The Wavy Leading Edge Performance at very Low Reynolds numbers

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The objective of this paper is to investigate wavy leading edge performance for very low Reynolds numbers. Experimental investigations are carried out in order to understand this phenomenon. Several combinations of wavelength and amplitude were considered for two-dimensional models with NACA 0012, NACA 0020 and NACA 0030 airfoils at Reynolds numbers of 80,000 and 50,000. Differently from the most previous studies regarding wavy leading edge phenomena that present soft stall behaviour as a unique benefit of the wavy configurations, in this study, the tubercle effect indicates an increase in terms of maximum lift values. Besides, the decrease in Reynolds number and the increase in airfoil thickness raise the benefits of the wavy leading edge. Thus this study carried out at Reynolds number below 100,000 here indicates a possible optimum wavy leading edge performance in the specific range of Reynolds numbers for thick airfoils. These findings imply in thinking that seems reasonable future applications of wavy leading edge airfoils in UAV and MAV design.

Nomenclature

A = Wavy leading edge amplitude
MAV = Micro aerial vehicle
Re = Chordwise Reynolds number
UAV = Unmanned aerial vehicle
λ = Wavy leading edge wavelength
ΔC LMAX = Increase or decrease in maximum lift caused by wavy configurations

I. Introduction

Passive flow control devices have been extensively studied. The motivation involves a potential gain in hydrodynamic and aerodynamic performance for engineering designs such as aircraft wings, control surfaces, propellers, fans, wind turbines and racing cars wings. At a low Reynolds number regime (15,000-500,000), aerodynamic performance is determined by laminar boundary layer separation behavior. In this situation, the aircraft performance can be deteriorated even at low angles of attack. Since unmanned aerial vehicles (UAVs) and micro aerial vehicles (MAVs) fly at these conditions, and they have critical requirements of performance and maneuver, the use of passive flow control devices is potentially desirable for these applications. Therefore, currently, there are many researches in flow control for low Reynolds number applications. Recently, the wavy leading airfoil phenomenon has been investigated, as flow control mechanism, in order to improve aerodynamic performance in this particular regime.

The possibility of using sinusoidal leading edge to obtain an improved aerodynamic performance started receiving attention after the work of Fish and Battle. They suggested that the tubercles present in the pectoral flipper of the humpback whale might act as a mechanism to delay the stall. A sinusoidal leading edge is an idealization of these irregular tubercles, which can be seen in figure 1.

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Miklosovic et al\textsuperscript{3, 4} performed experiments for the sinusoidal leading edge effect in two-dimensional geometry (full-span) and three-dimensional geometry (half-span). They studied wings with a NACA 0020 profile in a wind tunnel for Reynolds number around 275,000 for the full-span models and 550,000 for the half-span model. Their results show that the waviness delays stall and improve the maximum lift coefficient for the half-span model, while it only improves the post-stall performance in the full-span case.

Figure 1: A humpback whale breaches with the Virginia Beach oceanfront in the background and the details of its pectoral flipper. The prominent tubercles on the leading edge: [http://hamptonroads.com/2013/01/photo-gallery-whale-sightings-spike-va-beach]. Accessed on 22 June 2015.

Johari et al\textsuperscript{5} carried out tests with full-span model in a water tunnel using a NACA 634-021 profile, which is similar to that of the whale's flipper. They conducted their study at Re = 183,000, and obtained results consistent with the ones for the full-span model of Miklosovic et al. Stanway\textsuperscript{6} performed tests in a water tunnel with a model similar to the half-span model of Miklosovic et al\textsuperscript{3}, however for lower Reynolds numbers in the range from 44,000 to 120,000. The stall behavior is more gradual, and the results showed a strong dependency on the Reynolds number, with the maximum lift coefficient increasing only for the highest value of Re, which exhibited a behavior similar to that of Miklosovic et al\textsuperscript{3}.

Although promising results appear in recent research\textsuperscript{7, 8}, the effect of sinusoidal leading edge on airfoils and wings is not simple to understand, since it involves boundary layer control by varying the leading edge geometry. The leading edge area has strong influences in the flow behavior such that a small geometric variation can completely change the flow over the entire airfoil. In addition, at low Reynolds number conditions there is a laminar bubble phenomenon, which is highly nonlinear and dependent on the Reynolds number. The aim of this work is to investigate wavy leading edge performance for Reynolds numbers below 100,000, which has not been widely studied. Experimental investigations are carried out in order to understand the wavy leading edge phenomenon at very low Reynolds number. Several combinations of wavelength and amplitude were considered for two-dimensional models with NACA 0012, NACA 0020 and NACA 0030 airfoils. The experimental tests were carried out for full-span models at a subsonic blower-type wind tunnel of open loop with closed section, where lift measurements were performed. The paper is structured as follow. Section II describes the experimental setup, while section III presents the main results of this work, and finally section IV contains our conclusions.
II. Experimental methodology

In order to investigate the wavy leading edge performance for airfoil thickness variation, it were built three set of four airfoils, for distinct profiles (NACA 0012, NACA 0020 and NACA 0030), which one has a smooth configuration and three others have wavy configurations. The wavy leading edge geometry was varied by combination of the tubercle amplitude and wavelength in the range of the humpback whale flipper’s morphology in order to evaluate the variation effect of these parameters on tubercle performance (lift, drag and moment). It were design the follow wavy airfoils combinations (A= 0.03 c; \( \lambda \) = 0.40 c), (A= 0.03 c; \( \lambda \) = 0.11 c) and (A= 0.11 c; \( \lambda \) = 0.40 c) (figure 2).

The airfoils were designed using the software Inventor, a tool of Computer-Aided Design (CAD). The wavy leading edge configurations were built based on two-dimensional profiles with different chord lengths. These profiles were combined at leading edge following a sinusoidal path defined by wavy geometry. The profiles on trailing edge are linked by a straight line perpendicular to chord-wise. The models were fabricated of ABS using a prototype machine Stratasys Fortus 250mc. After that, the models were sanded and painted to achieve an appropriate homogeneity regarding superficial roughness.

![Figure 2. One set of four airfoils used on experiments.](image1)

![Figure 3. Wind tunnel facilities at ITA.](image2)

The airfoil chord-length was chosen based on a compromise between an airfoil plan-form that minimizes blockage and a chord-length that provides an appropriate Reynolds number range for this work. Therefore, the airfoil models have a chord-length of 150 mm, a span of 410 mm and the plan-form area is 0.0615 m².

The experimental investigations were carried out at Professor Feng Laboratory, that belongs to Aeronautical Engineering Division from Technological Institute of Aeronautics (ITA), in a subsonic blower-type wind tunnel of open loop with internal dimensions of the test section 457 mm x 457 mm x 1200 mm (figure 3). The maximum velocity achieved at wind tunnel is 30.6 m / s. An investigation in the central plane of the test section using hot wire anemometer showed that the RMS velocity value of the axial velocity fluctuation is approximately 0.5% of the average velocity.

The configurations were tested in a very low Reynolds number range (Re = 50.000 and 80.000). Measurements of lift were obtained using a three-axis balance fixed at one of the wind tunnel window side, suitable for this kind of measure in two-dimensional bodies. During the performance of the experimental tests, each angle of attack was fixed manually by a rotating device attached to the model’s metal axis. The rotating device is free to rotate 360 degrees with the uncertainty of ±0.5 degrees. The uncertainty increases with decrease in Reynolds number. At highest Reynolds number, the average uncertainty in drag is 7% and in lift 2%.
III. Lift performance results

The curves of lift coefficient for the wavy and smooth NACA 0012, NACA 0020 and NACA 0030 airfoils are plotted in this section. Discussions will be done based on wavy leading edge effect at pre-stall and post-stall regime for Reynolds number 50.000 and 80.000.

A. Wavy leading edge performance for NACA 0012 airfoil

Figure 4 presents the aerodynamic performance of the wavy and smooth configurations at Reynolds number 80.000 for the thinnest NACA 0012 airfoils. The configurations A3λ40 and A3λ11 show similar lift performance to smooth configuration up to $\alpha = 7^\circ$. On the other hand, the biggest amplitude configuration (A11λ40) undergoes a great aerodynamic deterioration since early angles of attack ($\alpha = 4^\circ$). In the post-stall regime, the configurations A11λ40 and A3λ11 show the absence of drop in lift at higher angles of attack so characterizing a soft stall behaviour. In contrast, the configuration A3λ40 presents drop in lift similar to baseline configuration. The post-stall behaviour of the configurations A11λ40 and A3λ11 establish the maximum lift coefficients very close to values of the smooth configuration. On the other hand, the configuration A3λ40 achieves the maximum lift coefficient slightly lower than the value of the smooth configuration. In addition, the stall angles for wavy leading edge configurations present higher values than the one of the smooth configuration.

![Lift curves for the smooth and wavy configurations at Re = 80,000 (NACA 0012 airfoil).](image)

At Reynolds number 50.000 (figure 5), in the pre-stall regime, the greatest amplitude configuration (A11λ40) presents the biggest aerodynamic deterioration similar to Re=80.000. On the other hand, the configurations A3λ40 and A3λ11 with similar results overcome the smooth airfoil performance showing a different behaviour compared to the lowest Reynolds number condition. The configurations A11λ40 and A3λ11 present soft stall behaviour and the configuration A3λ40 a drop in lift values at stall condition. Although the post-stall characteristics for the wavy configurations do not change with the increase in Reynolds number, all configurations achieve higher values of maximum lift coefficient compared to the baseline configuration ($\Delta C_{\text{LMAX}} = + 9\%$). In addition, the stall angles of wavy configurations keep higher values compared to baseline model.
B. Wavy leading edge performance for NACA 0020 airfoil

At Reynolds number 80,000, the figure 6 present for the smooth NACA 0020 airfoil three distinct lift slopes in the pre-stall regime. The wavy configurations follow this tendency where the configurations A11λ40 and A3λ11 undergo a great aerodynamic deterioration presenting lower lift values compared to baseline model. In addition, the greatest amplitude configuration (A11λ40) has the worst performance presenting tubercle effect similar to NACA 0012 airfoil. The configuration A3λ40 presents the highest wavy configuration performance keeping similar lift values to smooth configuration up to α = 7°. After that, the configuration remains lower values up to stall angle. The post-stall characteristics of the wavy configurations are similar to NACA 0012 airfoils where the configurations A11λ40 and A3λ11 present soft stall behaviour whereas the configuration A3λ40 follow the abrupt stall of the smooth model. However, differently of the thinner wavy airfoils, the wavy NACA 0020 airfoils present substantial decrease in maximum lift coefficient when compared to smooth configuration. The configurations A3λ40, A3λ11 and A11λ40 present values of ΔC_{LMAX} - 4%, -12% and -20% respectively. In addition, the wavy configurations present lower values of stall angle.
Figure 7 shows that a decrease in Reynolds number, for the wavy NACA 0020 airfoils, cause a improve in lift performance similar to the NACA 0012 airfoils. In the pre-stall regime, the wavy configurations present similar behaviour compared to the highest Reynolds number. However, in this case, the configuration \( \lambda_40 \) delays the abrupt stall in 4 degree achieving a stall angle of 9 degree. As consequence this configuration achieves the highest maximum lift coefficient of the all configurations. The configurations \( \lambda_40 \) and \( \lambda_{11} \) present a smooth stall behaviour overcoming the value of maximum lift coefficient for the smooth configuration. The configurations \( \lambda_40, \lambda_{11} \) and \( \lambda_{11} \) present values of \( \Delta C_{\text{LMAX}} + 19.4\%, +16.6\% \) and \(+16.6\%\) respectively. Additionally, the configurations \( \lambda_{11} \) and \( \lambda_{11} \) present higher values of stall angle.

![Lift curves for the smooth and wavy configurations at Re = 50,000 (NACA 0020 airfoil).](image)

A. Wavy leading edge performance for thin airfoil NACA 0030

At Reynolds numbers 80,000, the smooth airfoil undergoes great changes on lift curve (figures 8). There is no linearity on lift curve for lower angles of attack where the configuration reaches negative lift values up to \( \alpha = 10^\circ \). After that, the lift coefficient increases with angle of attack, but reaching low values. On the other hand, the configuration \( \lambda_{11} \) keeps the typical aerodynamic characteristics of an airfoil for lift performance. The configuration keeps the linearity on lift curve up to stall as on the smooth configuration for higher Reynolds numbers so reaching the highest lift. The configuration \( \lambda_{11} \) follows a behaviour similar to the configuration \( \lambda_{11} \), however, it presents early drop in lift \( \alpha = 4^\circ \) indicating flow separation condition. The airfoil \( \lambda_{11} \) keeps linearity on lift curve up to higher angles of attack with lower curve slope.
Figure 8: Lift curves for the smooth and wavy configurations at Re = 80,000 (NACA 0030 airfoil).

Figure 9 indicates that decreasing Reynolds number occur an increase in aerodynamic deterioration for the wavy configurations, and a consequent reduction in benefits of the wavy effect. In addition, the performance of the configurations A11λ40 and A3λ11 become close. However, these configurations still keep a linear behaviour in a great range of angle of attack.

Figure 9: Lift curves for the smooth and wavy configurations at Re = 50,000 (NACA 0030 airfoil).
Conclusions

Differently from the most previous studies regarding wavy leading edge phenomena that present soft stall behaviour as a unique benefit of the wavy configurations, in this study, the tubercle effect indicates an increase in terms of maximum lift values. Besides, the decrease in Reynolds number and the increase in airfoil thickness raise the benefits of the wavy leading edge. Thus this study carried out at Reynolds number below 100,000 here indicates a possible optimum wavy leading edge performance in the specific range of Reynolds numbers for thick airfoils. These findings imply in thinking that seems reasonable future applications of wavy leading edge airfoils in UAV and MAV design.

References