Numerical simulation of supersonic shear layer with plasma actuator

Ke Lin\textsuperscript{a}, Hong Yan\textsuperscript{b,}\textsuperscript{*}

\textsuperscript{a}Northwestern Polytechnical University, 127 Youyi Xilu, Xi'an 710072, China
\textsuperscript{b}Collaborative Innovation Center for Advanced Aero-Engine, Beijing, 100191, China

Abstract

The plasma actuator can make difference in changing the vortex characteristics in supersonic shear layer, leading to mixing enhancement and noise reduction in the supersonic shear layer. Large Eddy Simulation is performed to investigate the effect of plasma actuator on supersonic shear layer, in which the plasma actuator is simplified as heat source. A Mach 1.3 supersonic flow over a backward-facing step with a groove placed upstream of the step is simulated first. Then the plasma actuators are placed inside the groove, and the effect of the plasma actuator is studied. Results show that the cases with heat sources have larger growth of shear layer and area-averaged vorticity compared with the baseline case, and increasing the amplitude of the actuation is a more efficient way for mixing enhancement.

Keywords: plasma actuator; supersonic shear layer; large eddy simulation; flow control

1. Introduction

As turbulence noise getting more and more attention, many researchers have done a lot of work about the theory study, experiments and numerical simulation of turbulent jet, shear layer and associated structure, and noise fields on various flow conditions. Lele \textit{et al.} [1] numerically simulated the noise field during the vortex merging process generated in the two dimensional compressible shear layer. Recently, active flow control becomes popular around the world and gets much attention in the application of turbulence noise reduction.

Most of the earlier active flow control on free shear layer is done in low-speed and low-Reynolds flow [2,3], and acoustic drivers have achieved much success. However, it cannot provide sufficient bandwidth and amplitude to control high-speed and high-Reynolds flows. Recent experiments show that localized arc filament plasma actuators are successfully used to make sense in mixing performance of shear layer[4,5].

In this work, a three-dimensional planar free shear layer between Mach 1.3 supersonic flow and static standard atmosphere is simulated with ANSYS Fluent v14. The plasma actuators used are modelled as uniformly distributed heat sources inside the groove upstream of the shear layer. The time-dependent heating in pulse pattern with different pulse amplitude and duty cycle is compared with the no-heating case.
2. Numerical method

Large Eddy Simulation (LES) is used to capture the flow structures in details. The LES operator works on the Navier-Stokes equations to reduce the range of length scales of the solution, thus reducing the computational cost compared with DNS. The governing equations of the compressible flow are conservation of mass, momentum and energy.

\[
\frac{\partial p}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j}
\]

\[
\frac{\partial (\rho h_i)}{\partial t} + \frac{\partial (\rho u_i h_i)}{\partial x_j} = -\frac{\partial k}{\partial x_j} + \frac{\partial p}{\partial t} + \frac{\partial (\sigma_{ij} u_j)}{\partial x_j} + Q
\]

The equation of state is written as

\[ p = \rho RT \]

The three dimensional Navier-Stokes equations are solved by numerical discretization of space (x; y; z) and time (t). The third-order accurate AUSM scheme along with the MUSCL reconstruction is adopted for convective flux terms and the second order implicit method is used for time integration. The gradient reconstruction is based on node Green-Gauss method. Equations are solved using incomplete lower upper factorization (ILU), in conjunction with algebraic multigrid method. The Smagorinsky-Lilly subgrid model [6] is applied.

3. Flow configuration

A backward-facing step with a groove is used to form a supersonic shear layer which is used as a baseline flow for flow control using plasma actuators. The flow above the backward step is planar supersonic flow while the flow below the step is stationary atmosphere. The grooves placed 1mm upstream of the backward step end, as shown in Fig. 1(a). The plasma actuator is modelled as a uniformly distributed rectangular shaped heat source inside the groove for simplification. And its size is 1 mm, 3 mm and 0.5 mm in the streamwise, spanwise and vertical directions, respectively. The gap between two heat sources is 3 mm. The whole computational domain is 65 mm, 12 mm and 25 mm in the streamwise, spanwise and vertical directions, respectively. The flow zone is divided vertically into two regions by the backward step, and the initialization of the upper and lower region is a uniform Mach 1.3 supersonic flow and stationary atmosphere, respectively.

The boundary conditions are set as follows in Fig. 1(b). The top boundary is at uniform supersonic Mach 1.3 condition, same as the inlet boundary, and the backward step is set as adiabatic wall and the bottom boundary is at stationary atmosphere condition.

4. Numerical results

A Mach 1.3 supersonic shear layer with the static temperature of 224.22 K and the static pressure of 101325 Pa interacting with stationary atmosphere is analyzed. First, the accuracy of the no-heating baseline flow is established. The simulation first runs about 0.002 s which is more than ten times the flow-through time for the initial flow transients to convect out of the computational domain. And another 1000 more time steps are required to get quasi-steady-state of the baseline case without heating. Then the simulation runs for 5000 time steps to get flow characteristics and statistical data of the baseline case. For the heating cases, the plasma actuators are turned on once the baseline flow is converged, then 10 heating time periods are simulated after the quasi-steady-state of the heating cases is achieved.

Three heating cases are designed to analyze the effect of pulse amplitude and duty cycle of the plasma actuation with the pulse frequency fixed at 20 kHz. Case 1 has pulse amplitude of $8 \times 10^9 (W/m^2)$ and duty cycle of 0.5. Case
2 doubles the pulse amplitude of case 1 with the same duty cycle and case 5 halves the duty cycle of case 1 with the same pulse amplitude.

The Q criterion is used to identify the vortical structures. Figs. 2 show the iso-surface of the normalized $Q=0.1$ colored by the x-component vorticity for the baseline case, case 1 and case 2. It is shown in Fig. 2(a) that the vortices at the head of the shear layer form a W-shaped vortical structure. As the vortices move downstream, these W-shaped structures become the origin of the horseshoe vortex which is of significant importance in the mixing enhancement. The vortex structures in the heating cases are quite different from those in the baseline. As shown in Figs. 2(b) and (c), the heating generates much bigger streamwise vortices which is beneficial to mixing. The streamwise vorticity component which makes up the legs of the horseshoe vortices structure plays an important role in mixing effect, so the larger horseshoe vortices in size is more efficient.

The input energy of the case 5 is half of the case 2 since its duty cycle is half of the case 2. Higher duty cycle leads to longer heating time and less time for the flow to absorb the heat. Case 2 with higher duty cycle has higher temperature region, which creates larger thermal bump acting like tabs to disturb the main flow and affect the shear layer downstream. Different bump effects lead to quite different flow situation at the head of the shear layer. For the development of the shear layer, the significant streamwise vortex which we concern the most is closely related to the x-component vorticity. The distribution of the x-component vorticity at the plane $x=5$ mm in case 2 and case 5 is shown in Fig. 3. It is found that there is less x-component vorticity in case 2 than that in case 5. So higher duty cycle
can produce larger thermal bump, but not the x-component vorticity at the head of the shear layer. The area-averaged vorticity along the streamwise direction in the baseline, case 2 and case 5 are shown in Fig. 4. At the head of the shear layer, the x-component and y-component vorticity in case 2 and case 5 are all lower than that in baseline, and lowest in case 2 with higher duty cycle. Then the x-component and y-component vorticity in case 2 increases to be higher than that in baseline and case 5. Due to higher duty cycle, the peak in case 2 is a little higher than that in case 5. The effect on the development of the x-component vorticity by actuation is greater compared to the effect on the development of the y-component vorticity. Since the pulse amplitude in case 1 is half of that in case 2, the input energy in case 1 is half of that in case 2, but it is same as that in case 5. The area-averaged x-component vorticity along the streamwise direction in the baseline, case 1 and case 2 is shown in Fig. 5. Compared with the Fig. 4(a), it is found that the effect on the development of the x-component vorticity by actuation is greater in case 5 than in case 1, which indicates that increasing pulse amplitude is more efficient than duty cycle. And the reason can be seen in the iso-surface of the normalized $Q=0.1$ in Fig. 6. The streamwise vortical structures downstream in case 5 are larger than those in case 1, so the more efficient actuation is obtained in case 5 compared with case 1.

5. Conclusions

LES is applied to simulate a three-dimensional planar free shear layer between a Mach 1.3 supersonic flow and stationary atmosphere. A reasonable grid is used for the analysis of flow structure. Both the baseline case and heating cases are simulated and analyzed to evaluate the effect of plasma actuators. Although the thermal bump caused by heat source reduces the vorticity intensity at the head region of the shear layer, the larger vortex shedding is observed.
with the plasma actuator compared to the baseline case. It is observed that the growth rate of the shear layer and vorticity intensity downstream are increased compared with the baseline case. The effect of the pulse amplitude is more efficient compared to duty cycle in terms of mixing enhancement. The higher pulse amplitude produces larger streamwise vortical structures, resulting in stronger fluctuations, thus mixing enhancement downstream.

Acknowledgements

The support of this research by the National Natural Science Foundation of China with the grant number of 51176157 is greatly appreciated.

References