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Mechanism of shock train rapid motion induced by variation of attack angle

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A R T I C L E I N F O

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A B S T R A C T

Numerical simulation was conducted to study the effect of attack angle variation on the quasi-steady motion characteristics of shock train leading edge. Simulation results indicate the motion of shock train has jumping feature, which is mainly caused by the strength changing of the local flow separation. During the process of attack angle decreasing, the reflection points of background wave move downstream, and the one of which approaches the separation zone of shock train. Thus a rapid forward movement is induced by the increasing local adverse pressure gradients. In attack angle increasing case, shock train is not moving back continuously but can be temporarily stabilized at the front part of the reflection point, because of the local adverse pressure gradient that formed by background waves. Once the refection point moves forward and surmounts leading edge of shock train, the pressure boost from background wave to the separation zone is lost, and a suddenly backward jumping will occur.

1. Introduction

For a hypersonic airbreathing propulsion system, without a mechanical compressor, airflow and compression ratio for the engine are provided totally by the inlet and isolator [1,2]. The isolator of a hypersonic airbreathing engine functions to isolate the combustion pressure rise from reaching the inlet and reduce the sensitivity of the inlet to combustor pressure perturbations [2,3]. When the hypersonic engine operates in the ramjet mode, a pre-combustion shock system that takes the form of shock train in the isolator is required to compress the flow to subsonic [2,4]. This shock system is defined as shock train, and which will move upstream to the entrance of inlet with the rising combustion pressure [5,6]. Once the combustion pressure rises to a value that cannot match the pre-combustion shock system in isolator, the leading edge of the shock train will reach the entrance, and then inlet unstart will occur, which results in higher aerodynamic drag, less airflow mass captures and lower total pressure recovery coefficient [6]. To characterize the stable margin for a hypersonic inlet, the location of the STLE (shock train leading edge) can be used for characterizing unstart margin and preventing unstart [7]. There are many techniques presented to detect the location of the STLE [8]. However, before inlet unstart occurs, the movements of STLE are nonlinear and have rapid motion features in the forward/backward motion [9,10], which make the detection of stable margin more complex. In previous flight tests, inlet unstart occurred frequently, and these flight accidents can be listed as follows, CIAM/-NASA's Mach 6.5 flight test encountered inlet unstart in the mode transition process in 1999 [11,12], HyCAUSE flight test failed due to inlet unstart that caused by the fault of attitude control in 2008 [13,14], and X-51A flight test faced inlet unstart two times respectively in 2010 [15] and 2011 [16]. So the jumping feature of STLE motion is an important issue that must be considered.

In recent years, flow characteristic during the process of shock train propagation has been investigated extensively. And these studies are useful for better understanding the mechanism of shock train motion. The results of these investigations indicate that the pressure increment in the downstream part of the flow plays a leading role in the process of shock train forward movement, which chokes the supersonic flow and forms the upstream propagating shock system [17–19]. For a straight duct, Billig [20,21] in 1993 proposed an empirical correlation for the shock train, which relates the steady length of shock train with BP (backpressure) and freestream condition. But for a real hypersonic inlet/isolator that has background waves, recent studies indicate that the shock train movement is unstable and shows the characteristic of sudden jumping under certain circumstance [9,10], which makes the unstart detection and control more complex [8]. Wagner [10] in 2009 tested the transient behaviors of the shock train propagation in an inlet-isolator model and found the velocity of the forward propagating shock system is not always equal during the whole process [10]. Do [22,23] in 2011

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Nomenclature

M_∞	freestream Mach number
p_∞	freestream static pressure
T_∞	freestream static temperature
p_B	back pressure
p	static pressure
α	angle of attack
k	order of accuracy of numerical scheme
L_i	domain size in the direction of integration
ΔL_i	cell size in the direction of integration
n	number of time steps
$n_{\max}$	maximal allowable number of time steps
R_s	reliability of results
S_i	relative error in the direction of integration
S_{err}	relative error in several directions of integration
S^{max}	allowable value of total error
x	x-axis coordinate
t	time

Table 1
Boundary conditions of the testes.

tests	T_∞	p_∞	M_∞	α	p_B
case1	101.7 K	891.7Pa	5.9	0	$p_B(t)$
case2	101.7 K	891.7Pa	5.9	$\alpha_2(t)$	$p_B(t)$
case3	101.7 K	891.7Pa	5.9	$\alpha_3(t)$	$p_B(t)$

reported the speed of the shock train movement is depended on the evolution of the separated flow near wall as the region thickens, and found that if the shock train is downstream of a reflection point of background waves, the shock system moves more slower than it has just surmount this reflection point, which is because the reflection of background waves delays the shock propagation upstream and a greater downstream pressure buildup is required to overcome this local favorable pressure gradient for further propagation. Tan [24] in 2012 test the shock train movement with complex background waves and found the oscillation phenomenon is closely related to the interaction of its leading shock, background shocks, and the local boundary layer, when STLE moves upstream. Xu [25] in 2016 tested the jumping features of STLE which are formed by linear variation of BP with steady background waves, and reported that the effect of background waves on the growing of separation flow plays a leading role in the jump characteristic of STLE. Li [26] in 2017 investigated the path of STLE in complex background waves and reported a mathematical model for the path.

Background flow field of isolator will be changed by AOA (angle of attack) condition. As we known, when AOA varies, STLE will move forward or backward because the static pressure of main stream at upstream region of shock train are being changed. But there are fewer tests on the motion characteristics of STLE under AOA variation condition. And the mechanism of this motion characteristic of shock train in this condition is still an open question. Therefore, numerical simulation was conducted to study the effect of changing inner flow structures caused by AOA variation on the motion characteristics of shock train. Then, the processes of the obvious rapid motions are analyzed using transient numerical Schlieren and pressure distribution. The laws of these motion characteristics of shock train are summarized. And some conclusions are given finally.

2. Inlet model and numerical method

2.1. Inlet model and boundary conditions

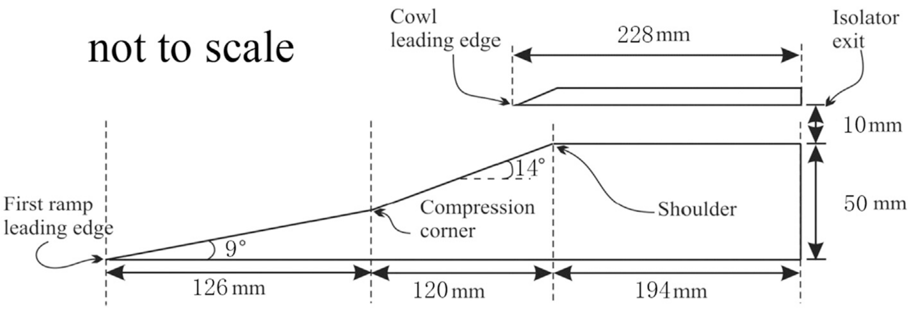

Fig. 1. Sketch of inlet-isolator configuration.

The simulation model in this paper is a two-dimensional flow field of an inlet/isolator model. The inlet model quotes the hypersonic inlet experiment of Li [27]. The inlet section model contains a compression ramp and a constant area isolator, as shown in Fig. 1. The length and height of this isolator are 0.194 m and 0.01 m respectively. In this simulation, T_∞, P_∞, M_∞ and unit Reynolds number were set as 101.7 K, 891.7Pa, 5.9 and $1.3 \times 10^5\ \mathrm{m}^{-1}$ respectively.

The boundary conditions of the numerical tests are listed in Table 1. Where α is AOA of incoming flow, and P_B is the static pressure at exit of isolator. The variation processes of them are given in (1) and (2) respectively. The inlet is fully started at the beginning of the test, and the time is set as $t = 0$s. An increasing BP pushes the shock train to a suitable position for measurement. Then, the increment of BP is stopped and AOA will change as (2).

$$p_{B(t)} = \begin{array}{ll} p_B(t) = 2300 & (t \le 0.001) \\ 2000 + [123758 \times (t - 0.001)/0.05] & (0.001 < t \le 0.024) \\ p_B(t) = 76928.68 & (0.024 < t \le 0.045) \end{array} \quad (1)$$

$$\begin{array}{ll} \alpha_2(t) = 0, \alpha_3(t) = 0 & (t \le 0.025) \\ \alpha_2(t) = -5 \times (t - 0.025)/0.02, \alpha_3(t) = 5 \times (t - 0.025)/0.02 & (0.025 < t \le 0.045) \end{array} \quad (2)$$

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