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Experimental characteristics of oblique shock train upstream propagation

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Abstract The structure and dynamics of an oblique shock train in a duct model are investigated experimentally in a hypersonic wind tunnel. Measurements of the pressure distribution in front of and across the oblique shock train have been taken and the dynamics of upstream propagation of the oblique shock train have been analyzed from the synchronized schlieren imaging with the dynamic pressure measurements. The formation and propagation of the oblique shock train are initiated by the throttling device at the downstream end of the duct model. Multiple reflected shocks, expansion fans and separated flow bubbles exist in the unthrottled flow, causing three adverse-pressure-gradient phases and three favorable-pressure-gradient phases upstream the oblique shock train. The leading edge of the oblique shock train propagates upstream, and translates to be asymmetric with the increase of backpressure. The upstream propagation rate of the oblique shock train increases rapidly when the leading edge of the oblique shock train encounters the separation bubble near the shock reflection point and the adverse-pressure-gradient phase, while the oblique shock train slow movement when the leading edge of the oblique shock train is in the favorable-pressure-gradient phase for unthrottled flow. The asymmetric flow pattern and oscillatory nature of the oblique shock train are observed throughout the whole upstream propagation process.

1. Introduction

The oblique shock train (OST)[1] flow diffusion phenomenon, which involves an interaction between the duct's peripheral boundary layer and central oblique-shock-wave field (Fig. 1d), usually appears in constant or nearly constant cross-sectional area supersonic/hypersonic duct flows. The study of such a complex flow structure in a confined duct under a finite adverse pressure gradient has important implications for the design and operation of a variety of devices including hypersonic vehicle inlet/isolator, wind tunnel diffusers, supersonic ejectors, etc. To develop the design methods and control strategies of the flow devices, it is necessary to fully understand the mechanism of the OST. Different flow conditions will lead to different kinds of shock train structure: normal shock train occurs for lower incoming Mach numbers of

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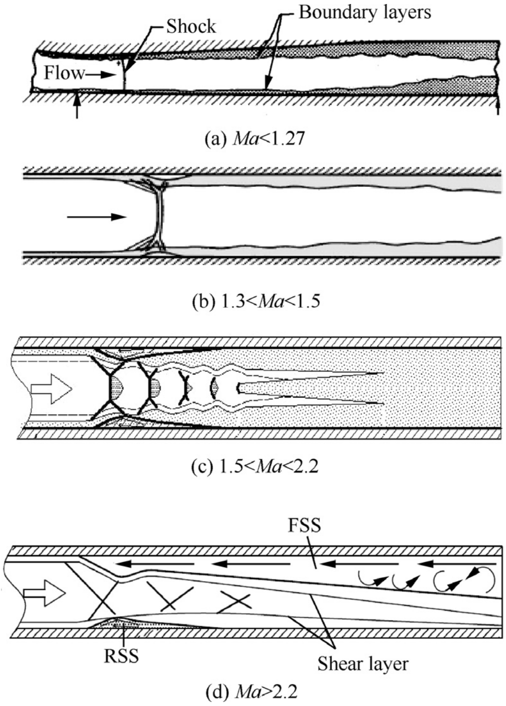
about 1.2–2.2 (Fig. 1c), whereas oblique shock train (Fig. 1d) occurs for higher incoming Mach numbers. Yet the mechanisms of compression of supersonic gas flow in normal shock train and oblique shock train flow diffusion may be different. Both of them coincide with different topology of shock boundary layer interaction. Many studies have been conducted on the normal shock train fluid structure to better understand the influence of different pressure levels and Mach numbers.[2–12] Nevertheless, studies on the OST are not very abundant in the literature.[13,14]

According to the previous studies, the flow pattern of the shock wave/boundary layer interaction in a duct can be classified into different configurations (Fig. 1). While the freestream Mach number just upstream of the shock is less than about 1.27(Fig. 1a),[15] the shock is close to a normal shock and no flow separation occurs at the foot of the shock. For the Mach number between about 1.3 and 1.5 (Fig. 1b),[16] a nearly normal shock with bifurcated foots is observed and a small boundary layer separation region exists immediately downstream of the bifurcated shock. As the Mach number increases further, the interaction between shock waves and boundary layer is significant, a Mach reflection (MR) is established at the center region of the duct flow (Fig. 1c), and more than one shock appear in central shock wave field of the duct flow. A series of shocks as illustrated in Fig. 1c has been called "normal shock train" in the paper[1] to indicate such a sequence of shocks. The initial normal shocks bifurcate for the normal shock train case and interact with the separating wall boundary layer at the foot of the bifurcated shocks. The pattern shown in Fig. 1d, named after an "oblique shock train"[1], tends to appear at higher freestream Mach number than that of a normal shock train and regular reflection (RR) does, and it starts with initial oblique shock waves that separate the boundary layer. The shock-induced separation flow shapes are also different besides the shock pattern between both the shock trains. The restricted shock separation (RSS)[17] is present in the normal shock train case, and RSS is characterized by a restricted length scale of the separation region in which the mean flow tilts away from the wall before the flow reattaches and continues downstream as an attached boundary layer. Depending on the strength of the secondary shock, more than one separation bubble may be present. For an oblique shock train case, the flow pattern is usually asymmetric and both the RSS and free shock separation (FSS)[17] exist simultaneously (Fig. 1d). In FSS, the oblique-shock-induced separation region on the random upper or lower wall fails to reattach on the downstream length of the duct. The separated shear layer forms as it is convected downstream.



(a) Ma<1.27
(b) 1.3<Ma<1.5
(c) 1.5<Ma<2.2
(d) Ma>2.2

Fig. 1 Schematic of shock wave/boundary layer interaction in a duct.

In recent years, the dual-mode scramjet has received more and more research interests and an isolator, also called a supersonic diffuser, is regarded as an essential component of a high-speed dual-mode ramjet engine. The isolator portion is actually a constant-area duct located between the engine inlet and combustor section, and its purpose is to contain the shock train caused by the downstream rise in pressure from combustion. In the scramjet mode of operation, an OST often forms in the isolator for higher freestream Mach number.[13,18] Wagner et al. studied the dynamics of the unstart shock system in an isolator model in Mach 5 flow by controlling unstart through the deflection of a flap located at the exit plane of the isolator. Unstart was seen to progress upstream in the form of an "unstart shock system". This "unstart shock system" took the form of OST but not the form of the normal shock trains as reported by O'Byrne et al.[18] Wagner et al. used schlieren and high frequency pressure sensors to investigate the OST feature. The data were used to calculate the unstart shock system speed moving upstream and characterize the flow structure. The particle image velocimetry(PIV) measurement was also used to show the velocity field of the started and unstarted OST flow.[19] The quasi-steady state properties of an OST in a Mach 2.75 ducted flow were studied by Klomparens et al.[14] including the shock train location, the amplitude of shock displacement and the shape of time-averaged pressure distribution. The fine flow structures of the shock train in an isolator flow were revealed by Zhi et al.[20,21] who performed Nano-tracer Planar Laser Scattering (NPLS), which makes it propitious for studying flow mechanism. Tan et al.[22] and Li et al.[23] investigated the transient flow structures of the unstarted flow by downstream choking in generic rectangular hypersonic inlets. For the purpose of preventing combustor-inlet interaction, the detection of the location of the isolator shock train is of utmost importance. Le et al.[24] found that monitoring the standard deviation of wall pressure appears to be the best method. Chang et al.[25] observed one of two novel oscillatory patterns of inlet buzz: a non-oscillatory violent pattern in which the OST stays at its most upstream position and oscillates just slightly.

Although substantial work has been performed, the OST dynamics is an area which is still not very well understood. For example, one of key issues is the influence of background waves on the OST. Tan et al.[26] in 2012 thought that the actual flow condition in a scramjet isolator is much more complex since background waves exist, including the impingement shock, separation shock and expansion waves. The interaction of the background waves and the leading shock of the OST

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