The Impact of Undulating Leading-Edge Modifications on the Flow Characteristics of NACA 0021 Foils

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Abstract

In contrast to active flow control schemes that require an external energy source, passive flow control methods have been of great interest to engineers and scientists, due to their potential in augmenting the performance characteristics of various engineering systems, in addition to reducing fabrication, operation and maintenance costs. In aerodynamics, while the two primary passive flow control approaches, known as leading-edge and trailing-edge modifications, have proven successful in improving performance efficiency, complexities may arise in determining the design guidelines that ensure minimal penalties such as an increase in the drag force while improving lift-generation capabilities.

Operating at high attack angles, wings with undulating leading-edge modifications, in the form of protrusions similar to those on the humpback whale's pectoral flippers (tubercles) and wavy leading-edge configurations, have been shown to render aero-hydrodynamic loading benefits with negligible penalties in the transitional flow regime. These advantages include higher post-stall lift, reduced drag and lower tonal noise, in comparison with unmodified wings of the same cross-sectional profile. Hence, the undulating leading-edge modification has been proposed as a viable passive flow control method.

To account for the superior behaviour of the modified wings, a number of studies have attributed the observed advantages to the generation of streamwise vortices. Accordingly, analogies of tubercles to vortex generators, wing fences and delta wings have been proposed. Consensus, however, on the underlying flow mechanism triggered by the presence of a tubercled leading edge in different flow regimes has not been reached. In addition, the formation mechanism of streamwise vortices over tubercled foils is in question.

The present project aims to contribute to this research area by exploring the mechanism associated with the flow over full-span wings with undulating leading edges in the laminar, transitional and near-turbulent regimes. The project also aims to investigate the underlying flow dynamics responsible for the development of streamwise vortices. To this end, theoretical, experimental and numerical approaches were adopted.

In the theoretical approach, *Prandtl's non-linear lifting-line theory* was employed to examine the effect of an undulating leading edge on the spanwise circulation distribution of the bound votex. Experimental work in the form of wind tunnel force and pressure measurement tests were performed on a wavy wing to study the similarities and differences in the loading behaviour of a tubercled and a wavy wing in the transitional flow regime. On the numerical front, Computational Fluid Dynamics was utilized to perform comprehensive investigations into the flow structure around modified wings in three flow regimes. This allowed investigation of higher Reynolds number flows.

The results of the study demonstrate that wings with undulating leading edges (tubercled and wavy leading edges) alter the flow field in a fundamentally similar manner across the laminar, transitional and near-turbulent regimes. The presence of an undulating leading edge induces a spanwise pressure gradient that gives rise to flow skewness, which in turn leads to the development of streamwise vortices in line with a mechanism known as *Prandtl's secondary flow of the first kind*. In addition, spanwise circulation of the bound vortex associated with pairs of counter-rotating streamwise vortices behaves in a cyclic manner along the span of a modified wing. The spanwise vortex sheets, accordingly, appear to be rippled in the immediate vicinity of a wing with an undulating leading edge.

The loading behaviour of the wings with tubercles is shown to be dependent on the flow regime in which they operate. In the laminar and transitional flow regimes, the counter-rotating streamwise vortices induce a momentum-transfer enhancement effect whereby the flow from the separated flow region is transported to the neighbouring areas where the boundary layer remains attached to the surface of the wing. Whereas the unmodified wing loses lift abruptly in the lower limit of the transitional flow regime, possibly due to the burst of a laminar separation bubble, the tubercled foil maintains more attached flow which leads to a more gradual loss of lift at high attack angles.

In the near-turbulent flow regime, numerical results show that, contrary to the trend in the lower limit of the transitional flow regime, post-stall lift generated by a full-span tubercled wing is lower than that of an unmodified wing. It is observed that the unmodified wing's loss of lift is less abrupt in the near-turbulent regime than in the transitional regime due to the presence of higher momentum fluid within the boundary layer. On the other hand, the momentum transfer effect associated with the tubercled foil is still at play, however the lift coefficient of the tubercled foil is lower than that of the unmodified foil at post-stall attack angles. The inferior performance of the tubercled wing, compared with that of the unmodified, highlights the significance of the role played by Reynolds number effects and the influence of the cross-sectional profile on the performance of the modified wing in question.

The present project provides a better understanding of the impact of full-span wings modified with undulating leading edges on the underlying flow mechanism across a wide spectrum of the Reynolds number.

Contents

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Nomenclature

AOA / α	angle of attack (deg)
A	foil planform area (m^2)
C	foil mean chord (m)
C_D	drag coefficient
C_f	skin friction coefficient
C_L	lift coefficient
C_p	pressure coefficient
D	drag force (N)
L	lift force (N)
p	static pressure (Pa)
p_∞	freestream static pressure (Pa)
Re	Reynolds number
S	foil span (m)
T_u	turbulence intensity
U_∞	freestream speed ($m.s^{-1}$)
$\underset{\sim}{u}$	velocity ($m.s^{-1}$)
y^+	wall – normal, non-dimensionalized distance
δ	boundary layer thickness
Γ	circulation ($m^2.s^{-1}$)
$\underset{\sim}{\omega}$	vorticity (s^{-1})
ρ	density ($kg.m^{-3}$)
υ	kinematic viscosity ($m^2.s^{-1}$)
τ	wall shear stress (Pa)