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Experimental study on the flow separation and self-excited oscillation phenomenon in a rectangular duct

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ABSTRACT

To study the characteristics of flow separation and self-excited oscillation of a shock train in a rectangular duct, a simple test case has been conducted and analyzed. The high-speed Schlieren technique and high-frequency pressure measurements have been adopted to collect the data. The experimental results show that there are two separation modes in the duct under M3 incoming condition. The separation mode switch has great effects on the flow effects, such as the pressure distribution, the standard deviation distribution and so on. The separation mode switch can be judged by the history of pressure standard deviation. When it comes to the self-excited oscillation of a shock train, the frequency contents in the undisturbed region, the intermittent region, and the separated bubble have been compared. It was found that the low-frequency disturbance induced by the upstream shock foot motions can travel downstream and the frequency will be magnified by the separation bubble. The oscillation of the small shock foot and the oscillation of the large shock foot are associated with each other rather than oscillating independently.

1. Introduction

The isolator is a key component for an air-breathing scramjet, which plays a significant role in preventing the interactions between the combustor and the inlet [1]. Under the high back-pressure condition induced by the combustion, the boundary layer in the isolator will be separated and the typical shock train (or pseudo shock) will form in the isolator [2]. Commonly, the isolator is simplified to be a rectangular duct in the research.

In recent years, much research has been done to study the characteristics of the shock train and much has been learnt about it, such as the length [3], the fine structure [4,5], the self-excited oscillation of a shock train [6,7], and so on. Matsuo [8] and Gnani [9] have reviewed the previous research in 1999 and 2016.

Flow separation induced by back-pressure is a prevalent phenomenon in a scramjet isolator. The asymmetric separation often occurs in the isolator under high back-pressure condition [10,11], which has significant effects on the quantity of the outflow of the isolator. The asymmetric separation phenomena have been found in some other devices, such as the convergent-divergent nozzle which works under the over-expanded condition [12]. Papamoschou et al. [12,13]made pressure measurements and found that there was a low-frequency, piston-like unsteady shock motion. After that, Johnson et al. [14] made some new studies based on the previous work and they found that the unsteadiness of the shock motion was coupled to enhanced shear layer instability.

What is more, the flow separation mode may switch in the isolator, which has ever been observed in previous experiments [15]. When it comes to the separation mode switch, Yu et al. [16] studied the separation mode switch in an over-expanded single expansion ramp nozzle. They found that the separation patterns changed between the restricted shock separation and the free shock separation during the startup process. The separation mode switch has never been discussed in an isolator, especially the effects of the separation mode switch on the flow characteristics. Actually, it is very important to know and even predict the separation mode switch in an isolator.

In addition, the self-excited oscillation of a shock train is also a main problem in an isolator [17–19]. The self-excited oscillation means that the shock train keeps moving back and forth without any external excitations. The motion of the shock train is coupled with the pressure fluctuations which may generate noise or fluctuated wall loads. In previous studies, many researchers have studied this phenomenon. Yamane et al. [20] measured the pressure at several locations to determine the correlation coefficient and the coherence between them and they found that the upstream turbulent disturbance is the source of the high-frequency oscillation. Sugiyama et al. [21]

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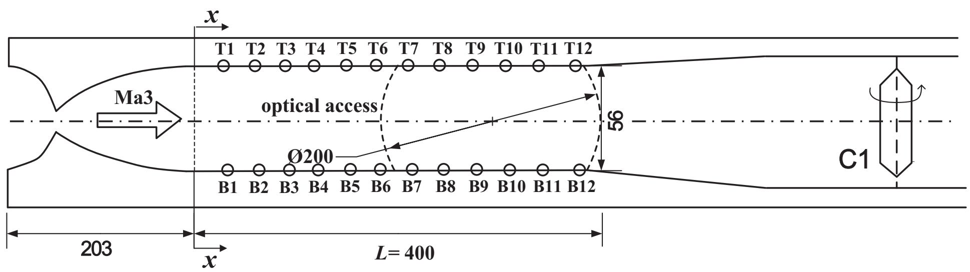

Fig. 1. Schematic diagram of the wind tunnel.

concluded that the source of the self-excited oscillation is in the shock train region. However, the mechanism behind the shock train oscillation remains still unclear.

The main aim of this paper is to examine the separation mode switch in a rectangular duct and the effects it brings to the flow fields, such as the pressure distribution, the self-excited oscillation of shock train, and so on. In addition, the characteristics of shock train oscillation have been analyzed for two separation modes. It is hoped that the experimental phenomenon will have inspiration on the future research.

2. Experimental facility and data acquisition

2.1. Experimental facility

The experiments presented in this paper are conducted in a continuous supersonic wind tunnel of NUDT (National University of Defense Technology) Scramjet Laboratory. The Schematic diagram of the wind tunnel is illustrated in Fig. 1. The atmospheric air passes through a 2-dimensional Mach 3 nozzle designed with viscous correction. The test section is a rectangular duct with the cross section 120 mm wide and 56 mm high. The total length of the test section is 400 mm. The reference location x=0 is defined as the inlet of the test section and x is the distance between the local position and the inlet of the duct, as shown in Fig. 1. In the side of the rectangular duct, the optical window is opened. It is shown in Fig. 1 as the dashed circle. In the downstream of the test section, a throttling device is equipped and the throttling effects are generated by a throttling valve, as presented C1 in Fig. 1. The valve is controlled by an actuating motor, thus leading that the throttling ratio and the turning speed is adjustable. The throttling ratio (TR) is defined as following:

$$\mathrm{TR} = A_{th}/A_{duct} \tag{1}$$

where A_{th} means the throttling area caused by the Butterfly Valve and A_{duct} means the cross area of the test section. During each test, the throttling ratio (TR) can be set to any value between 0% (Butterfly Valve is parallel to the flow direction) and 52.14% (Butterfly Valve is perpendicular to the flow direction). The Butterfly Valve is controlled by a type of servo motor, which has a feedback system. Thank to the feedback system, the movement of the Butterfly Valve can be controlled precisely. Thus, the real-time throttling ratio is known. By keeping the constant throttling ratio, a steady back-pressure condition will be generated in the downstream of the test section and then the shock train can form in the duct. A huge vacuum container is equipped in the outlet of the wind tunnel. In our experiment, the stagnation pressure of the incoming flow is 1 atm ± 0.5 kpa, and the stagnation temperature is 288 K ± 1.5 K.

2.2. Data collection

The structure of the shock train in the duct is captured by the high-speed Schlieren images. The window shown in Fig. 1 provides the optical access for Schlieren visualization. During the test, high-speed images are captured using a Photron Fastcam SA5 high-speed camera fitted with a 105 mm lens at a frame rate of 1000 Hz and a resolution of 768×512 pixels sensitivity. The light source used in our experiments is a constant one and the exposure time of the camera is chosen as 1/1000 s.

Along with the Schlieren visualization, the high-frequency pressure measurements were adopted. The pressure measurements were made by 24 high-frequency transducers labeled with T1–T12 for the top wall and B1–B12 for the bottom wall. The 12 top transducers are located equidistantly along a line displaced by 10 mm from the median plane and the 12 bottom transducers are located equidistantly along the center line. These pressure transducers are all piezo-electric type. The measuring range of each transducer is 0–100 kpa, and the overload pressure is 200% F.S (full scale). The temperature shift below 0.05% F.S/K, and the comprehensive accuracy is ± 0.8% F.S. For the data acquisition, the anti-aliasing filter has been adopted to cut off the frequencies which are higher than 1/2 the sample frequency. The locations of the 24 transducers are presented in Table1. The pressure signals were all sampled at a rate of 5 kHz.

3. Experimental results

3.1. The switch of flow separation mode

In the internal duct flow, the structure of the shock train will become asymmetric when the incoming Mach number is high. That is to say, the large scale separation of the boundary layer occurs on one side of the duct (the top wall or the bottom wall), and the small scale separation occurs on the other side. The asymmetric flow separation phenomena in a symmetric duct have been observed by many researchers in experiments or CFD. In our experiments, the switch of flow separation mode has been observed and the effects bought by the separation mode switch will be analyzed.

In one test case, the TR is set to change as the Fig. 2 shown and the pressure histories of transducer T10 and B10 are also presented in Fig. 2. The wall pressure is non-dimensioned by the reference pressure p_{ref} which is 3 kpa. The theoretical static pressure (isentropic flow) at the outlet of the Ma3 nozzle is 2.76 kpa for total pressure 1 atm. So we choose 3 kpa, which is close to 2.76 kpa, as the reference pressure. At about t=2 s, the downstream valve steps to an angle and keeps constant, thus leading the shock train forms in the duct. After t=2 s, the downstream throttling ratio keeps constant. However the shock train begins to self-excited oscillated in the duct, and the wall pressure thus fluctuates violently. It can be obviously seen that the mode of the pressure fluctuations changes at about t=2.850 s. During the phase 1, the pressure at the top wall T10 fluctuates more violently than the

Table1
The location of 24 transducers at top wall and bottom wall.

Transducer	**T1,B1**	**T2,B2**	**T3,B3**	**T4,B4**	**T5,B5**	**T6,B6**
***x*(mm)**	44	74	104	134	164	194
Transducer	T7,B7	T8,B8	T9,B9	T10,B10	T11,B11	T12,B12
***x*(mm)**	224	254	284	314	344	374