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PERFORMANCE OF LEADING EDGE TUBERCLES FOR A THIN AIRFOIL

Adson Agrico de Paula
Technological Institute of Aeronautics
Praça Marechal Eduardo Gomes, 50 - Vila das Acácias
CEP 12228-900 – São José dos Campos – SP – Brazil
adson@ita.br

Julio Romano Meneghini
Polytechnic School of the University of São Paulo
Praça Marechal Eduardo Gomes, 50 - Vila das Acácias
CEP 12228-900 – São José dos Campos – SP – Brazil
jmeneg@usp.br

Bruno Ricardo Massucatto Padilha
Bento Silva de Mattos
Roberto Gil Annes da Silva
Technological Institute of Aeronautics
Praça Marechal Eduardo Gomes, 50 - Vila das Acácias
CEP 12228-900 – São José dos Campos – SP – Brazil
brunomassucatto@gmail.com, bmattos@ita.br, gil@ita.br

Abstract. *In the 2000´s, researchers have been conducted flow control investigations for sinusoidal leading edge airfoils. Many studies carry on in this area. However, In terms of airfoil geometry effect on wavy leading edge performance, particularly thickness, there is a lack of studies since the previous studies focus the evaluation of the wavy configurations in airfoils that represent humpback whale flipper morphology (NACA 0020). Besides, there are few studies that investigate the Reynolds number effect on tubercle performance. Therefore, in order to contribute to research in wavy leading edge performance by expanding the investigation to thin airfoils and Reynolds effect, the aim of this work is to investigate the wavy leading edge performance for the thin airfoil NACA0012 by experimental investigation measuring forces and moments at low Reynolds number regime (50.000 - 290.000). The work showed important results where the wavy leading edge performance is sensitive to airfoil thickness and Reynolds number variation. At Reynolds number 50.000 an optimum wavy configuration increases maximum lift in contrast to many results at literature for full-span models. In addition, at Re = 120.000 the post-stall and pre-stall characteristics for optimum tubercle showed better results than airfoil NACA 0021 from previous studies. So, it is important in future works to explore a huge diversity in thickness and Reynolds number variation to understand better the influence of these parameters on wavy leading edge performance in order to achieve potential applications.*

Keywords: *Aerodynamics, flow control, tubercles, wavy leading edge, thin airfoil, Reynolds number effect*

1. INTRODUCTION

Passive Flow Control Devices have been extensively studied in the past years. 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 automobilist airfoils. At low Reynolds number regime, aerodynamic performance is determined by laminar boundary layer separation characteristics. In this flow regime, the aircraft performance can be deteriorated even at low angle of attack. Since UAVs and MAVs flight at low Reynolds number regime, and they have critical requirements of performance and maneuver, application of passive flow control devices are potentially desirable for this specific design. Therefore, currently, there are many researches in flow control for low Reynolds number applications. Recently, the wavy leading edge airfoil phenomenon has been investigated, as flow control mechanism, at low Reynolds number condition in order to improve aerodynamic performance in this particular regime.

In the 2000´s, researchers have been conducted flow control investigations for sinusoidal leading edge airfoils. Miklosovic et al (2004), inspired on tubercles of humpback flipper (figure 1), carried out experimental studies of sinusoidal leading edge that showed a potential gain in aerodynamic and hydrodynamic efficiency.

Miklosovic et al (2007) studies the sinusoidal leading edge effect for two-dimensional flow (full-span) and three-dimensional flow (partial-span). Two-dimensional results at Reynolds number range 274.000-277.000 show delay in stall angle, but there is an increase in drag and decrease in lift. On the other hand, for three-dimensional results at

Reynolds number range 534.000-631.000 appears a delay in stall angle of 5 degrees, and also the benefits of maximum lift increasing in 4%. In addition, the drag increases in pre-stall region.

Johari et al (2007) carried out tests with full-span model to study in detail the nature of the flow imposed by sinusoidal leading edge. Tests were performed in a water tunnel using airfoil NACA 63_4-021, an airfoil similar to founded in the humpback whale flipper morphology, at Reynolds number 183.000. The results show deterioration in performance at pre-stall regime with lift reduction and drag increase for the modified airfoil. On other hand, at post-stall regime occurs performance enhancement for modified airfoil with lift increased in 50% with little or no drag penalty.

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. Hutchins (2015).

Custodio (2007) using the same data base from Johari (2007) explains the mechanism of tubercles at post-stall regime for NACA 63_4-021. Stanway (2008) performed tests in water tunnel with a model similar to Miklosovic et al (2004) maintaining the same airfoil NACA 0020 for Reynolds number from 44,000 to 120,000. The stall behavior for wavy configurations is more gradual, and the stall angle delays in all conditions of Reynolds number when compared to smooth airfoil. This behavior is similar to Miklosovic et al (2004) results.

Hansen et al (2009) carried out full-span experimental tests to investigation effect of amplitude (0.06c to 0.11c) and wavelength (0.21c to 0.86c) of the tubercles for airfoils NACA 0021 at Reynolds number 120.000. In terms of amplitude effect, at pre-stall regime, the smaller amplitude tubercles achieve larger C_{Lmax} and a higher stall angle with increase in linear range at lift curve. At post stall regime, larger amplitude tubercles achieve softer stall characteristics. The results show that tubercle wavelength noticeably influences the airfoil performance. The results illustrate that reducing the wavelength occurs beneficial for both pre-stall and post-stall regimes.

Chen et al (2012) investigates geometric variation effect on tubercles for the thin airfoil NACA 0012 considering three amplitudes (0.05c, 0.1c, and 0.15c), at constant wavelength (λ=0.25c), for Reynolds number 120.000. The wavy leading edge performance, for aspect ratio 2, has no deterioration in maximum lift, and the drag values were reduced in most angle of attack range. The smallest amplitude achieves the best lift performance. In contrast, the greatest amplitude has smallest drag values.

Guerreiro (2010) performed three-dimensional tests at Reynolds number 70.000 and 140.000 for wing with different aspect ratios in order to evaluate its influence on the sinusoidal leading edge performance. The results demonstrate a large dependence of aspect ratio.

Although promising results appear in recent researches, the wavy leading edge phenomenon is not simple to understand, since it involves the boundary layer control by varying of the leading edge geometry. The leading edge area has strongly influences on flow characteristics such that little geometric variation can completely change the flow over airfoil. In addition, at low Reynolds number regime occurs the laminar bubble phenomenon highly nonlinear and sensitive to Reynolds number and airfoil geometry variation. In terms of airfoil geometry effect on wavy leading edge performance, particularly thickness, there is a lack of studies since the previous studies focus the evaluation of wavy configurations in airfoils that represent humpback whale flipper morphology (NACA 0020). Although Chen et al (2012) carried out experimental investigation of the tubercle performance for the thin airfoil NACA 0012, the airfoil tested is a partial-span model so combining airfoil geometric effect with wingtip effect when compared with a thicker full-span model from previous studies. Besides, there are few studies that investigate the Reynolds number effect on tubercle performance. Therefore, in order to contribute to research in wavy leading edge phenomenon by expanding the investigation to thin airfoils and Reynolds number effect, the aim of this work is to investigate the wavy leading edge performance for the thin airfoil NACA 0012 by experimental investigation measuring forces and moments at a low Reynolds number regime (50.000 - 290.000).

2. EXPERIMENTAL METHODS

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

Figure 2. The set of four airfoils for profile NACA 0012.

Figure 3. Wind tunnel facilities at ITA.

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 profile on trailing edge is 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 regards to superficial roughness.

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 and span of 410 mm, and the plan-form area is 0,0615 m^2.

The experimental investigations were carried out at Professor Feng Laboratory that belongs to Aeronautic 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. A investigation in the central plane of the test section using hot wire anemometer showed that the RMS value of the axial velocity fluctuation is approximately 0.5% of the average velocity.

The configurations were tested in a low Reynolds number range at Re = 50.000, 80.000, 120.000, 200.000 and 290.000. Measurements of lift, drag and pitching moment were obtained using a three-axis balance fixed at one of the wind tunnel side windows, 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%.

3. RESULTS

This section shows the wind tunnel results for wavy and smooth leading edge configurations of the thin airfoil NACA 0012 in order to understand the wavy leading edge performance for thin airfoil. First of all, it will be evaluated the smooth airfoil configuration to establish the aerodynamic characterizes of the thin airfoil NACA 0012 helping to understand the flow changes caused by wavy leading edge. The wavy leading edge performance will evaluate in detail at Reynolds 290.000 because in this conditions the experimental apparatus achieves the minimum uncertainty. In Addition, The Reynolds number effect on wavy leading edge performance will be analyzed by changes on plots of the experimental tests at Re = 50.000, 80.000, 120.000, 200.000 and 290.000. Although the uncertainty increases with decrease in Reynolds number, the qualitative evaluation of the Reynolds number effect is not affected.

3.1 Baseline airfoil at low reynolds number

The figures 4-6 show the aerodynamic characteristics of the thin airfoil NACA 0012 at low Reynolds number regime. The figure 4 shows the lift curves for different Reynolds number conditions. Considering the pre-stall regime, the theoretical curve that comes from thin profile theory is indicated on plot. At lower Reynolds number (Re = 50.000, 80.000 and 120.000), there is an first straight line segment (α < 2°) with higher curve slope when compared to theoretical curve. This behavior is due to the presence of a separation bubble on the airfoil upper surface (Hansen, 2010). After that, a second linear segment starts with same slope than theoretical curve, and decrease the curve slope with increase in angle of attack depending of the Reynolds number condition. However, at lowest Reynolds number (Re = 50.000) there is a drop in lift coefficient at α = 5º.

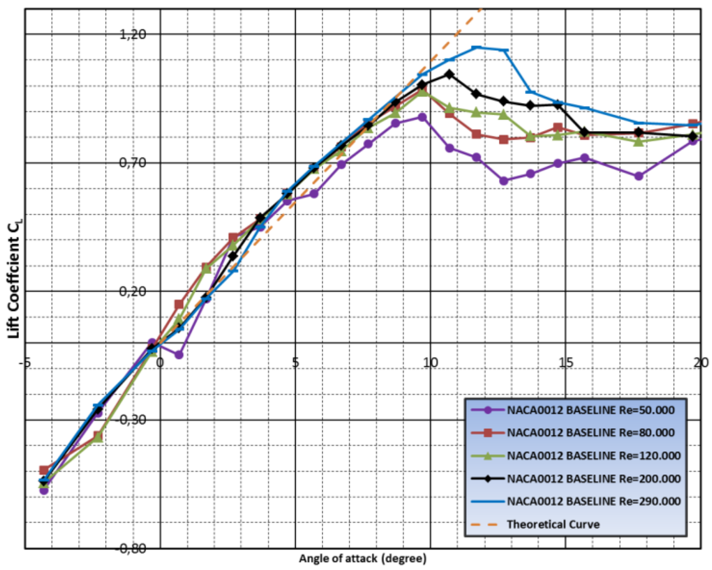

Figure 4. Lift curve for airfoil NACA 0012 at low Reynolds number (Re = 50.000 - 290.000).

For higher Reynolds number conditions, the increase in curve slope when compared to theoretical curve occurs later than lower Reynolds numbers at α = 2º and 3º respectively for Re = 200.000 and 290.000. After that, the slope curve follows the same tendency from higher Reynolds number. The delay in slope change occurs, probably, because the laminar bubble size decreases with increase in Reynolds number (O´Meara and Mueller, 1987). Thus, for higher Reynolds number when compared to low Reynolds number a similar bubble effect in change slope occurs at higher angle attack.

At post-stall regime, the airfoil NACA 0012, at all Reynolds number conditions, has characteristics of a typical thin-airfoil stall (Jones (1933, 1934) & McCullough (1951)). There is a partial abrupt stall with an intermediate drop in lift coefficient values as consequences of the long separation bubble burst on the airfoil suction surface. The stall angle and maximum lift coefficient increases with the raise of the Reynolds number.

The figure 5 shows the drag curves for airfoil NACA 0012. The drag coefficient at zero lift increases with the Reynolds number decrease as consequence of the boundary layer thickness reduction. The drag coefficient at Re = 50.000 has a huge raise in the entire angle of attack range. Besides, for all Reynolds number conditions a great increase in drag occurs at stall angle as result of the bubble burst. The great increase in drag is anticipated with decrease in Reynolds number as consequence of stall onset anticipation caused by decreasing of the Reynolds number. In addition, for higher angle of attack the scale effect is less sensitive.

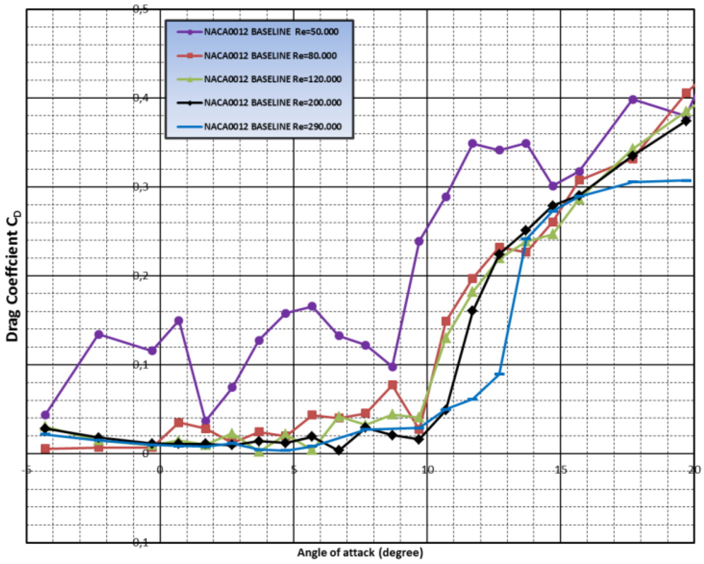

Figure 5. Drag curve for airfoil NACA 0012 at low Reynolds number (Re = 50.000 - 290.000).

The pitching moment coefficient for higher Reynolds number conditions (Re = 200.000 and 290.000) keeps constantly null up to stall angle when a huge decrease in moment occurs (figure 6). At Re = 120.000, the moment coefficient has a similar behavior to higher Reynolds number, except at moderate angle of attack where occurs a decrease in moment. At Re = 80.000, the pitching moment characteristics change drastically. The curve keeps a quite linear behavior decreasing moment values from angle of attack zero. At lowest Reynolds number, up to stall angle, the moment coefficient increases achieving positive values, and after that follows the same tendency of higher Reynolds number

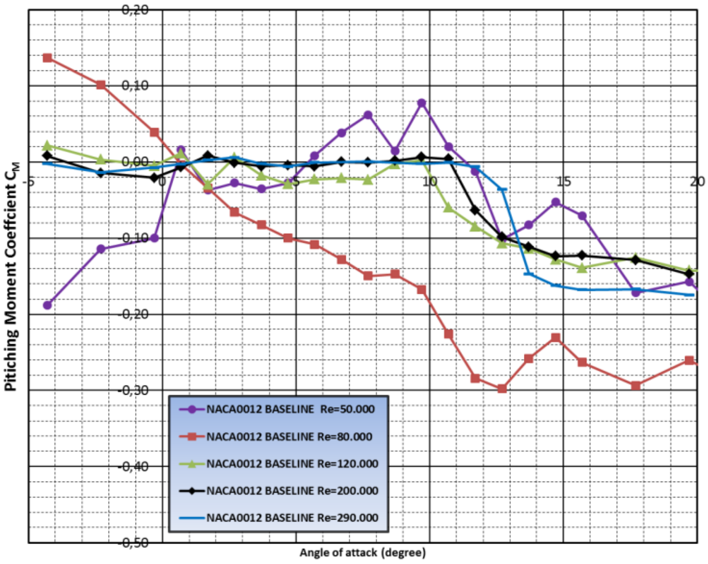

Figure 6. Moment curve for airfoil NACA 0012 at low Reynolds number (Re = 50.000 - 290.000).

3.2 Airfoils with tubercles at reynolds number 290.000

Considering the wavy leading edge effect for lift performance on thin airfoil (NACA 0012), the lift coefficient values are plotted in the figure 7 as function of angle of attack for all leading edge configurations. At pre-stall regime, all wavy leading edge configuration follow the smooth configuration curve up to $\alpha = 2°$.The wavy configurations delay the increase in lift curve slope in one degree when compared to baseline configuration. In addition, for higher angle of attack up to stall, the configurations A3λ40 and A3λ11 keep close and with similar tendency to smooth configuration (theoretical curve slope) having lift values slightly lower.

In the case of the configuration A11λ40 occurs an aerodynamic performance deterioration for higher values of angle of attack ($\alpha > 5°$) where the lift curve linearity decreases quite when compared to smooth configuration. In terms of maximum lift coefficient and stall angle, the configurations A3λ40 and A3λ11 achieve similar values close to baseline configuration. For configuration A11λ40, the C_{Lmax} is lower than other configurations with the highest stall angle. At post-stall regime, all wavy leading edge configurations have a soft stall keeping the lift coefficients near C_{Lmax} at higher angles of attack , differently of the partial abrupt stall (Jones (1933, 1934) & McCullough (1951)) that occurs for baseline configuration.

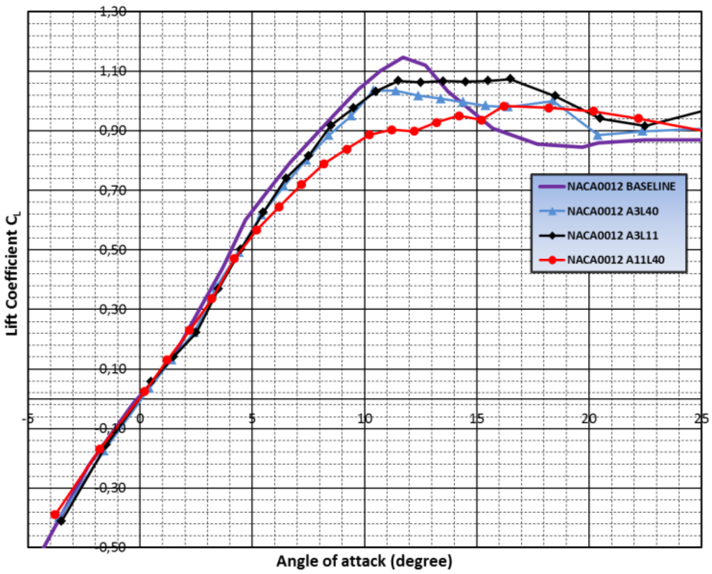

Figure 7. Lift curves for airfoil NACA 0012 configurations at Re = 290.000 (Baseline, A3λ40, A3λ11, A3λ40).

The wavy leading edge geometries defined by amplitude and wavelength domains the pre-stall and post-stall characteristics. By increasing the wave leading edge amplitude at same wavelength (λ40) occurs a huge decrease in linearity on lift curve at pre-stall regime where the configuration A11λ40 achieves quite lower lift values then baseline configuration whereas the smaller amplitude configuration (A3λ40) has similar performance to smooth configuration up to stall. However, as consequence of a higher stall at greater amplitude, occurs similar maximum lift coefficient for configurations A11λ40 and A3λ40 with values of ΔC_{Lmax} ´s 0.98 (ΔC_{Lmax} = -14.8%) and 1.03 (ΔC_{Lmax} = -10.5%) respectively. In contrast with pre-stall, an increase in amplitude does not change the post-stall characteristics keeping a soft stall behavior.

By increasing the wavy leading edge wavelength for same amplitude (A3) at pre-stall regime does not occur significant changes on the lift curve for pre-stall and post-stall regime. The maximum lift coefficient for configurations A3λ40 and A3λ11 achieve ΔC_{Lmax} ´s 1.03 (ΔC_{Lmax} = -10,5%) and 1.07 (ΔC_{Lmax} = -7,0%) respectively.

In terms of maximum lift, the amplitude and wavelength effect does not cause effective changes, and only at pre-stall regime the amplitude effect causes considerable changes. The wavy leading edge configurations for smallest amplitude wavelength (A3λ11 and A3λ40) achieve better result for pre-stall regime.

This indicates that smaller wave leading edge amplitude establishes for airfoil NACA 0012 a better combination between pre-stall and post-stall characteristics having similar to smooth airfoil pre-stall behavior and C_{Lmax} keeping soft stall characteristics.

The table 1 summarizes the changes caused by wavy leading edge geometries on lift curve of the thin airfoil NACA 0012.

Configuration	$\left(\frac{\partial C_L}{\partial \alpha}\right)_{1st}$	$\left(\frac{\partial C_L}{\partial \alpha}\right)_{2nd}$	$\left(\frac{\partial C_L}{\partial \alpha}\right)_{3th}$	***Stall type***	C_{Lmax}	ΔC_{Lmax}	α_{stall}	$\Delta \alpha_{stall}$
Baseline	reference	reference	reference	Partial abrupt	1,15	reference	11,7	reference
A3λ40	similar	similar	similar	soft	1,03	-10,5%	10,40	-1,7%
A11λ40	similar	similar	decrease	soft	0,98	-14,8%	16,20	38,5%
A3λ11	similar	similar	similar	soft	1,07	-7,0%	11,50	-11,1%

Table 1. The wavy leading edge effect on lift performance for thin airfoil NACA 0012.

The figure 8 shows the wavy leading edge performance in terms of drag. At low angle of attack ($\alpha < 2°$), the configurations with greater wavelength (A3λ40 and A11λ40) have similar drag coefficient values, and higher than smooth configuration . For smaller wavelength configuration (A3λ11) the drag coefficient at zero lift achieves the highest value when compared to smooth configuration.

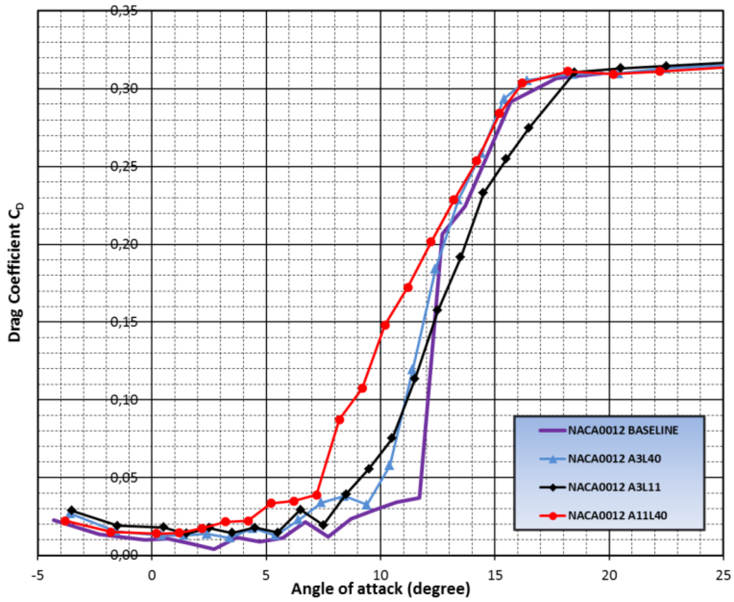

Figure 5. Drag curves for airfoil NACA 0012 configurations at Re = 290.000 (Baseline, A3λ40, A3λ11, A3λ40).

For intermediate angle of attack ($2° < \alpha < \alpha_{stall}$), the wavy leading edge geometry effect on drag coefficient curves depends on how the configurations resist to beginning of the stall. The configuration A11λ40 anticipates the stall onset at $\alpha = 5°$ and thus reduce the extent of the drag bucket increasing drag. On the other hand, the configurations A3λ40 and A3λ11 keep a parabolic raise in drag coefficient up to $\alpha = 10°$, however, with higher drag values than smooth configuration.

At post-stall regime, a huge increase in drag coefficient for configurations A3λ40 and A3λ11 occurs at stall angle keeping drag values higher than baseline configuration up to $\alpha = 12{,}5°$. In the case of configuration A11λ40 how mentioned previously the stall is anticipated keeping the highest drag coefficient values from $\alpha = 5°$ up higher angle of attack.

In terms of amplitude effect, an increase in amplitude at fixed wavelength (λ40) reduces the drag coefficient at lift zero and anticipates the stall onset resulting in a huge increase in drag. Considering the wavelength effect, the configurations A3λ40 and A3λ11 have similar drag values showing a negligible effect of wavelength variation at low angle of attack. For higher angles of attack at post-stall regime, the bigger wavelength configuration shows tiny higher drag values.

The figure 6 shows results of pitching moment for different wavy leading edge configurations. All configurations have similar pitching moment characteristics to smooth configuration behavior with same $C_M = 0$ for $\alpha = 0°$ up to 4°. After that, the configuration A11λ40 anticipating the stall onset change the pitching moment characteristics establishing a curve with a huge negative slope. The configurations A3λ40 and A3λ11 follow the trend of the baseline curve decreasing abruptly the pitching moment at $\alpha = 11°$. The amplitude effect is effective on pitching moment characteristics decreasing moment values with increase in amplitude.

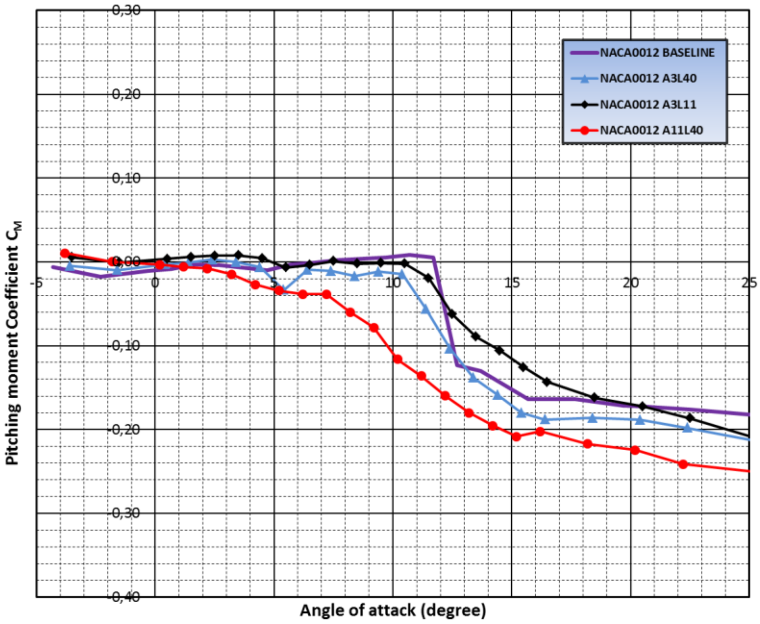

Figure 6. Pitching moment curves for airfoil NACA 0012 configurations at Re = 290.000 (Baseline, A3λ40, A3λ11, A3λ40).

3.3 Reynolds number effect on tubercle performance

The figures 7-11 show the Reynolds number effect on wavy leading edge performance for airfoil NACA 0012 at lift curve. The maximum lift coefficient for smooth configuration keeps higher than wavy configurations at all Reynolds number regime, except for lowest Reynolds number condition (Re= 50.000). Besides, at Reynolds number 290.000 and 200.000, the wavy leading edge configurations A3λ40 and A3λ11 keep stall angle lower than baseline configuration. On the other hand, at Re = 120.000, 80.000 and 50.000, the stall angle of the all wavy configurations overcomes the smooth configuration.

Considering pre-stall regime, for configurations A3λ40 and A3λ11, there is not a sensitive effect on performance where the lift curves are very close to smooth configuration. For configuration of huge aerodynamic deterioration (A11λ40), there is an improve in performance up to stall with increase in Reynolds number.

There is no Reynolds number effect on influence of the tubercle geometry on wavy leading edge performance. Thus, for entire Reynolds number regime, the configuration A3λ11 achieves the best performance. On the other hand, the configuration A11λ40 suffers the highest aerodynamic deterioration. The aerodynamic deterioration in terms of maximum lift coefficient caused by wavy configurations decreases with reduction of the Reynolds number overcoming the smooth performance at Re = 50.000 (figure 12). At post-stall regime, for higher Reynolds number (Re = 290.000, 200.000 and 120.000) the wavy leading edge configurations have a soft stall behavior in contrast to partial abrupt stall from smooth configuration. At Reynolds number 80.000 and 50.000 the configuration A3λ40 follows the partial abrupt stall as smooth configuration.

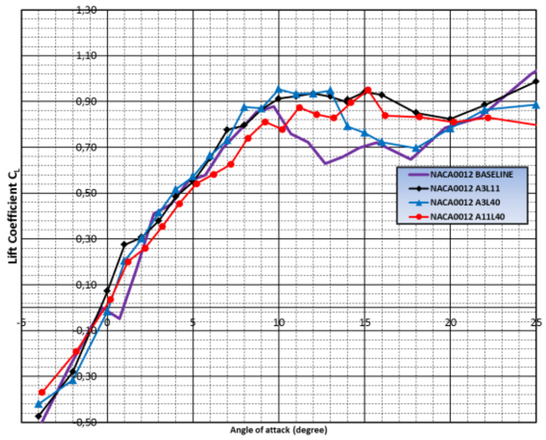

Figure 7. Lift curve at Re =50.000.

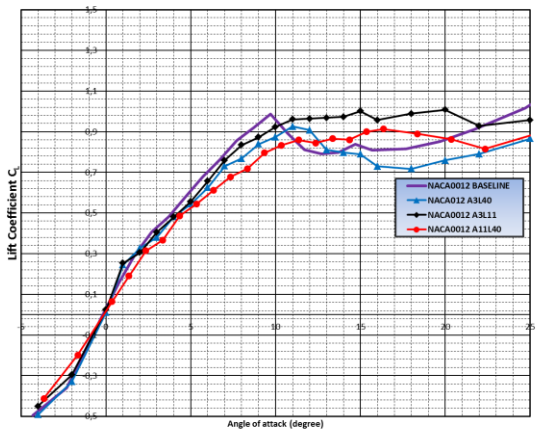

Figure 8. Lift curve at Re =80.000.

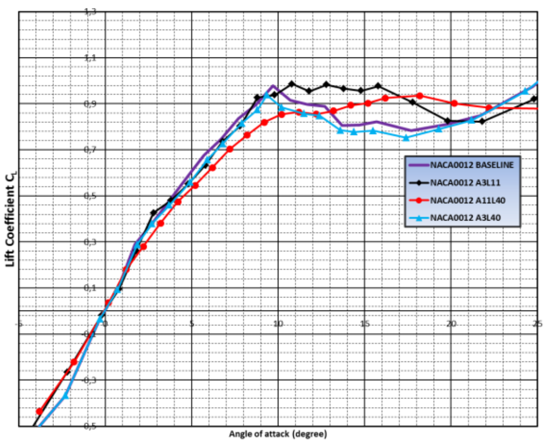

Figure 9. Lift curve at Re =120.000.

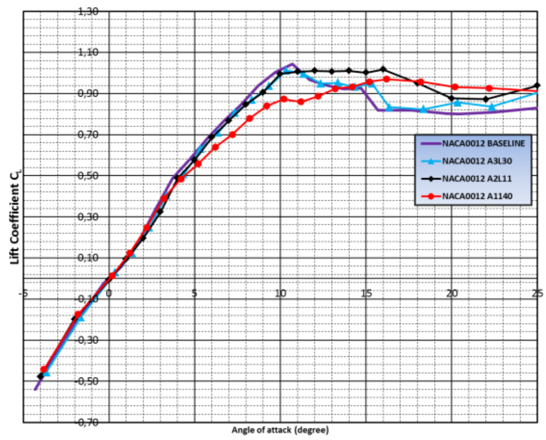

Figure10. Lift curve at Re =200.000.

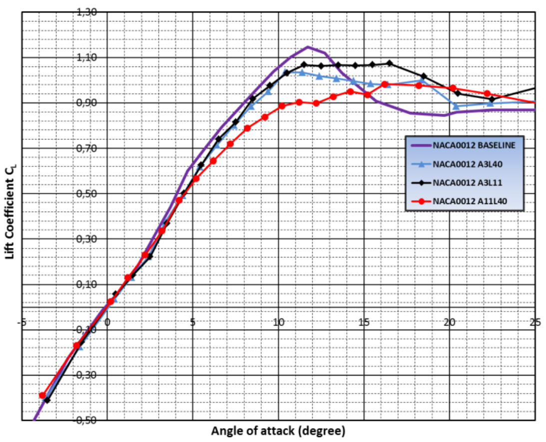

Figure 11. Lift curve at Re =290.000.

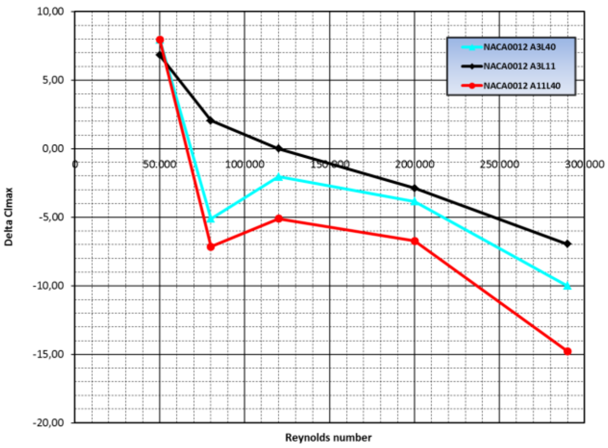

Figure 12. Reynolds effect on C_{Lmax}.

In terms of drag (figures 13-17), at Reynolds number 290.000, 200.000 and 120.000 the wavy leading edge performance is similar increasing drag at zero lift for all configurations achieving the highest values for configuration A3λ11 and anticipating a huge increase in drag, because of early stall, for configuration A11λ40. At Reynolds number 80.000 the wavy configurations keep similar drag values to smooth configuration from low angle of attack up to α =15°. At lowest (Re = 50.000) Reynolds number, the configuration A11λ40 has drag values closer to smooth configuration up to α =14° whereas the configurations A3λ40 and A3λ11 keep lower drag values than smooth configuration up to higher angle of attack.

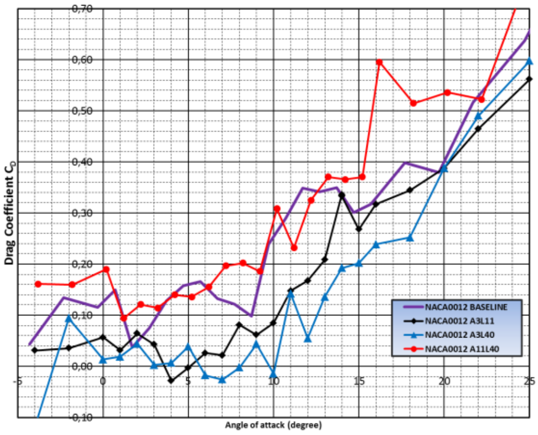

Figure 13. Lift curve at Re =50.000.

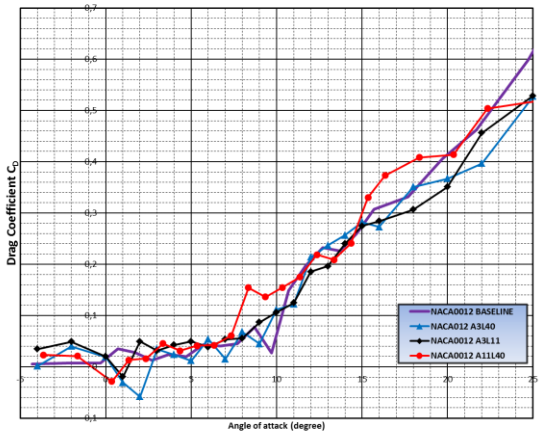

Figure 14. Lift curve at Re =80.000.

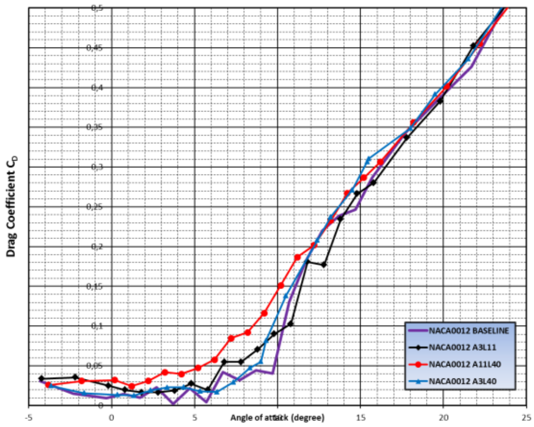

Figure 15. Lift curve at Re =120.000.

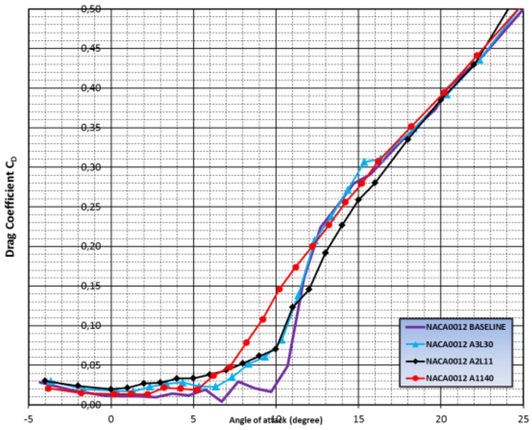

Figure 16. Lift curve at Re =200.000.

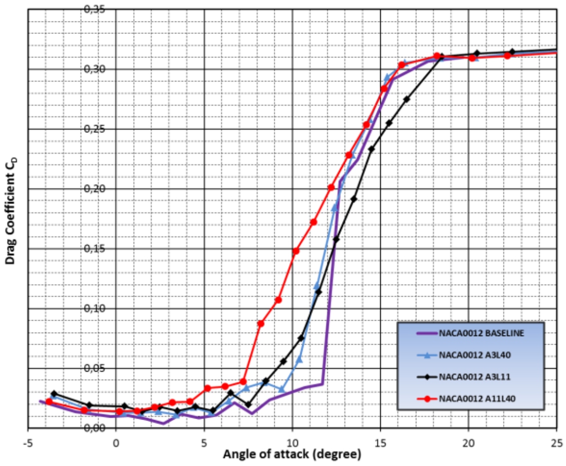

Figure 17. Lift curve at Re =290.000.

The figures 18-22 show that there are no significant changes on pitching moment curves with increase in Reynolds number. The moment values keep near zero moment up to stall angle, and after that occur a decrease in pitch moment by a huge negative curve slope as result of the stall characteristics. The exception occurs at Re = 80.000 where the smooth configuration has a huge negative curve slope since negative values of angle of attack. In addition, the configuration A3λ11 keeps constant higher values in the entire angle of attack range.

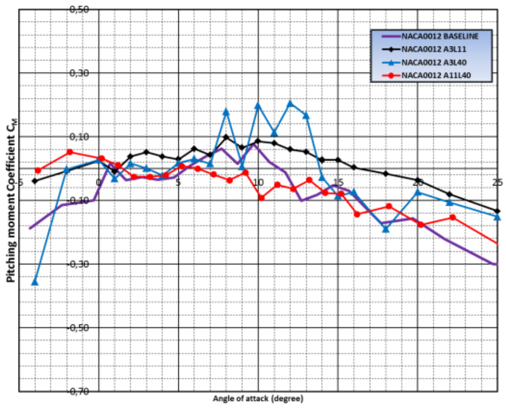

Figure 18. Moment curve at Re =50.000.

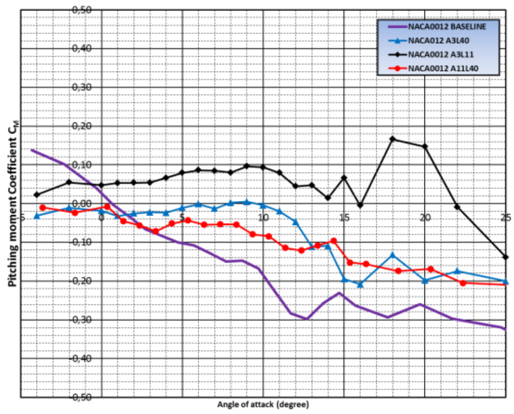

Figure 19. Moment curve at Re =80.000.

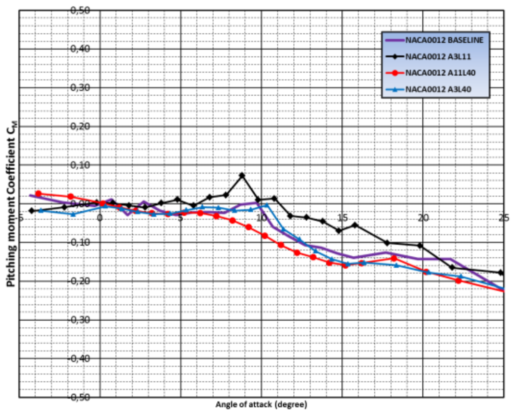

Figure 20. Moment curve at Re =120.000.

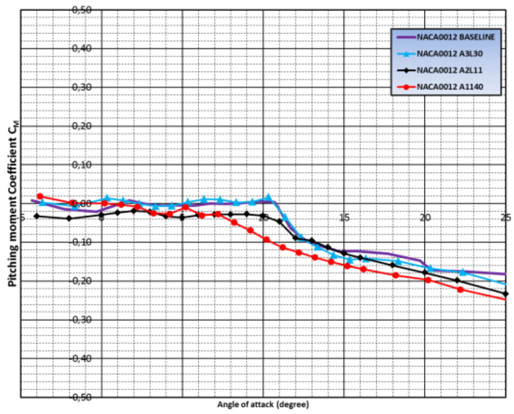

Figure 21. Moment curve at Re =200.000.

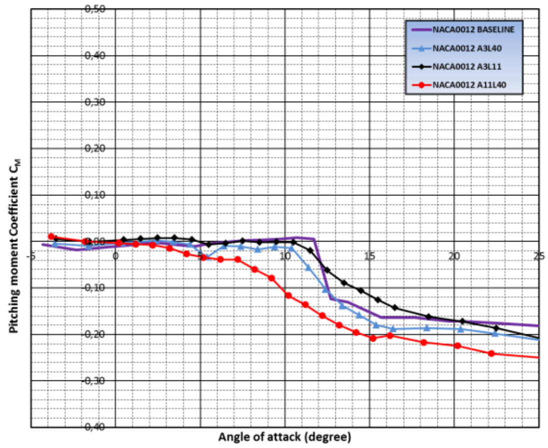

Figure 22. Moment curve at Re =290.000.

4. CONCLUSIONS

To understand the wavy leading edge effect on flow over a thin airfoil (NACA 0012) is necessary to evaluate the aerodynamic characteristics from smooth airfoil at low Reynolds number. The experimental results show characteristics regards separation bubble phenomenon where the curve slope changes in different angle of attack range at distinct Reynolds number. The stall characteristics for the low Reynolds number regime studied (50.000 - 290.00) presents partial abrupt behavior stall indicating long bubble burst in a thin airfoil. Thus, the wavy leading edge on thin airfoil NACA 0012 modifies a laminar flow with long bubble separation.

It is clear in this work and in previous papers that the wavy leading edge change the flow over airfoil in two distinct ways: pre-stall and post-stall. Considering these distinct effects on the airfoil NACA 0012, at Reynolds number 290.000, for pre-stall condition, wavy leading edge configurations with smaller amplitude present at lift curve a delay on first change of curve slope that cause a small decrease in lift up to stall. In this sense, small amplitude keeps the pre-stall lift curve similar to baseline curve. The greater amplitude configuration shows the worst aerodynamic performance from all configurations at pre-stall.

At post-tall regime, all wavy configurations keep a soft stall in opposition to smooth configuration, and for smaller amplitude configurations the maximum lift keeps closer to baseline configuration value.

In terms of drag, the configuration A3λ11 achieves highest drag at zero lift whereas other configurations keep the drag similar, and also higher than smooth configuration. At higher angle of attack, the drag characteristics are a consequence of stall behavior for each wavy configuration having a huge increase drag at stall angle. The pitching moment curves show for lower angle of attack negligible effect of the wavy leading edge. However, for higher angle of attack the wavy configurations anticipate stall establishing a huge decrease in pitching moment. Considering the effect of the wavy geometry, the amplitude effect causes significant changes on aerodynamic performance whereas wavelength effect can be neglected.

The evaluation of the scale effect shows that the maximum lift deterioration decreases with reduction of Reynolds number and the wavy configurations achieve improve in C_{Lmax} at lowest Reynolds number. This result brings a important contribution and open possibility to study the wavy leading edge performance at Reynolds number lower than 50.000 as potential benefit of increase in maximum lift. In terms of drag, the Reynolds effect change general characteristics only for lower Reynolds number approaching the drag curves for Re = 80.000 and splitting curves into two levels of drag at Re = 50.000.The Reynolds effect does no change the characteristics of the pitching moment performance for wavy leading edge airfoils.

The results show different characteristics for thin airfoil when compared, at same Reynolds number condition (Re = 120.000), to thicker airfoils NACA 0021 investigated by Hansen (2010). Although the optimum tubercle geometry for airfoil NACA 0021 founded by Hansen (2010) showed also better results for the thin airfoil NACA 0012, the thin airfoil keeps pre-stall characteristics closer to smooth configuration than airfoil NACA 0021. In addition, the airfoil NACA 0012 achieves the same maximum lift than smooth configuration whereas the thicker airfoil has deterioration in maximum lift. Furthermore, the airfoil NACA 0012 has a softer behavior than the thicker airfoil. In common, both airfoils (NACA 0012, NACA 0021) show the larger amplitude configuration as an index of aerodynamic deterioration.

This work showed important results indicating that the wavy leading edge performance is sensitive to airfoil thickness and Reynolds number variation. So, it is important in future works to explore a huge diversity in thickness and Reynolds number variation to understand better the influence of these parameters on wavy leading edge performance in order to achieve potential applications.

5. ACKNOWLEDGEMENTS

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