A Critical Review on Tubercles Design for Propellers

A Seeni, P Rajendran and H A Kutty

School of Aerospace Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Pulau Pinang, Malaysia.

Email: aeparvathy@usm.my

Abstract. The design of propellers in aeronautics is still earning high interest. This has led to the application of biomimetic for improving aerodynamic performance. One such design is the usage of tubercles in either leading or trailing edge of airfoils. So the usage of tubercles has so far been in the design of wing or wind-turbines. Recent studies have aimed to study tubercles for the design of a propeller. The studies have so far gained reputations in improving the aerodynamic performance on a few but not all of the airfoil shapes. Similar results have been identified for propeller designs with improvement in thrust at low torque. We have so far led research works on developing new propeller designs with the aim to improve the thrust and torque performance of propeller. A review of recent studies has been performed to study the state-of-the-art. The results of this work will be discussed in this paper.

1. Introduction

Significant research has been witnessed in aircraft propeller design in recent years. Much of the research’s focus can be attributed to straight-edged propellers [1]. Modern propeller research has focused on providing modifications to existing designs [2]. This has been achieved by development of new designs and modifications to either leading or trailing edge of propeller surface which are made up of airfoil cross-sections. One of these modifications amongst others is tubercles.

Tubercles are sinusoidal wavy formations on the leading edge (LE) that takes the form throughout the surface from leading to trailing edge (TE). The implementation of tubercles on modern airfoil surfaces originated from the works of Fish and Battle in 1995 [3]. Tubercles are essentially designs based on biomimetic. The pectoral flippers of humpback whales are found to provide improved aerodynamics with reduced drag while diving and catching prey (Figure 1). The tubercle design has so far been adapted to many but not limited to design of aircraft, marine propeller as well as wind turbine blades.

In this paper, a review of recent studies performed in the topic of tubercle propeller designs will be made. Although many studies have reported on this particular development in aircraft components such as wing, new studies on its usage on propeller design have emerged. Current research calls for an improvement in propeller design with high thrust, low torque characteristics. With this in mind, a detailed survey has been undertaken in order to review the state-of-the-art. The discussion on the same is divided into the following sections in this paper.
In section 2, recent research made in the field of designing propellers with tubercles will be discussed. In addition, a comprehensive survey of various studies related to tubercles that are not only limited to propellers but also on other airfoil applications will be provided. In section 3, a discussion of results from the various studies will be provided. In section 4, new improved designs will be suggested with a goal to provide future improvements. Section 5 provides conclusive remarks.

![Humpback whale's pectoral flipper with tubercles on leading edge](image)

**Figure 1.** Illustration of humpback whale's pectoral flipper with tubercles on leading edge [4].

### 2. Methodology

Most of the studies on tubercles so far have been on non-thrust generating designs of fixed aircraft wing and wind turbine and very few studies exist that have been implemented directly on either aircraft or marine propellers. Studies on non-thrust generating platform try to improve lift and stall angle whereas propellers with tubercles have been studied to improve thrust generation. Recent research in this topic will be discussed subsequently.

#### 2.1. Propellers designs

The study by Ibrahim and New [5] is on marine propellers designed with tubercles. Tubercles are implemented on LE of the airfoil. The wavelength, amplitude, airfoil, propeller diameter and blade number are fixed for a single design. The analysis is performed numerically in CFD for different advance ratios. The amount of performance in thrust and torque and aerodynamic efficiency improvements are predicted and compared with a baseline propeller. The baseline propeller is typically a propeller with straight LE of similar dimensions. The results of the study are provided in Table 1.

| Propeller design |
|------------------|
| Author | Ibrahim and New (2015) [5] |
| Study type | Numerical |
| Enhancement | 1.5% ↑ in thrust co-efficient ($C_T$) |

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The study by Moore and Ning [6] focuses on studying performance improvements of tubercles in small scale propellers. The design comprises of Clark-Y airfoil cross-sections. LE tubercular structure
is in the shape of oblate spheroid. The sizes of the oblate spheroid are varied as well as the spacing between them and tested for 9 different cases in total. The widths are assumed to be 5, 6.25 and 8 percent of propeller radius. The tubercle intervals are assumed to be 7.14, 8.33, and 10 percent of the effective propeller radius. The height of the spheroid tubercle is assumed to be 2/3 of widths. All the 9 cases were tested for similar Reynolds number (RN) of 5x10^4. The results of the study are summarized in Table 2.

**Table 2. Description of study by Moore and Ning [6].**

| Propeller design | Author | Study type | Enhancement |
|------------------|--------|------------|-------------|
| Author | Moore and Ning (2016) [6] | Experimental | C_T lower than baseline; Efficiency lower than baseline |

2.2. Other studies

Other studies done so far were on wing and wind turbine models. The studies have tried to examine the aerodynamic performance improvement such as lift and drag and efficiency over unmodified straight-edged models. These studies will be discussed subsequently.

In 2001, Watts and Fish [7] have performed a numerical study on aircraft wing with tubercle LE modifications. Both aerodynamic performance and efficiencies are compared to a baseline model. The model with tubercles is assumed to be similar to that of the humpback whale flipper’s cross-section resembling a NACA 634-021 airfoil. A free stream velocity (V_{infty}) of 1 m/s is assumed for the analysis. The results from the study are provided in Table 3.

**Table 3. Description of study by Watts and Fish [7].**

| Propeller design | Author | Study type | Enhancement |
|------------------|--------|------------|-------------|
| Author | Watts and Fish (2001) [7] | Numerical | 4.8% ↑ in lift, a 10.9% ↓ in induced drag, 17.6% ↑ in lift to drag ratio |

The study by Pedro and Kobayashi [8] is on studying tubercles for designing of wings of small Unmanned Aerial Vehicles (UAVs). The study consists of both numerical and experimental tests of two tubercled models, also known as flippers, namely scalloped and smooth. The model uses tapered wing tips. The tests were performed for a RN of 5x10^5. The description and results of the study are summarized in Table 4.

Hansen et al. [9] has performed an experimental study on LE tubercles of a full and finite wing. A NACA 0021 airfoil section is assumed. The lift coefficients (C_L) and drag coefficients (C_D) are found for wings with tubercle wavelength variations of λ = 7.5, 15, 30 and 60. Also amplitude variation of 2 and 4 is considered for a fixed wavelength. Both C_L and C_D variations are studied and compared with unmodified airfoil. Also both 2D and 3D airfoil is considered with fixed RN at 1.2x10^5. The results of the study are summarized in Table 5.
Table 4. Description of study by Pedro and Kobayashi [8].

| Propeller design | Pedró and Kobayashi (2008) [8] |
|------------------|-------------------------------|
| Study type       | Numerical and Experimental    |
| Enhancement      | Scalloped flipper exhibited better performance than smooth model |

Table 5. Description of study by Hansen et al. [9].

| Propeller design | Hansen et al. (2010) [9] |
|------------------|--------------------------|
| Study type       | Experimental             |
| Enhancement      | ↑ in performance of tubercles for RN ≥ 5x10⁴; ↓ in performance for RN < 3x10⁴ |

The study by Lohry et al. [10] is on studying the aerodynamic performance of a 3D wing model with tubercled LE. NACA 0020 airfoil section is used in this study. The RN assumed for flow condition is from 6.25x10⁴ to 5x10⁵. The details of this study are provided in Table 6. The study by Xingwei et al. [11] is on studying tubercles for gliding and flapping flight of Micro Air Vehicles. A CFD approach is followed for studying tubercled airfoils with NACA 0014 cross-sections. A low RN of 1x10⁴ is assumed. The results of the study are also summarized in Table 7.

Table 6. Description of study by Lohry et al. [10].

| Propeller design | Lohry et al. (2012) [10] |
|------------------|--------------------------|
| Study type       | Numerical                |
| Enhancement      | 4.8% ↑ in lift, a 10.9% ↓ in induced drag, 17.6% ↑ in lift to drag ratio |

The study by Zhang et al. [12] is on the aerodynamics of LE protuberances with models operating at a $V_{inf}$ of 7.5 m/s and RN of 5x10⁴. The models are of NACA 63₁₄₀₂₁ airfoil cross-sections. The aerodynamic loads, stall characteristics and stream-wise vortices were studied experimentally with fixed amplitude and wavelength. The details of this study are provided in Table 8. The study by Ibrahim et al. [13] is on studying both tubercles and slotted blades for wind turbine blades. Tubercles are implemented at the TE in this study. The test model consists of a blade with NACA 4412 sections.
and diameters of 60 cm. Different $V_{\text{inf}}$ from 4 to 8 m/s are assumed. The results from the study are provided in Table 9.

### Table 7. Description of study by Xingwei et al. [11].

| Author            | Xingwei et al. (2013) [11] |
|-------------------|---------------------------|
| Study type        | Numerical                 |
| Enhancement       | Gliding flight. Tubercles provide negligible effect compared to baseline at zero Angle of attack (AoA). At higher AoA, tubercles improve flight performance. |

### Table 8. Description of study by Zhang et al. [12].

| Author            | Zhang et al. (2013) [12] |
|-------------------|--------------------------|
| Study type        | Numerical                 |
| Enhancement       | 25% ↑ in $C_L$, 20% ↑ in CD, 39.2% ↑ in L/D. Aerodynamics performance decreased i.e. lessened lift in near stall region due to complicated flow modification compared to baseline. |

### Table 9. Description of study by Ibrahim et al. [13].

| Author            | Ibrahim et al. (2015) [13] |
|-------------------|-----------------------------|
| Study type        | Experimental               |
| Enhancement       | Improved steady behavior for $V_{\text{inf}}$ changes compared to baseline; Stall occurs at higher wind speed than baseline |

The study by Rostamzadeh et al. [14] is on predicting performance using CFD on the effects of $R_N$ on two different tubercled models and straight-edged model. Both models are identical with one a scaled up version of the other and having similar NACA 0021 cross-sections. The models are compared to a straight-edged model of similar sizes. The study was performed for flow conditions of $1.2 \times 10^5$ and $1.5 \times 10^5$ $R_N$. The results are provided in Table 10. The study by Serson et al. [15] on tubercles is on an infinite wing for a very low $R_N$ of $1 \times 10^3$. The analyses was performed for 9 designs with different wavelengths and amplitude and compared to a baseline design. The results are provided in Table 11.
Table 10. Description of study by Rostamzadeh et al. [14].

| Propeller design | Rostamzadeh et al. (2017) [14] |
|------------------|----------------------------------|
| Author           | Numerical                        |
| Study type       | Inferior performance of tubercled model with lower $C_L$ post-stall, as compared to straight-edged models. In turbulent regime, the baseline experiences gradual stall and produces more lift than the tubercled model. Baseline model yields higher $C_L$ at post-stall angles. |

Table 11. Description of study by Serson et al. [15].

| Propeller design | Serson et al. (2017) [15] |
|------------------|---------------------------|
| Author           | Numerical                 |
| Study type       | Weakening of suction peak causes reduction in AoA. Lower effective AoA caused by LE waviness leads to reduction in lift. |

3. Discussion

The above discussed studies are categorically summarised in tabular form and compared in Table 12. The discussion of the results is two-fold. The aerodynamic improvement values for the designs considered are provided in terms of augmentation in thrust or power and torque. Studies that have discussed design of aircraft wing or turbine blades, the maximum lift co-efficient ($C_{L_{max}}$) and $C_D$ achieved in simulation or experiments is provided. The discussion on the same is provided subsequently:

- Watts and Fish [7] and Zhang et al. [12] have performed tests on tubercles with NACA 63,4-021 airfoil sections. The results of both the studies indicate positive maximum increment of $C_L$ of 4.8% and 25% respectively compared to baseline. Similarly, the $C_D$ has shown a 10.9% and 20% decrement. A value of RN was not provided but tests measured at a $V_{inf}$ of 1 m/s. The numerical results of Zhang et al. [12] were obtained for RN of $5 \times 10^6$.

- The study by Miklosevic et al. [16] and Lohry et al. [10] is on tubercled models with NACA 0020 sections. Miklosevic et al. [16] has studied two different variants – scalloped and smooth whereas Lohry et al. [10] has performed analysis on point design. A $C_{L_{max}}$ of 0.93 and 0.88 is achieved for scalloped and smooth flipper model cases respectively by Miklosevic et al. [16]. In the case of Lohry et al. [10], the $C_{L_{max}}$ is approximately 0.9. 13% decrease in $C_L$ is found at AoA 12⁰ for smooth case. Both models have shown to develop higher $C_D$ at 34% and 69%. Therefore lower aerodynamic performances have been observed in both. Irrespective of RN in both these studies, the above results has been found.

- The studies by Hansen et al. [9] and Rostamzadeh et al. [14] are on models with NACA 0021 airfoil cross-section. Both studies have been conducted for a RN assumption of $1.2 \times 10^5$, while Rostamzadeh et al. [14] has considered high additional RN values of $1.2 \times 10^7$ for a different model variant. Both $C_L$ and $C_D$ have shown a large decrement compared to baseline in the study.

- Xingwei et al. [11] have conducted tests on NACA 0014 airfoil cross-sectional models for flapping and gliding of MAVs. A higher $C_{L_{max}}$ was reached for tubercled model as compared to baseline. The RN assumed in $1 \times 10^5$. The study by Serson et al. [15] also has similarity in these
observations, however for a lower order RN of 1x10⁴. A marginally higher C_L,max is observed for AoA (α) of 21°.

- The study by Pedro and Kobayashi [8] on flipper models with hypothetical airfoil cross-section have yielded higher C_L for scalloped model as compared to smooth, although the stall AoA is delayed to a higher value which confirms observations made by Miklosevic et al. [16].
- The study by Ibrahim et al. [5] is on the usage of tubercles on TE. A pressure co-efficient (C_p) of 0.39 is achieved marginally higher over straight edged.
- Only two studies have studied the direct implementation of tubercles on propellers. Ibrahim et al. [5] studied tubercled LE propellers for marine applications on marine propellers. Clark-Y sections are considered. A 1.5% increase in C_T and 6% increase in Torque levels were observed. Moore and Ning [6] have focused on studying small scale propellers identified for UAVs. A C_T of 0.75 at advance ratio, J=0.1 and ~0% increase of C_T for all Advanced ratio (J) is observed. Both studies seem to agree that with increase in J the C_T gradually decreases. This is not so the case with propeller efficiency. As per Ibrahim et al. [5], the propeller efficiency increased with increasing J and the efficiency exceeds that of the baseline at J=0.85. However, the results seem to show negative feasibility of tubercles for UAV.

### Table 12. Summary of results from studies.

| Study                  | RN                | Variant       | Improvement                                                                 |
|------------------------|-------------------|---------------|----------------------------------------------------------------------------|
| Watts and Fish [7]     | V_{inf}=1m/s      | Baseline      | C_T / C_T, C_L,max, C_D,max, ∆C_L, ∆C_D                           |
|                        |                   | Tubercle      | NA - - NA - 4.8% ↑ 10.9% ↓                                                |
| Miklosevic et al. [16] | 5.05x10⁻⁵ - 5.2x10⁻⁵ | Baseline     | NA - - NA -                                                            |
|                        |                   | Scallop flipper | NA 0.93 - - 34% ↑                                                      |
|                        |                   | Smooth flipper | NA 0.88 - - 13% ↓ at α=12° 69% ↑                                       |
| Pedro and Kobayashi    | 5x10⁵             | Scallop       | NA <1 at α=18° 0.25 at α=21° - -                                      |
|                        |                   | Smooth        | NA >-0.9 at α=12° 0.225 at α=18° - -                                    |
| Hansen et al. [9]      | 1.2x10⁵           | Baseline      | NA >1 at α=12° - -                                                      |
|                        |                   | Tubercle      | NA >-0.95 at α=14° - - 1% C_T 1% ∆C_T                                  |
| Lohry et al. [10]      | 6.25x10⁻⁴ - 5x10⁴ | Tubercle      | NA >-0.9 at α=15° 0.24 at α=20° - -                                     |
| Zhang et al. [12]      | 5x10⁴             | Baseline      | NA - - NA -                                                            |
|                        |                   | Tubercle      | NA - - 25% ↑ 20% ↑                                                      |
| Xingwei et al. [11]    | 1x10⁴             | Straight      | NA >-0.125 at α=15° 0.08 at α=15° - NA NA NA NU                        |
|                        |                   | Tubercle      | NA >0.2 at α=15° - -                                                   |
| Ibrahim et al. [5]      | 2.9x10⁻⁷ - 5.3x10⁻⁴ | Tubercle     | 1.5% ↑ C_T 6% ↑ Torque NA NA NA NA                                     |
| Moore and Ning [6]     | 5x10⁴             | Tubercle      | ↑ C_T for all J NA NA NA NA                                             |
| Rostamzadeh et al. [14] | 15x10³           | Baseline      | NA 0.588 0.010 NA NA                                                   |
|                        | 1.2x10³           | A2W7.5        | NA 0.165 0.020 NA NA                                                   |
|                        | 15x10³            | A14W52.5      | NA 0.588 0.010 0 0                                                    |
| Serson et al. [15]     | 1x10³             | Baseline      | NA >0.8 at α=21° >0.4 at α=21° NA NA                                   |
|                        |                   | Tubercle      | NA >0.8 at α=21° (>baseline) >0.4 at α=21° (>baseline)                  |
| Ibrahim et al. [16]    | Varied            | Straight      | Mean C_p 0.36 NA NA NA                                                 |
|                        |                   | Tubercle      | Mean C_p 0.39 NA NA NA                                                 |

c=chord, ∆C_L=Lift co-efficient difference ∆C_D=Drag co-efficient difference, NA=Not Applicable
From the above discussions, the following remarks can be made. It can be concluded that the usage of tubercles,

1. Is suitable for delaying stall and therefore higher AoA can be reached for $C_{L_{\text{max}}}$.
2. Is for maintaining laminar flow during gust conditions. Therefore better performance during turbulence than straight-edged.
3. There is no concrete evidence of tubercles providing significant improvement in design for propeller design. For NACA 0020 and NACA 0021 sectional models, the lift and drag performance are found to be inferior compared to baseline straight-edged models. Only for NACA 634-021 airfoil sectional designs, a relatively higher lift and lower drag values have been achieved. This does not preclude the fact that for a propeller, the results showed only a marginal change in $C_T$ over baseline in all test cases.
4. The design of propellers is driven by a large number of factors. More detailed studies are required in order to provide concrete evidence on the usage of tubercles for propeller design.

The usefulness of tubercles for propeller design is not yet well-established. Other design modifications such as slots on airfoil surface could be used as high lift, low drag devices. Slots are devices that employ modification of flow control. Slotted designs of propellers have not yet been studied extensively. New innovative designs in slots could be useful for improving existing designs of propeller.

4. Conclusion

A review of studies based on tubercled LE has been conducted. The most significant results that were obtained so far have been discussed. The results primarily present a not-so-highly optimistic case for tubercled propellers. Future work on propeller will be directed based on these findings and conclusion.

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