THEORETICAL STUDY OF SUPERSONIC UNSTEADY FLOW PAST BLUNTED BODIES

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THEORETICAL STUDY OF SUPERSONIC UNSTEADY FLOW PAST BLUNTED BODIES

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Let us consider the supersonic flow past a blunted body of revolution (for example, a sphere—cone) executing plane angular oscillations with frequency ω about some center located on the axis of symmetry, according to the law

$$\alpha = \alpha_0 \cos \omega t, \tag{1}$$

where α is the instantaneous value of the angle of attack; α_0 is the amplitude of the oscillations. In aerodynamics problems the conditions

$$\alpha_0 \ll 1, \qquad \alpha_0 \omega L / v_\infty \ll 1, \tag{2}$$

are usually satisfied with high accuracy; these ensure that the velocities of displacement of points of the body surface in the direction of the normal are small in comparison with the velocity of the oncoming flow v_∞ (L is a characteristic linear dimension).

The conditions (2) make it possible to restrict ourselves to a linear approximation in the oscillation amplitude (^{1}) and to represent the gasdynamic functions in the form

$$\begin{gathered} f = f_0 + \alpha f_\alpha + \dot{\alpha} f_{\dot{\alpha}}, \\ f = \dot{v},\ p,\ \rho. \end{gathered} \tag{3}$$

Fig. 1. Distribution of the coefficients of the rotational derivatives c_n^α, $\dot{c}_n^{\alpha(0)}$, $m_z^{\alpha(0)}$ and $\dot{m}_z^{\alpha(0)}$ along the generatrix of a blunted cylinder sphere ($\theta_s = 0°$) at Mach numbers $M_\infty = 3$ (solid curves) and $M_\infty = 20$ (dashed).

The parameters with subscript 0 describe the basic field arising in steady flow past the body; the parameters with subscripts α and $\dot{\alpha}$ describe the fields of unsteady disturbances that are in phase with the angle of attack α and the angular velocity $\dot{\alpha}$, respectively.

Fig. 1. Distribution of the coefficients of the rotational derivatives c_n^{α}, $\dot{c}_n^{\alpha(0)}$, $m_z^{\alpha(0)}$ and $\dot{m}_z^{\alpha(0)}$ along the generatrix of a blunted cylinder sphere ($\theta_s = 0°$) at Mach numbers $M_\infty = 3$ (solid curves) and $M_\infty = 20$ (dashed).

Figure 1: Fig. 1. Distribution of the coefficients of the rotational derivatives c_n^{α}, $\dot{c}_n^{\alpha(0)}$, $m_z^{\alpha(0)}$ and $\dot{m}_z^{\alpha(0)}$ along the generatrix of a blunted cylinder sphere ($\theta_s = 0°$) at Mach numbers $M_\infty = 3$ (solid curves) and $M_\infty = 20$ (dashed).

Figure 2

Figure 2: Figure 2

Substituting the expansion (3) into the system of gas-dynamic equations, written for absolute motion in a moving coordinate system rigidly attached to the body, and restricting ourselves to a linear approximation in the oscillation amplitude, we obtain a system of nonlinear partial differential equations for determining the steady flow field, as well as two linear systems describing the propagation of disturbances in phase with α and $\dot{\alpha}$ ([1]).

It should be noted that the method of treating unsteady disturbances in the linear formulation is widely used ([2,3] et al.); however,

for blunt bodies up to the present time solutions have not been obtained, owing to the great difficulties in determining the gas-dynamic functions of the steady flow.

The development of numerical methods has made it possible to solve the problem of the steady flow of a supersonic gas stream past blunt bodies both for the subsonic and for the supersonic regions of the flow.

In the present paper results are given of investigations of the unsteady characteristics of the flow past blunt bodies. The systems of differential equations and the boundary conditions for the supersonic unsteady flow past blunt bodies are given in paper ([1]), where a numerical method for their solution in the subsonic and transonic regions is presented. In solving systems of differential equations with indices 0, α, and $\dot{\alpha}$ in the supersonic region, the numerical method proposed in paper ([4]) was used.

Fig. 2. Distribution of the steady pressure p_0 and of the coefficients p_α and $p_{\dot{\alpha}}$ along the generator of a cylinder for $M_\infty = 3$ (solid curves) and $M_\infty = 20$ (dashed line)

Systematic calculations were carried out for cones blunted by a sphere in the range of Mach numbers of the incident flow $M_\infty = 2.5 \div \infty$ and cone semi-vertex angles $\theta_s = -10 \div 30°$. It should be noted that, since for bodies of the sphere-cone type at the junction point the curvature of the surface undergoes a discontinuity, then along the characteristic issuing from the point of discontinuity of the contour curvature there will be discontinuities in the first derivatives

Fig. 3. Distribution of p_0, p_α, and $p_{\dot\alpha}$ along the generator of reverse cones blunted by a sphere, with inclination angles $\theta_s = -5^\circ$ (solid curves) and $\theta_s = -10^\circ$ (dashed), at $M_\infty = 20$

Figure 3: Fig. 3. Distribution of p_0, p_α, and $p_{\dot\alpha}$ along the generator of reverse cones blunted by a sphere, with inclination angles $\theta_s = -5^\circ$ (solid curves) and $\theta_s = -10^\circ$ (dashed), at $M_\infty = 20$

of the gas-dynamic parameters of the steady flow, as well as in the functions themselves that describe the disturbance fields. In order not to construct solutions separately for the regions before and after the discontinuity characteristic, analytic smoothing of the contour was carried out.

To clarify the influence of the number M_∞ on the distribution of pressure disturbances p_α (in phase with the angle of attack α) and $p_{\dot\alpha}$ (in phase with the angular velocity $\dot\alpha$), calculations were performed for a cone blunted by a sphere, with semi-vertex angle $\theta_s = 15^\circ$, at $M_\infty = 2.5;\ 3;\ 4;\ 20$. At large values of M_∞ ($M_\infty = 20$), the presence of bluntness leads to a sharp drop in pressure (the appearance of "pressure hollows") in steady flow (^{5}).

For the disturbance in phase with α, the bluntness leads to a sharp drop in the value of p_α, and p_α reaches a minimum considerably earlier than p_0. The quantity $p_{\dot\alpha}$ continues to increase also in the region of the "hollow" of the steady pressure p_0, since the distance from the center of oscillation to the current section increases (for all variants the center of oscillation was located in the nose of the sphere). The angle of inclination of the curve $p_{\dot\alpha}$ to the axis of symmetry of the body in this region has the smallest value. At $M_\infty = 2.5;\ 3$, the intens—

the intensity of the detached shock wave is considerably weaker, the "pocket" of steady pressure is practically absent, the deviation of p_α from the mean value does not exceed 10–15%, and the dependence of $p_{\dot\alpha}$ on $\bar z$ for $\bar z > 2$ is linear, which corresponds to a sharp cone ($\bar z$ is the body length referred to the bluntness radius and measured from the center of the sphere).

As the cone semi-vertex angle decreases at $M_\infty = 20$, the "pocket" of p_α shifts toward larger z, becomes more extended but of lower intensity; the curve of $p_{\dot\alpha}$ monotonically approaches an asymptote.

Of particular interest are the aerodynamic characteristics of a cylinder blunted by a sphere. The point is that the presently widely used method of local cones does not make it possible, at zero angle of attack, to determine the contribution of the cylindrical surface to the rotational derivatives of the resultant aerodynamic forces and moments. The calculations performed show that, for a sufficiently long body, the total damping characteristics are determined by the cylindrical surface (Fig. 1).

Fig. 3. Distribution of p_0, p_α, and $p_{\dot\alpha}$ along the generator of reverse cones blunted by a sphere, with inclination angles $\theta_s = -5^\circ$ (solid curves) and $\theta_s =$

Fig. 4. Distribution of p_0, p_α, and $p_{\dot\alpha}$ for a body with a positive break in the generatrix at Mach number $M_\infty = 2.5$

Figure 4: Fig. 4. Distribution of p_0, p_α, and $p_{\dot\alpha}$ for a body with a positive break in the generatrix at Mach number $M_\infty = 2.5$

−10° (dashed), at $M_\infty = 20$.

As for the distributed characteristics (Fig. 2), at $M_\infty = 20$ p_α, in absolute value, decreases monotonically along the generator of the cylinder, reaching zero at $\bar{z} = 10$; at $M_\infty = 3$ the quantity p_α changes sign, then approaches zero. The curve $p_{\dot\alpha}$ has a maximum, the position and magnitude of which are determined by the Mach number of the oncoming flow.

Figure 3 gives the dependences of p_0, p_α, and $p_{\dot\alpha}$ on $\bar{z}$ for reverse cones ($\theta_s = -10°; -5°$) joined to a sphere, at $M_\infty = 20$. The graph illustrates the monotonic decrease of p_0, p_α, and $p_{\dot\alpha}$ with increasing inclination angle of the reverse cone.

It should be noted that the distribution of $p_{\dot\alpha}$ shown in Fig. 3 indicates that the contribution of the conical surface to the total damping characteristics must be taken into account. The steady aerodynamic characteristics of bodies of this kind are determined mainly by the frontal surface. On the basis of the calculations performed, it may be assumed that the contribution of the reverse cone to the damping characteristics will be significant not only for the bodies considered here, but also for bodies of the segment-reverse-cone type.

The quantities $m_z^{a(0)}$ and $\dot{m}_z^{\dot{a}(0)}$ (in Fig. 1) are determined relative to the nose of the sphere; the quantity $\dot{a}$ is referred to w_m/R; $\dot\alpha$ to v_∞/L; p_0, p_α, and $p_{\dot\alpha}$ to $\rho_\infty w_m^2$ (w_m is the velocity of outflow into vacuum, R is the radius of the spherical bluntness). To determine the damping moment $m_z^{\dot\alpha}$ relative to another center of oscillation located on the axis of symmetry of the body, it is sufficient to use the formula

Fig. 4. Distribution of p_0, p_α, and $p_{\dot\alpha}$ for a body with a positive break in the generatrix at Mach number $M_\infty = 2.5$

$$\bar{m}_z^{\dot\alpha} = m_z^{\dot\alpha(0)} - \left(c_n^{\dot\alpha(0)} + m_z^{\alpha(0)}\right)\Delta x/L + c_n^{\alpha}(\Delta x/L)^2. \tag{4}$$

Here a positive value of $\bar{m}_z^{\dot\alpha}$ corresponds to damping.

The program compiled for the electronic digital computer makes it possible to calculate bodies with positive and negative breaks in the generatrix. In this case, when solving the problem in a nonuniform field, either an attached shock wave or a discontinuity characteristic is incorporated. As an example, Fig. 4 gives the distribution of p_c, p_α, and $p_{\dot\alpha}$ over the surface of a cylinder and cones joined to it with $\theta_{\text{yu}} = 5,\ 10$, and 15°.

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