Numerical Study of B-Screw Ship Propeller Performance: Effect of Tubercle Leading Edge

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Abstract— **various attempts to modify the ship's propeller have been made to improve performance as a propulsion component. This paper analyzes the effect of modification of the B-Series propeller by adopting a whale fin shape (Humpback Whale). Also, it analyzes the flow in the propeller before (standard) and after modification. Modifications are made to the leading edge, which is called the tubercle leading edge (TLE). It adds and subtracts sections with a wavelength of 0.2R and amplitude of 2.5% of the chord section length in the propeller leading edge. The numerical study is used using CFD on different J values (0.2, 0.4, and 0.6). It was found that the modification of TLE has a less significant effect on performance. Instead, it decreased at a low J value (0.2). Meanwhile, the largest decrease was at a high J value (0.6), namely up to 10.4% for thrust, 4.3% for torque, and 6.4% for efficiency. Whereas at J=0.4, the torque increases only 0.4%, and the torque and thrust decrease, although less significant. The flow analysis indicates that the shape of the TLE provides a decrease in pressure. However, on the positive side, this modification provides a reduction in noise on the propeller surface.**

Keywords—CFD, leading-edge, propeller, simulation, tubercle.

I. INTRODUCTION

The main propulsion on various types of ships generally uses a propeller. The type of propeller used varies according to the needs and types of ships operated while sailing. Like tugboats, these ships usually use a type of Kaplan accompanied by a ducted nozzle to increase power. This ship requires the ability to push with great force without speed or so-called bollard pull. Meanwhile, the typical propeller used for commercial ships is the B-series [1].

Various modifications have been made to improve the propeller's performance (thrust, torque, and efficiency). Also, the results of the cavitation and vibration tests are needed [2]-[4]. Parts that are often engineered on a propeller are the propeller blade, hub, and add components. The propeller's geometry applies Bernoulli's law. There are differences in the face area and the back area to provide lift. A difference can also be seen between the leading and trailing edges. The shape of the root in direct contact with the hub is also different from the propeller's tip. The use of variable pitch propellers is currently more commonly used because of its main advantage in increasing efficiency [5].

The leading edge is attractive because the fluid interacts directly with this part for the first time. When the fluid hits this part, some possibilities are differences in pressure contours and even flow shapes. Modification in sinusoidal resembles a whale fin (Humpback Whale) is interesting to be applied to the propeller. Several researchers have observed a possible increase in propeller blades' performance using numerical and experimental tests [6]–[8]. Visually with a low Reynold

Number value, the flow that occurs at the leading edge protrusion is dominated by a streamwise structure. The boundary layer slowly blends with the propeller leaf wall adjacent to the protrusion peak position [9]. Almost all researchers have examined this modification with a Reynold Number value of less than 1×10^6 [10]. That is, the applications that have been observed have been of various fluid velocities and density.

The tubercle leading edge (TLE) shape of the tip and the entire leading edge of the current turbine have been carried out at the Emerson Cavitation Tunnel (ECT), Newcastle University. The research conducted by Shi et al. [11] used NREL S814 turbines with a diameter of 400 mm with a modified TLE amplitude of 10% of the chord. The experiments conducted show that the TLE modification results provide greater force, torque, and thrust than without modification but in slow experimental conditions. The lower the pitch angle used seems to improve the performance of the modification results.

The research continues by looking at the flow through the approach used, namely using PIV (Particle Image Velocimetry). This method is through analysis using a camera directed to the tunnel [12]. Two methods were used to analyze this trial's results, namely 2D PIV and Stereo PIV, which differed in the number of vectors observed. The results of several experiments using the tip speed ratio (TSR) found that in slow conditions (TSR=2), the flow separation is more directional and increases the torque for starting. Meanwhile, optimum conditions (TSR=3) and Overspeed (TSR=5) can weaken the tip's vortex. From this trial, the more protrusions in the TLE, the greater the power and thrust coefficient in slow conditions.

The application of TLE to ship propellers is different because the leading edge is not straight, such as foil and turbine. Numerical and experimental tests are conducted using the advance ratio variation (J). The numerical tests are found that the value of torque and thrust increase at low J values. At high J values, the efficiency increases slightly. However, at low J, the efficiency values are

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small [13]. These studies only use a speed of 2 m/s. For further research, it is recommended to study at high speeds. From several experiments, it can be concluded that TLE affects propeller performance.

However, several types of propeller blades have been tested to determine the performance caused by TLE. This paper's discussion is intended to determine how specifically it affects the type of B-Screw propeller. It was initially observed how the propeller's torque, thrust, and efficiency with several J and compared variations without modification were observed. Moreover, it also discussed the modification effect on the propeller flow and noise generation.

II. METHOD

This study used a standard B-Screw propeller type as the main comparison with modified TLE. It is numerically studied using the CFD simulation method in several variations of J value. The primary identifications of the study are propeller performance, flow characteristics, and noise. However, in this section, propeller modeling is explicitly described for the standard and TLE shape details, such as the initial standard propeller design, specification, and TLE design details. Numerical study method specification is also well explained, such as the boundary condition, meshing, and simulation condition.

TABLE 1.
PROPELLER DESIGN SPECIFICATION

Type	Db (m)	P/Db	n (RPM)	Pitch
B4-50	1.96	0.7	395	1.37

A. Propeller Modification Design

The study uses two-propeller models, namely without modification (standard) and with modification (TLE). Propeller type B-Screw is used as the standard as in the specifications in Table 1. As mentioned in Table 1, the propeller is type B4-50, which means it has four blades with 50% of the area. The propeller diameter (Db) is about 1.96 m. The pitch is about 1.37, which results in a pitch and diameter ratio (P/Db) of about 0.7. Moreover, the propeller runs at 395 RPM.

Modifications are made by changing the leading edge with the amplitude of about 2.5% chords. Moreover, the wavelength is about 0.2R, as in Table 2. However, the entire trailing edge is formed sinusoidally according to the shape of the propeller. It should be noted that each

section's position is adjusted without shifting the centerline of the propeller blade. Thus, when a protrusion of "x" is formed, the section's center position is adjusted by shifting by minus x/2 and vice versa.

Figure 1 shows the standard propeller blade (Figure 1a) and TLE shaped (Figure 1b). It depicts no difference between the TLE propeller and the normal propeller surface. When a section has formed a peak, one section next to it is formed a valley as the additional peak. However, it might be a slight difference in the blade volume. The design is refined to be prepared through a meshing process to the three-dimensional shape to be shaped. Eight sinusoidal peaks were generated on the modified propeller.

TABLE 2.
CHORD PROPELLER MODIFICATION DETAILS

r/R	Chord	MidC: GL
0.99	0.16	0.10
0.98	0.21	0.10
0.95	0.30	0.08
0.90	0.37	0.06
0.85	0.45	0.03
0.80	0.46	0.02
0.75	0.51	-0.01
0.70	0.50	-0.01
0.65	0.54	-0.03
0.60	0.51	-0.03
0.55	0.54	-0.05
0.50	0.50	-0.04
0.45	0.52	-0.05
0.40	0.48	-0.04
0.35	0.49	-0.06
0.30	0.44	-0.05
0.25	0.44	-0.05

(a)

(b)

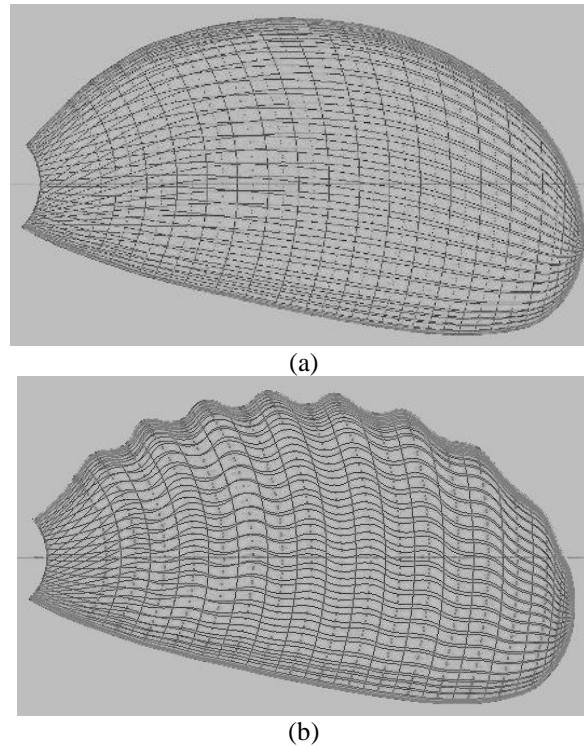**Figure. 1.** The design of (a) standard and (b) tubercle propeller.
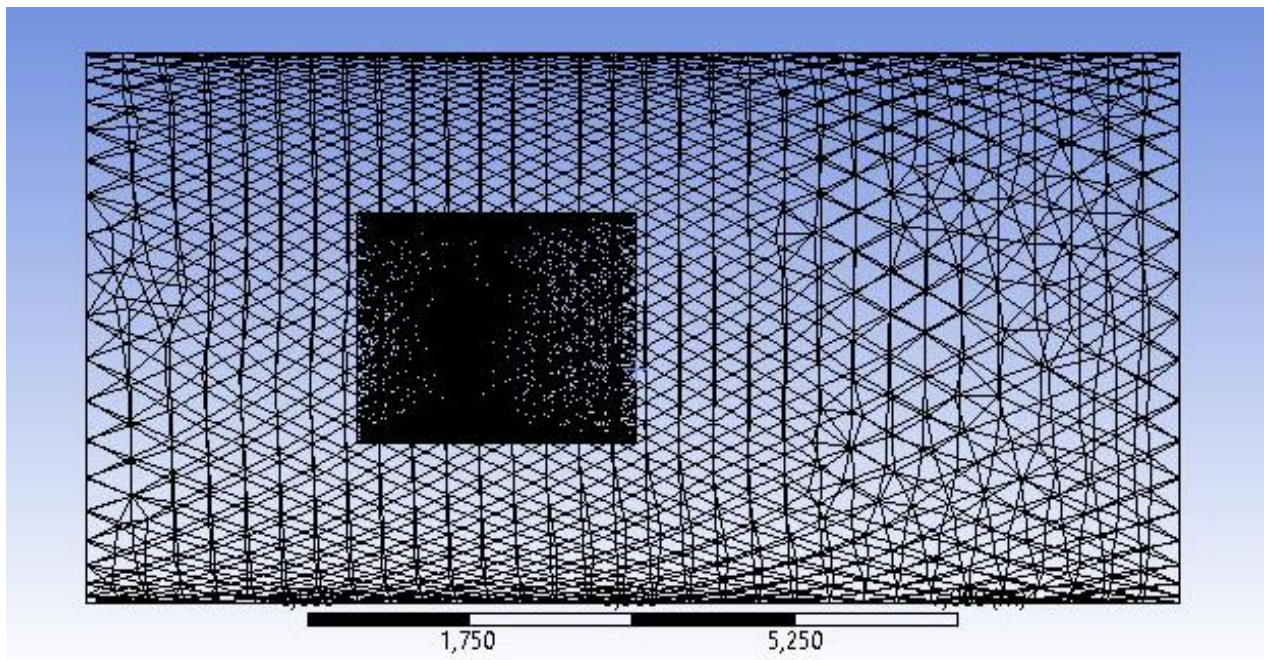

1,750   5,250

Figure. 2. Meshing boundary and propeller.

B. Numerical Study

The numerical testing approach for modifying this TLE uses CFD software with an open water test arrangement formed from a boundary formation (Figure 2). Moreover, two boundary types are developed for the simulation. The outer boundary is a fixed boundary for the water flow. The inner boundary is a rotating boundary for the rotating propeller. The boundary's specific approach is to use a Multiple Reference Frame (MRF) for testing ship propellers. However, in this study, the "coarse" type was selected for propeller testing. The coarse meshing type is chosen for the initialization study, which has less time to run the simulation.

$$K_T = \frac{T}{\rho n^2 D} \tag{1}$$

$$K_Q = \frac{T}{\rho n^2 D^3} \tag{2}$$

$$\eta = \frac{K_T}{K_Q} \frac{J}{2\pi} \qquad (3)$$

$$J = \frac{V}{nD} \qquad (4)$$

The overall performance of the propeller can be calculated from the value of thrust (T) (Eq.1), torque (Q) (Eq.2), and efficiency (η) (Eq.3). This data is obtained during numerical testing on each advanced coefficient (J) (Eq.4), wherein this test at J=0.2, J=0.4, and J=0.6. Thus, the V_a value obtained also varied when tested, namely 2.6, 5.2, and 7.7 m/s. Then the coefficient of thrust, torque coefficient, and efficiency of the two coefficients' accumulation was obtained.
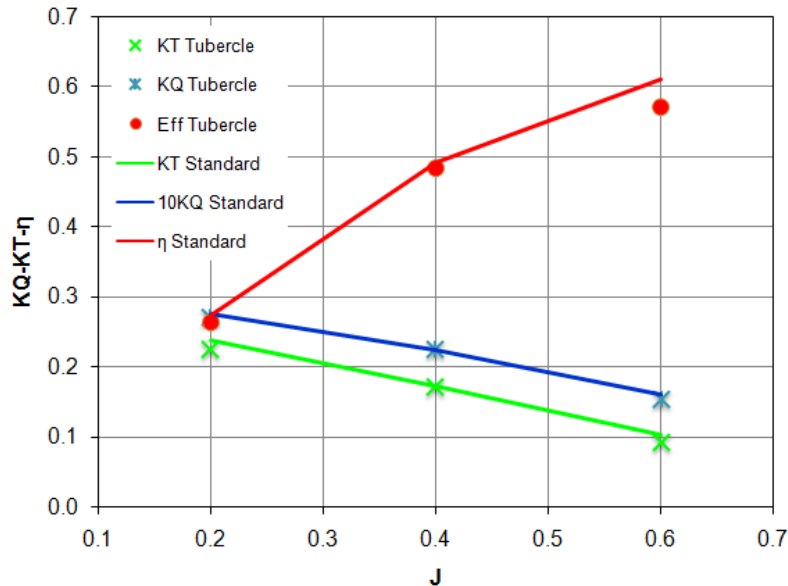

Figure. 3. Propeller performance in standard and TLE design.

III. RESULTS AND DISCUSSION

A. Propeller Performance

The results of the propeller performance after the overall modification decrease in terms of thrust, torque, and efficiency. Figure 3 shows the effect of TLE design on the propeller to the propeller performance, namely thrust, torque, and efficiency, compared to the standard propeller design. It shows that the thrust (KT) magnitude decreases to 10.4% in J=0.2 and almost the same at J=0.6. Meanwhile, at J=0.4, the thrust decreases only 1.1%.

Moreover, the torque value decreased to 4.3% in J=0.2 and almost the same at J=0.6 but increased only 0.4% at J=0.4. From the accumulated value of thrust and torque, it is found that the efficiency value decreases to 6.4%, decreases only 1.5% when J=0.4. The smallest decrease was only at J=0.4, but it almost doubled at J=0.6 compared to J=0.2.

The decrease in propeller performance is most likely due to the reduced propeller surface area due to modification. Some sections have reduced size among other sections. Also, this causes a streamwise waveform whose boundary layers coalesce due to differences in section thickness. The surface area is noticeably reduced, and the overall volume decreases. However, the propeller performance is also affected by the surface flow, especially at the leading edge after the modification. The details of the flow effect on the blade are discussed in the next section.
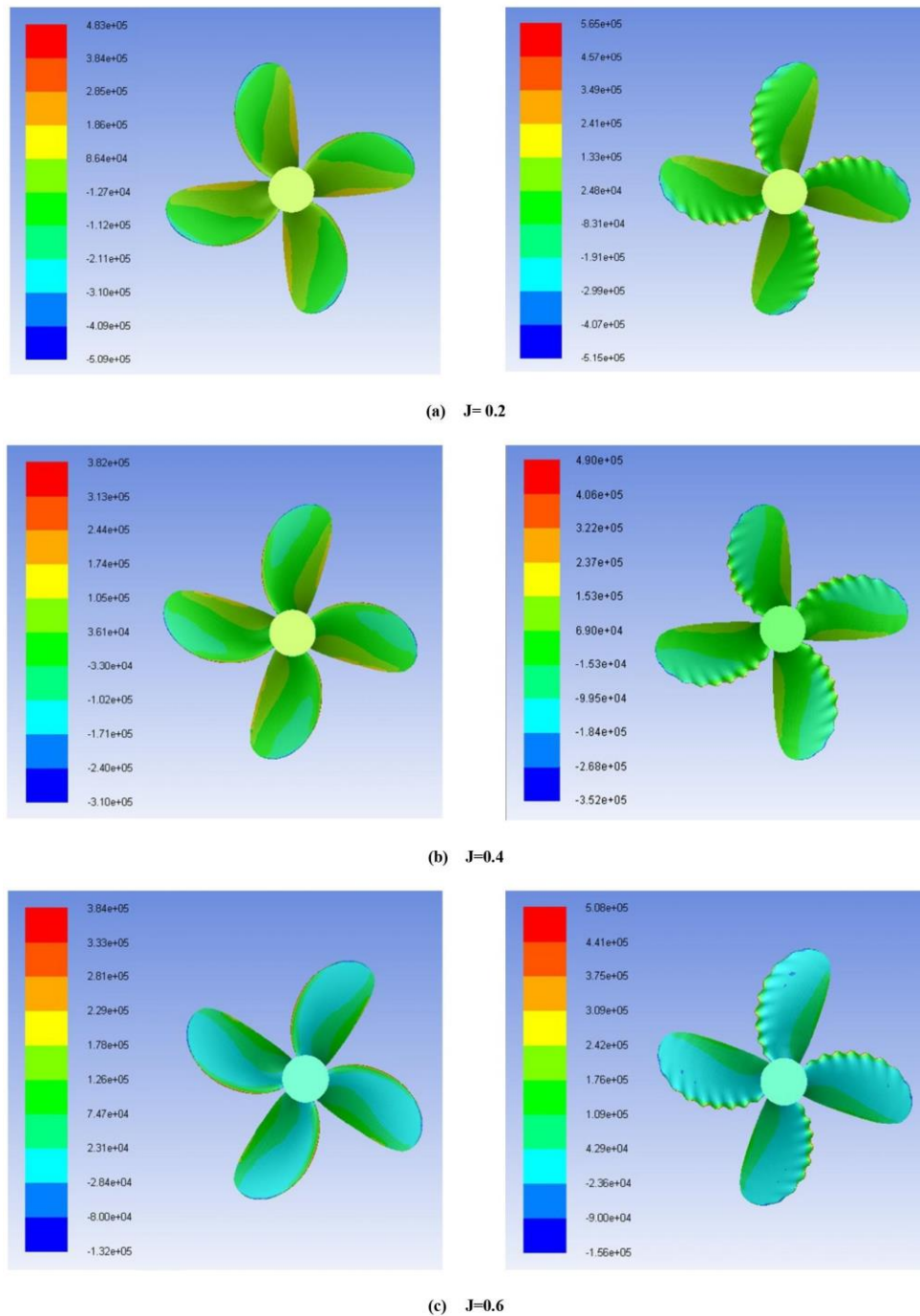
(a)   J= 0.2

(b)   J=0.4

(c)   J=0.6

Figure. 4. The total pressure on standard and tubercle propeller surface.

B. Total Pressure on The Propeller

Figure 3 shows the total pressure pattern on the standard and TLE propeller back surface in several J values. Overall, the total pressure is higher in the trailing edge but lower in the leading edge, both standard and TLE propeller. It is evident due to the blade shape, which thicker in the trailing edge. The trailing edge flow becomes faster than the leading edge due to Bernoulli's law, increasing the total pressure. The total pressure in the leading edge is initially high due to the fluid separation's initial force through the back and face surface. Moreover, a wider surface with low total pressure was detected near the propeller tip. However, the blade shape near the propeller tip is thicker than near

the boss cap; thus, the fluid freely flows through the surface and lowers the total pressure.

Figure 3 also shows that both standard and TLE propeller at high J value lowers total pressure to the propeller surface. The fluid velocity is proportional to the J value. At a high J value, the fluid velocity is higher than at a low J value, leading to lower pressure as the Bernoulli law.

However, the TLE design lowers the total pressure in the leading edge with a more expansive low total pressure in the blade. Moreover, a wider low total pressure surface shows a higher J value. The TLE surface increases the flow velocity on the leading edge, thus lowers the total pressure.
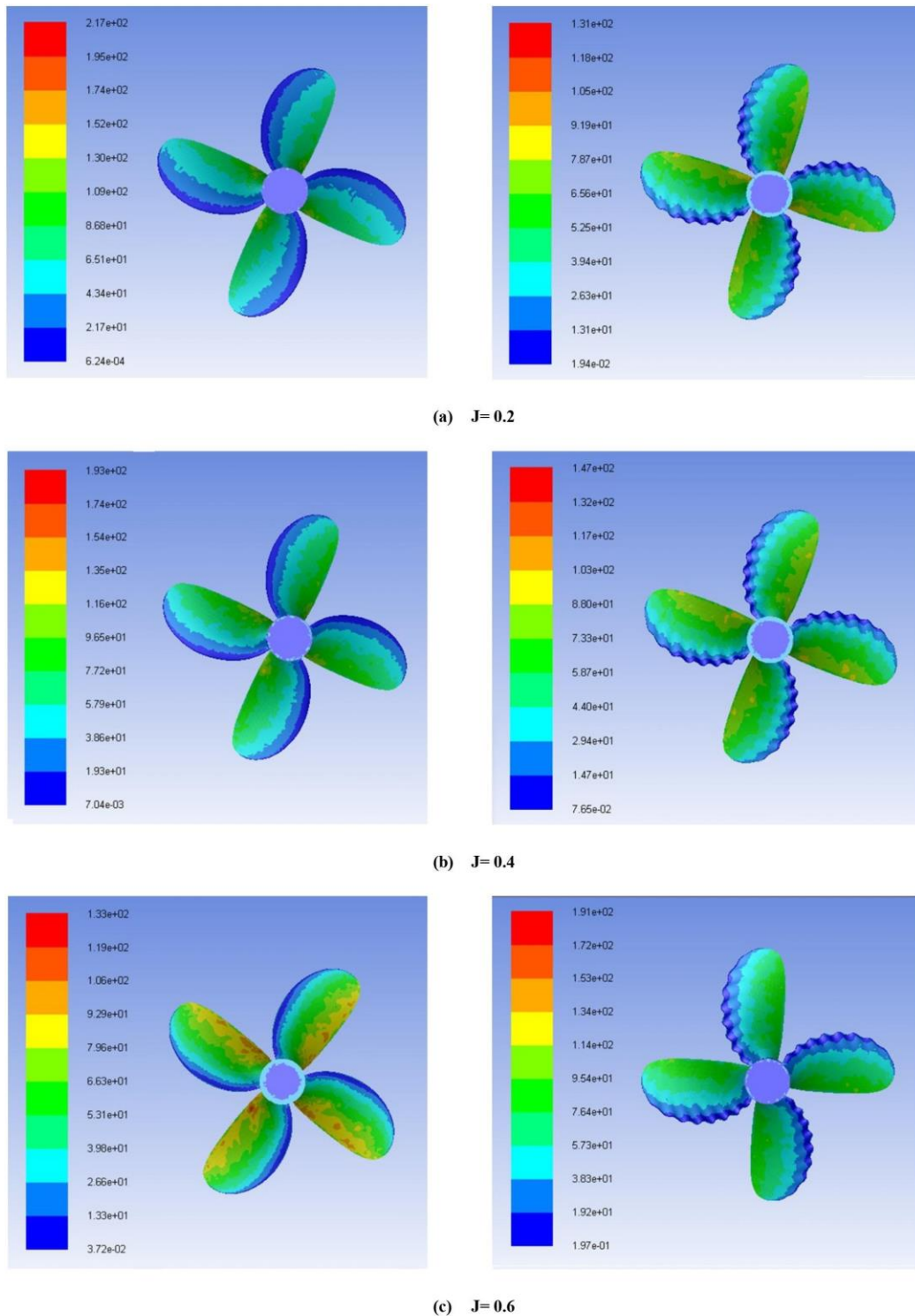
(a) J= 0.2

(b) J= 0.4

(c) J= 0.6

Figure. 5. Reynold number on standard and tubercle propeller surface.

C. Reynold Number on The Propeller

Figure 4 depicts the Reynold Number (Re) of the flow-through propeller blades (standard and TLE) with several J values. It shows that the Re at the leading edge is low and gradually higher to the trailing edge. It means that the flow tends to be laminar at the leading edge, and at the trailing edge, the flow tends to be turbulence.

However, a high J value leads to an increase in the standard propeller's surface turbulence. In contrast, TLE leads to lower turbulence. The standard propeller at low J value has a broader area at the leading edge with low Re. The area decreases as higher J value, but it is the opposite of the TLE. Besides, the TLE propeller's low Re area tends to be low and constant at all J values. It is due to the TLE shape, which separates the fluid flow and generates more turbulence flow at the blade surface.
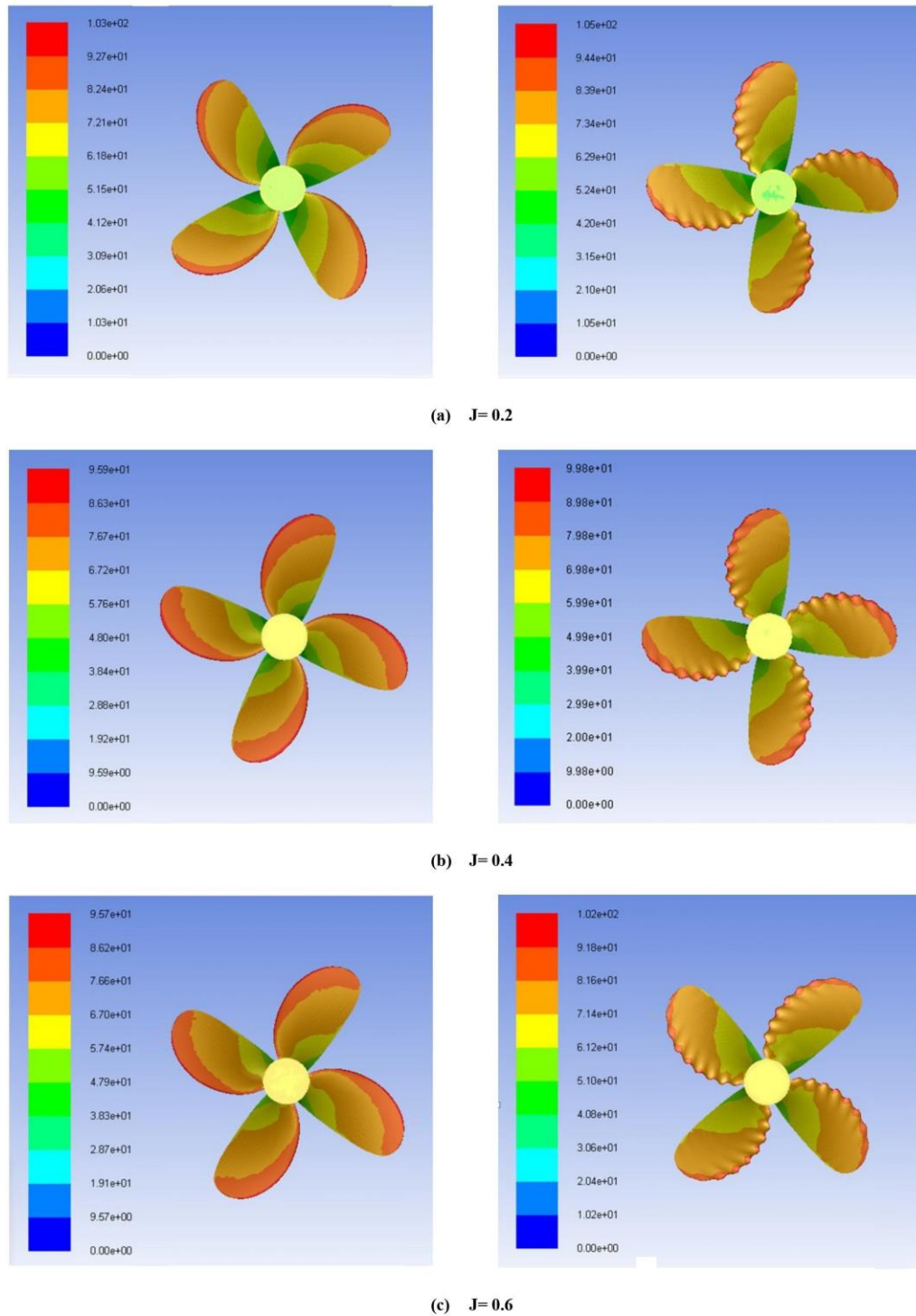
(a) J= 0.2

(b) J= 0.4

(c) J= 0.6

Figure. 6. Power surface acoustic on standard and tubercle propeller surface.

D. Power Surface Acoustic on The Propeller

Figure 5 shows the power surface acoustic on both standard and TLE propeller. The power surface acoustic indicates the noise which is generated to the propeller surface. However, the noise decreases after the leading edge in the standard and TLE propeller. Due to low pressure near the leading edge, it is then gradually higher to the trailing edge (specifically near the trailing edge). In low fluid pressure, the flow is generated in high resistance; thus, the noise increases. A Higher J value increases the fluid velocity, thus lowering the pressure through the blade; therefore, the fluid resistance increases, leading to increased noise. Besides, the highest J value (J=0.6) slightly decreases the noise near the leading edge. It is due to low pressure leads to very high velocity; thus, lower turbulence occurs.

Moreover, the noise in the propeller tip is higher than near the boss cap. It indicates that the fluid turbulence forms significantly at the propeller tip rather than near the boss cap. However, in Figure 5, TLE design at the leading edges decreases turbulence intensity and decreases noise.

IV. CONCLUSION

This research analyzes the propeller's effect with TLE design on the performance, total pressure, and noise compared to standard design in several J values. A CFD modeling method is used to identify the effect of TLE design. There are several conclusions from the identification:

a. The streamwise shape on the leading edge (TLE) significantly impacts the flow produced by propeller rotation in several variations of the advance ratio (J).

b. The TLE shape affects the slightly decreased performance at low J (0.2) and high (0.6) in torque, thrust, and efficiency. Whereas at J=0.4, the torque value increases, although it is not very significant at 0.4%. The thrust's value decreases only slightly by 1.1%, with the efficiency slightly decreasing by around 1.5%. However, this value is much lower than the decline that occurred in other J. The largest decrease was J=0.6, with a decreased torque value of 4.3%, a decrease in thrust value by 10.4%, and a decrease in efficiency by 6.4%.

c. The propeller's pressure and noise decrease due to the flow separation due to the sinusoidal shape.

Overall, this modification of the TLE propeller provides the advantage of a more regular flow with reduced noise. However, in terms of performance, it decreases slightly in the same dimensions. It is possible to get the same performance and benefits with a larger surface area.

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