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Control of pseudo-shock oscillation in scramjet inlet-isolator using periodical excitation

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ABSTRACT

To suppress the pressure oscillation, stabilize the shock train in the scramjet isolator and delay the hypersonic inlet unstart, flow control using periodic excitation was investigated with unsteady Reynolds averaged Navier-Stokes simulations. The results showed that by injecting air to manipulate the cowl reflected shock wave, the separation bubble induced by it was diminished and the pressure oscillations of the shock train were markedly suppressed. The power spectral density and standard deviation of wall pressure were significantly reduced. The simulations revealed that this active control method can raise the critical back pressure by 17.5% compared with the baseline, which would successfully delay the hypersonic inlet unstarts. The results demonstrated that this active control method is effective in suppressing pressure oscillation and delaying hypersonic inlet unstarts.

1. Introduction

Hypersonic inlet is a key component that captures and compresses air for scramjet combustors. Interactions between the inlet flow and the combustion play an important role for dual-mode scramjet engines [1–3]. The amount of air that the inlet captures and its flow conditions at the exit of the isolator can significantly influence the performance of scramjet combustion. Meanwhile, the combustion will generate back pressure and affect the flow field in the isolator. The back pressure can cause separation in the boundary layer and form shock trains [4], generating pressure oscillation in the diffuser of ramjets [5], and the inlet-isolator of scramjets [6,7] and pulse detonation engines [8]. If the back pressure exceeds a critical value, the original shock system and the resulting large separation bubbles can be pushed out of the throat and results in inlet unstart [9–12].

Once the hypersonic inlet goes into unstart, it can cause additional unsteady aerodynamic load and the drag will increase sharply. The unstart flow field oscillates unsteadily, which can cause a transient load to the structure up to a factor of ten or more due to the swiftly moving shock waves [3]. Moreover, the violent oscillation of the unstart inlet field can extinguish the engine flame and make the engine lose thrust, which has been observed in the failure of the second X-51A flight experiments. Consequently, it is very important to model the transient dynamics of the hypersonic inlet unstart [13–15] and develop some effective flow control methods to delay or prevent the inlet unstart.

In order to study the hypersonic inlet unstart, different kinds of throttling apparatus including plugs [10], deflecting flaps [11], pins and fluidic mass additions [12,16] have been used to simulate the combustion-induced back pressure of scramjet engines. These experiments have shown that the pressures in the isolator oscillate violently when the inlets operate under the ramjet mode or scramjet mode, which is far before the occurrence of inlet unstarts.

Previous research about the ramjet inlet has found that the displacement of the terminal normal shock's motion is closely associated with the frequency and amplitude of the pressure oscillation in the inlet-diffuser, among which the low frequency oscillation mode is easy to cause the inlet to unstart [17]. Therefore, it may be a good approach to delay the inlet unstarts by controlling the low frequency oscillation mode.

For scramjet, as the combustion-induced pseudo-shock is different with the terminal normal shock of ramjet inlet, it is not clear whether the inlet unstart can be delayed by suppressing the pressure oscillation. In recent years, some methods such as bleeding [18,19], suction [20,21], and vortex generators [22] have been used to control the flow field in scramjet engines. Whereas, there are many challenges for these flow control methods. For example, due to the high temperature and high heat flux rate in the boundary layer [3], it is difficult to conduct the high temperature gas out of the inlet through pipes under the highly

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Nomenclature

A	pressure amplitude of the jet
C_f	skin friction coefficient
C_μ	jet momentum ratio
f_j	frequency of the jet
H_c	the height of the capture area for scramjet inlet
L	the length of the inlet
L_j	the length of the jet along the streamwise direction
M	Mach number
N	the number of grid cells
p	pressure
S	entropy
T	temperature
t	time
$\mathbf{V_j}$	jet velocity
y^+	dimensionless wall distance
γ	specific heat ratio
ρ	density
σ	standard deviation

Subscripts

b	backpressure
t	stagnation conditions
0	free stream condition
j	jet

integration of airframe and engine.

For vortex generator, although the maximum back pressure can be raised as high as 32% with the combination of the passive wheeler doublets and active jets, the success rate of this method is only 50% because the time scale of the unstart process is in the order of 10 ms, which make it difficult for the actuator to respond in time [22].

Till now, there is no effective and mature flow control methods for controlling the scramjet inlet-isolator unstart. Therefore, it is very necessary to develop some new flow control methods to delay the hypersonic inlet unstart.

In this paper, an innovative flow control method that delays the hypersonic inlet unstarts by suppressing the pressure oscillation of pseudo-shock in the scramjet inlet-isolator was investigated. For this control method, the air jet from a slot after the cowl lip is used to control the reflected shock wave, which would have an effect on the cowl reflected shock-wave/boundary layer interaction. As a result, the separation induced by the cowl reflected shock wave will be modified and the pressure oscillation of the pseudo-shock will be suppressed.

2. Computational methods

2.1. Configuration

As displayed in Fig. 1, a two-dimensional hypersonic planar inlet with a total contraction ratio of 4.5 was designed. The distance from the cowl to the leading edge is 640.99 mm. Three successive ramps with turning angles of 4.0°, 4.5° and 5.5°, respectively, were adopted on the external compression surface. The internal contraction ratio is 1.43. The height of the isolator is 33.5 mm and the aspect ratio is 4.0.

In order to control the cowl reflected shock wave, a slot was opened on the top wall from $x = 670.82$ mm–672.82 mm, which is located after the cowl lip as illustrated in Fig. 1. When the jet is on, air can be injected from the slot to control the cowl reflected shock wave. The velocity of the air jet from the jet is at an angle of $-85°$ with respect to the x axis, and it is perpendicular to the inlet wall.

2.2. Numerical methods and flow conditions

A computational fluid dynamics code based on a structured-grid finite-volume method was used to solve the conservation form of the Reynolds-averaged Navier-Stokes Equations. In hypersonic inlets, the cowl reflected shock wave can interact with the turbulent boundary layer and the turbulent flow is highly three dimensional as the aspect ratio is small. Under this condition, the effect of the side wall on the flow field three-dimensionality cannot be ignored. However, the recent research of shock wave turbulent boundary layer interaction has shown that for large aspect ratio case, the time-averaged flow field in the central plane is close to that of the corresponding quasi-2D case [30] and the flow filed three-dimensionality caused by the side wall is minor. Consequently, a two dimensional model is adopted in the current research.

The molecular viscosity was calculated by Sutherland's law with thermally perfect gas assumption. The turbulent viscosity was obtained from Menter's shear stress transport k-ωturbulence model [23]. For hypersonic flow, compressibility effects cannot be ignored, so compressibility corrections suggested by Wilcox [24] were employed in the simulations.

The inviscid flux vectors were discretized with a second-order Roe Flux-Difference Splitting scheme [25]. Implicit dual-time-stepping Lower–Upper Symmetric Gauss–Seidel algorithms were used for time advancement, where the time term was dicretized with a backward differencing method [26] so that second-order accuracy can be obtained for unsteady simulation.

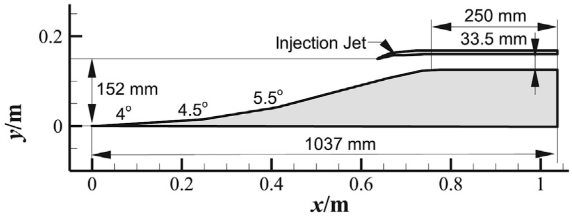
The Mach number, pressure, temperature and the unit Reynolds number of the free stream are 6.0, 2549 Pa, 221 K and 4.95×10^6/m, respectively, at an operating altitude of 25 km above the sea level. For turbulence, the incoming turbulence kinetic energy can be calculated from the turbulence intensity I_∞ and Mach number of the free stream M_∞

$$k = 1.5 \times (I_\infty \times M_\infty)^2 \tag{1}$$

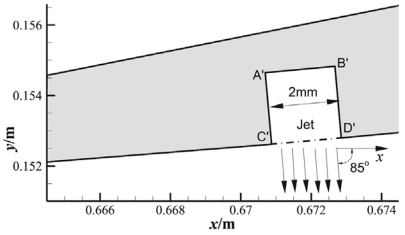
The incoming turbulent viscosity is set to

$$\mu_t = 0.1\mu_{l,\infty} \tag{2}$$

The value of turbulence intensity is 0.001 in calculating the free stream turbulence kinetic energy for the current research. Other



(a) Schematic diagram of the inlet



(b) Zoom in view of injection jet

Fig. 1. Schematic diagram of the inlet and active jet.