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# Hysteresis phenomenon of shock train in an isolator with incident shocks

*Nan Li*[1], *Kejng Xu*[2], *Yanping Song*[3]

## Abstract

The behaviours of the shock train, associated with the separation flow within it, depend on not only the incoming flow conditions but also the characteristics of the boundary layer heavily. Understanding the sensitivity of the shock trains to the near-wall flow is also useful for controlling the movement of the shock train. The hysteresis characteristic of a shock train in an isolator has been investigated in a direct-connect wind tunnel. High-speed Schlieren imaging and high-resonance frequency pressure measurements were used to capture the flow features during the movement of the shock train. With the upstream movement of the shock train, the rapid movement of the shock train leading edge (STLE) can be observed near the shock wave-boundary layer interaction (SWBLI) region. To examine the bistability and route dependent behaviour of the shock train, the backpressure was driven to decrease along the same route it increases. The results indicate that with a same pressure ratio, the shock train leading edge could be either downstream or upstream of the SWBLI region. The hysteresis behaviour of the shock train was also confirmed.

**Keywords**: *hypersonic inlet/isolator; incident shocks; shock wave-boundary layer interactions; hysteresis*

## Nomenclature

p – static pressure

x – location of the shock train leading edge

*Subscripts*

0 – conditions of the incoming flow

## 1. Introduction

For inlet unstart detection and control, researchers have emphasized on the unstart process [1-4]. The essence of these investigations is ultimately to have a better understanding of the shock train behavior. Usually, the investigations of isolator flow are undertaken in a uniform condition, in which the flow parameters vary gradually along the tunnel and the movement of the unstart shock is considered as continuous. While the flow in a realistic inlet/isolator is very complex and far from two-dimensional. The inherent oblique shocks reflected from the compression surfaces result in a non-uniform flow field in a real isolator, especially in the streamwise boundary layer. Strong interactions exist between the shock wave and boundary layer, showing significant influences. Previous investigations have observed the rapid movement of the shock train in the SWBLI region. Due to the sudden change in the shock train position, namely catastrophe phenomenon, one should also concern the existence of the hysteresis behavior for a control purpose. It is very common in supersonic/hypersonic flow. Such as the start/unstart transition in a supersonic/hypersonic inlet [5], the mode transition in a dual-mode scramjet [6], and the RR-MR transition in shock reflection [7]. The current paper aims at uncovering the bistability of the STLE, examining the route dependent behavior of the shock train near the SWBLI region and proving the existence of the hysteresis phenomenon of the shock train with the influence of the incident shocks.

[1] *School of Energy Science and Engineering, No.92, West Da-Zhi Street, linan4489@stu.hit.edu.cn*
[2] *School of Energy Science and Engineering, No.92, West Da-Zhi Street, xukejing87@gmail.com*
[3] *School of Energy Science and Engineering, No.92, West Da-Zhi Street, songyanping@hit.edu.cn*

## 2. Experimental set-up

Two mechanical systems were needed to conduct these experiments: the test section and the flap mechanism. A wedge with an angle of 14° as a shock generator was mounted at the bottom of the wind tunnel as shown in Fig 1. A mechanical flap driven by a stepper motor was used to simulate the pressure rise in a combustor. At the beginning, the flap was fully up with an angle of 0°. When the flap was instructed to increase its angle to a certain value, the area of the exit decreased. Twenty high-frequency response pressure transducers with a range of 0 - 100 kPa and an effective frequency response of about 20 kHz were used. The transducers were mounted in a row with a spacing of 20 mm near the spanwise centerline of the test section. The distribution of the transducers is shown in Fig 1. The signals were recorded with a sampling frequency of 10 kHz and all subsequent data processing was performed on a PC. A Z-type Schlieren system was used in our research. The Schlieren images were captured by using a high-speed camera at a frame rate of 5000 fps with an exposure time of 200 µs and a resolution of 1280 × 300 pixels. The triggering signal was also recorded by the data acquisition system to obtain synchronization between the two measurement systems. Further details regarding the experimental apparatus and measurement methodology can be found in a previous study [8].

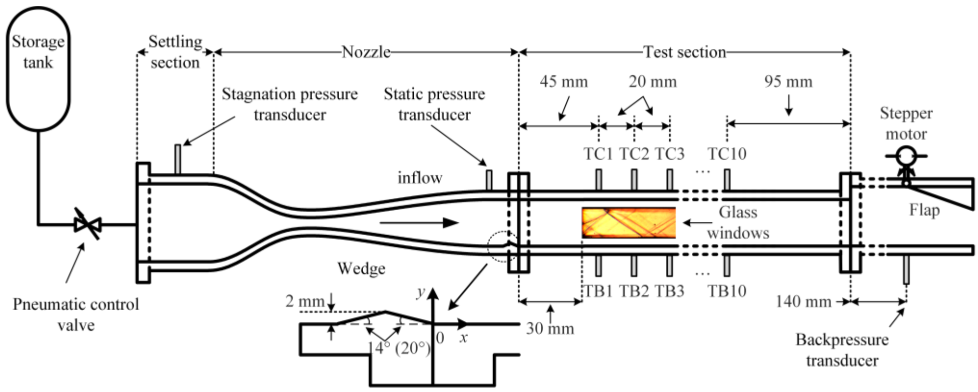


**Fig 1. Schematic of the model in the wind tunnel with instantaneous pressure measurements setup.**

## 3. Results

### 3.1. Unthrottled and throttled flow with incident shocks

Firstly, a brief description of the typical throttled flow fields with incident shocks will be given. In Fig 2, the incident shock, the reattachment shock and their reflected shocks form the complex oblique shocks. The incident shock (*i*) generated by the wedge impinges the ceiling, near the linkage of the wind tunnel and the test section. In Fig 2 (a), at top left a separation shock (*iii*) together with a reattachment shock (*iii'*) can be observed. From the shock patterns, it can be speculated that a separation bubble forms at impingement point due to the strong SWBLI. However, in the downstream, the separation shock merge with the reattachment shock. At bottom left of the image, a reattachment shock (*ii*) induced from the wedge can be observed, impinging at the ceiling of the duct close between the pressure transducer TC 3 and TC 4. Oblique shocks (*iv*) generated by the linkage in the test section can be observed clearly in Fig 2 (a), but at last they coalesce with the primary shocks downstream.

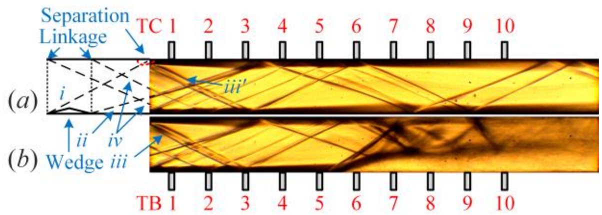


**Fig 2. Unthrottled and throttled flow fields in the test section (*i*: incident shock, *ii*: reattachment shock, *iii*: reflected shock of the incident shock.)**

For the unthrottled case as shown in Fig 2 (a), the wave structure indicates that the flow at the exit is supersonic. As we know, the adverse pressure gradient may induce the separation of the boundary layer, and if the scale of the separation is large enough, the shock train forms as shown in Fig 2 (b). With the separation proceeding upstream, the shock train also moves forward. In Fig 2 (b), a large separated region exists within the shock train. One can also notice that the STLEs and the separated regions at the two sides are obviously asymmetric. The separation shocks reflect between the shear layers along the core flow region. At this moment, the core flow deflects toward the top wall, where the separation is relative weak. While this asymmetry emerges in the entire process of the shock train movement and the core flow deflects to the two sides in turns.

### 3.2. Hysteresis bbehavior of the shock train with incident shocks

To simulate the reflected shocks in the isolator, wedges with different gradients are mounted at the entrance of the test section to generate incident shocks. Fig 3 (a) shows the time histories of the flap angles (right ordinate) and the backpressure (left ordinate) during the test. The backpressure signal is normalized by the static pressure. The flap is rotated to 12.6° slowly and paused for 0.5 s, then a ramp signal is triggered to rotate additional 3.78° in 1.27 s. After a stagnation for 0.5 s, the flap is then triggered to rotate back to its initial position. The trajectory of the STLE at the top wall is shown in Fig 3 (b). As the backpressure increases or decreases approximately linearly, the shock train exhibits different behaviours during the entire movement. For example, when the STLE approaches the first SWBLI region in the isolator at the top wall, the acceleration occurs. After that, the movement of the STLE turns gentle.

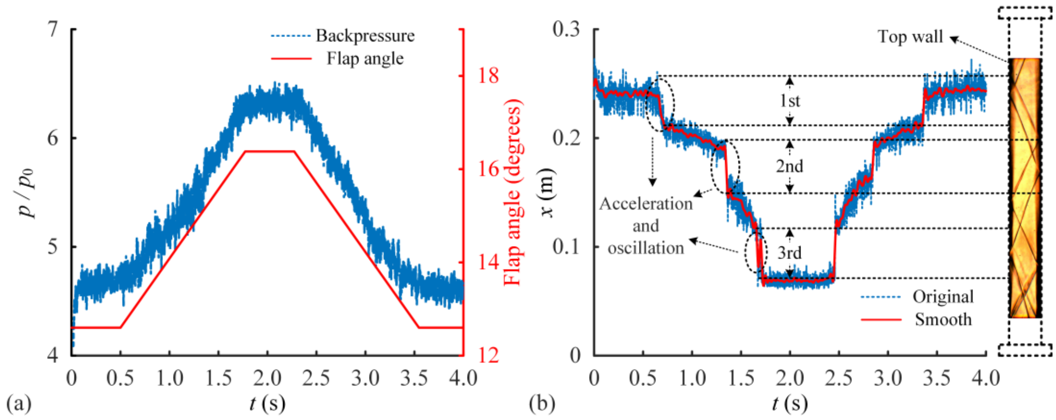


**Fig 3. (a) Backpressure and the flap angle histories; (b) Trajectory of the STLE at the top wall.**

The typical static pressure histories during this movement are plotted in Fig 4. The general trend of the pressure is nonmonotonic with oscillations, and the amplitudes and frequency characteristics are varying. As the shock train moves gently at the beginning, the pressure of TC 10 changes slowly. But when the acceleration occurs, for example at about $t$ = 0.67 s, the first separation shock sweeps the transducer TC 10 rapidly and a sudden rise emerges in the pressure signal.

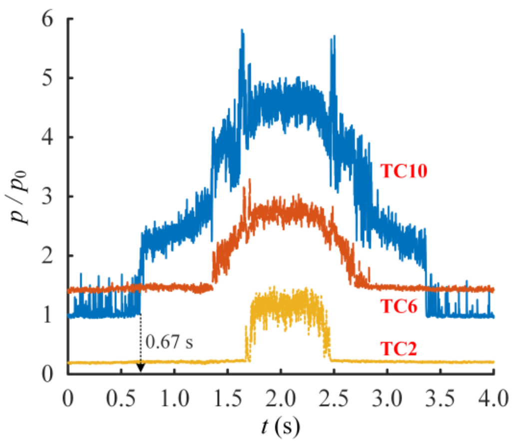


**Fig 4. Typical pressure histories during the test at the top wall.**

In Fig 5 we present the trajectories of STLE in the forward and backward movements. While in the backward movement, the pressure ratio, at which the acceleration occurs, is slightly smaller than those in the forward movement. From this phenomenon it can be concluded that once the STLE stabilizes upstream of the SWBLI region, decreasing the backpressure to the value which makes the acceleration occur could not drive the shock train backward to the downstream of the SWBLI region.

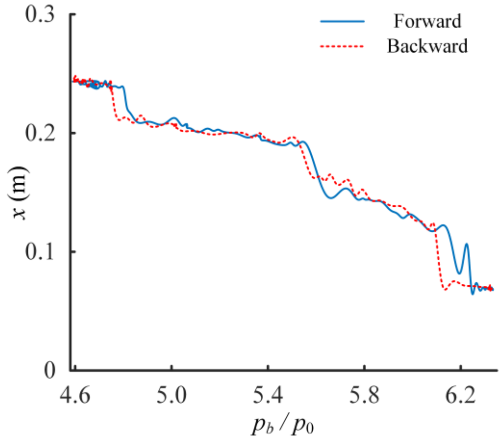


**Fig 5. Comparison of the STLE trajectories in the forward and backward movements.**

## 4. Conclusion

Experimental investigation has been performed to uncover the hysteresis behavior of the shock train with the influence of incident shocks. With a linear increasing backpressure, the STLE exhibits a rapid movement near the SWBLI region, and the wall pressures also have a sudden rise. While the backpressure decreases along the same route, the STLE does not follow the initial path it moves forward. The catastrophe phenomenon, bistability and the route dependent behavior together form the necessary conditions for the hysteresis loop.

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