus protecting marine ecosystems and improving crew welfare.

Future research should focus on refining real-time cavitation monitoring systems, exploring biomimetic surface treatments, and enhancing the integration of machine learning for dynamic optimization. Collaborative efforts between academia and industry will be crucial for translating theoretical advancements into practical applications, ensuring the development of next-generation propellers that meet the evolving demands of sustainable maritime transportation. This integrated approach not only elevates propeller performance but also paves the way for a more environmentally responsible and technologically advanced shipbuilding industry.

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