Simulation of Aeroelastic System with Aerodynamic Nonlinearity

Muhamad Khairil Hafizi Mohd Zorkipli
School of Aerospace Engineering, Universiti Sains Malaysia, Penang, MALAYSIA

Norizham Abdul Razak
School of Aerospace Engineering, Universiti Sains Malaysia, Penang, MALAYSIA

Abstract: The phenomenon of Limit Cycle Oscillation (LCO) of NACA 0012 airfoil at low Reynolds number turbulent flow is studied numerically through unsteady two-dimensional aeroelastic simulation using RANS (SST) $k-\omega$ model with low Reynold number correction and a default value of $R_k=6$. The study of fluid structure interaction (FSI) were simulated using ANSYS FLUENT 16.1 by coupling structural equation of motion (1DOF) with an in-house user define function (UDF) codes. Simulation were run at limited free stream velocity range between 5 m/s to 13 m/s based on the available experimental data. The numerical simulation produced the trends as expected and found to produce reasonably accurate limit cycle pitching oscillations (LCO). Laminar separation plays an important role for the oscillation to kicks in and sustaining the pitching oscillations. The computed results revealed that the LCOs was mainly sustained in the range of 6.5 m/s to 12 m/s and no LCOs observed below velocity 6.5 m/s and also no oscillation at velocity 13 m/s.

Keywords: Flutter, Aeroelasticity, Limit Cycle Oscillation (LCO)

1 INTRODUCTION

Aeroelastic phenomenon are the dynamical phenomenon resulting from the mutual interaction of aerodynamic forces, elastic force and elastic forces. Limit Cycle Oscillations (LCO) is one of the vibration phenomenon which require at least one nonlinear element in a given system to occur (Razak & Dimitriadis 2013). For an aeroelastic system, the nonlinearity can be from structural, aerodynamic or both. Flutter caused the system to vibrate and when nonlinearity elements is introduced, LCO phenomenon happened to sustain the vibration without any decay in the system.

Recent wind tunnel aeroelastic observations by (Poirel et al. 2008) of 1 DOF free pitching low amplitude confirmed the self-sustained oscillation and LCO happened in the low turbulent Reynold regime. Laminar separation at the tailing edge play an important role in initiate the oscillation was mentioned by the investigator.

In this paper, the investigation is taken one step further by studied the aeroelastic system numerically. The coupling between the flow and the elastic structure were solved by focusing on an RANS approach which is sufficient to capture the nature of the problem. The objectives are to reproduce numerically the aeroelastic LCOs using the default setting $R_k=6$ value in the (SST) $k-\omega$ model with low Reynold number correction. Also, to investigate the prediction of numerical solution in order to produce LCOs results within a given Reynolds number range in the experimental observation.

2 NUMERICAL METHOD

2.1 Computational setup

The flow solver used in this study are ANSYS FLUENT 16.1. The flow solver is coupled with the dynamic of the elastically mounted rigid airfoil. Spatial and temporal discretization are performed with second order schemes for all quantities. The velocity-pressure coupling is based on the PISO segregated algorithm for better accuracy. The two dimensional Reynold Averaged Navier Stokes (RANS), Shear Stress Transport (SST) $k-\omega$ model is used is this paper to capture more robust additional flow around the airfoil.

Unstructured meshes were used in the flow domain with inflation structured meshes at the airfoil boundary layer in this simulation process. The two dimensional pitch-oscillating airfoil were solved in the frame of reference which does not require mesh deformation and re-meshing at the boundary layer in order to obtain better accuracy of the calculations. A circular non-conformal sliding interface which center located at the elastic axis were used, which only the inner part rotates rigidly along with airfoil while the outer domain remain stationary. Thus, no mesh deformation is required. Periodic boundary condition
is applied at the interfaces between the rotating and stationary domain which allow the flows to enter the rotating domain. Also, this method has been validated in the previous studies (Kinsey & Dumas 2008). Figure 1 shows the computational setup for fluid domain and airfoil. The rotating domain were set 10% from the point of elastic axis and the static domain were set big enough about 50% to avoid reverse flow error in the fluent software. This reverse flow error happened were caused by the domain as it too small for the fluid to flow.

Figure 1. Computational domain and grid details.

2.2 Aeroelastic modelling

Pitching motion, one-degree of freedom in pitch mounted rigid body airfoil is modelled based on the equation of motion for aeroelastic system:

\[ I_{EA} \ddot{\theta} + D \dot{\theta} + K \theta = M_{EA} \]  

(1)

The right hand side represent the aerodynamic moment at the elastic axis which is located 0.186% of the chord length, where \( I_{EA} \) is the mass moment of inertia at the elastic axis. The other two parameters \( D \) and \( K \) is the structural damping coefficient and structural stiffness respectively.

The equation of motion is then solved using Newmark Beta direct time integration method which requires Newmark’s constants. The Newmark Beta method solved and provides pitch position, pitch rate and pitch acceleration at every time step.

\[ \theta_{t+\Delta t} = \hat{R}_{t+\Delta t} \frac{\Delta t}{\Delta t} \]  

(2)

\[ \dot{\theta}_{t+\Delta t} = \frac{\theta_{t} + \Delta t - \theta_{t}}{\Delta t} + \dot{\theta}_{t} \left( \frac{\Delta t}{2\Delta t} - 1 \right) \]  

(3)

\[ \ddot{\theta}_{t+\Delta t} = \ddot{\theta}_{t} + \ddot{\theta}_{t+\Delta t} (\beta \Delta t) + \ddot{\theta}_{t} \Delta t (1 - \beta) \]  

(4)

From the above equations, \( \hat{R} \) is the effective stiffness, \( \hat{R}_{t+\Delta t} \) is the effective load at each time steps and \( \Delta t \) is the time step size use in the calculation. The value for newmark constants \( \alpha \) and \( \beta \) is 0.25 and 0.5 respectively. This values is based on average acceleration method in Newmark method.

In Fluent it is possible to solve the above equations at each time steps by using user defined functions (UDF) and then coupled structural equation of motion with fluid solver (ANSYS UDF 2011). At each time step, Fluent will calculate the forces around the airfoil when fluid interacted with the rigid body. Angular velocity is required to update the rotating position of the airfoil at each time step. The steps of calculation can be simplify in Figure 2.

Figure 2. Calculation loop.

2.3 Parameter setup

The parameters was obtained physically in the lab and provided to use in the numerical study based on the experimental data. The mass moment of inertia about the elastic axis located at 18.6% of the chord length from the leading edge were \( I_{\theta} = 0.00135 \text{kgm}^2 \). The structural stiffness by the spring and structural damping were \( K_{\theta} = 0.30 \text{Nm/}\text{rad} \) and \( D_{\theta} = 0.002 \text{Nms/}\text{rad} \) respectively.

As in the available experimental result (Poirel et al. 2008), NACA 0012 airfoil was used as the test case. The airfoil had a chord length of \( c = 0.156 \text{m} \). The air stream velocity were performed at twelve different Reynold numbers corresponding to wind tunnel freestream velocities range from \( 5 \text{ m/s} < V_{\infty} < 16 \text{ m/s} \).

In the experiment setup, the airfoil were not given any initial condition. As for this simulation, the airfoil were given with initial perturbation condition at position \( \theta = 0.2 \text{ pitch degree} \) at the beginning of the
simulation and the air flow around the airfoil were let steady before the airfoil is released.

### 2.4 Turbulence modelling

In this study RANS Shear-Stress Transport (SST) \( k-\omega \) model is used and this model was develop by Menter (Menter 1994) to effectively blend the robust and accurate formulation of the standard \( k-\omega \) model. It is the combination of a \( k-\omega \) model and \( k-\varepsilon \) model which produce SST \( k-\omega \) which is reliable for a wider class of flows (ANSYS Inc 2013). Also, the Low-Reynolds Correction option activated, this options specifies a low-Reynolds-number correction to the turbulent viscosity and allow for more accurate representation of the actual flow, which is expected to exhibit an attached laminar boundary layer up to separation.

### 3 COMPUTED RESULT

The computed results are presented and discussed in terms of aeroelastic dynamic responses followed by aerodynamic flow and also comparison between numerical and experimental results.

#### 3.1 Aeroelastic dynamics

The numerical simulation were simulated within range air stream velocity of \( 5 \text{ m/s} < V_\infty < 13 \text{ m/s} \) where the LCOs were observed experimentally. The simulation results able to produce similar trends compared to experimental observations in term of LCO pitch amplitude, LCO pitch frequency and LCO critical velocity onset at which LCO phenomenon starts to occurred within the Reynolds number range given in the experimental observations.

![Figure 3. Comparison of LCO pitch amplitude between experiment and simulation.](image)

![Figure 4. Comparison of LCO pitch frequency between experiment and simulation.](image)

As shown in the Figure 3 and Figure 4 the results shows the good agreement between the experiment and simulation. The comparison is reasonably good as the simulation results produced the similar trends.

Figure 4 shows the comparison LCO pitch frequencies, frequency increases as the velocity increases. This trends can be observed on both results. Natural frequency of the system were obtained at \( V_\infty = 0 \text{ m/s} \) as no forces were applied to the system. Zero value indicates that no LCO happened at the tested velocity. Frequencies obtained from computations are quite close to experiment, but slightly higher, discrepancies between the results can be caused by turbulence modelling as RANS prediction tend to overestimate the lift.

There are differences at point which LCO starts to occur, for experimental observations, LCO starts at \( V_\infty = 6.0 \text{ m/s} \) while simulation predicted LCO starts at \( V_\infty = 6.5 \text{ m/s} \). This happened probably because of the \( R_k \) value that had been used in \( k-\omega \) SST model, as \( R_k=6 \) is the default value in Fluent. This value need to be adjusted to produce similar result with the experimental observations. As far, these results are accepted as the differences LCO onset between the experimental and numerical observations in the accepted range. Both results agreed that above \( V_\infty = 12 \text{ m/s} \) no LCO happened and noticed no oscillations appeared at velocity greater than \( V_\infty = 13 \text{ m/s} \). From the observations from Figure 3, the maximum LCO amplitude were at \( V_\infty = 7.8 \text{ m/s} \) and it starts to decrease as the velocity increases and finally LCO disappeared.
Figure 5. Pitch responses time history at $V_\infty = 7 \text{ m/s}$. Simulation SST $k-\omega$ $R_k=6$.

Figure 5 shows the pitch response when LCO started at $V_\infty = 7 \text{ m/s}$. To recall that the simulation starts with initial perturbation, the airfoil was given with small initial displacement at $\theta = 0.2$ pitch degree. The small initial condition seems not to affect the results as the LCO pitch amplitudes are in the reasonable range.

3.2 Aerodynamic flow

The location of the flow separation is taken as the points where the wall shear stress equal to zero and the reattachment flow is defined when the wall shear stress becomes positive and stay positive. In order for oscillation kick in at the beginning of the simulation, laminar boundary layer separation plays an important role and responsible for the dynamic responses of the airfoil.

From the Bernoulli’s theory, a region with high velocity have a low-pressure distribution and vice versa. As observed from the $C_p$ distribution at $\theta = 4.0$ pitch up, the upper surface has low pressure distribution compared to lower surface due to upper surface is much exposed to incoming high velocity when the airfoil pitching up. High pressure at lower surface of the airfoil tends to push the airfoil pitch upward. This trend of flows characteristics was as expected based on the Bernoulli theory and similar trend can observed when the airfoil pitching down.
Figure 7 shows the comparison of turbulent vorticity ratio contour when the airfoil pitching up at the maximum amplitude, the vorticity ratio value is highest at the trailing edge compared to leading edge which recorded the lowest vorticity ratio value. Figure 7 shows the turbulent viscosity ratio at $V_\infty = 7\text{ m/s}$ and $V_\infty = 11\text{ m/s}$ as the freestream velocity increases, Reynold number also increases. The trends continues with turbulent viscosity ratio, at $V_\infty = 11\text{ m/s}$ viscosity ratio is 25 higher compared to at $V_\infty = 7\text{ m/s}$ which has a value of 16.5. As mentioned earlier, the amplitudes of both experimentally and numerically simulated LCOs amplitude decreases as the Reynolds number increases. A possible explanation for this phenomenon is the increases of turbulence level in the near wake of airfoil. The higher Reynolds number case is much better behaved due to the increased turbulent viscosity ratio which tends to dissipate the large amplitude, high frequency and fluctuations. At free stream velocity above 12 m/s the oscillation are destroyed by increasing the freestream turbulence level in the near wake regime of the airfoil.

4 CONCLUSIONS

Numerical solutions were performed for NACA 0012 pitch oscillations using RANS (SST) k-ω model and the predicted LCO amplitude and LCO frequencies shows a good trend with the experimental data.

The simulation shows that the default Rk value of 6 be able to produces results that have a good agreement with the experimental observations. Besides, Newmark-Beta approach gave the similar trend of results compared with others direct time integration method such Adam-Bashforth formula.

ACKNOWLEDGMENTS

Financial research grant support from Universiti Sains Malaysia.

REFERENCES


