A Critical Review on Slotted Design for Propellers

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Abstract. The usage of slots has gained renewed interest in aerospace particularly on propeller design. Most of the works have focused on improving the aerodynamic performance and efficiency. Modern research on propeller design aims to design propellers with high thrust performance under low torque conditions without any weight penalty. This paper aims to review recent studies made in slotted designs of aerospace structures as well as other applications such as wind turbines. A review on the usage of slots is performed in order to understand the state-of-the-art in current technology. A review of the various studies has been made and general recommendations are provided in order to perform future research in propeller design.

1. Introduction
The use of propellers as a thrust generation device has not diminished ever since the first flight of Wright Brothers. Propellers are axial rotating devices that impart forward motion for an aircraft. Initial designs modifications have so far been in increased thrust performance [1-2]. From 1920s to 1950s several inventions were patented in propeller design. The slotted propeller was a new development during this period such as those of Fairey (1938) [3] and Barnett (1939) [4].

Slots are devices that enable flow control modification around airfoil surface. This slotted concept is based on the principle that when an internal flow is introduced within the blade, the velocity of air is increased at the slot exit, disrupts the streamline flow and creates a flow separation reducing fluid velocity. The reduction in velocity increases pressure underneath the blade, thus generating more lift.

Slotted designs can be either active or passive. Active slots employ modification of flow control through blowing or suction or jets. Stored fluids are pumped and blown either tangential or vertical to the surface. Passive slots do not employ any additional active devices but rather use free stream air velocity. An illustration of a passive slot is given in Figure 1.

Figure 1. Illustration of a slotted airfoil cross-section [5].
Although patented inventions on slots are available decades earlier, very few studies exist in literature on slotted propeller design. 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 understand the state-of-the-art.

One of the earliest studies that examined the positive effect of slots on propellers was of Braslow in 1981[6]. The study examined the feasibility of slots as circulation control (CC) devices through the development of “Coanda effect”. A propeller with 2.13m diameter fitted with active CC is assumed. The airfoil shapes studied are elliptical and ellipses with modified trailing edge (TE) shapes. The TE of airfoils is blunted in order to improve lift. The Reynolds number (RN) assumed for the test case is $5 \times 10^5$.

The study demonstrated an increase in aerodynamic performance with the presence of slots. However the aerodynamic efficiency suffered. The study also suggested that blowing requires more engine power at cruise speed and altitude than baseline. Blowing causes reduction in propeller diameter needed for cruise; Blowing can provide additional thrust for climb and acceleration at lower speeds; Blowing also increases noise levels due to jet velocity at low altitudes; The study concluded that there is greater than 7% reduction in fuel consumption with CC.

Since then only a few more studies have been witnessed. Most of the studies are on improving the aerodynamic performance of aircraft wing and wind turbines. The cross-sections of a wing, wind-turbine and propeller are similar and therefore recent studies that have so far used slotted designs on either will be discussed in this paper. The discussion will be made henceforth. In Section 2, recent research made in the field of designing propellers with straight-edge will be discussed.

In addition, a comprehensive survey of various studies related to slots 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. New improved designs will be suggested with a goal to provide future direction. Section 4 provides conclusive remarks.

2. Methodology
Most of the studies on slot 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. Propellers with slots have been studied to improve thrust generation. Recent research in this topic will be discussed subsequently.

2.1. Passive slot
The study by Kweder et al. [7] is on performing a design feasibility study on using passive slots for small scale propellers. The propellers consisted of Clark-Y airfoil sections. The diameter of tested propeller is 0.609 mm which is small-scale and applicable for UAVs. The design is based on the principle of using the forward velocity of the aircraft to pressurize the internal CC plenum. The system is shown to provide 5.12% increase in aerodynamic efficiency over all range of flight envelope cases. The results of the study are provided in Table 1.

2.2. Other studies
2.2.1. Active slots. Huang [8] studied the suction and blowing flow control techniques on a NACA 0012 airfoil. A RN of $5 \times 10^5$ is assumed in this study. The results are briefly described in Table 2. Shojaeefard et al. [9] presents a numerical investigation concerning flow control by suction and injection. The investigation consists of a subsonic airfoil with four suction and injection slots on the
suction side of the airfoil. Five different AoA where 0°, 5°, 10°, 13.3° and 20° at a Mach number of 0.15 were studied. The effects of suction and injection on aerodynamic performance for each AoA are studied. The results of the study are provided in Table 3.

**Table 1.** Description of study by Kweder et al. (2014) [7].

| Study type  | Enhancement                                                                 |
|-------------|------------------------------------------------------------------------------|
| Experimental| 5.12% ↑ in aerodynamic efficiency on all flight envelope cases; Output thrust force marginally higher than baseline for all advance ratios \(J\); Power and torque co-efficient are ↑ than baseline design; As \(J\) increases, net negative thrust output is generated leading to power taken from free stream producing “wind milling” effect. |

**Table 2.** Description of study by Huang [8].

| Study type  | Enhancement                                                                 |
|-------------|------------------------------------------------------------------------------|
| Numerical   | When jet location and angles of attack (AoA) were combined, perpendicular suction at the leading edge (LE) increased lift coefficient \(C_L\) better than other suction situations; Tangential blowing at downstream locations was found to lead to the maximum increase in the \(C_L\) value. |

**Table 3.** Description of study by Shojaefard et al. [9].

| Study type  | Enhancement                                                                 |
|-------------|------------------------------------------------------------------------------|
| Numerical   | Suction increases the \(C_L\) by 10% over baseline. The injection mechanism causes reduction in friction drag. |
The study by Goodarzi et al. [10] is on the impact of slots on aerodynamic performance. The model is a 2D NACA 0015 airfoil sections and has assumed to have a slot with a width of 2.5% chord (c). Three slot positions, 10% c, 30% c and 50% c are considered. The analysis was performed for AoA between 12° and 17°. The flow conditions are assumed to have a RN of 4.55x10^5. The results of the study are provided in Table 4.

Table 4. Description of study by Goodarzi et al. [10].

| Author          | Goodarzi et al. (2012) [10] |
|-----------------|-------------------------------|
| Study type      | Numerical                     |
| Enhancement     | Blowing increases the amount of lift and reduces drag. At higher AoA, the separation is delayed and improves the performance of the airfoil. |

Yousefi et al. [11] performed a numerical study on slotted design with tangential and perpendicular blowing at the TE of a NACA 0012 airfoil. Perpendicular suction at the LE was applied on the airfoil upper surface. The jet widths were varied from 1.5% to 4% of the c and the jet velocity (Jet_A) varied between 0.3 and 0.5 of the free stream velocity. The performance improvements are provided in terms of lift-to-drag (L/D) ratio instead of $C_L$ and drag coefficient ($C_D$) increase or decrease. The results of the study are provided in Table 5.

Table 5. Description of study by Yousefi et al. [11].

| Author          | Yousefi et al. [11] |
|-----------------|---------------------|
| Study type      | Numerical           |
| Enhancement     | As the blowing jet width ↑, the L/D ratio ↑ continuously in tangential blowing and ↓ quasi-linearly in perpendicular blowing; The L/D ratio improves when the suction jet width ↑ and reaches its maximum value at 2.5% c. |

Eggert and Rumsey [12] have studied the impact of slots as an effective means of flow control on NACA 0018 airfoil. CFD method is used in this study. The flow control device consists of a blowing slot located on the upper surface of an NACA 0018 airfoil near the LE. The analyses were performed for RN of 2.5x10^5. Numerical analyses were performed using RANS and experimental study was performed in a wind-tunnel. The results of the study are provided in Table 6.

2.2.2. Passive slots. A study was conducted by Kang and Park [13] for a wind turbine with S809 airfoil sections. The RN assumed in this study is at 2x10^6. Five different AoA conditions, 0°, 1.02°, 5.13°, 9.22°, 14.24° and 20.15° were studied. The results of this study are described in Table 7. Xie et al. [14] has studied a flow control mechanism called split blade that is identical to slot. In this study, the effect of slots was studied on S809 airfoil that is investigated both numerically and experimentally.
The results show that at lower AoA from 0° to 10° the flow is unchanged. The $C_L$ is increased and $C_D$ decreased from AoA 15° to 20°. The results of this study are described in Table 8.

**Table 6.** Description of study by Eggert and Rumsey [12].

| Author                  | Eggert and Rumsey (2017) [12] |
|-------------------------|-------------------------------|
| Study type              | Numerical and Experimental    |
| Enhancement             | Blowing with high momentum coefficient ($C_\mu$) will ↑ the lift of the airfoil and delay flow separation. Slot with low $C_\mu$ will ↓ the lift and induce separation even at low AoA. |

**Table 7.** Description of study by Kang and Park [13].

| Author                  | Kang and Park (2013) [13] |
|-------------------------|----------------------------|
| Study type              | Numerical                  |
| Enhancement             | At 0.6$c$ slot location, maximum lift coefficient ($C_{L_{max}}$) is observed at AoA 14.24°. At 0.024$c$, a stall delay of 14.24° and 20.15° AoA is found. |

**Table 8.** Description of study by Xie et al. [14].

| Author                  | Xie et al. (2013) [14] |
|-------------------------|------------------------|
| Study type              | Numerical and Experimental |
| Enhancement             | 4.9% ↑ in $C_L$ at AoA 20°, 1.6% ↑ at AoA 15° |

Belamadi et al. [5] has studied the effect of slots as a passive flow control mechanism on wind turbines. The blade is assumed to be made of S809 airfoil sections. CFD analysis is performed for different configurations by varying slot location, slot width and slot slope. The analysis was performed on 2D models for varying AoA. The $RN$ for all analyses is $1x10^6$. The results of this study are described in Table 9. In addition to tubercles design, slotted designs are studied by Ibrahim et al. [15]. The test model consists of a blade with NACA 4412 sections and a diameter of 60 cm. Different free stream velocities from 4 to 8 m/s are assumed. The results from the study are provided in Table 10.
Table 9. Description of study by Belamadi et al. [5].

| Propeller design |
|------------------|
| Author           | Belamadi et al. (2016) [5] |
| Study type       | Numerical |
| Enhancement      | Aerodynamic improvement can be found only on specific range of AoA from 10° to 20°. At lower AoA there is significant drag penalty. |

Table 10. Description of study by Ibrahim et al. [15].

| Propeller design |
|------------------|
| Author           | Ibrahim et al. (2015) [15] |
| Study type       | Experimental |
| Enhancement      | Slotted blade was able to generate up to 60% more power at a lower speed compared to the straight blade |

3. Discussion

The various studies discussed have been summarized and the results are compared in Table 11. The discussion of the results is two-fold. The aerodynamic improvement values for the propeller designs considered are provided in terms of augmentation in thrust or power and torque. The discussions are provided subsequently:

- The study by Kweder et al. [7] confirmed that both aerodynamic performance and efficiency can be increased using slots. This is an improvement on the old design by Braslow [6]. The study by Kweder et al. [7] is different as it is on passive control on small scale propellers of UAVs with Clark-Y sections. Here a significant improvement in thrust co-efficient ($C_T$) values of 50% is achieved only with a small 17% ↑ in power co-efficient ($C_P$) for $J>0.25$ typical of normal operating conditions of UAVs. A 5.12% ↑ in aerodynamic efficiency is derived through this passive control.
- Huang [8] and Yousefi et al. [11] have studied slots with active jets on NACA 0012 airfoil models. The studies were conducted for a RN of 5x10^{-5}. The results indicate $C_L$ ↑ and $C_D$ ↓ over baseline for all test cases of section, perpendicular and tangential blowing. A high $C_L$ ↑ of 75% and 45% ↓ in $C_D$ was found by Yousefi et al. [11] for suction case. The study by Goodarzi et al. [10] is on NACA 0015 employing active blowing and assuming a RN of 4.55 x10^{-5}. Here an 80% ↑ and 45% ↓ in $C_L$ and $C_D$ values respectively has been achieved.
- Kang and Park [13], Xie et al. [14] and Belamadi et al. [5] have investigated passive flow control on S809 airfoils with different $c$ and RN. Still, all studies show a positive improvement in aerodynamic performance over unmodified baseline airfoil case. Xie et al. [14] has achieved a ↑ $C_{L_{max}}$ of 4.9% at AoA 19°. Belamadi et al. [5] has achieved a relatively low of 3.75% ↑ $C_{L_{max}}$ for AoA 16°. A 6.12% ↓ in $C_D$ at AoA 19° is also found.
- The study by Shojaeifard et al. [9] on Aerospatiale A-airfoil with 1.026 m $c$ indicates a 10% ↑ $\Delta C_L$ for suction case and 23% ↑ for injection.
In the case of wind turbines, the results from the study by Ibrahim et al. [15] with slotted blades provided a 60% ↑ in power compared to baseline. Slotted blades are shown to provide a high performance.

A different type of study was by Eggert and Rumsey [12] in which different blowing conditions at different coefficients were studied on a NACA 0018 test model using CFD. The results showed for Cp =5%, the C1 is much higher at 1.75 compared to 0% Cp.

Only two studies have so far been undertaken for employing slotted designs on propellers. Braslow [6] showed that a 7% ↓ in fuel consumption during cruise could be achieved. Kweder et al. [7] showed a 5.12% ↑ in aerodynamic efficiency.

**Table 11. Summary of results from studies.**

| Study name | Type | RN | Variant | Improvement |
|------------|------|----|---------|-------------|
| Braslow [6] | Active | 5x105 | Blowing | Propeller: >7% reduction in fuel consumption during cruise |
| Kweder et al. [7] | Passive | Varied | Not Applicable | 8-10% ↑ in torque at J<0.2; 50% ↑ bin Cp and 17% ↑ in Cp for J>0.25 and J<0.55. 8-10% more power required for all J |
| Huang [8] | Active | 5x105 | Suction | 1.243 0.805 - - - - |
| Shojaeifard et al. [9] | Active | M=0.15 | Suction | 1.295 0.708 <1.8 at AoA 14° ≤0.18 at AoA (0-18°) 75% ↑ at AoA 18° 56% ↓ at AoA 18° |
| Goodarzi et al. [10] | Active | 4.55x105 | Blowing | 1.070 0.926 <1.2 at AoA 14° <0.2 at AoA (0-18°) 7% ↑ 7% ↓ |
| Yousefi et al. [11] | Active | 5x105 | Tangential blowing | 1.021 0.897 <1.2 at AoA 14° <0.4 at AoA (0-18°) 8.5% ↓ at JetA=0.3 14.5% ↓ at JetA=0.5 8% ↑ at JetA=0.3 5% ↑ at JetA=0.5 |
| Eggert and Rumsey [12] | Active | 2.5x105 | Blowing | 1.021 0.897 <1.2 at AoA 14° <0.4 at AoA (0-18°) 8.5% ↓ at JetA=0.3 14.5% ↓ at JetA=0.5 8% ↑ at JetA=0.3 5% ↑ at JetA=0.5 |
| Belamadi et al. [5] | Passive | 1.8x106 | Not Applicable | ~1.12 at AoA 5° - 3.75% ↑ at AoA 16° 6.12% ↓ at AoA 19° |
| Ibrahim et al. [15] | Passive | Varied | Not Applicable | Wind turbine: 60% more power generated by slotted compared to straight-edged turbine blade. |
From the above, the following remarks can be made.

- Slotted designs provide a high $C_L$ regardless of airfoil shape and $RN$. Using blowing, a maximum $\Delta C_L$ over unmodified baseline of up to 80% is realistically achievable.
- Using suction, a maximum $\Delta C_L$ over unmodified baseline of up to 75% is realistically achievable.
- Active slotted designs have so far provided better $\Delta C_L$ increment to baseline. Therefore, active designs provide better performance enhancement over passive designs.
- Improvements in performance and efficiency for propeller design can be realistically achievable even by using passive designs. The thrust levels could be improved even at low torque inputs. The improved efficiency may reduce the total fuel consumption and take-off weight.

4. Conclusion

A review of studies based on slotted designs has been concluded. The most significant results that were obtained so far have been discussed. It can be found that slots provide significant aerodynamic improvements. Only very few studies exist that has studied slots directly for propeller blade design. New slotted designs will be studied extensively in the future.

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