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Unsteady supercritical/critical dual flowpath inlet flow and its control methods

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Abstract The characteristics of unsteady flow in a dual-flowpath inlet, which was designed for a Turbine Based Combined Cycle (TBCC) propulsion system, and the control methods of unsteady flow were investigated experimentally and numerically. It was characterized by large-amplitude pressure oscillations and traveling shock waves. As the inlet operated in supercritical condition, namely the terminal shock located in the throat, the shock oscillated, and the period of oscillation was about 50 ms, while the amplitude was 6 mm. The shock oscillation was caused by separation in the diffuser. This shock oscillation can be controlled by extending the length of diffuser which reduces pressure gradient along the flowpath. As the inlet operated in critical condition, namely the terminal shock located at the shoulder of the third compression ramp, the shock oscillated, and the period of oscillation was about 7.5 ms, while the amplitude was 12 mm. At this condition, the shock oscillation was caused by an incompatible backpressure in the bleed region. It can be controlled by increasing the backpressure of the bleed region.

1. Introduction

A Turbine Based Combined Cycle (TBCC) engine is a reusable, low-cost, and high-durability propulsion system.[1–3] It is one of the most promising propulsion systems for next-generation vehicles. This combined cycle engine can operate well in low and high Mach numbers through a turbine engine and a dual-mode scramjet engine, respectively. The inlet should provide proper airflow for the combined cycle engine during the whole flight envelope. Therefore, the performance of inlet is critical to the whole propulsion system. Especially, when large-amplitude pressure oscillations and traveling shock waves occurred in the inlet, it would cause structural damage, engine surge, combustion flameout, or non-recoverable thrust loss.[4]

On one hand, the TBCC inlet has been investigated through experimental tests and numerical simulation. A tandem co-axial configuration TBCC engine with an inlet was tested at a free inflow Mach number of 5.0. A terminal shock oscillation phenomenon was detected, and the net thrust of the engine was sensitive to the terminal shock posi-

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tion.[5] The aerodynamic design of a dual-flow hypersonic inlet for a TBCC propulsion system and the performance, starting characteristics, and mode transition of an over/under configuration TBCC inlet were investigated through numerical simulation and experimental tests.[6–10] An inward-turning inlet design for a TBCC propulsion system was tested at NASA's Langley wind tunnel.[11] On the other hand, shock oscillation in supersonic and hypersonic inlets has been investigated widely. Trapier et al.[12] investigated the onset of supersonic inlet buzz through the analysis of pressure records. Lee et al.[13] investigated flow characteristics of small-sized rectangular and axisymmetric supersonic inlets. The buzz phenomenon of a small-size inlet is identical to that of a large inlet, but a small inlet can be easily affected by separation bubble. The buzz phenomena in hypersonic inlets were investigated by Tan et al.[14,15], Chang et al.[16–18], and Li et al.[19] However, to our knowledge, few of them have investigated the unsteady flow in a TBCC inlet as it operates in supercritical/critical conditions. There are two main differences between a TBCC inlet and a normal supersonic inlet, which may lead to the differences in unsteady flow characteristics. Firstly, a TBCC inlet is characterized by a dual flowpath which provides airflow for turbojet and ramjet engines. During the inlet mode transition, two engines work together to provide the thrust. The backpressure of TBCC inlet is determined by the operation conditions of these two engines, so when the inlet operates in supercritical condition, the terminal shock position is determined by the backpressure from the turbojet and ramjet flowpath. Secondly, the operation range of a TBCC inlet is wider than that of a normal supersonic inlet. To provide the required airflow for turbine/ramjet engines, mass-flow should be bled at an off-design condition. That makes it different from others. The TBCC inlet researched in this paper could still remain start due to a large amount of bleed when the shock was located upstream from the throat, which may cause a normal supersonic inlet into unstart. At this condition, the terminal shock position of the TBCC inlet was affected by the backpressure from the diffuser and the bleed region.

To sum up, unsteady subcritical flow in supersonic and hypersonic inlets have been investigated widely, but few of the research has been conducted on TBCC inlets. Therefore, this paper focuses on the investigation of unsteady flow in a TBCC inlet. Firstly, the characteristic of pressure oscillation near the terminal shock was investigated through wind tunnel tests. Then, the characteristic of terminal shock oscillation was explored by numerical simulation. Finally, based on the analyses of terminal shock oscillation, effective control methods were put forward.

2. Method

2.1. Descriptions of the TBCC inlet model

A dual-flowpath inlet is designed for a tandem co-axial configuration TBCC propulsion system. The sketch of this inlet model is shown in Fig. 1. It is devised to work from takeoff to Mach number 3.0. As shown in this figure, the inlet shares the same external compression ramps and rectangular-to-round diffuser. The angles of the second and third ramps vary with free inflow Mach number. At Mach number 2.0, the inlet achieves external air compression using three ramps inclining at 6.0°, 2.0°, and 4.0°, respectively. The throat of the inlet is a rectangular duct with a constant cross section of 80 mm wide by 30 mm high. The geometry of the diffuser is rectangle-to-round shape transition based on the mathematic method mentioned in Ref.[20]. The area ratio of exit to entrance section of the diffuser is 3.7. Downstream from the diffuser's exit plane, the duct is separated into two flowpaths. The inner round duct is the turbojet flowpath and the outer annular duct is the ramjet flowpath. The area ratio of turbojet flowpath to ramjet flowpath is 0.77.

2.2. Experimental conditions and measurements

Experimental tests were conducted in the NH-1 high-speed wind tunnel at Nanjing University of Aeronautics and Astronautics (Fig. 2). The tunnel was operating in a blown-down mode with a usable run time longer than 40 s. The tunnel has a rectangular working section with a constant cross section of 600 mm wide by 600 mm high. The length of the working section is 1580 mm. The upstream working section is an interchangeable two-dimensional Laval nozzle, providing nominal free-stream Mach numbers from 0.5 to 2.0. For current tests, a Mach number 2.0 nozzle was used. The total pressure of free-stream was 208 kPa, and the total temperature was 300 K. The unit Reynolds number was $2.5 \times 10^7\ m^{-1}$. During inlet mode transition tests, the angle of attack and yaw angle were 0°.

Time-accurate pressure measurements were performed by six dynamic pressure transducers to monitor unsteady flow patterns of the inlet. The probes of dynamics pressure transducers are shown in Fig. 1. There are two dynamic pressure transducers in the third compression ramp (R3-R4), three in the lower surface of the diffuser (D1-D3), and one in the upper surface of the diffuser (U1). These transducers have an accuracy of $\pm 0.1\%$ of the full range and a natural response frequency of 50 kHz. The dynamic pressure along the surface was measured by a TST5913 data acquisition system. The data

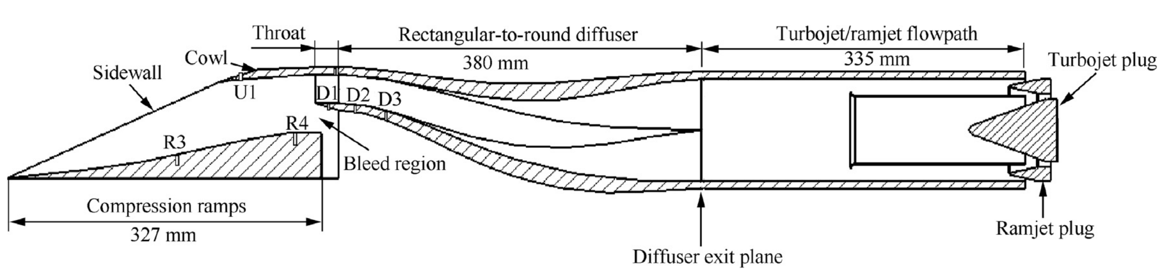

Fig. 1 Sketch of TBCC inlet model.