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Short communication

Experimental exploration of inlet start process in continuously variable Mach number wind tunnel

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ABSTRACT

The flow structures of the inlet in continuously variable Mach number inflow are studied experimentally to evaluate accurately the performance of scramjet inlet during acceleration/deceleration in ground experiments. To break the limitation in which majority of supersonic wind tunnels operate at a fixed Mach number condition, a continuously variable Mach number wind tunnel has been built. The running Mach number of the wind tunnel varies continuously from 2.0 to 3.0 under suction mode. The experiments of the inlet at fixed and variable Mach number inflows are conducted successively in the continuously variable Mach number wind tunnel. In the fixed Mach number experiment, the typical flow structures of the inlet under the unstart/start conditions are captured. The pressure distributions on the lower wall of the inlet, which were obtained from the experiments, are consistent with numerical ones. Thus, the effectiveness and accuracy of the experiments and numerical simulations were verified. In the continuously variable Mach number wind tunnel experiment, we found the inlet suffers from four flow structures. With the exception of typical unstart/start flow structures, the inlet undergoes pseudo unstart/start conditions under the influence of the wind tunnel unstart. By analyzing the pressure and Schlieren result, variations in the flow structures are observed in detail, which can provide useful references for the subsequent experiments in continuously variable Mach number wind tunnels. In particular, pseudo unstart/start conditions must be distinguished from real ones in the case wrong experimental data are obtained in the following experiments.

1. Introduction

The inlet is widely known to be an important component in the scramjet engine. The starting characteristics of the inlet have a significant effect on the performance of scramjet. A variety of research has been conducted to obtain the starting characteristics or prevent the inlet from unstart mode [1–5]. In recent years, experiments that focus on the inlet at the fixed free stream Mach number have been conducted widely, which can help researchers grasp a broad understanding of the flow mechanisms of the inlet. However, fixed Mach number experiments cannot present the actual flight conditions for the inlet. Hence, understanding inlet flow structures comprehensively is difficult. Therefore, inlet performance in the continuously variable Mach number inflow, which is studied mainly through numerical simulations owing to the lack of necessary experimental facilities, attracted scholarly attention. This paper will focus on the experimental exploration of the inlet in the continuously variable Mach number wind tunnel in relation to the previous research conducted by our group [6,7]. The flow structures of the inlet under the continuously variable Mach number inflow can be observed in detail. This paper also offers novel experiences for the following experiments in the continuously variable Mach number wind tunnel.

In terms of numerical simulations, Wang [8] studied the impulse starting characteristics of the inlet using numerical simulation methods, and found the starting duration increases with the decrease in the free stream Mach number. Wang concluded that the accelerating performance of the booster has nearly zero influence on the self-starting ability of the inlet. Jiao [9] investigated the pulse-starting characteristics of the hypersonic inlet using numerical simulation methods, which differs from that of Wang's. Jiao posits that the free stream Mach number is higher than the design value. He also explored the effects of the initial back pressure and temperature of the test section on the hypersonic inlet pulse-starting characteristics. The above-mentioned authors studied mainly the influence of impulse on the starting characteristics. The Mach number of the inflow increased suddenly to the specified one, which cannot reveal the performance of the inlet in the flight trajectory. Su [10] utilized numerical simulation methods to

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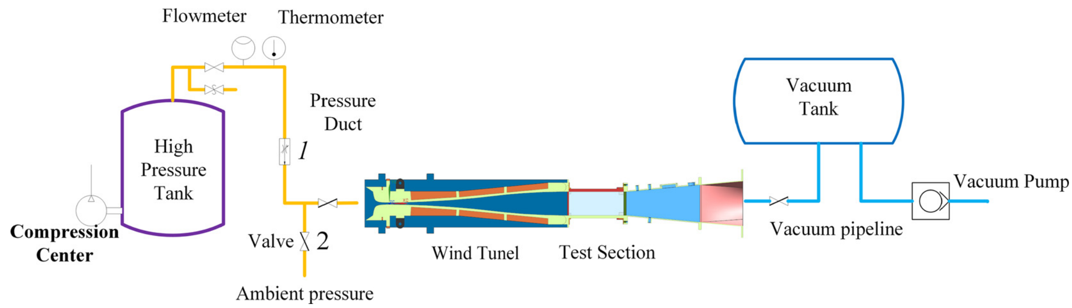

Fig. 1. Configuration of the continuously variable Mach number experimental platform.

study the influence of the acceleration of the Mach number and trajectories on the inlet restarting capacity and concluded that acceleration can remarkably affect the restarting process. However, in the field of the experiments, relevant literature on inlet experiments in the continuously variable Mach number inflow is relatively few. The main reason lies on the limitation of the wind tunnel. Majority of the current wind tunnel can only produce the supersonic flow with the fixed Mach number. In relation to the relevant experiments related to the inlet and wind tunnel together, studies are relatively few. A typical example can refer to Wang's study [11]. Wang investigated the starting process of the inlet in the free-jet wind tunnel and obtained the influence of the starting procedure of the wind tunnel on inlet performance. However, the effect of the continuously variable Mach number inflow on the inlet is not mentioned.

In the present study, the experimental exploration of the inlet in the continuously variable Mach number wind tunnel is conducted. The Mach number of the wind tunnel can vary from 2.0 to 4.0 in theory. Compared with the experiment in the fixed Mach number wind tunnel, the experiments conducted in continuously variable Mach number wind tunnel can reproduce the variations in the flow structures of the inlet in actual flight circumstances. First, the experimental setup and numerical approach are introduced. Then, the result of the inlet in the fixed Mach number inflow is obtained using numerical simulation methods and experiments, respectively, to validate the accuracy and effectiveness of the two methods. Next, the experiment on the inlet in the continuously variable Mach number wind tunnel is conducted. The flow structures in the experimental process are observed in detail, which yields the results for the following variable Mach number experiments of the inlet.

2. Experimental setup and numerical approach

2.1. Continuously variable Mach number wind tunnel

The experiments of the inlet model under the continuously variable Mach number inflow are conducted in the continuously variable Mach number supersonic wind tunnel, which is built in Nanjing University of Aeronautics and Astronautics. The design, geometric structure, and experimental calibration of the wind tunnel can be found in Ref. [6]. The wind tunnel utilized in this study adopts the direct-connect configuration instead of the free-jet operation mode, which was adopted in the wind tunnel introduced in Ref. [6] to reduce experimental cost. The nominal operating Mach number of the wind tunnel varies from 2.0 to 4.0. The cross-section area of the wind tunnel test section is 120 × 160 mm. To conduct the optical measurement, the test section of the wind tunnel is assembled into four pieces of K9 optical glasses. To achieve the goal that the Mach number of the supersonic flow generated by the wind tunnel should alter continuously and accurately during the experiments, the opposite walls of the facility nozzle are rotated around the fulcrum located at the exit of the tunnel. In addition, a home-made control system is developed to rotate the walls. The active force is provided by the servo motor (Panasonic Inc., A52 series). Moreover, the contour lines of the wind tunnel are elaborately designed accompanied by the optimization method, which guarantees the accuracy and uniformity of the Mach number of the supersonic flow generated by the wind tunnel.

Table 1
Typical calibration result of the continuously variable Mach number wind tunnel.

Ma	$\overline{Ma}_E$	σ_E
2.0	1.9910	0.0077
2.5	2.5011	0.0134
3.0	2.9957	0.0082

Fig. 1 illustrates the configuration of the continuously variable Mach number experimental platform, which is composed of a high-pressure tank, wind tunnel, vacuum tank, and valves. Under this configuration, high-pressure gas supplied by the compressors supports wind tunnel operation. The maximum total pressure can reach up to 1 MPa, and mass flow rate can be kept constant at 1 kg/s. To reduce the experimental cost, the experimental platform can work under suction mode by switching the opening of valves 1 and 2. Then, the wind tunnel inlet connects directly to the ambient gas. In that operation mode, the maximum Mach number the wind tunnel can achieve is 3.0. Calibration experiments have been conducted previously, the details of which can be found in the Master's thesis of Qi [12]. Table 1 shows a typical calibration result, where $\overline{Ma}_E$ is the average Mach number and σ_E is the standard deviation. In Table 1, the uniformity and accuracy of the Mach number of the supersonic flow can be verified.

2.2. Inlet model

Fig. 2 displays the geometric details of the inlet model. It has a single ramp with $\delta = 11°$. The included angle of the ramp and cowl is 3°. A constant cross-sectional duct, which acts as the isolator, is constructed behind the inlet throat. The height and length of the isolator are h_t and $10.63h_t$, respectively. The total length of the test model is $23.2h_t$. The internal contraction ratio of the inlet is 1.16. Fig. 3 illustrates the three dimensional shapes of the inlet model, which has no sidewall compression. The aspect ratio of the inlet model is 2.56. Besides, to obtain a detailed flow field in the inlet model, two pieces of K-9 optical glasses are mounted at the inner sides of the inlet sidewalls.

2.3. Measurement facilities

The inner flow field of the inlet model is captured by the 300-cm-aperture Z-Type Schlieren visualization system. The Schlieren measurements rely on the intensity of the density gradient of the flow field. The variations in the flow structure are illustrated by the captured pictures. A surface pressure measurement is also