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Supersonic Flow around a Body of Small Elongation

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Abstract—Some results of experimental studies conducted in a wind tunnel at the Mach number M = 1.78 for a blunt body of small elongation are discussed. The effect of the attack angle on the drag and lift coefficients as well as on the static stability and the pressure center position is considered.

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1. INTRODUCTION

In order to ensure the ballistic entry into planetary atmospheres, the configurations of modern space vehicles should have the shape of blunt bodies of small elongation. This shape improves the aerodynamic deceleration and the energy dissipation into the surrounding space. Many theoretical and experimental studies were conducted to analyze the aerodynamic characteristics of segmental bodies and blunt-nosed cones [1, 2]. The interaction between nonuniform supersonic flows and blunt bodies was examined (see, e.g., [3]). The radiation heat fluxes near space vehicles during the flight in the Venus' atmosphere were studied numerically in [4]. In recent years, research is constantly in progress to solve the problems of space flight mechanics. As an example, it should be mentioned that a flexible device for the precision-targeting Mars entry vehicles [5] and an airbag landing system for the Beagle 2 Mars probe [6] were experimentally studied.

At the Babakin Science and Research Space Center, now the studies are conducted on the use of airbag landing systems to deliver cargos from the planetary orbits [4]. In this paper we discuss some experimental results obtained for the case of supersonic flow around a model of a small Martian balloon station at the Mach number M = 1.78.

2. EXPERIMENTAL CONDITIONS

Our experiments were conducted using the A-8 supersonic wind tunnel installed at the Moscow University Institute of Mechanics [7]. The shape of the model for the small Martian balloon station under study is an axisymmetric blunt body with a spherical forebody of radius $R_1 = 80$ mm and with blunt side edges (Fig. 1). The Reynolds number based on the midsection diameter $D = R_1$ and on the incident flow parameters at M = 1.78 was equal to $\mathrm{Re} = 3.0 \times 10^6$. The angle of attack was taken from the range $0° \le \alpha \le 12°$. The geometric characteristics of the model were $L_1 = 0.44D$, $L_2 = 0.1225D$, and $R_2 = 0.125D$.

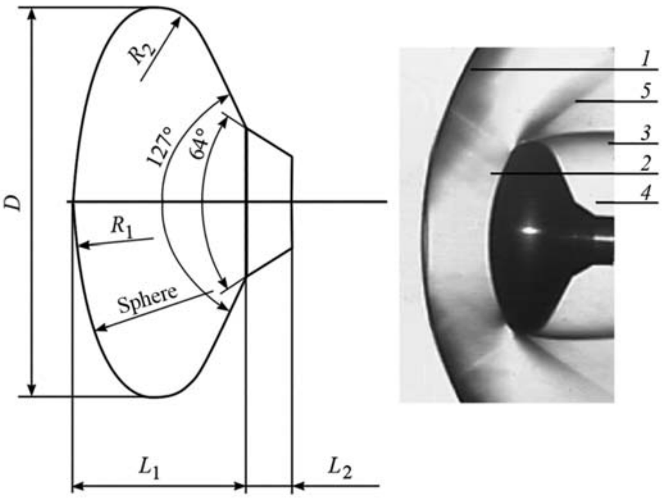

Fig. 1. Diagram of the small Martian balloon station and a photo visualizing the flow pattern at M = 1.78 and $\alpha = 2°$.

The aerodynamic force components were measured in a flow coordinate system with the use of an electromechanical balance [7]. The pitch moment was determined with respect to the tip of the model on the symmetry axis. In order to find the aerodynamic coefficients c_{xa}, c_{ya}, and m_z, the forces and the moments were nondimensionalized by the dynamic pressure, the area, and the midsection diameter D. The total root-mean-square error was less than 1% for the measurements of the drag coefficient c_{xa}. The measurement errors for the lift coefficient c_{ya} and for the pitch moment coefficient m_z were up to 4% of the range of these quantities; therefore, a number of retests were performed.

The IAB-451 schlieren system was used to visualize the flows.

3. EXPERIMENTAL RESULTS

A photo of the shadow pattern of flow around the model is presented in Fig. 1 for $\alpha = 2°$, where α is the angle of attack. This figure illustrates the bow shock wave *1*, the transonic region *2* in the shock layer, and the mixing layer *3* at the boundary of the bottom separation region *4* formed at the blunt side edge near the midsection of the body. The supersonic flow acceleration region is situated behind the transonic region; this acceleration region is formed on the rounded side edge and is ended by the oblique shock wave *5*. The subsonic flow region formed in the shock layer behind the detached bow shock lies within the spherical bluntness; therefore, the shock wave detachment is the same as in the case of flow around a sphere of radius $2R_1$.

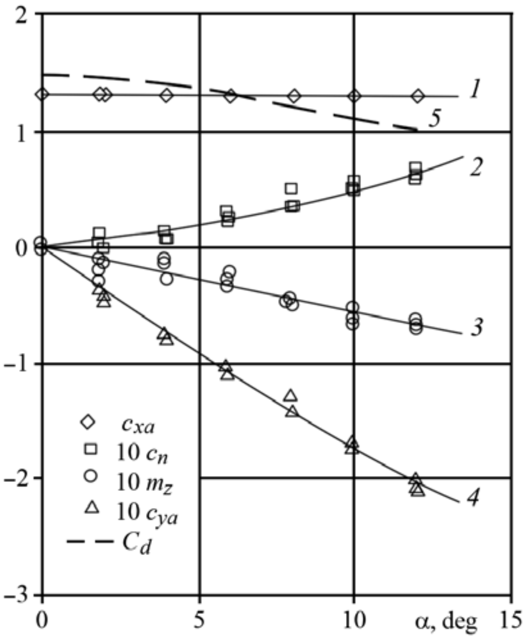

Fig. 2. The dependence of the aerodynamic coefficients on the attack angle: (*1*) c_{xa}, (*2*) c_n, (*3*) m_z, (*4*) c_{ya}, and (*5*) C_d.

Figure 2 illustrates some results of weight tests (the tenfold magnification is used for c_{ya} and m_z, since these quantities are small). The measurement results are marked, whereas the solid lines correspond to the smooth approximations of these data obtained by the least-squares method.

During the ballistic entry into the atmosphere, the drag force specifies the flight trajectory of a space vehicle. In addition, this force specifies the entry velocity, the aerodynamic heating, and the axial overload variations with time. Our tests show that the greatest values of c_{xa} are reached when the attack angle is equal to zero. The drag coefficient decreases insignificantly for $0° \leq \alpha \leq 12°$: $c_{xa} \approx 1.31 - 0.17\,\alpha^2$ (from here on, α is taken in radians in the approximation formulas). This result was compared with the experimental data obtained for cones with large apex angles [1, 2]. This comparison shows that the spherical bluntness has a little effect on the total drag of a space vehicle when the flight velocities and the apex angles correspond to the detached bow shock wave. In the case of similar segmental bodies, the values of c_{xa} increase by 5–7% over the entire range of M if D/R decreases from 1 to 0 [2].

The formula $c_{ya} \approx 2.057\alpha^3 - 1.054\alpha$ obtained during our study and illustrated by curve *4* in Fig. 2 shows that the lift force is negative. Such an abnormal behavior of the lift force can be explained by the peculiarities of flow around the model, since the redistribution of pressure on the blunt side edge near the bottom separation zone is of considerable importance (Fig. 1). Since the drag is large, the normal and lift forces are of opposite sign; this fact ensures the static stability of the small Martian balloon station in the case of supersonic flight. The following approximations are obtained for the normal force coefficient c_n and for the pitch moment coefficient m_z (curves *2* and *3* in Fig. 2):

$$c_n = c_{ya}\cos\alpha + c_{xa}\sin\alpha \approx 2.3\alpha^3 + 0.209\alpha, \qquad m_z \approx -0.2\alpha^3 - 0.31\alpha.$$

Now we consider the effect of the attack angle α on $C_d = -m_z/c_n$ (the pressure center position, curve *5* in Fig. 2). When α increases from 0° to 12°, the value of C_d decreases from 1.48 to 1.02; hence, the model is statically stable. However, this stability decreases when α increases. The segmental bodies and the blunt cones of small elongation can be close in shape to some deformed configurations of the balloon station under consideration. Comparing the values of C_d for our model and for other bodies of small elongation [1, 2], we can conclude that the attack angle and the Mach number have a low effect on the pressure center position situated behind the model.

Our studies show that the aerodynamic characteristics of the model satisfy the given trajectory parameters. The results we obtained can be used to verify the numerical methods developed to model the aerodynamics of landing space vehicles.

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