SEPARATION FLOW BEHIND PLANE BODIES STREAMLINED BY A SHOCK WAVE

A. N. Ivanov and V. I. Mikhailov

UDC 533.6.013.2.011.3/.5:532/582.2

To a considerable degree the nature of the flow in the near wake behind bodies of different shape governs their aerodynamic characteristics. A study of the transients that occur during a change in the velocity of stream flowing around a body from zero to a given quantity, for example during the sudden motion of bodies from a state of rest, is used to comprehend the steady flow pattern around bodies. The flow around a body by a plane shock is the analog of this problem if the stage of wave front diffraction is discarded.

The present paper is devoted to an investigation of the features of the flow pattern behind plane bodies of finite span during incidence of a plane shock on them, in particular behind disks and plates of different planform disposed across the stream. The structure and dynamics of the vortex formations are compared with data presented in [1] for the case of a spherical shock.

Formulation of the Experiment

The experiments were conducted in a shock tube with a 309 mm inner diameter.

A plane shock was formed as a result of rupturing a film diaphragm. The initial air pressure ahead of the shock was $p_0 = 10^5$ Pa, the relative pressure drop on the shock front was $\Delta p/p_0 = 0.3$-0.8 depending on the diaphragm thickness, and the stream Mach number was $M_1 = u_1/c_1 = 0.15$-0.4, respectively. Here c_1 and u_1 are the sound speed in the gas and the gas velocity behind the wave front. Considering the plane shock as the limit stage of a spherical wave for a compression phase duration $t_+ \to \infty$ characterizing the degree of nonstationarity of the streamlining process, the Strouhal number can be written in this case as $Sh = d/u_1t_+ = 0$, where d is the characteristic dimension of the body.

Circular plane disks of d = 10 mm diameter and h = 1.5 mm thickness, as well as flat plates of square planform 50 × 50 mm or ellipses with the axes 50 × 35 mm, and disks of d = 50 mm diameter and h = 1.5, 3 and 5 mm thickness were used as models. The models were mounted at the center of the tube on a 1.5 mm diameter axial holder.

Motion picture recording of the streamlining process was with a barrel type movie camera connected to a IAB-451 Toepler device. A generator of a series of short light pulses triggered through a regulated delay module from a synchronization sensor was used in order to obtain frames of the image on the moving film. The film length in the camera was 1 m, the maximum sweep velocity was 187 m/sec, the frequency of the scan was 13 kHz for a $(50\text{-}70)\cdot 10^{-9}$ sec light pulse duration, and the number of frames was 60-70. The pressure behind the shock front was measured by piezoelectric sensors mounted in the working section of the tube, as well as by an appropriate electronic amplifying and recording apparatus.

Flow Pattern behind a Circular Disk

The characteristic negative from the moving picture of the process of the flow around a 50-mm-diameter disk mounted perpendicularly to the free gas stream (angle of attack $\alpha = 90°$) is presented in Fig. 1. The dimensionless parameters in this case are $\Delta p/p_0 = 0.6$, $M_1 = 0.3$, $Re = 5.3\cdot 10^5$. The time in the scan corresponds to the dimensionless time $t/t_0 = 1.78$.

Exactly as for the flow around a disk by a spherical shock, because of separation of the stream at the edge of the disk a toroidal vortex spinning off backward and receding rapidly from the body is formed nearby. In the lapse of time $t/t_0 = 2$ the rate of vortex ring displacement diminishes and the slope of the curve $\ell(t)$ drops (Fig. 2). Here ℓ is the spacing between the planes of the vortex and the body. The ring displacement from the disk

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 98-102, November-December, 1986. Original article submitted October 9, 1985.

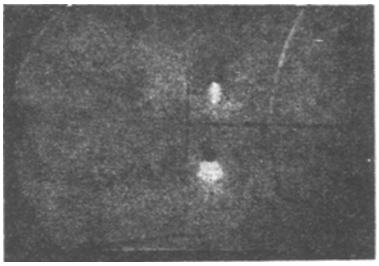

Fig. 1

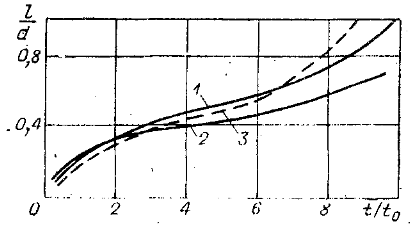

Fig. 2

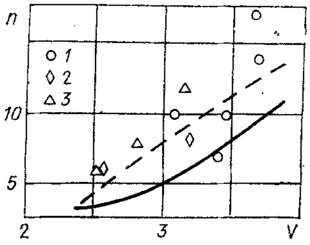

Fig. 3

along the wave front path is taken as the positive direction of ℓ, and as the characteristic time for reduction of the quantity t to dimensionless form is the time $t_0 = d_1/u_1$ of gas particle traversal of a path equal to the characteristic dimension of the body. Later, the dimensionless time t/t_0 is denoted as τ for convenience. Values of the experiment parameters for the curves presented in Fig. 2 are the following: 1) Sh = 0, $M_1 = 0.18$, d = 10 mm; 2) Sh = 0, $M_1 = 0.39$, d = 50 mm; 3) Sh = 0.03, $M_1 = 0.3$, d = 10 mm.

Later, after a period of relative stabilization, the rapid departure of the vortex ring from the plane of the disk and its destruction start. Such vortex ring behavior for Sh = 0 is practically completely analogous to the behavior of a vortex for a spherical shock when Sh = 0.03 [1] (curve 3 in Fig. 2). An increase in the value of the Strouhal number will result, as is shown in [1], in qualitative changes in the dynamics of the toroidal vortex, it starts to be displaced forward.

Investigations of the flow behind a plane shock showed that the dynamics of vortex ring development is practically independent of M_1; however, a certain difference in the $\ell(t)$ curves is noticeable for disks of different diameters (lines 1 and 2 in Fig. 2). This is apparently associated with the fact that a noticeable diminution in the stream velocity occurs for large models in the shock tube because of the shock reflected from the model, whereupon the vortex ring motion is retarded.

For Sh = 0 another qualitative difference exists in the flow pattern behind a flat disk, soon after the vortex formation at $\tau \geq 0.3$-0.4 a vortex sheet is shed from the disk edge and is separated into visible separate vortex formations which are then absorbed by the more powerful fundamental toroidal vortex. The appearance of the vortex sheet is due to the difference in the stream velocities shedding from the sharp edge of the disk. In the initial time period, the velocity of the external stream being shed from the leading (windward) side of the disk exceeds the stream velocity induced by the vortex on its rear surface substantially. Under the influence of the vortex the interfacial surface is twisted and the vortex causing its growth is thereby strengthened with time. An increase in the vortex results in a rise in the stream velocity on the rear surface of the disk and a drop in the intensity of the vortex sheet. In particular, for $\tau \geq 6$ the vortex sheet is not observed on the films in practice.

In the case of the spherical shock for the experiments presented in [1], there is no vortex sheet (for equivalent sensitivity of the optical system with these experiments). The low intensity or total absence of a vortex sheet in the stream behind a spherical wave are associated mainly with the rapid drop of the gas velocity behind the wave front in time and the equilibration of the stream velocities flowing around the disk edges. As is shown in [2], the vortex sheet is unstable since small perturbations of its shape are magnified and result in the formation of centers of vorticity along the sheet, and in the long run a disordered sequence of large and small vortices should be formed from the sheet. In the case investigated, however, the perturbations of the vortex sheet are sufficiently regular, where they have the shape of closed vortex rings whose plane is practically parallel to the plane of the disk. The distance between the centers of succeeding perturbations referred to the body diameter is s/d = 0.09 for a disk of thickness h = 1.5 mm and s/d = 0.17 for h = 5 mm and is independent of the stream parameters in the range investigated.

The data obtained agree sufficiently well with the results that can be obtained from an analysis of [3]. The magnitude of the relative distance between the centers of perturbation of the vortex sheet shed from the edges of a square plate suddenly set in motion is s/d = 0.05-0.10, where s/d grows as the plate relative thickness increases. Here d is the length of a rib of the square.

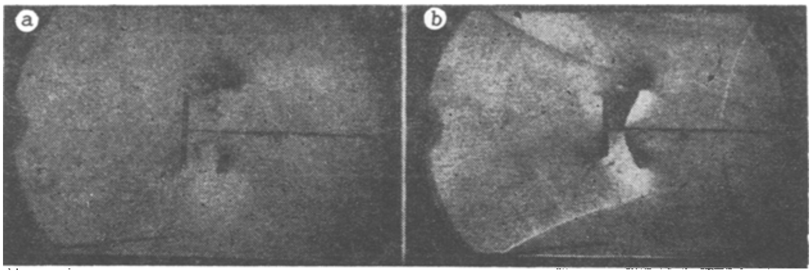

Fig. 4

As a comparison we note that the frequency of formation of the perturbations in the vortex sheet shed from the edges of a disk or a square plate is 30-100 times higher than the **vortex repetition** rate in a vortex street behind a cylinder and an infinite span plate [4].

The structure of the vortex ring being formed behind the disk during impingement of a plane shock on it changes differently in time than the structure of a toroidal vortex in the case of a spherical shock for $Sh > 0.03$ [1]. For a plane shock, soon after its formation a vortex ring experiences sinusoidal perturbations in the direction of gas stream motion, as is noted well in the photographs (see Fig. 1). Analogous perturbations should indeed be in the direction of the vortex ring radius. The perturbations observed are apparently associated with its instability that occurs under the action of periodic vortex formations being formed out of the vortex sheet.

The instability of an isolated vortex ring is investigated in [5]. According to theoretical computations verified by experimental observations, the thinner the vortex ring, the greater the number of waves around the azimuth that corresponds to the unstable mode. Moreover, the spatial magnification of the perturbations of a ring growing as the distance the ring has traversed grows is practically independent of the size of the core.

The dashed line in Fig. 3 displays the dependence obtained in this paper for the number of waves in the unstable mode n on the dimensionless velocity of the ring $V = V_0/(\Gamma/4\pi R)$, where V_0 is the velocity of translational vortex ring motion relative to its surrounding gas, Γ is its circulation and R is the radius of the ring.

The points 1 and 2 correspond to the times $\tau = 2.5, 5.6$. The quantity n was determined from photographs of a ring section $n = \pi D/\Delta H$ (D is the ring diameter, ΔH is the spacing between the wave troughs in the same phase of the oscillations). The value V is found analytically from the solution for a ring with small cross section and homogeneous vorticity distribution [6]: $V = \ln(8R/r) - 1/4$ (r is the core dimension). Theoretical and experimental values of n from [5] (the solid line and points 3, respectively) are also presented in Fig. 3.

Comparison of the results shows that the theory proposed in [5] is a satisfactory description of the vortex ring instability in a gas flow with constant parameters. It should be noted that the core size grows with the lapse of time, the number of waves diminishes, and the amplitude of the vortex ring perturbation increases so much that the ring is destroyed.

Analysis of the results of an experiment on the flow of a spherical shock around a disk showed that in this case an initial vortex ring instability also exists. However, in contrast to the flow behind a plane shock for $Sh \geq 0.04$ the amplitude of the ring perturbation drops with time, which results in an increase of its lifetime. The mentioned difference in the change in vortex ring structure for a spherical shock is possibly related to the rapid drop in the intensity of the vortex sheet shed from the disk edges and the diminution of its action on the toroidal vortex. Another reason for the attenuation of the oscillations can be the rapid growth of the vortex core because of the external pressure which results in vortex ring emergence outside the instability domain.

Such a phenomenon of diminution in ring instability was observed in [7] where, by assumption, the vortex core growth was caused by its turbulization.

Flow around Square and Elliptical Plates

To determine the influence of the plate planform on the stability of the vortex ring, the flow around a square plate as **well as around** elliptical plates with the semi-axis ratio $b/a = 0.7$ and 0.9 was investigated. The dimensionless flow parameters were $M_1 \approx 0.4$, $Re = 7 \cdot 10^5$ and the plate angle of attack was $\alpha = 90°$.

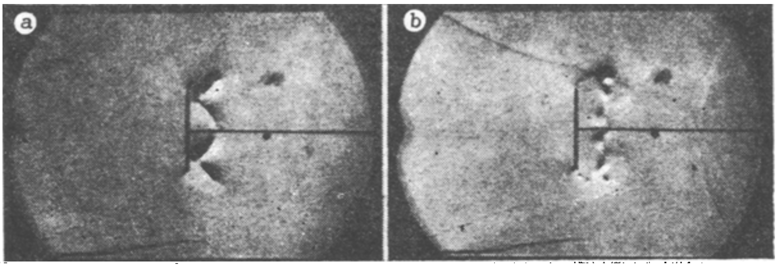

Fig. 5

Large and small scale perturbations of the vortex ring (Fig. 4a, $\tau = 4.5$) are observed simultaneously when a shock acts on an almost circular elliptical plate ($b/a = 0.9$). The minor axis, i.e., $t_0 = 2b/u_1$, was taken as the characteristic dimension to determine the time t_0 in this case. The major axis of the ellipse was along the scanning axis during the photography. As for a circular disk, the fine-scale perturbations are due to the vortex ring instability. The number of oscillation waves diminishes with time while their amplitude grows resulting in subsequent destruction of the ring. The large-scale perturbations are associated with the fact that after vortex formation its sections parallel to the plate major axis have a larger radius of curvature and a smaller intrinsic motion velocity than the perpendicular sections. Consequently, the "oblate" sections of the vortex are displaced more rapidly from the body plane under the action of the stream than the "prolate" sections, the mutual location of the different vortex ring sections here does not change with the lapse of time.

An increase in the span of the elliptic plate to $b/a = 0.7$ will result in the disappearance of the fine-scale ring oscillations and the growth of its large-scale perturbations (Fig. 4b, $\tau = 2.9$). The ring lifetime is shortened.

The vortex behavior for plane shock flow around a square plate is also analogous. The vortex ring sections corresponding to the lateral ribs of the plate noticeably lead the sections adjoining the plate corners soon after formation of the vortex (Fig. 5a, $\tau = 0.8$). As the vortex recedes farther from the plane of the plate, its "corner" sections can overtake the sections corresponding to the plate ribs for a short time (Fig. 5b, $\tau = 1.4$) but never lead them. No fine-scale vortex oscillations are observed for a square plate.

Under the effect of a spherical shock on a body of noncircular planform (elliptical or square plate, etc.) the different vortex ring elements experience significant periodic oscillations with respect to each other [1]. The mentioned difference in the behavior of the vortex rings in the case of a plane and spherical shock is apparently related to the fact that that the stream velocity behind a spherical wave front drops rapidly with time and the displacement of the vortex ring relative to the plate is small. The stream velocity behind a plane shock conserves its constant value, consequently the vortex recedes rapidly from the body. Therefore, the closeness of the body and the interaction of the vortex-induced gas stream with it is one of the fundamental reasons for the occurrence of large-scale vortex ring oscillations.

LITERATURE CITED

1. A. N. Ivanov and V. I. Mikhailov, "Investigation of separation flow behind plane and spatial bodies subjected to a spherical shock," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1984).
2. L. Prandtl, Hydro-Aeromechanics [Russian translation], IL, Moscow (1951).
3. D. Pierce, "Photographic evidence of the formation and growth of vorticity behind plates accelerated from rest in still air," J. Fluid Mech., 11, Pt. 3 (1961).
4. P. Chen, Separation Flows [Russian translation], Vol. 2, Mir, Moscow (1973).
5. S. Widnall and J. P. Sullivan, "On the stability of vortex rings," Proc. R. Soc. London, A332, 335-353 (1973).
6. H. Lamb, Hydrodynamics [Russian translation], Gostekhizdat, Moscow—Leningrad (1947).
7. T. Maxworthy, "Turbulent vortex rings," J. Fluid Mech., 64, Pt. 2 (1974).