

## Article

# Prediction of Transonic Shock Buffet over Supercritical Airfoil OAT15A Based on Zonal Detached-Eddy Simulation

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**Abstract:** The zonal detached-eddy simulation (ZDES) method divides the flow field into different computational modes, offering flexibility in the simulation of complex flows. The transonic shock buffet on the upper surface of the OAT15A supercritical airfoil is numerically simulated by ZDES based on the  $k-\omega$  SST model. The results show that the error in the low-frequency characteristics of the transonic shock buffet predicted by ZDES compared to experiments is within 3%. Its predictions of pressure fluctuations and averaged velocity agree better with the experimental data. Overall, ZDES is effective in predicting the periodic oscillations of shock waves along the streamwise direction, flow separation induced by shock wave motion, and the small-scale vortex structures in the wake region.

**Keywords:** zonal detached-eddy simulation; turbulence; transonic shock buffet



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## 1. Introduction

The transonic shock buffet is a distinct instability phenomenon in transonic flows. It occurs when shock waves on the airfoil or wing surface interact with the separated boundary layer, resulting in a self-excited transonic shock buffet over a wide range. During the oscillation of shock waves, the shock wave's position exhibits chordwise movement, while its intensity, the downstream separation points of the shock wave, and the thickness of the boundary layer undergo continuous variations.

The transonic shock buffet and transonic buffet phenomena are closely interconnected. Within a certain range of AOA and Mach number, the transonic shock buffet introduces additional vibrations to the wing. The prevalent use of relatively thick supercritical airfoil designs in modern commercial aircraft enhances the impact of the transonic shock buffet. Therefore, the investigation of the transonic buffet phenomena and a comprehensive understanding of their mechanisms are of great significance, aiming to reduce the amplitude of the transonic shock buffet, enhance the aircraft's cruising Mach number, and improve the flight envelope.

Lee [1] conducted a comprehensive summary and review of research on the transonic shock wave buffet and proposed a self-excited feedback model addressing the mechanisms behind the transonic shock buffet. Crouch [2] proposed that the origin of the transonic wing buffet is associated with global instability, leading to the transonic shock buffet and significant fluctuations in lift. Zhang [3] conducted a comprehensive review of transonic buffet research, examining both numerical simulation and experimental studies. They summarized the progress in understanding buffet mechanisms and associated structural response characteristics. Furthermore, they presented various methods for controlling the transonic buffet. Giannelis [4] published a comprehensive review article on transonic shock buffet research. They revisited the classification of the transonic shock buffet and highlighted the recent advancements in numerical studies. Furthermore, they conducted a comprehensive review of the three-dimensional transonic shock buffet research.

In the current study of numerical research, many researchers have employed the URANS method to analyze the motion of the transonic shock buffet and its underlying mechanisms. Goncalves [5] conducted numerical simulation of the transonic shock buffet for the RA16SC1 supercritical airfoil using multiple turbulence models. Carese [6] compared the performance of the  $k-\omega$  SST and RSM-W in the transonic buffet. The computational results indicated that the SST model better predicted the average shock wave position. Xiao [7] conducted research on the transonic buffet phenomena for the BGK-1 supercritical airfoil by URANS. Their results confirmed that downstream pressure waves radiate downstream within the separation region and, upon reaching the trailing edge outside the separation region, the disturbances generated waves propagating upstream. The transonic shock buffet frequency was found to support the signal evolution mechanism proposed by Lee [1]. Barakos [8] compared different turbulence models in the simulation of the transonic shock buffet for the NACA0012 airfoil, highlighting the necessity of a sufficiently small-time step to capture the transonic buffet. Crouch [2] further analyzed the mechanisms behind the transonic buffet for the NACA 0012 airfoil by URANS. They proposed that the generation of the transonic buffet is related to global instability, which results in the transonic shock buffet and lift fluctuations. Bhamidipati [9] investigated the transonic shock buffet with an unstructured mesh and found that the calculation results are sensitive to mesh distribution. Through stability, sensitivity, and susceptibility analysis, Sartor [10] suggested that the transonic buffet phenomena are influenced by Kelvin–Helmholtz-like instabilities. The transonic shock buffet exhibits both low-frequency unsteadiness and intermediate-frequency characteristics. They further noted that the frequency of transonic shock buffet is significantly influenced by the Mach number, while its dependence on AOA is less apparent. Though URANS simulation has been somewhat effective in capturing the low-frequency transonic shock buffet, they still fall short in accurately modeling the complex flow phenomena where shock waves and boundary layers interact, and they are unable to provide a wideband turbulence spectrum produced by intermittent separated flows [4].

RANS/LES hybrid methods provide a relatively cost-effective approach to the numerical investigation of the transonic shock buffet. Giannelis [4] indicated that the RANS/LES hybrid method was capable of capturing the energy spectra and secondary instability effects in the flow field associated with the transonic shock buffet. Grossi [11], with the same turbulence model as Deck, employed three-dimensional grid models in both the near and far-field regions. They compared the predictive abilities of the URANS and DDES for the same test case and studied the effects of compressibility corrections on the turbulence model. The results indicated that URANS could satisfy predictions for average flow field statistics. Furthermore, they emphasized that turbulence intensity has a significant impact on the simulation of the transonic shock buffet. However, the DDES results showed significant deviations in the lift coefficient power spectral density when compared to experimental data. Huang [12] conducted a numerical study on the same shock wave-boundary layer interaction phenomena with IDDES based on the SST model. They proposed a flow control method using vortex generators to suppress the transonic shock buffet. The computational results demonstrated the effectiveness of this control measure.

ZDES avoids the issues of Grid-Induced Separation (GIS) [13] and Modeled-Stress Depletion (MSD) by specifying RANS and LES regions in the computational domains. Furthermore, ZDES not only circumvents the problems associated with the Gray-Area [14] but also allows the application of different DES modes to corresponding flow separation types.

This flexibility in using different DES modes for various separation regions in the same flow field enhances the analysis of turbulent structures in separation areas.

Thus, it is suitable for investigating the complex flow phenomenon of the transonic buffet. Deck [15] conducted a numerical simulation on the OAT15A supercritical airfoil with ZDES based on S-A model. The results demonstrated that the method offered a superior simulation accuracy compared with URANS and DES. ZDES is capable of predicting the transonic shock buffet frequency, whereas the URANS and DES required higher angles of

attack to capture this frequency. Ehrle [16] utilized the AZDES method based on the S-A model to investigate the transonic buffet in the CRM model. A comparison with the DDES revealed that DDES led to lower-frequency motion and failed to capture the streamwise convective features of the buffet. The AZDES proved to be more suitable than DDES for reproducing the observed three-dimensional transonic vibrations on the CRM model within the frequency range of the experiment. Hashimoto [17] simulated the transonic shock buffet using ZDES based on an unstructured mesh. They compared the effects of the turbulence model and mesh resolution on the prediction results. The results indicated that grid density had a minimal impact on the prediction of shock wave position. Furthermore, they found that ZDES with a wall model performed well in predicting the transonic buffet.

In summary, the ZDES method is more accurate in predicting transonic shock buffet phenomena. However, existing studies are insufficient in exploring the related physical mechanisms, making it necessary to conduct numerical simulations using the ZDES method to analyze the evolution of flow separation during the shock motion process.

The solver used in this study was developed based on NASA's CFL3D open-source program. This study utilized ZDES based on the SST model to numerically simulate the transonic shock buffet for the OAT15A airfoil. The computational results were then compared to those obtained from the DDES, IDDES, and experiments, aiming to evaluate the modeling capabilities of ZDES. This study aims to investigate the unsteady phenomena and the corresponding physical mechanisms present during the shock oscillation process, which provides a reference for using the ZDES method to predict complex flow separation problems in engineering practice.

## 2. Numerical Methodology

### 2.1. Turbulence Simulation Methods

#### 2.1.1. ZDES Based on a Two-Equation $k$ - $\omega$ SST Model

In this paper, the  $k$ - $\omega$  SST model proposed by Menter [18] was utilized as the base model to construct the ZDES hybrid method. The conservative forms of the  $k$  and  $\omega$  equations are as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left( (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right) \quad (1)$$

$$\begin{aligned} \frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} &= \frac{\gamma}{\nu_t} P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left( (\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right) \\ &+ 2(1 - F_1) \frac{\rho \sigma_{\omega 2}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \end{aligned} \quad (2)$$

where  $\rho$  is the density,  $k$  is the turbulent kinetic energy,  $\sigma_k = 0.5$ ,  $\nu_t = \frac{\mu_t}{\rho}$  is the turbulent eddy viscosity,  $\mu$  is the molecular dynamic viscosity, and  $d$  is the distance from the grid point to the wall. The production term  $P$  is given by

$$P = \tau_{ij} \frac{\partial u_i}{\partial x_j} \quad (3)$$

where the Reynolds stress is given by

$$\tau_{ij} = \mu_t \left( 2S_{ij} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (4)$$

$$S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (5)$$

The turbulent eddy viscosity  $\mu_t$  and the vortex magnitude  $\Omega$  are given by

$$\mu_t = \frac{\rho a_1 k}{\max(a_1 \omega, \Omega F_2)} \quad (6)$$

$$\Omega = \sqrt{2W_{ij}W_{ij}}, \quad W_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) \quad (7)$$

ZDES selects the RANS and DES calculation regions based on the requirements: RANS is employed in the attached flow region, and DES is employed in the flow separation region.

In this study, ZDES is based on the  $k$ - $\omega$  SST model. Modification of the destruction term of the  $k$ -equation is necessary in ZDES. After introducing the length scale  $\tilde{l}_{ZDES}$ , the turbulent kinetic energy transport equation is rewritten in the following form:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\rho k^{3/2}}{\tilde{l}_{ZDES}} + \frac{\partial}{\partial x_j} \left( (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right) \quad (8)$$

For the original SST turbulence model, the length scale  $\tilde{l}_{ZDES}$  is given by

$$\tilde{l}_{ZDES} = l_{SST} = \frac{\sqrt{k}}{\beta^* \omega} \quad (9)$$

For ZDES, different hybrid length scales need to be defined for different separation types in the separation flow region. Deck [19] classified flow separation into three types: (I) Separation caused by external geometry, where the separation position is fixed; (II) Separation caused by a pressure gradient on the surface, where the separation position is uncertain; (III) Separation caused by the influence of the incoming boundary layer. This study currently focuses on the first two types of flow.

### 2.1.2. Construction of the Hybrid Length Scale

ZDES in this study is implemented based on a structured multi-block grid, achieved by defining different grid blocks to use different simulation methods in the same flow field. In a flow field composed of  $N$  grid blocks, for the  $n$ th grid block ( $0 < n < N$ ), when  $ides_n = 0$ , RANS is employed in that region; when  $ides_n = 1$ , DES is used in that region. The hybrid length scale can be expressed as follows:

$$\tilde{l}_{ZDES,n} = (1 - ides_n) \times l_{SST} + ides_n \times l_{DES}^{lorII} \quad (10)$$

The selection of the hybrid length scale  $l_{DES}^{lorII}$  is specified by  $imode$ . When  $imode_n = 1$ , it corresponds to the separation of Type I flow; when  $imode_n = 2$ , it corresponds to the separation of Type II flow. Therefore, it can be further written as follows:

$$\tilde{l}_{ZDES,n} = \begin{cases} l_{SST}, & \text{if } ides_n = 0 \\ l_{DES}^I = \min(l_{SST}, C_{DES} \Delta_{DES}^I), & \text{if } ides_n = 1, imode_n = 1 \\ l_{DES}^{II} = l_{SST} - f_d \max(0, l_{SST} - C_{DES} \Delta_{DES}^{II}), & \text{if } ides_n = 1, imode_n = 2 \end{cases} \quad (11)$$

where  $C_{DES}$  is 0.78 and  $f_d$  is the delay function defined in DES. ZDES redefines a new sub-grid scale, and the following section will provide a detailed introduction to it.

### 2.1.3. Definition of Sub-Grid Scale

The sub-grid scale  $\Delta$  plays a role in DES-type methods that is similar to its role in classical LES methods, controlling the computed wavelength and the level of vortex viscosity. Chauvent [20] proposed a new sub-grid scale for LES, considering the slow development of turbulence in the mixing layer:

$$\Delta_\omega = \sqrt{\frac{\|N_i\|^2}{s_{j+1/2}s_{k+1/2}} + \frac{\|N_j\|^2}{s_{k+1/2}s_{i+1/2}} + \frac{\|N_k\|^2}{s_{i+1/2}s_{j+1/2}}} \quad (12)$$

where  $N_i$ ,  $N_j$ , and  $N_k$  represent the components of the unit vector of the vorticity  $\omega$  along the three coordinate axes.

This new definition of the sub-grid scale helps to prevent the delay of shear layer instability and the delay of the transition to full turbulence after separation. This new definition has been successfully validated in the literature [20].

For the length scale associated with Type II separated flows, to ensure the rapid transition of the DES mode from the LES mode, the delay function  $f_d$  is introduced as a conversion channel from  $\Delta_{\max}$  to  $\Delta_{\omega}$ . Here, a value  $f_{d0}$  is introduced to mark the outer boundary of the boundary layer.  $\Delta_{\text{DES}}^{\text{II}}$  is expressed as follows:

$$\Delta_{\text{DES}}^{\text{II}} = \begin{cases} \Delta_{\max}, & \text{if } f_d < f_{d0} \\ \Delta_{\omega}, & \text{if } f_d > f_{d0} \end{cases} \quad (13)$$

The range of values for  $f_{d0}$  is (0.75, 0.99). The minimum value of  $f_{d0}$  is intended to maintain the original DDES behavior within the boundary layer, while the maximum value corresponds to the sub-grid length scale  $\Delta_{\max}$ . Therefore, as long as  $f_d < f_{d0}$ , Equation (13) remains in DDES mode.

In summary, the definition of the sub-grid length scale for ZDES is as follows:

For the first type of flow separation problem (fixed separation position), the sub-grid length scale in Equation (11) is given by

$$\Delta_{\text{DES}}^{\text{I}} = \Delta_{\omega} \quad (14)$$

For the second type of flow separation problem (uncertain separation position), the sub-grid length scale in Equation (11) is given by

$$\Delta_{\text{DES}}^{\text{II}} = (0.5 + \text{sign}(0.5, f_d - f_{d0})) \times \Delta_{\max} + (0.5 - \text{sign}(0.5, f_d - f_{d0})) \times \Delta_{\omega} \quad (15)$$

The sign function is defined as follows:

$$\text{sign}(a, b) = \begin{cases} +a, & \text{if } b \geq 0 \\ -a, & \text{if } b < 0 \end{cases} \quad (16)$$

## 2.2. Computational Model and Grid Generation

This study focused on the supercritical airfoil OAT15A. The basic parameters are described as follows: chord length  $c = 230$  mm, thickness of 12.3% $c$ . The OAT15A airfoil transonic shock buffet experiment was conducted in the S3Ch continuous wind tunnel of ONERA [21]. The freestream Mach number for the experiment is 0.73, and the AOA ranged from 2.5 degrees to 3.91 degrees. Transition strips were placed at 7% chordwise positions on both the upper and lower surfaces of the airfoil. The results indicated that the transonic shock buffet occurred on the upper surface of the airfoil at an AOA of 3.25 degrees. The buffet frequency remained constant with increasing AOA, with a primary frequency of  $f = 69$  Hz at 3.5 degrees.

In this study, a C-H grid topology was employed for grid partitioning, as depicted in Figure 1. Regarding the selection of the streamwise dimension of the computational domain, Deck [19] suggested a comparison between the airfoil thickness ( $e$ ) and the step height ( $H$ ) in the wake flow. For separated flow behind a step, a minimum streamwise dimension of  $4H$  is required to capture the maximum wavelength numerically. In the case of airfoil flow at small angles of attack, where the flow is separated, the height of the separation region can be set as half of the trailing edge curvature ( $e$ ). Thus, the streamwise dimension of the computational domain should be no less than  $2e$ . For the OAT15A airfoil, with a maximum thickness of 12.3% chord length, based on the above analysis, the streamwise dimension of the computational domain is set to a 26% chord length in this section.

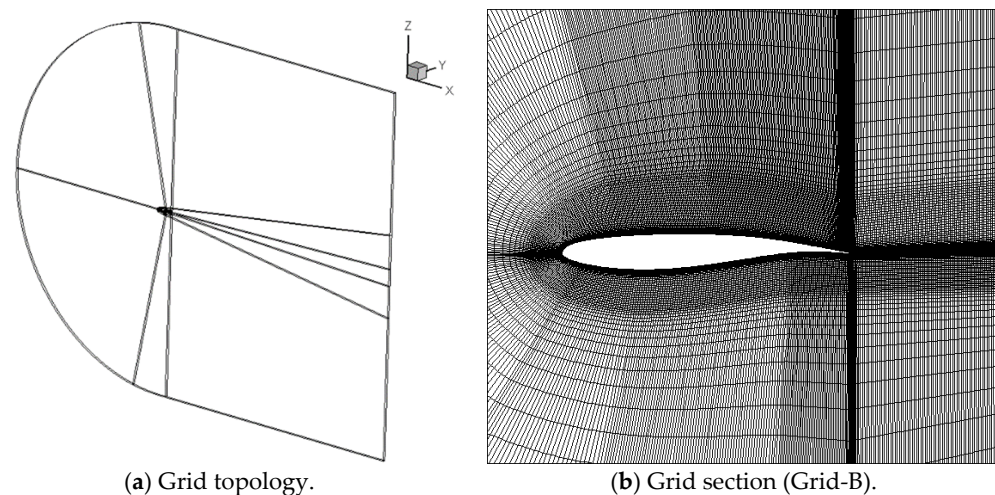


**Figure 1.** Topology and grid.

### 2.3. Validation of the Numerical Approach

To better simulate the motion of shock waves over the airfoil and the influence of the trailing-edge wake on the shock waves, the grid for the shock wave motion region on the upper surface and the downstream wake region behind the trailing edge was moderately refined (greater than or equal to c). Before the computations commenced, three sets of grids with different densities were established, and specific parameters can be found in Table 1. The grid cross-section is illustrated in Figure 1.

**Table 1.** The distribution of grid points.

|                        | Streamwise<br>Nodes | Chordwise<br>Nodes | Spanwise<br>Nodes | Total Nodes        |
|------------------------|---------------------|--------------------|-------------------|--------------------|
| <b>Grid-A (Coarse)</b> | 172                 | 89                 | 32                | $5.05 \times 10^5$ |
| <b>Grid-B (Medium)</b> | 220                 | 137                | 40                | $1.20 \times 10^6$ |
| <b>Grid-C (fine)</b>   | 265                 | 192                | 40                | $2.04 \times 10^6$ |

The three sets of grids were utilized to simulate the flow field at a freestream Mach number of 0.73 and an AOA of 2.5 degrees. According to the experimental results, no transonic shock buffet was observed in the flow field in this condition, and the shock wave position remained fixed. Steady-state computations were performed for the three grid sets by the SST model. The surface pressure distributions obtained from different grids are compared in Figure 2. It is evident that the pressure distributions from the three sets of grids are quite similar, showing a good agreement with experimental data. The calculated shock wave positions also align with the experimental observations. The streamline patterns shown in Figure 3 indicate that the shock wave induces a small localized separation region within the boundary layer, which is consistent with experimental observations. For subsequent calculations in this section, the second grid (Grid-B) was consistently employed.

The surface pressure distributions obtained from different turbulence models are compared in Figure 4, including the S-A model, the SST model, and the k- $\omega$  model. The shock wave occurred at  $x/c \approx 0.50$  in the experiment. Comparing the performance of the three models, the SST model predicted the shock wave position being in good agreement with the experiment; The S-A model was slightly downstream, while the Wilcox k- $\omega$  model deviated significantly from the experiment, placing the shock wave at  $x/c \approx 0.57$ , noticeably further downstream. Since transition strips were applied at 7% chordwise positions on both the upper and lower surfaces of the airfoil in the experiment, we further compared the impact of adding a fixed transition (FT) into the computational results. Compared to full-turbulence simulation, the shock wave positions predicted with the S-A model and

SST model are slightly advanced when a fixed transition is added. To better simulate the experimental conditions in unsteady simulation, a fixed transition was added at the corresponding positions in subsequent calculations in this section.

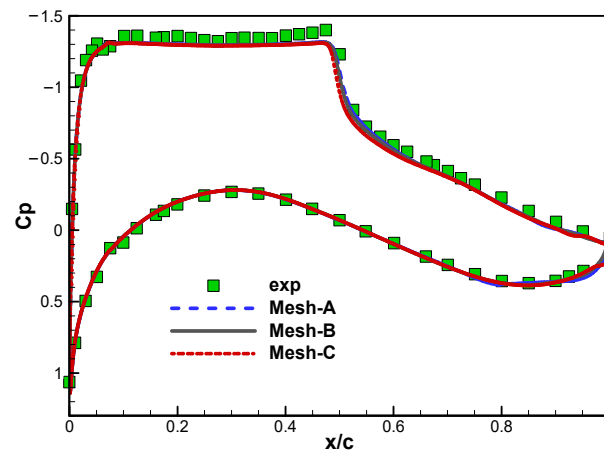


Figure 2. Surface pressure distributions obtained from grids with different densities.

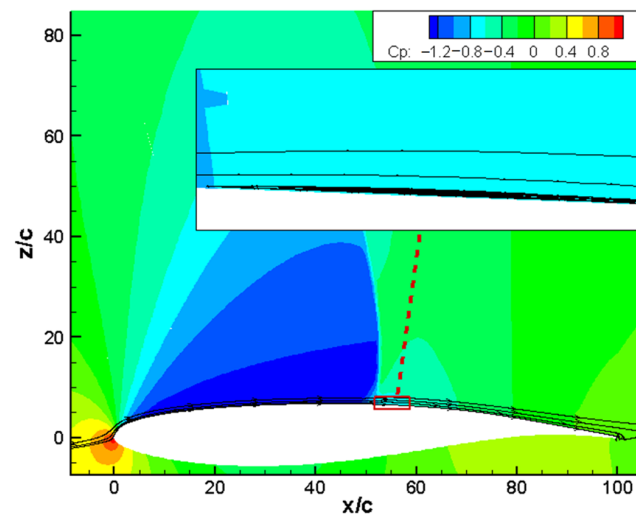


Figure 3. Streamline plots (Grid-B,  $\alpha = 2.5^\circ$ ).

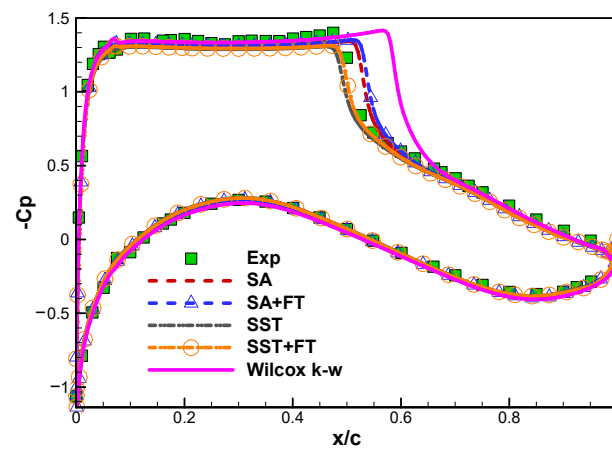


Figure 4. Comparison of pressure distributions with different turbulence models ( $\alpha = 2.5^\circ$ ).

The computational domain for the ZDES of OAT15A is shown in Figure 5, where DES was applied to the upper surface and wake region prone to transonic shock buffet, while

the rest of the domain utilized RANS. The time step for the unsteady simulation was set to  $1 \times 10^{-6}$  s, with 15 sub-iterations performed within each time step, which depends on a Courant–Friedrichs–Lewy number based on acoustic velocity and spanwise grid spacing of less than one.

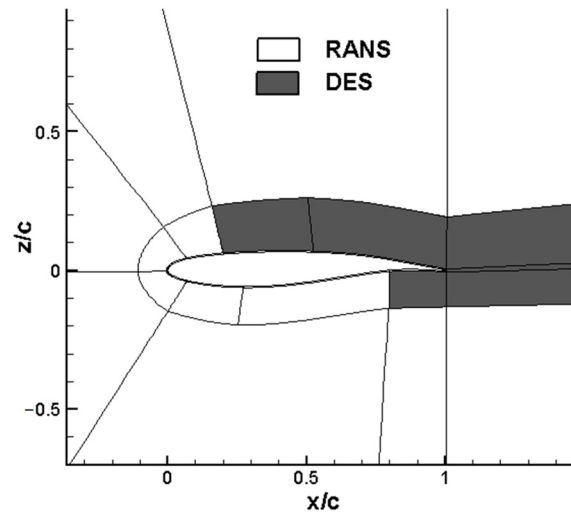


**Figure 5.** Schematic of OAT15A segmented computation.

### 3. Results and Analysis

#### 3.1. Time-Averaged Results

Figure 6 presents the time and spanwise averaged pressure coefficient distribution. On the upper wing surface, the IDDES predicted an average shock wave position located at around  $x/c = 0.25$ , which is approximately one-third ahead of the experimentally observed average shock wave position. The average shock wave position obtained with DDES was slightly closer to the upstream, and the pressure distribution in the trailing edge region was noticeably lower than the experimental results. In comparison, the average shock wave position predicted by ZDES in this study were essentially consistent with the experimental results. During the oscillation of the shock wave, the flow on the lower surface remained attached, and both global and zonal DES provided pressure distribution results consistent with the experiment.

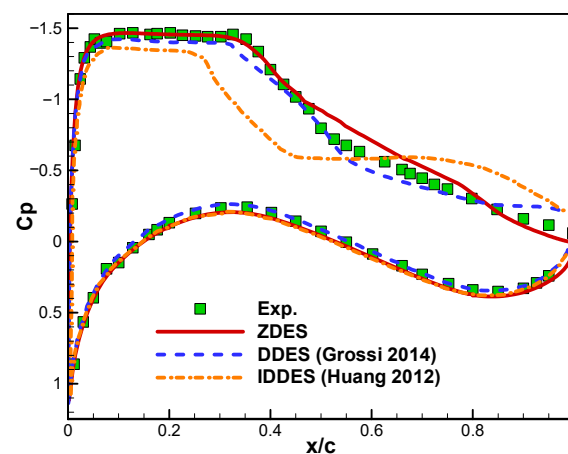


**Figure 6.** Averaged pressure coefficient distribution; Grossi 2014 [11], Huang 2012 [12].

The streamwise velocity distributions obtained with DDES and ZDES at different positions are compared in Figure 7. At the  $x/c = 0.28$  location, which was at the upstream position of the shock wave, the flow remained attached, and both the DDES and ZDES

velocity distributions agree well with the measured results. At the  $x/c = 0.45$  location, near the average position of the shock wave, the ZDES result predicted a velocity distribution in agreement with the experimental results. However, the DDES yielded a thicker boundary layer and lower velocities outside the boundary layer, due to the predicted advance of the average shock wave position by the DDES. This also led to slight discrepancies between the DDES and the experiment at the  $x/c = 0.60$  and  $x/c = 0.75$  locations. Overall, the streamwise velocity distribution obtained with ZDES better matched the experimental results.

The distribution of root-mean-square pressure fluctuations on the upper surface of the airfoil is illustrated in Figure 8. In the upstream region of the separation area, the flow remains fully attached throughout the entire oscillation cycle. Therefore, both global and ZDES predicted relatively low levels of pressure fluctuations. Under the influence of the transonic shock buffet, the level of surface pressure fluctuations rapidly increased, reaching approximately 30% of the maximum peak level at  $x/c = 0.45$ , and then quickly receded. The maximum fluctuation level obtained with DDES was approximately 36%, while the IDDES predicted a maximum peak value of 39%, both significantly higher than the experimental data. The root mean square of surface pressure fluctuations also partially reflected the range of shock wave motion. The shock wave motion range obtained with IDDES was overall shifted forward compared to the experimental results, consistent with the average shock wave position reflected in Figure 8.

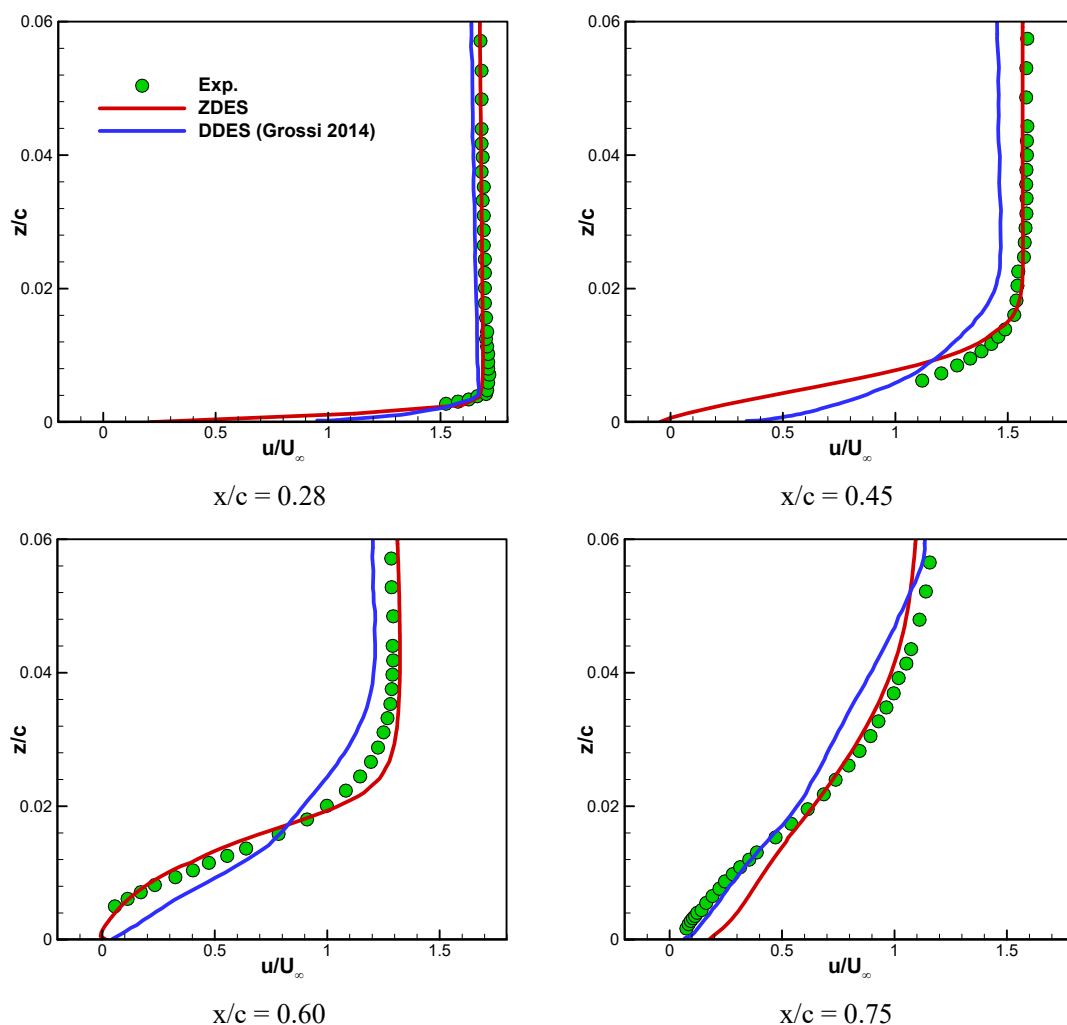


**Figure 7.** Mean streamwise velocity distribution at different streamwise locations on the upper surface of the airfoil, Grossi 2014 [11].

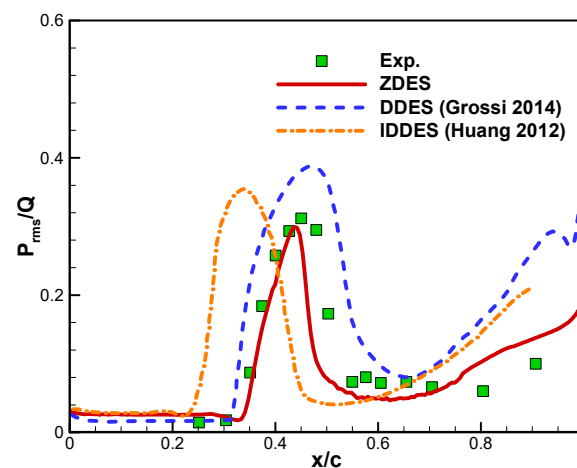


**Figure 8.** Root-mean-square distribution of pressure fluctuations on the upper surface of the airfoil; Grossi 2014 [11], Huang 2012 [12].

From Figure 8, it can be observed that the maximum pressure fluctuation level calculated with ZDES is slightly lower than the experimental value. This may be because the mesh currently in use may not be dense enough. In the separation region downstream of the shock wave, the pressure fluctuation levels obtained with DDES and IDDES were significantly higher than the experimental values. This may be influenced by the shedding of large-scale vortex structures at the trailing edge. Overall, the ZDES results are in good agreement with the experimental data.

### 3.2. Time-Dependent Results

The variation in the lift coefficient over time is depicted in Figure 9. Due to the formation of shock wave self-excited oscillations, the repetitive motion of the shock wave on the upper surface caused periodic fluctuation in the lift coefficient over time. To investigate the amplitude and patterns of the shock wave motion on the upper surface, eight representative flow field instances within one cycle were analyzed based on the fluctuation pattern of the lift coefficient. The specific positions at different moments in time are provided in Table 2. Due to the local fluctuations in the lift coefficient, it was challenging to precisely select a starting point for the cyclic motion of the shock wave, where the shock wave was positioned either at the limitation of the upstream or downstream. Therefore, an instantaneous cycle was defined from the recorded initial moment when the shock wave was at a certain downstream position until the moment when the shock wave returned to the same position. The time duration of this cycle is denoted as  $T$ .

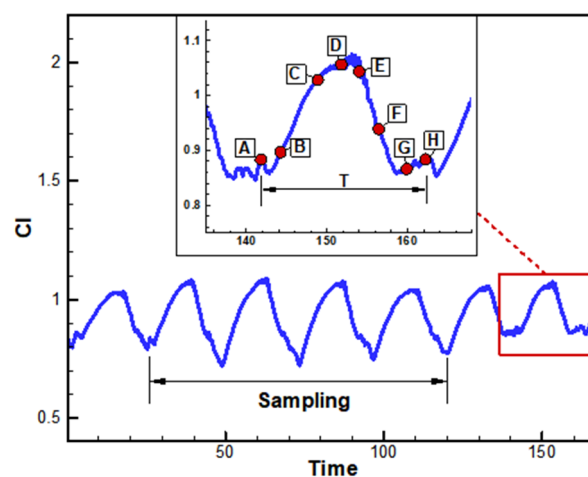


**Figure 9.** Temporal evolution of the lift coefficient.

**Table 2.** Transient position selection.

| Transient Location | A | B   | C   | D   | E   | F   | G   | H |
|--------------------|---|-----|-----|-----|-----|-----|-----|---|
| $t/T=$             | 0 | 11% | 35% | 49% | 60% | 73% | 90% | 1 |

Density gradient contours are presented in Figure 10 at selected instants in time. At the initial moment A, the shock wave was positioned at an approximately 30% chordwise location. At moment B, the shock wave moved downstream to around a 40% chordwise position, reaching the furthest downstream position at moment C, at an approximately 50% chordwise location. At moment D, there was no significant difference in the shock wave position compared to moment C, but the tilt angle of the shock wave increased, and small-scale high-frequency fluctuations in the lift coefficient began to appear. By moment E, the shock wave has started moving upstream and reaches  $x/c = 0.37$ . At moment F, the shock wave was positioned at  $x/c = 0.30$ , until moment G when the shock wave reached the furthest upstream position ( $x/c = 0.23$ ). Subsequently, the shock wave began to move downstream again, reaching the initial position at moment H, marking the completion of one cycle.

Figure 11 displays the iso-surfaces of the Q criterion in one cycle. The shock wave induced separation in the downstream boundary layer, and the shear layer exhibited strong two-dimensional characteristics. As it progressed downstream, the shear layer gradually breaks into small-scale three-dimensional turbulence structures, and some large-scale vortex shedding can be observed in the downstream wake region. Comparing the instantaneous flow at different moments revealed that the separation region induced by the shock wave undergoes periodic variations as the shock wave moves. During the downstream movement of the shock wave (from A to C), the separation region behind the shock wave gradually thinned, and the size decreased, resulting in an increase in lift. Conversely, during the upward movement of the shock wave (from E to G), the separated boundary layer thickened, and the separation region gradually enlarged, leading to a decrease in the lift coefficient. It is noteworthy that the lift coefficient did not reach its maximum peak when the shock wave reached the furthest downstream position. Combining Figures 10 and 11, it could be observed that the vortex structures of different scales at the trailing edge generated strong fluctuations.

The distribution of the average friction coefficient on the wing surface at different instants is illustrated in Figure 12. The surface friction coefficient can reflect the flow separation status after the shock wave. During the shock wave downward motion, as the shock wave traveled from the upstream ( $t/T = 0$ ) to the most downstream position ( $t/T = 40\%$ ), the separation region on the upper wing surface gradually approached the shock wave location until the entire surface was separated. During the shock wave upward motion, the upper wing surface was in a mostly separated state from the shock wave location to the trailing edge until the end of the upward motion.

Figure 13 depicts the temporal and spatial variations in flow separation and reattachment on the upper surface of the airfoil based on the distribution of the friction coefficients. The vertical axis represents the progression of time, which is dimensionless with respect to the transonic shock buffet period  $T$ , corresponding to the global time shown in Figure 9. The horizontal axis represents the streamwise position on the upper surface of the airfoil ( $x/c = 0$  for the leading edge, 1 for the trailing edge). The white region indicates the attached flow, while the dark region represents the separated flow. The figure clearly reflects the changing positions of the shock wave and flow separation regions over time. At the initial instant ( $t = 0$ ), the shock wave was in the downward phase. Local separation appeared in the trailing-edge region, while the flow in other areas remained fully attached. As the shock wave further moved downstream, separation bubbles occurred simultaneously at the base of the shock wave and in the trailing-edge region. When reaching the most downstream position, these two separation regions converged, leading to complete separation on the upper surface after the shock wave. During the upward motion of the shock wave, the region behind the wave remained fully separated until the shock wave approached

the most upstream position. At this point, the separation region divided into two parts again. As the shock wave moved downstream once more, these two regions gradually shrank, then expanded again, repeating the cycle. Although the results presented here represent only one cycle of flow separation, the flow separation patterns in other cycles were qualitatively consistent, with potential quantitative differences.

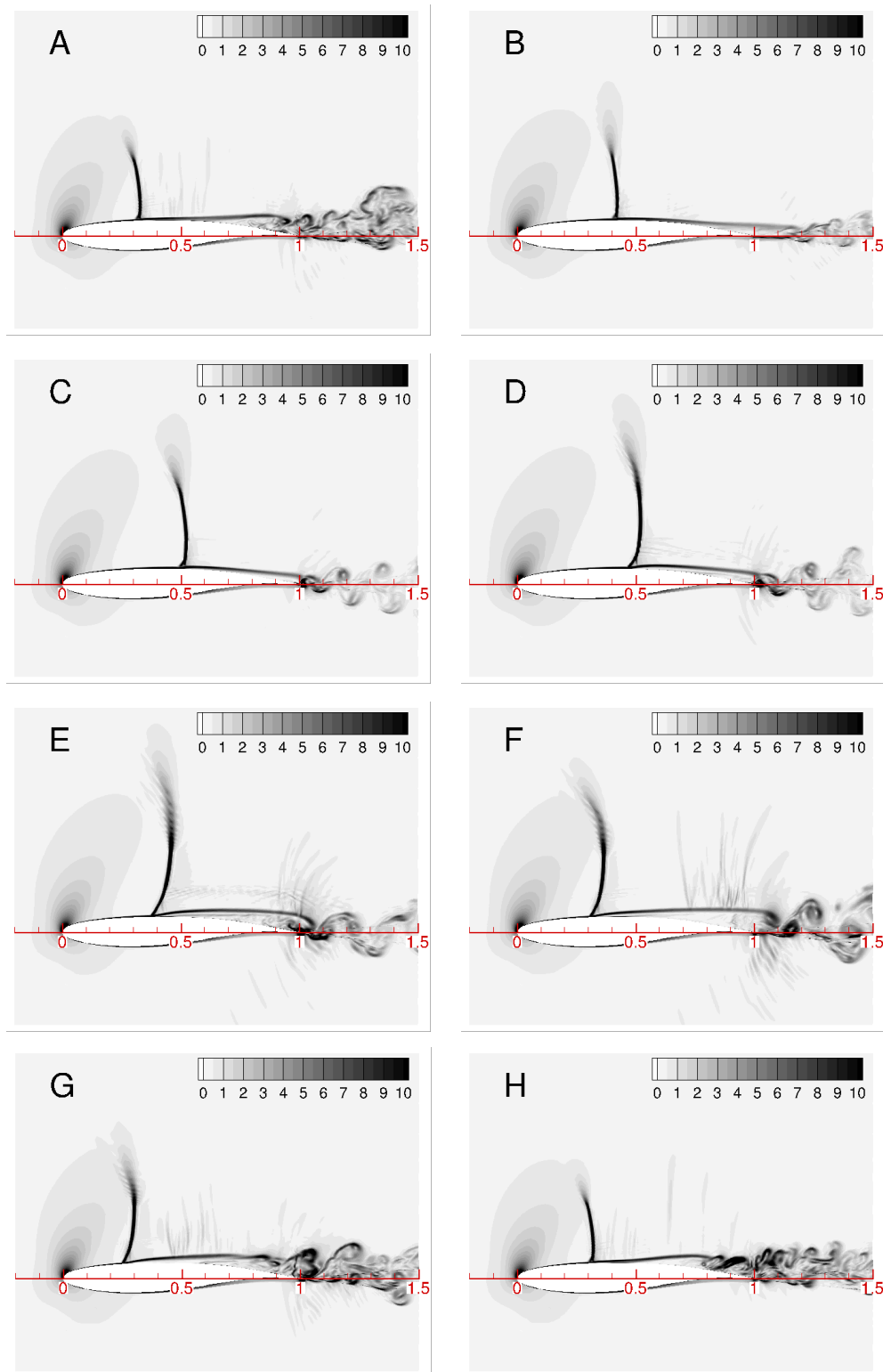


**Figure 10.** Instantaneous density gradient contours in one cycle.

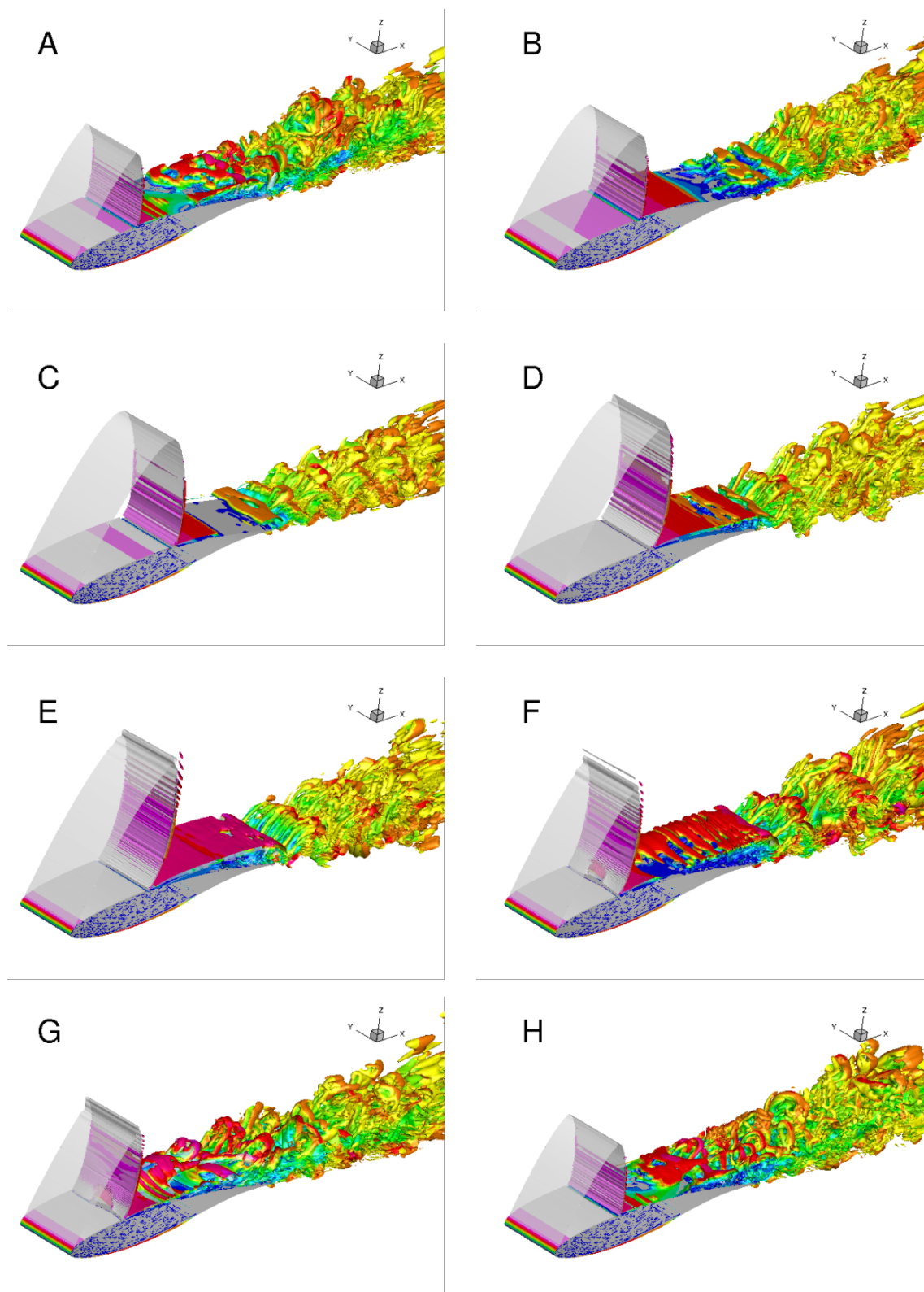


**Figure 11.** Instantaneous turbulent structures in one cycle (A–H).

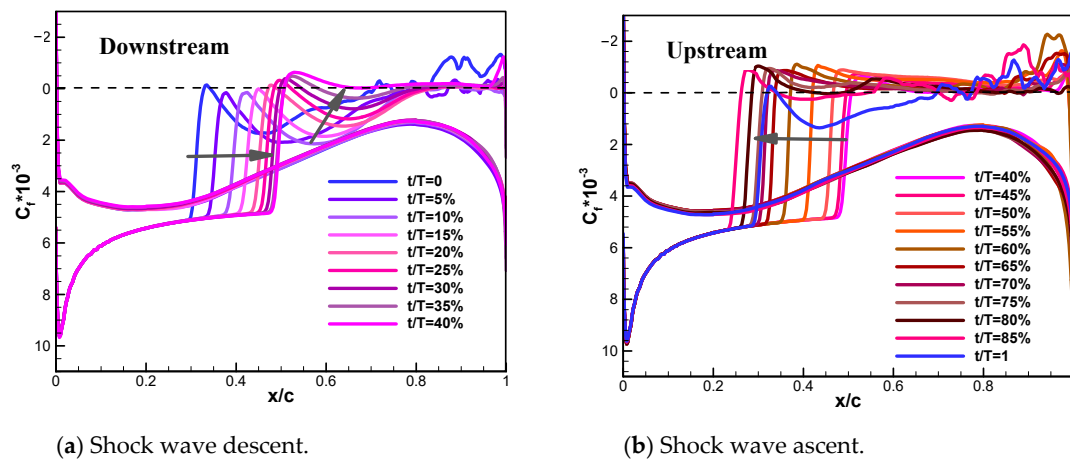


Figure 12. Surface friction coefficient distribution.

The variation trend of the shock wave movement speed during the transonic shock buffet process can be observed from Figure 13. In the first 40% of the time during the shock wave ascent or descent, the trajectory slope of the shock wave position showed a relatively large change with time, indicating a fast movement speed of the shock wave. The displacement during this period accounted for approximately 60% of the entire range of shock wave motion. During the subsequent 40%, the trajectory slope of the shock wave position over time decreased, indicating a slower movement speed. When approaching the most upstream or downstream position, the speed reached its minimum. Furthermore, within one cycle, the time taken for shock wave ascent and descent in this study was in a 1:1 ratio. In contrast, the DDES predicted that the time for shock wave ascent occupied approximately one-third of the single cycle, which was related to the shorter transonic shock buffet period predicted with DDES compared to the experimental period.

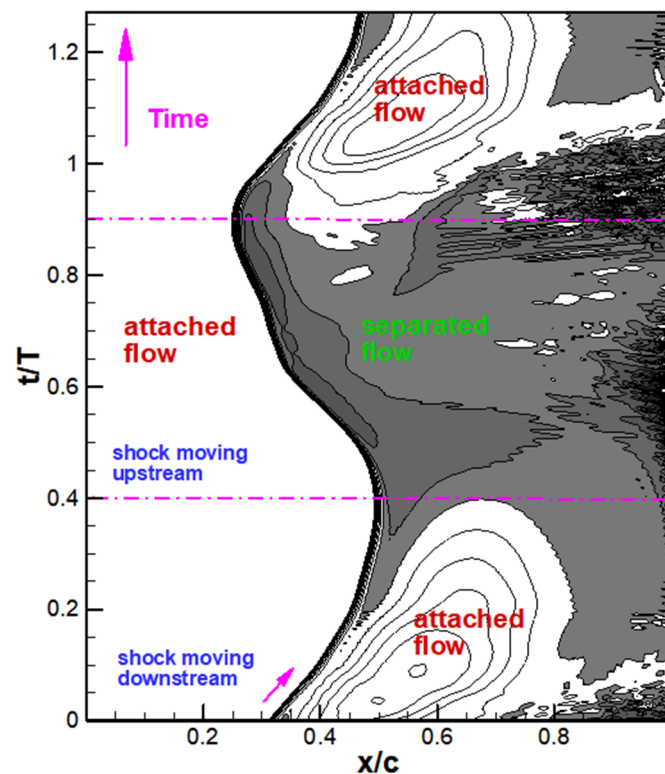


Figure 13. The evolution of flow separation on the upper surface of the airfoil.

Figure 14 illustrates the instantaneous wave field of the transonic shock buffet at different moments. During the downstream movement of the shock wave, the instability at the trailing edge is relatively weak. At this point, the pressure wave generated by the trailing edge is not enough to push the shock wave upstream. The shock wave-induced separation also caused the instability of the boundary layer to propagate downstream with the movement of the shock wave. When the disturbance reached the trailing edge, the instability of the trailing edge increased, and the strength of the pressure waves radiating upstream also intensified, initiating the upstream movement of the shock wave. During the downstream movement of the shock wave (as shown in Figure 14b), as the distance from the shock wave position to the trailing edge continuously increased, the disturbance of the boundary layer instability at the trailing edge diminished. Consequently, the strength of the pressure waves radiating upstream weakened, leading to the shock wave starting to move downstream again. This resulted in the periodic oscillatory motion of the shock wave on the upper wing surface.

The power spectral density (PSD) of the lift coefficient obtained with the parameter autoregressive method is shown in Figure 15. The experimentally observed main frequency of the transonic shock buffet was 69 Hz. The PSD results indicated a computed main frequency of 67 Hz, which closely matched the experimental findings, with a relative error of less than 3%. In previous numerical studies [11,15], DDES [15] yielded a main frequency of 80.5 Hz, approximately 17% higher than the experimental result. In comparison, the ZDES employed in this study exhibited a better agreement with the experiment, as shown in Table 3. Due to the influence of Kelvin–Helmholtz instability, a peak region was observed in the high-frequency range at 2000 Hz and 5000 Hz, generated by secondary oscillations with a central frequency approximately 40 times the experimental main frequency. This corresponded to the frequency of the Karman vortex shedding in the downstream wake region observed in the density gradient contour maps.

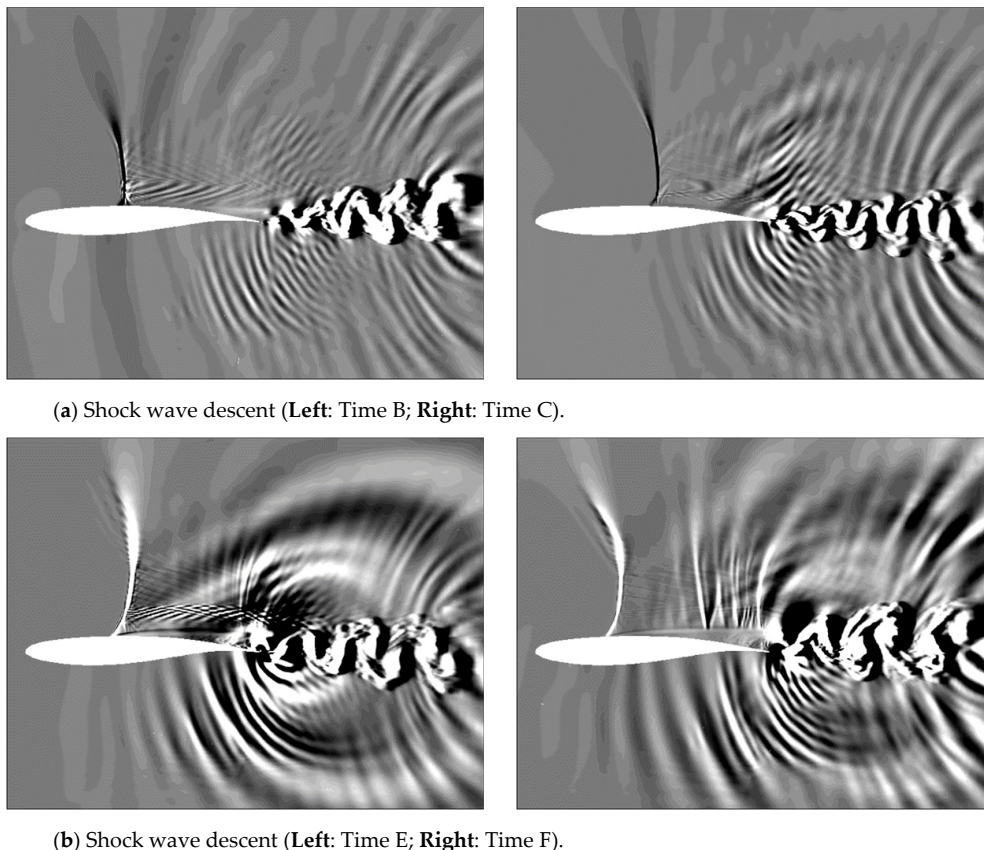


**Figure 14.** Instantaneous wave pattern of shock oscillation.

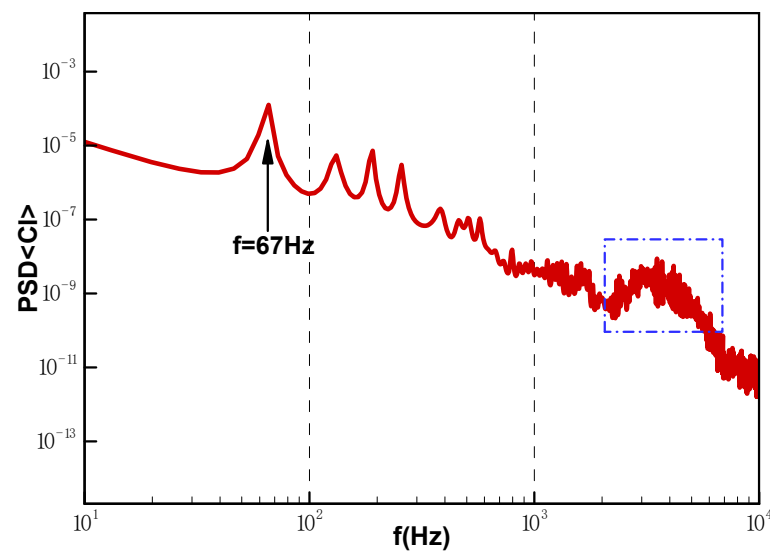


**Figure 15.** The power spectral density of the lift coefficient (ZDES).

**Table 3.** The oscillation frequency of shock waves obtained by different methods.

|           | DDES    | IDDES | ZDES  | EXP   |
|-----------|---------|-------|-------|-------|
| Frequency | 80.5 Hz | 78 Hz | 67 Hz | 69 Hz |

#### 4. Conclusions

This study conducts numerical simulation by ZDES based on the  $k-\omega$  SST model to investigate the transonic shock buffet phenomenon of the OAT15A supercritical airfoil under transonic conditions. The main conclusions can be drawn as follows:

(1) ZDES is suitable for fine numerical simulation of the transonic shock buffet, effectively capturing the phenomenon of a shock wave self-sustained buffet. Through the analysis of the evolution of the complex flow field during one cycle of the transonic shock buffet, it is observed that the motion of shock waves and the resulting flow separation and reattachment exhibit periodic characteristics, leading to oscillations in the overall aerodynamic forces. This provides further insights into the formation mechanism of a shock wave self-sustained buffet.

(2) In comparison with DDES and IDDES, the power spectral density of the lift coefficient suggests that ZDES can better capture the low-frequency characteristics of the transonic shock buffet. Analysis of the pressure distribution and pressure fluctuation distribution indicates that ZDES predicts the average shock wave position and the range of shock wave motion in better agreement with the experimental results. However, the maximum pressure fluctuation level is slightly lower, suggesting a possible limitation due to insufficient grid density. ZDES also exhibits better agreement with experimental results in predicting the average streamwise velocity.

(3) It has been found that the instability generated by flow separation interacts with the trailing edge during the periodic evolution of the instantaneous wave field. This interaction affects the intensity of pressure waves radiated upstream from the trailing edge, and the intensity of these pressure waves determines the direction of shock movement, which is the key mechanism behind the self-excited transonic shock buffet.

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## Nomenclature

|                       |                                                     |
|-----------------------|-----------------------------------------------------|
| AOA                   | Angle of Attack                                     |
| S-A model             | Spalart–Allmaras Model                              |
| k- $\omega$ SST model | k-omega Shear Stress Transport Model                |
| RANS                  | Reynolds-Averaged Navier–Stokes Simulation          |
| LES                   | Large-Eddy Simulation                               |
| URANS                 | Unsteady Reynolds-Averaged Navier–Stokes Simulation |
| DES                   | Detached-Eddy Simulation                            |
| DDES                  | Delayed Detached-Eddy Simulation                    |
| IDDES                 | Improved Delayed Detached-Eddy Simulation           |
| AZDES                 | Automated Zonal Detached-Eddy Simulation            |
| RSM                   | Reynolds Stress Model                               |
| CRM                   | Common Research Model                               |

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