Numerical Investigation for Separation Characteristics of Transonic Shock Oscillations Based on Parallel Computing

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Abstract. Shock-induced oscillation is transonic flow instability phenomenon, which brings additional vibration to the aircraft. In this study, the RANS-LES methods with parallel computing were applied to investigate the transonic shock oscillations over a supercritical airfoil. The third-order MUSCL and fifth-order WENO based Roe scheme with adjustable dissipation were applied to study the effects of numerical dissipation. The results shown the numerical dissipation of the spatial schemes has a great influence on the calculation, and the small scale flow structure are suppressed by excessive numerical dissipation. The numerical results present the separation evolution on the upper surface. And periodic variation characteristics of the separation region downstream of the shock wave was discussed. The ratio of the time taken by the shock moves downstream and upstream is 1:1.

1. Introduction
Shock oscillation is a typical instability phenomenon in transonic flow. The interaction of shock wave and boundary layer resulting in a wide range of self-sustained shock wave oscillations without external disturbances. Transonic shock oscillations impart additional vibration to the wing, which seriously affects the ride comfort and the maneuverability, especially for modern commercial aircraft with supercritical wing.

Recently, Giannelis [1] reviews the latest developments in the classification and numerical studies of shock oscillations and provides a comprehensive review of the study of three-dimensional shock oscillations. Therefore, understanding the separation characteristics and flow physics of the shock wave oscillation has a very positive significance for reducing the shock oscillation effect in the design stage, improving cruise Mach number and improving the flight envelope of aircraft. Therefore, studying the flow physics of the shock wave oscillation has a very positive significance for reducing the shock oscillation effect in the design stage, improving the aircraft cruise Mach number, and improving the flight envelope.

2. Turbulence Modelling and Numerical Methods

2.1. Turbulence Modeling
Zonal detached-eddy simulation (ZDES) approach is based two-equation $k-\omega$ SST model proposed by Menter [2]. Therefore, the $k$-equation of SST model need to be modified, new dissipation term is formed by introducing the hybrid length $l_{hyb}$, to construct ZDES approach. The modified turbulent kinetic energy equation is
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_k)}{\partial x_j} = \tau_y S_y - \rho \frac{k^{3/2}}{l_{ob}} + \frac{\partial}{\partial x_j} \left( \mu + \sigma_\kappa \mu_\kappa \frac{\partial k}{\partial x_j} \right)
\] (1)

In the frame of ZDES approach, the different hybrid length scale is taken according to different flow separation, which corresponding to desired transformation from RANS to LES. Deck [3] proposes three types of flow separation based on the incentives of separation: (I) the flow separation caused by geometry, (II) the separation caused by a pressure gradient, and (III) the separation is influenced strongly by the dynamics of the incoming boundary layer. Only the first two types are considered in the current study.

For the flow separation caused by geometry, the separation position is fixed and the \( l_{ob} \) is defined as

\[
l_{ob} = l_{ob}^{ZDES} = \min(l_{SST}, C_{DES}\Delta_1)
\] (2)

Different from the grid scale in original DES, for the structured grid the \( \Delta \) is

\[
\Delta_1 = \Delta_\omega = \sqrt{N_x^2 \Delta y \Delta z + N_y^2 \Delta \Delta x + N_z^2 \Delta \Delta y}, \quad \vec{N} = \frac{\partial \phi}{\|\vec{\phi}\|}
\] (3)

An assumption needs to be introduced, and there is a vorticity \( \omega \) in a specified direction if it is not zero. \( \vec{N} \) is unit vector of local vortex axis.

For the separation caused by a pressure gradient, the separation position is fixed and the hybrid length scale is similar to DDES [4] which is

\[
l_{ob} = l_{ob}^{N} = l_{SST} - f_d \max(0, l_{SST} - C_{DES}\Delta_H)
\] (4)

However, the grid scale is different from DDES, but the \( \Delta_H \) depend on the parameter \( f_d \): \( \Delta_H = \Delta_{max} \) if \( f_d < f_{d0} \); \( \Delta_H = \Delta_\omega \) if \( f_d > f_{d0} \), where the constant \( f_{d0} \) is equal to 0.75, which ensures the ZDES has the same performance as DDES in the boundary layer.

2.2. Numerical Methods
The current work was based on cell-central finite volume method, and the multi-block structured grid was implemented. Time discretization uses the second-order fully implicit LU-SGS-\( \tau \)TS algorithm.

The accuracy of the spatial scheme has a great influence on accurately predicting the interaction between the shock wave and the boundary layer. Due to excessive numerical dissipation, the original Roe scheme will suppress the fluctuations in turbulent boundary layer and wakes. In current study, the Roe scheme was modified for discrete the inviscid term, it is rewritten as

\[
\hat{F}_{i+1/2} = \frac{1}{2} \left[ \hat{F}(q_L) + \hat{F}(q_R) \right]_{i+1/2} - \varphi \times \frac{1}{2} |\hat{A}_m| (q_L - q_L)_{i+1/2}
\] (5)

where \( \hat{A}_m \) is the Jacobian matrix of inviscid flux; the subscript \( L \) and \( R \) represent variables located on both sides of the interface. The dissipation level of Roe scheme was controlled by \( \varphi \) according to Bui [5] which has been implemented in the flow around a multi-element airfoil [6]. When \( \varphi = 0 \), equation (5) is central scheme, and it is original Roe scheme when \( \varphi = 1 \). In present work, 25% dissipation level was considered.

The dissipation effect of interpolation accuracy is also considered in current work. The third-order monotone upstream centered scheme for conservation laws (MUSCL) [7] and the fifth-order weighted essentially non-oscillatory (WENO) interpolation [8] are used in numerical prediction of shock wave oscillations, and the performance of two schemes was compared.
3. Computational Description
The supercritical airfoil OAT15A is used as the test case. The shock wave oscillation experiment of OAT15A was completed in ONERA [9]. In the measurement, the shock wave oscillations appear on the upper surface at 3.25°. As the angle of attack increases, the frequency of shock oscillation remains constant, and \( f = 69 \text{Hz} \) at 3.5° which is the angle of attack in calculation.

3.1. The Grid System
The C-H grid topology was applied in present work, the grid in \( x-y \) plane is shown in figure 1. The computational domain is 26% chord (c) in spanwise. The distance between the leading edge and the inlet is 20c, and 40c between the trailing edge and outlet. Appropriately refine the grid in the shock wave motion area and wake area of the upper wing. The normal distance of the first layer grid on the wall satisfies \( y^+ < 1 \) to ensure that the viscous sub-layer in the boundary layer can be solved. The total cell number of whole flowfield is \( 6.07 \times 10^6 \).

3.2. Zonal Calculation
Figure 2 shows the computational zone of OAT15A. The DES is used in the upper wing surface where shock wave oscillation occurs and wake area, and the RANS is used in other areas. The time step of unsteady calculation is set to \( 1 \times 10^{-6} \)s, and 15 sub-iterations in each time step.

4. Effects of Numerical Dissipation of the Spatial Scheme
In order to study the influence of numerical dissipation on the prediction of shock wave oscillation, third-order MUSCL and fifth-order WENO was applied in calculations in this section, and the instantaneous and mean results were compared.

The instantaneous density divergence at 50% spanwise location is shown in figure 3, and the difference in instantaneous vorticity structure, especially in small-scale structure, between two spatial schemes is shown in the figure. Although the calculation is performed under the same grid, 5th WENO scheme provide more small scale flow structure than 3rd MUSCL especially in the wake. The main reason for the difference is the excessive numerical dissipation of 3rd MUSCL suppress the small scale structure.
Figure 4 compares the average pressure distribution obtained by the two spatial schemes. The difference between numerical and experimental results is mainly concentrated on the pressure distribution on the suction surface where the shock wave oscillation occurs, and 5th WENO can be consistent with measurements. Furthermore, the RMS (root-mean-squared) pressure fluctuations on the suction surface is compared in figure 5. 3rd MUSCL scheme gives lower level fluctuations than 5th WENO schemes due to the excessive numerical dissipation, and the latter agrees well with the measurements.

Figure 4. Mean pressure distributions. Figure 5. Root-mean-squared pressure fluctuations.

5. Separation Characteristics
The history of the lift coefficient over time is shown in figure 6. The motion of the shock wave on the upper surface causes a periodic change in the lift coefficient. Figure 7 show the instantaneous turbulent structure. The shock wave induces the separation of the downstream boundary layer. The shear layer has strong two-dimensional characteristics, and gradually breaks down into many small-scale three-dimensional structures as moving downstream, the large-scale Hairpin vortex can be seen in the wake area.

Figure 8 is the power spectral density of the lift coefficient. The frequency of the shock oscillation observed in the experiment was 69 Hz. The ZDES calculation results show that the frequency of the shock oscillation is 67 Hz, which basically matches the experimental results. In previous numerical studies, the frequency predicted by DDES [10] is 80.5Hz, and IDDES [11] is 80.5Hz. By contrast, the ZDES used in present work is in good agreement with the experiment.

Figure 9 shows the evolution of flow separation and re-attachment over time in one cycle based on the distribution of the upper surface friction. In the figure, the ordinate is the time advance direction, and the abscissa is the flow direction of the upper surface of the airfoil. The white areas in the figure represent the attached flow state, and the dark areas represent the flow in the separated state.

Figure 6. Time history of the lift coefficient Figure 7. Instantaneous turbulent structure
Local separation occurs in the trailing edge region at the initial moment, when the shock was moving downstream and the flow completely attached in the other regions. As the shock wave moves further downstream, the separation bubble appears simultaneously in the root and trailing edge regions of the shock. When the most downstream position is reached, the two separated regions merge together and the airfoil behind the shock is completely separated. During the shock wave moving upstream, the post-wave region is always in a state of complete separation until the shock wave approaches the most upstream position, and the separation region is restored to the previous two parts. As the downstream moves again, the two area gradually became smaller, then it became bigger.

Furthermore, in one cycle, the time taken by moving downstream of the shock wave and the time taken by moving upstream are 1:1. The time of moving upstream obtained by the DDES [10] accounts for about one-third of one cycle, which is also related to the fact that the shock oscillation period predicted by DDES is shorter than the experimental period.

As in figure 10, the average shock position predicted by the IDDES method is located at x/c=0.25, which is about one-third earlier than the average shock position in the experiment. The average shock position obtained by DDES is slightly close to the upstream, and the pressure distribution in the trailing edge region is significantly lower than the experimental results; in contrast, the ZDES is basically consistent with the experiment.

As in figure 11, the ZDES calculation results are in good agreement with the experiment. However, the maximum fluctuation level of DDES is about 36%, while the IDDES is 39%, which is significantly higher than the experimental pressure fluctuation level. In the downstream separation area of the shock wave, the pressure fluctuation level obtained by DDES and IDDES is significantly higher than the experimental value, which may be affected by the large-scale vortex structure falling off at the trailing edge of the airfoil.

**Figure 8.** Power spectral density of the lift coefficient.

**Figure 9.** Spatiotemporal evolution of flow separation on the upper surface.

**Figure 10.** Mean pressure coefficient distributions.

**Figure 11.** Root-mean-squared pressure fluctuations.
6. Conclusion
The numerical investigation of transonic shock oscillations of a supercritical airfoil based on parallel computing. Zonal detached-eddy-simulation was constructed based on SST turbulent model. In order to investigate the effect of the numerical dissipation on the calculations, 3rd MUSCL and 5th WENO schemes based on Roe with Dissipation adjustment factor were implemented. The comparison and between different calculations are performed separately in the instantaneous and averaged flowfield. Furthermore, the separation characteristics of transonic shock oscillations are further analyzed.

- The numerical dissipation of the spatial schemes has a great influence on the calculation. The small scale flow structure are suppressed by excessive numerical dissipation, but 5th WENO schemes agree well with the measurements in the pressure distributions and RMS press fluctuations.
- The calculation results show that ZDES can better predict the low-frequency characteristics of shock oscillations compared with the DDES and IDDES.
- According to the calculation results of ZDES, the separation characteristics in one cycle are analyzed. And the ratio of the time taken by the shock moves downstream and upstream is 1:1.

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