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THREE-DIMENSIONAL SUPERSONIC FLOW AROUND A POINTED BODY WITH UPSTREAM ENERGY SUPPLY

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The effect of a local source of energy on a three-dimensional supersonic flow and the aerodynamic characteristics of a pointed ogival body is numerically studied. The results obtained show that the position of the local source of energy upstream of the body on the axis or its deviation from the axis can affect significantly the aerodynamic characteristics of the body (drag, lift, and pitching moment) and the flight trajectory of the vehicle.

Many researchers display great interest in the study of a nonuniform supersonic gas flow around various bodies. The nonuniform distribution of the flow parameters can be caused by many factors, including the presence of a local source of energy supply. It is shown in [1–7] that the action of energy on the free stream allows one to alter the flow regimes and to affect the aerodynamic characteristics of the bodies located in the wake behind the energy supply region.

Two approaches are used in numerical studies of this phenomenon:

• Setting the volumetrically distributed sources of energy; the power of the sources is considered to be a known function of coordinates and time, in particular, the energy can be supplied in accordance with the Gaussian distribution [1–3];

• Setting flow nonuniformity in the form of a local region of lower density, which is equivalent to the temperature increase at constant pressure [4–6].

In both cases, the studies were performed for axisymmetrical and plane flows under the assumption of a perfect heat-nonconducting gas. A complex three-dimensional structure of the flow has not been studied in the cited papers. The present paper partly fills this gap. As a continuation of [1–3], the flow around an ogival body was studied using a similar way of setting the energy supply. In contrast to [1–3], the location of the source was changed not only along the axis of symmetry of the body, but also normally to it. In this case, the flow is essentially three-dimensional, and the local source of energy affects not only the drag force, but also the lift and the pitching moment.

1. We consider a supersonic inviscid heat-nonconducting gas flow around an ogival body located in the wake behind the region of energy supply (Fig. 1). The power of the source of energy $\dot{Q}$ (the amount of heat supplied to a unit mass of the gas per unit time) is assumed to be a known function of coordinates and time [1–3]

$$\dot{Q} = q_0\Big(\frac{p_\infty}{\rho_\infty}\Big)^{3/2}\frac{1}{R_s}\exp\Big(-\frac{\Delta r^2}{R_s^2}\Big), \tag{1.1}$$

where $\dot{Q} = dQ/dt$, R_s is the effective radius of the thermal spot, Δr is the distance between the current point and the source of energy, p_∞ and ρ_∞ are the free-stream pressure and density, and q_0 is a parameter that characterizes the intensity of energy supply.

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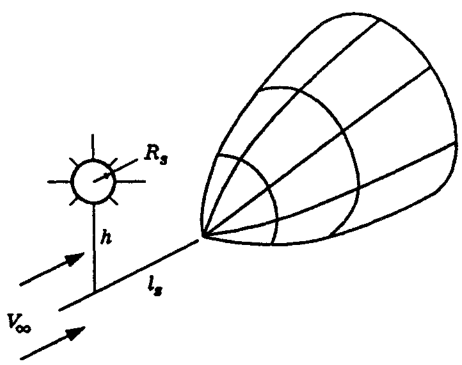

Fig. 1

The equations that describe the gas motion without regard for the heat conduction, viscosity, and mass forces are written as

$$\dot{\rho} + \rho \operatorname{div} \bar{V} = 0, \quad \dot{\bar{V}} + \frac{1}{\rho} \operatorname{grad} p = 0, \quad \dot{f}_s = \frac{æ - 1}{p} \rho \dot{Q}. \tag{1.2}$$

Here f_s is an entropy function that, taking into account the equation of state for a perfect gas, takes the form $f_s = \ln(p/\rho^{æ})$, æ is the ratio of specific heats, and the dot denotes the total time derivative. The first equation is the law of mass conservation, the second is the law of momentum conservation, and the third is the law of the entropy-balance conservation.

The parameters of a uniform incoming flow at infinity and the no-slip conditions on the body surface are used as the boundary conditions, and the free-stream parameters are prescribed as the initial conditions. The values of the flow parameters are nondimensionalized: the density is normalized to ρ_∞, the velocity to $|V_\infty|$, the pressure to $\rho_\infty V_\infty^2$, the entropy function to $f_{s\infty}$, and the energy to V_∞^2.

Numerical studies were performed using the finite-volume method without bow shock capturing. The flow was calculated by the marching method (if the flow is supersonic everywhere), or global iterations were performed (if the local subsonic regions appear). The computational algorithm was described in [7]. The algorithm was verified using wind-tunnel experimental data without regard for the source of energy.

2. A numerical analysis was performed for a supersonic flow around an ogival body in the wake behind a local source of energy (Fig. 1). The flow that is uniform at infinity and has a Mach number of 3 hits the body at zero incidence. The aspect ratio of the ogive is $\lambda = l/2R_M = 2.5$ (l is the length of the body and R_M is the mid-section radius). According to [1–3], the power of the source is assumed to be constant in time and to depend only on the coordinates (1.1), $q_0 = 20$, since it was shown in [1] that the "effect of stabilization with heat supply" is observed, i.e., for $q_0 > 20$ the efficiency of increase of energy supply is small from the viewpoint of its action on the aerodynamic characteristics.

The calculations were performed for different distances between the source of energy and the tip of the body and for different heights from the axis of symmetry at an axial distance from the tip equal to $l_s = 4R_s$, where $R_s = 1/q_0$ is the effective radius of the source. The calculations were performed on a three-dimensional grid of 75,000 points.

Figure 2 shows the most typical distributions of the fields of the entropy function $f_s = \ln(p/\rho^{æ})$ (Fig. 2a) and the pressure (Fig. 2b) in the plane of symmetry and in a cross section ($X = \text{const}$) far from the tip of the body for one of the heights of the source ($h/R_s = 3$).

The calculations show that the presence of a source of energy exerts a significant effect on the flow character. It was found that a local source of energy placed into the flow alters the flow field in the wake behind the source and forms a divergent axisymmetrical flow. Near the axis of the region disturbed by the source, the angle of inclination of the velocity vector to the free stream is close to zero. In the bow shock wave formed by the source, this angle is rather large and decreases with distance from the source as the intensity

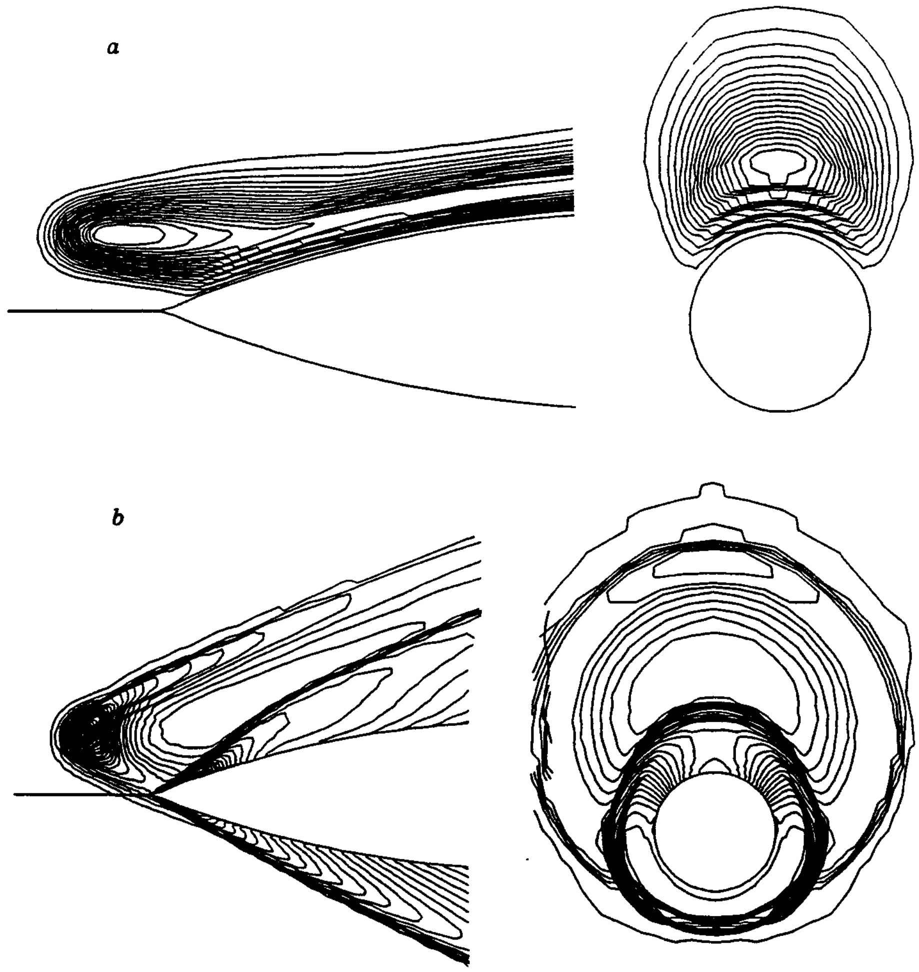

Fig. 2

and the angle of wave inclination are decreased. A high-entropy region is formed near the source. This region extends in the wake behind the source and has the form of an almost cylindrical high-entropy vortex. The position of this vortex relative to the body changes, depending on the distance between the source and the axis of the body. For example, if the source is located on the axis of the body, the vortex is uniform over the surface. If the source is shifted from the axis, the structure of this vortex changes, and it becomes thicker on the upper part of the body (Fig. 2a). For large distances between the source and the axis, the vortex hangs over the body and forms a high-entropy region in the upper part of the flow around the body. The value of entropy remains almost unchanged along the streamlines. The characteristic feature of the flow in the wake immediately behind the source is that the local Mach number decreases significantly near the source and increases rapidly with distance from it. A normal compression wave is formed ahead of the source. Diverging on the periphery, this wave damps rapidly, as in the case of bluntness. The pressure reaches a maximum value in the core of the source. With distance from the source, the pressure and the density drop to values substantially lower than the corresponding free-stream values.

Thus, an ogival body located in a flow on the axis of symmetry common with the source experiences the action of a rarefied high-entropy gas with a decreased local angle of attack to the nose part of the body. As a result, the total drag coefficient decreases. One can find a distance between the source and the body such that the averaged local angle of attack has the least value. If the source located at the axis of symmetry is placed at the distance $l_s = R_s$ from the tip of the body, the drag force increases. The bow shock waves

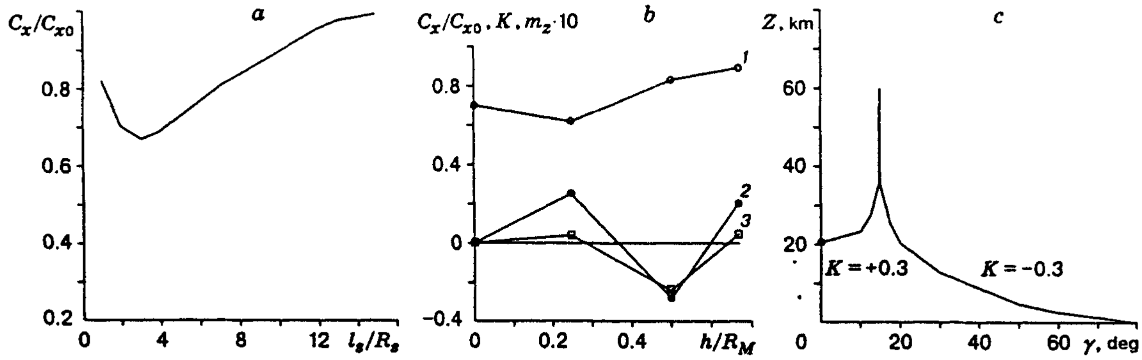

Fig. 3

from the body and the source merge near the tip to form a common wave of greater strength and create an elevated-pressure flow field between the body and the wave. The high pressure directly from the source affects the tip of the body.

A different position of the source relative to the axis of the body changes significantly the flow pattern. On the one hand, the local angles of attack redistribute with distance from the source to the axis of the body; hence, the drag, the lift force, and the pitching moment relative to the tip change. Both the increase in the drag, the lift force, and the pitching moment and a certain decrease in the drag coefficient and the decrease in the lift force and the pitching moment to negative values are possible. On the other hand, as the height of the source is increased, the high-entropy vortex is no longer uniform around the body, which leads to the detachment of the bow shock wave from the body and the pressure decrease on the ogival surface (Fig. 2b). The pressure difference between the upper and lower surfaces reverses the direction of the lift force and the pitching moment. As the height of the source of energy above the axis of symmetry is increased, the predominance of the first type of action over the second one is of alternate character.

If the source position deviates insignificantly from the axis, the shock waves from the source and from the body merge on the lower part of the body to form a high-pressure region. Vice versa, a rarefaction region is formed on the upper part of the body, which increases the lift force. The subsequent change of the position of the source relative to the body forms a weakly compressed, but extended region on the upper part of the body. On the lower part, the pressure drops behind the nose part, and the lift force decreases. A further increase of the distance between the source and the body axis leads to the formation of a flow where the compression wave from the source hits the nose part of the body, and then, going around the body, it can create significant compression from below (Fig. 2b), thus increasing the lift force and the pitching moment.

Figure 3 plots the total aerodynamic characteristics as functions of the position of the local source of energy and the possible effect of this position on the flight trajectory.

The total values of the wave drag coefficients of the ogival body versus the distance between the body and the source in an axisymmetrical flow are presented in Fig. 3a. Here C_x is the wave drag coefficient of the body in the presence of a source, C_{x0} is the same in the absence of a source, the distance is given in terms of the effective radius of the source ($l_s = R_s$). It is seen that, for $l_s = R_s$, the drag of the body is lower than in the absence of a source, but significantly higher than for $l_s = 4R_s$. As l_s increases to values of the order of $14R_s$, the ratio C_x/C_{x0} approaches unity.

Figure 3b shows the values of C_x/C_{x0} (curve 1), the lift-to-drag ratio $K = C_y/C_x$ (curve 2), and the pitching moment coefficient m_z (curve 3) relative to the tip of the body, depending on the position of the source relative to the axis of symmetry of the body over the height normalized to the mid-section radius (h/R_M) for $l_s = 4R_s$. It is seen that this dependence is not monotonic because of the change in flow regimes and can cause a scatter in the lift-to-drag ratio ($K \approx \pm 0.3$).

The effect of the source on the flight trajectory can be estimated on the basis of Fig. 3c borrowed from [8]. For a body with the ballistic coefficient $\sigma = m/(C_x S) = 48.8$ g/m^2, the entry velocity $V = V_E$, and the entry angle $\gamma_E = 15°$, the effect of the lift-to-drag ratio on the trajectory angle is shown as a function of the flight altitude Z. The filled point on the curve marks the altitude where the gliding flight is observed, i.e., the lift force balances Earth's gravity. It is seen from the plots that the scatter of the lift-to-drag ratio within $K \approx \pm 0.3$ can cause significant changes in the flight trajectory of a flying vehicle.

Based on the results presented, one can conclude that a local source of energy placed upstream of a body moving with a supersonic speed can exert a significant effect on the aerodynamic characteristics and the flight trajectory. Hence, it is possible to control both the velocity and direction of the flight of a vehicle by introducing a local source of energy into the flow.

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