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Influence of leading edge tubercles on aerodynamic characteristics of a high aspect-ratio UAV

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ABSTRACT

An experimental investigation was carried out to study the aerodynamic performance of a typical UAV whose wings were modified to incorporate tubercles on the leading edge. The aerodynamic characteristics of three configurations: a baseline (without leading edge tubercles), one with tubercles of constant wavelength and amplitude along the span (Case I) and the third with tubercles of varying amplitude and wavelength along the span (Case II) were evaluated using force measurements and surface flow visualization at Reynolds numbers ($Re_{\bar{c}}$) of 0.18 million and 0.27 million. At $Re_{\bar{c}} = 0.18$ million, the wings with tubercles exhibited increased lift, stall angle and reduced drag as compared to the baseline over the range of incidences studied. Further, wing with tubercles significantly improved the aerodynamic efficiency (C_L/C_D) (up to 25%). At $Re_{\bar{c}} = 0.27$ million, both the baseline and the modified wings exhibited identical lift characteristics, but the former had a higher drag. At both Reynolds numbers, the modified wings did not exhibit the hysteresis present in the baseline case. Additionally, the modified wings exhibited stable pitching moment characteristics even in the post stall regime. The Case II wing outperformed both the baseline and Case I wings. The results show that tubercles on the leading edge have beneficial effects especially when UAVs encounter sudden vertical gusts during operation.

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UNCORRECTED PROOF

1. Introduction

Unmanned aerial Vehicles (UAVs) perform preprogrammed missions without having an onboard pilot. With recent advancements in technology, an increased interest is seen in the design and development of small UAVs around the world due to the potential to perform tasks like surveillance, search and rescue, damage assessment and reconnaissance without a direct risk to the crew. The flight regime of these vehicles ranges from Reynolds number 30,000 to 500,000 [1]. The most prominent fluid dynamic feature on the airfoil/wing in this Reynolds number range is the formation of a laminar separation bubble. The presence of the bubble on the airfoil/wing adversely affects its performance. Apart from a reduced lift and an increased drag, the bubble has severe effects on the stall characteristics (steep stall and hysteresis loop) [2,3]. Controlling the formation and extent of the laminar separation bubble is essential to improve performance (drag reduction, stability) and to increase the range and endurance within the limited onboard energy source available. This can be achieved by promoting early transition of the boundary layer prior to separation [4]. The early transition of boundary layer can be achieved either via free transition enabled by a modification of shape of the airfoil geometry or forced transition by introducing artificial disturbances like wires, zigzag tape strips, grits, grooves and bleed-through holes. Though the usage of trips results in an improvement in the lift performance, it is accompanied by an increase in the drag. Further, the factors such as trip size, location and distribution must be optimally set for obtaining better performance without drag penalty [5–7].

Tubercles on the leading edge of humpback whale flippers (Fig. 1) are believed to be the reason for their better maneuverability, aiding them to make sharp turns to catch the prey [8]. Earlier studies [9–11] on the application of leading edge tubercles (protuberances) and serrations on airfoils and wings showed an improvement in their aerodynamic characteristics.

Experimental investigations [9,10] on the effect of leading edge tubercles on the airfoils at low Reynolds number have shown better aerodynamic performance in terms of higher lift, lower drag and higher lift to drag ratio at the post-stall angles of attack of the airfoil without leading edge tubercle. However, the airfoil with tubercles was shown to have drag penalty in the pre-stall angles

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Nomenclature

C_L	Lift coefficient	α	Angle of incidence
C_D	Drag coefficient	$\wedge$	Sweep angle
C_M	Pitching moment coefficient	$\bar{c}$	Mean aerodynamic chord
C_L/C_D	Lift to drag ratio	AR	Aspect ratio

Fig. 1. Humpback whales flippers with tubercles [9].

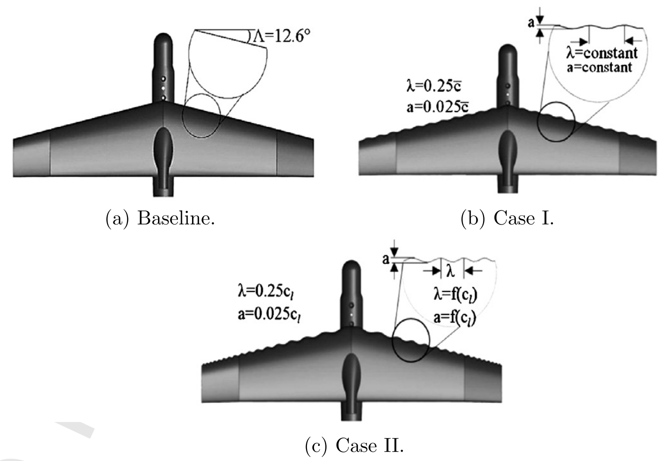
of attack of the baseline (unmodified) airfoil. They suggested that the increase in drag for the modified airfoil at pre-stall angles could be due to the earlier flow separation in the trough section of the modified airfoil as compared to the baseline airfoil. A PIV study on a NACA-4415 airfoil with tubercles showed a reduction in the extent of the laminar separation bubble (length and height) at pre-stall angles and a larger attached flow region at the post-stall angles of the baseline [12]. A study on the static and dynamic stall characteristics of a NACA-0021 airfoil incorporating leading edge serrations (tubercles) showed that the tubercles minimized the area of the hysteresis loop [13].

A computational study on a wing with leading edge tubercles at a 10° angle of attack using a 3D panel method [14] showed 4.8% increase in the lift, 10.9% reduction in the induced drag, and a 17.6% increase in the lift to drag ratio. The reason for decrease in the induced drag could be due to the compartmentalization of the lift between the troughs. A wind tunnel study on a scaled-down model of a humpback whale flipper showed an increase in the maximum lift coefficient and the stall angle without a drag penalty [11]. The generation of streamwise vortices between adjacent crests was suggested [11] as a possible mechanism for the effectiveness of the tubercles. This results in an enhanced momentum transfer within the boundary layer causing an increase in the lift, accompanied by a reduced drag and better post-stall characteristics. A survey of literature cited above shows that the application of tubercles on airfoils and wings are more effective at high angles of attack (near stall) for improved performance without a drag penalty.

It is important to design UAV wing planforms with maximum aerodynamic efficiency to ensure stable flight even at high angles of attack, especially in situations when it encounters sudden gusts. This paper reports the experimental results on the effect of addition of tubercles to the leading edges of the wings of a typical high aspect ratio UAV configuration. The influence of tubercles on the performance of the UAV is evaluated through force measurements and surface oil flow visualization.

2. Experimental setup

The experiments were carried out in the 1.5 m low speed wind tunnel at EAD, CSIR-NAL. The cross-section of the tunnel test section is 1.5 m × 1.5 m and 6.5 m in length. The tunnel is capable of achieving freestream velocities of 10 m/s to 50 m/s. The tunnel freestream velocity can be varied by controlling the RPM of a 112.5 kW variable speed DC motor. The tunnel has a contraction ratio of 12:1 with turbulence intensity of less than 0.1% for the velocity range 10–40 m/s and 0.14% at 50 m/s. The tunnel is equipped with a pitching sector and a turn-table mechanism for varying the pitch and yaw angles.



(a) Baseline. (b) Case I. (c) Case II.

Fig. 2. UAV CAD models.

2.1. Model configuration

In general, UAV wing configurations vary widely (conventional, canard, tandem wing and flying wing). The UAV wing configuration chosen for the present study is a high aspect ratio conventional wing configuration. This particular wing configuration (conventional wing configuration) has been extensively used for short range applications with all up weight less than 20 kg and is therefore chosen here for the present study [15,16]. The models were fabricated using CNC machining and the model profile accuracy is within 200 microns. The UAV model (base line) has a wing area of 0.048 m^2 and a span of 0.537 m resulting in an aspect ratio of 6. The wing has a swept leading edge ($\Lambda = 12.6°$ sweep) and a straight trailing edge (Fig. 2a). The wing has a 10° dihedral angle starting at a location of 0.2 m from the root. The wing has been designed using a high lift airfoil section (S1223) [17] with a 3° wing setting angle with respect to the fuselage reference line. The wing has a root chord of 0.12 m and a mean aerodynamic chord ($\bar{c}$) of 0.091 m. The leading edge of the wing is modified with two different tubercle configurations. The first one (Case I) has leading edge tubercles with amplitude (a) and wavelength (λ) maintained constant throughout the span (Fig. 2b) and the second (Case II) with amplitude and wavelength varying along the span (Fig. 2c). The wave length and the amplitude for the constant wave length and amplitude tubercle configuration (Case I) are 25%$\bar{c}$ and 2.5%$\bar{c}$ respectively, whereas in the varying wavelength and amplitude tubercle configuration (Case II), the wave length and amplitude are 25% and 2.5% of the local chord (c_l).

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