Experimental Investigations on Aerodynamic Characteristics of Parachutes in Mars Probe Decelerator System

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Keywords: Aerodynamic performances, Parachutes, Mach, Transonic wind tunnel, Angle of attack.

Abstract. An experimental study is conducted to characterize the aerodynamic performances of two parachutes in the Mars probe decelerator system and the experiments are carried out in the 2.4 m×2.4 m transonic wind tunnel. The lift, drag and pitch moment coefficients versus the angle of attack from 0 to 25 degrees at Mach 0.4 and 0.8 are accurately measured and carefully analyzed. A novel mathematical model is proposed to express the aerodynamic characteristics of the parachutes. The obtained results show that the drag coefficient of the parachutes varies in a small range of 0.525~0.575 at Mach 0.4 and 0.8 as the angle of attack increases from 0 to 25 degrees. The simulated results of the propose model have a well agreement with the wind tunnel experimental data. The investigations in the present paper have a good significant to the engineering development of the parachutes in Mars probe decelerator system.

Introduction

The Parachutes have been widely used with a variety of loads due to their abilities to slow the motion of an object through the atmosphere by creating drag forces [1, 2]. To obtain the accurate aerodynamic characteristics of the parachute is very significant for its application, such as decreasing the landing velocities of aircraft and spacecraft [3, 4].

There are two approaches to gain the aerodynamic coefficients of a parachute, one is the numerical computation [5-16] and the other is the wind tunnel test [17, 18]. Among the parachute’s descent process of deployment, inflation and terminal, the aerodynamic performances are so complex that the numerical computation method is usually not correct. For many years, the wind tunnel tests have proven to be an invaluable, accurate and cost-effective tool to obtain the aerodynamic behaviors of a parachute [19]. The lifting parachutes with lift-to-drag ratios of 0.5-0.7 were tested in the Vought Corporation 7×10-ft low speed wind tunnel and the static, inflation and dynamic forces are obtained by Klimas et al. [20]. An experimental study was conducted to characterized the flow structures in the turbulent wake of a cross parachute canopy by Jin et al. [21]. The Stereoscopic Particle Image Velocimetry technique was utilized in his research and the flow structures of the cross parachute were measured and analyzed. Besides the common parachutes used in aircrafts and missiles, the parachutes adopted in Mars exploration missions have also been studied in wind tunnel tests by NASA [22, 23] and Mars Science Laboratory [24-26]. Most of the previous publications about the aerodynamic characteristics of the parachutes were numerical and simulate. And only some of the parachutes for Mars Exploration were experimented in wind tunnels. Moreover, most of the wind tunnel tests were carried out under the condition of low speed environments and zero attack angle [27].

In the present paper, the wind tunnel experiments of two parachutes used in the Mars probe decelerator system are performed at Mach 0.4 and 0.8 with the attack angle from 0 to 25 degrees in
the 2.4 m×2.4 m transonic wind tunnel. The tested two parachutes are made from Kevlar. One of them is the low air permeability and the other is the general air permeability. In addition, in order to ensure the smooth conduct of the experiments, an improved support structure of the parachutes in large transonic wind tunnels is also depicted in the present paper. Summing up, the purposes of this paper are (i) to describe the performances of the wind tunnel, the structural parameters of the tested parachutes and the experimental details (Section 2), (ii) to analyze and discuss the measured data of the aerodynamic characteristics (Section 3), (iii) to give some conclusions in the last (Section 4).

Experimental Study

The abilities of the wind tunnel, the structures of the tested objects and the experimental processes are closely related to the correctness of the measured data. In this section, the wind tunnel and the tested parachute models are represented. The details of the wind tunnel experiments are also given in Section 2.

Wind Tunnel

The aerodynamic tests of the parachutes are conducted in the 2.4 m×2.4 m transonic wind tunnel (shown in Figure 1), located at CARDC in Mianyang. The 2.4 m×2.4 m transonic wind tunnel is an ejector-driven semi-circuit, intermittent facility and was put into use at the end of 1999. The force and pressure tests with full model, half model and components could be performed in it. The special tests of buffet, flutter, and dynamic derivative can also be carried out and many flow visualization technologies have been used to render the results, such as PSP, PIV, colored oil flow, laser vapor screen and so on. The size of the test section is 2.4 m×2.4 m, which is sufficient to allow the testing of the reasonably-sized models that closely resemble their full-scale counterparts, without excessive blockage of the test section. The total pressure is 1.1×10^5 Pa~4.5×10^5 Pa, the velocity pressure is 0.068×10^5 Pa~1.94×10^5 Pa and the range of Reynolds number is from 1.76×10^6 to 17.00×10^6 with the reference length of 0.24 m. The Mach number range of the 2.4 m×2.4 m transonic wind tunnel is from 0.3 to 1.4, and it could be able to provide a transonic and supersonic test environment. The present tests of the parachutes are performed at Mach 0.4 and 0.8, meeting the test conditions of the 2.4 m×2.4 m transonic wind tunnel.

Parachute Models

In the present study, two types of parachute models used in the Mars probe decelerator system are experimented in the present paper. The two parachutes are both made from Kevlar, one is low air permeability and the other is general air permeability. The canopy is attached by 12 nylon suspension lines to a stationary streamline forebody. The suspension lines could provide the necessary force to restrain the canopy wandering without adversely affecting other aeroelastic effects. The structural parameters of the two parachutes are same.

The projection area of the parachutes is 0.288 m^2, the nominal area is 0.5878 m^2, the nominal diameter is 0.8651 m, the length of the suspension lines is 1.4706 m, and the blocking ratio is 5%. The connection strap of the suspension lines is of 0.42 m length and it is fixed to a designed rotor structure which could keep the parachute spinning around the body axis line freely in the blowing
processes. When the parachutes are inflated, the axial length is about 1.8 m. The sketch of the parachutes is displayed in Figure 2.

![Figure 2. Sketch of parachutes.](image)

**Experimental Setup**

In the present study, an ejector-driven semi-circuit wind tunnel located at CARDC is used to perform the experimental investigations. In order to carry out the tests of parachutes with attack angles, a novel parachute attachment mechanism capable of handling the aerodynamic loads with an adequate safety factor was designed. And the risks, which is associated with the parachute failures during the experimental process, primarily in regard to the potential for the facility damage, have been understood and controlled exhaustive.

Two force-measured sensors are installed to obtain the lift, drag and pitch moment coefficients, one is 4N6-70E and the other is 4N6-64E. 4N6-70E is mounted in front of the connection strap and 4N6-64E is positioned at the back of the canopy. The static states of the experimental system at the attack angle of 0 degree and 25 degrees are given in Figure 3.

![Figure 3. Static states of the experimental system.](image)

The aerodynamic characteristics of two parachutes used in the Mars probe decelerator system are investigated at Mach 0.4 and 0.8 with the attack angle from 0 to 25 degrees, i.e. 0, 2.5, 5.0, 7.5, 10, 12.5, 15.0, 20.0, and 25.0 degrees. In the process of the wind tunnel tests, the state of the parachute is shown in Figure 2. The values directly measured by the force-measured sensors are the axial force coefficient $C_T$, the normal force coefficient $C_N$ and the pitch moment coefficient $C_m$. Then lift and drag coefficients $C_L$ and $C_D$ can be given as

$$
\begin{align*}
C_L &= C_N \cos \alpha - C_T \sin \alpha \\
C_D &= C_N \sin \alpha + C_T \cos \alpha
\end{align*}
$$

where $\alpha$ is the angle of attack.
Results and Discussions

The wind tunnel testing technology is the most effective and reliable way of obtaining the aerodynamic characteristics of aircrafts [28, 29], spacecrafts [30], missiles, parachutes and so on. During the experiments, the total pressure and the temperature were kept at 110KPa and 287K, respectively. The measured data were sampled at 300 Hz and handled by 1 Hz lowpass filter. The directly obtained data include the influences of two parts: the contributions of the parachute and the effects of the attachment mechanism. The lift, drag and pitch moment coefficients of the low air permeability and the general air permeability parachutes at Mach 0.4 and 0.8 are display in Figure 3, Figure 4 and Figure 5, separately.
As is seen in Figure 3, the lift coefficients at Mach 0.4 are smaller than that at Mach 0.8 and the lift coefficients of the general air permeability parachutes are larger than that of the low air permeability parachutes. The lift coefficients become smaller as the attack angle increases from 0 to 15 degrees for all the four cases showed in Figure 3. In Figure 4, the drag coefficients of the general and low air permeability parachutes at Mach 0.4 vary in a small range from 0.525 to 0.575 as the attack angle increases from 0 to 25 degrees. And for the case of Mach 0.8, the drag coefficients are nearly the same between the attack angle 0 and 10 degrees. In addition, the drag coefficients increase expeditiously as the attack angle varies from 10 to 20 degrees. From Figure 5, we can see that the pitch moment coefficients decrease as the angle of attack increases from 0 to 25 degrees. With the same attack angle, the pitch moment coefficient of the low air permeability parachute at Mach 0.4 is the largest one and that of the general air permeability parachute at Mach 0.8 is the smallest one. The pitch moment coefficients of the general air permeability parachute at Mach 0.4 is the same as the low air permeability parachute at Mach 0.8.

In order to characterize the aerodynamic performances of the parachutes used in Mars probe decelerator system furtherly, the angle of attack and the Mach number are considered as the input variables and the aerodynamic coefficients are denoted as the output functional values. An aerodynamic model is proposed in the present paper, which is given as follow:

\[
\begin{align*}
C_L &= a_1 + b_1 \alpha + c_1 \alpha^2 + d_1 \alpha^3 + e_1 M + f_1 \alpha M + g_1 M^2 \\
C_D &= a_2 + b_2 \alpha + c_2 \alpha^2 + d_2 \alpha^3 + e_2 M + f_2 \alpha M + g_2 M^2 \\
C_m &= a_3 + b_3 \alpha + c_3 \alpha^2 + d_3 \alpha^3 + e_3 M + f_3 \alpha M + g_3 M^2
\end{align*}
\]

where \(C_L\) is the lift coefficient, \(C_D\) is the drag coefficient, \(C_m\) is the pitch moment coefficient, \(\alpha\) is the angle of attack, \(M\) is the Mach number, \(a_i, b_i, c_i, d_i, e_i, f_i, g_i\) \((i = 1, 2, 3)\) are unknown parameters which could be determined by the wind tunnel experimental data. The parameters can be solved by the given optimization problem:

\[
\min J = \sum |C_{L, \text{Cal}} - C_{L, \text{Exp}}|^2 + \sum |C_{D, \text{Cal}} - C_{D, \text{Exp}}|^2 + \sum |C_{m, \text{Cal}} - C_{m, \text{Exp}}|^2
\]

where \(C_{L, \text{Cal}}\), \(C_{D, \text{Cal}}\) and \(C_{m, \text{Cal}}\) are the simulated results, \(C_{L, \text{Exp}}\), \(C_{D, \text{Exp}}\), and \(C_{m, \text{Exp}}\) are the measured data. Eq. (3) is solved by the nonlinear least square method and the obtained parametric values are listed in Table 1. Furthermore, the simulated results at Mach 0.4 and 0.8 are compared with the experimental data, which are respectively illustrated in Figure 6, Figure 7, Figure 8 and Figure 9.
Table 1. Identified parameters.

|   | $a_i$  | $b_i$  | $c_i$  | $d_i$  | $e_i$  | $f_i$  | $g_i$  |
|---|--------|--------|--------|--------|--------|--------|--------|
| 1 | 8.144  | -0.0074| 1.5215e-4| 2.9654e-6| -30.5979| 0.0044| 25.5249|
| 2 | -0.6372| -0.0061| 3.8171e-4| -1.1605e-5| 4.5463| 0.0083| -3.9806|
| 3 | -1.2486| -8.4649e-4| -5.0332e-4| 1.1339e-6| 4.7284| -0.0067| -3.9506|
| 1 | 4.2044| -0.0114| -2.597e-4| 1.8799e-5| -15.789| 0.0118| 13.1593|
| 2 | 9.6629| -0.0066| 6.2228e-4| -1.7758e-5| -33.9197| 0.0042| 27.9776|
| 3 | 4.6106| 0.0033| -6.8959e-6| -1.7541e-5| -17.2824| -0.0117| 14.4054|

Figure 6. Compared results of general air permeability parachute at Mach 0.4.

Figure 7. Compared results of general air permeability parachute at Mach 0.8.

Figure 8. Compared results of low air permeability parachute at Mach 0.4.
Figure 9. Compared results of low air permeability parachute at Mach 0.8.

From Figure 6, Figure 7, Figure 8 and Figure 9, the proposed aerodynamic model can express the aerodynamic characteristics of the two parachutes. Using the parameters listed in Table 1, the calculated results of the lift, drag and pitch moment coefficients agree well with the wind tunnel experimental data, both for the general air permeability parachute and the low air permeability parachute at Mach 0.4 and 0.8. It can be easily found that the aerodynamic model, expressed by Eq. (2), has a wide range of applicability and describe the aerodynamic performances of the parachutes.

Above all, the aerodynamic features of the parachutes are analyzed and discussed. A polynomial model is adopted to express the aerodynamic performances of the parachutes, such as the relationship between the lift coefficient and the attack angle, Mach number. The results show that the drag coefficient of the parachutes varies in the range of 0.525–0.575 as the attack angle increases from 0 to 25 degrees.

Conclusions

In order to obtain the aerodynamic characteristics of the parachutes utilized in Mars probe decelerator system, two kinds of parachutes are tested at Mach 0.4 and 0.8 in the 2.4 m×2.4 m transonic wind tunnel. The lift, drag and pitch moment coefficients are measured and the aerodynamic characteristics of the two parachutes are analyzed and discussed. A polynomial model is proposed to describe the aerodynamic performances of the parachutes, i.e. the general air permeability parachute and the low air permeability parachute. The results show that the drag coefficient of the general air permeability parachute and the low air permeability parachute varies in a small range of 0.525–0.575 at Mach 0.4 and 0.8 as the angle of attack increases from 0 to 25 degrees. The simulated results of the propose model have a well agreement with the wind tunnel experimental data. The investigations in the present paper have a good significant to the engineering development of the parachutes in Mars probe decelerator system.

Acknowledgement

The authors want to thank Beijing Institute of Space Mechanics & Electricity for the supports of the experiments.

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