

# Numerical Simulation of Cavitation in High-Speed Marine Propellers

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**Abstract---** As the Energy Efficiency Design Index (EEDI) criteria become more stringent, enhancing propeller (PP) efficiency has become critical in advancing environmentally sustainable vessels. Cavitation (CV) unavoidably transpires, diminishing the hydrodynamic efficiency of the PP and eroding the blade (BD) surface, resulting in heightened fuel consumption. Mitigating CV is essential for vessels to comply with the EEDI standard. This study examines the PP's fatigue (FQ) life and hydrodynamic efficiency at various CV numbers and velocities. The correlation between PP FQ lifespan and propulsion effectiveness under CV circumstances is reviewed. The Schnerr-Sauer mathematical framework is used as the CV concept in the experiment. The nominal stress technique (S-N method) is employed to determine the FQ durability of BDs. The PP is the subject of the study. The hydrodynamic efficiency of the PP under varying CV numbers is analyzed using the finite volume approach. The pressure on the BD's exterior and wall shearing stress throughout the cycle are computed and then included in the dynamical process to determine the stress and strain of the PP via the finite element approach. The FQ lifespan of the PP is then determined using the S-N curve of the BD's materials. The study's reliability is confirmed by comparing the CV leads with experimental data from the Ocean Engineers Research Center for the ship at an average speed of 16.8 knots, where the CV amount in the wake area is 3.6, demonstrating excellent consistency. The results underscore the substantial influence of CV on BDs' longevity and vibrational dynamics.

**Keywords---** Numerical Simulation, Cavitation, Marine, Propellers.

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## I. Introduction

The trajectory of ship innovation over the last two decades of the twentieth century is as follows: The primary engine of high-speed vessels is evolving towards increased velocity and authority, directly connected to the propeller (PP) (Tadros et al., 2021).

1) Cavitation (CV) (Wang et al., 2021) frequently happens on the PP of this kind of vessel, hence fostering the study and creation of the so-called CV PP or fully cavitating PP.

2) As the vessel's size increases, the main engine power escalates, resulting in a heightened PP burden. The non-uniform stream at the stern of this sort of vessel sometimes induces CV on the PP, leading to erosion damage of the blades (BD) (Prieto & Karlsson, 2021), often accompanied by significant tail vibrations. The issue of CV is increasingly essential. It has garnered considerable attention from academics, aiming to enhance the comprehension of the CV process and identify principles and strategies to prevent CV on PPs.

Research has shown that several historical conceptions are erroneous, including the belief that CV can be mitigated using traditional engineering methods and that the CV behavior of actual vessels can be forecasted based on uniform flow outcomes of tests in a CV cylinder. These cognitions provide a range of subjects for study, including: What are the workings of CV? 2) Can CV have an inverse impact? 3) What mechanisms underlie CV-induced PP erosion, and what measures are implemented to mitigate it? 4) In what manner does CV influence PP effectiveness? 5) In what manner does the non-uniformity of the stern flow field influence CV production? 6) How can the generating process of PP turbulence be forecasted to enhance PP construction according to real requirements? These issues remain unresolved, although a few remedies have been implemented in business and academia.

This research presents a methodology for forecasting PP turbulence and evaluating fatigue (FQ) (Zhang et al., 2024) life using Computational Fluid Dynamics (CFD) (Tsang et al., 2023) and Finite Element Methodology (FEM) (Kudela & Matousek, 2022). The research assesses the PP BD strength under various CV numbers and pinpoints the stress risk zones of the BDs. The research recognizes that it failed to account for the effects of CV

collapses on strain and PP longevity. The research uses the BD substance's S-N distribution to assess the PP design's FQ life. The results provide important insight regarding the changing trends of PP strength during FQ and hydrodynamic loads over various CV values. This work is a significant reference for establishing PP CV, power testing, and differentiation parameters.

## **II. Background**

Examining the dynamic process underlying the CV phenomenon has garnered scientists' interest. Researchers use many CV methods to conduct numerical investigations and enhance the CV concept. Study employed the multibubble version of the revised Rayleigh-Plesset equation to investigate the relationships among bubbles, which are crucial in the first stages of CV growth. Karabelas and Markatos examined the condensing of vaporized water in convection over an airfoil, including the effects of turbulence using the Spalart-Allmaras one-equation system. The Transportation Equation Model (TEM) (Deng et al., 2021), including a governing solution for the liquid-vapor stage fraction, has been utilized. Research contrasted the numerical outcomes of the Large Eddy Simulation (LES) (Chiaradia et al., 2025) technique and the Reynolds-Averaged Navier-Stokes (RANS) method to simulate turbulence flow over Bluff bodies with experimental data. Research simulated cavitating streams in a Francis turbine working at overload circumstances using the Zwart-Gerber-Belamri (ZGB) CV theory. Research examined the variations among several CV simulators for simulating a hydrofoil cavitating stream.

Studies, informed by assessments of current models, found the disparities in the impacted regions between the two condensation and vaporization processes and presented a modified density-based CV theory. Research introduced a linked CV framework, including the gas core effect, which markedly enhanced the predictive precision of tip spacing vortex CV.

The hydrodynamic efficiency and CV properties of the PP have been examined. The potential flow approach is a widely used computational technique in the research of PP performance. Research has yielded remarkable advancements in this domain. The viscous flow CFD approach does not need artificial manipulation of Kutta parameters and has advanced significantly in recent years. The cavitating flow of a steeply tilted PP in a uniform stream and aftermath is modeled.

The PP's thrust ratio and torque coefficients have been accurately predicted compared to the observations. The fluctuating viscous maritime PPs are analyzed using a sliding grid operation, and the outcomes are juxtaposed with the empirical data.

## **III. Methodology for Calculating BD FQ Intensity**

The methodology used to ascertain the capacity for FQ of a PP is grounded on the fundamentals of material mechanics about FQ. The PP BD's endurance limit under present operational circumstances is calculated by integrating the linear cumulative harm of the substance with the substance's life curves. An S-N curve is obtained for a given material exposed to FQ testing at a specified cyclic characteristic R, which is the ratio of the lowest stress to the maximum strain. This graph depicts the correlation between the strain range (S) encountered under alternating strain and the number of stress cycles (N) necessary for failure at that stress. The S-N curve, essential in FQ studies, is the foundation for determining FQ limit and lifespan. Fluctuations influence the S-N curve of a substance in the cyclical characteristic R. The linearly cumulative harm hypothesis posits that the FQ degradation of a component builds linearly under alternating workloads. The harm resulting from varying stress levels is deemed separate and unconnected. When accumulated damage exceeds a certain level, FQ manifests in the element (Figure. 1).

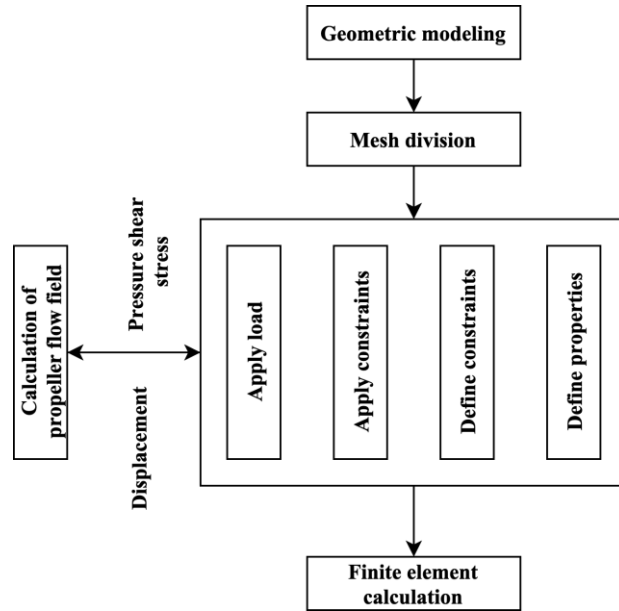


Figure 1: BD Strength Computation Process

A finite element FQ model is conducted using Fe-Safe 2023 to analyze the capacity for FQ of the PP. Before commencing the computation, it is essential to ascertain the most significant location on the BD and observe its stress status over time. Examining the stress fluctuations at this pivotal juncture, the stress-induced cycle and the associated cycle count are derived to evaluate the degree of the substance's FQ damage. Fig. 2 delineates the procedural stages included in the computation of the BD FQ value.

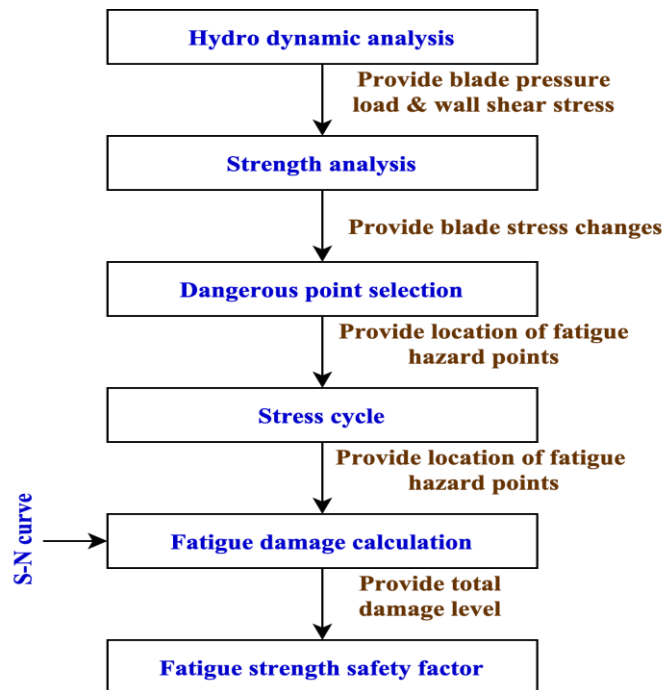


Figure 2: Process of BD FQ Strength Computation

#### IV. Calculations of FQ Capacity

The S-N curve is crucial for determining the degree of FQ in the FQ analysis modules. Figure 15 illustrates the S-N curve for the metallic aluminum PP materials. The PP undergoes considerable fluctuations in surface stress throughout its 360° rotational cycle, exhibiting various cyclic properties. The node located around 0.7R

of the BD's leading edge, displaying the largest amplitude of stress variation, is designated as the crucial node. Strain distribution computations are conducted at 144 stages, each separated by  $2.5^\circ$ , all over the BD's rotating orientation. The little stress generated by the PP mould suggests that this weight does not pose a danger of structural failure when the cycle count surpasses 10. Stress amplification is essential before FQ computations to better examine its intrinsic behavior. By boosting the load on the PP shafts by a ratio that might induce FQ destruction, provided this factor meets the requirements for PP FQ damage.

It illustrates the outcomes of FQ life computations for various CV numerals, with strain multiplication by a factor of 50 for the advance factor  $J = 0.4$ . The BD lifetime curve shows a steep increase when  $On < 1.5$ , suggesting a significant CV zone, often known as super CV movement. Despite the extended lifespan of the BDs, the PP's propelling capability is somewhat compromised. As  $On$  exceeds 1.5, the BD life curve first decreases and thereafter increases as  $On$  surpasses 2. This behavior is ascribed to the PP reaching the second phase of CV, when CV generates both BD CV and irregular tremors, leading to a reduced lifespan. The increase when  $On > 2$  occurs due to a reduction in the CV region diminishes the influence of CV collapses on the BD. As a result, the PP BD undergoes steadier oscillations during the second phase of CV.

The cloud model illustrates the BD's life post-cyclic loading, indicating that most damage is localized near the root. The erratic formation and dissolution of CV on the PP's BD provide a variable load, causing inconsistent vibrations that easily cause BD breakage. The second phase of CV impacts the PP not only via CV itself but also by causing CV from the uneven vibrations of the BD, hence diminishing the PP's lifespan.

## V. Conclusion

This research utilizes the techniques of CFD and FEM to investigate the foaming characteristics and FQ resistance of the PP under circumstances of axial uniform entering flow, resulting in the following findings:

- The surface area and CV volume diminish gradually as the advance factor increases. With a consistent advance factor, the extent and weight of CV diminish as the number of CVs escalates.
- A constant advance factor indicates that the first stage of CV does not affect PP efficiency. However, it leads to decreased BD longevity. In contrast, the subsequent CV stage has little influence on BD longevity while impairing the hydrodynamic efficiency of the PP.
- The vibration amplitude diminishes as the progression coefficient increases, with the peak vibration magnitude occurring at the CV critical position.
- CV development generates vibrations in the PP BDs, jeopardizing the BD root's integrity.

This study's FQ evaluation only examines the effects of stress on the BD, excluding the role of CV. As a result, a PP's lifespan is reduced compared to forecasts. The PP power study fails to account for the actual PP dimensions, and the FQ analysis amplification factor fails to accurately forecast the PP's lifespan. It efficiently emphasizes the FQ-sensitive regions of the PP subjected to CV waves.

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