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CFD simulation of shockwave-boundary layer interaction inducted oscillation in NACA SC2-0714 transonic airfoil

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Abstract

To develop an advanced way of designing transonic airfoil for the industry, the reliable and user-friendly mesh generator and robust CFD solver are necessary. Especially the prediction of the unsteady shock buffet phenomenon is always a focus for the CFD simulation of transonic airfoil. In this study, BOXERmesh (automatic mesh generator) and NEWT (robust CFD solver), which are developed by CFS (Cambridge Flow Solutions) in collaboration with MHI (Mitsubishi Heavy Industries), are used to perform the CFD simulation of NACA SC2-0714 transonic airfoil. CFD simulation is conducted at two different attack angles with Mach number as 0.74 and Reynold number as 1.5×1.0E7 (non-buffet: α=2°; shock buffet: α=3°). Hexahedral dominant mesh is generated by BOXERmesh with the cell number as 5.52 million. Both unsteady RANS (URANS) and LES simulation are performed using the CFD solver NEWT. Specifically, the governing equation is discretized by central differencing scheme with the 2nd order accuracy in space by applying Swanson and Turkel type artificial viscosity, and the dual-time stepping method is applied for temporal discretization in the density-based solver. Results show CFD simulation could reproduce the time averaged chordwise distribution of pressure coefficient at two conditions. Both URANS and LES successfully capture the unsteady shock buffet phenomenon when increasing attack angle from 2° to 3°. However, the peak oscillation location and frequency of the shock buffet are different between URANS and LES, among which URANS simulation shows the better agreement with the experiment data, with the deviation of the shock buffet frequency less than 6% (Exp.: 69 Hz; CFD: 73 Hz). The reason is considered that the mesh refinement near the airfoil surface is not enough for LES simulation to correctly capture the unsteady behavior of boundary separation. On the other hand, URANS simulation is enough to capture the periodic moving of the onset of boundary separation.

Keywords: transonic airfoil, shock buffet, CFD, URANS, LES

1. Introduction

With the rapid increase of the calculation capacity of the high-performance computer, computational fluid dynamics (CFD) has become a more and more important tool for the design and optimization of the fluid machineries, such as the aircraft. When the flow Mach number and the attack angle are in particular range, the so-called transonic shock buffet phenomena might occur on the upper surface of a highly loaded airfoil. It is characterized by self-sustained displacements of the shock wave location and periodic boundary-layer separation downstream from the shock wave. Transonic shock buffet is one of the most important compressibility-based off-design problems, affecting the safety operation of the aircraft.

To guide the design of airfoils, transonic shock buffet phenomena have been extensively investigated by both the wind tunnel tests and the numerical CFD simulations. Based on the wind tunnel tests, NASA [1-3] built the detailed database including the experiment data of the various airfoils at the different Reynold number, Mach number and attack angle. Based on the experiment results, the transonic shock buffet phenomena are thought to involve multiple physics occurring over the airfoil, such as turbulence structures in the thin turbulent boundary layer at high Reynolds number, unsteady shock wave, shock-induced separation, acoustic wave generation and propagation, etc. Specifically, Lee [4] proposed that the transonic shock buffet phenomena are induced by the acoustics waves generated from the trailing edges.

Because the transonic shock buffet phenomena are strongly affected by the turbulence structure at the high Reynolds number and the interaction with the unsteady shock wave, it is a significant challenge for the CFD community to accurately reproduce the shock buffet phenomena. Thomas [5] and Izumi [6] have conducted the unsteady RANS (URANS) simulation to study the shock buffet phenomena. And it is found the prediction accuracy of URANS largely depends on the turbulence model and the employed numerical methods both in spatial and temporal discretization schemes. Apart from URANS, layer-eddy simulation (LES) is an attractive choice to study the detailed physics in the complicated shock buffet phenomena. However, the conventional wall-resolved LES (WRLES) requires the resolving both the inner- and outer-boundary layer, which is difficult to be applied due to the huge calculation cost. Because, the turbulence scales in the inner-boundary layer ($y \leq 0.1\delta$) progressively decreases with the Reynolds number increases, the required number of grid points in the WRLES is estimated as $N_{\mathrm{total}} \propto \mathrm{Re}_c^{13/7} \sim \mathrm{Re}_c^{1.8}$ [7,8]. Instead, Fukushima [9] applied the wall modeled LES (WMLES) for the simulation of the shock buffet phenomena. In the WMLES, as only the outer-boundary layer is directly resolved, the required number of grid points is reduced to $N_{\mathrm{total}} \propto \mathrm{Re}_c$.

The aim of this study is to develop an advanced and reliable way of accurately predicting the transonic shock buffet phenomena using the BOXERmesh and NEWT, which are both developed by CFS (Cambridge Flow Solutions) in collaboration with MHI (Mitsubishi Heavy Industries). Both of URANS and LES simulations were conducted.

2. Experiment data and computational mesh

In this study, the experiment data of NACA SC2-0714 transonic airfoil [3] at two different attack angles with Mach number as 0.74 and Reynolds number as 1.5 ×1.0E7 are selected: non-buffet: α=2°; shock buffet: α=3°. The geometry and the computational mesh of NACA SC2-0714 airfoil are shown in Fig.1. Hexahedral dominant mesh is generated by BOXERmesh, by using a volume-to-surface method based upon a background octree mesh. The grids close to the airfoil surface and in the trailing edge region are specifically refined (grid size~0.6mm), and the total number of grids is 5.52 million.

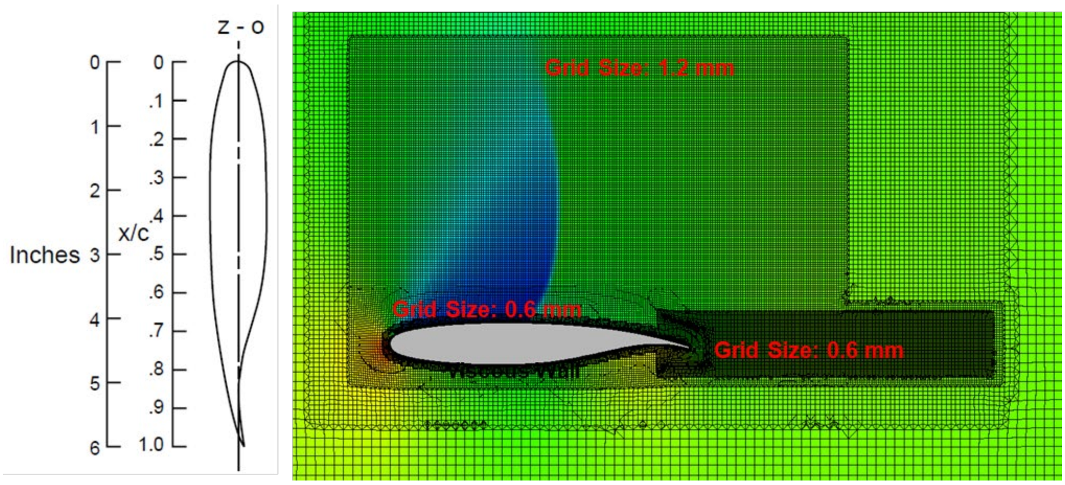

Fig. 1 Geometry and computational mesh of NACA SC2-0714 airfoil

The FFT analysis results of pressure coefficient on the airfoil upper surface of NACA SC2-0714 are shown in Fig. 2. It can be seen the transonic shock buffet is activated by increasing the attack angle from 2° to 3°. In this study, the transition from the steady condition to the shock buffet condition, and the oscillation frequency and amplitude chordwise distribution are the main focus to evaluate the CFD simulation accuracy.

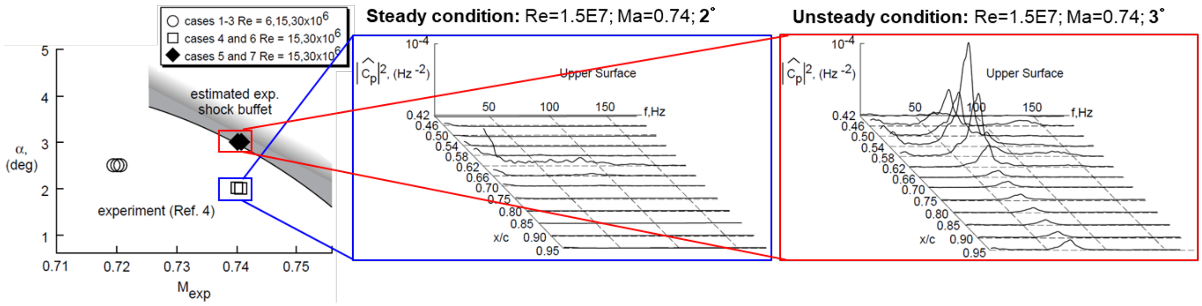

Fig. 2 Experiment data of NACA SC2-0714 airfoil at the different conditions [3]

3. Numerical methods

In this study, the robust CFD solver, NEWT, developed by CFS (Cambridge Flow Solutions) in collaboration with MHI (Mitsubishi Heavy Industries) is applied. Specifically, the governing equation is discretized by central differencing scheme with 2nd order accuracy in space by applying Swanson and Turkel type artificial viscosity, and the dual-time stepping method is applied for temporal discretization in the density-based solver.

$$\frac{\partial u}{\partial t} + a\frac{\Delta u}{\Delta x} = \varepsilon^{(2)}|a|\Delta x \cdot \frac{\Delta^2 u}{\Delta x^2} - \varepsilon^{(4)}|a|\Delta x^3 \frac{\Delta^4 u}{\Delta x^4}$$

(Theories and equations of discretization schemes and artificial viscosity)

Both of URANS and LES simulations are conducted. SST k-ω turbulence model with the low Reynolds number correction is applied in URANS simulation, and Lily-Smagorinsky sub-grid model is applied in LES. The time interval, dt, is an important parameter in the unsteady CFD simulation. The influence of the time interval on the residual and the instantaneous pressure coefficient distribution are shown in Fig. 3. It can be seen, the residual at each time step is quite huge and there are the obvious unphysical numerical fluctuations on the lower airfoil surface, when the time interval is 0.2ms and 0.05ms. Finally, dt = 0.01ms is selected, and the case list is shown in Table 1.

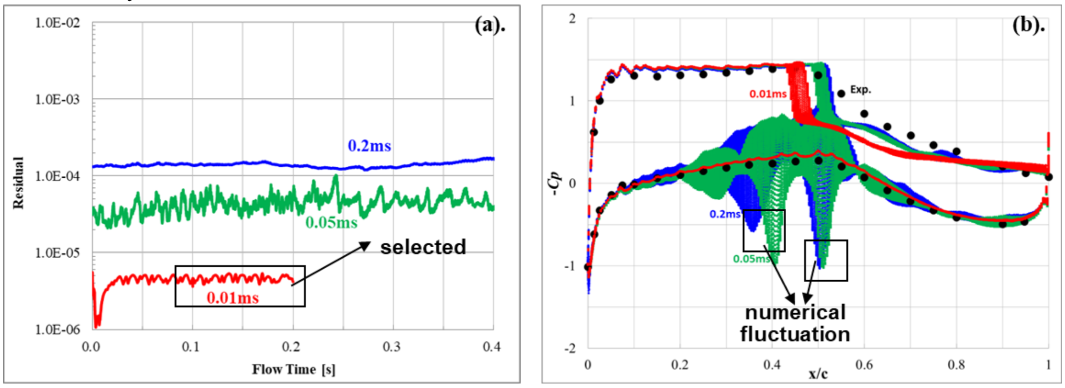

Fig. 3 Influence of the time interval on (a). residual; (b). instantaneous pressure coefficient distribution

Table 1 List of CFD simulation

ID	Condition					Setting		
	Fluid	Temp.	Mach	Re	Attack Angle	Turbulence	Time Interval	Inner Iteration
case1	Air	117K	0.74	1.50E+07	2°	RANS	0.01ms	100
case2					3°	RANS		
case3					3°	LES		

4. Result and discussion

4.1 Results of URANS

Chordwise pressure coefficient distribution results of case1-2 by URANS at 2° to 3° attack angles are summarized in Fig. 4. It can be seen, the time-averaged chordwise pressure coefficient distribution at two conditions are close to experiment data, which means URANS is of a good accuracy. Moreover, the instantaneous and time-averaged pressure coefficient distribution result at 2° attack angle are almost totally overlapped, which means the fixed shock wave location at the stable condition. On the contrary, there is an obvious difference between the instantaneous and time-averaged pressure coefficient distribution result at 3° attack angle, which indicates the periodic oscillation of the shock wave location at the shock buffet condition.

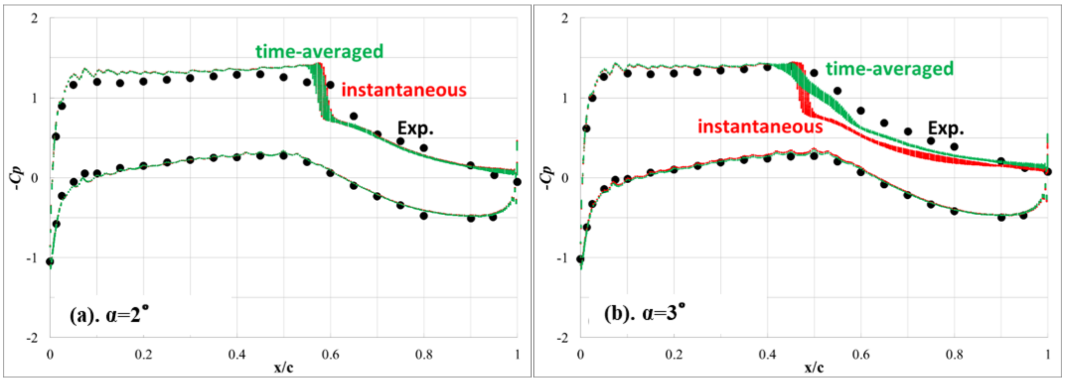

Fig. 4 Chordwise pressure coefficient distribution by URANS: (a). 2°; (b). 3°

The different behavior of the shock wave at the stable and the shock buffet conditions could be more clearly compared by the temporal evolution of the density gradient contour as shown in Fig. 5. At α=2°steady condition, the location of the shock wave is almost fixed from 0.5 ms to 18.5 ms; on the contrary, the shock wave location is periodically oscillating at α=3°unsteady condition. The comparison in Fig. 5 means URANS simulation successfully reproduced the transition from the steady condition to the shock buffet condition when increasing the attack angle from 2° to 3°.

In order to quantitively evaluate the accuracy on shock buffet simulation, a series of sampling probes are plated on the airfoil upper surface (Fig. 6-a), and the pressure fluctuation history at each probe is output (Fig. 6-b), then FFT analysis is conducted (Fig. 6-c) and the result is compared with the experiment data (Fig. 6-d). It can be seen, the pressure oscillation frequency at points P1 and P2 are the same, which is consistent with the physics that the transonic shock buffet phenomena are induced by the acoustics waves generated from the trailing edges. The remarkable frequencies of the shock buffet with the maximum amplitude predicted by URANS simulation are 73 and 146 Hz, which is quite close to experiment data 69 and 138 Hz. Moreover, URANS simulation predicts the chordwise oscillation amplitude distribution and especially the peak location with the high accuracy.

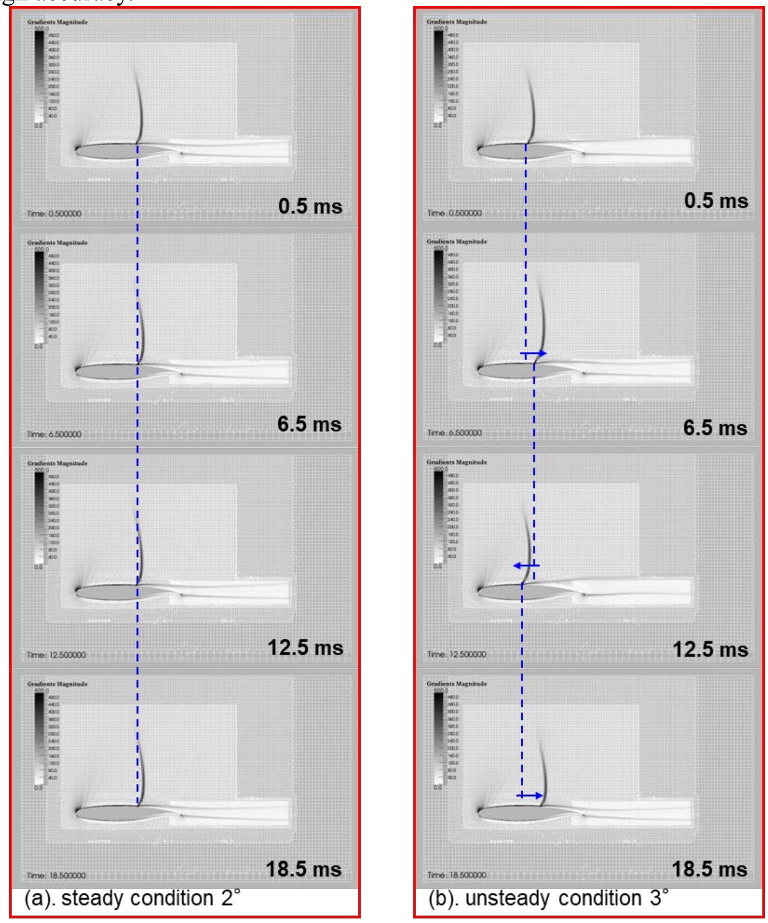

Fig. 5 Temporal evolution of density gradient contour by URANS: (a). 2°; (b). 3°

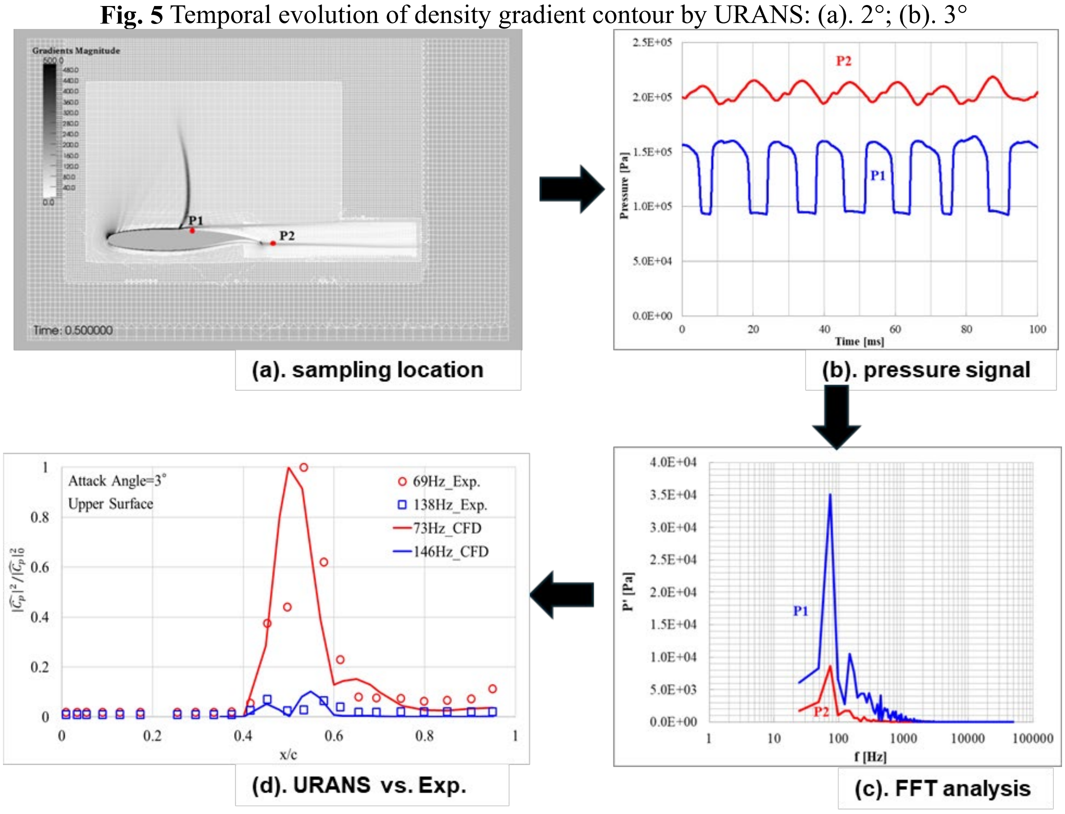

Fig. 6 Quantitively comparison between URANS simulation and experiment at α=3° shock buffet condition

4.2 Results of LES

The instantaneous density gradient contour at α=3°shock buffet condition by URANS and LES simulations are compared in Fig. 7. It seems the turbulence structure in the trailing edge region is better captured by LES than URANS simulation. Similar to that in Fig.6, the pressure signal and FFT results at points P1 and P2 in LES simulation are shown in Fig. 8. Different from URANS simulation, the representative oscillation could not be distinguished from the FFT results of LES simulation. This means LES simulation failed to accurately predict the shock buffet phenomena. The appropriate wall model is not yet introduced into the CFD solver NEWT. The mesh resolution near the airfoil surface and in the trailing edge region is too coarse to directly resolve the inner-boundary layer. This is considered as the main reason of the worse performance of LES than URANS simulation in this study. To improve the accuracy of LES simulation at a relative coarse mesh resolution, introducing the appropriate wall model like Fukushima [9] or applying the RANS/LES hybrid approach such as detached-eddy simulation (DES) are the possible solutions.

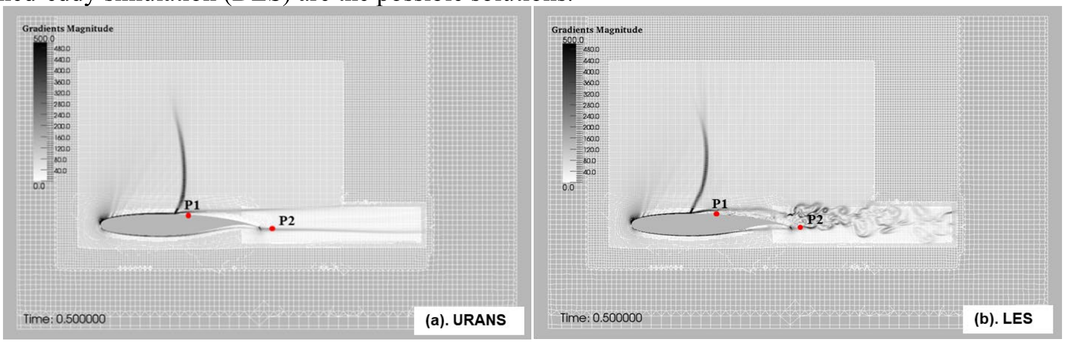

Fig. 7 Instantaneous density gradient contour by URANS and LES at α=3° shock buffet condition

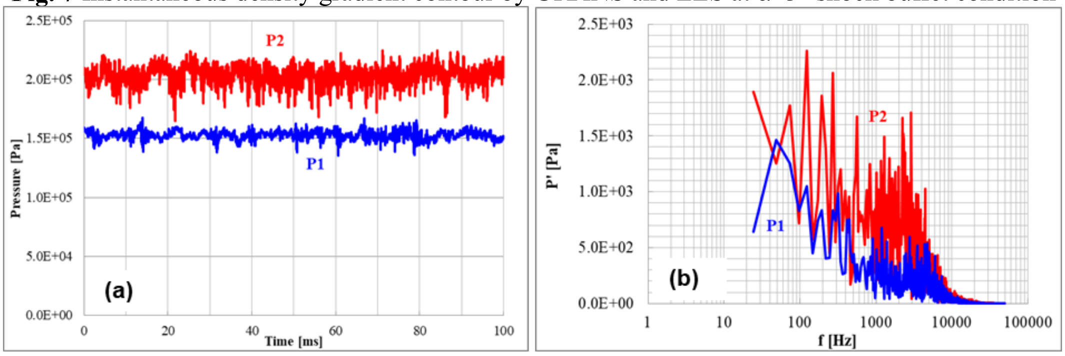

Fig. 8 Pressure signal and FFT analysis results at points P1 and P2 in LES simulation

5. Conclusions

CFD simulation of NACA SC2-0714 transonic airfoil is conducted by using the automatic mesh generator (BOXERmesh) and the CFD solver NEWT, which are both developed by CFS (Cambridge Flow Solutions) in collaboration with MHI (Mitsubishi Heavy Industries). URANS simulation could well reproduce the time-averaged chordwise pressure coefficient distribution at both of the steady condition and the shock buffet condition. URANS simulation successfully captures the activation of the shock buffet phenomena when increasing the attack angle from 2° to 3°, a condition consistent with the estimated buffet criterion boundary [3]. Specially, the most two representative oscillation frequencies are predicted with the high accuracy: 73 and 146 Hz by URANS; 69 and 138Hz in experiment. Moreover, URANS simulation predicts the chordwise oscillation amplitude distribution and especially the peak location with the high accuracy. The results mean the numerical methods both in spatial and temporal discretization schemes, and the introduction of the artificial viscosity scheme in the CFD solver NEWT is appropriate to predict the main characteristics of the shock buffet phenomena in the transonic airfoil.

With the same mesh resolution, LES simulation seems to better capture the turbulence structure in the trailing edge region, but it could not accurately reproduce the shock buffet phenomena. The reason is considered as the mesh resolution is not fine enough to direct resolve the inner-boundary layer.

Acknowledgement

This study was performed by using BOXERmesh and NEWT developed by CFS.

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