Aerodynamic Force Measurement Techniques in JF12 Shock Tunnel

YF. Liu, YP. Wang, CK. Yuan, CT. Luo, and ZL. Jiang

Abstract An aerodynamic force test was conducted in JF12 long-test-time shock tunnel. The test time of JF12 is 100–130 ms. The nominal Mach number is Ma7.0 and the exit diameter of the contoured nozzle is Φ2.5 m. The total enthalpy is 2.5 MJ/kg which duplicates the hypersonic flight conditions of Ma 7.0 at 35 km altitude. The test model is the standard aerodynamic force model of 10° half-angle sharp cone. The length of the test model is 1.5 m and the weight is 57 kg. The aerodynamic forces were measured with a six-component strain balance. The experimental results show that in the 100–130 ms test duration, the signals of strain balance have 3–4 complete vibration cycles. The aerodynamic force coefficients of JF12 are in good agreement with that of conventional hypersonic wind tunnels. This research demonstrates that aerodynamic force test can be conducted in shock tunnel with test time longer than 100 ms.

1 Introduction

Conventional hypersonic wind tunnels usually produce test flows with low total temperature and low sound speed; therefore, the thermochemical reaction, one of the key mechanisms in hypersonic flows, is ignored in its experiments. As a result, the real-gas effects on the aerodynamic force and moment measurement become a very difficult problem in the hypersonic ground tests and were identified as an unknown "unknown" [1]. At an enthalpy of about 3 MJ/kg or higher, air molecules become vibrationally excited, dissociated, and ionized behind a shock wave. These real-gas phenomena absorb heat. As a result, the effective specific heat ratio decreases and compressibility increases.

Y. Liu (✉) · Y. Wang · C. Yuan · C. Luo · Z. Jiang
Institute of Mechanics, Chinese Academy of Sciences, Beijing, China

School of Engineering Sciences, University of Chinese Academy of Sciences, Beijing, China
e-mail: liuyunfeng@imech.ac.cn

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These phenomena cause changes in pressure distribution and thereby aerodynamic characteristics of the hypersonic vehicle. To design an efficient hypersonic vehicle, the influence of real-gas effects on force and moment must be known accurately. To experimentally verify the accuracy of those design parameters, wind tunnel tests are needed. To produce flows with desired temperature, Mach number, and Reynolds number in the test section, such tunnels must be operated at very high enthalpies and reservoir pressures [2, 3].

Considering the thermochemistry in hypersonic flows, high-enthalpy shock tunnels are capable of generating high-temperature flows, but its effective test duration is too short to do force and moment measurement. Under the support of National Major Project of Scientific Instrumentation Research and Development, a super-large detonation-driven shock tunnel was developed based on backward-running detonation driver in Institute of Mechanics, Chinese Academy of Sciences in 2012 [4, 5]. It has the capability of reproducing pure airflows with Mach numbers from 5 to 9 at an altitude of 25–50 km. More important, it has a test duration of more than 100 ms which makes it the first shock tunnel in the world to conduct aerodynamic force and moment measurement by using conventional strain balances.

The force and moment measurement of hypersonic vehicles is one of the main long-term research projects of JF12 shock tunnel in order to study the aerodynamic characteristics under real-gas conditions. In this paper, as the first step of this project, we conducted the force and moment measurement of 10° half-angle sharp cone at Mach 7.0 under the duplicated hypersonic flight conditions of about 35 km altitude with the total enthalpy of 2.5 MJ/kg. The aim of this paper is to examine whether JF12 can be used to conduct force measurement and obtain high accuracy data in 100 ms test time. The primary experimental results are given and compared with conventional hypersonic wind tunnel results. This research will be continued further in JF12 shock tunnel under high-enthalpy conditions.

2 Experimental Setup and Test Model

The picture of JF12 long-test-time shock tunnel is shown in Fig. 1. The total length of the facility is 265 m. It consists of five main parts. From right to left, they are E-shaped vacuum tank and test section, nozzle, driven section, detonation driver section, and damping section. The contoured nozzle is 15 m long with an exit diameter of Φ2.5 m. The nominal Mach numbers are Ma5–7 with exchangeable throats. The driven section is 89 m in length and Φ720 mm in inner diameter. The detonation driver is 99 m in length and Φ400 mm in inner diameter. The driver is operated in the backward-running detonation mode. The detonation driver and the driven section are connected with a transition section by which the tube diameter is gradually reduced from Φ720 mm to Φ400 mm. There is a diaphragm rig between the detonation driver and the transition section, which is used to produce the proper incident shock wave in the shock tunnel after the direct detonation initiation.

Fig. 1 Photo of JF12 long-test-time shock tunnel

Fig. 2 The 10° half-angle cone model installed in JF12 shock tunnel

The test model is a 10° half-angle sharp cone, and it is a standard aerodynamic force model. There are many experimental results obtained in conventional hypersonic wind tunnels to compare with. The length of the model is 1.5 m with a base diameter of Φ528 mm. It is made of aluminum alloy and weighs 57 kg. Figure 2 is the photo of test model installed in JF12 shock tunnel. Pressure transducers were also installed on the bottom surface to measure the base pressure of the model during the experiments. Up to now, it is the biggest and most heavy aerodynamic force model in shock tunnel in the world.

Fig. 3 The six-component strain balance designed for JF12 shock tunnel

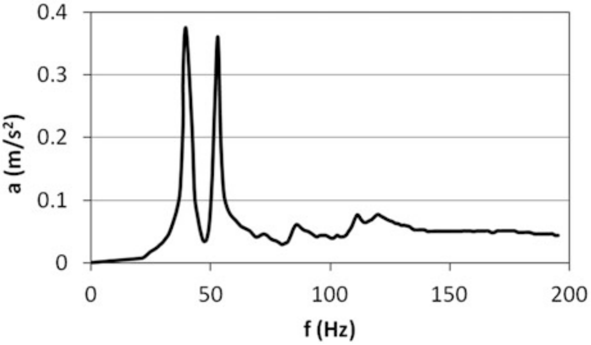

Fig. 4 The normal vibration frequency of JF12 model supporting system

A six-component strain balance specially designed for JF12 shock tunnel was used to measure the aerodynamic force and moment. Figure 3 shows the photo of this strain balance. The maximum diameter of this balance is Φ106 mm. In the JF12 shock tunnel experiments, the mechanical vibration of the test model, the balance, and the sting will not be damped within the test time of 100 ms. Therefore, the balance output signals contain inertial force. In order to reconstruct the force and moment from the balance output signals and obtain high quality data, we must make sure that we can get at least 3–4 complete vibration periods in the 100 ms test time. Therefore, the balance was designed with high stiffness. In addition, the strength of the sting and model supporting system was also strengthened.

Before the wind tunnel experiments, the vibration frequency of model supporting system of JF12 shock tunnel was measured by dynamic calibration with fracture-stick technique. The model supporting system includes the model, the balance, the sting, and the supporting equipment. The sting was made of alloy steel with a diameter of Φ100 mm. The vibration frequency in the normal direction was recorded by accelerometers, and the results are shown in Fig. 4. From Fig. 4 we can see that the first order modal frequency is about 40 Hz, which means that we can get at least four complete vibration periods in the normal force direction within 100 ms test time. In the axial force direction, the first order modal frequency is more than 100 Hz. So, at least ten complete vibration periods can be obtained in 100 ms test time.

In this study, the nominal Mach number of the nozzle is Ma 7.0. The total enthalpy is 2.5 MJ/kg, and the total pressure is 3.0 MPa, which duplicates the flight conditions at about 35 km altitude. The test conditions were monitored by Pitot probes in each run. The free stream is assumed to be in equilibrium, and the parameters were calculated by considering real-gas effects in the stagnation chamber. The angles of attack were set to be −5°, 0°, 5°, 10°, and 14°, respectively. The angle of sideslip was zero. The runs at 5° angle of attack were repeated six times and the runs at other angles of attack were repeated three times in order to study the repeatability precision of force and moment measurement.

3 Results and Discussion

The typical output signals of the balance are shown in Fig. 5, including the axial force, normal force, and pitching moment. It can be seen clearly that the balance signals can be divided into two parts. In the first 30 ms, the signals are irregular, which means that the model undertakes irregular mechanical vibration. This is caused by the unsteady establishment process of the flow field. This unsteady starting process can also be confirmed by the base pressure signals of the model, which are shown in Fig. 6 here. Therefore, the results in this starting process cannot be used to calculate the aerodynamic force and moment.

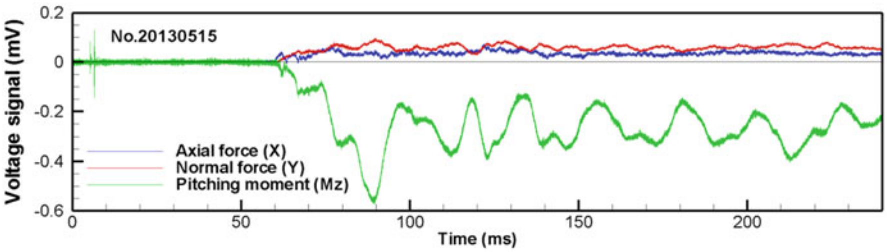

Fig. 5 Balance output signals of JF12 shock tunnel

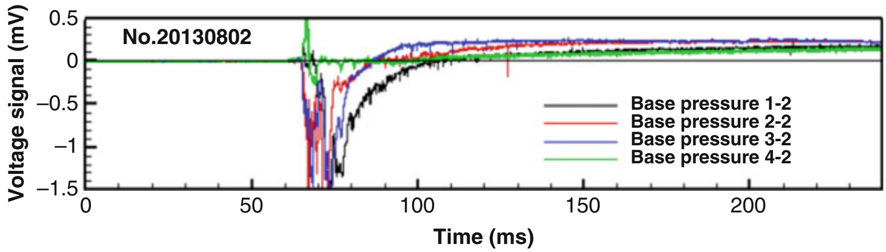

Fig. 6 Base pressure signals of JF12 shock tunnel

After the unsteady starting process, the output signals of the balance become regular, and there are at least three complete periodical cycles within the 100 ms test duration. The forces measured by the balance contain aerodynamic force and inertia force. The inertia force can be easily removed by averaging the balance signals. Therefore, we do not need to use acceleration compensation method to reconstruct the aerodynamic forces and moments. It means that the high accurate data could be obtained with this conventional strain balance by applying simple data processing techniques. As to the axial force, its high frequency oscillations make sure that there are more than ten periodical cycles to achieve high accurate data. The periodicity of the balance signal data from the JF12 shock tunnel indicates that its accuracy could be as high as that of conventional hypersonic wind tunnels.

The normal force coefficients and axial force coefficients at different attack angles are plotted in Figs. 7 and 8. The average results of FD-07, FD-03, and Langley 11-inch conventional low-enthalpy hypersonic wind tunnels are also shown in these figures for comparison [6]. All the JF12 experimental results are plotted in these figures, while only the average results of other wind tunnels are given. First of all, we can find that the force measurement data of JF12 shock tunnel has high repeatability precision. The repeatability error of normal force coefficient is less than ±1.0%. The repeatability error of axial force coefficient is less than ±2.0%.

From Figs. 7 and 8 we can see that normal force coefficients Cn of JF12 at different angles of attack agree very well with the results of other conventional hypersonic wind tunnels with a discrepancy of less than 1%. The coefficient of

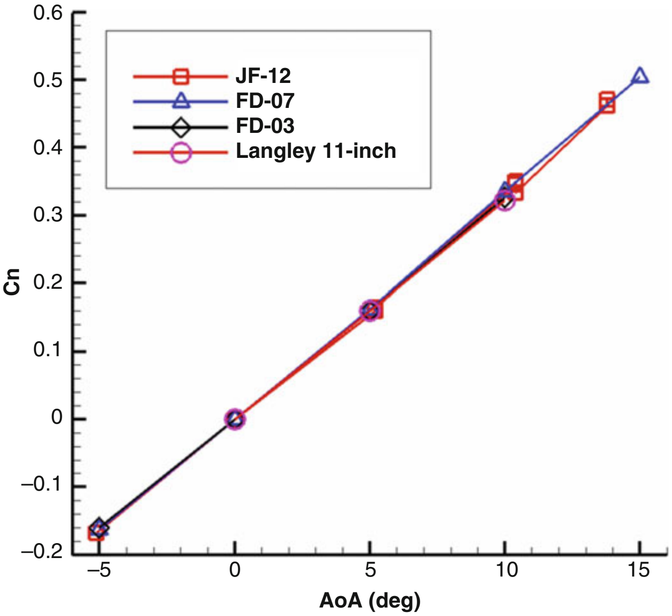

Fig. 7 The normal force coefficients at different attack angles

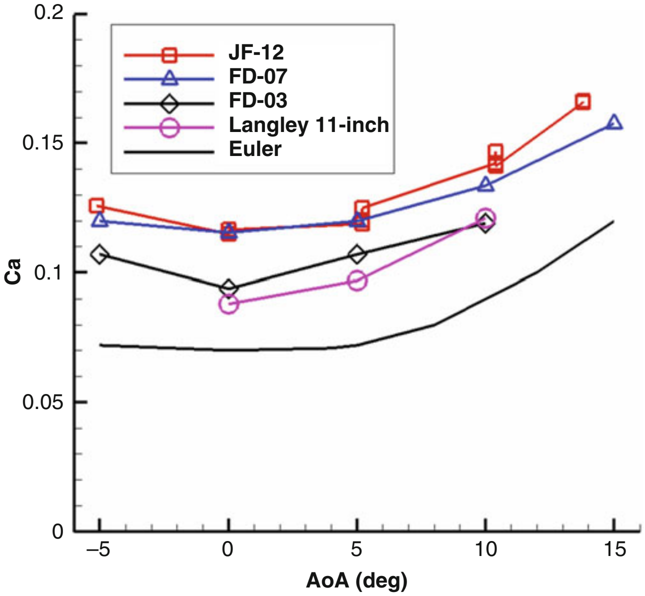

Fig. 8 The axial force coefficients at different attack angles

pressure center Xcp is also in accordance with the theory result of Xcp = 0.6874. The axial force can be divided into two parts: one is the pressure force and the other is the friction force. In Fig. 8, the axial force coefficients calculated by Euler equations are also shown. The difference between the experimental results and Euler results is the friction force coefficients. For the laminar boundary layer, the friction force coefficient is inversely proportional to the square root of the Reynolds number ReL based on the length of the model.

4 Conclusions

Aerodynamic force and moment measurements of a 10° half-angle sharp cone were carried out in JF12 shock tunnel at Mach 7.0 under the duplicated hypersonic flight conditions of about 35 km altitude. The results show that high accuracy force measurement data can be obtained in JF12 shock tunnel. The maximum repeatability error is less than 2%. The experimental results are in good agreement with that of conventional hypersonic wind tunnels. The discrepancy of normal force coefficients between JF12 and conventional hypersonic wind tunnels are less than 1%. These results demonstrate that aerodynamic force measurement by conventional strain balances can be conducted in shock tunnel which has a test time longer than 100 ms.

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