# Advancements in Marine Propulsion: Design, Development, and Testing of a Bionic - Toroidal Propeller

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**Abstract - Ship propellers hold vast potential for application in various marine sectors. From cargo shipping to passenger vessels, the innovative propulsion systems can significantly improve efficiency, reduce emissions, and enhance manoeuvrability. The quiet and smooth operation of the propeller makes it ideal for use in ecologically sensitive areas and for maintaining passenger comfort. Toroidal propellers are more efficient than standard types because of their special design, which maximizes thrust while minimizing drag also less tip vortices help is reducing noise. As a result, there is less noise and vibration, which improves environmental friendliness. Toroidal propellers exhibit outstanding mobility at low speeds, especially in complex docking operations. Bionic Propellers translate evolutionary principles into mechanical structures by taking cues from genuine biological features like bird wings and whale fins.**

**This study presents a computational fluid dynamics (CFD) simulation analysis aimed at assessing the performance of a novel propulsion system combining toroidal and bionic propellers. The study investigates various parameters affecting the system's efficiency and performance through numerical simulations. The different input parameters were varied during the simulation such as rotation of the propeller, designing of toroidal propeller blade including bionic design such as tubercles on the blade edges and on its surfaces. The prime focus during the simulation was to analyse the impact on the cavitation formation, wake formation, skin friction coefficient, kinetic energy variations, turbulence, the tip, hub and blade vortices formed which will help in reducing underwater noises by combining the design of toroidal and bionic propeller.**

**By merging the benefits of both toroidal and bionic designs, we propose an optimized solution for marine propulsion. Our novel approach aims to maximize combined efficiency, minimize ecological footprints, minimize underwater noises and cater to emerging demands in maritime transportation. Ultimately, this investigation seeks to revolutionize marine propulsion, addressing pressing economic, environmental, and operational challenges faced by industry stakeholders.**

**Keywords:** Toroidal Propellers, Bionic Propellers, Marine Propulsion, Efficiency Improvement, Noise Reduction

## INTRODUCTION

A propeller plays a critical role in marine propulsion by converting rotational motion into thrust, which propels the vessel forward. The design of a propeller significantly impacts various hydrodynamic factors such as drag, lift, turbulence, and cavitation. Drag is the resistance that opposes the propeller's motion through water, and minimizing it is essential for improving fuel efficiency and speed. Lift generated by the propeller blades helps in pushing the vessel forward but must be optimized to avoid excessive turbulence and cavitation. Turbulence, caused by irregular flow patterns, can reduce the efficiency of propulsion and increase noise. Cavitation, the formation of vapor bubbles on the propeller blades due to low pressure, can lead to damage and increased noise levels, contributing to underwater pollution.

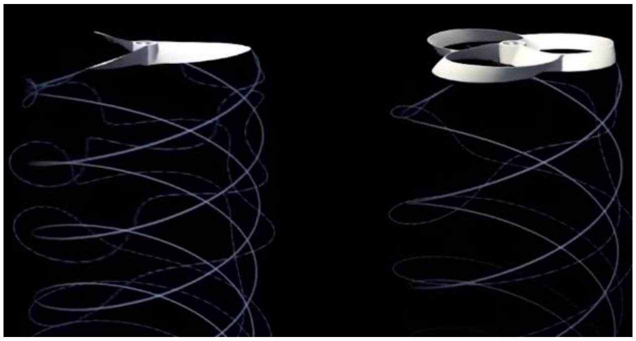

Fig. 1 Sound Reduction in Propeller

Different types of propeller designs aim to address these hydrodynamic challenges. Traditional designs include fixed-pitch and variable-pitch propellers, each offering different advantages in terms of efficiency and adaptability. Emerging designs like toroidal, Sharrow, and bionic propellers bring innovative solutions. The toroidal propeller, characterized by its ring-shaped blades, reduces vortex formation at the blade tips, thereby minimizing drag and improving efficiency. The Sharrow propeller, with its unique looped blade design, offers reduced cavitation and noise.

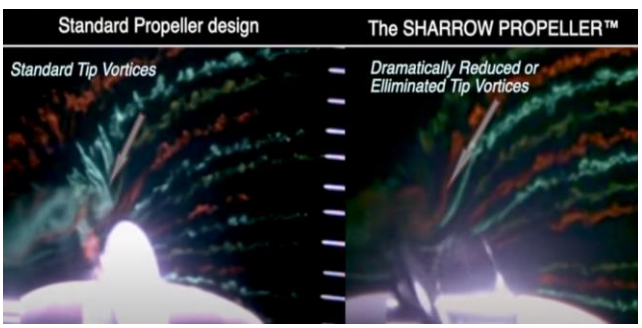


Fig. 2 Fluid puller from afar to increase thrust

Bionic propellers, inspired by biological systems such as fish fins and bird wings, aim to replicate the efficiency and adaptability found in nature, providing smoother flow patterns and reduced energy losses.

The toroidal propeller is gaining popularity due to its ability to significantly reduce drag and improve fuel efficiency. By minimizing tip vortices, it enhances thrust and reduces the energy lost in turbulent wake, making it a highly efficient option for various marine applications. Bionic designs, on the other hand, help in improving several factors by mimicking natural propulsion mechanisms. These designs can enhance the hydrodynamic performance of propellers, leading to reduced drag, improved thrust, and lower noise levels. Incorporating bionic principles can also mitigate cavitation, thereby extending the lifespan of propeller blades and reducing maintenance costs.


Fig. 3 Whale tubercles - reduces cavitation

Combining the toroidal propeller with bionic design elements offers the potential to achieve superior performance. This hybrid approach could lead to propellers that not only minimize drag and turbulence but also operate more quietly and efficiently. By leveraging the advantages of both designs, such a propeller could significantly reduce underwater noise pollution, benefiting marine life and aligning with environmental regulations.

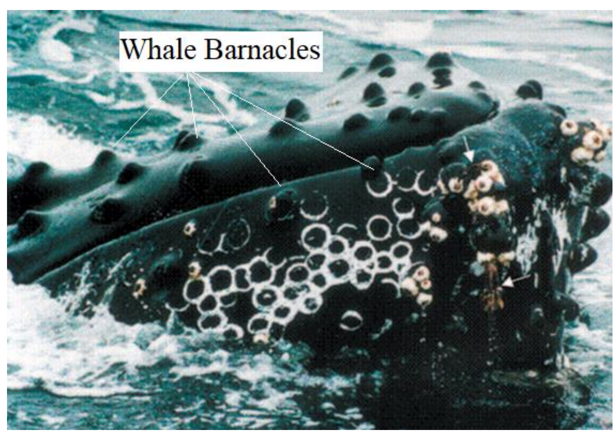


Fig. 4 Whale barnacles increase lift and reduces drag

Overall, the integration of toroidal and bionic principles in propeller design represents a promising advancement in marine propulsion technology, offering enhanced efficiency, sustainability, and operational performance.

**METHODOLOGY**

The research will systematically evaluate the performance of the bionic-toroidal propeller design, providing valuable insights into its potential benefits for marine propulsion systems.

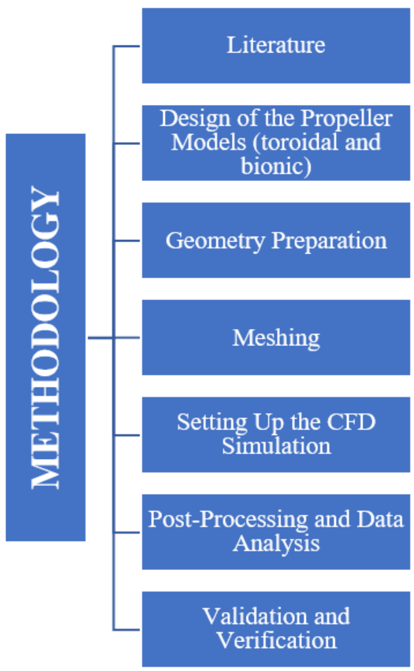


Fig. 5 Methodology

**LITERATURE SURVEY**

A study using Computational Fluid Dynamics (CFD) with Improved Delayed Detached Eddy Simulations (IDDES) examined the impact of leading-edge (LE) tubercles on a 19A accelerating duct. The results showed that LE tubercles increased thrust by up to 7.15% and disrupted the coherent vortex structures, potentially reducing the noise signature of the ducted propeller [1]. Another research developed a mesh refinement method for simulating tip vortex cavitation (TVC). By optimizing the blade surface and tip vortex wake mesh sizes and using adaptive mesh refinement (AMR) based on Q-criterion and wall distance, the study effectively improved TVC simulation accuracy. Numerical results confirmed the method's effectiveness [2]. The effects of bionic tubercle leading-edges on the cavitating wake dynamics were studied using detached eddy simulation at cavitation numbers $\sigma = 1.76$ and 2.016. The analysis focused on propeller loads, cavitation extents, wake topology, and kinetic energy spectra. Results showed that bionic tubercles form counter-rotating vortex pairs, altering streamline distribution on the leading edge and reducing cavitation and blade shed vortexes [3]. Another research paper compares the performance of toroidal propellers with varying blade numbers using computational fluid dynamics (CFD) analysis. The study demonstrates how the number of blades affects thrust, efficiency, noise, vibrations, and cavitation risk. By modelling fluid flow with different blade configurations, the paper evaluates the impact on propeller efficiency and optimization [4]. Research also examines an innovative toroidal hull design for underwater autonomous craft, integrating a centre-line propeller to reduce drag. The design achieved a 13% drag reduction compared to conventional hulls, optimizing hydrodynamic efficiency and power consumption for extended endurance [5].

A study also explores the use of leading-edge (LE) tubercles, inspired by Humpback whale pectoral fins, on marine propellers to mitigate cavitation. Using STAR-CCM+ and IDDES methods, the research found that LE tubercles can reduce sheet cavitation by up to 50% and improve thrust and propulsive efficiency by up to 10% and 6.5%, respectively, under various cavitating conditions [6].

Another study explores the aerodynamic performance of the Toroidal Joined Blade Tips (T-JBT) propeller, which features interconnected blades forming a continuous loop. Numerical simulations demonstrate that the T-JBT propeller generates higher thrust and torque compared to conventional propellers by eliminating tip vortices, although it exhibits complex flow structures and increased flow acceleration [7].

One paper investigates the cavitation mitigation capabilities of leading-edge (LE) tubercles inspired by Humpback whale pectoral fins on a benchmark marine propeller using STAR-

CCM+. Under heavy cavitation conditions, the inclusion of LE tubercles reduced sheet cavitation by up to 2.75%, resulting in a maximum improvement of 3.51% in propulsive thrust and 1.07% in hydrodynamic efficiency [8].

Simulating two fish-like swimming models—rigid flapping foils and deformable anguilliform swimmers—using the δ+-SPH model under laminar flow, the study validates SPH's accuracy through numerical benchmarks. The investigation reveals that thrust generation is closely linked to vortex shedding patterns, with higher Reynolds and Strouhal numbers and larger motion amplitudes enhancing thrust. The results highlight SPH's potential for bionic propulsion simulations due to its Lagrangian and mesh-free nature [9].

## DESIGN OF PROPELLER MODEL AND GEOMETRY

Following is the toroidal propeller (design made on CREO) is taken for the study, three blade propeller shows best results as per the literature survey.

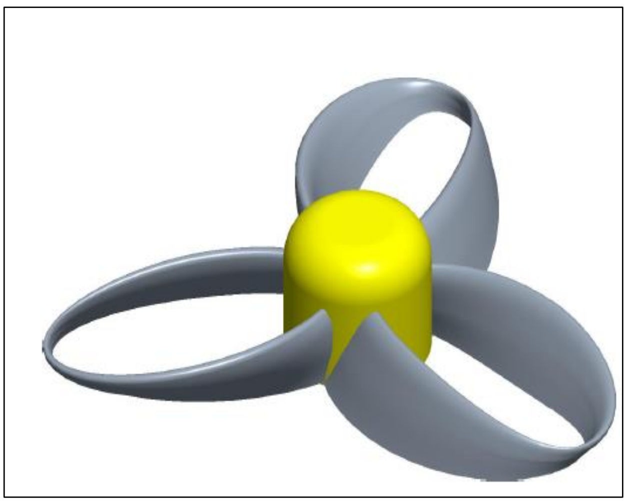

Fig. 6 Toroidal Propeller as a reference for analysis

Table 1: Propeller Geometry

| Propeller Anatomy | |
|---|---|
| Hub Diameter | 400 mm |
| Blade root Diameter | 280 mm |
| Propeller Diameter | 800 mm |
| Blade thickness | 30 mm |

Important design parameters for selecting toroidal propeller geometry include the number of blades, blade profile, pitch angle, and blade thickness. These parameters influence the propeller's hydrodynamic efficiency, thrust generation, cavitation characteristics, and noise levels.

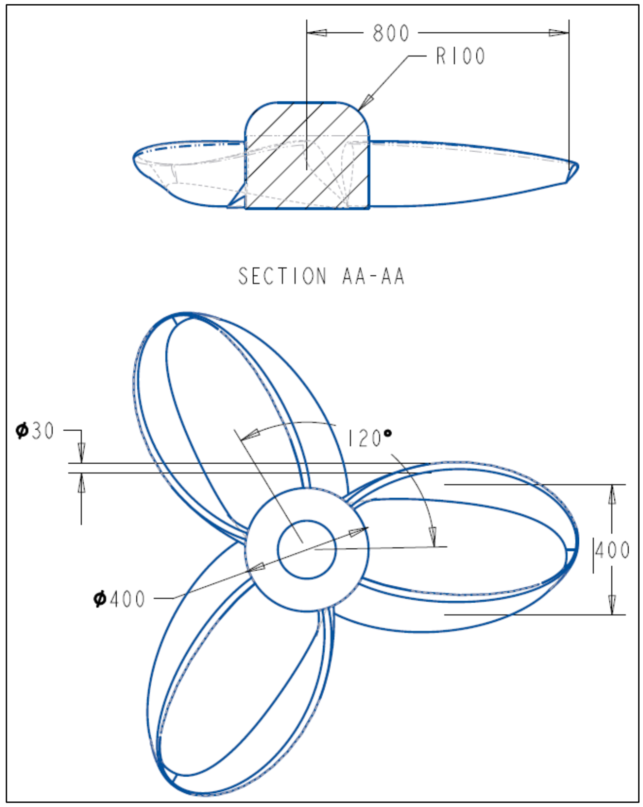


Fig. 7 Geometry of a Toroidal Propeller

Propellers used in Recreational boats is studied for the geometry of the toroidal propeller and CFD is analysis is done. Further the blades of the plain normal propeller are modified using attributes of bionic propeller and the CFD analysis is repeated and comparison is done for performance comparison.

For the comparison, two more toroidal propellers are designed with bionic features resembling the wavy shape of a whale's fin, particularly seen on the leading edge.

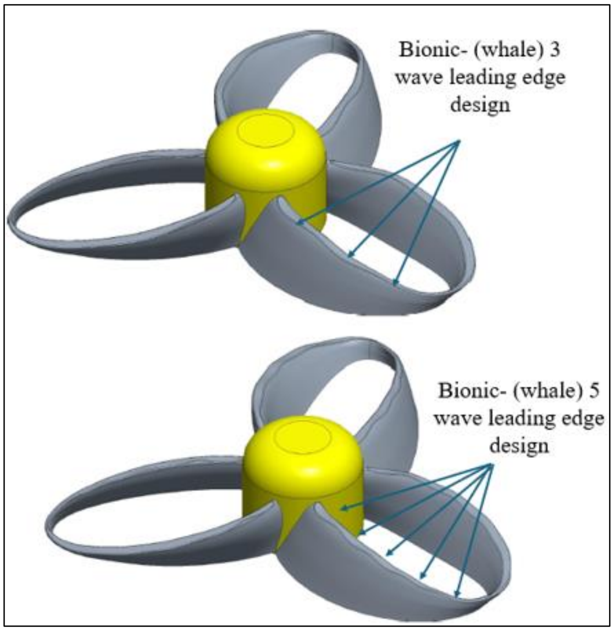


Fig. 8 Bionic toroidal propellers with 3 and 5 wave shape on leading edges

The airfoil structure on propeller blades is crucial as it optimizes the lift-to-drag ratio, enhancing the efficiency of thrust generation. The airfoil shape of tested propeller is as follows,

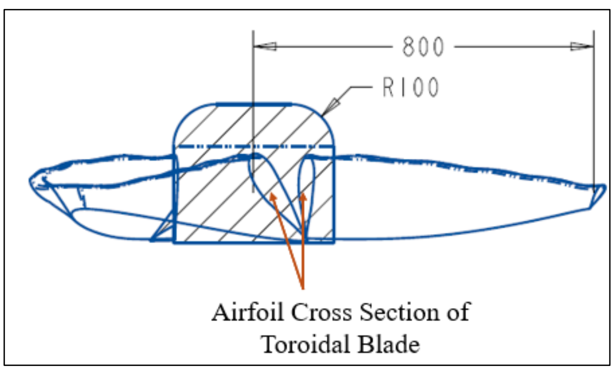


Fig. 9 Airfoil cross section of propeller blade

**E. MESHING AND CFD SETTINGS**

When drawing an enclosure for an object in ANSYS Fluent, it is ensured that the enclosure is large enough to capture relevant flow features, typically 5-10 times the object's length. Symmetry planes are used to reduce computational effort.

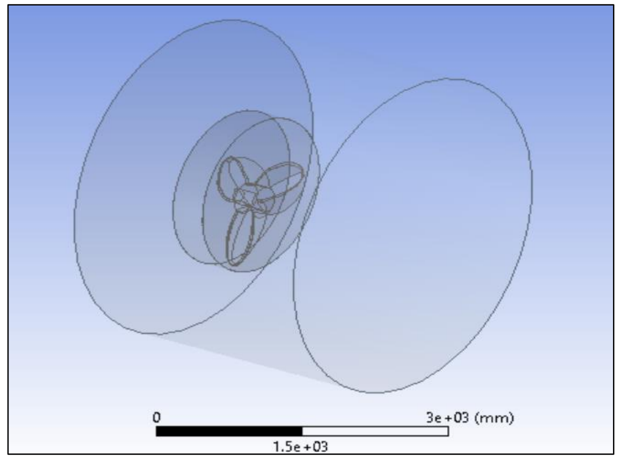


Fig. 10 Design modular with enclosure to propeller

Appropriate boundary conditions are defined, and outlet boundaries are placed far enough downstream to avoid backflow. Mesh refinement zones are created around the object, ensuring a smooth transition in mesh size. Additionally, intersections between the enclosure and the object are avoided, and the enclosure geometry is simplified as much as possible while maintaining the necessary features for accurate simulation.

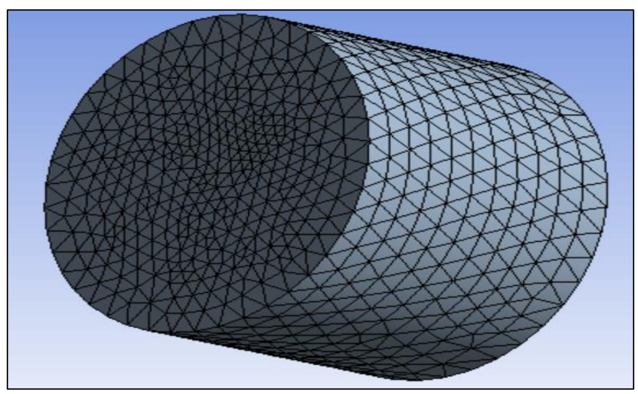

Fig. 11 Meshing (Nodes:202436, Elements: 1102580)

When creating a mesh in ANSYS Fluent, it is crucial to ensure high quality and appropriate resolution.

Table 2: Mesh Details

| Domain | Nodes | Elements |
|---|---|---|
| Rotary_domain | 198271 | 1081543 |
| Static_domain | 4165 | 21037 |
| All domain | 202436 | 1102580 |

A structured hexahedral mesh is preferred for its accuracy and convergence, but tetrahedral meshes are used for complex geometries.

Table 3: Settings for the analysis

| **Domain** | Boundries | |
|---|---|---|
| rotary_domain | **Boundry- contact_region src** | |
| | Type | INTERFACE |
| | Location | contact_region-sre |
| | **Boundary propeller** | |
| | Type | WALL |
| | Location | propeller |
| | | |
| static_domain | **Boundary contact_region trg** | |
| | Type | INTERFACE |
| | Location | contact_region-trg |
| | **Boundry - inlet** | |
| | Type | VELOCITY-INLET |
| | Location | inlet |
| | **Boundary - outlet** | |
| | Type | PRESSURE-OUTLET |
| | Location | outlet |
| | **Boundary wall static_domain** | |
| | Type | WALL |
| | Location | wall-static_domain |

Mesh refinement is applied in regions with high gradients, such as near walls and wake regions, to capture detailed flow features. A smooth transition between different mesh sizes is ensured to prevent numerical errors. Additionally, a mesh independence study is conducted to confirm that the solution is not significantly affected by further mesh refinement.

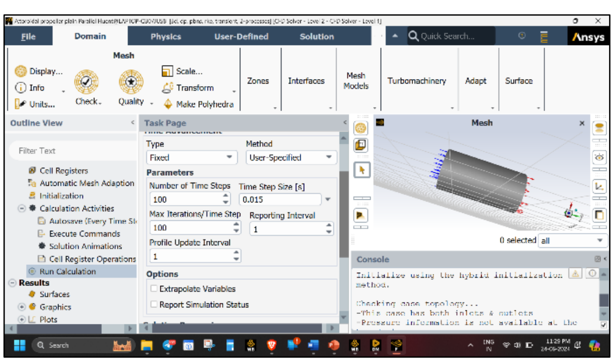


Fig. 12 Settings for time steps and iterations

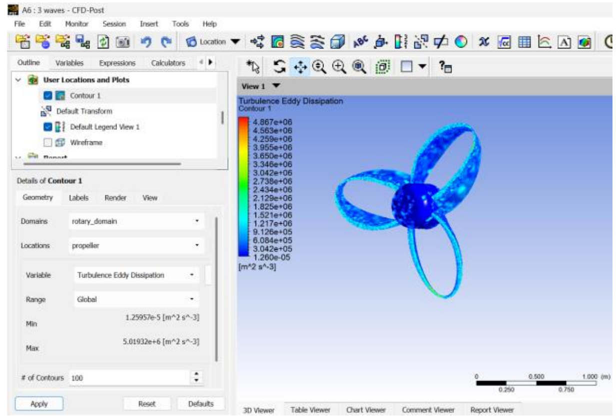


Fig. 13 Pressure on propeller blades

**RESULTS AND DISCUSSIONS:**

For the experiment, 3 toroidal propellers are selected as it is explained earlier named as normal toroidal, bionic toroidal with 3 waves on leading edge and 5 waves on leading edge to check their performances against different parameters such as Static Pressure, Turbulent Kinetic Energy, Wall Shear Stress, Skin friction Coeff., and Stain rate etc. These properties eventually depict the performance of propeller in terms of its efficiency, thrust and underwater noise production.

*A) Static Pressure:*

The distribution of static pressure around the propeller blades helps determine the thrust generated. Higher pressure on the blade's front and lower pressure on the back indicates effective thrust production.

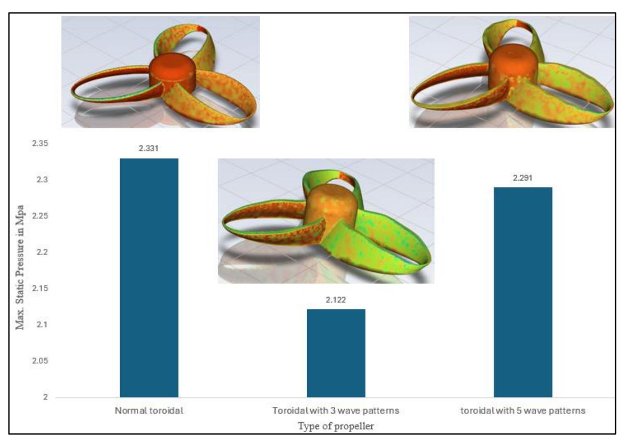


Fig. 14 Graph of Static pressures in different propellers

Normal toroidal propeller shows 8.69% more static pressure than 3 wave and 4.7% more static pressure which indicates slight upper hand to normal propeller when it comes to thrust creation. The normal toroidal propeller exhibits higher static pressure due to its simpler blade geometry, leading to more direct thrust generation without complex flow disruptions. The 3 and 5 wave pattern designs, while beneficial for reducing turbulence and drag, create less static pressure due to their intricate blade structures, which can diffuse the pressure distribution.

*B) Turbulent Kinetic Energy (TKE) and Wall Shear stress:*

Lower TKE indicates less turbulence. The 3-wave pattern propeller has the lowest TKE, suggesting it generates the least turbulence.

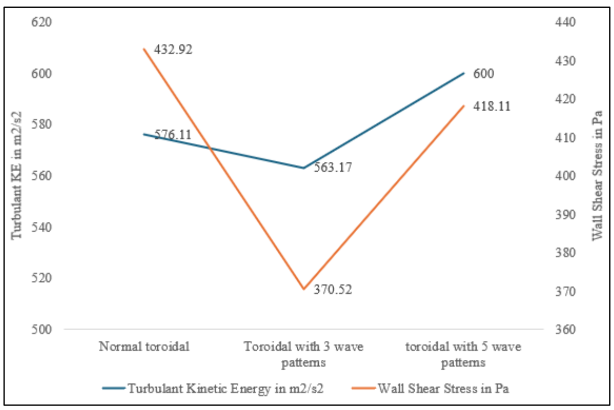


Fig. 15 graphs of TKE and wall shear for different propellers

Lower wall shear stress indicates reduced viscous drag, enhancing efficiency. The 3-wave pattern propeller has the lowest wall shear stress, suggesting it is the most efficient. The 3-wave pattern propeller's design smoothens the flow around the blades, reducing turbulence and lowering TKE. This streamlined flow also minimizes viscous drag, resulting in reduced wall shear stress and improved efficiency.

*C) Skin Friction Coefficient:*

The skin friction coefficient quantifies the drag due to viscous effects. A lower skin friction coefficient implies less drag, enhancing the propeller's efficiency by reducing energy losses.

The 3-wave pattern propeller has the lowest skin friction coefficient, indicating it experiences the least drag and is the most efficient. The 5-wave pattern propeller also shows improvement over the normal propeller.

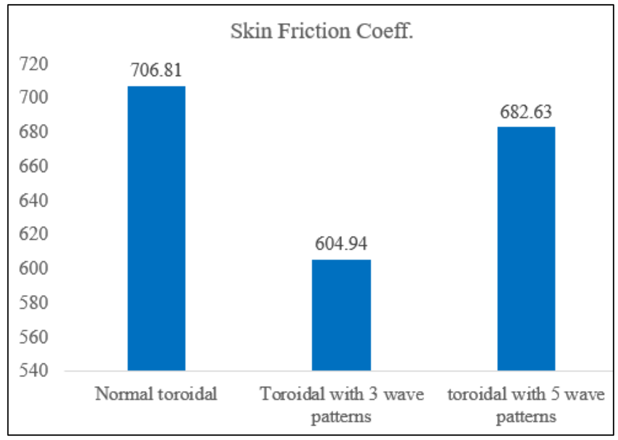


Fig. 16 Graph of skin friction Coeff. in different propellers

The 3-wave pattern propeller's design reduces surface roughness and disrupts less fluid, leading to lower skin friction and less drag. This results in higher efficiency by minimizing energy losses compared to the normal and 5-wave pattern propellers.

*D) Strain Rate:*

Strain rate measures the rate of deformation in fluid elements; it is crucial in this study for understanding flow smoothness and its impact on turbulence and cavitation. It also provides insights into the deformation of fluid elements and the generation of turbulence. A lower strain rate indicates smoother flow with less turbulence. Reduced strain rates contribute to lower levels of cavitation and noise, promoting quieter operation and improved performance.

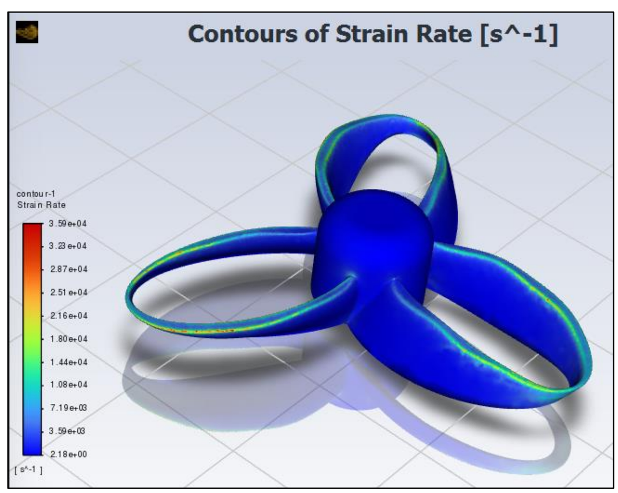


Fig. 17 Strain Rate of 3 wave pattern propeller

The 3-wave pattern propeller's design creates smoother flow, leading to lower strain rates and reduced turbulence. This results in less cavitation and noise, enhancing the propeller's performance.

The CFD analysis of the three toroidal propeller designs normal, with 3 wave patterns, and with 5 wave patterns reveals significant performance differences. The 3-wave pattern propeller excels in reducing turbulence, drag, and underwater noise, demonstrating a 14.41% improvement in skin friction coefficient and a 22.07% reduction in strain rate, although with a slight 8.95% reduction in thrust. The 5-wave pattern propeller strikes a balance, maintaining thrust close to the normal propeller while still offering efficiency improvements. Future research could focus on optimizing the number and configuration of wave patterns to enhance both thrust and efficiency. Exploring material innovations and advanced manufacturing techniques could further improve propeller performance and durability, offering promising advancements in marine propulsion technology.

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