

## Some properties of regular and irregular interaction of shock waves(\*)

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ONE OF THE MOST essential aspects of the shock wave interaction problem which attracts the attention of researchers is the aspect involving the determination of the interaction parameter regions where the regular or Mach type of the shock wave intersection is observed. The present paper contains some conclusions derived from the analysis of the solution for mutual reflexion of two shock waves of arbitrary strengths as well as the experimental data on the shock reflexion from a plane inclined surface. This is obtained when both regular and Mach types of reflexion are theoretically possible. Some peculiarities of the regular collision of two shock waves with unequal intensities are found.

Jednym z podstawowych aspektów zagadnienia oddziaływania fal uderzeniowych, przyciągającą uwagę wielu badaczy, jest problem dotyczący wyznaczania obszarów parametrów oddziaływania, w których obserwuje się przecinanie się fal uderzeniowych regularnych lub typu Macha. W pracy podano pewne wnioski wyciągnięte z analizy rozwiązania problemu wzajemnego odbicia dwóch fal uderzeniowych o dowolnej mocy, jak również z pomiarów doświadczalnych dotyczących odbicia fali uderzeniowej od płaszczyzny skośnej. Dotyczy to przypadku, gdy istnieje teoretyczna możliwość odbić regularnych, jak również typu Macha. Stwierdzono pewne osobliwości występujące przy zderzeniu dwóch fal uderzeniowych o różnej intensywności.

Одним из наиболее существенных вопросов при описании взаимодействия ударных волн является проблема определения тех областей параметров взаимодействия, в которых наблюдаются регулярные или маховские пересечения ударных волн. В работе содержатся некоторые результаты полученные на основе анализа решений взаимного отражения двух ударных волн произвольной амплитуды, а также экспериментальные результаты по отражению ударных волн от наклонной плоскости, полученные для таких условий, когда теоретически возможны как регулярные, так и маховские отражения. Найденны некоторые особенности при регулярном соударении двух ударных волн различной интенсивности.

### 1. Introduction

ONE OF THE MOST essential aspects of the shock wave interaction problem which attracts the attention of researchers is the aspect involving the determination of the interaction parameter regions where the regular or Mach type of the shock wave intersection is observed.

It is known that there are two solutions for the regular reflexion from a rigid wall and in the case of the regular collision of two shocks when the shock wave local theory is used. Besides, at certain initial parameter regions of the interaction both the regular and Mach interaction types are theoretically possible. No answer has yet been given to the question as to which of the possible configurations is realized in the concrete interaction

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processes. The additional conditions, allowing to choose the true solution from the possible ones, should be sought on the basis of a more profound analysis of the theoretical solutions as well as in the course of detailed experimental investigation of the shock wave interaction processes.

The present paper contains some conclusions derived from the analysis of the solution for mutual reflexion of two shock waves of arbitrary strengths as well as the experimental data on the shock wave reflexion from a plane inclined surface. This is obtained when both regular and Mach types of reflexion are theoretically possible. Some peculiarities of the regular collision of two shock waves with unequal intensities are found. The collision regularity boundary not coinciding with the boundary of oblique shocks of the weak and strong families is of the greatest importance. The regular intersection of two strong shock waves of unequal intensities is shown to be theoretically possible in a more narrow range of the collision angles than in the case of collision of the corresponding shock waves with equal intensities. It was experimentally established that the reflexion of the moving shock wave from an inclined plane surface resulted in the regular or irregular reflexion type depending on the "pre-history", the downstream parameter values behind the reflected shock wave far from the point of reflexion.

## 2. Regular collision of two shock waves of arbitrary intensity

Consider the four-shock configuration shown in Fig. 1. It is assumed that the shock wave fronts are plane with the uniform flow behind them. The values given are the intensities

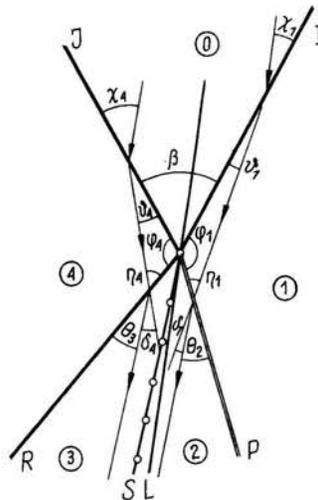


FIG. 1.

of shock waves as well as the angle of shock wave collision. The intensity may be characterized by the gas density ratio across the front. The principal relationships determining the intensities of the reflected shock waves and the geometrical parameters of the four-shock

configuration obtained from the mass, momentum and energy conservation equations and from the conditions at contact discontinuity may be

$$(2.1) \quad \Gamma_{10} = \frac{\operatorname{tg} \chi_1}{\operatorname{tg} \vartheta_1},$$

$$(2.2) \quad \Gamma_{40} = \frac{\operatorname{tg} \chi_4}{\operatorname{tg} \vartheta_4},$$

$$(2.3) \quad \frac{n - \Gamma_{10}}{\Gamma_{10}} \sin^2 \chi_1 = \frac{n - \Gamma_{40}}{\Gamma_{40}} \sin^2 \chi_4,$$

$$(2.4) \quad \chi_1 + \chi_4 = \beta,$$

$$(2.5) \quad \Gamma_{21} = \frac{\operatorname{tg}(\varphi_1 + \vartheta_1)}{\operatorname{tg} \theta_2},$$

$$(2.6) \quad n\Gamma_{10} - 1 = \frac{n - \Gamma_{21}}{\Gamma_{21}} \left[ \frac{\sin(\varphi_1 + \vartheta_1)}{\sin \vartheta_1} \right]^2,$$

$$(2.7) \quad \Gamma_{34} = \frac{\operatorname{tg}(\varphi_4 + \vartheta_4)}{\operatorname{tg} \theta_3},$$

$$(2.8) \quad n\Gamma_{40} - 1 = \frac{n - \Gamma_{34}}{\Gamma_{34}} \left[ \frac{\sin(\varphi_4 + \vartheta_4)}{\sin \vartheta_4} \right]^2,$$

$$(2.9) \quad \frac{n\Gamma_{10} - 1}{n - \Gamma_{10}} \frac{n\Gamma_{21} - 1}{n - \Gamma_{21}} = \frac{n\Gamma_{40} - 1}{n - \Gamma_{40}} \frac{n\Gamma_{34} - 1}{n - \Gamma_{34}},$$

$$(2.10) \quad \beta + \varphi_1 + \varphi_4 + \theta_2 + \theta_3 = 2\pi.$$

The following designations are used in the equations:  $\Gamma_{IJ} = \frac{\rho_i}{\rho_j}$  — density ratios across the shocks  $I, J, P, R$ . The subscripts  $i, j$  denote the flow regions before and behind the shock wave, respectively,  $n = \frac{(\gamma + 1)}{(\gamma - 1)}$  — maximum density ratio,  $\gamma$  — specific heat ratio of the gas used.

Equations (2.1), (2.2), (2.5) and (2.7) relate the density ratio values at the oblique shock fronts with the tangents of the incidence and refraction angles of the streamlines. Equation (2.3) indicates that the sound velocity in the „0” region may be expressed in terms of the parameters of either colliding wave. Equation (2.6) and (2.8) provide that the parameters of the flow behind the colliding waves are the incoming flow parameters for the reflected ones.

Equation (2.3) provides the equality of pressures at contact discontinuity expressed in terms of the pressure ratio. The relationships (2.4) and (2.10) are evident. The system of equations (2.1)–(2.10) can be reduced to the system of two nonlinear equations containing only two new variables  $v_1 = \operatorname{tg} \varphi_1$ ,  $v_4 = \operatorname{tg} \varphi_4$  numerically solved. Figure 2 represents the change of the angle between the reflected shocks as a function of the collision angle for the following pairs of the colliding shock waves:

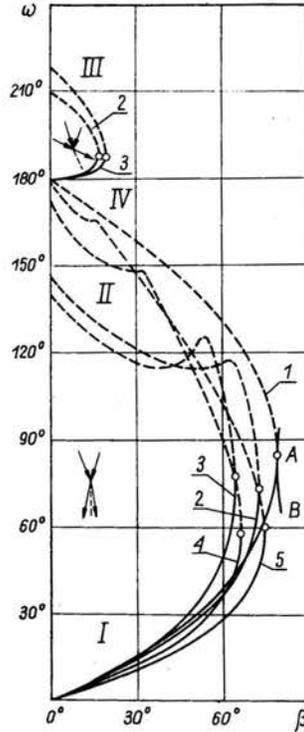


FIG. 2.

curve 1	$M_1 = 2,$	$(\Gamma_{10} = 2.67);$	$M_4 = 2,$	$(\Gamma_{40} = 2.67);$
curve 2	$M_1 = 2,$	$(\Gamma_{10} = 2.67);$	$M_4 = 5,$	$(\Gamma_{40} = 5.0);$
curve 3	$M_1 = 2,$	$(\Gamma_{10} = 2.67);$	$M_4 = 20,$	$(\Gamma_{40} = 5.92);$
curve 4	$M_1 = 5,$	$(\Gamma_{10} = 5.0);$	$M_4 = 15,$	$(\Gamma_{40} = 5.87);$
curve 5	$M_1 = 10,$	$(\Gamma_{10} = 5.71);$	$M_4 = 15,$	$(\Gamma_{40} = 5.87).$

As is seen the system (2.1)–(2.10) has one or several solutions (up to four) depending on the initial parameters  $M_1, M_4, \beta$ . The detailed analysis of the solutions (I)–(IV) shows that the upper series of the curves in Fig. 2 (branches III–IV) describes the interaction at the intersection point of three shock waves originating from the independent sources with two of them following each other and colliding at the intersection point with the third one moving in the opposite direction. This results in the shock wave and contact discontinuity. The lower series of curves (Fig. 2, branches I–II) refers to the shock regular oblique collision leading to the appearance of two shocks and a contact discontinuity.

These four solutions do not necessarily exist at any value of the initial parameters of the problem. As in the case of regular shock wave reflexion at the rigid wall, there exist such values of the angle  $\beta = \beta_{cr}$  for each pair of colliding wave intensities at which the pairs of the roots the I–II and III–V merge into one. At  $\beta > \beta_{cr}$  regular collision of shock waves is impossible. The points, corresponding to the critical values of the collision angle, are denoted by circles in Fig. 2. If the ratio of gas densities across the fronts of colliding waves with equal intensities satisfies  $\Gamma_{ij} > 2$ , then the critical value of the angle  $\beta_{cr}$  depends

but little on the shock wave intensity (the line  $AB$  in Fig. 2). The data obtained indicate that the regular collision of two strong shock waves with unequal intensities is theoretically possible in a narrower range of angles of shock encounter than in the case of waves of equal intensities.

Interesting properties of shock wave collision are revealed while considering the shock polars of the reflected shocks in the plane  $(\eta, \delta)$ , where  $\eta$  is the angle between the shock and incoming flow direction,  $\delta$  is the angle of deflection of the flow by the shock wave. Figure 3

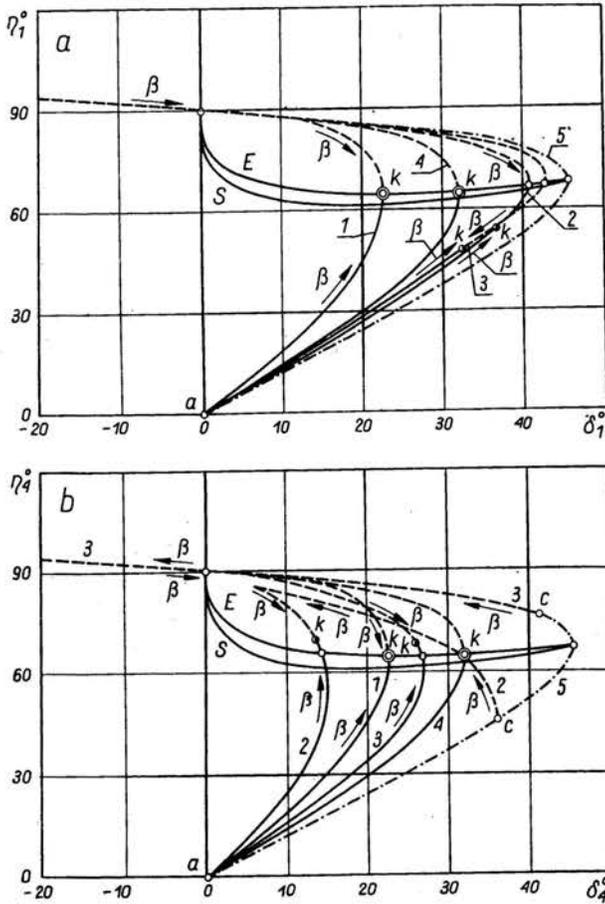


FIG. 3.

(“a” and “b”) presents the polars of the reflected shock waves  $P$  and  $R$ , showing the change of values  $\eta, \delta$  with the change of the shock wave collision angle for pairs of colliding waves with fixed intensities: curve 1 ( $\Gamma_{10} = \Gamma_{40} = 2.67$ ), curve 2 ( $\Gamma_{10} = 2.67; \Gamma_{40} = 5.0$ ), curve 3 ( $\Gamma_{10} = 5.71; \Gamma_{40} = 5.87$ ), curve 4 ( $\Gamma_{10} = \Gamma_{40} = 6$ ).

Solid and dotted lines mark parts of the polars corresponding to the solutions I and II of the problem. The arrows show the direction of the angle  $\beta$  to increase from 0 to the critical value. Points  $a$  and  $c$  refer to the 0 value of the angle  $\beta$ , points  $k$  (semi-blackened circles) refer to the critical angle  $\beta_{cr}$ .

To analyse the solutions obtained, some lines are plotted in Figs. 3a and 3b, defining the properties of the oblique shock. Curve 5 in these figures is the shock polar of the oblique shock for the incoming flow with  $M = \infty$ . All possible shock transitions occupy in the plane  $(\eta, \delta)$  the region between curve 5 and the ordinate axis. It is known that at the fixed  $M$ -number the incoming flow may be deflected by a shock wave at an angle not exceeding the certain value  $\delta = \delta_{\max}$ . Curve  $E$  in Figs. 3a and 3b is the locus of the points at which the maximum value of the flow deflection angle  $\delta = \delta_{\max}$  is attained for given  $M$ -values. This curve divides the region of possible shock transitions into two parts: above the curve the flow deflection at an angle  $\delta$  is due to the shock wave of the strong family, whereas below the curve it is due to the shock wave of the weak family. Curve  $S$  is the locus of the points for which the  $M$ -number of the flow behind the gasdynamic discontinuity is equal to unity.

Curves 1 and 4 are plotted for the symmetrical case of regular collision of two shock waves or, which is the same, for regular reflexion from an inclined rigid wall. The region of the parameters  $\eta, \delta$ , is smaller in this case than the values of  $\eta, \delta$  for shock transitions (within curve 5). It is easy to show that in the case of the regular collision of two similar shock waves the curve  $E$  divides the polars  $(\eta, \delta)$  into parts corresponding to the two (the first and the second) solutions of the regular collision problem. It is natural that within the region restricted by curve 4 the curve  $E$  itself is the locus for the pairs of values  $\eta, \delta$  which correspond to the critical values of the initial problem parameters. Since curve  $E$  is also a boundary separating the shock of the strong and weak families on plane  $\eta, \delta$ , solutions I appear to contain shock waves of the weak family whereas solutions II belong to the strong family in all cases of reflection of shock waves with equal intensity. Coincidence of the boundary of weak family shocks, and strong family shocks with the polar points  $\eta, \delta$ , corresponding to the critical parameters of the problem is an important property of oblique regular collision of shock waves with equal intensities.

The range of possible values of  $\eta, \delta$  for colliding waves of unequal intensities is wider than that for colliding waves of equal intensities. In the range of shock intensities considered above, the values  $\eta, \delta$  for one of the reflected waves lie outside the limiting polar of regular reflexion (curve 4), while those for the other wave lie within the region restricted by this polar. The characteristic feature of collision of shock waves with unequal intensities is the fact that the pairs of values  $\eta, \delta$ , corresponding to the critical interaction parameters for one reflected wave, lie below  $E$  (Fig. 3a), while those for the other wave lie above curve  $E$  (Fig. 3b). The "critical" points of regular collision do not coincide with the boundary points separating waves of the weak and strong family. Therefore solutions I and II contain reflected shocks of both weak and strong families. This feature of regular collision of shock waves with unequal intensity may prove to be essential when solving the problem of whether the regular shock wave interaction can be realized. If the reflected shock waves of the strong family are not realized, one may expect the transition to the irregular type of collision of two shock waves at the collision angle values to be smaller than the critical values at which the system of equations (2.1)–(2.10) has one root. The interaction parameter region where the solution I yields the strong reflected shock appears to be worth devoting further experimental research.

### 3. Experimental investigation of the onset of irregular reflexion

In determining the conditions in which irregular reflexion occurs, we shall consider only the case of a moving shock wave reflected from an inclined surface. It is convenient to use the value of the angle between the direction of the incident shock wave front propagation and the reflecting surface as well as the value of the incident shock wave intensity as the initial interaction parameters.

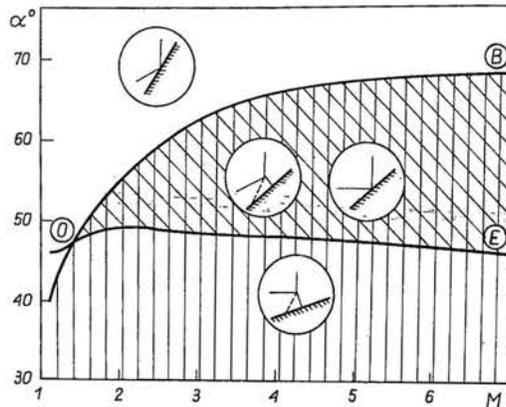


FIG. 4.

Figure 4 shows regions of exiting solutions in the local theory of regular reflexion and in the elementary theory of Mach reflexion [2] in the plane of initial interaction parameters  $(\alpha, M)$  for gas with a specific heat ratio  $\gamma = 1.29$ . Curve  $E$  in this figure is a boundary curve of regular reflexion. Regular reflexion is theoretically possible above curve  $E$ . As regards irregular reflexion, the curve of the "stationary" Mach configuration (curve  $B$ ) actually is a boundary curve. At the parameters  $\alpha, M$  on the  $B$  line the angle of the triple point trajectory is equal to zero according to the elementary Mach reflexion theory. At parameters  $\alpha, M$  in the region between the curves  $E$  and  $B$  both the regular and Mach reflexion types are theoretically possible. Until recently it was believed that when regular reflexion is possible this particular type of reflexion is realized. This conclusion was originally based on [3] investigating moving shock wave reflexion from a wedge in a shock tube. This study proved that in the vicinity of the regular reflexion boundary curve (curve  $E$  in Fig. 4) the regular reflexion is replaced by Mach reflexion. The regions of the regular and Mach reflexion were determined most thoroughly for a moving shock wave reflected from a wedge [3-5]. Special attention was given to regular reflexion being replaced by the Mach reflexion in the vicinity of the boundary curve but somewhat lower, i.e. regular reflexion was observed in the narrow region of the initial interaction parameters, for which the regular reflexion is theoretically impossible. Until [6], stationary reflexion of a shock wave from a wall or stationary intersection of shocks with equal intensities, had not been investigated. However, data were available to account for the fact that the replacement of the regular reflexion by Mach reflexion occurs at the interaction parameters, close to the regular reflexion boundary curve [4, 7, 8]. The first work to record the Mach

reflexion in the parameter regions  $\alpha$ ,  $M$ , where regular reflexion is theoretically possible, was [6]. Having studied the conditions for transition from regular to Mach reflexion in the case of the stationary intersection of two shock waves with equal intensities, the authors found that at  $M = 2.2$  the transition to Mach reflexion occurs at the parameters corresponding to curve  $B$ . It was noticed that in the region between curves  $E$  and  $B$  Mach reflexion yields the solution with a lower pressure behind the reflected shock wave in comparison to that obtained for regular reflexion, that is, it yields a weaker reflected wave. Mach reflexion was also obtained in the parameter region extending up to the curve  $B$  in [9] where both stationary reflexion and stationary intersection of shock waves in a wind tunnel were studied. The authors believe the disagreement between the data on stationary and pseudo-stationary reflexion to be only apparent and assert that in the region of the interaction parameters between the curves  $E$  and  $B$  when the moving shock is reflected from a wedge, there occurs the Mach reflexion. It is not the regular one but the configuration cannot be resolved because of its proximity to the reflecting surface. The work [9] contains no direct evidence of this assertion which leaves the question of the triple interaction parameter ranges, where one of the two reflexion types is realized, unanswered even in the most simple case of the plane shock wave reflexion from a plane inclined surface.

This article presents the results of the experimental research on plane shock wave reflexion from a double wedge. The aim of the present study is to determine how the conditions in the area behind the reflected shock wave (the "downstream" parameters) influence the realized wave pattern, when both regular and irregular reflexions are theoretically possible. Reflexion of a moving shock wave from a double wedge is one of the simplest cases of the unstationary reflexion. This model permits to vary the flow parameters at the apex of the second wedge retaining constant values of the shock wave intensity and the angle between the incident shock and the reflecting surface of the second wedge. The experiments were conducted in a shock tube with the model shown in Fig. 6. The model used consisted of two wedges. The gap was maintained between the two wedges to allow the boundary layer to bleed off and eliminate the possibility of separation at the corner intersection of the wedges. The experiments were carried out in carbon dioxide at the incident shock Mach number  $M = 2.9$ . The angle between the reflecting surface of the second wedge and the direction of the incident shock wave propagation was  $\alpha = 50^\circ$ . The wave configurations developing during shock wave reflexion from the secondary wedge surface were determined. According to the local reflexion theory, both regular and irregular types of reflexion are possible at  $M = 2.9$  and  $\alpha = 50^\circ$ .

The experiments show that reflexion is regular in the case of a moving shock reflexion from the single-corner wedge with an apex angle of  $50^\circ$ . At any rate, while observing reflexion of a shock wave at distance of 100 mm from the wedge apex, Mach reflexion is unresolved although, according to the Mach reflexion elementary theory, the angle of the triple point trajectory  $\chi = 2.1^\circ$  and at this distance the Mach stem might be expected to be  $\sim 5$  mm.

Figures 5(a-d) present four photos from the shadow photograph series showing the dynamics of the wave pattern development at shock wave reflexion from the double wedge. The apex angle of the first wedge is  $15^\circ$  and the second wedge apex angle is  $35^\circ$ . Reflexion of the incident shock wave from the surface of the first wedge results in the Mach configu-

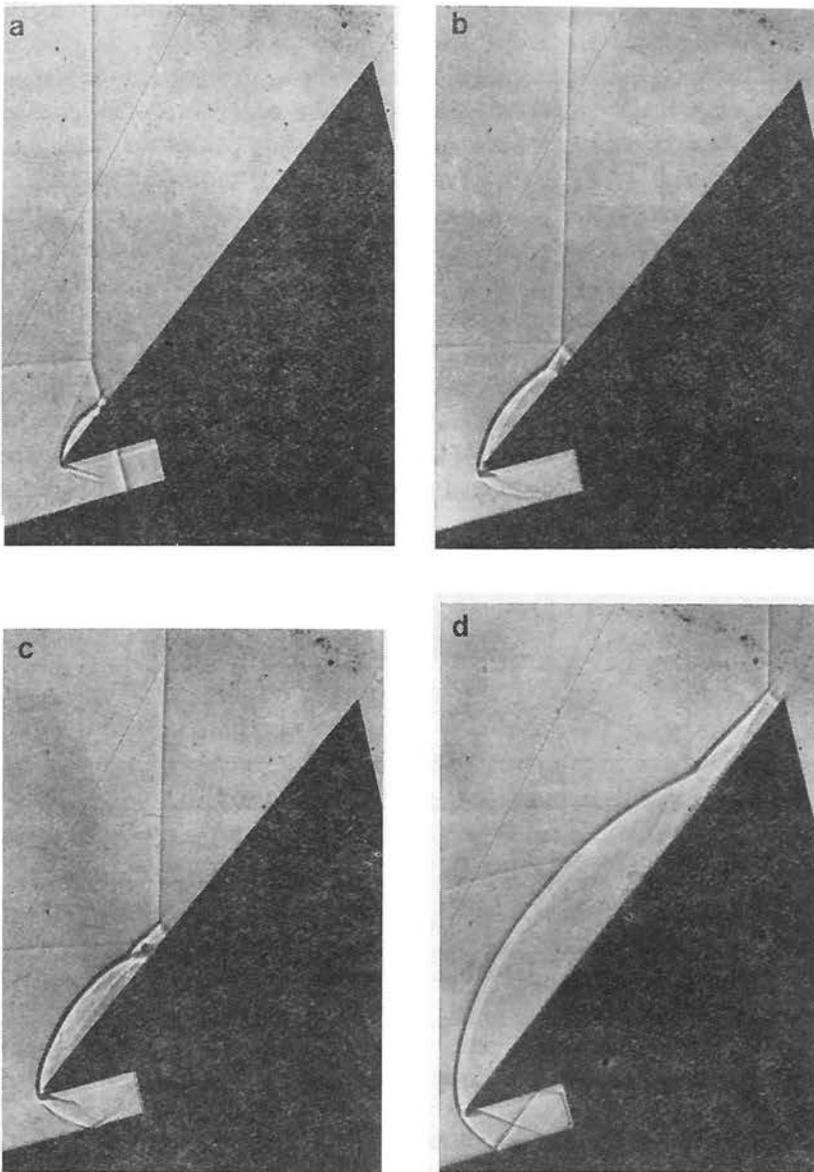


FIG. 5.

ration. Its geometric characteristics are in good agreement with the Mach elementary theory. Figure 5a shows the shadow pattern observed at the moment when the Mach stem of this primary triple configuration is reflected from the surface of the second wedge. One can see two triple points formed as the incident shock is reflected from the first wedge and the Mach stem is reflected from the second wedge. Reflexion of the Mach stem of the primary triple configuration from the second wedge surface occurs as a double Mach reflexion. The latter is characterized by the fact that behind the reflected shock wave there

occurs a secondary shock and the reflected shock front has a kink. The work [10] proves that the double Mach reflexion is realized only when the flow behind the reflected shock is supersonic in the system of reference bounded by the triple point and the pressure in the flow over the wedge is higher than the reflexion pressure. As a matter of fact, the secondary shock behind the reflected shock wave is a local boundary of the two simultaneous processes: Mach reflexion of the shock wave from the wedge surface and formation of the flow round the wedge. Figure 5b presents the shadow pattern of the wave configurations at the intersection of the triple point trajectories of the first and second Mach reflexions. At this moment the incident shock wave "learns" about the change of the reflecting surface slope. As is seen from Fig. 5c, a new three-shock configuration arises after the interaction of the triple points of the first and second Mach reflexions. The shadow photos of the successive stages of the shock wave-double wedge interaction show that the new Mach configuration moves first towards the second wedge surface and then the Mach stem begins to grow. The trajectories of the first, second and third triple points with respect to the second wedge surface are shown in Fig. 6. Plotted on axis  $x$  is distance from the apex of the second

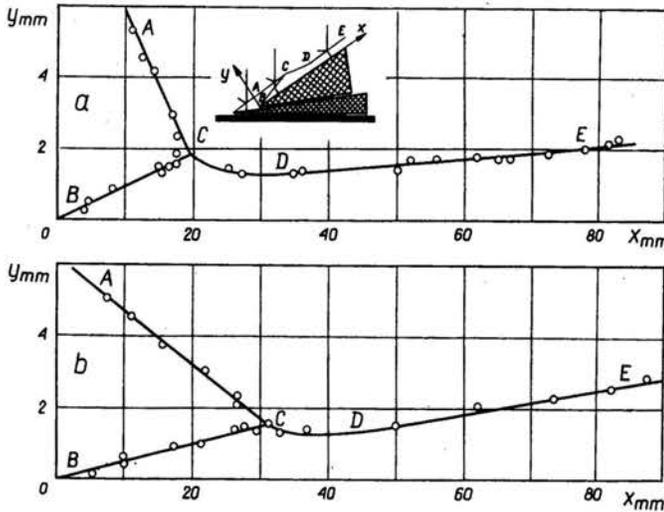


FIG. 6.

wedge to the intersection point of the normal from the triple point with the wedge surface, the distance along the normal between the triple point and the surface being plotted on axis  $y$ . The straight line  $AC$  is a portion of the trajectory of the triple point formed by reflexion of the incident shock wave from the first wedge. The trajectory  $BC$  of the second triple point produced by reflexion of the Mach stem is a straight line, too. The curve  $CD$  is a region of unsteady transitional process. Further, the triple point trajectory becomes straight (see the line  $DE$ ), which points at the self-similar development of the triple configuration. The wave pattern observed at this interaction stage is presented (in Fig. 5d). This is a system of gasdynamic discontinuities typical of the pseudo-stationary case of strong shock wave reflexion — the double Mach reflexion. The angle characteristics of the three-shock configuration are in good agreement with the theoretical values. The measured

value of the angle between incident and reflected shock waves is  $f_{\text{exp}} = 133.5^\circ$ , while the value calculated from the elementary theory of Mach reflexion  $f_{\text{th}} = 132.4^\circ$ . Thus, when a moving shock wave is reflected from a plane inclined surface of the double wedge, Mach reflexion is observed in the interaction parameter range where both regular and irregular types of reflexion are theoretically possible.

Significant results are obtained while studying reflexion of the shock wave with  $M = 2.9$  from the second surface of the double wedge when  $\alpha = 47.5$ . At reflexion from the ordinary wedge, a configuration which looks like a two-shock one is observed although at  $M = 2.9$  and  $\alpha = 47.5^\circ$  regular reflexion is not theoretically possible.

In the case of shock wave reflexion from the second surface of the double wedge, a system of gasdynamic discontinuities similar to that shown in Fig. 5d is observed. Figure 6b shows the trajectories of the triple points produced at shock wave reflexion from the first wedge, and reflexion of the Mach stem from the second wedge as well as the trajectory of the triple point resulting from the intersection of the two initial three-shock configurations. Similar to the case considered above the trajectories of the first and second points  $AB$  and  $BC$  are straight lines, the trajectory of the third triple point being curved at  $CD$  and straight at  $DE$ . In this region the angle between the triple point trajectory and the wedge surface is  $= 2.6^\circ$  which agrees well with the theoretical value calculated in the elementary theory of Mach reflexion.

Thus, the pressure decrease "downstream" behind the reflected shock due to the thinner wedge (the double wedge model) results in a noticeable increase of the angle of the triple point trajectory. The magnitude of the Mach stem in the case of stationary reflexion (reflexion of a stationary shock wave from a wall) is known to be determined by pressure at the exit of the channel. The unsteady process of shock wave reflexion from the double wedge considered above clearly reveals one of the possible mechanisms by which the "downstream" parameters influence the system of gasdynamic discontinuities.

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