Numerical Simulation for Fluid Flow Analysis of a Wavy Aircraft-Wing

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Abstract: **This research focuses on 3D fluid flow analysis of the wing having tubercles on its leading and trailing edge. These protuberance act as passive flow control devices, enhancing their performance at a higher angle of attack when compared to the smooth leading edge wing. The present study aims to investigate the effect of heterogeneous waviness on the aerodynamic performance of rectangular aircraft wing. For that purpose, three-dimensional models of wavy wing are analyzed and their aerodynamic performance is compared with model having plane leading-edge wing called baseline model. The two models having tubercle effect were designed, one wing model having span wise waviness wavelength (tubercles effect) in increasing order from root to tip and while second one possessing span wise waviness wavelength in decreasing order wavelength from root to tip. Results of Numerical simulations are conducted at Reynolds Number *Re*= *2.4*x10^5 and 20^o angle of attack. Reynolds-averaged Navier–Stokes equations (or RANS equations) are solved for flow analysis in Computational Fluid Dynamics (CFD) simulation by using k–omega (k–ω) Shear Stress Transport (SST) turbulence model. The numerical simulation results reveal that wing model possessing span-wise waviness in growing order from root to tip showed favorable results whereas the second wing model with shrinking waviness along the span underperformed accomplishing lower Lift to drag (L/D) ratio when compared with smooth leading-edge wing at 20^o angle of attack.**

Keywords: **Passive flow control technique; Aerodynamic performance; Heterogeneous leading-edge waviness; Reynolds number; Angle of attack (AOA); Finite wing.**

I. INTRODUCTION

For the long times, many studies regarding passive flow control techniques have been carried out and employed in order to achieve an efficient aerodynamic performance. These techniques include the distributed roughness, vortex generator, uniform-blowing & suctions are amongst other strategies which incorporate passive flow control schemes/techniques. Afterward research study [1], tubercles as passive flow control techniques become one of frequently used methods employed on a wing in different ways to get efficient aerodynamic performance, study [1] performed analysis of the geometric shape (tubercles/protuberance) on flippers of humpback in terms of hydrodynamic performance. Results revealed that humpback whale accomplished lift at advanced angle of attacks (AOA) by avoiding flow separation (stall) thus performing maneuverability proficiently.

Encouraged from an unique design as flow control [2] developed the 3D panel technique which was used at 10° AOA to perform comparison between aerodynamic performance of conventional wing model and wing with tubercles effects. Results of this study showed that lift associated with press stall region found to be 4.8 percent more and drag 10.9 percent less, this research study delivered backing to study of[1]. Later, [3]investigational study of idealized wing model encouraged from humpback whale flipper was conducted and its results were compared with conventional model. The study revealed that flipper model achieves 6% increase in lift and also there is 40% rise associated with stall angle. Results also indicated that model with tubercle effect leads to decrease in drag force for 11 to 18 degree angle. Additionally [4] completed an experimental study in order to carry out an analysis on half span and full span model with leading edge tubercles, their results were compared with their conventional wing models. Study showed that when half span model with tubercles effect(LEP) tested at Reynolds number=6x10^{5}retains the lift at higher angle by delaying stall but full span model showed premature stall at same Reynolds number, full span model showed better behavior at reduced Reynolds number= 2.7x10^5. This study disclosed idea that plan form of wing and Reynolds number greatly impacts the aerodynamic efficiency.

Additionally[5]completed a numerical study in which protuberance geometrical parameters were focused for their impacts on flow and aerodynamic performance, this study provided insight that finite wing delivers aerodynamic performance lower than that of infinite wing besides that it is also disclosed in this study that wing having the smallest amplitude distance along with the lowest wavelength provides better aerodynamic performance. Additionally, [6]performed numerical simulations with target to carry out investigation of impact of tubercles geometrical parameters at Reynolds number =800 and 20° case angle . When engaged with wavelength and amplitude equivalent to tubercles description, simulations showed that there is 35% decline in drag force and meanwhile there is considerable decrease in lift when compared to conventional leading-edge model. This study also specified flow characteristics such recirculation zone and wake topology and vortices strength are highly influenced by varying wavelength and amplitude values highly influence the flow parameters such as wake topology, recirculation zone, and also the strength of wake vortices. Upon further analysis it was shown that for amplitude to chord (A/c) ratio more than 0.07, vortices strength too little to dodge flow separation. But in the meantime wake vortex shedding is debilitated when (A/c) ratio is increased more than 0.07. Recently the impact of tubercles geometry was analyzed, and Direct Numerical Simulation (DNS) was conducted at Reynolds number =1000 for infinite wing [7]. The DNS results showed that for given Reynolds number, leading protuberance wing model having peak to peak distance (λ) greater than 50% of chord accepts decline in L/D ratio further more in similar fashion enlargement in magnitude of peak to trough distance (amplitude) provides more falls in L/D ratio. Moreover this study also showed leading edge protuberance model with shorter peak to peak distance showed very less impact on aerodynamic performance.

All these experimental studies of analysis on wing with tubercles effect (passive control) provide different conclusions regarding aerodynamic performance and flow mechanism approach. These conclusions may differ but there is unanimity that tubercles geometrical parameters, wing plan form and Reynolds number ominously influence flow mechanism hence aerodynamic performance. Post the work of [8] it was further decided that tubercles geometry and Reynolds number has great influence on the underlying flow mechanism. In this concerned matter, they conducted DNS aimed for examining the influence of different Reynolds numbers on flow mechanism. They considered Reynolds number 1000, 10000 and 50000 respectively, it was decided in this study flow mechanism is predisposed by Reynolds number but tubercles geometrical parameters are more effective for flow analysis and aerodynamic efficiency in respect of performance, thus tubercles effect is more considerable than Reynolds number for understanding flow behavior thus performance.[9]. From literature review it is concluded that usage of the tubercles along section of wing (airfoil) is one of actively used passive flow technique and this has been tried in different ways in numerous research works to examine and inspect its impact on aerodynamics performance, however in this study the effect of varying waviness wavelength span-wise from root to tip in increasing order and vice versa on wing aerodynamic performance and its flow physics is investigated.

II. CFD Modeling and Meshing:

Pro E software is used for developing the 3D model of wing, for that coordinates were obtained from university *University of Illinois at Urbana-Champaign* website, after obtaining coordinates 2D model is designed and then 3D wing is developed. For designing wing, NACA 0021 airfoil is used because it has similar specification as that humpback whale flipper. To apply waviness wavelength on wing model, following transformation equation is used.

$$\bar{X} = x + \xi(Z) = x - \frac{h}{2}\cos\left(\frac{2\pi}{\lambda}z\right) \tag{1}$$

In Equation. (1) Transformation at span-wise position is specified by $\bar{X}$, chord length by x and Z is showing the length in span-wise direction meanwhile tubercles specification is described by h and λ i.e. amplitude λ wavelength correspondingly. Tubercles specification peak to peak distance and peak to trough are within range of humpback whale flipper, data from literature showed amplitude must lie within 5 to 10 percent of chord and wavelength must lie within 25 to 50 percent of chord. As the tri dimensional model is generated, the 3D wing model is introduced to ANSYS Design modeler, in ANSYS fluid domain is created which is specified in chord length, and upstream fluid domain is up to 15c downstream, bottom and top fluid domain is also 15c but lateral fluid domain is given 7c boundary. As wing is supposed be to finite, there it is fixed with one end (fixed with fluid domain) and from other end it is free. Tetrahedral meshing is performed, patch confirming algorithm is used for unstructured mesh so that non-uniform mesh can be generated in fluid domain easily and same non periodic mesh is used for all three wing models. Inflation layer scheme used for refining mesh near wall for finding precise effect near wall, in this study Y^+ values is reserved less in magnitude than 1 ($Y^+ < 1$) close to the vicinity of wing conforming the height of first element was 0.035mm.

With varying waviness along the span wing model with tubercles effect is created, both tubercles wing models are given below in table. The peak to peak distance (λ) is changing from 50 to 30 percent of chord and which is reduced with 5 percent of chord along span. Models details are given below in Table.1. These tubercles wing models are named in such a way that all four digits between λ and h1 show some wing specification.

Table 1 Baseline model and Tubercle wing models details

Models	*h/c* ratio	λ / c from root to tip	% of *c* increase/ decrease along span in each wavelength
Baseline model	0.0	----------	----------
λ0503h1	0.1	0.5-0.3	0.05
λ0305h1	0.1	0.3-0.5	0.05

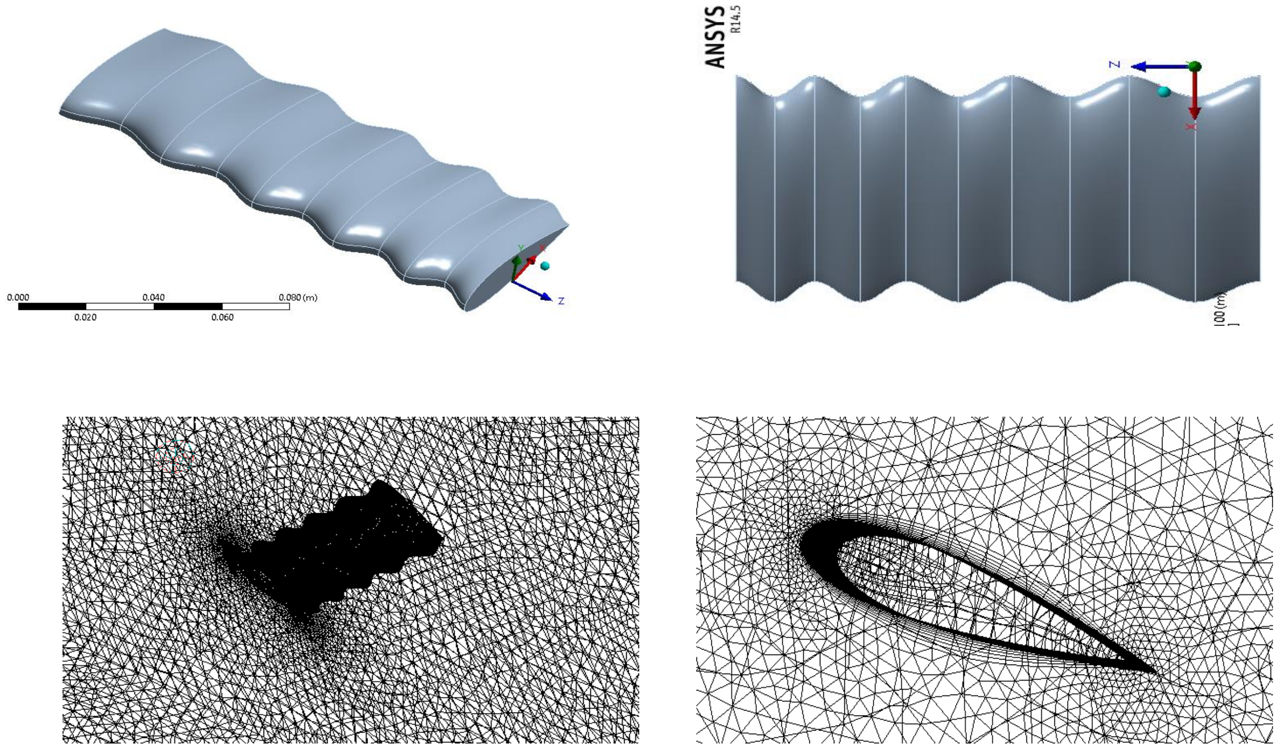

Fig.1 (a) Tubercle wing (Isometric View) (b) Tubercle wing (Top view) (c) fluid domain meshed model (d) elevation view mesh refinement in near wall region.

III. CFD governing equations

Present study is conducted at chord based Reynolds Number Re=240000, the corresponding upstream velocity at the chord length of 70mm is 50m/s at sea level conditions. As at this value of free stream velocity Mach number is much lower than 0.3 thus the flow is considered as incompressible. Therefore the continuity equation and momentum equation for the incompressible flow are given as follow.

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\frac{\partial}{\partial x_j}\left(\rho U_i U_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho \overline{u}_i' \overline{u}_j'\right) \tag{2}$$

In above equation (2) parameter U_i is velocity, ρ is density, μ is dynamic viscosity and P is pressure of the flowing fluid stream respectively. And Equation (2) contains Reynolds stresses is on right hand side of the equation and designated by $-\rho \overline{u}_i' \overline{u}_j'$, all turbulences occurring in underlying flow are specified by Reynolds stresses. Fluent^{TM} offers the different kind of models of turbulence available used for modeling Reynolds stresses according to physical sate of concerned flow. In current study Reynolds stress is modeled by k–omega (k–ω) Shear Stress Transport (SST) turbulence model to solve RANS equations. Results of the turbulence model are compared to experimental results, where the close agreement with experimental results was found. Along with the air as being working fluid, the pressure-based steady state solver in simulations to neglect compressibility. Flow velocity is provided with 0.8% turbulence intensity and is in direction of (1, 0, 0)[5]. Tubercles wing surfaces possess no slip condition (surface velocity zero) moreover at outlet pressure condition is implemented with zero magnitude. SIMPLE algorithm is employed to solve governing fluid flow equation, although three-dimensional discretization is done through 2nd order upwind method.

IV. Results & Discussions

The aerodynamic performance of the tubercles wing models i.e. one wing model with increasing span-wise waviness wavelength from root to tip and other declining span-wise waviness wavelength from root to tip is compared with baseline model and is shown in Figure. 2. The results presented are showing the lift to drag ratio for all the three model wings tested. It can be seen from graph tubercle wing with growing waviness along span achieved greater L/D ratio than baseline model but wing with declining span-wise waviness results in lower L/D ratio at this *Re* and 20^{o} angle of attack. Among baseline model and wavy wing model with declining waviness along span, it can be observed that wing model with growing span-wise waviness accomplished highest L/D ratio followed by baseline wing model and other tubercle wing model. Further, flow behavior governs this aerodynamic behavior is presented in proceeding sections.

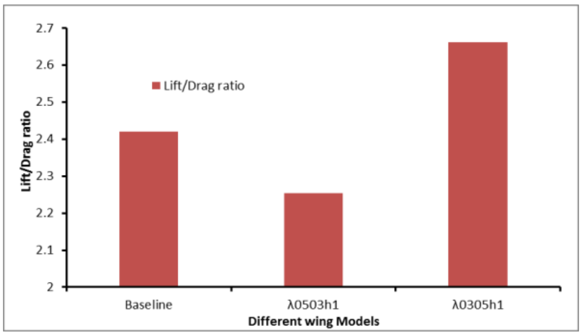

Fig.2 L/D ratio of two tubercle wing models and baseline

The critical pressure distribution analysis is conducted of two tubercle wing models i.e.λ0503h1 and λ0305h1 and baseline model in fig 3 at 20 degree (AOA) for Re=240000. From Fig. 3 (a) it is observed that at 20 degree (AOA) there is no suction peak on baseline model and it has maximum pressure distribution along span and it drops very little along the span. But for tubercle wing model i.e.λ0503h1 ,Fig. 3(b)shows that suction occurs in the middle trough region but for tubercles wing model λ0305h1 with span growing waviness suction peak is large at 20 degree case thus it behaves better, therefore it can be concluded from the both the wavy model that in post stall regime, the pressure distribution happens to be stronger at higher (AOA). Tubercles wing model with growing span-wise waviness at higher (AOA) provides improved force behavior at same Reynolds thereby increasing an aerodynamic performance.

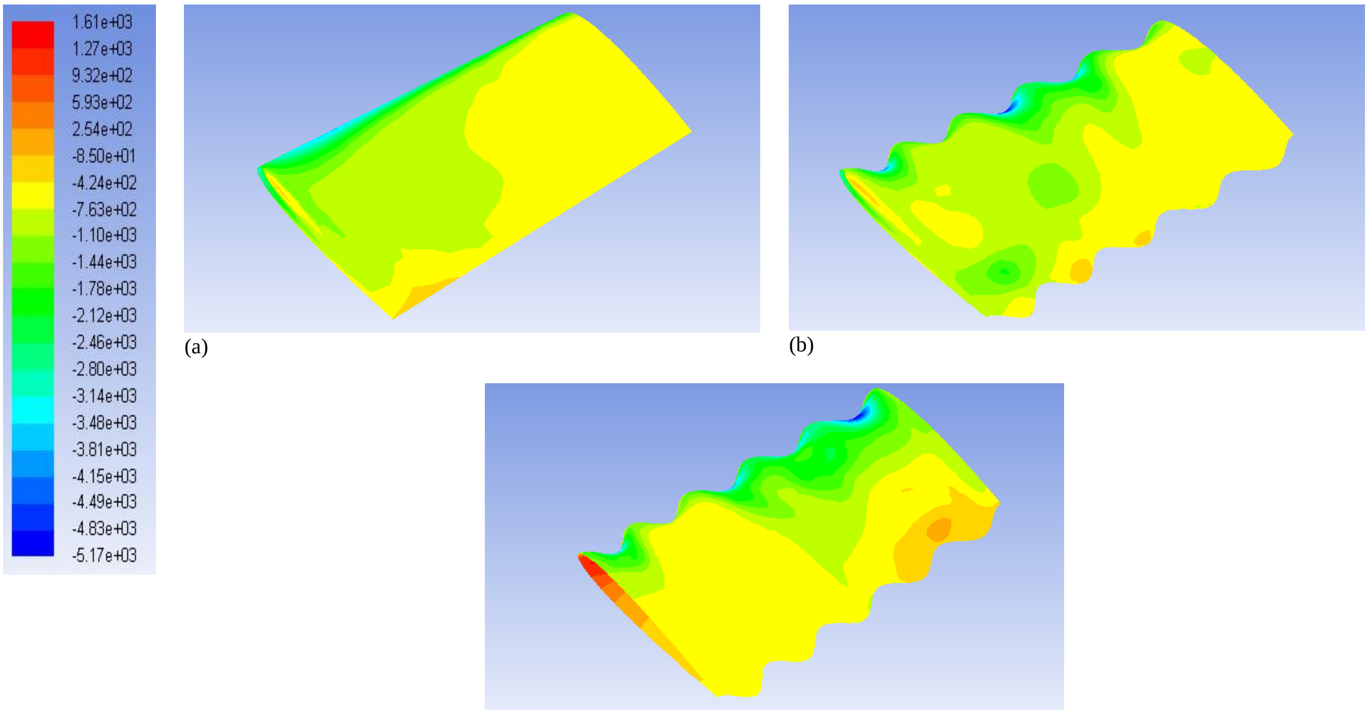

Fig 3 Pressure distribution (static) for Re=240000 & at 20 degree(a) baseline model (b) λ0503h1 (c) λ0305h1

Wavy wing models are undergoing changes in terms of different flow parameters, the flow mechanism can also better understood in velocity vector shown in Fig. 4(a-d). It can be observed from Fig. 4(a) which is representing the nearest valley from fixed end of a wing at a distance 17.5mm that the flow separation is higher at valley and almost complete wing is under strong flow separation or deep stall. Whereas in Fig.4(b) the velocity are shown at the near peak of protuberance from fixed end at a distance of 35mm, it observed from Fig.4(b) that flow remain attached to the some value chord length. These results showed a close agreement found from previous studies that flow behind waviness peak remains attached. However, the complete opposite flow behavior is observed at the valley from free end of the wing. In Fig.4(c) velocity vector at the waviness valley is shown where it is noticed that flow remains attached to the wing behind the waviness valley. But in this case flow separation was observed over the wing behind the waviness peak.

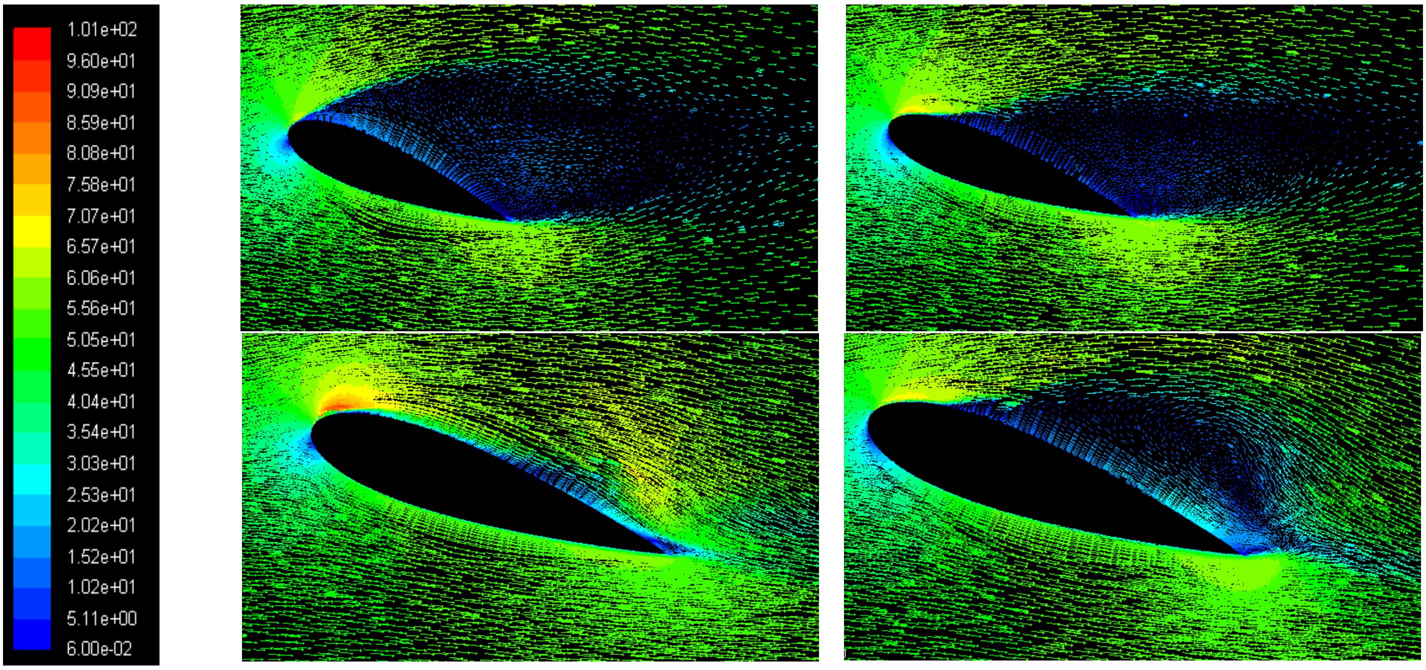

Fig. 4 Velocity vector showing flow separation at AOA=20º for (a) At 17.5mm from fixed end of the wing behind valley (b) At 35mm from fixed end of the wing behind peak (c) At 128.5 from fixed end of the wing behind valley (b) At 119mm from fixed end of the wing behind peak

V. Conclusion

The present study aims examine the tubercles effect on aerodynamic efficiency in terms of lift and drag force behavior of finite rectangular aircraft wing. For given Re=240000 associated post stall region at 20 degree. This chord based *Re* has corresponding free stream velocity of 50m/s at this velocity Mach number is much lower than 0.3 thus flow is considered as incompressible. Study tested two tubercles wing models one with growing span-wise waviness wavelength and other with declining one along the. Moreover, simulation is carried out in Fluent 14.5. Reynolds average Navier Stokes Equations used and solved by turbulence model for steady state flow condition. Aerodynamic performance of both tubercles wing models were compared with conventional (smooth leading and trailing edge) wing model. Study results concluded that wing with growing span-wise wavelength showed increase in aerodynamic performance; while wing with declining waviness along span results decrease in wing performance compared to the baseline model at 20º angle of attack.

Nomenclature

$\bar{X}$ Transformation at required span position
x Chord length
z length in the span-wise direction
h Tubercles amplitude
λ Tubercles wavelength
U_i Velocity component
ρ Density
μ Dynamic viscosity
P Free-stream pressure
C_L Coefficient of Lift
C_D Coefficient of Drag

Abbreviations

Re Reynolds Number
NACA *National Advisory Committee for Aeronautics*
AOA *Angle of Attack*
L/D *Lift-to-Drag*
LES *Large Eddy Simulation*
DNS *Direct Numerical Simulation*
RANS *Reynolds-averaged Navier–Stokes*
SST *Shear Stress Transport*
GIT *Grid Independency Test*
CFD *Computational Fluid Dynamics*

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References

[1]. Fish, F.E. and J.M. Battle, Hydrodynamic design of the humpback whale flipper. Journal of Morphology, 1995. 225(1): p. 51-60.

[2]. Watts, P. and F.E. Fish. The influence of passive, leading edge tubercles on wing performance. in Proc. Twelfth Intl. Symp. Unmanned Untethered Submers. Technol. 2001. Auton. Undersea Syst. Inst. Durham New Hampshire.

[3]. Miklosovic, D., et al., Leading-edge tubercles delay stall on humpback whale (Megaptera novaeangliae) flippers. Physics of fluids, 2004. 16(5): p. L39-L42.

[4]. Miklosovic, D.S., M.M. Murray, and L.E. Howle, Experimental evaluation of sinusoidal leading edges. Journal of aircraft, 2007. 44(4): p. 1404-1408.

[5]. Hansen, K., R. Kelso, and B. Dally. An investigation of three-dimensional effects on the performance of tubercles at low Reynolds numbers. in 17th Australasian Fluid Mechanics Conference, Auckland, New Zealand. 2010.

[6]. Favier, J., A. Pinelli, and U. Piomelli, Control of the separated flow around an airfoil using a wavy leading edge inspired by humpback whale flippers. Comptes Rendus Mecanique, 2012. 340(1-2): p. 107-114.

[7]. Serson, D., J. Meneghini, and S. Sherwin, Direct numerical simulations of the flow around wings with spanwise waviness at a very low Reynolds number. Computers & Fluids, 2017. 146: p. 117-124.

[8]. Skillen, A., et al. Investigation of wing stall delay effect due to an undulating leading edge: An LES study. in TSFP DIGITAL LIBRARY ONLINE. 2013. Begel House Inc.

[9]. Serson, D., J.R. Meneghini, and S.J. Sherwin, Direct numerical simulations of the flow around wings with spanwise waviness. Journal of Fluid Mechanics, 2017. 826: p. 714-731.

[10]. Johari, H., et al., Effects of leading-edge protuberances on airfoil performance. AIAA journal, 2007. 45(11): p. 2634-2642.

[11]. Yoon, H., et al., Effect of the wavy leading edge on hydrodynamic characteristics for flow around low aspect ratio wing. Computers & Fluids, 2011. 49(1): p. 276-289.