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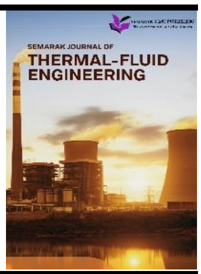

Analysis on the Turbulence Flow on Propeller with Varying Blades Counts

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ABSTRACT

This paper aims at investigating the impact of changing the number of blades on the thrust force and efficiency at turbulent flows to improve the propeller design. The propeller performance is important in many applications, such as aviation and marine propulsion systems, where efficiency and thrust force are important. A CFD approach was used to study the flow field and thrust and torque characteristics of propellers with two, three, and four blades. These simulations were based on the velocity and pressure distributions, thrust force, and aerodynamic efficiency, all of which were maintained at optimal levels of operation. Quantitative analysis revealed a clear trend: greater numbers of blades increased the thrust force and efficiency of the system. In particular, the thrust force increased three times when comparing the blade numbers of two and three, changing from 0.3556 N to -1.2766 N. The same trend was observed for the thrust force, which increased from 1.4966 N for the three blades to 2.9818 N for the four blades. This shows that the addition of blades does increase efficiency, but the degree to which this increases efficiency decreases as the number of blades increases: an example of a nonlinear relationship. The thrust coefficient also increased with the number of blades, suggesting better aerodynamics. Additional information was obtained from the velocity and pressure contours. For the two-blade configuration, the flow separation resulted in high pressure around the rotation domain and low pressure in the static domain for the thrust force. The three- and four-blade designs showed that the flow was smoother, the flow separation was less pronounced, and the pressure differences were higher, which contributed to higher thrust and efficiency. The results of this research advance the understanding of propeller behavior in turbulent flow fields. This paper proposes a mathematical model that establishes the correlation between the blade count and aerodynamic performance, which will be useful for future propeller design in aviation, marine, and other forms of transport. More studies should be conducted to understand higher blade geometries and materials to enhance efficiency.

1. Introduction

Propellers are mechanical devices consisting of blades connected to a hub [1,2]. Propellers can be found everywhere, in aircraft engines, turbines, and boats. Propellers are generally used to

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transfer rotational power to thrust [3]. In addition, turbines are used to convert energy from fluid flow to electrical power. A ship is accelerated based on Bernoulli's principle and Newton's third law [4]. A pressure difference is created on the forward and aft sides of the blade, and water is accelerated behind the blades. The thrust from the propeller is transmitted to move the ship through a transmission system that consists of a rotational motion generated by the main engine crankshaft, intermediate shaft and its bearings, stern tube shaft and its bearing, and finally by the propeller itself [5,6].

The thrust forces can be calculated from the theoretical equation. However, the complexity of the flow characteristics cannot be replicated in the theoretical calculation. Hence, simulating the flow characteristic using CFD software such as ANSYS is optimal to identify the flow characteristic as close to real life as possible. The propeller design originated from the Archimedes screw, where the fundamental principle was derived from sculling. The was applied to irrigation and bailing boats. The first known application of a modern propeller design was on a submarine. The Archimedes screw consists of a helical surface surrounded by a cylindrical pipe.

There is various propeller types used in different applications, and each type is designed to meet specific requirements [7,8]. A fixed pitch propeller has blade angles that are not adjustable, providing optimal efficiency at forward speeds [9]. The ground-adjustable propellers can have their blade angle and pitch changed only when the blades are not rotating, allowing customization for specific conditions. Controllable pitch propellers have blades that can be adjusted during operation, but their pitch positions are restricted to a minimum and maximum angle [10-12]. Constant-speed propellers maintain a steady speed during operation using a mechanism called a propeller governor [13]. The feathering propellers can adjust the blade angle to minimize drag if one blade fails, thereby ensuring continued operation [14-16]. The reverse pitch propellers can change the blade angles to negative values while operating, producing negative thrust to rapidly reduce the speed [17,18].

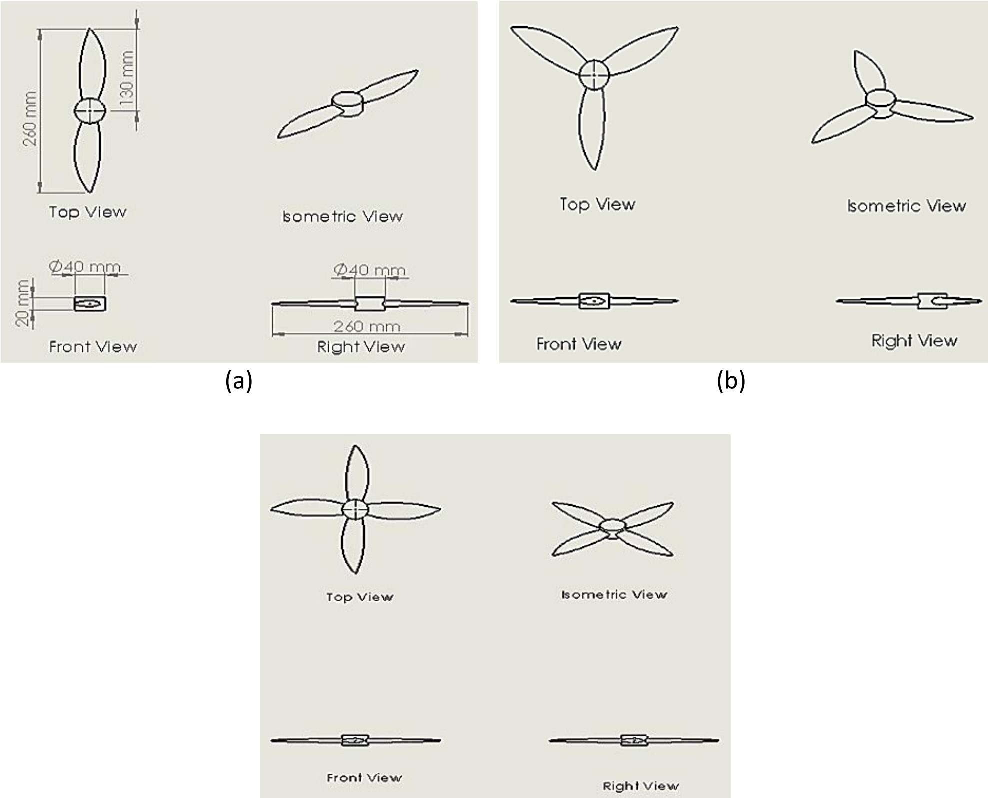
Skew-back propellers feature blades swept back against the direction of rotation along the longitudinal axis, reducing cavitation for quieter operation [19]. The modular propellers are designed for easy adjustment, thereby allowing greater control over the performance. The Voith Schneider propellers have four untwisted straight blades that turn around the vertical axis, providing thrust in any direction. Propeller designs play a crucial role in ensuring the system efficiency. A key aspect of this design is the number of propeller blades, which directly influences the amount of force produced and the overall system efficiency. This study explores the impact of varying the number of propeller blades on the force produced, aiming to reveal the relationship between the blade count and the system performance.

The primary aim of this study was to investigate the relationship between the number of propeller blades and the system efficiency, particularly, the effects of turbulent flows. By understanding this relationship, this study aimed to determine how varying the number of blades affects the performance and efficiency of the propeller system. The scope of this study is strictly defined to ensure precise and relevant outcomes. This study is limited to propellers with the same outer diameter and profile but different numbers of blades. The analysis focused solely on the immediate surroundings of the propeller, excluding any other components. In addition, this project is confined to identifying the magnitude of efficiency loss associated with different blade configurations.

2. Methodology

2.1 Three Different Geometries of Propeller

A simplified single-propeller model was designed using the commercial computer-aided design software SolidWorks, as illustrated in Figure 1(a). Multiple variations of the model were created by modifying the number of blades, as shown in Figures 1(b) and 1(c). The propeller models have four views: top view, front view, right-side view, and isometric view. Each propeller has an approximate length of 260 mm and width of 40 mm. The distinguishing feature of the models lies in the arrangement of the blades on the propeller. The reference body used was based on the model used in Kuty *et al.,* [20].



(a) (b)

(c)

Fig. 1. Single propeller (a) With two blades (b) With three blades (c) With four blades

2.2 Discretization of the Fluid Domain of the Propeller

After creating the air domain, the meshing process was performed to divide the propeller model into smaller elements that could be easily analyzed numerically. Discretization is critical in computational studies because it replaces the continuous domain with a finite number of elements to which the governing equations can be solved. This step is important for simulating the flow characteristics and accuracy of the simulations in areas of complex geometry, such as propellers. To confirm the accuracy of the meshing and to check whether the element size affected the results, a grid independence test (GIT) was carried out. This test determines the mesh density by comparing the simulation results obtained for different element sizes. The purpose of the GIT is to ensure that the changes caused by further mesh refinement do not have a substantial impact on the simulation results, which is important for achieving the optimal ratio between the computation time and the accuracy of the results. The final model contained 356,795 elements and 63,963 nodes, demonstrating that the chosen mesh was appropriate for the analysis. The meshed model is shown in Figure 2 to illustrate the discretized form employed for the CFD analysis.

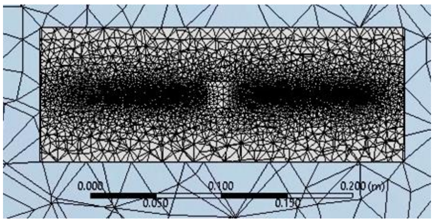


Fig. 2. Meshed model

2.3 Boundary Condition

Boundary conditions play the most important role in CFD simulations, and setting proper boundary conditions is crucial because they directly affect the simulation outcomes. In selecting the boundary conditions for this study, the following criteria were adopted based on Kuty *et al.,* [20]. Appropriate boundary conditions are useful for determining the flow pattern at the domain edges and for modeling physical problems.

2.3.1 Inlet velocity

The velocity inlet boundary condition was set at the top of the static domain, as shown by the red-highlighted face in Figure 3. An inlet velocity of 30 m/s was prescribed, and the flow was in the downward direction across the domain. This assumption is in line with the expected flow conditions experienced in propeller operation.

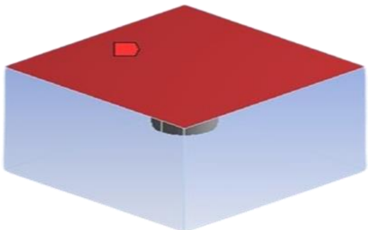


Fig. 3. Red location indicates the velocity inlet

2.3.2 Pressure outlet

The pressure outlet boundary condition was assigned to the domain's bottom face (see Figure 4). This condition allows air to exit the domain while maintaining continuity and preventing artificial reflections or disturbances at the boundary.

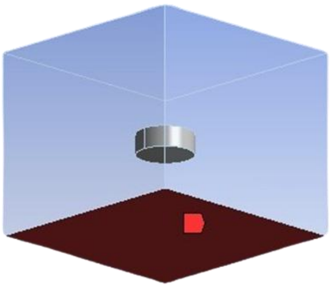


Fig. 4. Red location indicates the pressure outlet

2.4 Simulation Configuration and Parameters

Several parameter assumptions were used in the simulation to ease the analysis while simultaneously ensuring physical realism. The flow was considered incompressible because the inlet velocity of 30 m/s is below the critical velocity for which compressibility effects are important and density variation is negligible. On the propeller surfaces, a no-slip condition was imposed to make the relative velocity between the air and the solid surface equal to zero for better simulation of the boundary layer. Moreover, in the present study, air was considered to be an incompressible Newtonian fluid with constant viscosity and a linear relationship between stress and strain. These assumptions offer a practical and numerically accurate model for studying a propeller and its relation to the airflow around it. The solution setup for the reference model was based on pressure because the air was considered incompressible.

The energy equation was deactivated because thermal effects were not considered in this study. A realizable k-ε turbulence model with standard wall functions was used to simulate the near wall turbulent flow characteristics. The inlet boundary conditions were an air velocity of 30 m/s, turbulence intensity of 0.1%, and turbulence viscosity ratio of 10. At the outlet, the turbulence intensity was defined as 5%, and the turbulence viscosity ratio was 10. The air properties were defined using default values: density=1.225 kg/m³, temperature=288.16 K, and dynamic viscosity of 1.7849×10^{-5} kg/m.s. The rotational speed of the rotating domain of the single propeller was set at 3008 rpm. This simulation was performed for 1000 iterations using second-order upwind discretization schemes for the momentum, turbulence kinetic energy, and turbulence dissipation rate. The turbulence viscosity factor was kept constant at 0.8. Hybrid start was performed to set the conditions at the beginning of the calculations. The setup details are provided in the following Table 1.

Table 1
Solver setup of the simulation

Turbulence model	Realizable k-	
Near-wall treatment	Standard wall function	
Energy equation	Off	
Fluid properties		
Type of fluid	Air	
Density (kg/m^3)	1.225	
Viscosity (kgm^{-1}s^{-1})	1.7894 x 10^{-5}	
Inlet velocity		
Velocity specification method	Magnitude and direction	
Velocity magnitude (ms^{-1})	30	
Turbulent specification method	Intensity and viscosity ratio	
Turbulence intensity	0.1%	
Turbulence viscosity ratio	10	
Pressure outlet		
Gauge pressure (Pa)	0	
Backflow direction specification method	Normal to boundary	
Turbulent specification method	Intensity and viscosity ratio	
Backflow turbulence intensity	5%	
Backflow turbulence viscosity ratio	10	
Pressure-velocity coupling scheme	Coupled	
Spatial discretization	Least square cell based	
Pressure	Second order	
Momentum	1000 iteration	Second order upwind
Turbulence kinetic energy	1000 iteration	Second order upwind

Table 1
Solver setup of the simulation

Turbulence model	Realizable k-	
Turbulence dissipation rate	1000 iteration	Second order upwind
Energy	1000 iteration	Second order upwind

3. Results

3.1 Single Propeller with Two Blades

The study of the two-blade propeller showed that it has different velocity and pressure profiles. These results agreed with the velocity contours shown in Figure 5, where the light blue region represented an air velocity of 30 m/s and the green regions near the rotation domain represented high-pressure areas due to flow separation. The low-pressure zones in the static domain shown in Figure 6 were the main sources of the thrust force. Additional analysis in Figure 7 shows the continuation of streamlined flow until the bottom part of the static domain, where recirculation and backflow are observed. The velocity in the rotation domain was significantly higher than that in the static domain, which emphasized the blade rotation effect.

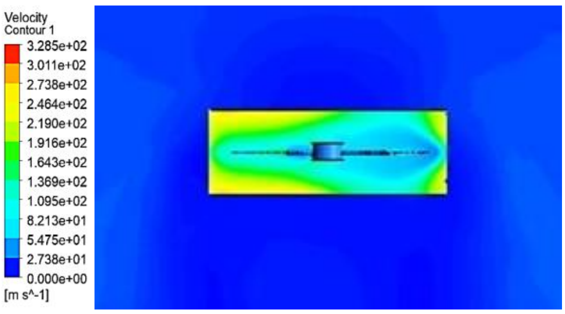
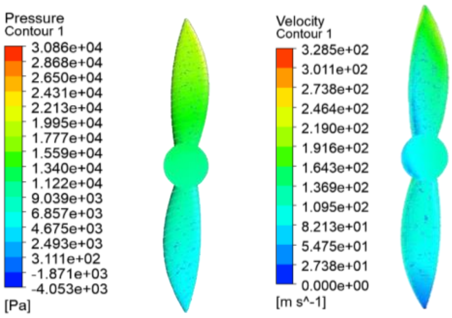


Fig. 5. Velocity contours of the two-blade propeller model



(a) (b)

Fig. 6. Contours of two blade propeller (a) Velocity (b) Pressure

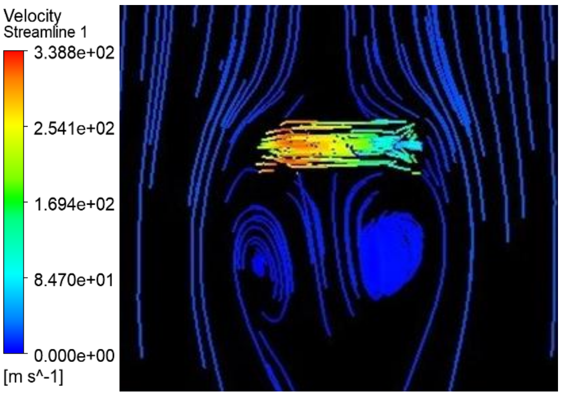


Fig. 7. Velocity contours of two blade propeller

3.2 Single Propeller with Three Blades

In the case of the three-blade propeller, the velocity contours, as depicted in Figure 8, showed larger areas of high velocity than those of the two-blade propeller. The pressure contours shown in Figure 9 exhibit higher pressure gradients near the blades, which augment the thrust force generation. The velocity streamline in Figure 10 also shows that the airflow was more uniform and the backflow was less compared to the two-blade propeller. These results imply that an increase in the number of blades to three enhances the aerodynamic efficiency and thrust force production.

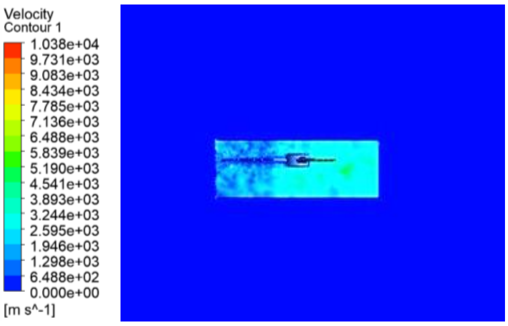


Fig. 8. Velocity contours of three blades propeller model

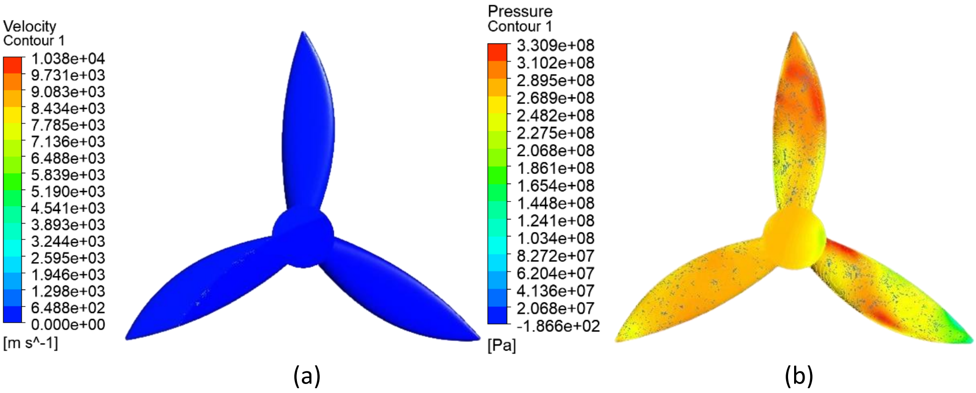


Fig. 9. Contours of three blades propeller (a) Velocity (b) Pressure

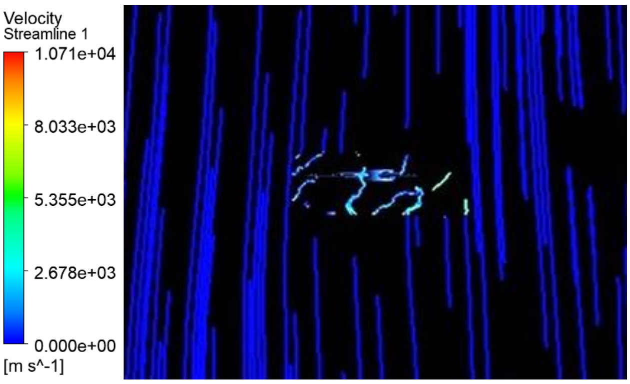


Fig. 10. Velocity streamline of three blades propeller

3.3 Single Propeller with Four Blades

The four-blade propeller showed even better flow characteristics than the three-blade propeller. The velocity field in the form of velocity contours is depicted in Figure 11, where larger zones of high velocity are observed around the blades, while the pressure contours in Figure 12 depict more prominent pressure gradients that contribute to the thrust force. The velocity streamline in Figure 13 depicted better circulation of air at the bottom of the rotation domain, where the rotation domain attained higher velocities than in the three-blade configuration. These results prove that the number of blades affects the thrust force and that the rate of increase is not as great with each new blade added.

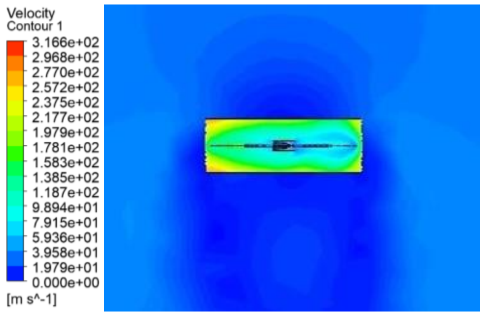
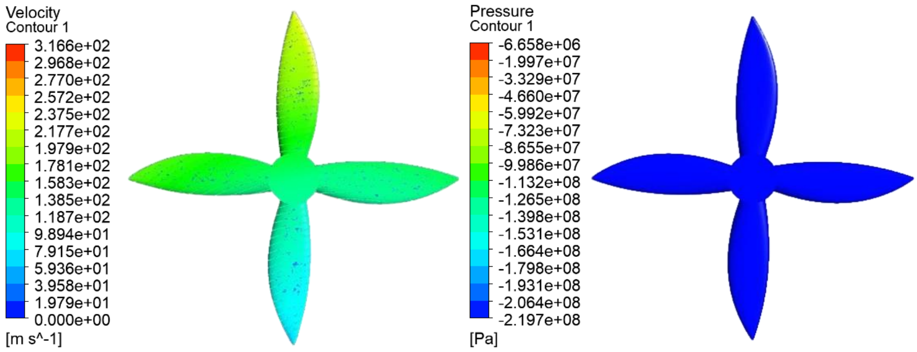


Fig. 11. Velocity contours of four blades propeller model



(a) (b)

Fig. 12. Contours of four blades propeller (a) Velocity (b) Pressure

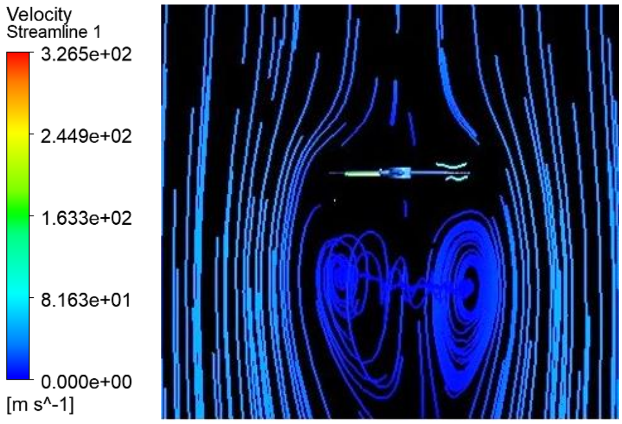


Fig. 13. Velocity streamline of four blades propeller

3.4 Thrust Force Analysis

The thrust force analysis summarized in Table 2 reveals a clear trend: the total thrust force increased with increasing number of blades. More specifically, the thrust force was three times higher when moving from two to three blades and two times higher when moving from three to four blades. This nonlinear relationship showed that there was a decrease in the efficiency improvement as the number of blades used in the wind turbine increased. The thrust coefficient also increased with the number of blades, indicating that there was a continuous improvement in the efficiency even though the rate of increase decreased.

Table 2
Forces by direction vector for propeller with two blades, three blades and four blades

Number of blades	Total forces (n)
Two blades	0.3556
Three blades	-1.2766
Four blades	-2.9818

4. Conclusions

The effect of changing the number of blades on the thrust force and efficiency of the propeller during operation under turbulent flow was investigated in this study. The results show that the number of blades has a positive effect on the thrust force and the thrust coefficient, exhibiting qualitative changes. The thrust force increased threefold when moving from two to three blades and doubling when moving from three to four blades. However, the rate of increase was not as steep as the blade number, indicating that the efficiency increase was not linear with the number of blades. In addition, the thrust coefficient increased with the number of blades, which suggests that multi-blade rotors offer better aerodynamics. These results can be useful in improving the propeller design and show that more work is needed to understand the blade shapes and arrangements for the highest performance.

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