Numerical investigation of the impact of tubercles and wing fences on the aerodynamic behaviour of a fixed-wing, tactical Blended-Wing-Body UAV platform

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Abstract. In this work, a study on the impact of passive flow control techniques on an Unmanned Aerial Vehicle (UAV) Blended Wing Body (BWB) is presented. The novel BWB layout integrates smoothly the wing to the fuselage, creating an aerodynamically superior platform. However, the lack of vertical stabilizers in the form of a tail, creates the need for aerodynamically stable and efficient wings that can withstand the spanwise flow. To that end, two passive flow control techniques are implemented in this study, namely the wing fences and the tubercles. Wing fences are vanes or airfoils attached vertically to the lifting surface and are one of the oldest flow control techniques used in aerospace applications to stop the spanwise flow. To that end, two passive flow control techniques are implemented in this study, namely the wing fences and the tubercles. Wing fences are vanes or airfoils attached vertically to the lifting surface and are one of the oldest flow control techniques used in aerospace applications to stop the spanwise flow. Wing fences extending from the leading edge to the trailing edge completely stop the spanwise flow. On the other hand, tubercles are sinusoidal modifications of the blade’s leading edge. This is a novel flow control technique, with the original concept inspired from the characteristic flipper of the humpback whale (Megaptera Novaenagiae). Each bump creates a set of counter-rotating vortices that acts as a virtual fence and stops the spanwise flow. The results from this comparison show that flow control techniques can offer a considerable benefit to the flying capabilities of a BWB UAV platform, by improving the lift distribution and increasing the maximum coefficient of lift.

1. Introduction
In the last decades, Unmanned Aerial Vehicles (UAVs) have been an engineering concept with increased development. A plethora of advantages that the UAVs have to offer, such as reduced operational risks and increased payload availability due to the lack of personnel [1], makes UAVs an appealing alternative. However, as aerodynamic designers struggle to stretch the range and endurance of the UAVs, conventional approaches can offer only so much. Adverse flow phenomena such as spanwise flow, transitional flow during take-off and landing, the wingtip vortices and flow separations introduce flow anomalies and hence reduce the efficiency of the vessels. In order to treat these flow disturbances, researchers have invested in the use of flow control techniques (FCT). Flow control is the manipulation of the free stream flow and can be done either actively, at the expense of extra energy (e.g. plasma actuators), or passively, by permanently altering the external shape of the wing (e.g. vortex generators).

The baseline platform of the present study is a Tactical Blended Wing Body (BWB) UAV. The novel BWB layout integrates smoothly the wing to the fuselage, creating a smooth transition and an
overall increased aerodynamic efficiency compared to a conventional tube and wings aircraft [2]. Its specifications are described in detail in the work of Panagiotou et al. [3] and its configuration layout can be seen in figure 1.

![Figure 1. The baseline platform: a Tactical Blended Wing Body UAV [3].](image)

The UAV has a total span of 7.2 m, and a center body length of 3 m. However, the lack of vertical stabilizers in the form of a tail, creates the need for aerodynamically stable and efficient wings. Furthermore, the highly swept wings (33°) mean that major spanwise flow is present, a flow phenomenon which further reduces the lift capability of the platform.

A novel passive flow control technique (PFCT) with considerable potential is the tubercles (figure 2), an array of sinusoidal bumps located at the leading edge of the wing. This concept has originated from the humpback whale’s (Megaptera Novaeangliae) fin. The whale can achieve high manoeuvrability, despite their disproportionate size, something that has been attributed to the tubercles [4]. The basic geometric characteristics of the tubercles, as shown in Figure 2, are the frequency length ($\lambda$) and the amplitude (A) of the bumps. The most plausible flow mechanism is VGs, while a second theory is that it acts as a virtual fence that can stop the spanwise flow [5].

![Figure 2. The tubercles: from inspiration to application.](image)

A more conventional approach to counter the spanwise flow is the wing fences (figure 3). Wing fences are thin vanes or airfoils, positioned on top of the wing, parallel to the free stream. The shape and length of the fence can vary, covering part of, or the whole wing [6]. The previous century saw a lot of experimental research at Reynolds numbers relatively close to the ones of the baseline platform [6-9]. It has been proved that the wing fences can effectively stop the spanwise flow development and flow detachment [6, 9], especially in high angles of attack. In addition, the negligible weight penalty, together with the ease of construction and application, provide an extra advantage in the implementation of the wing fences.
2. Aim of the study
The aim of this study is to test the ability of two PFCTs to improve the aerodynamic behaviour (Coefficient of Lift - $C_L$, Coefficient of Drag - $C_D$, Moment Coefficient - $C_M$, stall angle) of the baseline platform. The baseline platform is cruising at 20,000 ft, with a Reynolds number of 3,000,000.

3. Tools and methods
Initially, the baseline model results were analysed. Using surface wall shear stress streamlines (figure 4) the spanwise flow, a typical adverse phenomenon of swept wings was visually identified.

3.1. Tubercles
The Reynolds number of 3,000,000 is regime with little to no published literature data, as most of the work refers to Reynolds numbers smaller than $6 \times 10^5$ and to non-swept wings [10]. In addition, most of the tubercle arrays seem to have a positive effect only in the post-stall area, with few exceptions. Wei et al. [11] experimentally studied an array of tubercles with $A$ equal to 12% of the chord and $\lambda$ equal to 8.5% of the span on a wing with 30° sweep for a Reynolds number of $5.5 \times 10^5$. Results showed increased $C_L$ and Lift to Drag ratio ($L/D$) for the pre-stall region. Regarding slightly larger Reynolds numbers of 2.2-2.7x10^5 experiments showed that tubercles can reduce the $C_D$ [12], increase the $C_L$ [13] and enhance the $L/D$ [14] for both the pre-stall and post-stall regions. For these studies, the values of $A$ and $\lambda$ were between 4-8% of the chord (or sometimes Mean Aerodynamic Chord, MAC) and 12-18% of the span. No experiments exist in higher Reynolds numbers, therefore CFD calculations, validated by these experiments were instead used. The authors proved the potential advantages of the tubercles’ application
[15] in Reynolds numbers larger than $1 \times 10^6$ with the results indicating higher $C_L$ but at the cost of higher $C_D$ values. Following the literature, the author selected an $A$ value of 5% and 12% of the chord, reflecting the lower and upper limit of the successful tubercles’ demonstrations. However, to the authors knowledge, all published studies use constant $\lambda$ values, in contrast with the flipper of the whale, where each tubercle is has variable $A$ and $\lambda$ values. Therefore, in this study a $\lambda$ value of 25% and 50% of the chord has been selected. Furthermore, the application of tubercles on the winglets is considered. The four cases under study are summed up in table 1 and shown in figure 5.

| Tubercles | Tubercles on winglet |
|-----------|----------------------|
| Case A    | No                   |
| Case A+   | Yes                  |
| Case B    | No                   |
| Case B+   | Yes                  |

Table 1. The four tubercle cases under study.

Figure 5. The four tubercle cases under study (half model view).

3.2. Wing Fences

Wing Fences were first employed in the 50s and have since been empirically used [6-9]. Although decades of wing fence use have past, no guidelines exist regarding the optimum use of the vast number of existing shapes and sizes. For the purposes of this work, the height of each wing fence is set as 5% of the chord, as the literature data suggest that further increasing the fence height has no positive effect [6]. Literature indicates also that using fences extending both on the pressure and the suction side of the wing, can have positive effects on the stability and lift production by stopping the leading-edge separation vortices Jaquet [16]. Therefore, two types of fences are studied (figure 6) i.e., one extending on both sides (100% of the chord on the suction side and 20% on the suction side) and one smaller, extending only on the suction side (100% of the chord). The fence extends from leading edge to trailing edge, in an attempt to completely stop the spanwise flow.
Furthermore, for each case a single and a triple fence study takes place. The single fence is positioned at 35% of the span in the spanwise direction, while the second and third fences at 10% and 65% respectively (table 2). This is a result of the baseline platform analysis (figure 4). The single fence is positioned in the point of maximum spanwise flow, while the second and third fences are positioned in the points of maximum spanwise flow after the employment of the single fence. This selection is made in an attempt to tailor the procedure to the specific baseline model rather than using literature suggested positions.

**Figure 6.** The four wing fence cases under study (half model view).

| Wing Fences | Number of fences | Extension to pressure side |
|-------------|-----------------|----------------------------|
| Case A1     | 1               | YES                        |
| Case A3     | 3               | YES                        |
| Case B1     | 1               | NO                         |
| Case B3     | 3               | NO                         |

### 3.3. CFD calculations

In order to evaluate the effect that the PFCTs have on the aerodynamic behaviour of the platform, CFD calculations are performed. The CFD calculation is conducted using the ANSYS Fluent commercial software (ANSYS @ Scientific Research, Release 20.1). An unstructured grid of approximately 5,500,000 computational nodes is generated (figure 7). The mesh used is the same as in the baseline study, for consistency reasons. In each case, 20 inflation layers are implemented on the walls, the first of which is placed at $1 \times 10^{-5}$ m, and resulted in an average $y^+$ of 1, so that the boundary layer phenomena can be properly modeled.
Regarding the turbulence modelling, the 1-equation Spalart-Allmaras model [17] is used, as it has been widely used and validated to be accurate in aircraft applications [18]. The aerial inlet turbulence intensity is set at 1% and the eddy viscosity ratio at 0.21, representing typical flight conditions [19].

4. Results
The aim of this work is to explore the possible benefits of the application of PCFTs on a BWB tactical UAV. Figure 8 presents the coefficient of lift and drag for the tubercle arrays. No significant difference can be observed up to 4°. However, from 4° up to 13°, the baseline platform seems to have a greater $C_L$ compared with all tubercle arrays. Nevertheless, while the baseline platform stalls at 12°-14°, all tubercle arrays seem to postpone the $C_{L_{\text{max}}}$ Angle of Attack (AoA) to an angle larger than 16°. A similar trend can be observed for the coefficient of drag. Up to 4° angle of attack, all tubercle arrays seem to have a $C_D$ equal to that of the baseline. However, from AoA greater than 4°, the tubercles produce greater $C_D$ compared to that of the baseline. The setups A and A+ seem to perform better than B and B+ for both the $C_L$ and $C_D$. The addition of tubercles on the winglet did not have any significant effect.

In figure 9 the coefficient of lift and drag for the wing fence modifications can be observed. Again, no significant difference can be observed up to 8° for both the $C_L$ and $C_D$. However, from 8° AoA all wing fence setups appear to have better $C_L$. Regarding the coefficient of drag, the single fence has a much better behaviour compared to the triple fence, even presenting values lower than the baseline platform.
Figure 9. The coefficient of Lift and Drag for the wing fences modifications compared with the baseline.

While all PFCTs seem to increase the $C_{l_{max}}$ and the stall angle, some setups present additional useful characteristics (table 3). For example, the tubercles case A can offer an increase of payload up to 2.5 kg for the cruising AoA, while the wing fence case A3 has a 7% smaller $C_D$ values for the pre-stall region.

Table 3. Formatting sections, subsections and subsubsections.

| Tubercles       | Case TBR A                  | Case TBR A+                | Case TBR B                  | Case TBR B+                |
|-----------------|-----------------------------|---------------------------|-----------------------------|---------------------------|
|                 | • Up to 2.5kg increase of payload | • Up to 1.5kg increase of payload | • Greater stall angle      | • Greater stall angle      |
| Wing Fences     | Case WF A1                  | Case WF A3                | Case WF B1                  | Case WF B3                |
|                 | • Greater stall angle       | • Up to 7% smaller $C_D$  | • Greater stall angle       | • Up to 1.3kg increase of payload |
|                 |                             |                           | • Greater stall angle       | • Greater stall angle      |

5. Conclusions
In conclusion, this work proves that PFCTs can possibly increase the efficiency of a UAV by delaying stall and even in some cases reducing the $C_D$. The most promising PFCTs seem to be the wing fence setup WF A3, which can reduce the $C_D$ in the pre-stall region and increase the $C_L$ in high AoA, while the most promising tubercles array is the setup TBR A, with the capability of up to 2.5 kg increase in the payload. It is, however, understood that the flow behaviour of the FCTs needs to be investigated in a more detailed manner. A turbulence model sensitivity study should focus on the large AoA, as the flow separations increase the complexity of the CFD calculations. Furthermore, the effect of the PFCTs on the pitching moment coefficient is also suggested, since it plays a significant role in the design procedure of tailless configurations, such as the BWB.

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