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Research Paper

Numerical Investigation on the Influence of Turbulence on Limit Cycle Oscillations

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ABSTRACT:- This article presents the influence of atmospheric turbulence on the Limit Cycle Oscillations (LCO) that occurs because of a nonlinear coupling between the structural response of an airplane wing and unsteady aerodynamic forces.The presence of nonlinear structural characteristics of modernairplane wing is another crucial reason behind the aero elastic interactions thus resulting self-sustained dynamic vibrations. If an aircraft is flying at an altitude through variable turbulence intensities, then the influence of structuralelastic deformations are more important during uncertainty conditions. The response of an airplane against the LCO is not possible to predict through present flow/structural solvers directly. Hence, a novel scheme through loosely coupled approach has been used to predict the aerodynamic load variations in the presence of random turbulence. LCO response of an airfoil made of NACA0012 series is investigated at various Reynolds numbers and different turbulence conditions. The Numerical and computational simulation resultsare compared to verify the consistency of the proposed approach. The pressure based ideal flow conditionis selectedfor the flow simulation process andtheobtained results are significant enough to prove the reliability of the method.

Keywords:- Turbulence, Limit Cycle Oscillation, Reynolds number, Aerofoil, CFD.

I. INTRODUCTION

The airplane wing construction changed from semi-cantilevered configuration to cantilever ones over the past several decades. The benefit of a cantilever wing arrangement isits flexibility to design through cost effective manufacturing techniques. If such a wing configuration is operated at a flight speed above its critical flutter speed then ensuing vibration amplitude is significant [1].Typically, the amplitude of Limit Cycle Oscillations (LCO) is a function of two variables such as the air speed and frequency. The source of the nonlinearity may be fluidic in nature (Eg: shock formation, flow separation, stalling behaviour, etc.) or structural characteristic (buckling, stress-stiffening). These nonlinearities results in a supercritical LCO branch or a subcritical branch [2].Numerical and experimental simulation of LCO'siscomplicated and intensive process. However, the nonlinearities should be included in the aeroelastic simulationsto achieve certain level of modelling fidelity and sophistication [3].

According to the linear theory,a system will continuously go away from the unstable equilibrium point to infinity (or material failure).LCO's are not only necessarily a result of a linear instability but also can be induced by certain disturbances. Basically, if the disturbances are not small, then the response cannot be predicted by theories that are linearized about a nonlinear steady state. Depending on the vibration amplitude of the LCO, the structure may or may not experience immediate failure yet, for an airplane LCO's pose substantialproblems in their own right. This vibration also causes fatigue problems and reducing the useful life of the wing structure. Consequently, efficient prediction of LCO is vital during design phase, especially for airplanes flying near the limits of the linear assumptions.Texas A&M University developed the Nonlinear Aeroelastic Test Apparatus (NATA) consists of NACA 64A010 and supercritical NLR 7301 airfoils to investigate the linear and nonlinear aeroelastic behaviorexperimentally [3]. NATA provides a wing mount (made of rigid NACA 0015wing section) that offers for 2 Degrees of Freedom (DoF)movement in pitch and plunge motions[4].

The limit cycle amplitudes are very sensitive to variations in angles of attack [5]. The 'buzz' responses are observed in a number of practical situations and implications for airplane safety purposes. Sedaghatet al (2000) provides the experimental and theoretical characteristics of LCOs for a three DoF airfoil system with a freeplay in the flap [6].It was the first successful initiative to quantify the LCO behavior in the bending-torsion coupling modes. Later, various theoretical, computational, and experimental capabilities to analyze the LCO are exposed.In particular, aerodynamic flows with large shock motions and flow separation are discussed through Volterra series Reduced Order Modeling (ROM) approachfor the purpose of flutter prediction, aeroelastic control design, and aeroelastic design optimization [7].However, this approach is unsuccessful while applied to other aeroelastic phenomena, such as aerodynamically induced LCO’s [8].Especially with certain high-performance airplane configurations, nonlinearities in the aeroelastic system induce abnormal structural behavior such as the observed store-induced LCO’s[9].

Watkins et al (2010) tested the flat airfoils at a Reynolds Number (RN) of 7.5 x 10^4in the presence ofdifferent percentage turbulence conditions. When the length scale of turbulent region was increasedwith the constant intensity, the slope of lift curve was increased significantly and itreduces maximum lift coefficient (C_{Lmax})[10].If an airplane iscruising continuously in low turbulence, then the prevailing response would be LCO and it cannot be classified as gust response. Nevertheless, if the airplane wereflying in severe turbulence, then the gust response would be primarily that due to turbulence with bursts of LCO.The flow separation is also severe and the wing has high-frequency panel-type modes of vibrations[11]. In this article, a simplified analysis procedure is developed to quantify the influence of turbulence on the basic aerodynamic coefficients by CFD. For low and severe turbulence conditions, the initiation of LCO boundary can be well established through the proposed aeroelastic analysis by the means of computational flow simulations. The presence of LCO would probably have little or no effect on wing loads that could result in structural damage[12]. However,in the secondary structure, it is very sensitive to fatigue damage caused by LCO loadings.

II. MATHEMATICALMODELLING

A two DoF aeroelastic system modeled as an airfoil section that allows pitching and plunging motion is illustrated in Figure 1. In the proposed methodology, the pitch and plunge frequencies alone considered for simplifying the frequency response analysis. For this model, the governing equations for the 2-DoF aeroelastic system can be written as follows,

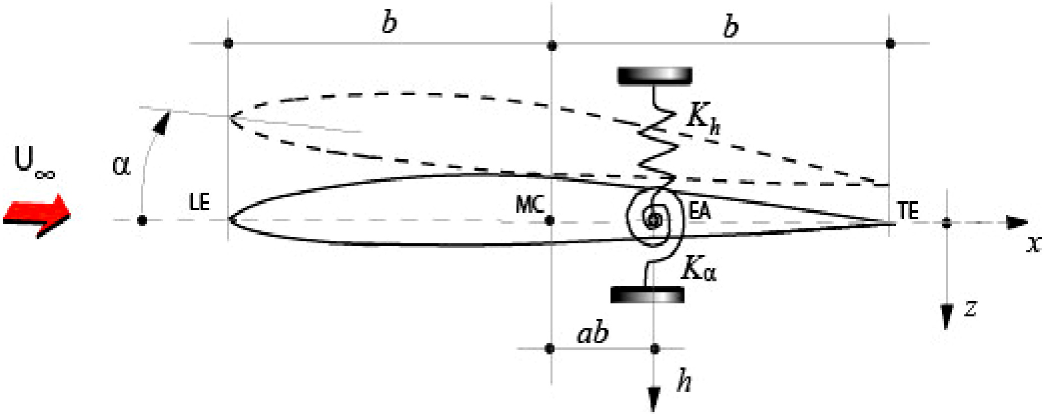

Figure 1. Representation of 2-DoF pitching and plunging wing section

$$m\ddot{h}+m\,x_{\alpha}\mathrm{b}\,\ddot{\alpha}+ch\,\dot{h}+k_h\,h=L(t)+L_d\,(t)+L_c\,(t) \qquad (1)$$

$$I_{\alpha}\,\ddot{\alpha}+m\,x_{\alpha}\mathrm{b}\,\ddot{h}+c_{\alpha}\,\dot{\alpha}+k_{\alpha}\,(\alpha)\alpha=M(t)+M_d\,(t)+M_c\,(t) \qquad (2)$$

Where, α = Angle of attack
K_h = Bending Stiffness
K_α = Torsional Stiffness

Most of the research worksreported in the past decade have been utilized the flat plates and symmetrical airfoils for analyzing the LCO properties computationally. Since, the influence of change in RN on the dynamic pressure is a required quantity, the present analysis also done using the symmetrical airfoil(NACA 0012) configuration. The basic airfoil selection procedure is followed based on the thickness, C_L, drag co-efficient (C_D), camber and chordlength[13]. Airplane performance mainly depends on C_L and C_D magnitudes that are influenced in proportion with the change in RN. The bending and torsional stiffness magnitudes of Aluminum alloy 6061-T6 material (ISTM Standard) is assumed for the purpose Finite Element Analysis.Once the fundamental frequencies for the selected mode shapes are computed then the pressure fluctuations are related with the appropriate twisting/bending modes. In the case of experimental validation, the analysis will be carried out by establishing the similarboundary condition inside the wind tunnel through thesame airfoil fabricated with suitable material and dimensional similarity.

III. COMPUTATIONAL MODELING

A 3D model of commercial transport airplane wing using NACA 0012 airfoil is prepared by CATIA modeling tool. Numerical investigation of flow and structural properties of this modelis preparedby ANSYS workbench.It offers a comprehensive range of engineering simulation solution sets providing access to virtually any field of engineering simulation that a design process require.The complete design specifications of CATIA model is listed in Table 1. The 2D and 3D view of the wing configurationare presented in Figure 2. Structural properties of the model such as stiffness, empty weight, Young's Modulus and Poisson's ratio are computed separately by the Mechanics of materials approach.

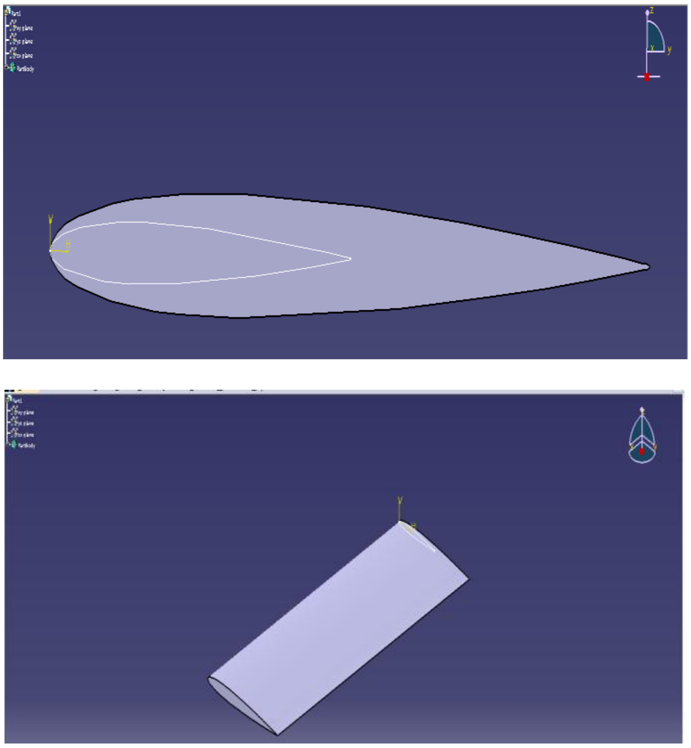

Figure 2.2D and 3D wing model made of NACA 0012 airfoil

3.1BOUNDARY CONDITION

The boundary condition assumed for the prediction of fundamental frequencies using Finite Element Analysis tool (FEA)is given in Table 1.In the input boundary condition,pressure based ideal flow caseis considered without any friction. Turbulence Intensity (TI) is calculated at different RN and at various altitudes.

Sl.NO	Specifications	Values	Assumptions	Values
1.	Chord	10.2 cm	Speed of Sound, a	328m/s
2.	Span	27.33 cm	Velocity, v	238.3m/s
3.	Area	0.057m^2	Mach number M	0.7
4.	Mass	0.609 kg	Dynamic viscosity, μ	17.93x e^{-6} Ns/m^2
5.	Material	Al 6061-T6	Density, ρ	2710 kg/m^3

Table1. Specifications for CATIA modeling and assumtions for flow simulations

3.2ANSYS MODELING

Thewing model is exported toFEAtool for the meshing and simulation process. The solutions are obtained for the given boundary condition at various RN with an operating Mach number about 0.7.Fine meshing is prepared for theFEA of wing model with an element sizing of 1.5 mm as highlighted in Figure 3. The unstructured tetrahedral cells [14] of fine elements formed in the meshing pattern with slightly coarse mesh near the maximum thickness location for fluid domain meshing.

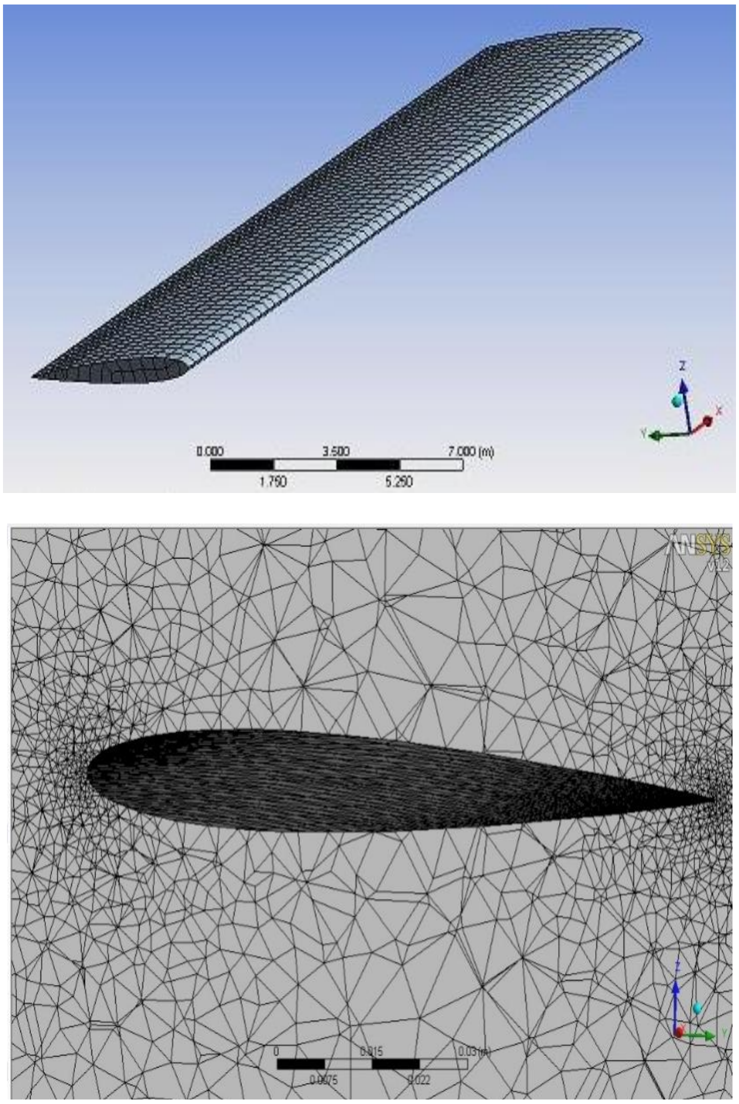

Figure3.Structural and Fluid domain Meshesfor the wing model

Figure 3 shows the full scale drawing of the cross section of NACA 0012 airfoil and the conditions surrounding the airfoil (upper and lower surface = wall). Based on the flow analysis domain, the mesh pattern consists of 3,14,289nodes and for FEA 34,300 nodes are prepared with SOLID 185 element. For most aeroelastic applications, where the magnitudes of viscous and turbulent effects are similar, it is preferable to keep the range of y+, smallest as possible between 5 and 30. This is to ensure that the simulation runs as close as possible to the airfoil. For this simulation, the y+ value denoted by the flow solver is about 12.

IV. RESULTS AND DISCUSSION

4.1FREQUENCY RESULTS

Pre-stressed wing model is used to determine the frequency of vibrating body when it has the aerodynamic loading conditions. It clearly depicts that the static air loads imposed on the wing is the key motivation for getting high frequency forced vibrations. Hence, the pre-stressed modal analysis is used for the selected wing configuration to ensure the usable range of dynamic vibration frequencies. The result of modal analysis is displayedin Figure 5.

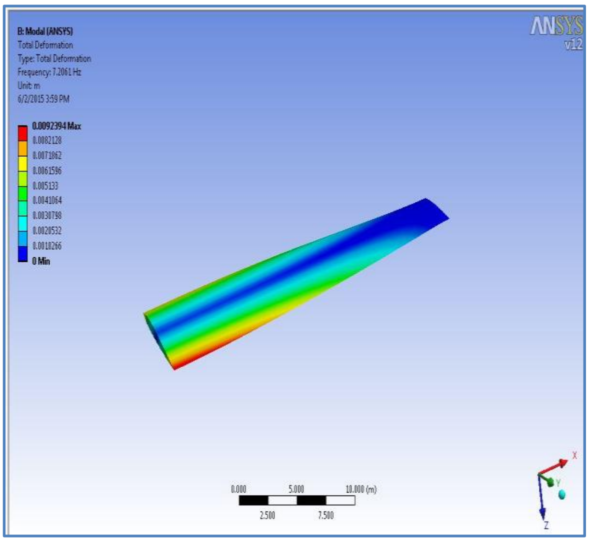

Figure 4. Angle of attack Vs Frequency

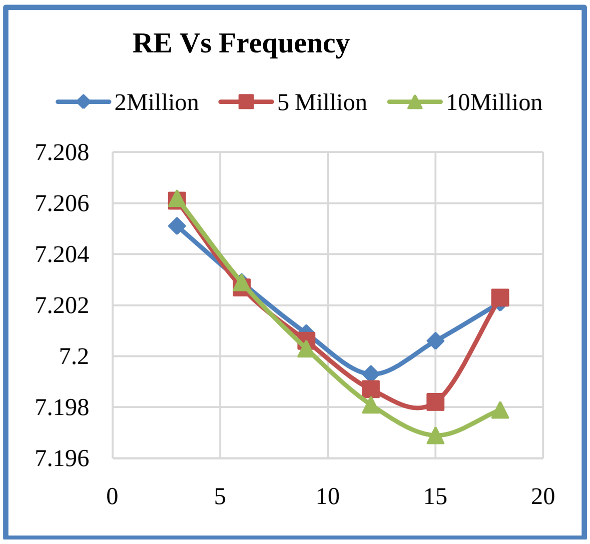

Figure 5.Frequency at bending mode of wing

Frequency is the number of occurrences of a repeating event per unit time. It is also referred to as temporal frequency, which emphasizes the contrast to spatial frequency and angular frequency. The period is the duration of one cycle in a repeating event, so the period is the reciprocal of the frequency. Frequencies of different mode shapes are plotted in Figure 4.When coming into the bending mode shapes wings are getting high deflection due to the forced vibration at their tip chords.

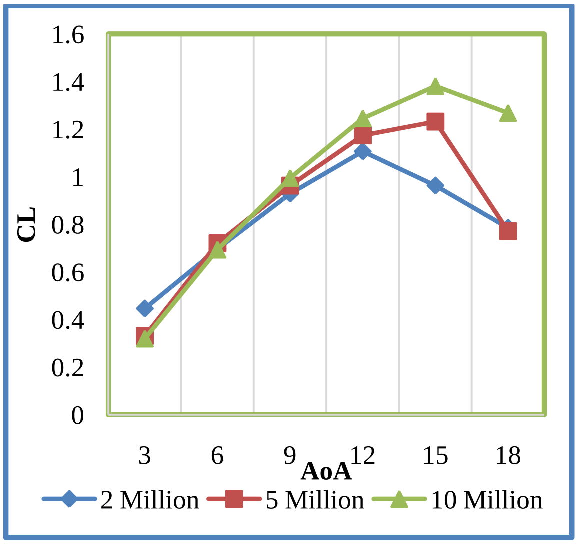

Figure 6. Reynolds Number Vs C_L

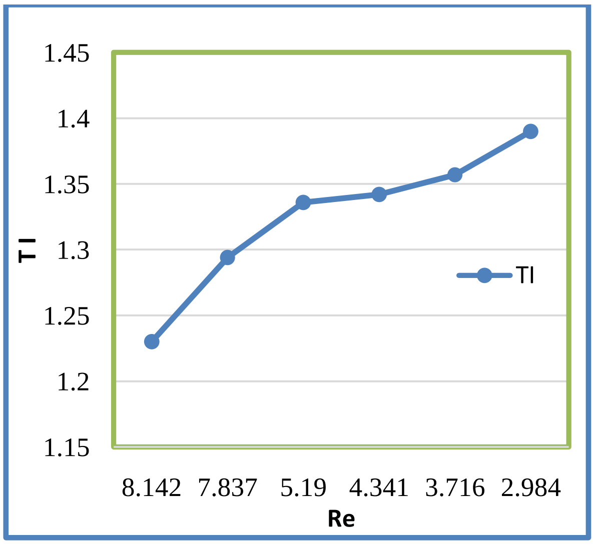

Figure 7. Turbulence Intensity VsRN

Figure 6 shows the lift coefficient computed for the model kept at various angles of attack and RN. At various RN,the coefficient of lift changes considerably and when RN is about 10 million it reaches the maximum. It is well known that the incremental RN could also influence the C_D magnitude that tends the airplane to damp out the LCO[16]. Similarly, Figure7 represents the TI at various Reynolds numbersover thesymmetric airfoil. It shows a striking result that increment in RN decreases the Turbulence intensity approximately in a linear manner. Further, the pitch and plunge oscillations prevail according to the local stiffness of the wing section as described in the mathematical model.

4.2 VELOCITY AND PRESSURE CONTOURS

At 0^0Angle of attack, the wind elements collide with the airfoil stagnation pointas shown in Figure 8. Since it is symmetric in nature, velocity distribution of the wind is approximately same on both upper and lower surface of the airfoil. Therefore, the equal pressure distributions on the upper and lower layer representzeroresultant aerodynamic force that can be negligible. However, at various RN this pressure distribution possess high TI that creates a shift in location along the chord line for peaks and valleys of velocities over the airfoil.

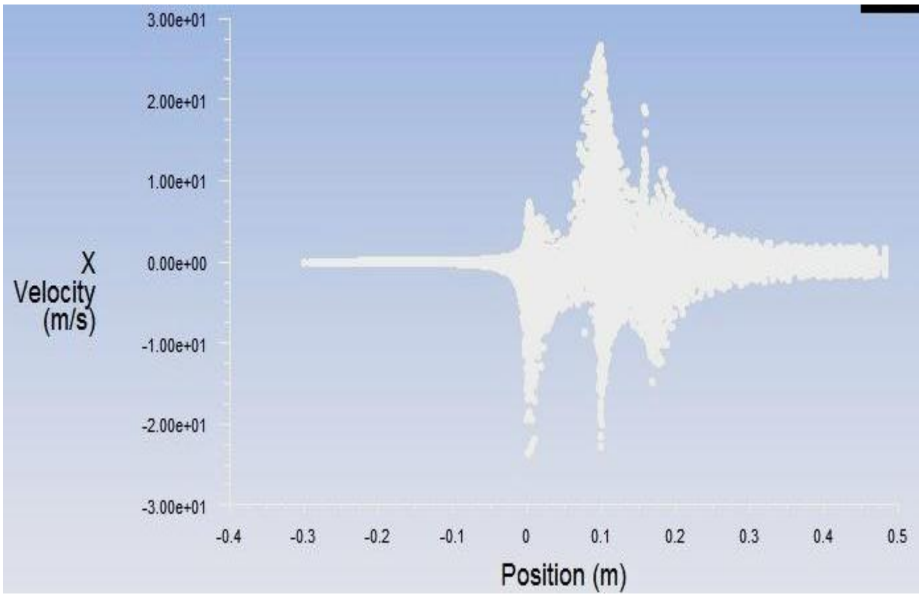

Figure 8.Velocity distribution at Reynolds number = 2 million

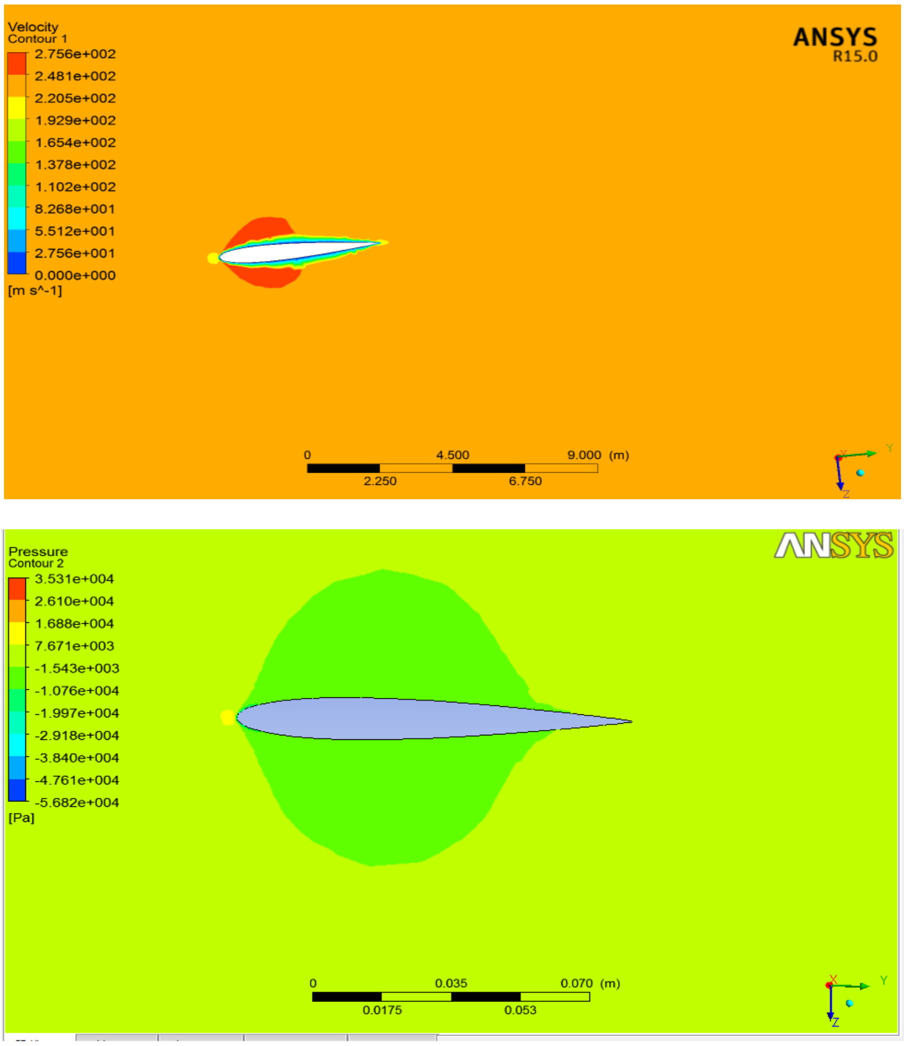

Figure 9.Velocity and pressure distribution contours

Figure 9shows the flow of velocity and pressure distribution contoursover the wing model at sea level conditions.The maximum velocity is reachedat the maximum thickness location of the airfoil as expected about 275.4m/s. At different high RN input conditions, the velocity distribution is modified even at zero angle of attack as stated above. This differential aerodynamic forces tend to initiate low amplitude oscillations based on the free stream Mach number. At high AoA, this similar velocity/pressure distribution on both upper and lower layer of airfoils is broken and amplitude of LCO begins to increase. Hence, the present investigation provides striking information that forthe same pressure on both the surface of airfoil with different RN flow induced oscillations begin to occur.

V. CONCLUSIONS

The present article is intended to compute the influence of structural excitation modeson the LCO's.Through, modal analysisthefundamental frequencies are observed for the assumed wingmodel at sea level conditions. Through the baseline studies, aerodynamically induced LCO andits boundaries of the prototypical wing model can be evaluated by a transonic wind tunnel testing. The coefficient of lift and drag at various altitudesare calculated from the CFD simulations to quantify the influence of RN on the aerodynamic quantities. The frequency response at various RN conditionsis plottedalong with the response of TI for differentAoA. The pressure, velocity, and turbulent kinetic energy are evaluated from FLUENT flow solver for various degrees of turbulence. In future, the Wind Tunnel experiments can be conducted using the same wing modelto calculate the LCO response.

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