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Transient behavior of shock train with and without controlling

Zhi Chen [a,b,*], Shi he Yi [a], Noor A. Ahmed [b], Xiao ping Kong [a], Peng cheng Quan [a]

[a] College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia

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ABSTRACT

The present paper is a study of the transient behavior of shock train in a constant area isolator with and without controlling method. Two kinds of vortex generators were installed and tested. Planar laser scattering technique was performed to study the three dimensional structure of the shock train and its temporal evolution. High frequency pressure measurements were conducted to reveal the shock train movement and its frequency-domain feature. Three states of the shock train during its formation and movement were revealed based on the wavelet decomposition. The shock train location and its movements were detected by method of integral of pressure derivative and wavelet decomposition. And based on the comparison of the flow structures, shock train movements and the pressure recovery effect, a recommendation of applying passive control method for the isolator was proposed.

1. Introduction

After the concept of hypersonic flight was proposed in the 1950s in order to realize the single-stage-to-orbit with the range of Mach number from supersonic to hypersonic, the air breathing propulsion technique was taken seriously. A dual mode scramjet engine proposed by Curran and Stull in 1964 was supposed to be the most promising propulsion system for hypersonic flight [1]. It is able to operate initially as a subsonic-burning conventional ramjet at incoming flow Mach 3–5, and subsequently transit to supersonic combustion operation at a speed higher than Mach 5. To bring a primary scramjet into real application, basically components are needed such as the inlet, fuel-injection system, combustor and exhaust nozzle [2]. Normally the freestream air would be pre-compressed in the inlet before entering the combustor and mixing with the fuel, while the combustion occurs in a supersonic stream and finally the burned stream would expand and pushed out into the discharge environment. However, one key component, which is essentially needed and especially for low supersonic Mach number operation, is the isolator [2]. The isolator, which connects the inlet with the combustion chamber in the engine, plays an important role of providing additional compression and protecting the inlet flow from disturbance of adverse backpressure of combustion downstream.

Intensive shock waves/boundary layer interaction occurs in the isolator when the dual mode engine is under ramjet operation. Multiple shock waves and disturbed boundary layer consist of the complex pre-combustion shock system which decelerates the flow to subsonic, namely the shock train [3]. Actually similar multiple shock waves phenomenon appears not only in the isolator but also in ducts [4]. However, according to different entering conditions and exit conditions of the isolator, such as Mach number, pressure ratio and asymmetric boundary condition, the shock train can be a series of normal shock waves or a series of intercross oblique shock waves depended on the incoming flow Mach number and the thickness of the boundary layer in the isolator [5]. The compressed air can be adjusted in the isolator by the shock train to match the entering condition of the combustor. When the reverse pressure from the combustor rises, the shock train can adjust and balance the variation of the pressure between the isolator and the combustor by increasing its length.

Evidently the pressure ratio of the entrance pressure vs the exit pressure of the isolator is one of the important features. Given a certain isolator, the theoretical maximum pressure ratio, or in other words the theoretical maximum reverse pressure, can be evaluated by one dimensional normal shock wave equations assuming the shock train as a pseudo-shock. However the real maximum pressure ratio which the isolator can endure is lower than the theoretical evaluation. Notice that a higher and fluctuating reverse pressure may be caused by the inhomogeneous combustion downstream of the isolator, which would push the shock train upstream. But if the reverse pressure is higher than the maximum value, the shock train may be disgorged out of the inlet resulting in a detached bow shock upstream of the inlet and the engine unstart. Thus the engine unstart should be seriously

* Corresponding author at: College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China.

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considered when designing the isolator, because it would cause serious failure during the high speed flight [6–8]. Other parameters, such as the length of shock-train, unsteadiness and the total pressure loss, are in some extent responsible for the efficiency and performance of the engine [9–13].

Locating the leading edge of the shock train, detection of unstart and controlling the engine operation are very important to the success of the flight. Researches focusing on this issue have shown great progress [14–21]. Wagner et al. [14,15] used schlieren and high frequency pressure sensors to investigated the unstart feature in an inlet/isolator model. The shock train speed moving upstream to the inlet was measured and a high amplitude oscillation was observed when unstart occurred. PIV measurement was performed to reveal the velocity field of the unstart flow and large regions of separated flow appeared at the exit and the ceiling of the isolator. Unstart detection criteria were studied by Srikant et al. [16] including the increase in pressure, standard deviation and power spectral density. Donbar et al. [17,18] proposed another criteria that was the increase in the summation of the pressure, and 150% increase in pressure, standard deviation and power spectral density as the threshold value were selected to detect the unstart. However, Pettinari et al. [19] proposed a special method to detect unstart by processing only the flight control system data, without relying on engine data or measurement of the airflow across the isolator, which possessed a certain degree of robustness. A CUSUM algorithm was proposed by Chang et al. [20] and compared with the former algorithms. Applied to a carefully selected pressure sensor, this algorithm could eliminate the false detections. Flow structures including the shock train and the separated turbulent boundary layer were revealed by Zhi et al. [21] performing planar laser scattering. The visualization showed agreement with the pressure distribution. The shock train leading edge detection is quite important for monitoring the engine state and controlling the engine operation [22–27]. For the isolator controlling strategy, Valdivia et al. [28] employed active and passive vortex generators to apply a closed-loop control scheme, and set a threshold value to detect the unstart.

Although considerable work has been performed, the dynamics of the shock train and how the passive control strategy affects its behavior is an area still not very well understood. The present paper is to reveal the transient behavior of multiple shock/boundary layer interactions in a constant area isolator with and without controlling method. Planar laser scattering technique and high frequency pressure measurement are performed. Three dimensional structure of the shock train is revealed and analyzed. By varying the time interval of the laser sheet, the temporal evolution of the shock train is linked to the feature of the pressure data to explain the transient flow phenomena. By performing wavelet analysis, three states of the shock train during its formation and movement are studied, and the dynamics of reverse pressure transferring in the boundary layer and how it affects the movement of the shock train are inspected and discussed. The shock train location is detected by method of integral of pressure derivative and wavelet decomposition. And based on these aspects, how the vortex generators affect the shock train are compared and analyzed.

2. Experimental setup

The experiments were carried out in an indraft supersonic wind tunnel, as shown in Fig. 1. In the direction pointed out by the arrows, gas passes through the whole wind tunnel from the gas inlet to the vacuum chamber at the rear. The wind tunnel is installed with visualization system. More detailed information is shown in Fig. 2. The isolator (Part 4), which is 380 mm long and designed as a rectangular duct with a 100 mm × 40 mm constant

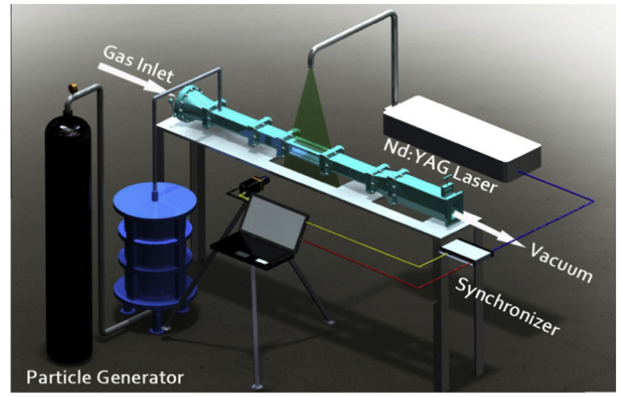

Fig. 1. Supersonic wind tunnel equipped with flow visualization system for the isolator testing.

cross-section, is furnished with 3 optical glasses on the top and side walls. To avoid the intensive scattering light of the incident laser sheet on the surface of the bottom wall and the convenience to drill pressure orifices, a high-class organic glass base is selected as the bottom wall of the isolator. A Laval nozzle (Part 3) designed by using B-Spline curve to control the Mach number distribution along the centre line [29], is installed upstream of the isolator to generate uniform supersonic flow. Limited by the precision of the boundary layer modification, the calibrated Mach number is 2.45, while it was designed and supposed to be 2.5. To stabilize and seed the incoming flow from the inlet (Part 1) before it entering the nozzle (Part 3), a settling chamber (Part 2) is used. A divergent section of 5 degree expansion angle (Part 5) and a diffuser (Part 6) are designed for pressure recovery and to connect with the duct (Part 7) which leads the flow to the vacuum chamber. The blockage adjustor (Part 8) installed at the rear is a throttle plate to choke the flow and to reproduce the complex shock-train structures in the real engine. A rake of Pitot tubes (Part 10) is used for verifying the total pressure loss. Two different shape vortex generators (Part 9) used for flow controlling are mounted respectively at the exit of the nozzle. As shown in Fig. 3, the trapezium shape vortex generator (T-control for short)is designed as $W = 35$ mm, $D = 20$ mm, $\beta = 20°$, $\gamma = 10°$, while the parameters for the delta shape vortex generator (D-control for short) are $h = 4$ mm, $c = 7.2$ h, $\alpha = 24°$. Two trapezium shape vortex generators are installed on the side walls upstream the optical access, while three delta shape vortex generators are configured on the bottom of the isolator, as shown in Fig. 4. However, to compare flow field of these two types of controlling method, they are not installed together at the same time but respectively. Thus three different isolator flow fields would be presented including non-control, T-control and D-control.

Planar Laser Scattering is used as the flow visualization method, as shown in Fig. 1. A dual-cavity Nd: YAG pulsed laser (Beam Tech 500 Vlite) is used as the light source, which emits two laser beams of 6 ns pulse width according to the schedule set by a synchronizer. A light sheet, less than 1 mm thick, illuminates the testing flow field. Because of the excellent following ability, nanoparticles (nominal 20 nm TiO2) are employed as the tracer. They could follow supersonic flow faithfully and scatter laser light effectively, which results in high SNR flow field images. Nanoparticles are separated and injected into the settling chamber by the particle generator driven by a high pressure air tank. An interline transfer double-exposure CCD (Imperx 4M15), whose resolution is 2 K × 2 K with a shortest double-exposure interval of 0.2 μs, takes charge of imaging. The lag time of nano particles is about 251 ns and the Stokes Number is about 0.015 by the so-called oblique