Flow Separation Control of Marine Propeller Blades through Tubercle Modifications

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Abstract Tubercles are essentially sinusoidal serrations that are present in the fins of humpback whales. They have been widely postulated as a form of passive flow control device for aerodynamic surfaces. Studies pertaining the implementation of tubercles into aerofoils and turbine blades are widely present, while efforts in incorporating these tubercles onto marine propeller blades and how their presence alters the original propeller blade flow behaviour are comparatively less well understood. In this study, tubercle modifications are investigated in marine propellers through the use of high-fidelity Computational Fluid Dynamics (CFD). The results indicate that while there is a substantial increase in thrust generation of up to 10%, there is also a 5% decrease in propeller efficiency. The results indicate that the particular design and implementation of leading-edge tubercles here confer selected favourable flow effects upon propeller performance by varying the pressure and velocity distributions of the propeller blades.

Keywords: tubercles, marine propeller, open water characteristics

1 Introduction

Tubercle Technology

The implementation of tubercles as a flow control strategy in aerofoils was motivated by observations first made by Fish and Battle [1] on the movements of humpback whales. Humpback whales (Megaptera Novaeangliae) can grow up to 36 tons, but have high manoeuvrability as seen in Figure 1. The ability to change direction quickly is attributed to the presence of tubercles in the ends of the flippers. Preliminary studies have indicated that the morphology and placement of leading-edge tubercles act like enhanced lift devices to better control flow over the flipper and maintain lift at high angles of attack. It is from these observations that the basis of the present bio-inspired propeller study is derived: to explore tubercles as a potential passive flow control/enhancement device so as to prevent flow separations at higher angles of attack, thereby increasing the stall angle, creating larger advance ratios (J) and eventually, better propeller performance.

Tubercles are essentially similar to wavy sinusoidal protrusions on the leading-edge of the aerodynamic surface. They have also been described as periodic variation in the width of the wake across the span of a wavy bluff body. These protrusions create significant change to the aerodynamics, more significantly so as the geometry is tilted at higher angles of attack Johari et al [2]. The flow changes are akin to strakes on aircraft which generate large vortices that change the stall characteristics of wings [1]. The improvements seen in utilizing tubercles is a 3-D phenomenon that is both a function of the plan form geometry shape, as well as the Reynolds number [3]. Earlier authors concluded that aerofoils with tubercles may have potential applications in lifting surfaces that are required to operate past their stall point, such as wind turbine blades. This is observed by changes in flow separation patterns and surface pressure distributions by adding tubercles at the leading-edge. Separation was delayed downstream of the tubercle crest [4] and vortices were produced and re-energized the boundary layer by carrying high-momentum flow close to the flipper's surface [5].

This study represents an extension to the previous investigation conducted by Ibrahim and New [6] on the implementation of tubercles on a marine propeller blade. The current work emphasizes on the modification that leads to the formation of ridges on the surfaces of the blade. Global performance quantities of propeller thrust, torque and efficiency are measured. These quantities are taken across various advance ratio values. Further descriptions of the design methodology, results and discussion will be shown later.



Figure 1. Left: The Humpback Whale (Megaptera Novaeangliae). Right - Close-up of the pectoral fin with tubercles.

Applications

Johari et al [2] conducted experimental research on the effects of tubercles on a NACA 63₄-021 aerofoil profile. Tubercle amplitudes and spanwise wavelengths are varied in the design of the tubercles. The results indicated that in the pre-stall regime, protuberances caused a reduction in the lift coefficient. However, drag penalties were also incurred. In the post-stall regime, protuberances on the leading-edge resulted in higher lift coefficients, by as much as 50%, with negligible drag penalties. The main finding of the research was that tubercles amplitude has a more significant effect on resulting forces and moments, as compared to the wavelength. The flow over the protuberances remained attached well past the stall angle of the baseline aerofoil. Also, flow separation at the leading-edge of modified foils occurred mainly only in the troughs between the adjacent protuberances.

Hansen et al. [7] conducted studies on NACA 0021 and NACA 65-021 aerofoils and compared the effects of incorporating tubercles on these two aerofoils. Results indicated that using smaller tubercle amplitudes lead to higher lift coefficient and stall angle. In the post-stall regime, performance with larger amplitude tubercles is favourable. Results also showed that reducing the wavelength leads to improvements in all aspects of lift, stall angle and post stall characteristics, which was a direct contradiction to the results obtained by Johari et al. [2]. The NACA 65-021 aerofoil, with its maximum thickness located at the mid-chord location, saw negligible effect with the addition of tubercles. On the other hand, NACA 0021 aerofoil, with its maximum thickness located at 30% of the chord, saw improved lift performance in the post-stall regime. However, it has to be mentioned that this comes at the expense of degraded lift performance in the pre-stall regime. The working principle of the tubercles was further compared to that of a vortex generator by the study, similar to other studies conducted earlier [1, 3-5].

The success of deploying tubercles as a flow control device on aerofoils provided motivation for their implementation onto commercial industrial fans, or High-Volume Low-Speed (HVLS) fans. Envira-North Systems Ltd. are known for producing HVLS fans for large buildings (e.g., factories, warehouses, arenas, dairy barns and etc) incorporated with leading-edge tubercles designed by Whalepower Corporation. In addition to being 25% more efficient, the HVLS fan is also 20% quieter as compared to conventional ceiling fans. Note that the suppression of tonal noise by the addition of tubercles to an aerofoil was observed in a low-speed wind tunnel before [7], where tonal noise was found to be most effectively reduced by tubercles of large amplitude and smaller wavelength.

A study by Zhang and Wu [8] investigated aerodynamic characteristics of a bionic wind turbine which used blades with modified sinusoidal leading-edges, based on 3-D Reynolds Averaged Navier-Stokes (RANS) simulations. The geometry that was investigated was a National Renewable Energy Laboratory (NREL) phase-VI wind turbine. The radius of the blade was 5.029 m and its chord length measured 0.737m. A variety of wavelengths and amplitudes values were investigated with a view to ascertain an optimal modified configuration. Note that, as with typical wind turbine studies, only the flow surrounding the wind turbine blades was simulated and analysed. The results indicated that strong flow separations occurred typically along the mid- chord locations for the baseline blade. In contrast, the use of a sinusoidal blade limited these flow

separations significantly closer to the leading-edge, as well as rendering them more organized and perhaps, more susceptible towards better flow control.

The applications thus far highlight the use of tubercles only in a single-axis curvature form. As the marine propeller blade 'twists' along the radial axis, it would be interesting to investigate the effectiveness of this implementation in this form of geometry. The methodology of designing the modified blades will be described next.

Recently, a study by Ibrahim and New [6] describes the effects of implementing leading edge tubercles to a marine propeller. The results indicate that although there was an increase in propeller thrust at the low advance ratios, propeller efficiency only increased from J=0.84 onwards. In this current work, we explore a different design methodology which, in addition in to the implementation of the tubercles, resulted in added ridges on the surfaces of the blade. The hypothesis is that these ridges create enhances flow attachment which will have an effect in overall propeller open water characteristics.

2 Methodology

The following section describes the blade design, numerical techniques and mesh analysis used in this study.

Blade design

The baseline and modified propellers are 375mm in diameter and is shown in Figure 2. The propeller consists of three blades and a circular hub which tapers at the pressure side of the blades. The modified blades are designed by the Computer Aided Design (CAD) software, SOLIDWORKS [9]. In this design methodology, the blade is lofted without the use of guide curves which results in *naturally* formed ridges. Therefore only one factor is constrained in this design methodology: The conservation of the propeller blade area. As a preliminary analysis, the tubercle profile of a wavelength of 25% the mean chord length of the blade, as well as an amplitude of 2.5% mean chord length was utilized. The mean chord length had been calculated as 80mm. The modification results in a tubercle profile consisting of six pairs of crests and troughs, as illustrated in Figure 2. The crests of the tubercles protrude above the baseline propeller leading edge indicating conservation in blade areas. Note also the ridges that are formed on the surfaces of the blade.



Figure 2. The baseline (blue outline) and modified (light brown) propellers superimposed and shown at the propeller suction side (left). A zoomed-image of the modified blade is shown on the right. Note that the image is coloured according to its curvature.

Numerical technique

The specifications of the simulation domain size are shown in Figure 3. The size of the simulation domain were deemed large enough to result in negligible change in the open water characteristics results based on

investigations previously conducted. A periodic simulation was also not utilized as a full propeller simulation did not incur significant computational costs.

The numerical predictions presented in this work were performed by Fluent 15 [10]. The Multiple Reference Frame (MRF) approach was applied in the simulation of the marine propeller. The propeller is placed within a subdomain called the *Rotating* domain, while the remaining portions were stationary or *Fixed*. Due to the large difference in impeller size relative to the simulation domain, the absolute velocity formulation was selected. The governing equations for fluid flow for a steadily moving frame can be written as follows:

Mass conservation:

$$\nabla \cdot \rho \vec{v}_r = 0 \tag{1}$$

Momentum conservation:

$$\nabla \cdot \left(\rho \vec{v}_r \vec{v}\right) + \rho \left[\vec{\omega} \times \vec{v}\right] = -\nabla p + \nabla \cdot \overline{\vec{\tau}} + \vec{F}$$
⁽²⁾

where

 $\rho = \text{Density } (\text{kg/m}^3) = 998.2 \text{ kg/ m}^3$ $\vec{v} = \text{Absolute velocity } (\text{m/s})$ $\vec{v}_r = \text{Relative velocity } (\text{m/s})$ $\vec{\omega} = \text{Angular velocity } (\text{rad/s})$ $\vec{\tau} = \text{Viscous stress}$ $\vec{F} = \text{Body force}$

The inlet, outlet and outer boundaries of the *Fixed* part were located at a distance which were large enough that would dispel any changes to the solution. The inlet boundary condition having a turbulence intensity of 5% and a normal free stream velocity component of 2 m/s. A zero Pascal static pressure was imposed at the outlet boundary. A no-slip boundary condition was applied to the propeller wall.

The realizable k- ε model with Enhanced Wall Treatment (EWT) was utilized as a turbulence model in this work. The key reasons in using the k- ε model are robustness, economy and reasonable accuracy for a wide range of turbulent flows. The realizable model is recommended relative to other variants of the k- ε family because of the improvements shown where the flow features include strong streamline curvature, vortices, and rotation. The EWT specification is also utilized in conjunction with the k- ε model. The EWT is a near-wall modelling method that combines a two-layer model with enhanced wall functions. This method is effective in combining the accuracy of a standard two-layer approach for fine near-wall meshes as well as conservative analysis for wall-function meshes.



Figure 3. Simulation domain size used in the analysis.

Mesh analysis

A mesh convergence study was conducted on the baseline propeller. Unlike previous numerical marine propeller studies which only investigates grid convergence on one advance ratio value, the present work analyses grid convergence across a range of advance ratios. Three different mesh settings were utilized and henceforth named 'Coarse', 'Medium' and 'Fine'. The 'wall' boundary condition employed to the propeller has been inflated with regular prismatic meshes to adequately resolve boundary layer growth. The thrust and torque characteristics were virtually similar for the three grid settings. To highlight their difference, the graphs are redrawn as a percentage difference to the baseline propeller curves.

The results indicate that for thrust, the profiles obtained for the 'Medium' and 'Fine' cases were almost identical. The results obtained had differences of between -3.5% and -11% at J=0.4 and J=0.9 respectively. For the torque results, the 'Medium' grid setting recorded a difference of -3% and 2% for the two advance ratio values. Based from the values, the 'Medium' grid setting was utilized in the simulations. The resulting average y+ value calculated for the baseline propeller blade and hub is 37. The average y+ values for the modified propellers lie in the range of 20~30. The simulation and towing tank results for the thrust and torque coefficients are shown in Figure 5. Good agreements can be inferred from the data. A close-up grid view of the baseline propeller blade for the 'Medium' setting is shown in Figure 6.



Figure 4. Differences in thrust (left) and torque (right) as a percentage to the baseline propeller curves.



Figure 5. Thrust and torque coefficients for the simulation and towing tank experiment.



Figure 6. Mesh view of the propeller (left) and zoomed near the blade (right).

3 Results

Classical propeller open water characteristics were used as performance metrics in this study. The metrics are: thrust coefficient, torque coefficient and propeller efficiency. These values were taken across a range of advance ratios from 0.4 to 0.9 and are expressed as:

Thrust Coefficient:

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

Torque Coefficient:

$$K_{Q} = \frac{Q}{\rho n^2 D^5} \tag{4}$$

Advance Ratio:

$$J = \frac{V_a}{nD}$$
(5)

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Efficiency:

$$\eta = \frac{K_T}{K_Q} \frac{J}{2\Pi}$$

where

T = Thrust (N) $\rho = \text{Density (kg/m^3)} = 998.2 \text{ kg/ m}^3$ n = Rotational speed (rps) D = Propeller diameter (m) = 0.375 mV = Characteristic velocity of flow (m/s) = 2 m/s

Thrust, Torque and Efficiency



Figure 7. Percentage differences in performance metrics of the modified propeller compared to the CFD baseline design results as denoted as the x-axis.

The performance metrics for the modified and baseline propellers are plotted in Figure 7. Compared to the earlier work conducted [6] which had only resulted in a small increase in thrust, the results in the present study show that implementing the tubercles modification, together with the surface ridges, improve thrust coefficient significantly to a maximum of about 10% at J=0.9. However, there is also an increase in torque to a maximum of about 10% across the range of the advance ratios, and therefore a decrease in propeller efficiency. The propeller efficiency increases with higher advance ratios, albeit lower than the results obtained for the baseline propeller. These trends were also similarly uncovered in [6]. However the major increase in thrust is a significant finding for propeller designers interested in enhancing the raw power output of the propeller. To fully understand the results of the open-water propeller characteristics, examination of the near-wall flows, for instance, the nature of the flow close to the blade surface, boundary layer separation and corresponding flow structures will be shown in the next sub-section.

Wall shear streamlines

The wall shear streamlines for the baseline and modified propellers at J=0.9 and J=0.4 are shown in Figure 8 and Figure 9 respectively. As an indication of flow direction, the bottom edge of the propeller is the leading edge, where the magnitudes of the streamlines are at their largest.

However what is of interest here is not so much the magnitude, but how the resulting streamlines meander along the surfaces of the blades. For J=0.9, the results show that the streamlines along the baseline propeller blade are virtually parallel to one another. However at J=0.4, at the blade tip vicinity, the streamlines meander in the radial direction towards blade tip. The meandering becomes more discernible for the modified propeller at J=0.4, particularly at trough closest to the blade tip. For the modified blades, the streamlines appears to emanate from the crests of the tubercles and propagate coherently downstream of the blades. This suggests

(6)

enhanced flow separation behavior at the troughs of the tubercles, more so than what had been observed in the previous study [6].



Figure 8. Wall shear streamlines for a baseline (left) and modified (right) propeller blade at J=0.9.



Figure 9. Wall shear streamlines for a baseline (left) and modified (right) propeller blade at J=0.4.

Blade surface pressure

Similarly, the contours of the surface pressure for the suction sides of the baseline and modified propellers at J=0.9 and J=0.4 are shown in Figure 10 and Figure 11 respectively. The surface pressure of the blades provide correlation to the forces acting on the blade, specifically resulting in thrust. At J=0.9, variations of the surface pressure between the baseline and modified propeller blades can be seen. A low pressure region is seen at the tubercles initiating from the central troughs to the blade tip. This changes downstream pressure profile of the blade. A low pressure depression (blue oval) can also be seen near the tip of the trailing edge of the modified blade.

At J=0.4, the pressure profiles are somewhat similar. However it can be seen that the ridges near the tip of the blade seem to disrupt the high pressure uniformity that had been present in the baseline blade. Figure 12 shows velocity contours of the baseline and modified propeller along various streamwise stations. Similar to what had been observed for the blade surface pressures, the modifications to the blade appears to have disrupted velocity profile uniformity by creating high velocity regions. At x=0.02m, a high velocity region can be observed at the troughs of the third tubercle from the root. The size of the region seem to increase as observed at the troughs of the tubercles at x=0.01m. The ridges also assist in maintaining characteristics downstream to x=0m. At x=-0.01m, the velocity contours for the baseline and modified are fairly similar.



Figure 10. Surface pressure for a baseline (left) and modified (right) propeller blade at J=0.9.



Figure 11. Surface pressure for a baseline (left) and modified (right) propeller blade at J=0.4.

Velocity contours along streamwise direction

Figure 12 shows velocity contours of the baseline and modified propeller along various streamwise stations. Similar to what had been observed for the blade surface pressures, the modifications to the blade appears to have disrupted velocity profile uniformity by creating high velocity regions. At x=0.02m, a high velocity region can be observed at the troughs of the third tubercle from the root. The size of the region seem to increase as observed at the troughs of the tubercles at x=0.01m. The ridges also assist in maintaining characteristics downstream to x=0m. At x=-0.01m, the velocity contours for the baseline and modified are fairly similar.



Figure 12. Surface velocity contours for the baseline and modified propellers at J=0.4 positioned along various streamwise locations.

Vortex core regions

A vortex core is an isosurface visualization technique that displays a vortex. Similar to that had been used in [6], a vortex core implementation based from the Q-criterion as described by index introduced by Hunt, Wray and Moin [11], was implemented. The formulation, also known as the *second invariant*, is defined as:

$$Q = \frac{1}{2} \left[\Omega^2 - S^2 \right] \tag{7}$$

where Ω and S is the vorticity and strain rate tensors respectively.

The Q-criterion identifies vortices as flow regions with positive second invariant. In this case, to isolate the vortical structures near the propeller, the Q value was set as $42000 \ 1/s^2$. The vortex core is rendered according to the pressure magnitudes of the isosurface.

The vortical wake structures for both the baseline and modified propellers in Figure 13 can be divided into two main parts; the vortex core generated at both the leading edge of the blade, as well as the blade tip vortices. The results indicate that the tip vortex size and magnitude for both baseline and modified propellers are similar. However, for the modified propeller, vortical structures can also be seen emitting from the troughs of the tubercles and seemed to be attempting to reattach themselves to the downstream vortical sheets. The length of these emissions increases nearer to the tip of the blade.



Figure 13. Vortex core regions for the baseline (left) and modified (right) propellers at J=0.4.

4 Conclusions

The results show that implementing the tubercles and the ridges to the propeller improves thrust coefficient significantly to a maximum of about 10%. However, there is also an increase in torque of about 10% across the range of the advance ratios and therefore a net decrease in propeller efficiency. The propeller efficiency increases with higher advance ratios, albeit lower than the results obtained for the baseline propeller. The major increase in thrust is a significant finding for propeller designers interested in enhancing the raw power output of the propeller. The results indicate that adding the ridges on the surfaces enhances flow separation which had been initiated from the troughs of the tubercles. This varies the downstream pressure and velocity characteristics of the propeller blades. It may be possible to use the isosurface plots to predict the extent of the cavitation regions. However, this would require careful calibration of the Q value for accurate and optimal predictions. Although no cavitation is observed for the baseline propeller in open water tests (and modelled as such in the present study), it remains to be seen whether the tubercles would induce this phenomena at higher operating speeds, particularly at the sharp edges of the crests.

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