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[9-D-03] Analysis of Exhaust Jet Effect on Unsteady Characteristics of Base Flow for Supersonic Vehicle

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Keywords: base flow, unsteady characteristics, base jet, supersonic

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Analysis of Exhaust Jet Effect on Unsteady Characteristics of Base Flow for Supersonic Vehicle

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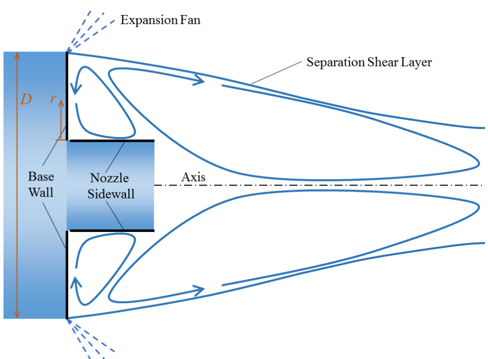
Abstract: The supersonic base flow with an exhaust jet is significantly unsteady, whose characteristics can be influenced by the exhaust jet states. By exhaust jet, we mean the working fluid produced by the rocket engine and exhausted by the base nozzle in supersonic velocity, which is used to generate thrust. A numerical investigation of the base flow at Mach 1.96 is carried out via the DDES (Delayed Detached Eddy Simulation). The effects of presence, expanded states, and temperature of the exhaust jet on the unsteady characteristics are analyzed. Compared with the exhaust jet off, the exhaust jet presence causes the base pressure fluctuation intensity to increase in the high-frequency band ($Sr_D > 0.5$) and changes the dominant mode from wake oscillation ($Sr_D = 0.12$) to the periodically expand-shrink of the exhaust jet diameter ($Sr_D = 0.16$). Compared with the underexpanded state, the overexpanded exhaust jet induces the flow separation inside the nozzle, which causes a decrease in the base pressure fluctuation intensity in the high-frequency band ($Sr_D > 1.0$), and the separation point movement and exhaust jet oscillation induced constitute the dominant mode ($Sr_D = 0.13$). Compared with the low-temperature jet, the base pressure fluctuation intensity is slightly reduced in the high-frequency band ($Sr_D > 1.0$) for the high-temperature jet, and the flapping motion of the jet shear layer becomes the dominant mode ($Sr_D = 1.55$).

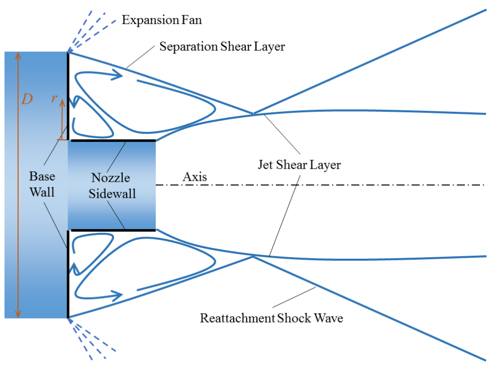
Keywords: Base Flow, Unsteady Characteristics, Exhaust Jet, DMD.

1 Introduction

Supersonic vehicles generally form a large separation region at the base, and its unsteady characteristic can pose a severe unsteady load to the vehicle. As a result, investigation of the unsteady characteristic is essential for structural safety and flow control. Furthermore, the unsteady characteristic can be influenced by the propulsion exhaust jet at the base, but the effects of the exhaust jet presence and its states have not been fully understood. Figure 1 shows a schematic of the base flow with and without an exhaust jet at supersonic speed.



(a) exhaust jet off



(b) exhaust jet on

Figure 1: Schematic of supersonic base flow fields

Early research is primarily devoted to predicting the time-averaged base flow field and pressure. Therefore, the semi-empirical formulations [1], multi-component method of characteristics [2], RANS, and hybrid RANS/LES numerical methods [3] have been used since the 1950s. Among them, the numerical method has higher accuracy and universality than other methods, and many researchers have carried out a large number of parametric investigations based on it [4]. More important, the unsteady characteristics only can be revealed by the numerical simulation. However, there are a few research focusing on the unsteady characteristics [5]. In the present study, the effects of the presence, expanded states, and temperature of the exhaust jet on the unsteady characteristics are revealed by a series of numerical experiments and simulations based on the DDES (Delay Detached Eddy Simulation). For each case, the dominant modes and corresponding unsteady motions of flow structures are analysed by PSD (power spectrum density) and DMD (dynamic mode decomposition). This paper is aimed to provide a full understanding to the unsteady base flow.

2 Computational Model

A typical vehicle model is selected from the experiments related to the base flow [6]. All of the numerical simulations in the present study were carried out using an in-house finite-difference program developed by the authors. The total number of grids is 22 million. The freestream conditions are shown in Table 1. where Ma_∞, T_∞, p_∞, μ_∞, TB_∞ are Mach number, static temperature, static pressure, molecular viscosity, and turbulence intensity of freestream, respectively. T_w denotes the wall temperature, and μ_t denotes the turbulent viscosity. The exhaust jet NPR is selected as 349.5 and 12.9 for underexpanded/overexpanded states, and the jet stagnation temperature ratio is selected as 1.78 and 8.90 for low/high temperatures, respectively. The exhaust jet inlet of the computational domain is located at the nozzle throat.

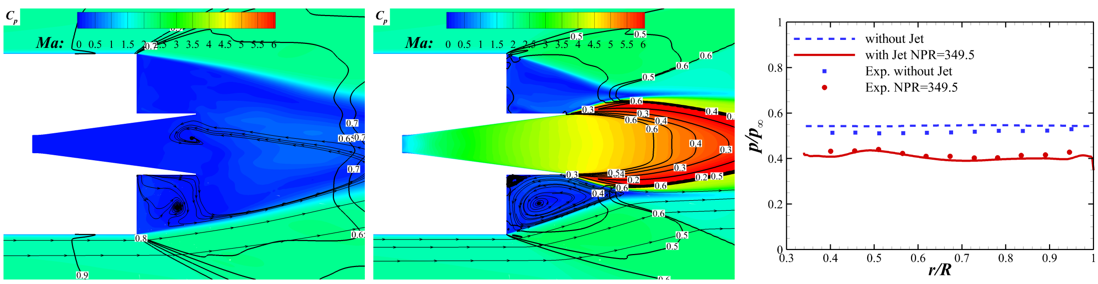
Table 1: Free-stream conditions

Ma_∞	T_∞/K	T_w/K	p_∞/Pa	TB_∞	μ_t/μ_∞
1.96	161.2	285	28300	0.1%	1

3 Result

3.1 Effect of Exhaust Jet Presence

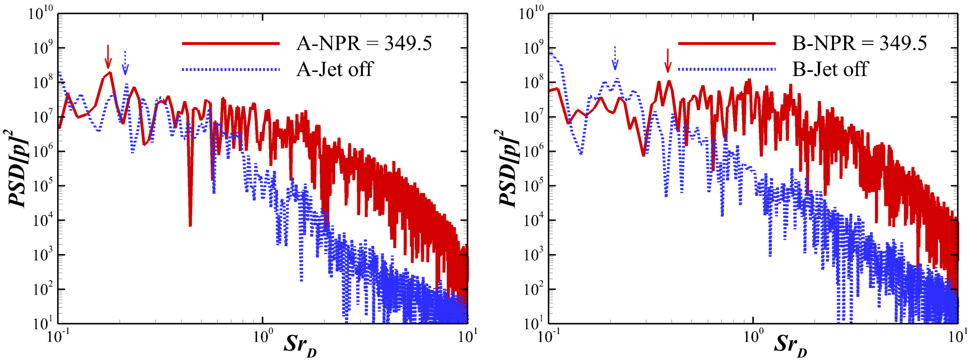
Firstly, the statistically averaged results of the base flow fields with/without exhaust jet are compared and shown in Figure 2, which show that the existing grids and computational methods are suitable to predict the base flow accurately. Subsequently, to quantitatively study the pressure fluctuation, two points located at the base wall and nozzle sidewall with significant unsteady effects are selected for PSD analysis. Figure 3 shows the pressure PSD results for them. In the high-frequency band $Sr_D > 0.5$, the fluctuation intensity is increased by one order of magnitude in the case with exhaust jet on, which suggests that the increase in pressure fluctuation is mainly contributed by the high-frequency band.



(a) exhaust jet off (b) NPR = 349.5 (c) computational and experimental

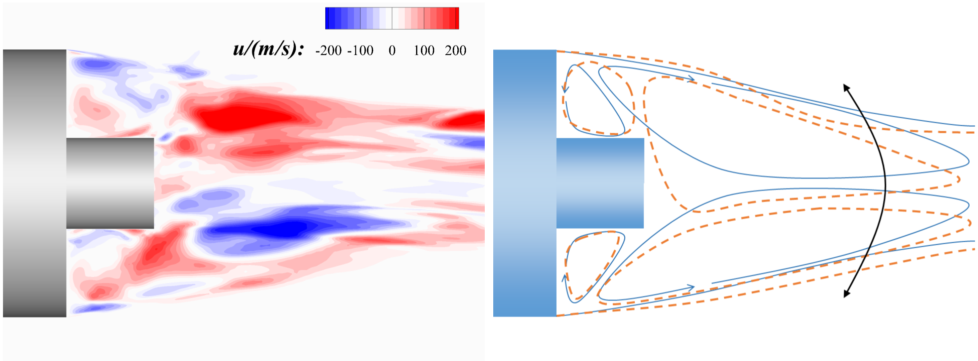
Figure 2: Time-averaged base flow fields comparison between exhaust jet off and NPR = 349.5

In order to further obtain the dominant motion of the flow structures, the modes corresponding to the high amplitude eigenvalues in the DMD are analyzed. Figure 4(a) shows the mode with $Sr_D = 0.12$ in the absence of exhaust jet. The mode is antisymmetric, and the velocity extremums are distributed in the separation shear layer and the base separation region. It can be seen that this mode corresponds to a form of unsteady motion in which the entire wake oscillates up and down, and a schematic of this motion is shown in Figure 4(b).



(a) base wall (b) nozzle sidewall

Figure 3: PSD comparison between exhaust jet off and NPR $= 349.5$



(a) streamwise velocity of $Sr_D = 0.12$ mode (b) schematic of $Sr_D = 0.12$ mode

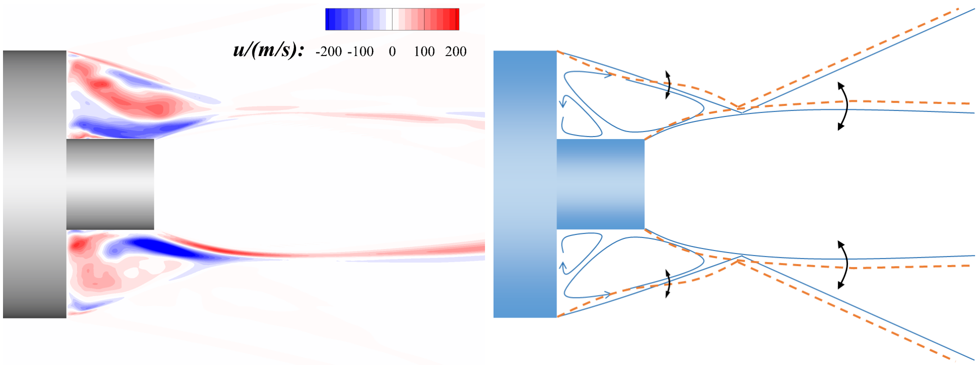
Figure 4: Visualization of DMD dominant mode for exhaust jet-off case

For the exhaust jet on, the wake region is occupied by the exhaust jet, and the wake oscillation motion as shown in Figure 4 must no longer exist but presents a new mode, shown in Figure 5. This dominant mode is symmetric, and the jet shear layer has a same-sign velocity distribution along the streamwise direction, which causes the exhaust jet diameter to expand and shrink periodically.

3.2 Effects of Exhaust Jet States

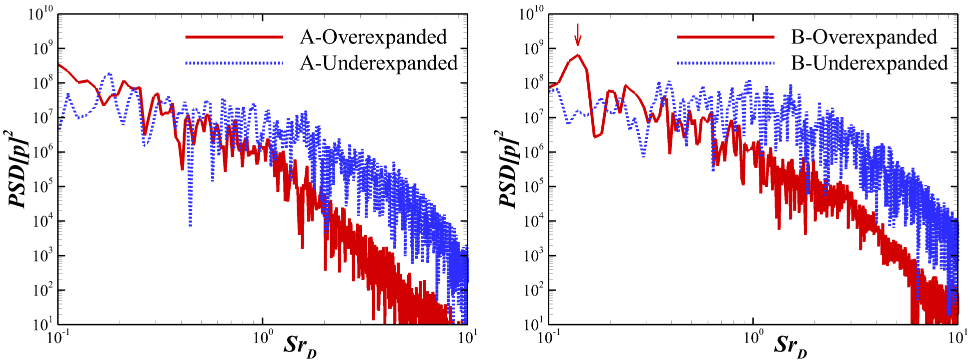
3.2.1 Underexpanded and Overexpanded States

NPR is the ratio of the jet total pressure to the ambient static pressure, which is one of the most critical parameters of the jet. Generally, the overexpanded exhaust jet can induce a flow separation inside the nozzle due to its lower total pressure. Figure 6 shows the PSD of pressure at the base wall and nozzle sidewall and compares them with the underexpanded jet case. Obviously, a decrease in NPR reduces the pressure fluctuation intensity in the high-frequency band ($Sr_D > 1$). The visualization of the dominant DMD mode is shown in Figure 7. In the overexpanded exhaust jet-on case, due to the flow separation in the nozzle, there is an apparent unsteady motion of the separation point, which is in the form of an antisymmetric back-and-forth movement. At the same time, this disturbance is transferred along the streamwise, leading to the exhaust jet oscillating soon after leaving the nozzle exit, which induces the change of the vortices in the base separation region.



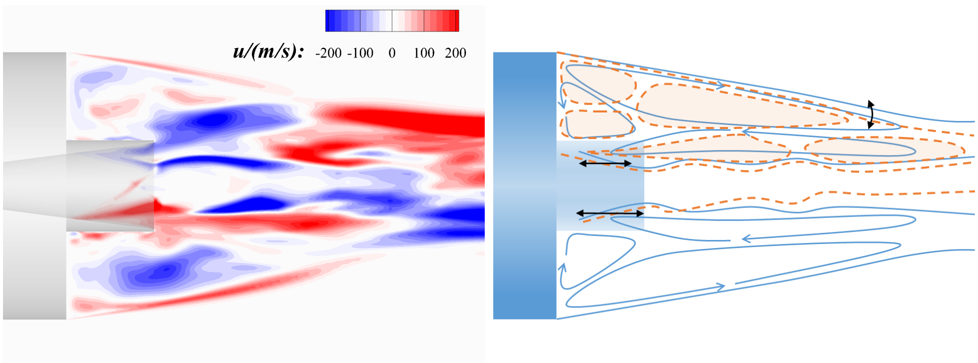
(a) streamwise velocity of $Sr_D = 0.16$ mode (b) schematic of $Sr_D = 0.16$ mode

Figure 5: Visualization of DMD dominant mode for exhaust jet NPR $= 349.5$



(a) base wall (b) nozzle sidewall

Figure 6: PSD comparison between overexpanded and underexpanded exhaust jet

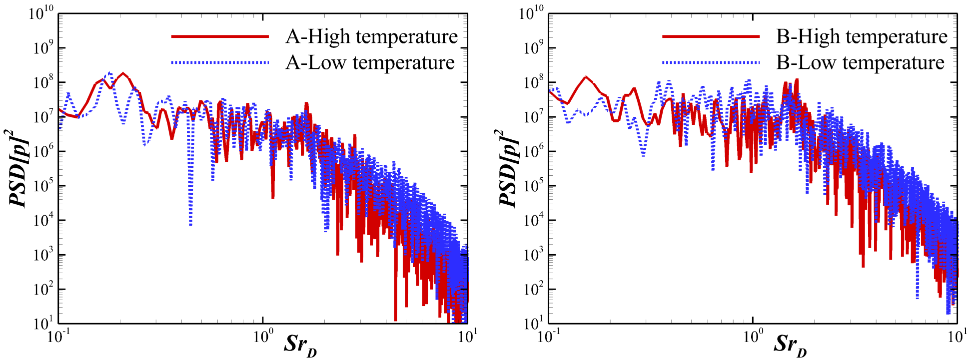


(a) streamwise velocity of $Sr_D = 0.13$ mode (b) schematic of $Sr_D = 0.13$ mode

Figure 7: Visualization of DMD dominant mode for overexpanded exhaust jet

3.2.2 Low and High Temperature

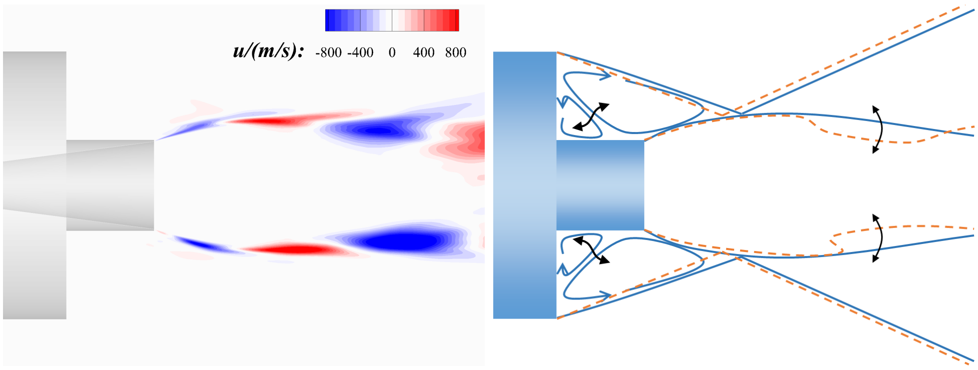
The PSD results for the wall points at the base are shown in Figure 8. It can be found that the amplitudes are the same as those with a low-temperature exhaust jet, which suggests that the high-temperature exhaust jet has no effect on the unsteady characteristics of the walls. But the high temperature induces a new unsteady motion. Figure 9 shows the visualization of the dominant DMD mode corresponding to $Sr_D = 1.55$. This mode is symmetric, and the velocity extremums are arranged at the edge of the exhaust jet in the form of positive and negative phases, indicating that the exhaust jet shear layer undergoes a high-frequency flapping motion.



(a) base wall

(b) nozzle sidewall

Figure 8: PSD comparison between high-temperature and low-temperature exhaust jet



(a) streamwise velocity of $Sr_D = 1.55$ mode

(b) schematic of $Sr_D = 1.55$ mode

Figure 9: Visualization of DMD dominant mode for high-temperature exhaust jet

4 Conclusion

In this paper, unsteady numerical simulations based on DDES (Delayed Detached Eddy Simulation) are carried out for the supersonic base flow. Using the PSD (Power Spectrum Density) and DMD (Dynamin Mode Decomposition) methods, the dominant modes of the whole flow field, and the fluctuation intensity are compared. The presence of exhaust jet and the effects of nozzle pressure ratio (NPR) and jet temperature on the unsteady characteristics of the base flow are investigated, and the following conclusions were obtained:

- Compared with the exhaust jet-off case, the underexpanded exhaust jet increases the wall pressure fluctuation intensity in the high-frequency band ($Sr_D > 0.5$). Meanwhile, the dominant mode of the base flow changes from wake oscillation ($Sr_D = 0.12$) to a periodic expand-shrink of the exhaust jet diameter ($Sr_D = 0.16$).
- Compared with the underexpanded exhaust jet at high NPR, the overexpanded exhaust jet reduces the pressure fluctuation intensity in the high-frequency band ($Sr_D > 1.0$). The oscillation of the exhaust jet induced by the back-and-forth movement of the separation point in the nozzle is the dominant mode of the flow field ($Sr_D = 0.13$).
- Compared with the low-temperature exhaust jet, the high-temperature exhaust jet has no apparent change in the base wall pressure fluctuation. The high-frequency flapping motion of the exhaust jet shear layer is the dominant mode ($Sr_D = 1.55$).

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