INVESTIGATION OF SEPARATED FLOW BEHIND TWO-DIMENSIONAL AND THREE-DIMENSIONAL BODIES ACTED ON BY A SPHERICAL SHOCK WAVE

A. N. Ivanov and V. I. Mikhailov

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The aerodynamic characteristics of bodies washed by an unsteady flow of gas behind a spherical shock wave differ appreciably from the values corresponding to steady flow, and have an appreciably different dependence on the basic flow parameters (Mach and Reynolds numbers) compared with the steady flow case [1, 2]. These variations are linked primarily with differences in the field of vortex formation and flow separation in the steady and unsteady cases, which leads to a change in the pressure distribution over the body.

The present paper studies special features of the flow field behind two-dimensional bodies of finite length and also some three-dimensional bodies with a two-dimensional cutoff exposed to an incident spherical shock wave. As two-dimensional bodies we used a circular disk, a square plate, and elliptic plates of different length; as three-dimensional bodies we used a hemisphere and a cylinder of finite length mounted with one end facing the flow.

1. Statement of the Experiment. The test body was suspended by means of fine tension wires in the field of view of an optical system consisting of a one-sided type IAB-451 Töpler schlieren instrument, a high-speed type SFR-2M photorecorder operating in the continuous scan regime, and a lamp forming a series of short light pulses. To generate the spherical shock wave we exploded a charge of solid explosive material set up at a distance R from the body. The parameters of the shock wave incident on the body were measured with the aid of a piezoelectric static pressure sensor connected to an electronic recorder.

The initial air pressure in the experiments was varied in the range $p_0 = (0.1–2)\cdot 10^5$ Pa, the distance from the body to the center of the explosion was R = 0.3–5 m, and the characteristic dimension of the body was d = 9–200 mm. The values of p_0, d, R and the amount of explosive were chosen so as to investigate the influence on the flow field of one of the dimensionless parameters of the process: the Mach, Reynolds, and Strouhal numbers, while keeping the other two constant. Here $M = u_1/c_1$; $Re = \rho_1 u_1 d/\mu_1$; $Sh = d/u_1 t_+$; ρ_1, u_1, μ_1, c_1 are, respectively, the density, velocity, and viscosity of the gas and the speed of sound in it; the subscript 1 refers to values immediately behind the shock wave; t_+ is the time of action of the compressive wave phase.

2. Vortex Field behind a Circular Disk. Figure 1a-f shows characteristic photographs from high-speed movies of flow over a disk of diameter d = 50 mm mounted perpendicular to the incident gas stream (angle of attack $\alpha = 90°$). The dimensionless parameters in this case had the values: M = 0.28, $Re = 4.5\cdot 10$, Sh = 0.16). The time, reduced to dimensionless form ($\tau = t/t_+$), from the start of action of the wave on the body to the time of the picture was, respectively, τ = 0.04; 0.11; 1; 1.8; 2.3; 3.2.

During passage of the shock wave over the edge of the disk annular tangential discontinuities are formed ahead of the body and behind it, separating regions behind the curved reflecting wave, the rarefaction wave moving over the forward surface of the disk and the compression wave propagating over its rear surface. Because of the flow separation at the disk edge a toroidal vortex forms near it, twisting in the other direction. At the initial time this flow field at the disk edge is entirely similar to flow over a planar shock wave over the edge of a plate of infinite length [3]. Later differences appear: After the vortex grows it separates at the plate, and then the vortex is carried away from the flow. For a disk the initial period of vortex formation, accompanied by growth of its dimensions and increasing distance to the disk plane, is ended by a period of stabilization. In this period, in spite of the variation of pressure, density, and velocity of the gas behind the shock wave front, the distance l between the vortex ring and the disk plane practically does not change, and on the $l(t)$ curve there is an extended plateau (Fig, 2 curve 2). In the positive direction l is assumed to be the displacement of the ring from the disk to the wave front,

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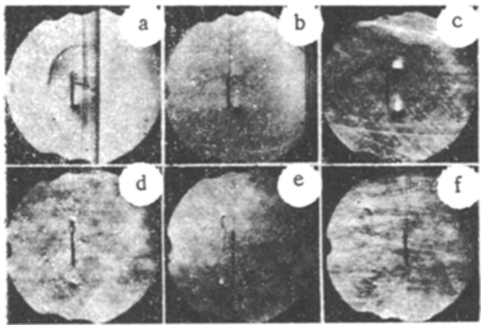

Fig. 1

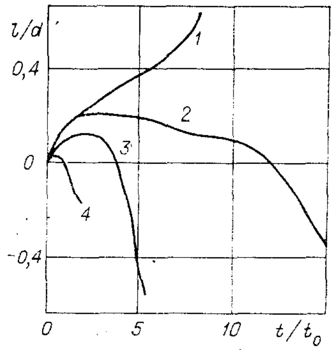

Fig. 2

and as the characteristic time in reducing the quantity t to dimensionless form we take the time $t_0 = d/u_1$ for the gas particles to travel a path equal to the characteristic body dimension. At the end of the compression wave phase the vortex ring begins to move towards the disk, and after a certain time it intersects the disk plane. The maximum velocity of motion of the ring reaches 20-30% of the flow speed behind the wave front.

In the subsequent motion of the ring in the direction towards the center of the explosion it withdraws from the disk, and the ring gradually decreases in intensity, begins to lose its planar shape, and then breaks up. The ring diameter increases monotonically with time, and at the time of vortex breakup it exceeds the disk diameter by a factor of 1.7-2.

This flow field in the near wake behind the disk with a spherical shock wave incident on it is the same as the field behind a circular cone at zero angle of attack [2]. The time t_e of existence of the vortex ring, reduced to dimensionless form, is $t_e/t_0 = 20$, which is close to the value for a circular cone at the same flow parameters. Investigations of the flow field have shown that the dynamics of development of the vortex ring and its lifetime are practically independent of the values of Mach and Reynolds numbers, which were varied sequentially in the ranges: $0.07 \leqslant M \leqslant 0.5$ for Re = $2.25 \cdot 10^5$, Sh = 0.56; $4.5 \cdot 10^4 \leqslant$ Re $9 \cdot 10^5$ for M = 0.3, Sh = 0.16.

The stabilization of the position of the vortex ring during changing external flow parameters can be explained as follows. It is known that a solitary vortex ring in a gas at rest moves relative to the gas with greater velocity, the smaller is its cross section [4]. In the formation of a ring behind the disk the ring velocity vector is directed opposite to the incident flow vector. Behind the front of a spherical shock wave the gas pressure decreases. This leads to a reduction of gas density inside the vortex region, while the total intensity of the ring is conserved (we neglect viscous losses in the first approximation), and to a corresponding increase of the area of cross section of the ring. As a result the velocity of motion of the ring relative to the external gas flow must fall with time, but, since the flow velocity in the compression wave phase also decreases monotonically, the total velocity of the vortex ring is close to zero for a considerable time. In the rarefaction phase the external pressure and correspondingly the dimensions of the vortex cross section vary slightly, while the gas flow velocity changes sign, and as a result the ring begins to move toward the center of the explosion.

It should be noted that the picture of vortex flow obtained in these experiments has no analogs in steady or unsteady separated flow of a liquid over bodies (see, for example, [5-8]).

3. Influence of Degree of Unsteadiness. In these experiments the value of Strouhal number varied in the range $0.03 \leqslant$ Sh $\leqslant 2.3$, the Mach number was fixed at M = 0.28, and the Reynolds number varied with the disk model used in the range Re = $(9\text{-}45) \cdot 10^4$. The displacement of the vortex ring as a function of time is shown in Fig. 2, and depends on the flow regime. The values of Strouhal number for the curves presented are: 1 — Sh = 0.03; 2 — 0.16; 3 — 0.7; 4 — 2.27.

For a small degree of unsteadiness of the flow process (Sh $\leqslant$ 0.03), when the gas velocity behind the shock wave front decreases slowly with time, the self velocity of the vortex ring is not enough to compensate the incident flow velocity. As a result the vortex formed is drawn away by the external flow and begins to withdraw rapidly from the body (curve 1 in Fig. 2). At a distance from the disk of $l \geqslant 0.5d$ the shape of the vortex ring begins to be distorted, it loses stability, and breaks up quickly. The vortex lifetime in dimensionless form t_e/t_0 is small in this case (Fig. 3).

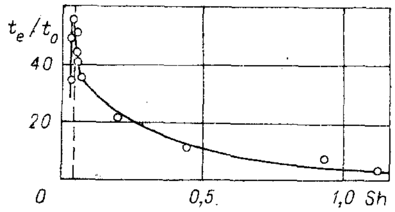

Fig. 3

An increase of the degree of unsteadiness results in the external flow velocity varying with time more rapidly, the result being that at the time of formation of the vortex ring the gas velocity becomes insufficient to carry away the vortex and break it up. In the region of Strouhal number $0.037 \leqslant Sh \leqslant 0.9$ in the compression phase of a spherical wave we observe stabilization of the position of the vortex ring relative to the body generating it, and the curves of $l(t)$ show corresponding plateaus (see Fig. 2, curves 2, 3).

The greatest vortex lifetime $t_e/t_0 = 55$ is reached for Sh = 0.04 near the boundary of the region of stability of the ring (broken line in Fig. 3). An increase of the degree of unsteadiness (Sh > 0.04) causes a rapid reduction of the relative lifetime of the vortex ring. This is linked, apparently, to the fact that an increase of Strouhal number and a corresponding increase of the velocity gradient of the gas behind the wave front lead to reduced drift of the vortex relative to the body. As a result of the more intensive interaction between the vortex and the body the circulation of the vortex rapidly reduces with time, and in its subsequent motion the vortex quickly loses stability and breaks up. An increase of the degree of unsteadiness also leads to the result that the period of formation of the vortex occupies a larger part of the shock wave compression phase, and the length of the vortex stabilization period is correspondingly curtailed. For $Sh \geqslant 0.9$ the vortex stabilization period disappears completely (curve 4 in Fig. 2).

4. Influence of Angle of Attack. In the experiments we used a disk of diameter d = 50 mm, and the parameters of the flow process were: M = 0.28, Sh = 0.16, $Re = 4 \cdot 10^5$. The disk angle of attack varied from 90 to 97.5° in steps of 2.5°. Photographs of flow over the disk at angle of attack $\alpha = 97.5°$ at times $\tau = 0.2$, 1.2 are shown in Fig. 4a and b, respectively.

Analysis of the results show that the downwash about the body when the disk is inclined initially causes a shift of the vortex ring over the disk surface. As a result, for a large enough slope angle of the disk one part of the vortex moves out completely into the incident gas flow, and the other is screened by the body. Later the part of the vortex located in the flow begins to lose its circular shape, erodes, and is simultaneously displaced against the flow under the action of the screened part of the vortex ring, and here its displacement occurs with a larger velocity than in the axisymmetric case (at angle of attack $\alpha = 90°$).

The reverse part of the vortex (Fig. 4a, b below) is close to the disk for a long time, in the aerodynamic wake behind it, and only after the external flow velocity becomes negative does this part of the vortex expand along the radius and begin to move towards the center of the explosion. The intensity of this part of the vortex is roughly the same as for $\alpha = 90°$, but its displacement velocity is noticeably less, linked to smearing and attenuation of the vortex in the upper half of the ring.

The result is that behind an inclined disk (inclined relative to the wave front) the vortex ring is also inclined with time, but in the opposite direction, and the angle of this slope increases with the slope of the disk, and in addition, it becomes appreciably asymmetrical in its cross sectional shape and intensity. These features of a ring vortex behind a body with angle of attack $\alpha \neq 90°$ do not allow a single-valued determination of its lifetime.

5. Flow over a Short Plate. To determine the influence of the plate shape in plan view on the stability of the ring vortex we investigated flow over a square plate, and also over elliptic plates with semiaxis ratio b/a varying in the range $b/a = 0.5$-0.96. The dimensionless flow parameters were: M = 0.28, $Re = 4 \cdot 10^5$, Sh = 0.16, and the plate angle of attack was $\alpha = 90°$.

When the shock wave acts on an elliptic plate the closed vortex formed is first planar and has the same shape in plan view as the plate. Later the "flattened" parts of the vortex ring, having a large radius of curvature and correspondingly less velocity of self motion,

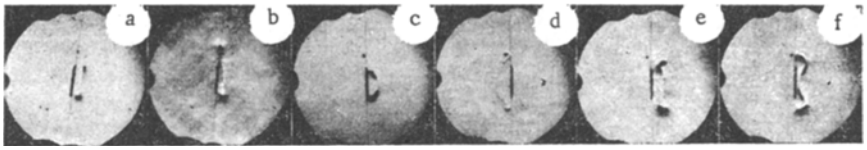

Fig. 4

are displaced under the action of the flow farther from the disk plane than the "elongated" parts. Figure 4c and d shows the flow field around an elliptic plate with semiaxis ratio $b/a = 0.6$. The large axis of the plate lies in the plane of the picture, and the time values are: c) $\tau = 0.15$, d) $\tau = 2.14$.

For a decrease of the external flow velocity the vortex sections corresponding to the small axis of the plate begin to withdraw from each other and simultaneously move towards the center of the explosion with a greater velocity than the sections corresponding to the large axis. As a result, at the end of the compression phase of the wave the large and small axes of the elliptic vortex ring exchange places, and there is also a change in the relative longitudinal position (in the gas flow direction) of the different sections of the ring (see Fig. 4d).

In the case of an elliptic plate with semiaxis ratio $b/a < 0.6$ the velocities of the different sections of the vortex ring differ so much that the vortex breaks up soon after it forms. An analogous result was obtained for elliptic cones [2].

In the interaction of a shock wave with a square plate at first the vortex sections corresponding to the plate corners retain their motion relative to the remaining part of the vortex. Then they begin to move more rapidly and there arise longitudinal oscillations of parts of the vortex relative to its mass center (see Fig. 4e, $\tau = 0.85$; f, $\tau = 1.14$). The amplitude of these oscillations attenuates slightly with time, and the dimensionless period of the oscillations at the start of the process is $T/t_0 = 1.8$ ($t_0 = d/c_1$, where d is the side of the square). Up to the end of the compression phase of the wave the period of the oscillations increases to $T/t_0 = 2.4$, due, apparently, to the increase of the transverse dimensions of the vortex ring.

6. Flow over Three-Dimensional Bodies with a Planar Face. Experiments show that the phenomenon of forming stable vortex rings in the unsteady gas flow behind a spherical shock wave is typical for the majority of bodies having a ratio of their transverse dimensions on the order of 1, and also having a planar afterbody cutoff located perpendicular to the incident gas flow. As an example Fig. 5a at time $\tau = 0.1$ shows flow over a hemisphere mounted at angle of attack $\alpha = 0°$.

In flow over bodies with a planar forward face a vortex ring is also formed, but its stability depends on the relative length of the body in the longitudinal direction. In particular, for a cone with a vertex angle of 30° mounted at an angle of attack of $\alpha = 180°$, the vortex ring breaks up soon after it is formed, due to interaction with the lateral surface of the cone [2]. On the other hand, for a hemisphere at an angle of attack of $\alpha = 180°$, the vortex ring is roughly the same as for $\alpha = 0$, but the distance between the plane of the ring and the body midsection at $\alpha = 180°$ is greater by a factor of about 1.5 (see Fig. 5b).

In the case of flow over bodies with two planar faces, a vortex ring forms on each, but the forward ring is usually rapidly smeared due to the proximity of the lateral surface of the body and is carried away by the flow, while the rearward vortex retains its shape and location for a long time. By way of illustration Fig. 5c and d shows pictures of the flow over a circular cylinder mounted with its face to the flow, at times $\tau = 0.07$ and 1.07, respectively.

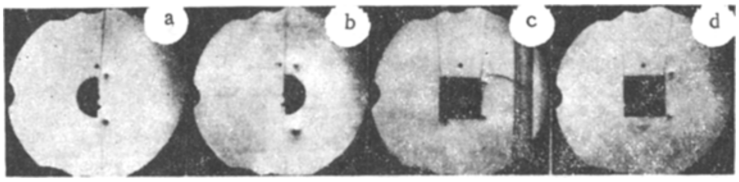

Fig. 5

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SUPERSONIC FLOW OVER A WING AT HIGH ATTACK ANGLES

V. N. Golubkin

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The thin shock layer method [1] is applied to the problem of supersonic gas flow with Mach number $M_\infty \gg 1$ over the windward surface of a thin wing. This method makes use of the significant increase in gas density at the compression discontinuity, together with the corresponding small parameter ε, which is equal to the ratio of the densities at the discontinuity. Consideration of the problem as $\varepsilon \to 0$ permits approximate consideration of the effect of the real physicochemical properties of the gas at high temperatures and determines the specifics of the problem's mathematical formulation and solution, as compared to theories in which together with the small parameter M_∞^{-1} geometric parameters are employed (attack angle α, relative wing thickness d, elongation λ), which vary over various ranges [2, 3].

If $d = O(1)$ (for example, [3-6]) or $d < O(1)$, but exceeds the compressed layer thickness in order of magnitude (for example, [7, 8]), then in the main "Newtonian" approximation the form of the discontinuity coincides with the body form, and the problem consists of finding subsequent approximations.

The most interesting and mathematically complex case is that in which the wing thickness is small and coincides in order of magnitude with the compressed layer thickness, and the form of the compression discontinuity must be determined in the process of solution. This case will be considered below. For flow over a thin wing of small elongation ($d = O(\varepsilon \tan \alpha)$, $\lambda = O(\varepsilon^{1/2} \tan \alpha)$, $\alpha = O(1)$, $\cos \alpha = O(1)$, when $\varepsilon \to 0$) the supersonic law of planar sections for thin bodies at large attack angles [2] is valid, which law in conjunction with the limiting transition $\varepsilon \to 0$ reduces the problem to calculation of a two-dimensional nonsteady-state flow in a plane perpendicular to the wing axis and moving with a velocity $V_\infty \cos \alpha$ [9, 10]. The problem of flow over a plane wing of small elongation at attack angles close to 90° ($\cos \alpha = O(\varepsilon)$) proves equivalent to the two-dimensional problem of stationary flow over a plate located perpendicular to the incident flow [11]. For the intermediate attack angle range ($\cos \alpha = O(\varepsilon^{1/2})$) such an equivalence is valid in the region adjacent to the compression discontinuity, but in the low velocity wall layer change along the chord must be considered.

For flow over a thin wing of finite extent ($d = O(\varepsilon \tan \alpha)$, $\lambda = O(1)$) at an attack angle $\alpha = O(1)$ ($\cos \alpha = O(1)$ as $\varepsilon \to 0$), the discontinuity adjoins the edge and in the fundamental approximation of the thin shock layer method the well-known law of bands is valid [12], permitting independent calculation in each plane along the wing chord of a two-dimensional flow, which in light of the unsteady state analogy [1] is equivalent to a one-dimensional unsteady

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