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The flowfield and performance analyses of turbine-based combined cycle inlet mode transition at critical/subcritical conditions

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ABSTRACT

The fluid dynamics and performance analyses of steady and continuous combined cycle inlet mode transition at critical/subcritical conditions were investigated through wind tunnel tests and three dimensional unsteady numerical simulations. When the inlet operated at critical condition, the terminal shock was unsteady and oscillated in the frequency between 40 Hz and 60 Hz around the shoulder of inlet and the downstream of cowl leading edge. In critical inlet mode transition the performance parameters of diffuser exit varied with positions of terminal shock. When the inlet operated at subcritical condition, terminal shock was steady at the upstream of cowl leading edge. The continuous mode transition test results reveal that the shock can be steady at subcritical condition. Considering the shock stability and performance parameters at the diffuser exit, subcritical inlet mode transition is better than critical condition for combined cycle inlet investigated in this paper.

1. Introduction

Turbine-based combined cycle is one of the promising propulsion systems for two-stage-to-orbit reusable launch vehicle [1]. A major goal driving current space propulsion research is to significantly decrease the cost of access to space. Turbine-based combined cycle propulsion system absorbs the oxygen in the atmosphere, thereby yielding significant specific impulse improvements over a wide range of vehicle's flight envelope. This propulsion system integrates the turbine engine and ramjet engine into a single propulsion system. The specific impulse of the turbine engine is superior than other propulsion systems from takeoff to around Mach 2–3. The ramjet engine is more efficient from there to about Mach 6 [2].

The inlet is one of the key components of this hypersonic airbreathing propulsion system. It should provide the required amount of air needed for turbine or ramjet engine performance while maximizing the total pressure recovery, supplying the air with tolerable flow distortion and providing a self-starting capability at the required Mach number [3,4]. The performance and starting characteristics of combined cycle inlet and hypersonic inlet have been investigated widely. Colville et al. [5] modified the SR-71 inlet to expand its operational envelope to higher speeds. Kubota et al. [6] investigated the starting characteristics of two dimensional inlets for the combined cycle engine in a Mach 4 wind tunnel. The shock oscillation in hypersonic inlets as the inlet operated in supercritical and subcritical condition were investigated by Chang et al. [7–12] and Tan et al. [13,14] etc.

Inlet mode transition is the process by which the inlet flow is diverted from the turbine flowpath to the ramjet/scramjet flowpath [15]. It is one of the key technology of turbine-based combined cycle propulsion system. The mode transition from turbine to ramjet engine has been investigated experimentally, numerically and analytically in many countries. HYPR90-C was the demonstrator of Japanese HYPR program. The smooth mode transition from turbine to ramjet mode was achieved in the test [16,17]. The smooth inlet mode transition tests at Mach 4 were done by NASA Glenn Research Center [18,19]. The numerical simulation of over-under TBCC inlet mode transition were done by Xiang et al. [20], Liu et al. [21]. The performance characteristics of a TBCC engine considering the transition mode from turbine to ramjet engine has been investigated by Moon et al. [22]. Chen et al. [23] used the multi-objective and multi-variable goal programming algorithm to guarantee the stable mode transition in tandem configuration turbo-ramjet engines.

The research list above mainly focus on design, starting characteristics of combine cycle inlet and mode transition procedure from turbine to ramjet engine. The research concerning about the fluid dynamics and performance in the inlet during mode transition was few. Recently, the authors' group have investigated smooth inlet mode transition as the inlet operated in supercritical condition [24]. During supercritical inlet mode transition, the terminal

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Nomenclature

A_{exit}	cross sectional area of the turbojet/ramjet flowpath
$A_{th,plug}$	throat area near the plug
DC_{60}	steady-state circumferential total pressure distortion
f	pressure or terminal shock oscillation frequency
Ma	Mach number
$\dot{m}$	mass flow rate
$\dot{m}_c$	inlet captured mass flow rate
P_e	mean total pressure at the diffuser exit
$P_{\min 60^\circ}$	mean total pressure in the 'worst' sector of the face, of angle 60 deg
P_∞	total pressure of free stream
$\overline{\Delta P}_{rms}$	average of the total pressure fluctuation at the diffuser exit
$(\Delta P_{rms})_i$	root-mean-square of total pressure fluctuation of a probe
t	time
TR	throttling ratio
ε_{av}	dynamic total pressure distortion
σ	total pressure recovery coefficient
ϕ	mass flow ratio
π	static pressure ratio

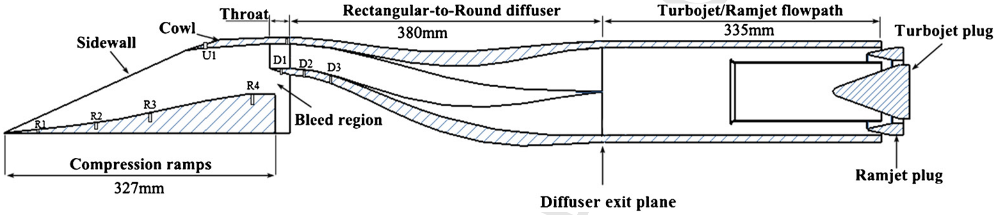

Fig. 1. Sketch of the TBCC inlet model.

shock located at the downstream of combined cycle inlet throat. The back pressure at diffuser exit was a constant number. But the back pressure would change suddenly due to ignition of ramjet combustor, which would push terminal shock to the upstream of throat. So this paper are going to discuss the fluid dynamics and performance of turbine-based combined cycle inlet mode transition as terminal shock located at the shoulder of the third compression ramp and around the cowl leading edge.

2. Method

2.1. Descriptions of the TBCC inlet model

The tandem configuration combined cycle inlet is devised to work from takeoff to Ma 3.0. The mode transition point is Mach 2.0. It is a dual-stream inlet system with turbojet/ramjet flowpaths coupled to a turbojet engine and ramjet combustor, respectively. The sketch of this inlet model is shown in Fig. 1. This inlet shares the same external compression ramps and rectangular-to-round shape transition diffuser. The angles of second and third ramps varies with freestream Mach number. At Mach 2.0 the inlet achieves external air compression using three ramps inclining at 6.0, 2.0, and 4.0 deg, respectively. To satisfy the requirement of airflow and control the Mach number at the throat, the area of bleed region and the total external compression are adjustable according to freestream Mach number. The throat of inlet is a rectangular duct with a constant cross section 80 mm wide by 30 mm high. The geometry of diffuser is rectangle-to-round shape transition, which is designed according to the mathematic method mentioned in Ref. [25]. The area ratio of exit to entrance section of diffuser is 3.7. In the downstream of diffuser exit plane, the passage is separated into two flowpaths. The inner round passage is turbojet flowpath and the outer annular passage is ramjet flowpath. The area ratio of turbojet flowpath to ramjet flowpath is 0.77.

During the tests, turbojet and ramjet mass-flow plugs were used to provide back pressure for each flowpath and simulate an actual engine. They were placed at the exit of turbojet/ramjet flowpaths. The positions were controlled by two motors and independent to each other during the mode transition tests. The throttling ratio (TR) is used to define the axial positions of these two plugs:

$$TR = (1 - A_{th,plug}/A_{exit}) \times 100\% \tag{1}$$

where $A_{th,plug}$ is throat area near the plug and A_{exit} is cross sectional area of the flowpath. During wind tunnel tests, TR could be set as a value between 0% (fully opened) and 100% (fully closed).

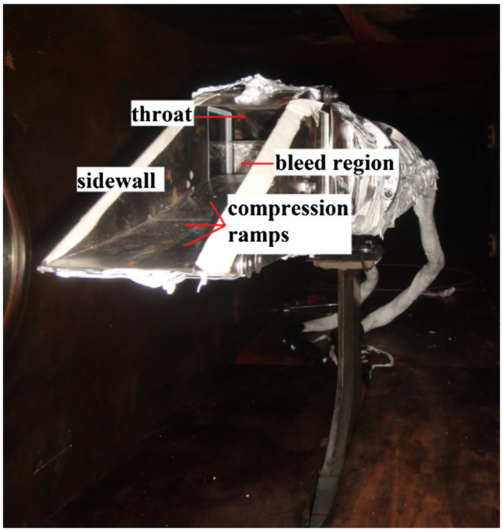

Fig. 2. Inlet model mounted in NH-1 wind tunnel.

2.2. Experimental conditions and measurements

The experiment tests were conducted in NH-1 high-speed wind tunnel of Nanjing University of Aeronautics and Astronautics (Fig. 2). The tunnel was operating in a blown-down mode with usable run time longer than 40 s. The tunnel has a rectangular working section with a constant cross section 600 mm wide by 600 mm high. The length of working section was 1580 mm. The upstream of the working section was an interchangeable two-dimensional Laval nozzle, providing nominal free-stream Mach numbers from

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