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Unsteady behavior of oblique shock train and boundary layer interactions

Chengpeng Wang, Chuan Cheng, Keming Cheng, Longsheng Xue

Department of Aerodynamics, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, Jiangsu Province, China

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ABSTRACT

The aim of present investigation is to analyze the unsteady oblique shock train and boundary layer interactions during the self-excited and forced oscillation. The oblique shock train is generated in a Mach 2.7 ducted flow and controlled by a downstream elliptical shaft. Cyclic rotating of the shaft leads to the forced oscillation. A Schlieren system as well as transient pressure measurements and particle image velocimetry have been used to capture quantitative and qualitative shock structure information. Results show that the behaviors of unsteady SBLIs structure are highly related to the dynamics of shock motion. For both self-excited oscillation and forced oscillation, the asymmetrical characteristics of first X-shock was found to be negatively correlated with shock velocity. There exist some relative motions between the first X-shock and the second shock, but the absolute variations are very weak. At lower excitation frequency, the relative motion is not noticeable to the oscillation amplitude, it could be treated as a rigid motion in the duct. At higher excitation frequency, the relative motion amplitude is significant to the oscillation amplitude, and the relative movement of shock cells becomes the dominant motion. There is a hysteretic effect and phase lag between the shock position and downstream pressure perturbation when the shock train travels along a different path for upstream and downstream movements, and the hysteretic effect becomes weaker with increasing frequency.

1. Introduction

The shock train is a complex flow phenomenon which involves an interaction between the restricted boundary layer and shock wave in many fluid devices such as hypersonic inlet/isolator, supersonic wind tunnel diffusers [1,2]. In such applications, it is common that the shock train is used to “isolate” downstream pressure rise and to compress the incoming flow. In a scramjet engine, the pressure rise induced by combustion will produce a series of shock train in the isolator and the inlet-isolator will impose the combined compression effect on the incoming flow. With different flow conditions, the shock train exhibits different kind of SBLI structures: normal shock train occurs for lower incoming Mach numbers and oblique shock train occurs for higher incoming Mach numbers. A shock train in the duct tends to oscillate [3], it shows the unsteady behavior even under steady flow condition. This oscillation can produce large-scale of undesirable local fluctuations in properties such as pressure, shear stress and heat transfer rate, which would distort the flow condition and cause a significant reduction in the performance of propulsion system. The unpredictable and potential dangerous in flow conditions could make a major concern for the design of hypersonic propulsion systems, such as causing the engine unstart [4].

In recent years, many researches [5,6] has been done to study the characteristics of shock oscillation and unsteady shock and boundary layer interactions that subjected to pressure disturbances. These unsteady shock motions mainly include two parts, one is the self-excited shock train oscillation [7,8], and another is the forced shock train oscillation [9,10]. The difficulty in predicting large-scale oscillating shock motion from a lack of understanding of how the SBLIs respond to external influences such as unsteady perturbations in flow properties. The interactions in shock oscillation region are very complicated and sensitive to both unsteady downstream pressure perturbations and potential upstream disturbances [11].

Experimental studies were performed by Kroutil and Sajben [7–10] on the shock response to downstream perturbations and in self-excited response. In these configurations, the flow is either attached or undergoes shock-induced separation, depending on shock strength or the presence of an adverse pressure gradient. Bruce [12–14] obtained a precise description of unsteady flow

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E-mail address: wangcp@nuaa.edu.cn (C. Wang).

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Nomenclature

M_0	incoming Mach number
P_0	incoming Stagnation pressure
P_b	downstream pressure perturbation
ΔP_b	variation of mean downstream pressure
p	wall static pressure
β	separated shock angle
f_b	downstream pressure perturbation frequency
f_s	shock oscillation frequency
T	periodic time
t	time
ΔT	phase lag
x	distance from the throat
Δx	variation of mean distance
TR	throttling ratio
H	the entrance height of the duct
U	mean streamwise velocity
c	sound velocity
V_s	shock velocity
A_s	shock oscillation amplitude
p_2/p_1	shock strength
V_b	propagation velocity
Φ	phase angle

by laser Doppler anemometry and found that the interaction structure between oscillating lambda shock and the transonic boundary layer varies during upstream and downstream motion. The changes are related to the relative strength of the shock and the effect on the extent of boundary layer thickening and shock induced boundary layer separation. Viscous effects in boundary layer have also been observed to affect unsteady interaction. An inviscid model was developed for predicting the amplitude/frequency relationship in parallel and diverging walled ducts. Experimental studies were performed by Bur [15–18] on forced shock wave oscillation and separated boundary layer interaction in a channel. A precise description of the unsteady flow to characterize the evolution of the boundary layer and shock was obtained, and passive and active control devices have been tested to analyze their effects on the shock wave/boundary layer interaction. Klomparens [19] studied the response of a shock train to downstream back pressure forcing in a $\mathrm{Ma} = 2.0$ duct. They found that the normalized path of shock train motion is independent of forcing frequency. But these conclusions may not be certain in high Mach number of high forcing frequency. Yu et al. [20] discussed the switch of separation modes in an over expanded single expansion ramp nozzle. They found the separation patterns changed between restricted shock separation (RSS) and free-shock separation (FSS) during the startup process. Fan et al. [21,22] performed an experimental study on the flow separation and self-excited oscillation phenomenon in a $\mathrm{Ma} = 3$ duct. Two separation modes were observed and can switch in the unsteady process. Also the frequency of the shock foot oscillation was found to be independent of the magnitude of separation region.

To date, many work have been conducted to study the unsteady SBLIs [23,24], including the oblique shock train [25,26], microramp based shock waves [27], background waves [28] and separated boundary layer interactions; no particular literatures have been published specifically on the forced oscillation of an oblique shock train and separated boundary layer interaction. An overview of the SBLIs and pseudo-shock waves in high-speed intakes has been published by Gaitonde [29], Gnani and Kontis [30] in 2015 and 2016. They mainly introduce the length [31], the back pressure resistance performance [26] and the impacts of flow Mach number, Reynolds number, pressure ratio, jet, etc. on steady and unsteady characteristic of flow structures. When the incoming Mach number increases, the shock structure evolves from a single normal shock towards multiple oblique shocks, and separation bubble becomes more distinctly due to oblique shock and boundary layer interactions. The shock train and the pseudo-shock phenomena are extremely complex and still not well understood. The different response of SBLIs between an oblique shock train and a normal shock oscillation with downstream excitations remains not clarified. When relative high frequencies of back pressure excitation are imposed, the response of shock train and boundary layer interactions remains still unclear.

In the present work, the unsteady oblique shock train and boundary layer interactions, including the self-excited oscillation and the forced oscillation are studied by experimental test. A high-speed Schlieren system as well as particle image velocimetry and transient pressure measurements have been used to characterize the unsteady shock behavior and SBLIs structure during the shock oscillation. The primary purpose of this work is to present the experimental description of unsteady SBLIs structure and to strengthen the understanding of the response of forced oblique shock train oscillation to different frequency of downstream distributions.

2. Experiment

2.1. Experimental arrangement

The experiments were performed in a blow down-type supersonic wind tunnel in Nanjing University of Aeronautics and Astronautics. The supersonic tunnel has been set to give a freestream Mach number of 2.7 in the test section, and the Reynolds number based on the throat height ranged from 0.5 to 1.2 $\times 10^7$. The stagnation pressure P_0 upstream could be set to a maximum to 800 kPa, while the downstream pressure is opened to the atmosphere. The stagnation temperature T_0 was set to approximately 290 K. The schematic diagram of the wind tunnel and the detailed parameters of test model are shown in Fig. 1. The tunnel has a rectangular working section with 40 mm wide by 45.1 mm high and with a 0.5 degree expansion angle on lower wall to eliminate the effect of boundary layer thickness. The total length of the straight section is 580 mm, and the origin of the co-ordinate system is defined at the centrality of throat. At the end of duct, a shaft with an elliptical shape is located in the middle of the duct (at $x = 537$ mm) and is designed with a size of 6 × 4.5 mm. The shaft is rotated by a DC motor at nominally frequency between 5–60 Hz; produce nearly sinusoidal periodic downstream pressure perturbation with a frequency double of the rotation. Thus, the rotating shaft leads to the variation of the throttling ratio (*TR*), which is defined as following:

$$TR = A_{shaft}/A_{duct}$$

where A_{shaft} means the throttling area caused by the rotating elliptical shaft and A_{duct} means the cross area of the duct. During the process of shaft rotation, the throttling ratio can be controlled to vary from 8.8% (the elliptical shaft long axis is vertical to the flow direction) to 11.7% (the elliptical shaft long axis is parallel to the flow direction).

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