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TRANSONIC BUFFET INVESTIGATION ON NACA0012 AIRFOIL

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ABSTRACT

The transonic buffet can be described as the oscillating behavior of the shock with the interaction of turbulent boundary layer and this phenomenon can cause severe performance degradation and even wing damage during flight. In order to restrain the adverse effects of the buffet on wing, the phenomenon is investigated in detail in terms of the conditions that trigger buffet, and the variations in the flow field characteristics during buffet. In this manner, the present study involves numerical investigation of the buffet characteristics and critical flight conditions that stimulate buffet on NACA0012 airfoil under certain conditions.

INTRODUCTION

Transonic buffet causes instabilities in the flow field as a result of the interaction of turbulent boundary layer with shock wave. The buffet phenomenon occurs in specific flow conditions and these are combinations of Mach number and angle of attack. The buffet onset is defined in terms of the critical Mach number and angle of attack conditions and each airfoil type has a unique buffet onset curve. The representative buffet onset curve of NACA0012 airfoil, which is obtained from the wind tunnel test database is presented in Figure 1 [McDevitt and Okuno,1985]. It is seen that as the Mach number increases, the critical angle of attack decreases, when the variation in the buffet onset curve is examined. The buffet onset curve is the representation of separation in the stability characteristics of the flow field. In the region below buffet onset, the flow around airfoil is highly stable and no characteristics such as oscillating shocks are observed in that region. Whereas, in the upper part of the curve, the flow is unstable and oscillating shocks and their interaction with boundary layer cause separation leading to buffet. The separation on the boundary layer and the oscillative characteristics of the shock wave can be determined by a dimensionless parameter called the Strouhal number. The Strouhal number is the frequency of the vortex shedding, and it is used for the identification of the buffet onset and buffet characteristics on the airfoil. It is dependent on mainly buffet frequency, f and nondimensionalized by reference length, l_{ref} and freestream velocity, u as indicated in Eq. 1.

$$St = \frac{2\pi f l_{ref}}{u} \qquad \text{Eq. 1}$$

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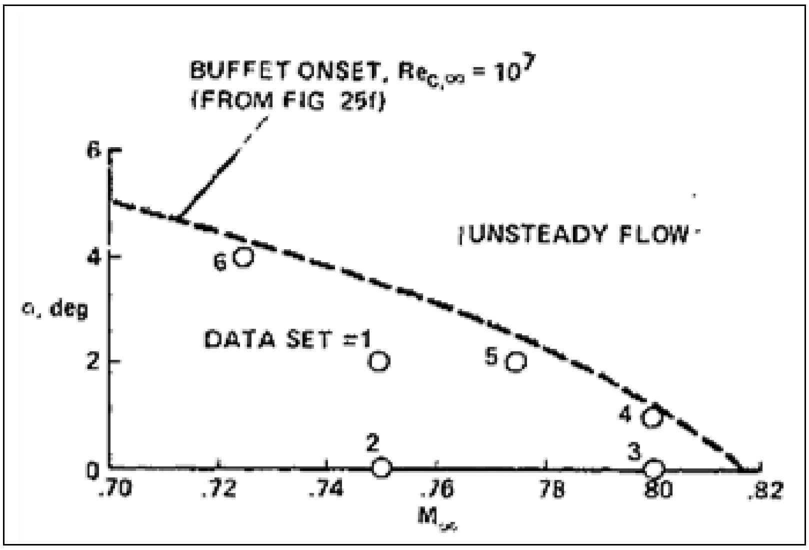

Figure 1*:* NACA0012 Buffet Onset [McDevitt and Okuno,1985]

For steady analyses, numerical solutions have been undertaken, where RANS equations have been solved using the FLUENT Commercial Software. Spalart-Allmaras turbulence model has been used for mesh independence study and three turbulence models have been used for the turbulence model set study as Spalart Allmaras, k-ε and k-ω SST. 89000 mesh elements have been used for low Reynolds number analyses and the mesh resolution is increased to 428000 for high Reynolds number analyses. The convergence criteria are set as the residual to be at least 10^{-4} up to 10000 iterations.

The transient analyses are conducted using URANS with k-ω SST turbulence model. The mesh resolution is kept the same for both low and high Reynolds number analyses as 428000 for the transient flow conditions. The convergence criteria are set as the residual to be at least 10^{-6} up to 20 iterations per timestep with 0.0001 timesteps during 2 seconds.

STEADY ANALYSES

The steady analyses are conducted for obtaining the optimum mesh resolution and appropriate turbulence model to best fit into the case. In this manner, the results of the steady analyses are compared with the wind tunnel data in terms of pressure coefficient distribution over the chord of the NACA0012 airfoil. The wind tunnel data that is the closest to the flow condition is used for comparison as M=0.808, α=0.97°, Re=4.1E+06, which is stated in [McDevitt and Okuno, 1985].

Figure 2 represents the verification of the numerical analysis results with wind tunnel data through the pressure coefficient distribution examination over chord. It can be seen that, the shock location and the pressure distribution is fairly well captured on the upper surface. On the lower surface, close match is obtained with numerical analysis up to 60% of the chord. After 60% of the chord, the numerical analysis cannot predict correctly the pressure distribution around the highly separated boundary layer region after shock according to the wind tunnel data. The overall results indicate that the shock wave location is correctly predicted on both upper and lower surfaces and the results are fairly well validated with wind tunnel data.

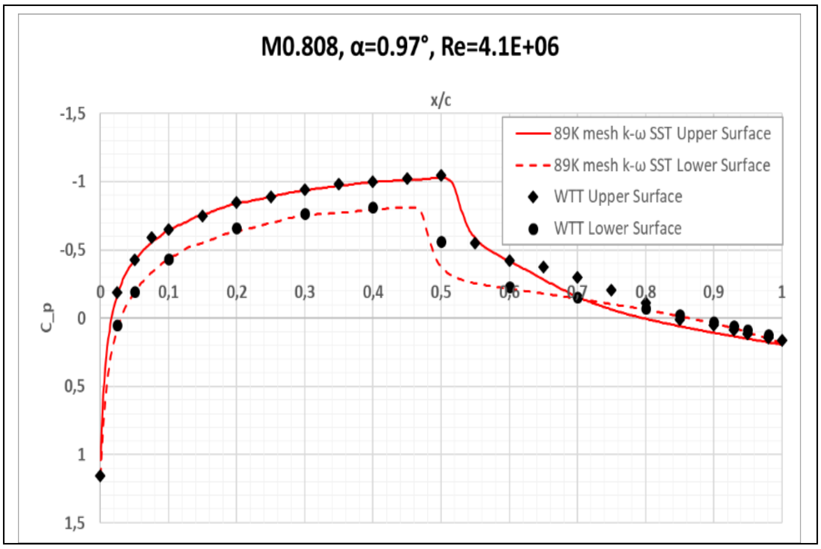

Figure 2: Verification of the numerical analysis with wind tunnel data

The buffet onset and the shock oscillation characteristics during buffet is highly sensitive to the Reynolds number [Algül, 2021]. As the Reynolds number increases, it is seen that the buffet frequency increases dependently, and the shock location on both upper and lower surfaces of the airfoil shifts downstream. In order to investigate the buffet characteristics at high Reynolds number, firstly the steady flow conditions are examined at M=0.793, α=1.0°, Re=10.3E+06 and compared with wind tunnel data [McDevitt and Okuno, 1985] as in Figure 3. The mesh resolution increased with different boundary layer thickness in order to satisfy the new flow condition with higher Reynolds number and the new resolution consists of 428K mesh elements.

When looking at the numerical results at Figure 3, it is seen that the results are closely matched with wind tunnel data up to 60% of the chord at upper surface. After 60% of the chord, a mismatch occurs and this mismatch reveals that the separation at the boundary layer is not predicted well. However, it is seen that the shock location is predicted with high accuracy at the upper surface. At the lower surface, the results are matched with wind tunnel data up to 48% of the chord and after that location, there is a serious mismatch. This reveals that neither the shock location, nor the separation at the boundary layer after shock is predicted well. The shock is predicted upstream of the experimental location. For the high Reynolds number, the pressure drop at the shock location cannot be predicted correctly from numerical solutions when looking at the wind tunnel data.

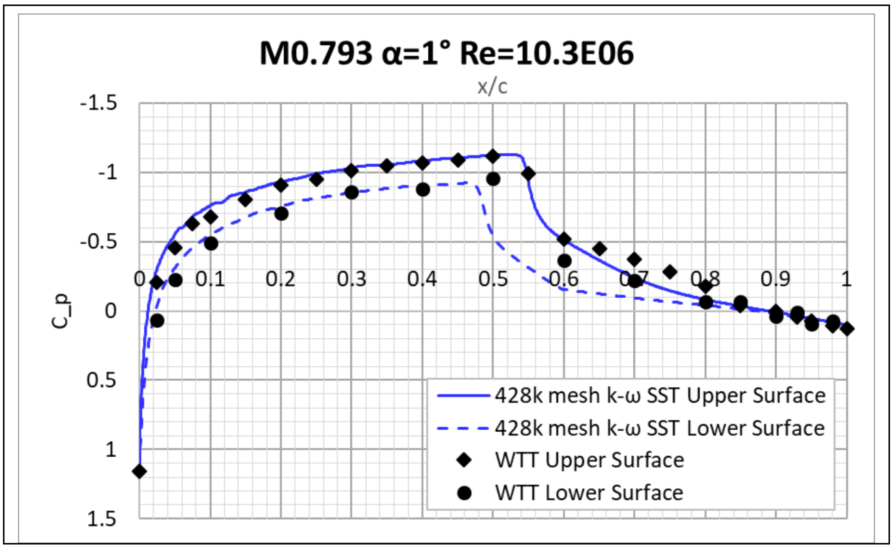

Figure 3: Verification of the numerical analysis with wind tunnel data at high Reynolds number

STEADY TRANSIENT ANALYSES

The buffet onset investigation is firstly conducted with steady transient analyses in order to obtain and examine the stable flow characteristics on the airfoil. The stable flow characteristics are observed at the lower region of the buffet onset curve as stated in Figure 1. For this purpose, the flow conditions for steady analysis are taken as M=0.8, α=1° and Reynolds number as 3.7E+06. The related mesh configuration is obtained from 89K mesh elements as a result of the mesh independence study and turbulence model set. The k-ω SST turbulence model is used with URANS during 2 seconds with 0.0001 seconds time step.

Figure 4 represents the time variant lift coefficient on the airfoil during steady transient analysis. When the streamflow reaches the airfoil, it instantly causes disturbance, which leads to oscillations in the lift coefficient in the first 0.25 seconds. After the uniform flow is reached, the oscillations in lift are damped between 0.25 and 0.5 seconds. Since the lift coefficient has a constant value for each time step after 0.5 seconds, the shock oscillation is not observed for this specific flow condition.

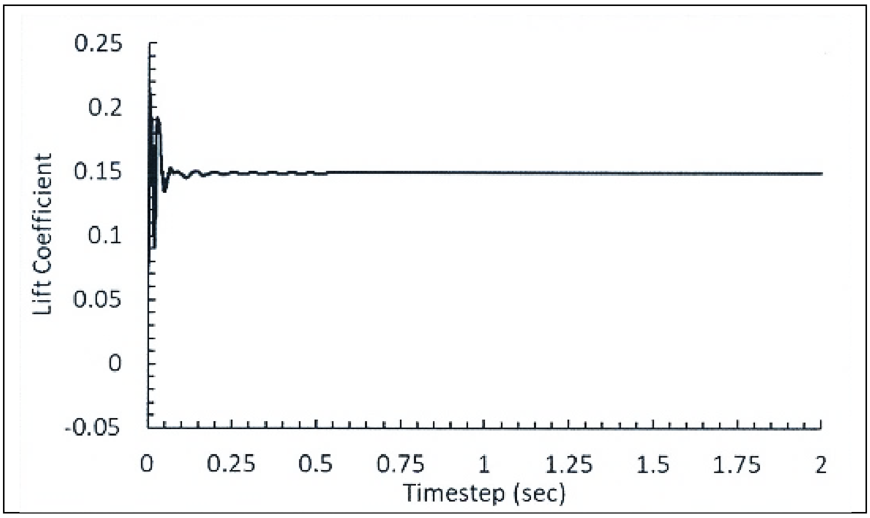

Figure 4: Lift coefficient history with time in steady transient analysis

UNSTEADY TRANSIENT ANALYSES AT LOW REYNOLDS NUMBER

The unsteady flow features of the buffet phenomenon with oscillating shock wave is seen on the region above the buffet onset curve as indicated in Figure 1. For this purpose, the flow conditions for unsteady transient analysis are taken as M=0.8, α=4° and Reynolds number as 4E+06. The unsteady flow condition is obtained from the steady condition with 3 degree of angle of attack increment with the same Mach and Reynolds numbers. The related mesh configuration is obtained from 428K mesh elements as a result of the mesh independence study and turbulence model set. The k-ω SST turbulence model is used with URANS during 2 seconds with 0.0001 seconds time step.

Figure 5 represents the time variant lift coefficient distribution on the airfoil during unsteady transient analysis. The oscillation of the lift coefficient can be clearly seen from the results and the root cause of this oscillating behavior in the lift coefficient is the shock wave/boundary layer interaction with oscillation [Lee,1990]. There is an undamped oscillation with constant frequency and wavelength especially after 0.1 seconds. During the first 0.1 seconds, the streamflow causes a disturbance when it firstly reaches the airfoil and this causes a peak at the lift coefficient variation.

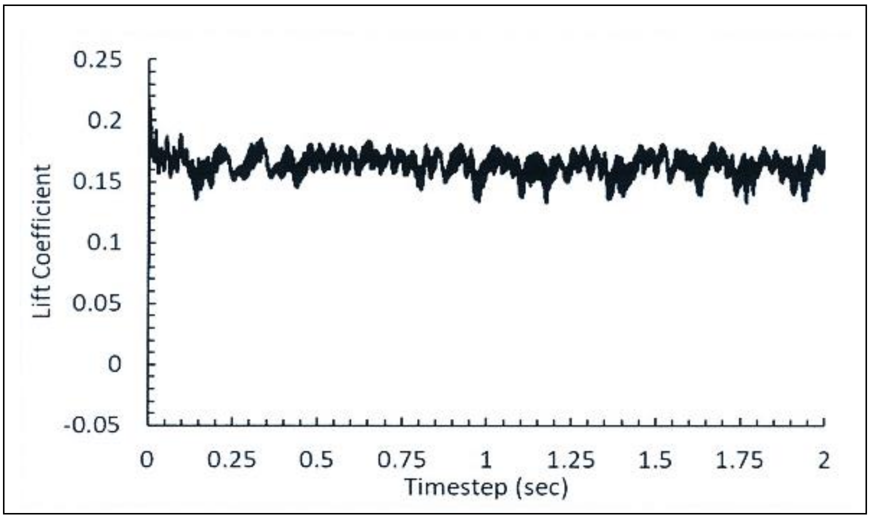

Figure 5: Lift coefficient history with time in unsteady transient analysis at low Reynolds number

The power spectral density variation of the lift coefficient with logarithmic scaled frequency can be seen at Figure 6. The peak point of the power spectral density is seen at 29.7 Hz, and this frequency is identified as the buffet frequency. The other bumps on the curve is due to the noise on the data.

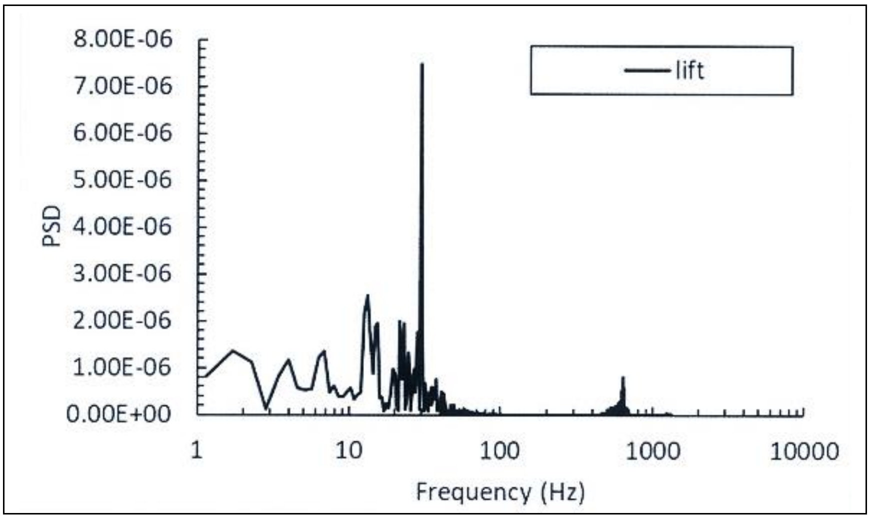

Figure 6: Power spectral density of lift coefficient history with frequency in unsteady transient analysis at low Reynolds number

Figure 7 indicates the pressure and velocity waveforms of the upper and lower surfaces of the airfoil at 50% and 80% of the chord. When looking at the steady analysis results, it is seen that the shock is originated from midchord and moves to the trailing edge; hence, the interaction of the shock wave with boundary layer becomes significant at the trailing edge. For that reason, the waveforms are investigated from 50% and 80% of the chord on both upper and lower surfaces. The frequency of the oscillation increases when going from 50% to 80% of the chord at the upper surface when looking at both pressure and velocity waveforms. For the lower surface, the oscillating behavior changes when going from 50% to 80% of the chord; however, it is hard to estimate the variance at the frequency. All of the pressure and velocity wave results for each individual location indicates that the frequency characteristics and values are different for each location. For that reason, there are four different dominant frequencies for each four locations. Since one single dominant buffet frequency cannot be obtained from these four individual frequency characteristics, the buffet frequency is obtained from the variation of the power spectral density of the lift coefficient with frequency.

The variations in the frequency characteristics of the wavelengths indicates the average location of the shock oscillations. When looking at the low frequency values at 50% of the chord at the upper surface, the shock oscillations have not started yet at this point. Due to the high oscillations of the boundary layer, there is a considerable rise in the frequency values of 80% of the chord at upper surface. For that reason, at the upper surface the shock oscillations start from a location between 50% and 80% of the chord. Since there is no distinctive difference between the frequency characteristics of midchord and 80% of the chord, the conclusion can be made as no oscillating shock originates at the lower surface of the airfoil.

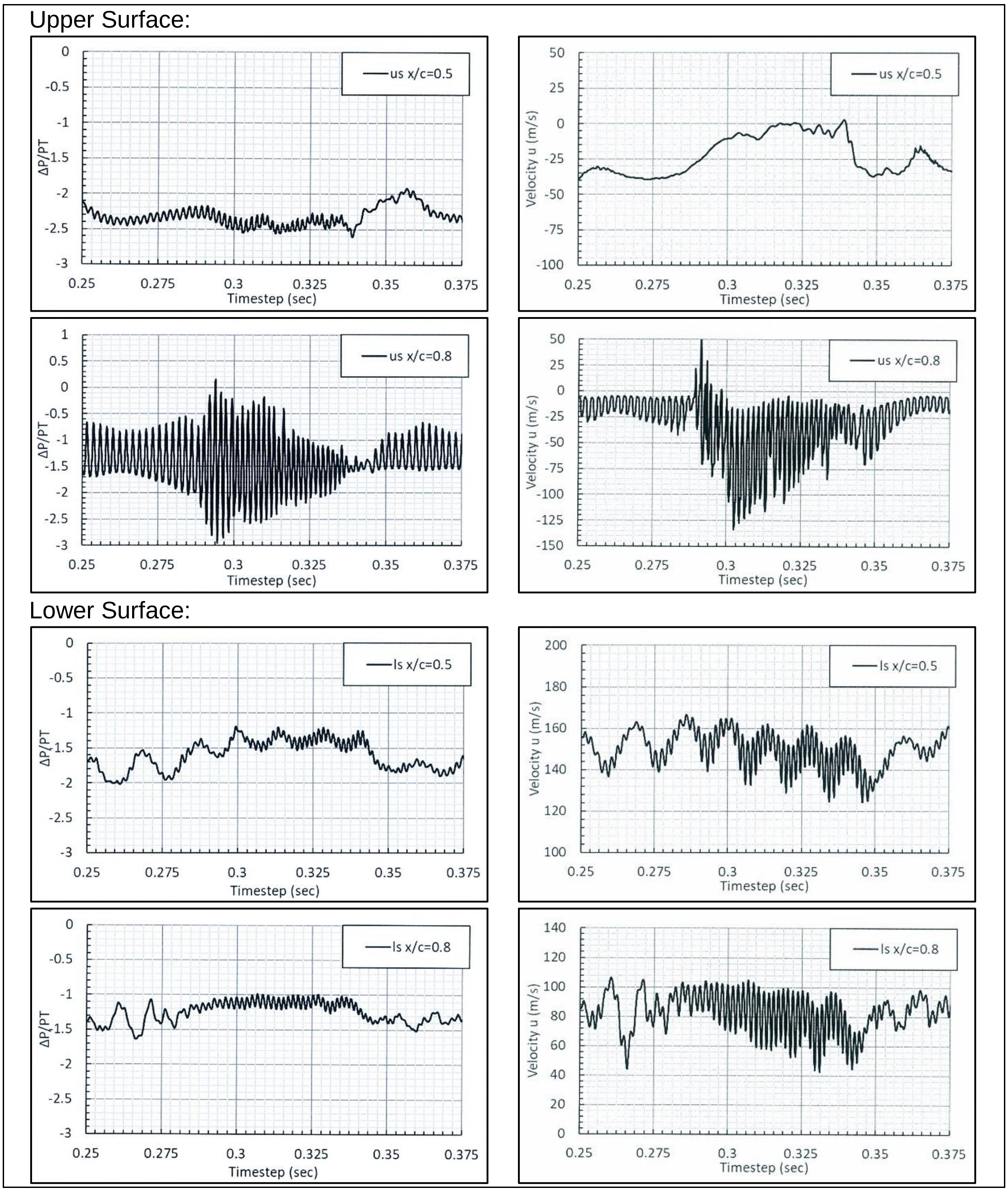

Figure 7: Pressure and velocity waveforms history with time in unsteady transient analysis at low Reynolds number

The results indicate the shock oscillation clearly and this oscillation has nearly constant bandwidth after buffet onset. The Strouhal number of the unsteady transient flow is calculated as around 0.14. The value might seem less to trigger buffet when compared to the previous findings [McDevitt and Okuno,1985]; however, since the flow conditions are for the low Reynolds number, Strouhal number is expected to be less.

UNSTEADY TRANSIENT ANALYSES AT HIGH REYNOLDS NUMBER

Since it is known that the buffet characteristics vary with Reynolds number, it is essential to identify these characteristics with the same flow conditions and higher Reynolds number. For this purpose, the flow conditions for analysis are taken as M=0.8, α=4° and Reynolds number as 10E+06. The Reynolds number is increased to three times higher with the same flow condition as in unsteady transient analysis at loe Reynolds number. The related mesh configuration is obtained from 428K mesh elements as a result of the mesh independence study and turbulence model set. The k-ω SST turbulence model is used with URANS during 2 seconds with 0.0001 seconds time step. The results are compared with wind tunnel data [McDevitt and Okuno,1985] for the same flow conditions in terms of Strouhal number of the buffet frequency.

Figure 8 represents the time variant lift coefficient distribution on the airfoil during unsteady transient flow at high Reynolds number. The oscillation of the lift coefficient due to the interaction of the shock wave with separated boundary layer can be clearly seen from the results. The random oscillating behavior of the lift coefficient due to the disturbance when the streamflow reaches the airfoil is seen at first 0.1 seconds. After 0.1 seconds, the regular behavior of the oscillation of the lift coefficient can be recognized from the results. Unlike the results at low Reynolds number, the oscillation frequency reaches a higher value as it is seen from the comparison of Figure 5 and Figure 8. As a result; it can be concluded that the increase in Reynolds number results in a rise in the buffet frequency.

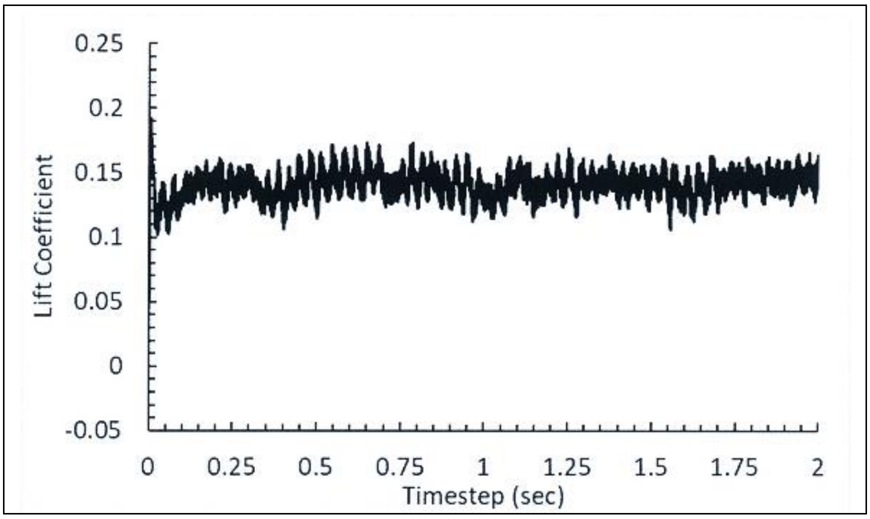

Figure 8: Lift coefficient history with time in unsteady transient analysis at high Reynolds number

This is further verified with the results of the spectral analysis. The power spectral density variation of the lift coefficient with logarithmic scaled frequency can be seen at Figure 9 for the flow conditions with high Reynolds number. The dominant peak at the power spectral density of the lift coefficient occurs at 70.3 Hz, which is identified as the buffet frequency. There is a significant increase at the buffet frequency with Reynolds number increase in the same flow conditions, as the power spectral density variations in Figure 6 and Figure 9 are compared. The fact that the increasing buffet frequency with increasing Reynolds number at the same flow conditions can be clearly identified from the power spectral density variation of lift coefficient with frequency. When the results of the numerical simulation and the wind tunnel data is compared, it is seen that the buffet frequency is measured as about 80 Hz at M=0.8, α=4° and Re=10E+06. The numerical results are not matched with wind tunnel data perfectly; however, it is seen that the similarity is high considering the relatively small difference between the frequencies.

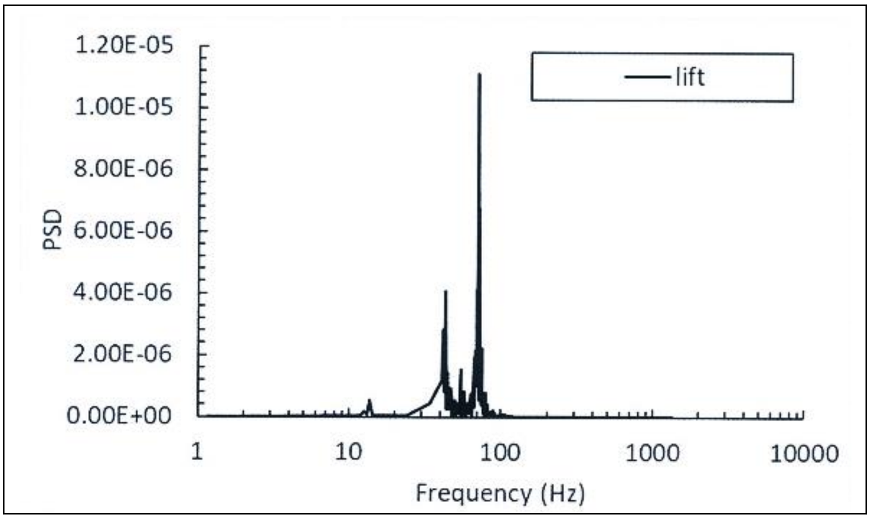

Figure 9: Lift coefficient distribution with frequency in unsteady transient analysis at high Reynolds number

Figure 10 illustrates the pressure and velocity waveforms of the upper and lower surfaces of the airfoil at 50% and 80% of the chord. The oscillation is still increasing when moving from midchord to 80% of the chord with higher Reynolds number at the upper surface of the airfoil when examining the pressure and velocity waveforms. However, the similar comparison cannot be made for the lower surface since the frequency characteristics are not distinctive. The comparison between low and high Reynolds number versions of the same flow conditions reveal that the amplitude and the frequency of the oscillation at each point increases with the increase in Reynolds number. In connection with this increase in frequency characteristics, the dominant frequency of the buffet increases with the increase in Reynolds number as well.

The shock oscillation at the upper surface starts at a location between 50% and 80% of the chord understood from the abrupt increase in the frequency values between these two locations. When the frequency characteristics and the values at midchord is compared for two different Reynolds number conditions, it is seen that the frequency is higher at the high Reynolds number case. For that reason, the shock starts at a location which is closer to the midchord at the high Reynolds number case than low Reynolds number case. Since the oscillation frequency characteristics are not distinctive, a similar conclusion cannot be made for lower surface. However, the frequency values are distinctively higher at the high Reynolds number at the lower surface of the airfoil.

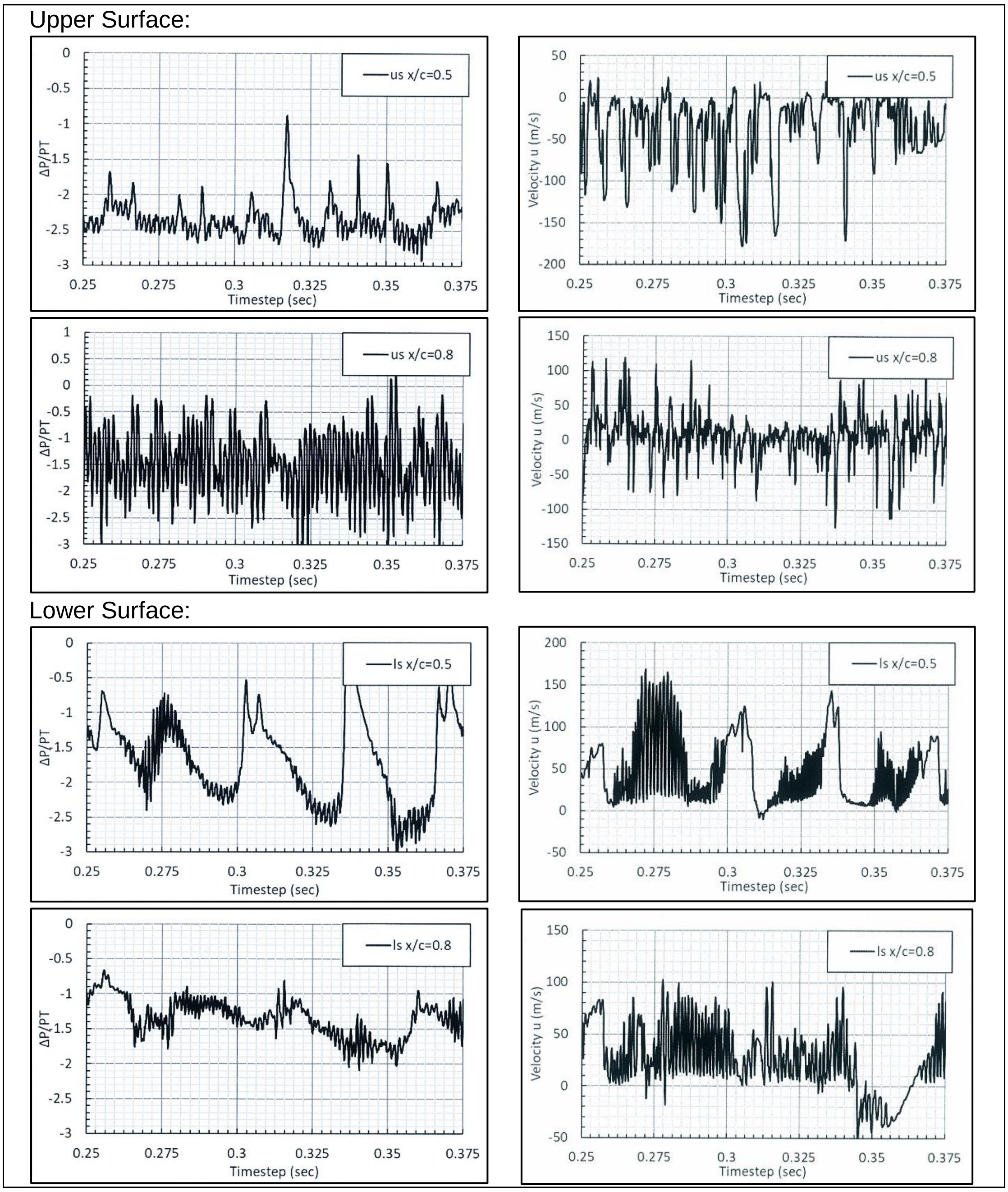

Figure 10: Pressure and velocity waveforms over time in unsteady flow at high Reynolds number

The frequency of the buffet is around 29.7 Hz for the low Reynolds number, for the high Reynolds number the frequency increases up to 70.3 Hz. The oscillations have higher frequency at high Reynolds number and the shock starts at an upstream location compared to that at low Reynolds number. For that reason, the increase in the Reynolds number results in a stronger flow separation during buffet.

The Strouhal number for M=0.80, α=4° and Re=10E+06 is calculated as 0.33 from the analysis results. The Strouhal number of the wind tunnel data for the same flow conditions is stated as 0.38 [McDevitt and Okuno, 1985]. The mismatch between numerical analysis and wind tunnel data is measured as 15%. The oscillations and the unsteadiness at the flow is determined from Strouhal number, and it is affected by the flow conditions, geometry and the convergence of the numerical flow solutions. Looking to the mismatch between two data, the flow cannot be modeled with high accuracy from numerical solution. The steady numerical results at high Reynolds number predicts the shock upstream of the experimental location obtained from the wind tunnel data. The shock location cannot be predicted with high accuracy with transient analysis either; hence, the frequency values of the numerical solutions differ from the wind tunnel data. The mismatch occurring at the frequency values due to the variation in shock location between two data results in a mismatch in the Strouhal number.

CONCLUSION

So far the flow characteristics on the airfoil just before the buffet onset is investigated using steady analyses for both low and high Reynolds numbers in addition to the mesh independence, turbulence model set and verification of the steady analysis results with wind tunnel data. The results are highly matching with wind tunnel data for low Reynolds number. However, for high Reynolds number, a mismatch occurs especially at the lower surface for prediction of pressure values at shock wave and boundary layer separation at the trailing edge. In addition, the flow characteristics before and after buffet onset for both low and high Reynolds number are investigated through transient analyses. The flow characteristics during buffet is investigated at low Reynolds number in terms of lift coefficient, pressure and velocity waveforms for different locations on airfoil. Since the shock wave/ boundary layer interaction with separation during buffet becomes more effective due to the variations in the flow characteristics, the buffet phenomenon is investigated at higher Reynolds numbers. In this manner, the unsteady transient analyses during buffet is investigated at high Reynolds numbers and the results are verified with wind tunnel data. The results of the analysis at high Reynolds number does not perfectly match with wind tunnel data. 15% mismatch occurs between the Strouhal numbers of numerical solution and wind tunnel data, and the possible reason is the frequency mismatch due to incorrect numerical prediction of shock location. The overall results have shown that, the transient buffet is triggered by Mach number and angle of attack and the buffet characteristics are also affected by Reynolds number in addition to these factors.

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