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# Performance Analysis of a Contra-Rotating Propeller with a Toroidal Blade Model

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**Abstract**

*This research analyzes the performance of contra-rotating propellers (CRP) with toroidal blade designs and compares them to conventional CRPs to evaluate propulsion efficiency. The study is motivated by the maritime sector's need for more efficient and reliable propulsion systems. The methodology employed is Computational Fluid Dynamics (CFD) simulation, utilizing variations in RPM (1000–3000) and pitch (228.6–336 mm) to test relevant operational conditions. Key findings indicate that the contra-rotating toroidal propeller generates 16% higher thrust (reaching 3193 N at 3000 RPM) and an average thrust coefficient (KT) of 0.47, which is 17% higher than conventional CRPs. However, the efficiency of the contra-rotating toroidal propeller (average 68,7%) was 9,6% lower than the conventional CRP with a 264 mm pitch (78.31%), despite its superior absolute thrust. Fluid flow contour analysis suggests that the toroidal propeller's circular blade design creates a more stable flow pattern. The significance of this research lies in highlighting the substantial potential of contra-rotating toroidal propellers in boosting propulsion thrust, though further optimization is required for efficiency. These findings underscore the necessity for refining geometric parameters like skew and rake. This study provides a crucial foundation for the development of innovative propellers that combine the advantages of contra-rotating systems and toroidal designs, promoting more efficient and reliable propulsion solutions in the future;*

***Keywords:*** *Toroidal propeller, contra rotating propeller, propulsion efficiency*

## 1. Introduction

This study aims to analyze the performance of a contra-rotating toroidal propeller (CRP) design and compare it with a similar conventional CRP to identify its advantages and limitations in terms of performance. Toroidal propellers are characterized by their annular blade geometry, which reduces noise and blade-tip vortices, offering the potential for higher efficiency in both air and water (Blain, 2023). A contra-rotating propeller is a dual-propeller system rotating in opposite directions that enhances efficiency and reduces vibration and noise by producing a more stable fluid flow (Finlay & Mitchell, 2024; Mahendra, 2018), and it is widely used in the aviation and maritime industries.

Recent studies (Johannessen et al., 2024) have confirmed the superior efficiency of CRP systems, particularly under variable loading conditions, although CFD simulations reveal complex flow interactions under extreme conditions. CRP efficiency can also be improved by optimizing rotational speeds, specifically by increasing the forward propeller speed and reducing the rear propeller speed under low inflow conditions (Hou et al., 2021). The advantages of toroidal propellers have been validated by BoatTest trials (2022) on the MX-1 design, which demonstrated higher speeds and lower fuel consumption, as well as by claims from Sharrow Marine (Weiss, 2024) that its toroidal CRP can improve propulsion efficiency by up to 30%. Other studies report toroidal propulsion efficiency improvements of up to 7.77% (Putra & Rayhan, 2023). Considering the potential of each technology, combining toroidal propellers with a contra-rotating system represents a highly promising research gap for the development of more efficient and reliable propulsion systems.

## 2. Fundamental Theory

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The advance coefficient for ship propeller analysis is a non-dimensional parameter used to evaluate propeller performance. The value of the advance coefficient is determined by the relationship between the propeller's advance velocity, its rotational speed, and the geometric characteristics of the propeller. The advance coefficient can be expressed as follows:

$$J = \frac{V_a}{n \cdot D} \tag{1}$$

$$V_a = n \cdot pitch \tag{2}$$

Where **J** is the advance coefficient [–], $\mathbf{V_a}$ is the advance velocity [m/s], **n** is the propeller rotational speed [rev/s], and **D** is the propeller diameter [m].

Thrust in a ship propeller is the propulsive force generated by the propeller to drive the vessel forward. The propeller, also known as the ship's screw, is a critical component of the ship's propulsion system. Ship speed depends on an effective propeller design to produce optimal thrust (Situmorang et al., 2020). The thrust value can be expressed as follows:

$$K_T = \frac{T}{\rho \cdot n^2 \cdot D^4} \tag{3}$$

$$T = K_T \cdot \rho \cdot n^2 \cdot D^4 \tag{4}$$

**T** is the propeller thrust [N], $\mathbf{K_t}$ is the propeller thrust coefficient [–], **ρ** is the fluid density [kg/m³], **n** is the propeller rotational speed [rev/s], and **D** is the propeller diameter [m].

Torque in a ship propulsion system is the rotational force generated by the main engine and transmitted through the drivetrain to the ship's propeller (Wibowo et al., 2017). High torque acting on the propeller has a negative impact on performance. The greater the torque value, the larger the portion of energy that is not converted into thrust, which can increase fuel consumption. The torque can be expressed as follows:

$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D^5} \tag{5}$$

$$Q = K_Q \cdot \rho \cdot n^2 \cdot D^5 \tag{6}$$

Where **Q** is the propeller torque [N·m], **K_Q** is the propeller torque coefficient [–], **ρ** is the fluid density [kg/m³], **n** is the propeller rotational speed [rev/s], and **D** is the propeller diameter [m].

Propeller efficiency refers to the extent to which a ship's propeller can convert mechanical energy into effective thrust. Propeller efficiency is influenced by the magnitude of thrust and torque. An efficient propeller produces high thrust with low torque (Putra & Rayhan, 2023).

$$\eta_0 = \frac{J \cdot K_T}{2\pi \cdot K_Q} \tag{7}$$

$\eta_0$ is the propeller efficiency [–], **J** is the advance coefficient [–], **K_T** is the thrust coefficient [–], and **K_Q** is the torque coefficient.

## 3. Methodology

The sequential workflow of this research can be seen in the flowchart shown in the figure below.

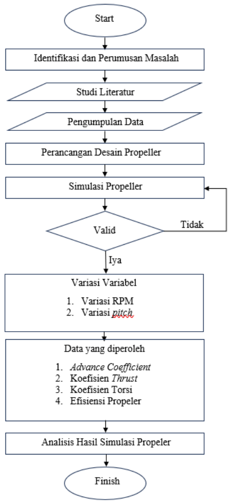

Figure 1 Flow Chart

**Propeler Design**

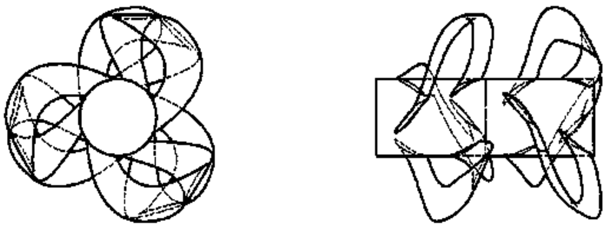
Figure 2 Design *contra rotating* toroidal propeler

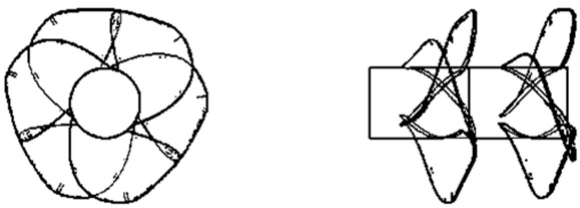
Figure 3 Design *contra rotating* propeler konvensional

Tabel 1 Variasi propeler

| Parameter | Value | Unit |
| --- | --- | --- |
| *pitch* | 228,6; 264; 288; 312; 336 | mm |
| RPM | 1000, 1500, 2000, 2500, 3000 | RPM |

After all propeller models (toroidal, conventional, and their variations) were completed, a Computational Fluid Dynamics (CFD) analysis was performed using SimScale to evaluate their hydrodynamic performance. The simulation process consisted of two main stages: meshing, which discretizes the geometry into small elements for numerical analysis, and the solver setup, where the physical and numerical parameters were defined. Fresh water was selected as the working fluid.

The computational domain was created following the ITTC 2014 guidelines for propulsion systems. The inlet boundary was placed at a distance of 2D upstream, the outlet at 4D downstream, and the radial boundaries at 4D from the propeller diameter. A rectangular main domain was used, with an additional rotating cylindrical zone surrounding the propeller to model its rotation.

The simulation employed an incompressible, steady-state solver with the k–ω SST turbulence model and the SIMPLE algorithm. Velocity inlet and pressure outlet conditions were applied, while domain walls were defined as slip walls and the propeller surface as a no-slip wall. Propeller rotation was modeled using a Multiple Reference Frame (MRF) approach. Forces and moments were monitored to obtain thrust, torque, and efficiency for performance comparison.

## 4. Result and Discussion

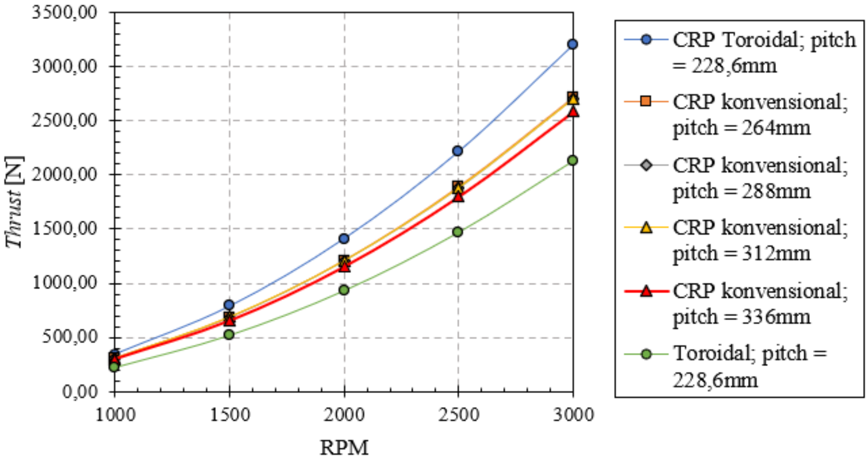


Figure 4 Comparison graph of thrust versus RPM

Based on Figure 4, the toroidal propeller exhibits an average thrust that is 16% higher than that of the conventional propeller, with a peak value of 3,193 N at 3000 RPM—an impressive figure even when compared to four other propellers with higher pitch. This advantage most likely arises from the contra-rotating system innovation that integrates two toroidal propellers, creating a unique configuration that optimizes water flow, reduces rotational losses, and enhances thrust efficiency as well as overall performance. This demonstrates that a contra-rotating toroidal propeller is capable of producing superior thrust even with a lower pitch. These findings are consistent with the study by Nanxuan Qiao (2022), which also confirmed that thrust increases significantly with increasing RPM, and that contra-rotating propellers generate higher thrust than other configurations at equivalent RPM.

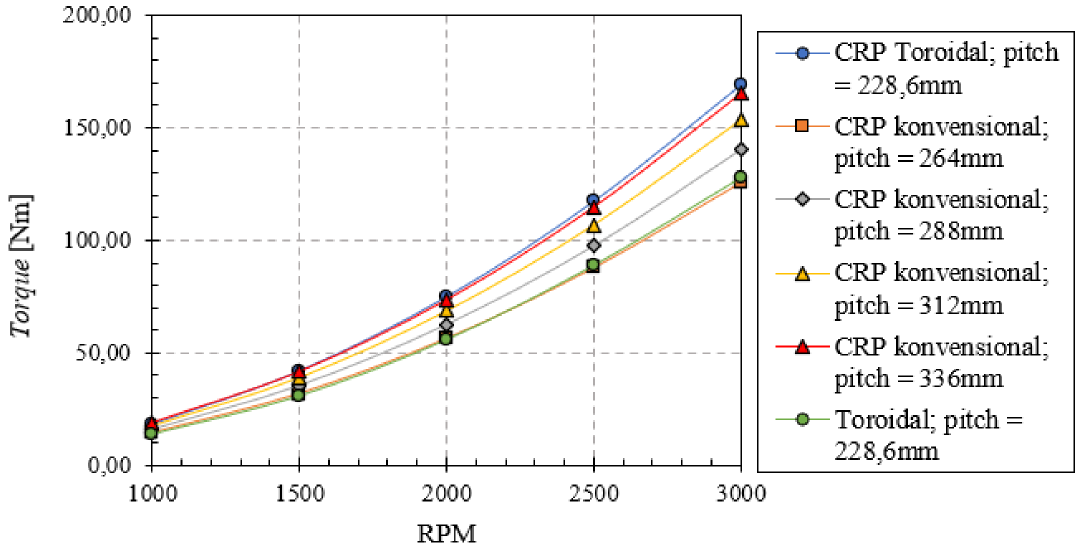


Figure 5 Comparison graph of torque versus RPM

This study analyzes the comparison of torque values between contra-rotating toroidal and conventional propellers. Based on Figure 5, the contra-rotating toroidal propeller exhibits an average torque that is 12% higher than that of the conventional propeller, with a peak reaching 169 N·m at 3000 RPM. Figure 5 further confirms that the torque of the contra-rotating toroidal propeller increases with rising RPM, a phenomenon consistent with previous research (Johannessen et al., 2024). This torque advantage is most likely attributed to the unique toroidal blade design, which forms a continuous annular structure, offering more efficient fluid interaction compared to the discrete blades of a conventional propeller. Interestingly, although increasing RPM generally correlates with higher torque, variations in RPM between the front and rear propellers also affect the results: increasing the RPM of the rear propeller results in higher torque, while increasing the RPM of the front propeller leads to lower torque (Johannessen et al., 2024).

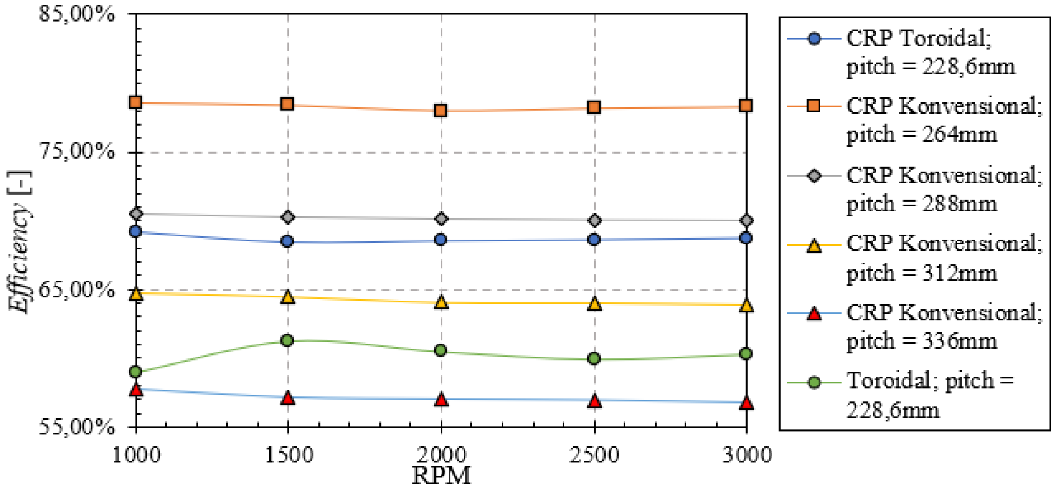


Figure 6 Comparison graph of propeller efficiency versus RPM

Based on the available data, although the contra-rotating toroidal propeller shows an average efficiency of 68.7%, which is 9.6% lower than that of the conventional contra-rotating propeller with a 264 mm pitch, this result challenges the assumption that toroidal propellers are always more efficient. However, interestingly, at higher pitch values, the contra-rotating toroidal propeller outperforms the conventional propeller in terms of efficiency. The decrease in efficiency with increasing RPM, as observed in the visualizations and consistent with the study by Yermias Rahadian (2022), is caused by a more significant increase in torque compared to thrust. Nevertheless, this contra-rotating toroidal propeller produces 16% higher thrust, a substantial improvement that enhances the vessel's operational effectiveness through higher speeds and shorter travel times.

## 5. Conclusions

Based on Computational Fluid Dynamics (CFD) simulations comparing contra-rotating toroidal propellers with similar conventional propeller variants, it is revealed that the toroidal propeller produces an average thrust that is 16% higher, reaching a peak of 3,193 N at 3000 RPM, even surpassing conventional propellers with higher pitch. Its average thrust coefficient is also higher (0.47 compared to approximately 0.40 for the conventional propellers, a difference of 17%).

In terms of torque, the toroidal propeller generates an average torque that is 12% higher, reaching 169 N·m at 3000 RPM, with the highest torque coefficient of 0.11, comparable to that of the conventional propeller with a 336 mm pitch. However, the average efficiency of the toroidal propeller (68.7%) is slightly lower (by 9.6%) than that of the conventional propeller with a 264 mm pitch (78.31%), although the toroidal propeller still outperforms in terms of absolute thrust by approximately 15%.

Fluid flow analysis indicates that RPM has little influence on the flow pattern of conventional propellers, and that pitch differences are more critical in determining efficiency. The annular blade design of the toroidal propeller is proven to be more effective in generating fluid flow compared to conventional propellers, except in the case of the conventional propeller with a 264 mm pitch.

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