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Shock wave interaction with cylindrical surfaces

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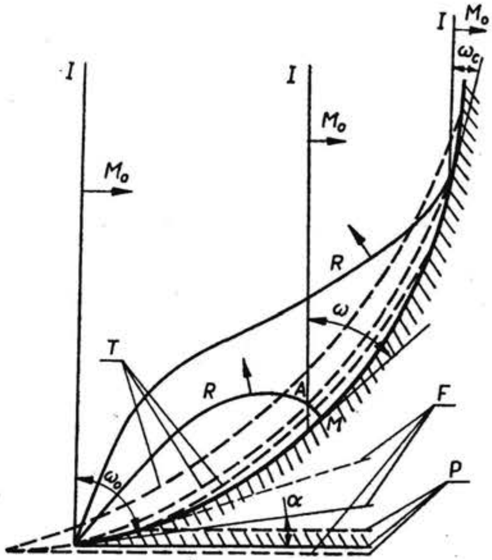
EXPERIMENTAL investigation of the reflection of plane shock waves at convex ($R = 100$ mm) and concave ($R = 123$ mm) circular cylinders has been made. The experiments were carried out in a shock tube of rectangular cross-section. The surface of the cylinder intersected the wall of the shock tube at different angles α. When the angle α was positive, the shock wave was reflected and when the angle α was negative, it was diffracted. The shadowgraphs taken at different moments of time were used to determine the triple point trajectory and angle of transition from Mach to regular reflection ω_c. The analysis of the results which were obtained with the values of the angle ω_c reported by other authors for different cylinder radii shows that the transition angle does not depend on the cylinder radius, but is fully determined by the angle of intersection. The disagreement among the data supplied by different authors may be accounted for by the fact that these works investigated only the dependence of ω_c on the shock wave parameters and disregarded the value of α. When studying diffraction at cylinders, some new features have been observed as compared to the diffraction observed at the sharp apex corner. Due to different conditions of secondary shock wave formation and its interaction with the boundary layer, the separation point was observed to be displaced downstream. The contact surface did not reach the rarefaction wave origin but interacted with the wall.

Przeprowadzono doświadczalne badania zjawiska odbicia płaskich fal uderzeniowych od wypukłych ($R = 100$ mm) i wklęsłych ($R = 123$ mm) powierzchni walców kołowych. Badania przeprowadzono w rurze uderzeniowej o przekroju prostokątnym. Powierzchnia walca przecinała ściankę rury uderzeniowej pod różnymi kątami α. W przypadku dodatnich kątów α fala ulegała odbiciu, a przy ujemnych — dyfrakcji. Posłużono się wykresami cieni sporządzonymi dla różnych wartości czasu w celu ustalenia trajektorii punktu potrójnego i kąta przejścia ω_c od odbicia Macha do odbicia prawidłowego. Analiza wyników otrzymanych dla wartości ω_c podanych przez innych autorów przy uwzględnieniu różnych promieni walca pokazuje, że kąt przejścia nie zależy od promienia cylindra, lecz jest w pełni określony przez kąt przecięcia. Niezgodności zachodzące między danymi pochodzącymi od różnych autorów można wytłumaczyć faktem, że badali oni zależność ω_c od parametrów fali uderzeniowej nie biorąc pod uwagę α. Badając dyfrakcję na walcach stwierdzono pewne nowe cechy tego oddziaływania w porównaniu z wynikami otrzymanymi przy badaniu dyfrakcji na ostrych wierzchołkach profilu. W wyniku odmiennych warunków tworzenia się wtórnej fali uderzeniowej i jej oddziaływania z warstwą przyścienną, zaobserwowano przesunięcie się punktu oderwania w kierunku przepływu. Powierzchnia nie sięgała początku fali rozrzedzenia, lecz współdziałała ze ścianką.

Проведены экспериментальные исследования явления отражения плоских ударных волн от выпуклых ($R = 100$ мм) и вогнутых ($R = 123$ мм) поверхностей круговых цилиндров. Исследования проведены в ударных трубах с прямоугольным сечением. Поверхность цилиндра перерезает стенку ударной трубы под разными углами α. В случае положительных углов α происходит отражение, а при отрицательных α — дифракция. Пользовались теневыми снимками, сделанными для разных значений времени, с целью установления траектории тройной точки и угла перехода ω_c от отражения типа Маха до нормального отражения. Анализ результатов, полученных для значений приведенных другими авторами при учете разных радиусов цилиндра, показывает, что угол перехода не зависит от радиуса цилиндра, но вполне определяется углом пересечения. Несогласия, имеющие место между данными происходящими от разных авторов, можно объяснить фактом, что они исследовали зависимость ω_c от параметров ударной волны не принимая во внимание α. При исследовании дифракци на цилиндрах, обнаружены некоторые новые свойства этого взаимодействия по сравнению с результатами, полученными при исследовании дифракции на острых вершинах профиля. В результате других условий образования вторичной ударной волны и ее взаимодействия с пограничным слоем, обнаружен сдвиг точки отрыва в направлении течения. Контактная поверхность не достигала начала волны разрежения, а взаимодействовала со стенкой.

1. Introduction

IN CONSIDERING the process of unstationary interaction of a plane shock wave with a circular cylindrical surface, two cases can be distinguished: if the angle α between the velocity vector $\mathbf{V}_0$ of the plane incident shock wave and the plane tangent to the cylindrical surface is greater than or equal to zero at the initial moment of interaction, then the wave is reflected from the surface (Figs. 1a, b, c and 2); if the angle α is smaller than or equal to zero, then diffraction of the shock wave takes place (Fig. 4). Reflection of plane shock waves from convex and concave circular cylindrical surfaces has been investigated ex-



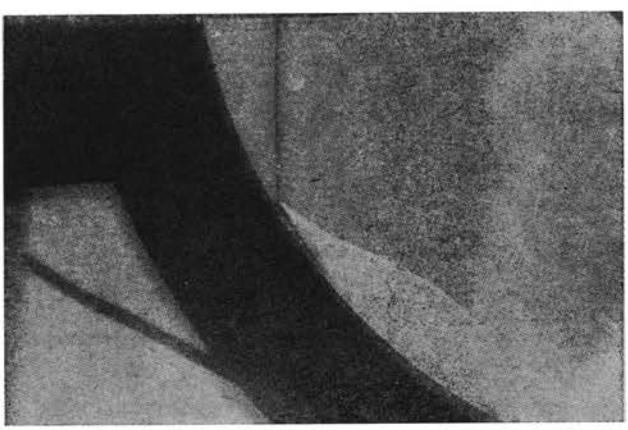


FIG. 1. a, b.

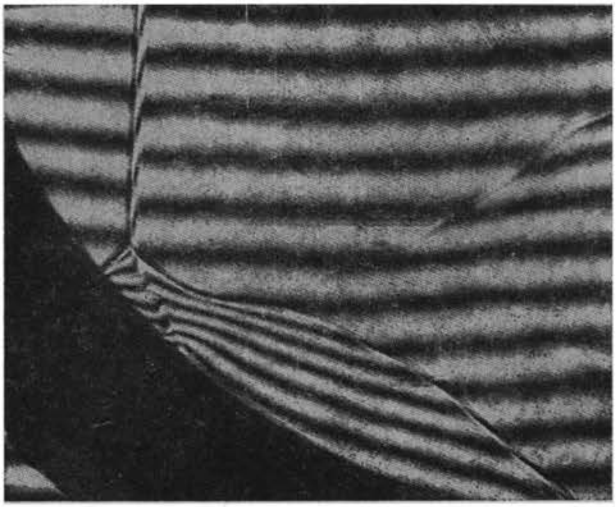


FIG. 1. Reflection of a shock wave from a concave circular cylindrical surface.
a — diagram, b — spark Schlieren photograph, c — interferogram.

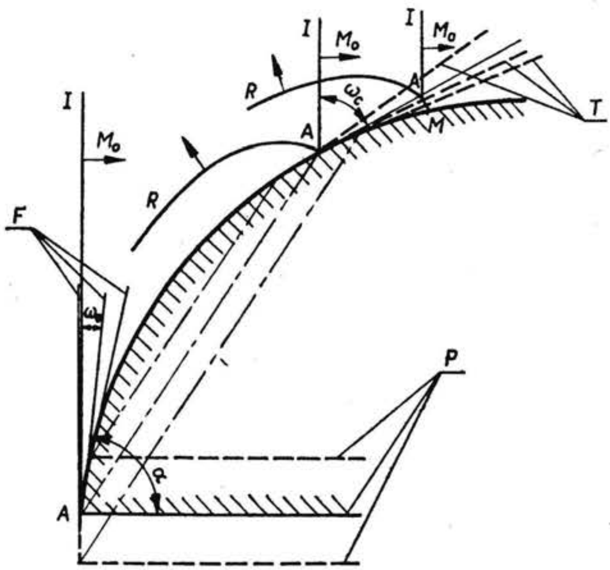


FIG. 2. Reflection of a shock wave from a convex circular cylindrical surface.

perimentally and theoretically in Refs. [2–8]. As is known, at small angles of incidence ω (Figs. 1a and 2) regular reflection takes place, whereas at large ω the Mach configuration of waves is observed. The above papers primarily deal with the determination of the critical angle, ω_c, at which a transition from one type of reflection to the other occurs and with the dependence of this angle on gas-dynamic, geometrical and other conditions.

Dependences of the transition angle, ω_c, on the incident shock wave intensity, ξ (the pressure ratio p_0 to p_1) and on the incident wave Mach number, M_0 are presented in

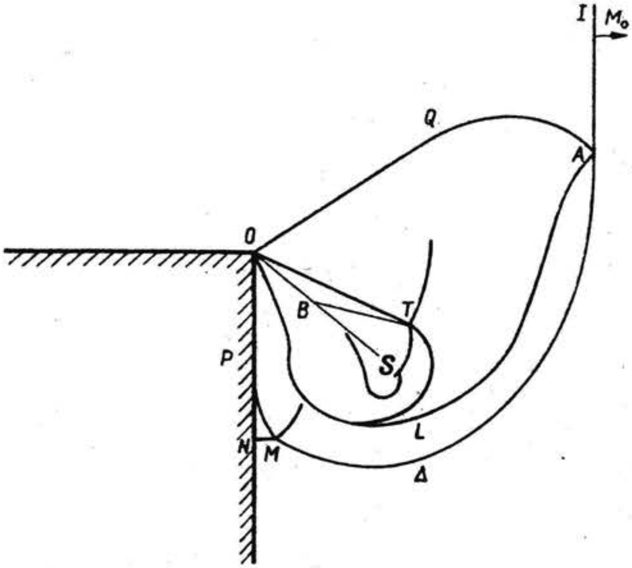


FIG. 3. Diffraction of a shock wave at a right dihedral angle.

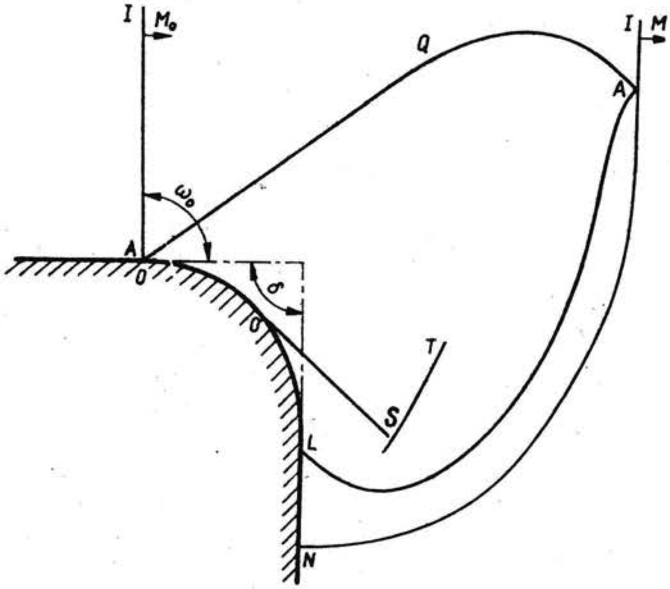


FIG. 4. Diffraction of a shock wave at a rounded-off angle.

Fig. 5. Curves *1* and *2* are calculated according to two-shock and three-shock theories. Experimental results taken from different papers are presented by curve 3 [1], curve 4 [2], points 5, 6, 7, 8, 9, 10, 11 [5], point 15 [7], and points 12, 13, 14 [9].

The experimental transition angles in reflection from the plane surface lie slightly above the theoretical curve *1*; the transition angles for convex circular cylindrical surfaces

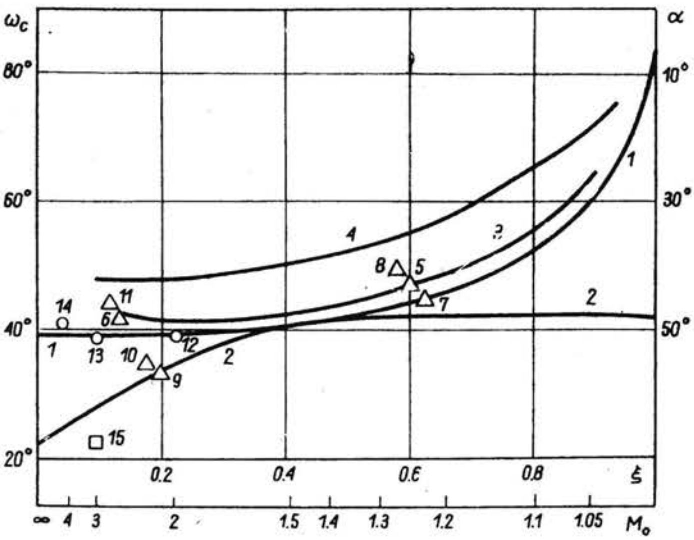


FIG. 5. Theoretical and experimental dependences of the transition angle on the shock wave intensity for convex, flat and concave surfaces.

1 — two-shock theory; 2 — three-shock theory; 3 — ref. [1]; 4 — ref. [2]; 5, 6, 7, 8, 9, 10, 11 — ref. [5]; 12, 13, 14 — ref. [9]; 14 — ref. [7].

with $\alpha = \frac{\pi}{2}$ and the radius $r = 12, 75, 100$ mm (curve *4*) and with $\alpha = 45°$ and $r = 130$ mm (point 11) lie also above the theoretical curve. For concave circular cylindrical surfaces the transition angles are located below curves *1* and *3*. See for instance, [5], where the transition angles for the reflection of shock waves from concave surfaces with $r = 145$ mm and 190 mm were obtained (points 9, 10). In all these papers the experiments were carried out in air. In [7] the transition angle was obtained under the reflection of a shock wave ($M_0 = 3.1$) from a concave cylindrical surface with $\alpha = 0$ and $r = 100$ mm in carbon dioxide (point 15). This result has been confirmed by computation in paper [8]. The analysis of Fig. 5 shows that for convex cylindrical surfaces the transition angles lie above those for the plane, while for concave surfaces they lie below.

However, the results obtained by different authors are located on the plane (ω_c, ξ) chaotically. For instance, ω_c obtained in [2] for convex cylindrical surfaces with $r = 12$ mm, 75 mm, 100 mm form a curve, and ω_c from [5] for a surface with $t = 130$ mm do not fit it. As is seen from the above papers, different authors used in their experiments reflecting cylindrical surfaces of different geometries. We attempted to study the effect of geometric characteristics of a reflecting cylindrical surface on the transition angle ω. The radius of the surface r and the angle between the plane P, intersecting the cylinder parallel to its axis, and the plane F tangent to the cylinder at the line of the intersection of surfaces (Figs. 1a and 2) characterize quite well the reflecting convex or concave circular cylindrical surface. The shock wave is oriented relative to the reflecting surface so that at each moment of time its front is parallel to the cylinder axis and normal to the intersecting plane P.

In the interaction between a shock wave and a convex cylindrical surface with the angle which is smaller than or equal to zero, it is of interest to consider the influence of the rounding-off of the angle flowed around by a shock wave upon the shape of the diffracted shock wave, the wave pattern behind the front and also upon the flow separation from the surface. Experiments have also been carried out to investigate the process of shock wave diffraction at a dihedral angle with a rounded vertex.

2. Experiments

Interaction of strong shock waves with curvilinear surfaces was experimentally studied in a shock tube of a square cross-section (72 mm × 72 mm) in air or nitrogen ($M_0 = 2 \div 8$). Models with concave and convex circular cylindrical surfaces were placed in one of the experimental chambers equipped for visualization of the interaction process. In our experiments the radii of reflecting surfaces were chosen so that at a given angle α both the regular and Mach reflections would occur from a model placed into an experimental section. The following parameters were chosen for concave surfaces: ($\alpha = 0°$, $r = 72$ mm), ($\alpha = 6°$, $r = 100$ mm), ($\alpha = 28°$, $r = 100$ mm), ($\alpha = 46°$, $r = 100$ mm); for a convex surface they were: ($\alpha = 64°$, $r = 123$ mm). To study the diffraction process the largest radii of surfaces were taken for the chosen angle δ (Fig. 4a) and the experimental section ($\alpha = 0°$; $\delta = 90°$; $r = 32$ mm). The process of reflection was investigated by optical methods according to schemes described in [10] and [11]. As a result of these experiments, Töpler pictures, interferograms and holograms of the interaction of shock waves with cylindrical surfaces were obtained. To make the results more reliable each surface was studied 20–30 times with a simultaneous recording of the wave position on the surface at different points. The photographs obtained were examined by a UIM-23 microscope to determine the trajectory of the triple point and the point of its intersection with the surface (i.e. the angle of transition ω_c). We have not succeeded in recording the Mach configuration for a concave surface with $\alpha = 46°$ and $r = 100$ mm, since the angle $\omega_0 = \frac{\pi}{2} - \alpha$ was chosen to be too close to ω_c, and the Mach wave did not develop up to a value resolved by optical methods. However, since all the transition angles for a concave surface lie below the curve for the plane (Fig. 5), the transition angle for the plane at the same M_0 was chosen as an upper limit of the existence of ω_c on this surface, and the lower limit was obtained in the experiment.

3. Discussion of results

3.1. Reflection

The angles of transition from one type of reflection to the other obtained experimentally for concave and convex surfaces were plotted on the coordinate plane (ω_c, α). It turned out that all these points: 1 — ($\alpha = 0°$; $r = 72$ mm), 2 — ($\alpha = 6°$; $r = 100$ mm), 3 — ($\alpha = 28°$; $r = 100$ mm), 4 — ($\alpha = 46°$; $r = 100$ mm) and 5 — ($\alpha = 64°$; $r = 123$ mm) fit one curve (Fig. 6). Point 6 for convex surfaces with $\alpha = 0$ and $r = 12$ mm, 75 mm, 100 mm from [2], point 7 calculated by the two-shock theory and point 8 for a plane surface [1] with $\alpha = 46$ and $r = \infty$ also fit this curve. Thus the points obtained for the surfaces with different r also lie on the curve constructed with $r = 100$ m. It has been assumed that at a fixed angle α the transition angle ω_c is independent of the reflecting surface radius in the whole range of variation of angles $\left(\text{from } 0 \text{ to } \frac{\pi}{2}\right)$. Indeed, the point corresponding to alteration of the curvature sign of the reflecting surfaces will also be the transition angle for a wedge ($r = \infty$) and, apparently, for concave and convex surfaces of any radius since in this case $\omega_c = \omega_0 \doteq$ const. This assumption is confirmed for convex cylindrical surfaces in Ref. [2] (Fig. 5). The results of Ref. [5] also support this assumption as applied to concave surfaces. Though the surface radii differ significantly ($r = 72.5$ mm and 190 mm), the transition angles almost coincide (Fig. 5). A slight difference can be explained by variance of angles α. The transition angles obtained in Refs. [5] and [7] for cylindrical surfaces do not coincide with our results. As follows from [5] and [6], for a convex cylindrical surface with $\alpha = 45°$ and $r = 130$ mm the transition angle $\omega_c = 45°$ (point 9 in Fig. 6), that is, the angle of incidence ω_0 corresponding to the initial moment of the

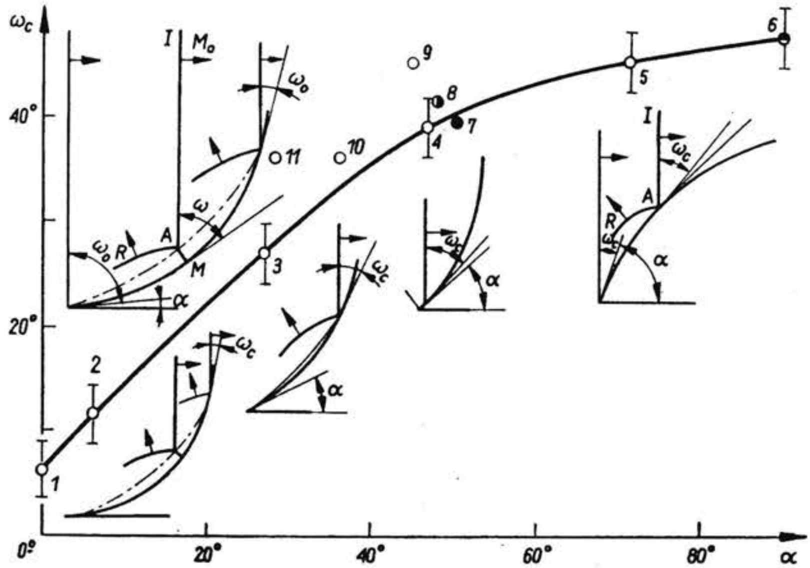


FIG. 6. Dependence of the transition angle, ω_c, on α: 1, 2, 3, 4, 5 — our experimental points, 6 — ref. [2]; 7 — two-shock theory; 8 — ref. [1]; 9, 10, 11 — ref. [5], [6].

interaction of the wave with the surface is taken as the transition angle (on condition that the tangents to the surface and the trajectories of the triple point coincide at ω_c). The reflection will be of the Mach type from the very beginning since the angle α equal to 45° for a given surface will be less than $\alpha = 46°$, corresponding to the transition angle on the plane surface. As for concave surfaces with $r = 145$ mm and 190 mm in Ref. [5] (points 10 and 11 in Fig. 6), non-coincidence occurs due to another reason: according to [6], at small values of the angle α, the trajectory of the triple point is a straight line, so the transition angle ω_c increases significantly. However, in our experiments this statement has not been confirmed: the graphs of the triple point trajectories for concave cylindrical surfaces are concave lines (Fig. 6). Therefore, the results of [5] differ from those mentioned above. Point 7 has been obtained for carbon dioxide; therefore, it also does not agree with the present results. In Ref. [4], basing on extrapolation of experimental data to the results of triple- and double-shock theories, the author concludes that the transition from the regular reflection to the Mach one under interaction of a shock wave with a convex cylindrical surface occurs at Mach numbers shown by curve *2* in Fig. 5, unlike the statements presented in his previous papers. The arguments of Ref. [4] do not seem to us quite convincing. In Refs. [5, 6] it is also stated that the angle of transition for convex, concave and plane surfaces depends on the Mach number according to curve *2* in Fig. 5. As is seen from Fig. 5, ω_c noticeably depends on M_0 for strong shock waves, provided the transition takes place along curve 2 obtained by means of the three-shock theory for stationary Mach reflection. We have performed a series of experiments for a surface with $\alpha = 28°$ and $r = 100$ mm in a wide range of Mach numbers ($M_0 = 2.5 \div 5.5$) and for a surface with $\alpha = 46°$ and $r = 100$ mm at $M_0 = 2 \div 4.5$. However, we have not succeeded in observing any dependence of ω_0 on the Mach number. The triple points have the same trajectory in the whole range of Mach numbers, which is in agreement with dependences 1 and 3 in Fig. 5. The experiments on measuring the pressure under the reflection of a shock wave from the plane [9] (points 12, 13 and 14 in Fig. 5) provide a convincing evidence in favour of the double-shock theory.

Thus we have shown by means of experiments and analyses of the literature data that the angle transition from one type of reflection to the other, ω_c, under the interaction of shock waves with cylindrical surfaces depends on the angle α and does not depend on the radius r of the reflecting surface at a fixed α. For concave surfaces the transition from the Mach reflection to a regular one takes place, and since the transition may occur at a less critical angle than it follows from the three-shock theory (Fig. 6), this is a reliable fact; what we observe is a three-shock configuration. For convex surfaces the transition from the regular to the Mach reflection takes place and the fact that we observe a regular configuration does not yet mean that it is not of the Mach type. It is thus possible that the dependence in the region of convex surfaces will lie below that given in Fig. 6 or it will be absent altogether, and the angle of transition will coincide with ω_c for a plane wedge.

3.2. Diffraction

In the experiments on the interaction of a shock wave with a cylindrical surface at $\alpha \leqslant 0$, Töplerograms, interferograms and holograms of the wave position on the surface at different moments were obtained. To investigate the effect of an angle rounding-off on the diffraction, experiments were carried out in which a shock wave moved around an angle with a rounded vertex and a sharp edge. In this case the angles α, ω_0 and δ (see Figs. 3, 4) were equal to $\frac{\pi}{2}$. Figures 3 and 4 show the wave pattern in the diffraction of shock waves at the angle with a sharp edge and with rounding-off for the case when the primary shock waves are at an equal distance from the vertical side of the angle. For the angle with a sharp edge the diffracted shock wave *ADMN* has an inflexion point *M*, the maximum velocity over the vertical surface being achieved at some distance from it at a point *D*. The wave diffracted at a rounded-off angle has no inflexion point and the maximum velocity along the vertical surface is observed in the near-wall part.

The contact surface *ALO* in Fig. 3 under the sharp-edge angle diffraction of a shock wave starts at point *A* of the primary shock wave, then envelops the wave *TS* and terminates at the vertex of the angle 0. For the rounded-off angle the contact surface *AL* (Fig. 4) terminates on the vertical surface at point *L*. The flow separation occurs not at the point 0, as was the case with the diffraction at a sharp corner, but down-stream at point 0′ (Fig. 4). The Prandtl-Mayer fan is decentered unlike that shown in Fig. 3. It should be noted that in this paper only the initial stage of the shock wave diffraction is considered. As the diffracted wave recedes from the vertex of the angle, the difference in two types of configurations is likely to diminish.

4. Conclusions

We have thus revealed that the angle of transition from the Mach reflection to a regular one depends on the angle α (Figs. 1 and 2) and does not depend on the reflecting surface radius at the fixed angle α. The dependence $\omega_c(\alpha)$ is presented for strong shock waves ($M_0 \sim 6$) in air. The influence of rounding-off of the right angle vertex on the process of diffraction has been investigated. Variation in the diffracted shock wave shape and in the wave pattern are observed. It has been shown that the maximum velocity of the diffracted shock wave along the vertical side of the angle is achieved for a sharp-edge angle at some distance from the surface, and for a rounded-off angle directly on the surface.

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