

PREDICTION OF SHOCK INDUCED BUFFET ONSET FOR FLOW OVER A SUPERCRITICAL AIRFOIL

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ABSTRACT

Transonic flow over a supercritical airfoil is associated with the appearance of shock wave in the flow field. At particular flow conditions, the interaction of shock wave with boundary layer leads to self sustained shock oscillations, lift fluctuations and thus initiate the buffeting phenomena. In the present study, Reynolds averaged Navier-Stokes equations has been applied to predict the onset of buffet for flow over NASA SC(2) 0714 supercritical airfoil. Results have been validated with the available experimental data. The buffet boundary and the corresponding fluctuating aerodynamic behavior have been numerically analyzed.

Keywords: Shock Oscillation, Buffeting Flow, Supercritical Airfoil.

1. INTRODUCTION

Shock buffet is a large-scale flow-induced shock motion which is self-sustained and repeated alternatively along the upper and lower surfaces of the aerofoil. This shock motion also involves alternating separation and reattachment of a boundary layer. For small angle of attack at a given free-stream Mach number the flow reattaches. Starting at a moderate lift coefficient, as angle of attack is increased the shock intensifies and moves aft over the airfoil. At sufficient high angles of attack, the boundary layer separates either as a bubble at the foot of the shock or at the trailing edge [1]. This separation moves upstream. At certain condition, the two separated flow regions can merge and the flow over the airfoil is fully separated. This ensuring flow is an alternating sequence of separation and reattachment. This cause buffeting [2]. Lee proposed a feedback criteria for self-sustained shock motion on supercritical airfoil [3]. Buffet onset is influenced by the geometry and trailing edge viscous-inviscid interaction. The physical mechanism for buffet onset is still not fully well established.

In several recent computational studies, prominent features of the shock buffet of the 18-percent-thick circular-arc airfoil have been computed with Navier-Stokes and thin-layer Navier-Stokes codes [4, 5]. Those studies highlighted the sensitivity of this problem to the type of turbulence and flow model and the importance of shock and trailing-edge separation in the onset of shock buffet. Although details of the shock buffet are sensitive to these factors, all computations have computed the onset Mach number for the circular-arc airfoil quite accurately.

The physical mechanisms important in this problem can be investigated from a variety of viewpoints. For

instance, shock strength is implicated in the identification of a Mach number range ahead of the shock for the 14-percent circular-arc airfoil in which shock buffet occurs [6]. Geometry and trailing-edge viscous-inviscid interaction play a role as well. The 18-percent circular-arc airfoil has trailing-edge separation prior to shock separation and shock buffet onset [7]. Trailing-edge separation has long been associated with the onset of shock buffet [8, 9]. Shock buffet for this airfoil is antisymmetric and displays hysteresis in the onset Mach number range, the latter of which is discussed in [10] in connection with the coalescing of a shock and trailing-edge separation. Questions remain, however, as to the important mechanisms involved for other airfoils.

The $k-\omega$ turbulence model embodies more flow physics than one-or zero-equation turbulence models and is applicable to boundary layer dominated flows. It allows solution of the turbulence equations to the wall including the viscous sublayer and also allows modeling of free-stream turbulence and the effect of varying surface roughnesses. This allows the effect of these modeling parameters on shock buffet onset to be investigated. The shear stress transport form of the model is used to compute details of the shock buffet of the NASA SC(2)-0714 airfoil [11]. Comparisons with the experimental shock buffet data at high Reynolds numbers [11] are shown at several Reynolds numbers; this represents the first numerical study of the effect of turbulent boundary layer Reynolds number scaling on shock buffet onset. The wind tunnel walls are not modeled computationally, and wind tunnel effects are only considered when using standard corrections to Mach number and angle of attack.

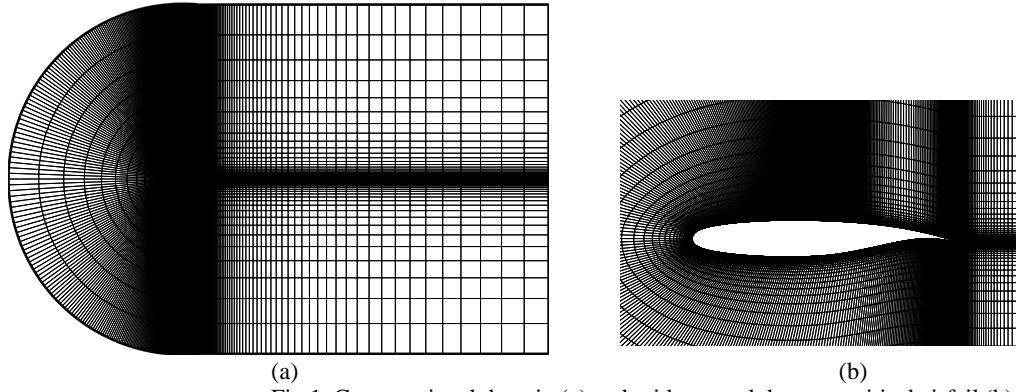


Fig 1. Computational domain (a) and grids around the supercritical airfoil (b)

In this paper study, the Reynolds average Navier-Stokes equations have been applied to compute the shock buffet onset region for the NASA SC(2)-0714 supercritical airfoil. The computational data first have been validated using the experimental data from high Reynolds number wind tunnel test conducted in the Langley 0.3-Meter Transonic Cryogenic Tunnel. The critical point at which buffet onset occurs has been detected by increasing the angle of attack by increments of 0.1° at free stream Mach number ranges from 0.72 to 0.75.

2. COMPUTATIONAL ANALYSIS

The governing equations are the 2D time-dependent Reynolds averaged, Navier-Stokes equations, with the $k-\omega$ SST (Shear-Stress Transport) turbulence model. The resulting equations are expressed in an integral form:

$$\Gamma \frac{\partial}{\partial t} \int_V \mathbf{Q} dA + \oint [F - G] dA = 0 \quad (i)$$

where F and G are the inviscid and viscous flux vectors in standard conservation form and Q is the dependent vector of primary variables.

$$\begin{aligned} F &= [\rho v, \rho v v_x + p \hat{i}, \rho v v_y + p \hat{j}, \rho v H]^T \\ G &= [0, \tau_{xi}, \tau_{yi}, \tau_{ii} v_j + q]^T \\ Q &= [p, v_x, v_y, T]^T \end{aligned} \quad (ii)$$

In the above equations, H is total enthalpy per unit mass and is related to the total energy E by $H = E + p/\rho$, where E includes both internal and kinetic energies. The preconditioning matrix Γ is included in Eq. (1) to provide an efficient solution of the present compressible flow.

The preconditioned governing equations are discretized spatially using a Finite volume scheme. For the time derivatives, an implicit time stepping scheme, which is advanced from time t to time $t+\Delta t$ with a 2nd order Euler backward scheme is used.

The chord length of the airfoil is 150 mm. The computational domain is discretized using structured C topology as shown in Fig. 1. The top and bottom far-field boundaries are located $12.5c$ lengths from the airfoil

surfaces. The upstream and downstream boundaries are located at $12.5c$ and $25c$ from the airfoil leading edge. The total number of grids is 51,000 which gives a grid independent solution. This spacing was considered to be sufficient to apply free-stream conditions on the outer boundaries. The first grid above the surface of airfoil is so close that the value of y^+ is around 1. A solution convergence was obtained when the residuals for each of the conserved variables were reduced below the magnitude of 10^{-4} . Another convergence criterion is to check the conserved quantities directly through the computational boundaries.

3. RESULTS AND DISCUSSION

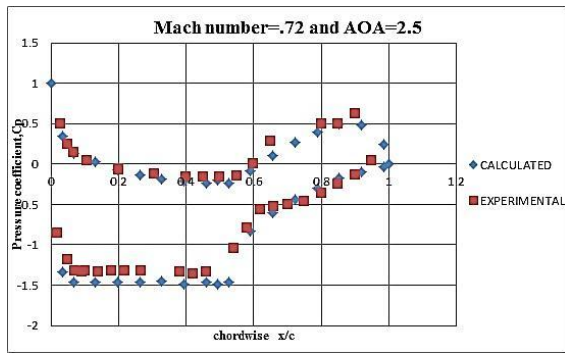
At first, the present numerical results are compared with the available experimental data of Bartels et al. [11]. The experimental was performed in a 0.3 m cryogenic wind tunnel at NASA Langley. Figure 2 shows the comparison of pressure coefficient along the airfoil surfaces at free stream Mach numbers of 0.72 with angle of attack (AOA) of 2.5° and 0.74° with AOA of 2° . A good comparison exists between the present computation and the experiment.

Computation starts with a known steady state combination of free stream Mach number, M_∞ and Angle of attack (AOA), α below the buffet onset. Then the unsteady calculation proceeds by increasing the angle of attack, α with small steps of 0.1° . To identify the shock induced oscillations the time histories of lift coefficient and static pressure at various points near the airfoil upper surface have been examined.

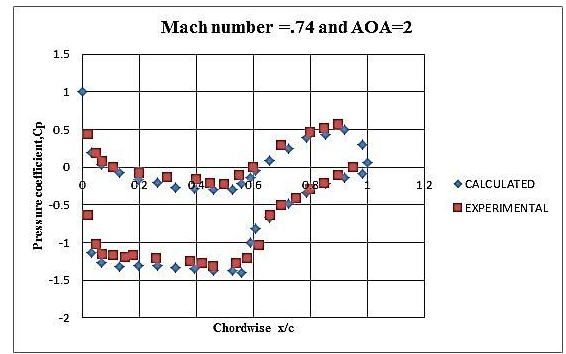
Figure 3 shows the lift coefficient evolution at angles of attack, α of 2.0° , 3.0° , 3.2° , 3.3° for a free stream Mach number, M_∞ of 0.72. At $\alpha = 2.0^\circ$ (Fig. 3(a)), 3.0° (Fig. 3(b)), the oscillation of lift coefficient is damped out after initial transients. At $\alpha = 3.2^\circ$ (Fig. 3(c)), though initially there was oscillation but it damped out after a while. With an increase of α of 0.1° , at $\alpha = 3.3^\circ$ (Fig. 3(d)), stable oscillation in lift coefficient is observed. This can be considered as the onset of buffet at $M_\infty = 0.72$.

Similar figures have been shown for $M_\infty = 0.74$ in Fig. 4. In this case the buffet onset can be considered at $\alpha = 2.8^\circ$.

To further prove the onset of buffeting flow the local static pressure data have been investigated. To examine the oscillatory behavior of static pressure a total of nine points have been considered on the upper surface of the

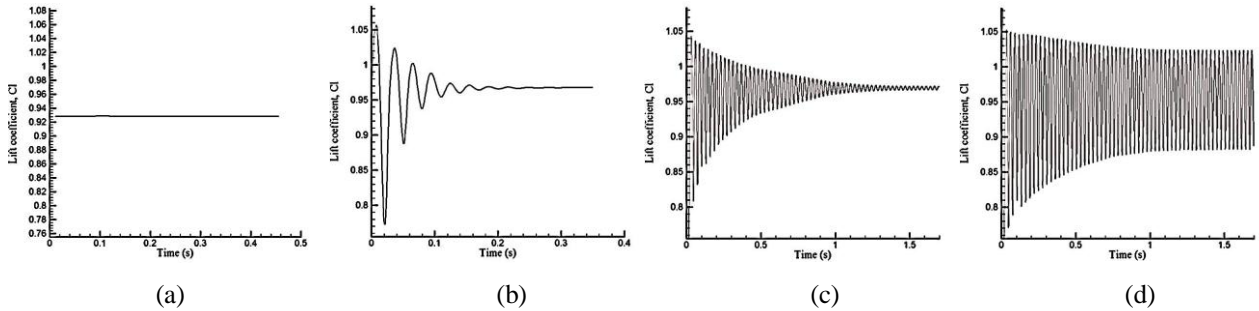


(a)



(b)

Fig 2. Comparison between experimental results and computational results; (a) $M_\infty = 0.72$ AOA = 2.5° and (b) $M_\infty = 0.74$ AOA = 2.0°



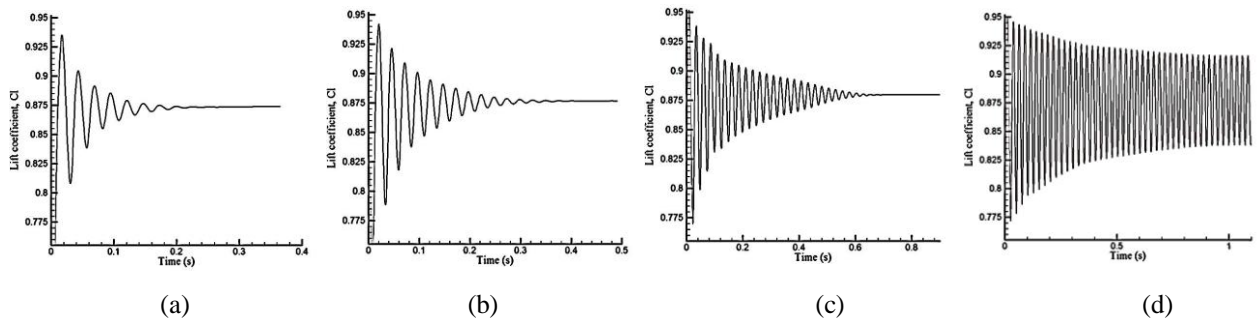
(a)

(b)

(c)

(d)

Fig 3. Evolution of lift coefficient at $M_\infty = 0.72$; (a) $\alpha = 2.0^\circ$, (b) $\alpha = 3.0^\circ$, (c) $\alpha = 3.2^\circ$, and (d) $\alpha = 3.3^\circ$



(a)

(b)

(c)

(d)

Fig 4. Evolution of lift coefficient at $M_\infty = 0.74$; (a) $\alpha = 2.5^\circ$, (b) $\alpha = 2.6^\circ$, (c) $\alpha = 2.7^\circ$, and (d) $\alpha = 2.8^\circ$

airfoil both upstream and downstream of the shock. For Mach number .74 the angle of attack for which buffet onset occurs is 2.8° .

Figure 5 shows the time histories of static pressure at the different axial positions over the airfoil upper surface for $M_\infty = 0.74$ and $\alpha = 2.8^\circ$. It is found that the amplitude of pressure oscillation increases from $x/c = 0.1c$ and reaches the maximum at the mid chord position of $x/c = 0.5c$ with amplitude of around 2.3 kPa. The unsteadiness of the static pressure is due to the interaction of shock waves with boundary layer. After the mid chord, the amplitude starts to decrease up to $x/c = 0.8c$. However, a slight increase of pressure amplitude is observed at $x/c = 0.9c$ due to trailing edge separation and the wake interaction. It can be concluded that the mean position of shock oscillation bounds around the region of mid chord of the airfoil.

Figure 6 shows the buffet onset boundary for NASA SC(2)-0714 airfoil estimated using Reynolds Average Navier-Stokes solver. It can be observed that the buffet boundary decreases with an increase of free stream Mach number, M_∞ . This is due to the increase of shock Mach number and subsequent intensification of shock induced

boundary layer separation at higher Mach number, M_∞ .

To clearly visualize the behavior of buffeting flow, the sequential Mach number contours are shown in Fig. 7 for the flow conditions of Mach number, $M_\infty = 0.72$ and angle of attack, $\alpha = 3.3^\circ$. Eight snapshots of Mach number contours are shown for buffeting flow. The frequency of self sustained shock oscillation is around 33Hz and time period T is 0.03s. These snapshots have been taken with a time difference of 0.038s. The shock waves are appeared at $x/c = 0.32c, 0.40c, 0.55c, 0.70c, 0.78c, 0.68c, 0.50c$ and $0.32c$ for $t/T = 0, 1/7, 2/7, 3/7, 4/7, 5/7, 6/7$ and 1.0 , respectively. From this figure, it is seen that pressure fluctuation appears to originate near the base of the shock and moves forward along the shock. The shock moves towards the leading edge and it reduces the supersonic region which is related to the lift coefficient. So the total lift force is also reduces due to this forward movement of the shock. When shock moves towards the trailing edge the reverse situation appears. Moreover, the intense shock induced boundary layer separation is observed in the case of forward movement of the shock waves and vice versa. In addition, the boundary layer remains almost attached when the shock

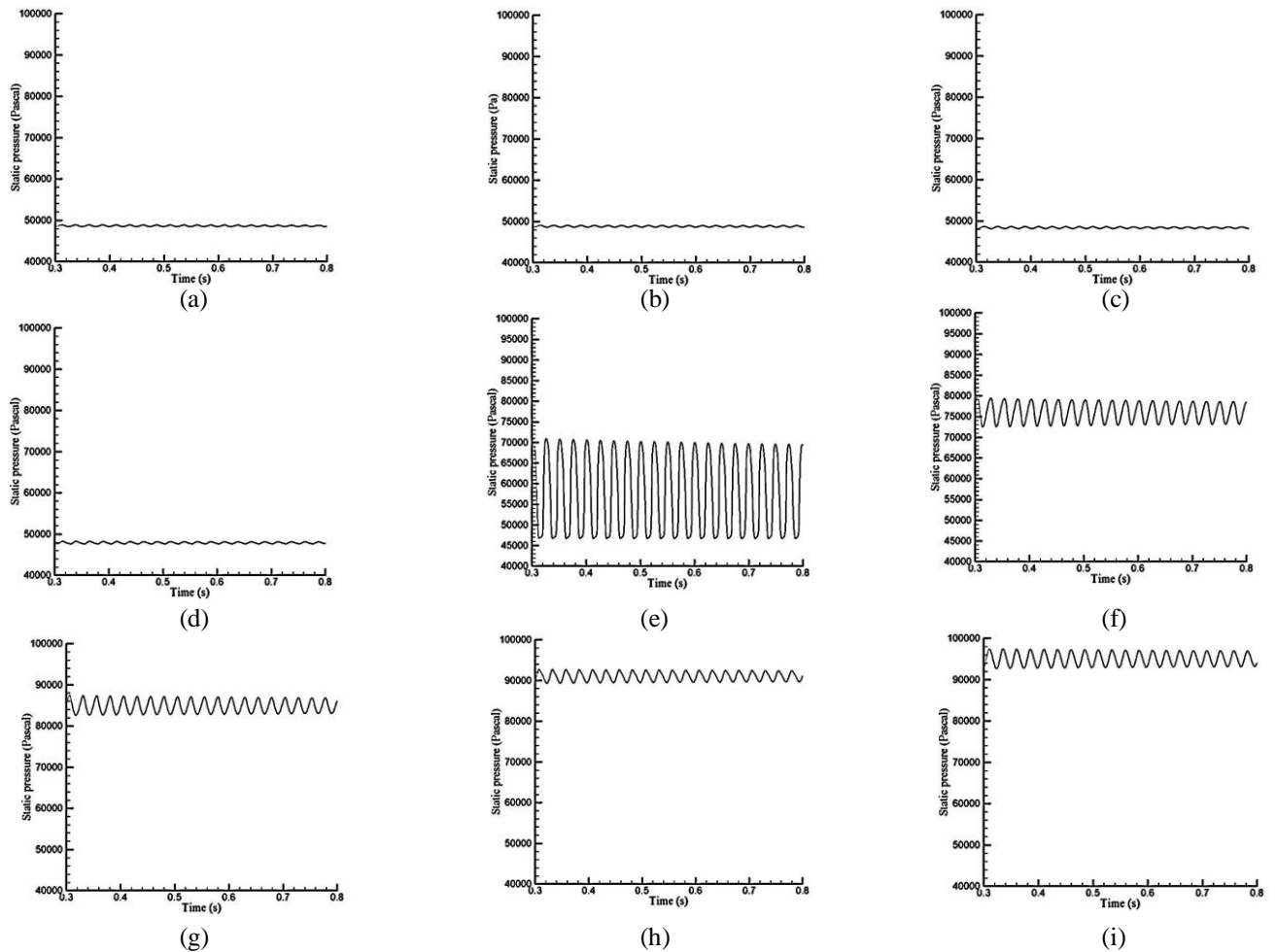


Fig 5. Time histories of static pressure at the upper surface of the airfoil for $M_\infty = 0.74$ $\alpha = 2.8^\circ$; (a) $x/c = 0.1c$, (b) $x/c = 0.2c$, (c) $x/c = 0.3c$, (d) $x/c = 0.4c$, (e) $x/c = 0.5c$, (f) $x/c = 0.6c$, (g) $x/c = 0.7c$, (h) $x/c = 0.8c$, (i) $x/c = 0.9c$

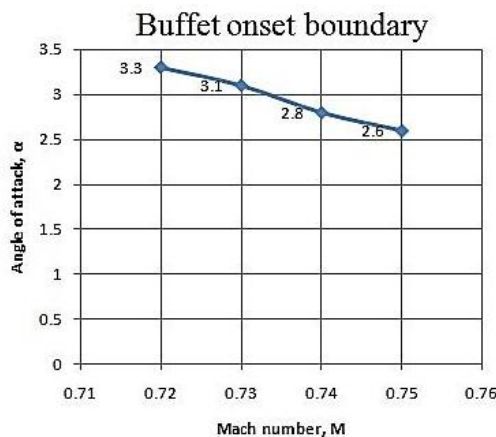


Fig 6. Predicted shock induced buffet onset for flow over NASA SC(2) 0714 supercritical airfoil

wave is at the end of the rearward motion. The self sustained shock motion (buffeting) imposes intense load on the aircraft structure. Thus the estimation of buffet onset boundary is very much important for the design of aircraft structure.

4. CONCLUSIONS

Reynolds averaged Navier Stokes equations with $k-\omega$ SST turbulence model has been applied to estimate shock induced buffet onset boundary for NASA SC(2) 0714 supercritical airfoil. The computational results have been validated with the available experimental results. This type of flow problem is very much challenging since the supercritical airfoil has a much strong viscous-inviscid boundary layer interaction behind the shock than the conventional airfoil. In this paper, the buffet boundary

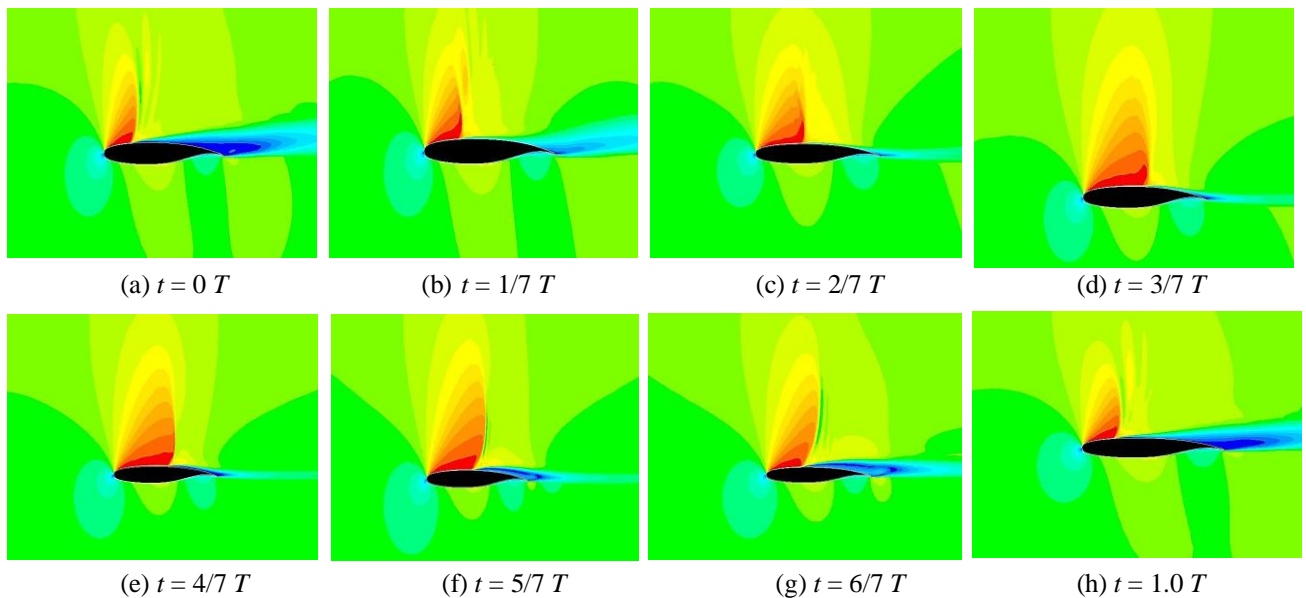


Fig 7. Sequential contour maps of Mach number for flow over NASA SC(2) 0714 supercritical airfoil at free stream Mach number, $M_\infty = 0.72$ and $\alpha = 3.3^\circ$

for a range of transonic flow conditions has been predicted. Low-frequency large scale shock oscillation around the airfoil upper surface is estimated. Unsteady shock interaction with the boundary layer is captured and is confirmed by the fluctuated static pressure time histories at different axial locations around the shock locations. This research will further continued to estimate the buffet boundary at higher free stream Mach numbers.

5. REFERENCES

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