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Numerical study of unsteady starting characteristics of a hypersonic inlet

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Abstract The impulse and self starting characteristics of a mixed-compression hypersonic inlet designed at Mach number of 6.5 are studied by applying the unsteady computational fluid dynamics (CFD) method. The full Navier–Stokes equations are solved with the assumption of viscous perfect gas model, and the shear-stress transport (SST) k–ω two-equation Reynolds averaged Navier–Stokes (RANS) model is used for turbulence modeling. Results indicate that during impulse starting, the flow field is divided into three zones with different aerodynamic parameters by primary shock and upstream-facing shock. The separation bubble on the shoulder of ramp undergoes a generating, growing, swallowing and disappearing process in sequence. But a separation bubble at the entrance of inlet exists until the freestream velocity is accelerated to the starting Mach number during self starting. The mass flux distribution of flow field is non-uniform because of the interaction between shock and boundary layer, so that the mass flow rate at throat is unsteady during impulse starting. The duration of impulse starting process increases almost linearly with the decrease of freestream Mach number but rises abruptly when the freestream Mach number approaches the starting Mach number. The accelerating performance of booster almost has no influence on the self starting ability of hypersonic inlet.

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1. Introduction

As the main compression component of a hypersonic propulsion system, the inlet affects the performance of scramjet greatly. The mixed-compression type, which may cause starting problem, is always employed in hypersonic inlet in order to obtain better aerodynamic performance. The starting problem is inherent to internal compression duct because the structure does not allow surplus mass flow to spill overboard.[1] The starting characteristics of a hypersonic inlet determine directly the flight envelope of aerocraft, so a variety of methods have been developed to prevent the inlet from unstarted mode and extend its stable operation envelope.

Over the past few decades, the starting problems of hypersonic inlet have been studied extensively.[2–11] Efforts have been made to understand the flow pattern at unstarted mode and explore the approaches of widening the flight envelope of hypersonic inlet. Mass flow spillage[12,13] and overspeeding[14] have been contrived to overcome the Kantrowitz limit, but these

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methods are considerably difficult to implement in scramjet inlet from a practical point of view. More viable methods can be categorized into two major classes[15] variable geometries and unsteady effects. The former approach improves the inlet starting ability through regulating the mass flow entry and the area of throat.[16] The latter approach makes use of highly unsteady effects to overcome the Kantrowitz limit.[1,17] Compared with variable geometry inlet, the structure of fixed geometry inlet is simple. So the unsteady effects are a better method to improve the starting ability of a fixed geometry inlet.

The unsteady starting characteristics of inlet have been studied numerically. Tahir et al.[14] has studied the unsteady starting process of inward turning supersonic inlets numerically, and the evolvement process of the flow field is described in detail. The results indicate that the removal of frangible structures such as sudden rupturing diaphragms may be employed near the leading edge of an inlet to sufficiently impose high spatial gradients, so as to permit starting beyond Kantrowitz's limit. The higher ratio initial values of external to internal pressure are conducive to unsteady starting. But this paper assumes that the gas is inviscid and neglects the viscous influence on inlet starting. The viscous influence on the unsteady starting is considered in Ref. [15], and the starting approaches of opening doors, rocket plugs and sliding doors are employed. Comparative analyses are conducted on the evolvement of flow field of inlet with different starting approaches, and the results indicate that the better starting capability could be obtained with the approach of sliding doors. However, these works mainly focus on the pure internal compression inlet and the unsteady starting process of inlet with different approaches. The unsteady starting characteristics of inlet in impulse wind tunnel, during which the unsteady starting shock of impulse wind tunnel will sweep the inlet, are not referred to.

Different from a bow shock standing ahead the pure internal compression inlet, an oblique shock generated by cowl will shoot into the internal compression duct of a mixed-compression inlet, which would benefit overcoming the Kantrowitz limit. The unsteady starting characteristics of mixed-compression hypersonic inlet in impulse wind tunnel and self starting process will be discussed in this paper.

2. Models and numerical method

2.1. Inlet model

A model of axial-geometry mixed-compression hypersonic inlet is sketched in Fig. 1. The inlet is designed for a shock-on-lip Mach number of 6.5 and a self starting Mach number of 4.0. The external compression is accomplished by a cone with one turning, for which the initial half angle is 12° and the turning angle is 6°. The internal contraction ratio equals 1.49. Downstream of the throat, a three-dimensional variable section duct for which the area ratio of exit to throat is 1.19, has been adopted.

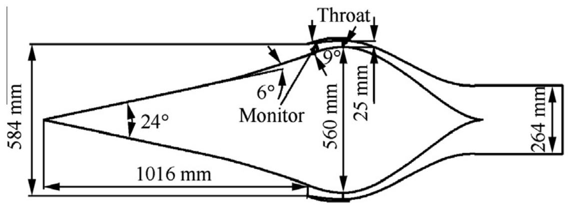


Fig. 1 Schematic diagram of the inlet model.

2.2. Numerical method

The flow was computed by solving the full Navier–Stokes equations. An implicit algorithm with second-order spatial accuracy and dual time-stepping is used for the computation of transient flow field. Multigrid convergence acceleration is employed and the transient flow field is converged at every global time step. The fluid is treated as compressible perfect gas with composition of standard air. The shear-stress transport (SST) two-equation Reynolds averaged Navier–Stokes (RANS) model is used for turbulence modeling. The body surfaces of the inlet are assumed to be no-slip and adiabatic.

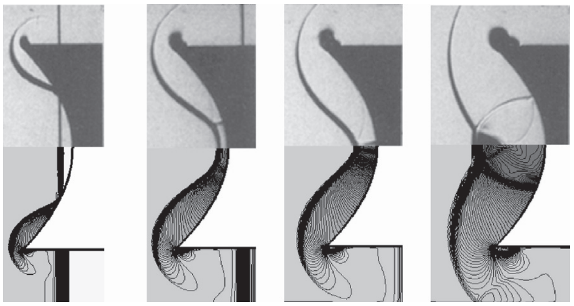
The variable laws of inflow parameters with time are controlled by defined functions. Residuals are continuously monitored for continuity, k, ω, axial-velocity, and radial-velocity. The convergence criterion is that all of these residuals are dropped below 10^{-3} with the mass flow rate and the Mach number of mass-weighted average at throat of inlet retaining constant.

2.3. Example of verification

The experiment, which is implemented by Izumi et al.[18] for studying the focusing process of shock waves reflected from parabolic reflectors, is employed to verify the unsteady treatment ability of the numerical method. The shape of the parabolic reflector is expressed by $X = CY^2$, and the C equals 0.5. The incident shock Mach number $Ma = 1.5$. The flow patterns at different moments are shown in Fig. 2, in which the upper pictures are the experimental data and the lower pictures are the computational results. The time t' is nondimensionalized with respect to $\gamma^{1/2}D/\alpha_1$, where γ is specific heats ratio, D is the diameter of parabolic reflector and α_1 is the speed of sound in air ahead of the incident shock. It indicates that the numerical results agree well with the experimental results so the numerical method adopted in this study could describe the unsteady process of complex flow.

2.4. Computational mesh and boundary conditions

The flow of an axial-inlet is axisymmetric when the freestream attack angle is set to 0°, so the two-dimensional axisymmetric computation method is used in this study.



(a)t'=0.24 (b)t'=0.35 (c)t'=0.48 (d)t'=0.82

Fig. 2 Comparison of experiment (upper picture) with computation (lower picture).

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