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Aerodynamic Performance Analysis of Leading Tubercle Aircraft Wing under Transonic Flow Conditions

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Abstract—Tubercles are a bio-inspired geometry of a humpback whale and its swimming behavior, several studies has revealed that tubercles at leading have significant role to control flow separation in incompressible flow. So these tubercles can be used as flow separation control devices. Present research work aim to analyze the aerodynamic performance of the tubercles Leading Edge (LE) aircraft wing at 3^0 angle of attack under transonic flow conditions. Aerodynamic performance of TLE wing were compared with baseline model i.e. (SLE wing) model. Numerical fluid flow analysis were performed through solving RANS by using finite volume method. The current study is performed at Reynolds = $3x10^6$, and Mach no 0.8 where flow is considered compressible in transonic regime. To comprise the flow physics of problem, the figures are plotted to represent the lift/drag ratio for both straight leading-edge wing and leading edge tubercle wing. In this research it is concluded that unlike subsonic flow the leading edge tubercle does not offer better performance at 3 degree angle of attack in transonic flow regime. The maximum decline of 4.5% was observed in tubercles leading edge wing.

Index Terms— **straight leading edge. Tubercle leading edge, wavelength, amplitude, transonic flow. Shockwave, Flow mechanism**

I.INTRODUCTION

To increase the aerodynamic performance of aircraft wing flow control devices has shown an important role since last decades. Especially the study has widely carried out about passive flow control, wings vortex generators, surface, wind turbines. Even this passive flow separation has certain application in automobile industry to increase the lift to drag ratio of wing. Current research studies are a bio- inspired concept. The idea was initially observed by the swimming behavior of humpback whale. Without being affected by its size, it remain able to move quickly and maintain its swimming style at high angle of attack. Initially it was proposed by Bushnell and Moore a significant role is played by tubercles on their flippers [1]. [2] Later, an analysis was presented by Fish and Battle that at high angle of attack the shape and position of leading edge tubercles can behave as lift enhancing devices by maintaining the flow over the wing at leading edge. In a subsequent study it was observed by an in-viscid simulation using 3D panel technique over an airfoil of NACA 63021 profile with finite span wing at high Reynolds number. [3] The simulation was a comparison between the performance of straight leading edge and tubercle leading wing at 10^0 incident angle. An outcome of 4.8% increased lift and 10.9% reduction in induced drag were recorded which makes a total 17.6% variation in the aerodynamic performance.

Figure. 1. Structure of Humpback whale Flapper

However an increment of 11% in form drag were recorded in viscous calculation. Which further motivated the research in this field. Later an experiment was performed to analyze the idealized model of Humpback flipper in which a leading edge wing and smooth leading edge wing were compared results shown that lift were increase up to 6% by increasing stall angle up to 40%. It is also observed in a study that for an angle of attack between 11 to 18, a fall of 32% in the drag were recorded due to application of tubercle on the leading edge by reducing post-stall regime. It is concluded that leading edge like sinusoidal wave can delay stall by generating more lift at higher angles of attack.

[5] It is also mentioned in various studies that minimum stall can be reduce by tubercle at a little cost of drag increment. [6] Initially it was understood that the flow mechanism for both tubercles and vortex generator is similar, however it is also revealed in study that vortex generator and described aerodynamics have different behavior as the waviness wavelength and amplitude are substantially higher than boundary layer thickness. [7-8] the subsonic regime has a variety of possible application are small unmanned air vehicles are one of them. Aircrafts with small chord length travelling in laminar to turbulent flow undergoes boundary layer separation at small angle of attack. Furthermore, sailboat boat rudders and wind turbine which also shares a major role in electricity production, tubercles can also enhanced the performance when incorporated at high

angle of attack. By optimizing the aerodynamic performance of control surface the smaller sized surface and reduced weight can be achieved. [9] In the subsequent study it was observed by Bolzon, M. D., et al**.** That critical Mach no can be rise by the application of tubercles at leading edge in transonic regime and supersonic region, in this way shock wave will reduce and lift can be improved. This research study investigate the transonic flow regime performance over a NACA 0012 airfoil wing numerically at a Reynolds number of 3 million and Mach number 0.8. Due to shortage of data in transonic flow region performance of wavy leading edge, it is intended to expose the impact of variation in the wing geometry to optimize the aerodynamic performance and understand the flow topology of an undulating of an amplitude of 3% and wavelength of 9%, of mean chord respectively. To precise the results of previous research other configuration has been analyzed due to unpredictable behavior of flow in transonic regime. The name A03W09 were specified in such a way that first two digits 03 represent the amplitude and 9 denotes the percentage of wavelength with respect to chord. The below mentioned table shows the detail of the wing design parameters.

TABLE I: Geometrical parameters of wing model

Models	**Wing span**	**Mean chord**	**Amplitude in %age of chord**	**Wavelength in %age of chord**
Baseline	136	140mm	-------	-------
A03W09	126mm	140mm	03	09

II. NUMERICAL APROACH

In transonic flow region the flow is compressible, so the governing equation will be the steady time filtered Navier Stoke equations. This study were performed at Mach no ranges 0.8 to 1.2 and high Re = 3*105 the discussed flow region is known as transonic flow regime, the flow is compressible. To analyze the aerodynamic performance the assumption for simulation were set according to compressible flow condition. The three dimensional, viscous and steady flow were modeled around the wing, therefore the differential equations for the current research such that RANS equation and continuity equation for above mentioned compressible flow were taken as.

$$\frac{\partial\overline{\rho}}{\partial t}+\frac{\partial}{\partial t}\left(\overline{\rho}\tilde{u}_j\right)=0 \qquad \text{eq (1)}$$

$$\frac{\partial}{\partial t}\left(\overline{\rho}\tilde{u}_i\right)+\frac{\partial}{\partial x_j}\left(\overline{\rho}\tilde{u}_i\tilde{u}_j\right)+\frac{\partial\overline{p}}{\partial x_i}-\frac{\partial}{\partial x_j}\underbrace{\left(\overline{\tau_{ij}}-\left(\overline{\rho u''_i u''_j}\right)\right.}=0 \text{ eq (2)}$$

$$\frac{\partial\overline{\rho}}{\partial t}+\frac{\partial}{\partial x_j}\left[(e+p)\tilde{u}_j\right]+\frac{\partial}{\partial x_j}-\frac{\partial}{\partial x_j}\Big[\,\tilde{u}_i\Big(\overline{\tau_{ij}}-\underbrace{\left(\overline{\rho u''_i u''_j}\right)}+\underbrace{u''_i\left(\overline{\tau_{ij}-\frac{\rho u''_i u''_j}{2}}\right)}\Big]+\frac{\partial q_j}{\partial x_j}=0 \qquad \text{eqn (3)}$$

So, in the given equation, mean flow quantities represented by over bars and over tilde denotes the mean properties of flow. Following equations carries three main terms (shown in under brackets) in which Reynolds stress tensor are in third equation respectively, and the Reynolds heat flux is mentioned in second equation. [10] Studies has revealed that in the transonic flow regime, the simple SA model will not be suitable for analyses due to high turbulence effect, regarding this issue the selection of modified closure model for physical representation can have better performance. To preform proposed numerical research study k-omega SST model is used for better output, in subsequent research studies it is observed that in transonic flow region k-w SST model shows significantly accurate result.

III. DESCRIPTION OF NUMERICAL PROBLEM

Research is based on the numerical analysis to observe the flow separation in transonic regime on the NACA 0012 airfoil wing having different leading edge configuration. As shown in table I.

$$c\,(z)=A\cos(\,2\pi W\,)+\bar{c} \qquad \text{eqn (4)}$$

The geometry of wings were obtained by equation (4) the transformation regarding coordinate were achieved at leading edge at the same chord length. The specification of wavelength and amplitude are based on the range of humpback flaps. [11] In subsequent studies it is measured that peak to peak distance for an adult humpback whale ranges from 0.25 c to .5c and 0.05 to 0.1 from crest to trough. The tubercle model were designed keeping amplitude constant as 3% of chord and wavelength is 9% of mean chord for leading edge tubercle model. Further detail are mention in table I. To perform this research study the modeling of wings were performed by using solid works as a designing tool. To design the wing geometry airfoil coordinates are required to select accordingly. The airfoil co-ordinates were obtained from university of Illinois to insert in sold work 15.0 to design the proposed wing. The designed wing than inserted in ANSYS fluent in IGES format. To create the fluid domain by meshing for flow analysis. The 3D model of wings were simulated at 3 degree, angle of attack by moving them with no flow separation of free stream to analyze the performance of wing. The wing was assume to be fixed with fuselage and the tip remained free to predict the real scenario. Later the wing were inserted to ANSYS 15.0 for simulation to analyze their aerodynamic effect and flow behavior at the various point of surface of wings of respective configuration. Simulations were performed by using energy equation by keeping the fluid/ air as compressible flow.

Figure. 2. Shows baseline model

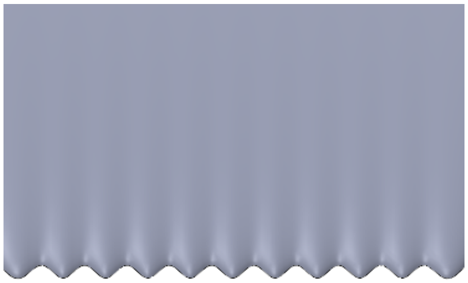

Fig. 3. Shows the top view of TLE model

IV. MESHING OF WING MODEL

Meshing is a process of split the complex geometries in to simple and regular geometry, for simulation. The quality of mesh depends upon the type of mesh, number of nodes and aspect ratio. In current study structure of mesh is tetrahedral.

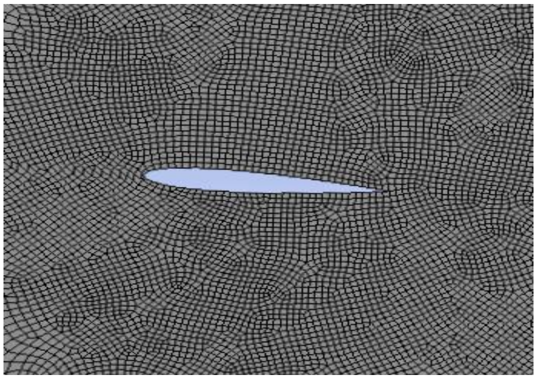

Figure.4. Meshing of Baseline Model

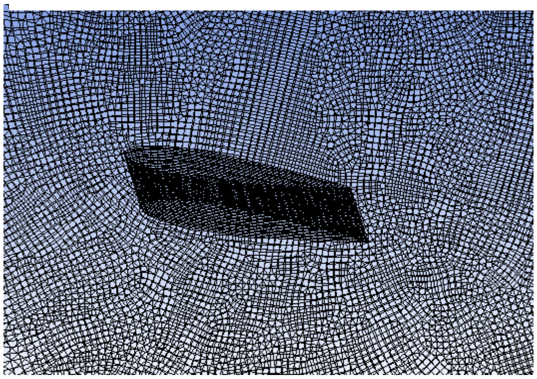

Figure. 5. Isometric view of Baseline Model

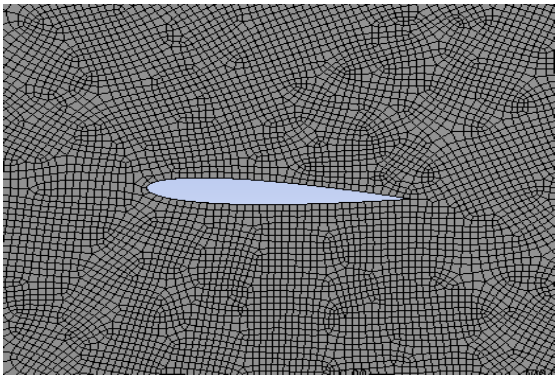

Figure. 6. Meshing of side view of wavy wing Model

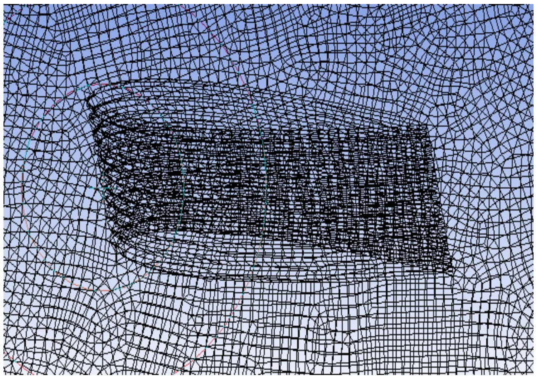

Figure. 7. Meshing of A03W09

V. RESULT AND DISCUSSION

A. Aerodynamic Forces

In this research study the aerodynamic performance of selected wavy wing model were compared with baseline model at 3 degree angle of attack to observe flow behavior and impact of Tubercles at leading edge on the aerodynamic performance wing. Due to presence of TLE a complexity in flow were achieved that was analyzed in the research on the basis of lift to drag ratio. In this numerical study it is revealed that baseline model has better lift to drag ratio in transonic regime at 3 degree angle of attack. Figure.7. shows that the baseline model has better aerodynamic performance than proposed wavy wing model at 3^0 angle of attack. The numerical simulation has revealed that the lift to drag ratio for baseline model was 7 and for proposed TLE wavy wing, L/D remained 6.68, making a difference of 4.52% in the aerodynamic performance at no flow separation.

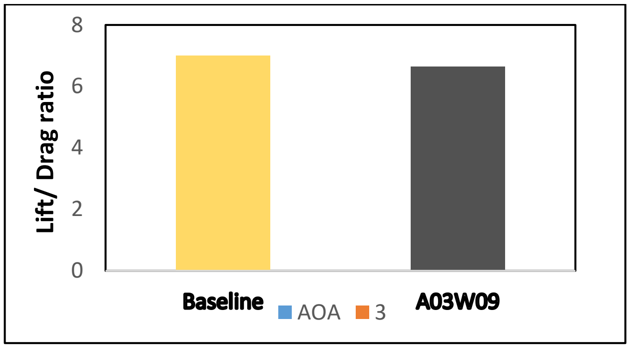

Figure. 8. Representation of Lift to drag ratio for SLE vs. TLE Model at 3^0 angle of attack

B. Surface Pressure Distribution

In this research the aerodynamic behavior of flow mechanism can be understand by critical analyses of static pressure distribution at surface of wing. The current study present the surface pressure distribution of baseline and, A0309W, model. It is observed that at 3 degree angle of attack the transonic flow regime shows different behavior than subsonic flow as it does not obtained advantage of high lift coefficients at given angle of attack. aforementioned results has shown that leading edge tubercles has lower performance than baseline model reducing upto 4.52% lift to drag ratio in a no separate flow condition.

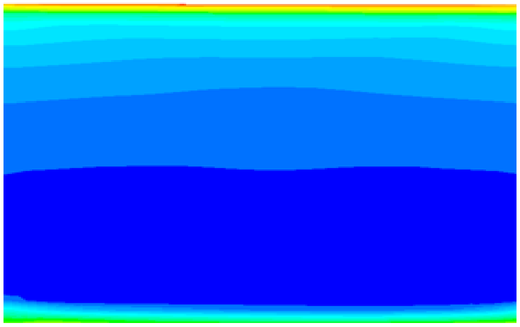

Figure. 9. Shows static pressure on the surface of Baseline Model

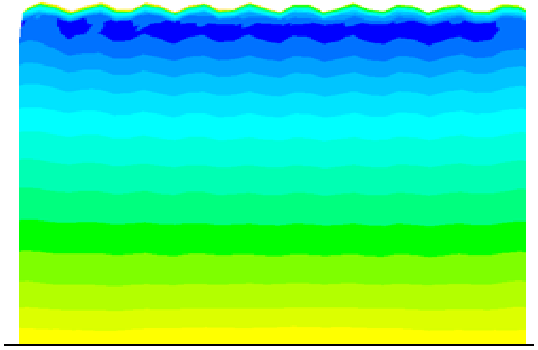

Figure. 10. Shows static pressure on the surface of Wavy Wing Model

It can be seen in given figure 9 and 10 that disadvantages of this modification is abrupt loss in the performance when detachment region appears. From the mentioned figure it is analyzed the shock wave produced in TLE is more than baseline model. In no flow separation conditions where performance can be increased by reducing shockwave by varying drag divergence possibly by variation in flow topology didn't show positive behavior at 3 degree angle of attack.

VI. CONCLUSION

Current study has revealed the effect of leading edge tubercles along the wing span on the aerodynamic performance of wing in transonic flow. The underlying flow mechanism of TLE is dependent on skin friction and wave drag which can be effected by the applying passive flow control devices. In the current study leading edge tubercle model were compared against baseline model of NACA 0012 airfoil at 3^0 angle of attack. A maximum decline of 4.57% were observed in the lift to drag ratio in TLE when the performance of baseline were compared. On the other side from the flow behavior it can be predicted that the performance of tubercles can be enhanced against the baseline model in transonic flow regime.

On the basis of results obtained by simulation it is suggested that performance of tubercle wing could be better at lower lift-coefficients which shown that increment in waviness can have better performance.

VII. RECOMMENDATIONS.

The study has revealed that in transonic flow regime the behavior of flow is very unpredictable. Study suggest to analyze the flow behavior at various flow condition by changing flow topology. Furthermore it is very important to suggest that the wavelength has very low impact on the aerodynamic performance of wing, at no flow separation condition baseline model is preferable over tubercles leading edge at higher lift coefficient. TLE can have advantages in subsonic flow.

VIII. FUTURE WORK.

The current work can be experimentally analyzed and compare with numerical results and flow behavior can be predict at other angle of attack and Mach number. To predict the flow behavior and the aerodynamic performance of analyzed wing model can be compare in subsonic region. The variation in flow topology can be analyzed to reveal its acoustic impact in transonic flow region.

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