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EXPERIMENTAL INVESTIGATION OF LATERAL PULSE JET INTERACTION FLOWFIELD IN HYPERSONIC FLOW

Zh.-Y. Ni*, N. Cao*, L. Xu*
***China Academy of Aerospace Aerodynamics, Beijing, China**

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Abstract

Reaction control engines set up laterally in a vehicle and operate in a pulse mode. When the engine is working, it includes the startup process and the shutoff process in which the jet interaction flowfield is unsteady. Compared to most of the existing work focusing on the flowfield characteristics of steady jet interaction, the characteristics of unsteady jet interaction induced by a pulse jet of an engine are rarely investigated, especially for hypersonic flow conditions. In present work an experimental method was developed to research the characteristics of unsteady flowfields induced by a pulse jet. The process of unsteady jet interaction flowfields during startup and shutoff interval was clearly visualized by a high-speed schlieren technique and the fluctuating pressures were obtained. The comparison of unsteady numerical and experimental results agreed well each other. The research is valuable and important to further investigate the effects of unsteady jet interaction.

1 Introduction

Jets in cross flow belong to classical flows that are found in many engineering applications, such as reaction control jets in rockets and missiles. When a sonic or supersonic jet is injected laterally into supersonic or hypersonic free stream, the complex jet interactive flowfield is generated which involves complex flow structures such as shock/boundary layer interaction, multi-shock interaction, flow separation vortices and flow reattachment, etc. Fig.1 shows typical three-dimensional structure of lateral jet interaction flowfield. The attitude control jets can interact with the oncoming flow besides providing thrust for the vehicles, interaction between jet and oncoming flow results in change of the surface pressure distribution, produces additional jet interaction force and moment and affects aerodynamic characteristics.

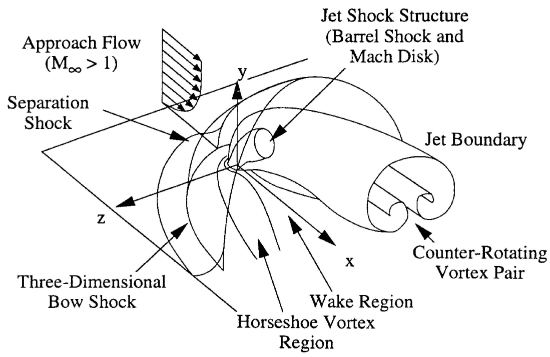


Fig. 1. Three-Dimensional Structure Diagram of Lateral Jet Interaction Flowfield

Over the last several decades, many experimental and computational investigations of jet interaction had been done [1~9]. Most of the existing works were focusing on the flowfield characteristics of steady jet interaction. The flowfield characteristics of unsteady jet interaction had been rarely investigated. The reaction engines set up laterally in the vehicles and operate in a pulse mode. There are certain differences between the flowfield characteristics of unsteady jet interaction and the flowfield characteristics of steady jet interaction. It has practical significance to study the characteristics of unsteady jet interaction.

In present work an experimental method was developed to research the characteristics of unsteady flowfields induced by a pulse jet. The process of unsteady jet interaction flowfields was clearly visualized by a high-speed schlieren technique and the fluctuating pressures were obtained during startup and shutoff interval. Experimental data provided a reliable basis for the verification of unsteady numerical method. And the comparison of unsteady numerical and experimental results agreed well each other. The research is valuable and important to further investigate the effects of unsteady jet interaction.

2 Experimental Procedure

2.1 Wind Tunnel

The experiment was performed in FD-07 hypersonic wind tunnel of China Academy of Aerospace Aerodynamics (CAAA). FD-07 hypersonic wind tunnel is a blowdown wind tunnel, as shown in Fig.2. The diameter of axis symmetrical nozzle exit is Φ500mm. Mach number is designed from 5 to 8. There is a Φ350mm optical glass window at the side wall of the test section for color schlieren device. The test was under conditions of Mach number 8, Reynolds number Re = 1.1×10^7/m.

Fig. 2. FD-07 Hypersonic Wind Tunnel

2.2 Test Model and Test Instrumentation

The test model was a kind of a wedge with an air engine set up at the base (as shown in Fig.3). The engine could produce a pulse air jet at a different interval. The total length of the three dimensional wedge was 300mm. The length of straight section of upper surface was 50mm. The dimensions of the model base were 100mm (height) × 100mm (width). A real pulse jet was placed at the base of test model. The distance between jet nozzle exit and upper surface of the three dimensional wedge was 30mm. Fig.4 showed the model set-up in FD-07 wind tunnel and the angle of attack is 0°.

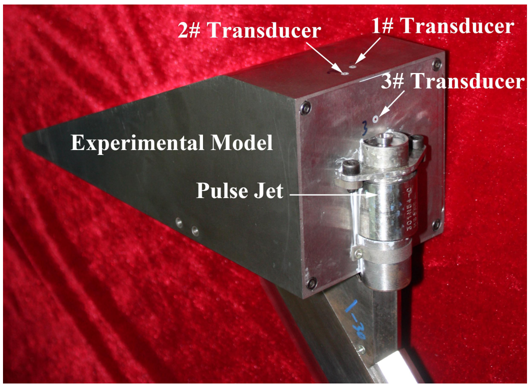


Fig. 3. Test Model with Pulse Jet Engine

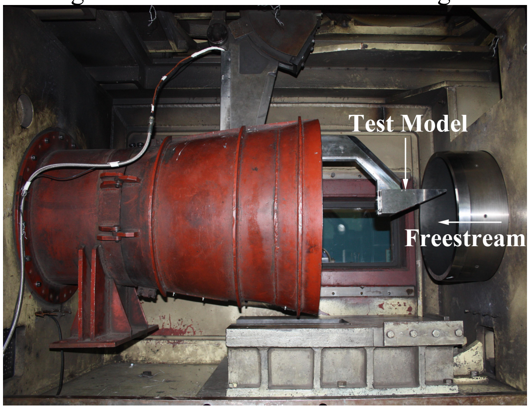


Fig. 4. Model Setup in FD-07 Wind Tunnel

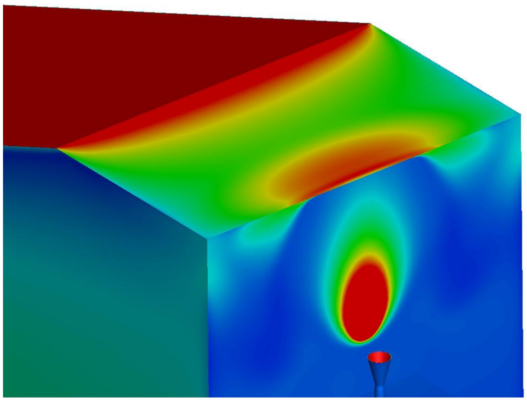
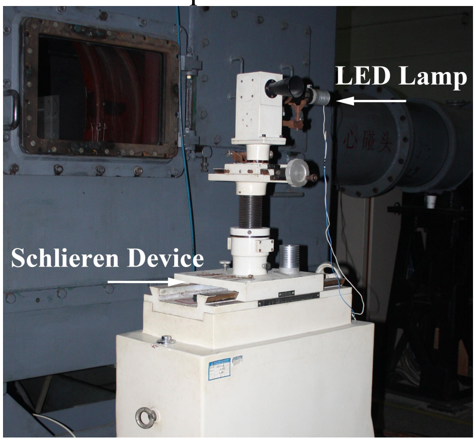


Fig. 5. Surface Pressure Contour of Jet Interaction

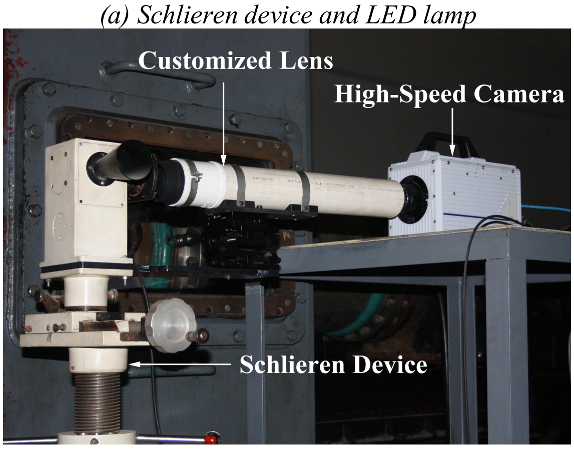
The jet interaction flowfield of the model is estimated by the numerical simulation, as shown in Fig. 5. Three Kulite XCL-100 fluctuating pressure transducers are employed for fluctuating pressure measurement, which are flush-mounted with the surface of model within the region of jet interaction (as shown in Fig.3). The fluctuating pressure process of jet interaction between the startup and shutdown interval of the engine can be measured.

A high-speed schlieren technique was developed to catch the process of the unsteady jet interaction between the jet startup and shutoff. Fig.6 showed the established high-speed schlieren system, which consisted of schlieren device (FD-07 wind tunnel), high-speed camera (Photron SA5), customized lens, LED lamp and computer, etc. By improving the light path and elevating the light luminance of schlieren system in FD-07 hypersonic wind tunnel, clear schlieren photos with 5000 frames per second were obtained successfully. Other parameters of high-speed camera were set as following:

- Photo frame:1024 pixels ×1024 pixels;
- Sustained acquisition time: 2 seconds



(a) Schlieren device and LED lamp



(b) High-speed camera and customized lens

Fig. 6. High-Speed Schlieren SyStem

2.3 Test Conditions

The experimental freestream conditions were given in Table 1. The experimental jet conditions were given in Table 2. The experimental test runs were repeated two times in order to get creditable results.

Table 1 Freestream Conditions

M_∞	P_0 (MPa)	T_0 (K)	Re/m ($\times10^7$)
8	5.0	750	1.1

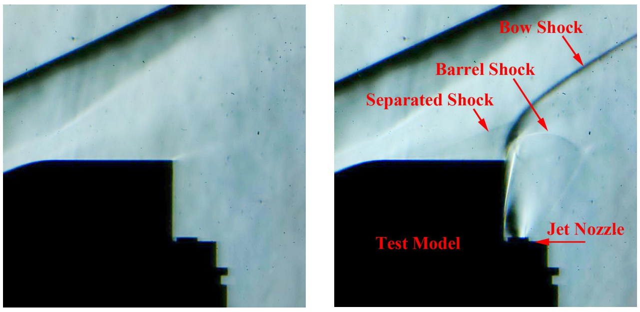
Table 2 Jet Conditions

M_j	P_{0j} (MPa)	T_{0j} (K)	$t_{startup}/t_{shutoff}$ (ms)
4.12	3.1	293	70/70

3 Results and Discussions

3.1 Results of High-Speed Schlieren

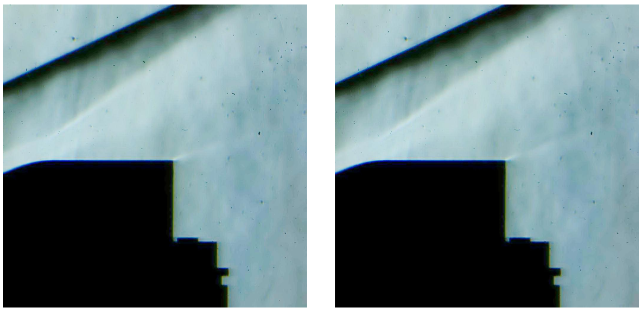
The comparison of high-speed schlieren photos at non-working and steady-working state was shown in Fig.7. The schlieren photo clearly visualized the shock wave structure of jet interaction, such as separated shock wave, bow shock wave and jet barrel shock wave, etc.



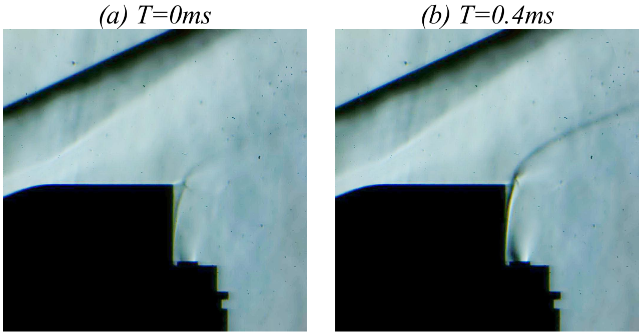
(a) Non-working state *(b) Steady-working state*

Fig. 7. Comparison of High-Speed Schlieren Photo at Non-Working and Steady-Working State

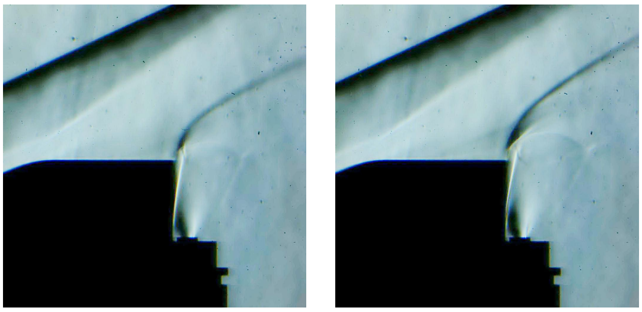
The unsteady flow process induced by pulse jet during startup and shutoff interval in hypersonic flow was visualized by the high-speed schlieren technique. High-speed schlieren photos at different pulse-working time of startup process were shown in Fig. 8. The interval between the pictures was 0.4ms. Jet interaction flowfield evolved and established within 2ms.



(a) T=0ms *(b) T=0.4ms*



(c) T=0.8ms *(d) T=1.2ms*



(e) T=1.6ms *(f) T=2.0ms*

Fig.8 High-speed schlieren photo at different pulse-working time of startup process

3.2 Results of Fluctuating Pressure

Experimental data of fluctuating pressure with the time during startup process and shutoff process are obtained, which can reflect unsteady characteristics of pulse jet interaction, as shown in Fig. 9. 3# transducer is located near the nozzle exit. The measured pressure is very low when pulse jet is shutoff. The measured pressure changes obviously when pulse jet is startup. The measured fluctuating pressure is affected by the pulse jet directly. 1# transducer and 2# transducer are located on the upper surface of the test model. The measured fluctuating pressure is affected by the interaction of freestream and pulse jet.

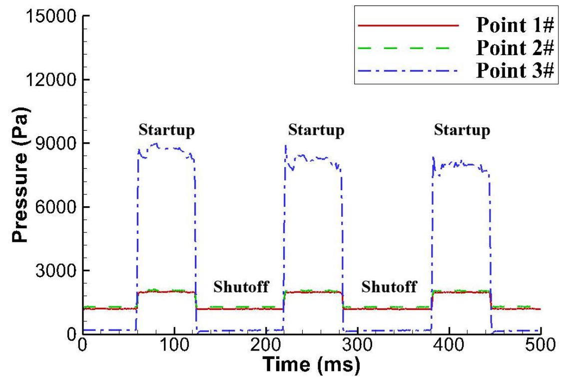
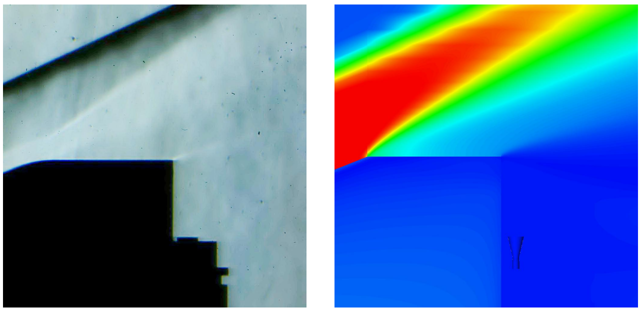


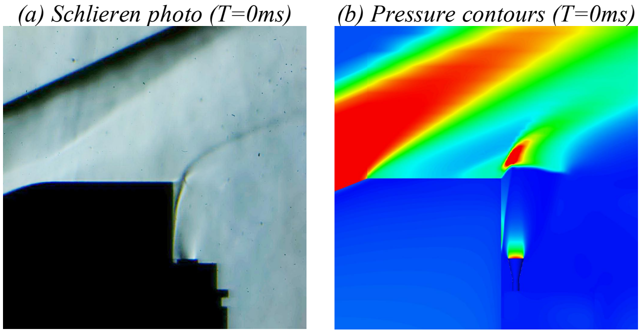
Fig. 9. Experimental Data of Fluctuating Pressure

3.3 Comparison of Numerical and Experimental Results

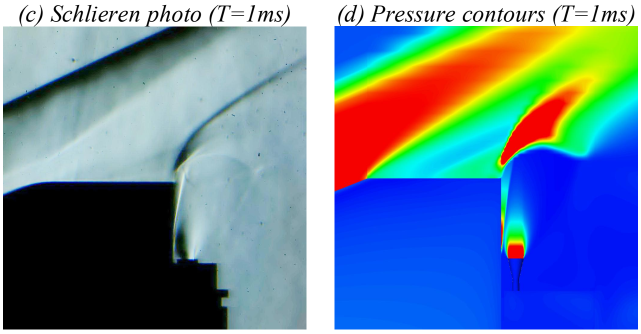
An unsteady numerical method was also developed to simulate the unsteady jet interaction process during startup and shutoff interval in hypersonic flow. And the comparison of unsteady numerical and experimental results at different pulse-working time was also accomplished and agreed well each other, as shown in Fig.10.



(a) Schlieren photo (T=0ms) *(b) Pressure contours (T=0ms)*



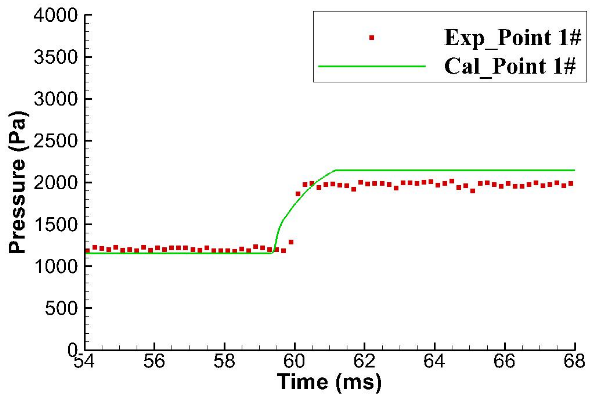
(c) Schlieren photo (T=1ms) *(d) Pressure contours (T=1ms)*



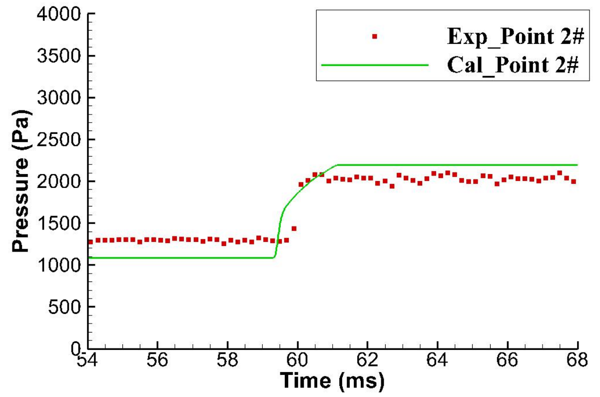
(e) Schlieren photo (T=2ms) *(f) Pressure contours (T=2ms)*

Fig. 10. Comparison of Numerical and Experimental Results at Different Pulse-Working Time

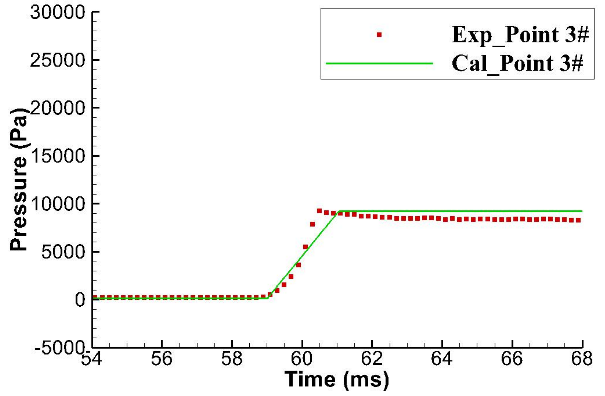
Experimental data of fluctuating pressure induced by pulse jet interaction provide a reliable basis for the verification of unsteady numerical method. Fig. 11 and Fig. 12 show the comparison of numerical results and experimental results when pulse jet is in start-up process and shutoff process. Unsteady numerical results are in well agreement with experimental results.



a) *pressure* comparison *at point 1*

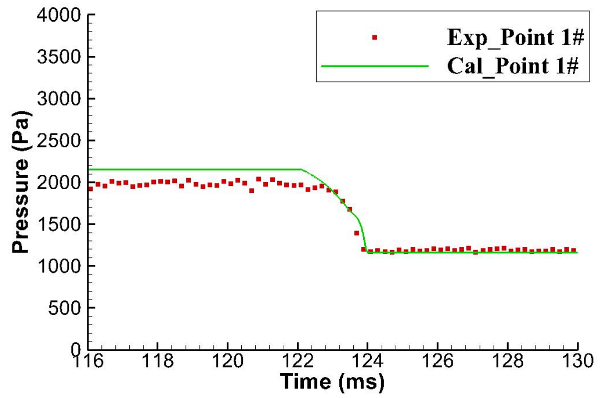


b) *pressure* comparison *at point 2*

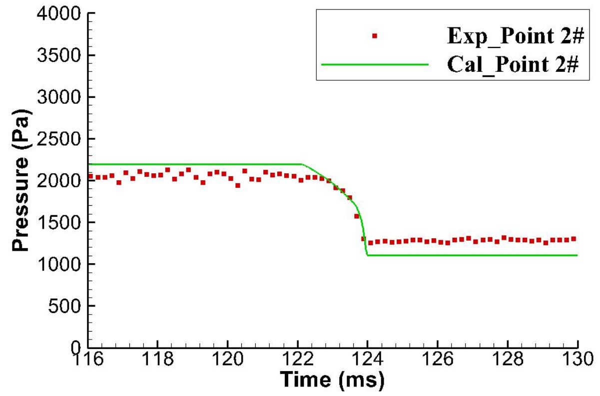


c) *pressure* comparison *at point 3*

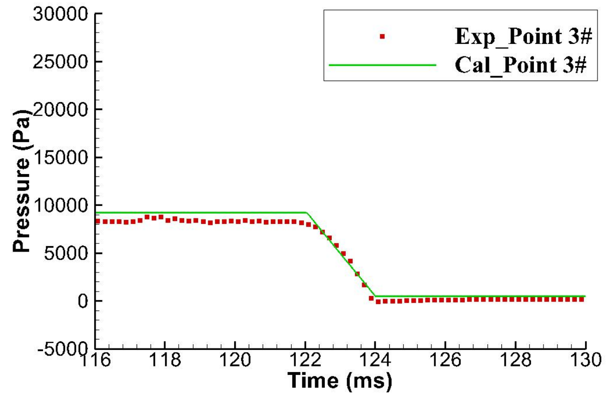
Fig. 11. Pressure Comparison at Start-up Process



a) *pressure* comparison *at point 1*



b) *pressure* comparison *at point 2*



c) *pressure* comparison *at point 3*

Fig. 12. Pressure Comparison at Shutoff Process

4 Conclusions

In this paper an experimental method was developed to study the characteristics of unsteady flowfields induced by a pulse jet in hypersonic flow. The process of unsteady jet interaction flowfields was clearly visualized by a high-speed schlieren technique and the fluctuating pressures were obtained during startup and shutoff interval with a air engine. And the comparison of unsteady numerical and experimental results agreed well each other. The research is valuable and important to further study the effects of unsteady jet interaction.

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5 Contact Author Email Address

nzhaoy@vip.sina.com

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