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Abstract**Full Text**

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HYDROMECHANICS

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UNSTEADY INTERACTION OF BLUNTED BODIES WITH A SHOCK WAVE*(Presented by Academician G. I. Petrov on July 6, 1965)*

A number of works of both theoretical and experimental character have been devoted to the unsteady interaction of a flow moving behind a shock wave with bodies of various shapes. In particular, in work ⁽¹⁾, by the method of through computation, the pressure and density fields in the flow around the most typical bodies were determined. In works ^(2, 3) the basic relations accompanying the interference of shock waves were established; diffraction of waves by a cylinder, a sphere, and a cone was considered in article ⁽⁴⁾; work ⁽⁵⁾ is devoted to unsteady flow around a wing. A survey of foreign investigations may be found in ⁽⁶⁾. Experimental investigations carried out recently have made it possible to establish certain criteria determining the formation of the bow shock in supersonic flow around a sphere and a cylinder ^(7, 8). However, the interrelation between the position of the unsteady bow wave reflected from the body and the corresponding pressure on the surface has not yet been clarified, and at present there are no data of any kind concerning the time required for the pressure on the surface of bodies to become established, a matter of considerable importance in applied aerodynamics.

In order to fill the indicated gaps the present work was undertaken. The unsteady flow around cylinders with flat and spherical bluntness was investigated, as well as around a cylinder with elongation $L/2R = 3.13$, whose axis of symmetry is directed perpendicular to the velocity of the incident flow. The experiments were carried out in a shock tube assembled according to a single-diaphragm scheme. The measurement of unsteady pressures and shock-wave velocities was carried out by methods analogous to those in works ^(9, 10). The Mach numbers M of the incident wave were varied within the range from 1.5 to 6.0, which corresponded to variation of the Mach numbers M_∞ of the flow behind the wave from 0.6 to 2.1.

The physical picture of the interaction of a shock wave with a blunted body is as follows. In the case of a cylinder having a flat bluntness, at the initial instant after reflection of the incident wave from the end face the pressure is constant over the entire surface of the end face and is equal to the pressure obtained when a shock wave is reflected from a flat infinite wall. With time the reflected shock

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

wave moves away from the end face, forming into a stationary bow compression shock. Disturbances arising at the edge of the bluntiness propagate toward the center of the end face in the form of an axisymmetric rarefaction wave moving with the speed of sound a behind the reflected shock wave. After the rarefaction wave reaches the center of the end face, its reflection occurs. In the direction from the center toward the periphery of the end face, the reflected rarefaction wave begins to move. If one introduces into the consideration the dimensionless time $\tau_w = wt/\Delta_0$ and the relative unsteady wave standoff $\delta = \delta_0/\Delta_0$, where w is the velocity of the reflected wave at the initial instant of time, Δ_0 is the magnitude of the maximum (steady) standoff of the reflected wave from the plane of the end face, δ_0 is the unsteady standoff of the reflected wave from the end face, and t is the current time, then the dependence of δ on τ_w is found to be linear in that

over the time interval where the rarefaction wave has not yet caught up with the reflected wave (Fig. 1a). The dimensionless time τ_1 at which the rarefaction wave catches up with the reflected wave on the axis of symmetry of the cylinder can be expressed as

$$\tau_1 = R/\Delta_0 \sqrt{(a/w)^2 - 1},$$

where R is the radius of the cylinder. On the interval $\tau_w \leq \tau_1$, the velocity of the reflected shock wave on the cylinder axis is constant and equal to w . As M increases,

Fig. 1. Dependence of δ on τ_w : a —cylinder with a flat bluntiness; b —cylinder with a spherical bluntiness; c —cylinder exposed to flow transverse to the axis of symmetry. 1— $M = 2.5$ ($M_\infty = 1.2$); 2— $M = 3.2$ ($M_\infty = 1.4$); 3— $M = 3.9$ ($M_\infty = 1.6$); 4— $M = 5.6$ ($M_\infty = 2.0$)

τ_1 approaches unity, which is caused mainly by a decrease in Δ_0 . Consequently, the end of the formation of the steady bow shock for large values of M occurs at smaller τ_w (Fig. 1a).

In the case of a cylinder with spherical bluntiness and a cylinder exposed to flow transverse to the axis of symmetry, the velocity of the reflected shock wave on the

Fig. 2. Dependence of Δp on τ_a at the critical point. 1—cylinder with a flat bluntiness; 2—cylinder with a spherical bluntiness; 3—cylinder exposed to flow

Fig. 3 and Fig. 4

Figure 3: Fig. 3 and Fig. 4

transverse to the axis of symmetry. $a-M = 1.5$ ($M_\infty = 0.6$); $b-M = 2.5$ ($M_\infty = 1.2$); $c-M = 3.9$ ($M_\infty = 1.6$); $d-M = 5.6$ ($M_\infty = 2.0$)

axis of the cylinder begins to decrease much earlier than for flat bluntness (Fig. 1b, c). This is associated with the earlier arrival of disturbances from the curvilinear portions of the surface. Therefore the linear segment of the dependence of δ on τ_w is insignificant. The tangent of the angle of inclination of the curves $\delta = f(\tau_w)$ at the point $\tau_w = 0$ does not depend on M and is equal to unity (Fig. 1).

It is convenient to consider the dimensionless unsteady pressure $\Delta p = (p - p_c)/(p_0 - p_c)$ as a function of the dimensionless time $\tau_a = at/2R$, where p is the unsteady pressure on the surface; p_0 is the maximum value of the pressure corresponding to plane reflection of the wave from an infinite wall; p_c is the value of the steady pressure on the surface.

Numerous experiments carried out with models of different diameter showed that throughout the investigated range of Mach numbers M the form of the function $\Delta p = \varphi(\tau_a)$ is practically independent of M (Fig. 2). This is true both for supersonic and for subsonic values of M_∞ of the flow moving behind the shock wave, where the reflected shock wave recedes from the cylinder to an unlimited distance with time.

The dimensionless time τ_a^0 , corresponding to the arrival of the expansion wave at the point ρ of the flat bluntness, can be determined from the formula $\tau_a^0 =$

Fig. 3. Dependence of Δp on τ_a for different points of the flat bluntness.

1 $-\rho = 0$; 2 -0.35 ; 3 -0.525 ; 4 -0.685

Fig. 4. Position of the reflected shock wave δ_1 , corresponding to the realization of the steady pressure at the critical point.

1 –cylinder with flat bluntness, 2 –cylinder with spherical bluntness, 3 –cylinder in crossflow, normal to the axis of symmetry

$$= 0.5(1 - \rho).$$

Before the arrival of the expansion wave ($\tau_a < \tau_a^0$), the quantity Δp remains constant, equal to unity (Fig. 2, 1 and Fig. 3). At subsequent times ($\tau_a > \tau_a^0$) the pressure falls, approaching the value $\Delta p = 0$, corresponding to steady flow. In the case $\rho = 0$ (the critical point), in the region $\tau_a \geq \tau_a^0$ the dependence of Δp on τ_a is approximated by the curve

$$\Delta p = 0.2440/(\tau_a - 0.3080) - 0.2745.$$

It is important to note that, in practice, the realization of the steady pressure occurs simultaneously over the entire surface of the face and, independently of the number M , corresponds to $\tau_a \approx 1.0$ — 1.2 (Fig. 3).

In the case of a cylinder with spherical bluntness and a cylinder in crossflow normal to the axis, the pressure at the critical point begins to fall practically immediately after reflection of the incident wave (Fig. 2, 2, 3).

The dependence of Δp on τ_a for the critical point of a cylinder with spherical bluntness is approximated by the curve

$$\Delta p = 0.1552/(\tau_a - 0.1333) - 0.1667,$$

and in the case of a cylinder in crossflow normal to the axis, by the curve

$$\Delta p = 0.7030/(\tau_a - 0.5870) - 0.1957.$$

The realization of the steady pressure at the critical point occurs: for a cylinder in crossflow normal to the axis, at $\tau_a \approx 2$ — 3.5 , and for a cylinder with spherical bluntness, at $\tau_a \approx 0.8$ (Fig. 2, 2, 3).

The relationship between the instant at which the steady pressure is realized at the critical point of the bluntness and the value of the corresponding relative standoff δ_1 can be established by using the relation

$$\tau_w = \frac{2wR}{a\Delta_0}\tau_0.$$

Substituting here the values of τ_a corresponding to the instant at which the steady pressure is realized, we obtain the dependence of δ_1 on M (Fig. 4), on the basis of which one can draw an interesting conclusion: the steady pressure at the critical point is established faster than the steady bow wave is formed. The delay in the formation of the bow wave is especially pronounced for small Mach numbers; for example, in the case of a cylinder with a flat bluntness, at $M \approx 3.0$ the steady pressure on the surface of the flat bluntness is realized when the shock wave has moved away to a distance amounting to about 60% of the distance corresponding to the steady bow wave (Fig. 4). At larger Mach numbers (of the order of 5.5), establishment of the pressure on the flat bluntness occurs at $\delta_1 \approx 0.9$. It may be expected that for $M > 6$ the completion of bow-wave formation will occur practically simultaneously with the establishment of the steady pressure on the surface.

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