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Some properties of the non-stationary interaction of two shock waves with a wedge (*)

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THE NON-STATIONARY interaction of two shock waves following one another with a fixed wedge has been investigated. The experiments were carried out in a two-diaphragm shock tube on wedges with apex angles $\beta = 30°$, 45°, 48,5°. The ranges of gas density ratios on the fronts of the first and the second shock waves were 2.8–3.6 and 1.1–2.3, respectively. The systems of gasdynamic discontinuities developing at the shock-shock interaction and the interaction of shocks with contact discontinuities and solid surfaces were analysed using large-scale shadow photos of the flow over the wedge. The data obtained show pressure changes on the wedge surface during the non-stationary interaction stage.

Rozpatrzono niestacjonarne oddziaływanie dwóch podążających za sobą fal uderzeniowych z nieruchomym klinem. Doświadczenia przeprowadzono w dwuprzeponowej rurze uderzeniowej na klinach z kątami wierzchołkowymi $\beta = 30°$, 45°. 48.5°, Zakresy stosunków gęstości gazu na czołach pierwszej i drugiej fali uderzeniowej wynosiły odpowiednio 2,8–3,6 oraz 1,2–2,3. Układy nieciągłości gazodynamicznych powstających przy oddziaływaniu fal ze sobą, z nieciągłościami kontaktu i ze sztywnymi powierzchniami, zbadano za pomocą wielkoskalowych zdjęć cieniowych przepływu wokół klina. Otrzymane wyniki wskazują na wahania ciśnienia na powierzchni klina w stadium niestacjonarnego oddziaływania.

Рассмотрено нестационарное взаимодействие двух движущихся друг за другом ударных волн с неподвижным клином. Эксперименты проведены в двухмембранной ударной трубе на клинах с углами при вершинах $\beta = 30°$, 45°, 48,5°. Интервалы отношений плотности газа на фронтах первой и второй ударных волн равнялись соответственно 2,8–3,6 и 1,2–2,3. Системы газодинамических разрывов, возникающих при взаимодействии волн с собой, с разрывами контакта и с жесткими поверхностями, исследованы при помощи многомасштабных теневых снимков вокруг клина. Полученные результаты указывают на колебания давления на поверхности клина в стадии нестационарного взаимодействия.

1. Introduction

AT PRESENT, many researchers attempt to solve, both theoretically and experimentally, some problems of the stationary and non-stationary shock-shock interaction as well as the shock wave — contact discontinuity and shock wave — solid surface interaction. In practice an interaction of this kind is observed when either a shock wave comes on a supersonic body or two gas-dynamic discontinuities come on a non-moving body. The latter kind of interaction is observed, for example, when two plane shock waves move one after another in the same direction towards a wedge. The first wave I propagates in an undisturbed medium while the second one J moves in the flow behind the first shock wave. The second wave overtakes the first one at a certain moment. As is shown by the

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exact analytic treatment [1], a new shock wave T and a rarefaction wave E as well as a contact surface C are realized if the specific heat ratio of the gas $\gamma < 5/3$. It is clear that the mode of the action of gas-dynamic discontinuities upon the wedge will be essentially different depending on the locus of shock waves merging relative to the wedge.

Presently, the case receiving the most attention is the following: the second wave J comes up to the wedge when the steady wedge flow produced by the first wave is observed. The wave pattern of the wedge flow at the moment of the second wave arrival is similar to that obtained in the case of a shock wave coming on a body moving at the supersonic velocity. Such a problem is solved most fully by the numerical method [2–4].

As yet there are no data whatsoever available concerning other cases of the gasdynamic discontinuities action upon a wedge. In this situation it is rather difficult and sometimes impossible to determine the type of interaction beforehand. The difficulty is due to the fact that the analytic solution of this non-stationary problem does not exist, while local theories of the interaction of shock waves offer multi-valued solutions [5, 6]. Besides, the regions of existence of different solutions may overlap. It is known, for example, that at the reflection of a shock wave from a wedge there exists an interaction parameter region (the parameters in question are the wedge apex angle, β, and the density ratio, Γ_{10}, at the front of the incident shock wave) where two solutions and, consequently, two types of reflection, namely the Mach reflection and the regular one, are theoretically possible. In the work [6] based on the experimental investigation of the shock wave non-stationary reflection from the double wedge it was shown that the actual type of reflection occurring on the second surface of the double wedge depends on the pre-history of this non-stationary process. By varying only the length of the first wedge surface one may observe the Mach or regular configurations on the second wedge surface.

The aim of the present work has been to study the dynamics and the essential features of the wave interaction process which are observed in different cases of the successive non-stationary interaction of gasdynamic (shock and contact) discontinuities with a wedge.

2. Experimental techniques

The experiment was carried out in a two-diaphragm shock tube of the rectangular cross-section 50 by 150 mm^2. For the generation of successive shock waves, the tube is provided by two high-pressure chambers. The first chamber length is 0.4 m, the length of the second is 1 m. The low-pressure channel has an 8.5 m length. A wedge is fitted in the working section at a distance 7.2 m away from the first diaphragm. In the experiments the wedges were used with the apex angle, β, of 30°, 45° and 48.5°. The wedge having $\beta = 48.5°$ was provided with a piezoelectric pressure transducer.

Nitrogen and carbon dioxide were used as working gases. Both high-pressure chambers were filled with nitrogen or hydrogen. The separating diaphragms used in the experiments were made of aluminium and copper 0.1–0.3 mm foil. A special knife served for cutting the diaphragms.

To obtain instantaneous shadow pictures of the wedge flow a standard schlieren device with a pulsed light source was employed. Synchronization of the light flash with the moment of the shock wave passing via the working section was accomplished by means of the piezoelectric transducer, the cathode follower and the starting circuit. A detailed description of this system is given in [7]. In the present work it was completed by the triggering stage which made it possible to initiate the pulse light source by the signal from the first or the second shock wave.

The measurement of velocities of the shock waves being generated was performed by means of the base method using the piezoelectric pressure transducer; the length of the base was 100 mm. The time interval was recorded by an electronic counter. The shock wave velocity was measured within 1.5%. The accuracy of the pressure measurements was 15%.

3. Experimental results

Three possible cases of the successive interaction of gasdynamic discontinuities with a wedge were investigated: the first case of two shock waves, (*IJ*), provided that the wave confluence occurred after passing the wedge; the second case of two shock waves, ($IJ \rightarrow TCE$), their confluence occurring at the moment of passing the wedge with the formation of a new shock wave *T*, a rarefaction wave *E* and a contact discontinuity *C*; the third case of a new shock wave *T* and a contact discontinuity *C*, (*TC*), waves *I*, *J* being merged before arriving at the wedge. These cases of the interaction *IJ*, $IJ \rightarrow TCE$ and *TC* were modelled in the two-diaphragm shock tube by means of a suitable choice of the initial conditions, i.e. absolute velocities of the shock waves being generated, the initial distance

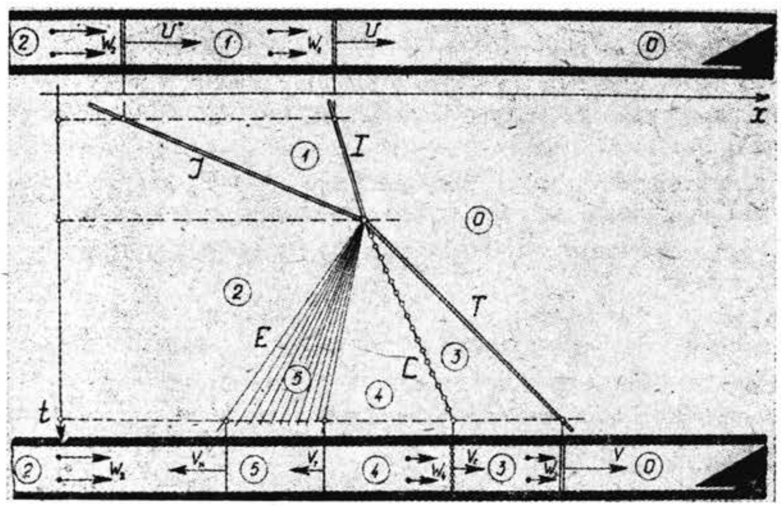

FIG. 1. The scheme of the head-on interaction of two shock waves, the first wave being overtaken by the second one.

between them, the distance from the model and the model dimensions. Figure 1 represents the diagram of the gasdynamic discontinuities and the flow regions before the beginning of the interaction with a wedge in the shock tube channel. In the upper part of the figure the discontinuities situation is shown for the interaction of the type *IJ* and $IJ \rightarrow TCE$ in the lower part — for the *TC* interaction type; in the middle the x, t — plot is given showing the interaction of two plane shock waves *I* and *J* moving in train.

For the analysis of the experimental results we shall introduce the symbols listed in Table 1.

Table 1

Gasdynamic discontinuities parameters \ Gasdynamic discontinuities symbols	First shock wave *I*	Second shock wave *J*	New shock wave *T*	Contact discontinuity *C*
Absolute wave front velocity	V	V^*	V	V
Absolute wave front Mach number	M_0	M_1^*	M	M_c
Gas density ratio at the front	$\Gamma_{10} = \frac{\varrho_1}{\varrho_0}$	$\Gamma_{21} = \frac{\varrho_2}{\varrho_1}$	$\Gamma_{30} = \frac{\varrho_3}{\varrho_0}$	$\Pi_{43} = \frac{\varrho_4}{\varrho_3}$
Gas pressure ratio at the front	$\Pi_{10} = \frac{p_1}{p_0}$	$\Pi_{21} = \frac{p_1}{p_2}$	$\Pi_{30} = \frac{p_3}{p_0}$	$\Gamma_{43} = 1$
Pressure gradient at the front	$\Delta\Pi_{10} = P_1 - P_0$	$\Delta\Pi_{21} = P_2 - P_1$	$\Delta\Pi_{30} = P_3 - P_0$	—

Let us consider the experimental data on the non-stationary interaction of the *IJ* type when the wave *I* approaches the wedge at the moment of the non-stationary diffraction of the wave *I*. In Fig. 2 six photos are presented; each of them records a certain moment of this complex non-stationary process. The experiment conditions are as indicated under Fig. 2. The shock waves of unequal intensity are generated, the condition $\Gamma_{10} > \Gamma_{21}$ being fulfilled. All shadow photos are obtained under similar initial conditions, except the distance between shock waves being generated which is reproduced in a series of experiments with some scatter. The consideration of the shadow photos in this order permits to get a qualitative notion about the time development of the non-stationary interaction process.

At the beginning one observes the *I* wave action upon the wedge. At the present interaction parameters, i.e. $\beta = 45°$, $\Gamma_{10} = 2.84$ the Mach reflection of the wave *I* from a wedge takes place. In Fig. 2a the Mach stem diffraction near the wedge top is recorded. Further changes of the wave pattern of the wedge flow are due to the arrival of the wave *J*. The time development of the flow wave pattern during this stage is shown in Fig. 2b-e.

At first, the passing shock wave *J* interacts with the curved bow shock (Fig. 2b). There occurs (at the point 0) the non-stationary oblique regular intersection of two shock waves with different intensities. The wave collision results in the formation of two new shock waves and a contact discontinuity *M* between them. As the wave *J* is passing, the conditions of the interaction between two colliding shock waves continuously change.

In our experiment, that is in the case of a weak shock wave interaction, the maximum value of the angle of encounter not exceeding 75°, only the regular type of wave collision

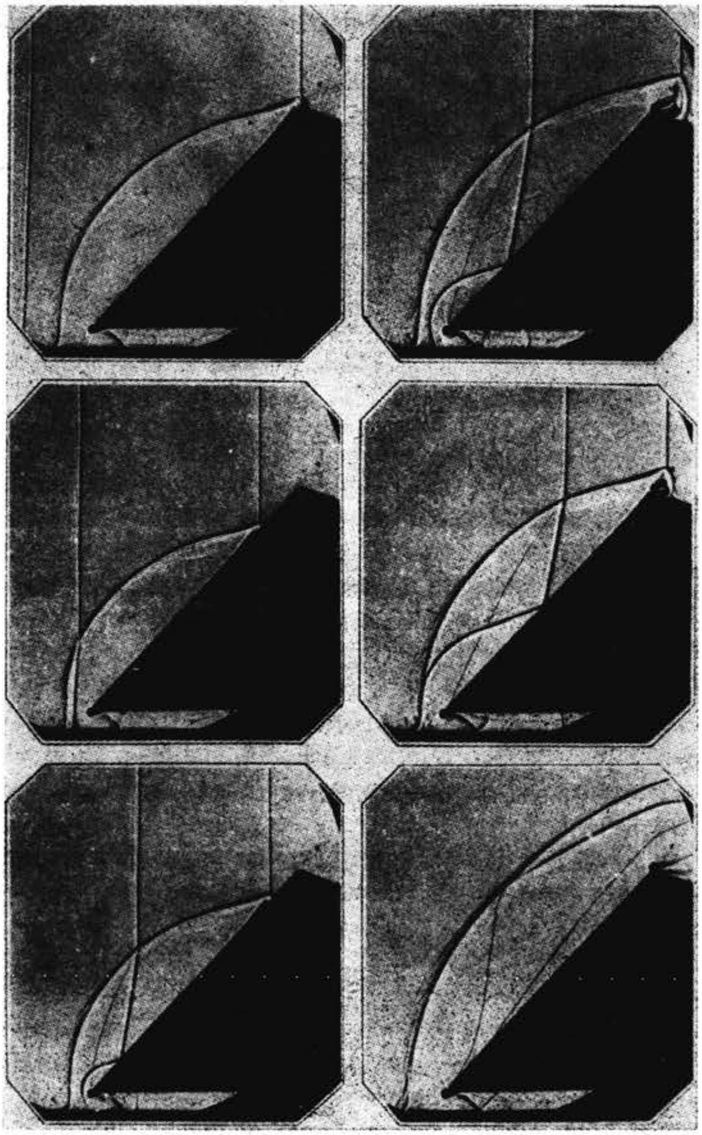

FIG. 2. The time development of the wave patterns of the wedge flow at the successive interaction of two shock waves.
Carbon dioxide, $\beta = 45°$, $P_0 = 0.658$ atm,
$U = 524$ m/s, $M_0 = 1.96$, $\Gamma_{10} = 2.84$, $\Delta\Pi_{10} = 2.1$ atm,
$U^* = 689$ m/s, $M_1^* = 2.12$, $\Gamma_{21} = 1.14$, $\Delta\Pi_{21} = 0.5$ atm.

is observed. As is shown by the calculations [5, 8], irregular collision occurs at much larger angles of encounter (80–95°) in comparison with the ones observed in the present experiment.

The effect of the interaction of the wave J with the primary bow shock (Fig. 2c) is such that the refracted shock wave J' strikes the wedge at an angle C which is smaller than the angle observed in the absence of the interaction. Further passing of the refracted shock wave along the surface of the wedge is accompanied by a decrease of the angle C (Fig. 2d, e). Undet these experimental conditions one observes the regular reflection of the refracted shock wave as it passes along the surface of the wedge. Within a certain parameter range the reflection of the refracted wave may be of the Mach type. In some cases the transition is possible from the Mach reflection to the regular one during the process of the reflection of the moving refracted wave.

The secondary bow shock wave forms within the region separated from the external flow by the primary (refracted) bow shock. As time goes on, the secondary bow wave overtakes the first one (Fig. 2e). There occurs the oblique interaction of these two waves which results in the formation of a new shock wave, a rarefaction wave and a contact discontinuity N originating at the point of merging P.

The contact discontinuity M emerging at the point 0 proves to be connected at its other end with a region of a vortex occupying the sharp front edge of the wedge (Fig. 2c, d). On the shadow photograph this region is seen as a black spot with a clear-cut contour. At the time moments that follow (Fig. 2e, f) the lower portion of the curved contact discontinuity is spreading along the wedge surface. The behaviour of the near wall portion of the curved contact discontinuity is determined by the longitudinal pressure gradient.

The observation time period in the present experiments ends at the moment at which the bow shock reaches the upper wall of the shock tube. In the experiment under discussion the bow shock interaction with the wall occurs earlier than the steady flow around the wedge becomes established. The wave pattern of the wedge flow at the stationary stage is determined by the properties of the gas flow produced by the second wave J.

Therefere, during the non-stationary stage of interaction with the wedge the complex

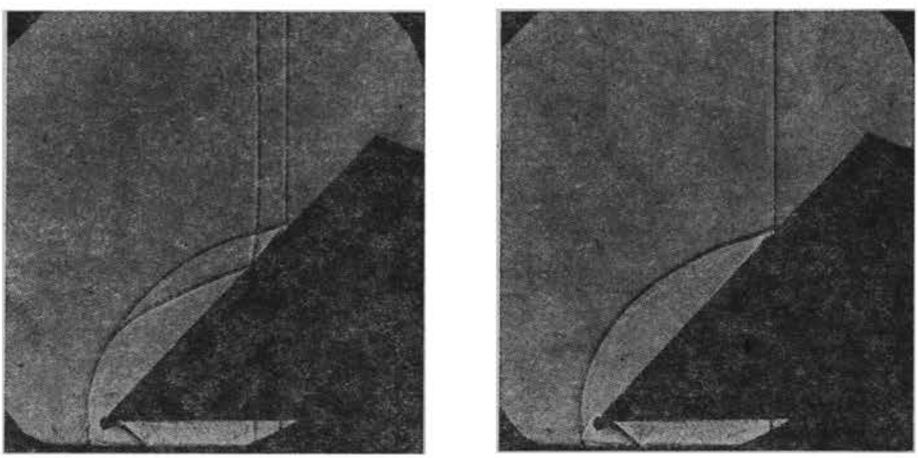

FIG. 3. The wave patterns of the wedge flow before and after the merging of two shock waves. Carbon dioxide, $\beta = 45°$, $P_0 = 0.658$ atm,
a) $U = 524$ m/s, $M_0 = 1.96$, $\Gamma_{10} = 2.81$, $\Delta\Pi_{10} = 2.1$ atm,
$U^* = 689$ m/s, $M_1^* = 2.12$, $\Gamma_{21} = 1.14$, $\Delta\Pi_{21} = 0.5$ atm.
b) $V = 565$ m/s, $M_c = 2.12$, $\Gamma_{30} = 3.12$, $\Delta\Pi_{30} = 2.6$ atm,
$V_c = 384$ m/s, $M_c = 1.15$, $\Gamma_{43} = 1.03$.

flow field is observed involving the multiple interactions of shock waves with each other, with contact discontinuities and solid surfaces.

Let us consider the experimental results on the interaction of $IJ \rightarrow TCE$ type. The process of the non-stationary interaction for the wedge with $\beta = 45°$ is represented by two, the most typical shadow photos (Fig. 3). The first photo shows the wave pattern of the wedge flow at the moment when two waves act simultaneously, the second photo refers to the time immediately after their merging. This pattern (Fig. 3b) records the front of a new shock wave and a contact discontinuity produced at the moment of two waves merging near the wedge. In the region bounded by the wedge surface and the bow shock one observes curved contact discontinuities M and N produced at the stage of the simultaneous action of two waves upon the wedge. The presence of the contact discontinuities in the flow field distinguishes the wave pattern from that obtained in the case of the single wave action.

The properties of a normal contact discontinuity briefly described are as follows. The contact discontinuity moves together with the gas flow and separates two regions differing with respect to density and temperature. Pressure and flow velocity are similar on both sides. Such a contact discontinuity is a natural interface of two states within a gas medium.

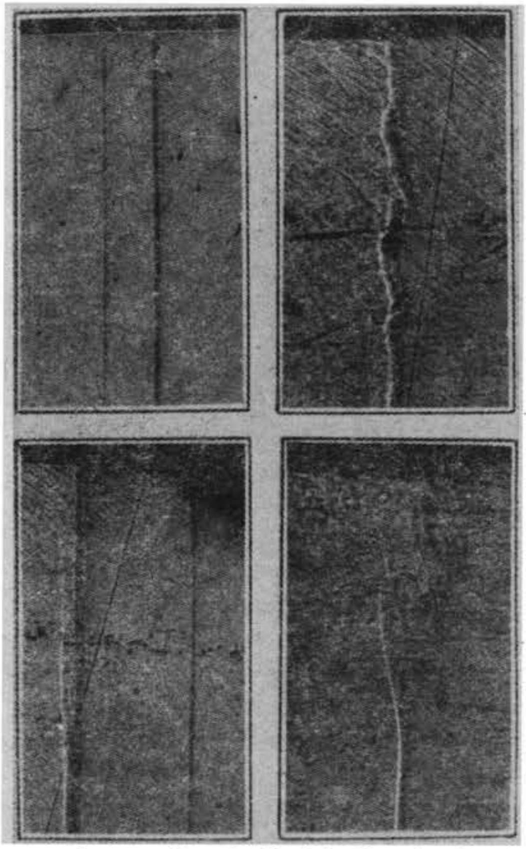

FIG. 4. The shape and structure of contact discontinuities being formed at the merging of two shock waves.

It may be used at the investigation of the shock wave refraction which up to now was carried out using a specially made membrane bringing certain disturbances in the process studied [9, 10].

In Fig. 4 shadow photos are presented allowing to observe the change of the shape and structure of contact discontinuities which form by merging of two plane shock waves (Tabl. 2). The shadow photos are obtained under various initial conditions and are demonstrated in the order of the time interval (t) increase elapsing from the moment of merging. At the moment of its appearance the contact discontinuity has a plane shape and the structure of its shadow image is similar to that of a shock wave (Fig. 4a). Contact

Table 2.

no	t μs	p_0 atm	Γ_{30}	Γ_{43}	Gas
a	57	0.105	4.45	1.17	Carbon dioxide
b	84	0.203	4.8	1.46	Nitrogen
c	198	0.213	4.84	1.5	Nitrogen
d	607	0.658	3.12	1.03	Carbon dioxide

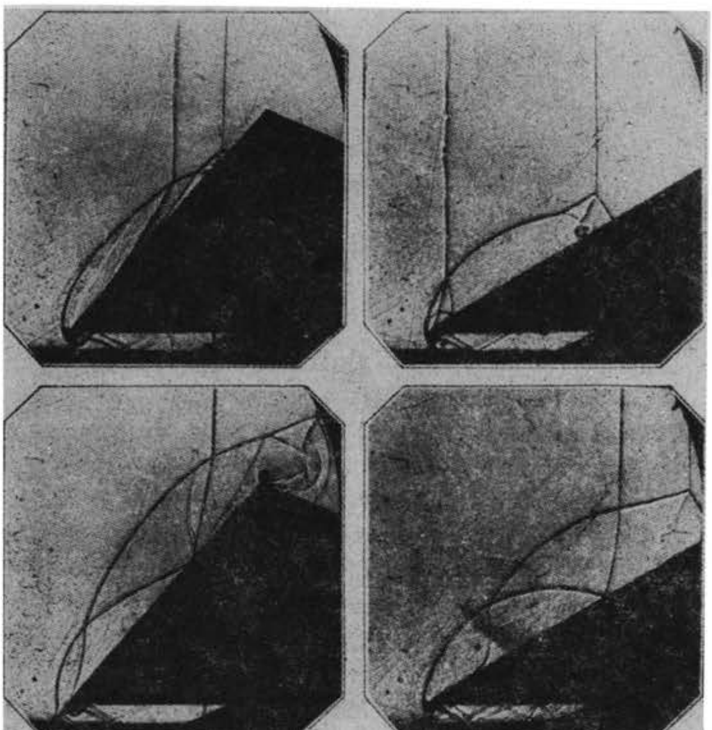

FIG. 5. The wave patterns of the wedge flow during the simultaneous action of two gasdynamic discontinuities.

a, b) shock wave T and contact discontinuity C; c, d) two shock waves, I and J.

discontinuities are inherently unstable (this instability is due to the action of heat conduction and viscosity). As time goes on, they lose their plane shape and blur transforming into turbulent regions (Fig. 4b, c). Through the interaction with the boundary layer being produced on the shock tube walls (Fig. 4d), the contact discontinuity is rolled up into a spiral vortex.

And now let us consider the last type of interaction of two successive gasdynamic discontinuities with a wedge – *TC*-type. The shock *T* and contact discontinuity *C* in this process are formed previous to their appearence at the wedge. The non-stationary process has two stages. The first involves the action of the shock wave *T* upon the wedge, the second stage follows the moment of arrival of the contact discontinuity *C* at the wedge. Wave patterns of the flow typical for the second interaction stage and obtained in two different experiments are shown in Fig. 5a, b.

At the point 0, (Fig. 5a), there occurs the oblique frontal interaction of the contact discontinuity *C* with the curved bow shock (Tabls. 3 and 4). This process may be interpreted

Table 3.

no	P_0 atm	$\beta°$	Gas	V m/sec	V_c m/sec	Γ_{30}	Γ_{43}	$\Delta\Pi_{30}$ atm
a	0.203	48.5	Nitrogen	1563	1237	4.8	1.46	4.5
b	0.203	30	Nitrogen	1593	1263	4.84	1.5	4.7

Table 4.

no	P_0 atm	$\beta°$	Gas	V m/sec	V^* m/sec	Γ_{10}	Γ_{21}	$\Delta\Pi_{10}$ atm	$\Delta\Pi_{21}$ atm
c	0.203	48.5	Nitrogen	970	1600	3.64	2.1	1.6	3.6
d	0.203	30	Nitrogen	930	1600	3.52	2.3	1.44	4.04

as a shock wave refraction at a contact surface. According to the classification of the possible types of shock wave stationary refraction proposed by HENDERSON [11], at this point one obtains the regular refraction of the shock wave with the passing shock *t* and the reflected rarefaction wave *e*, while the next Fig. 5b illustrates the similar refraction with the passing shock *t* and reflected *r* shock waves. The shock *r* strikes upon the wedge surface and reflects as a shock wave producing the additional pressure increase on the surface.

Thus the interaction of the passing contact discontinuity with a wedge in the supersonic flow leads either to the additional increase of pressure over the wedge surface or to presure decrease, depending on the wave system what will be realized at the point of the bow shock interaction with the passing contact discontinuity.

For comparison with the wave patterns considered just now in Fig. 5c, d, two more shadow photos are presented which are obtained under conditions similar to those of the shadow spectra in Fig. 5a, b with the exception of the distance between the shock waves generated. In the case presented in Fig. 5c, d, the wave J fails to overtake the wave I ahead of the wedge and thus the wedge is submitted to the simultaneous action of two shock waves. The time change of the load imposed on the plane-inclined surface under the experimental conditions (Figs. 5a, b and 5c, d) will be different. In Fig. 6 the pressure measurement results are presented as oscillograms recording the time change of pressure on the wedge surface for two types of gasdynamic discontinuity action upon the model; *TC* type (Fig. 6a, b) and *IJ* type (Fig. 6c, d). In the first case pressure recording was accomplished under experimental conditions illustrated by Fig. 5a, in the second case the conditions were as illustrated by Fig. 5c. It should be noted that the trend of the pressure change on the wedge surface (Fig. 6a) supports the assumption made earlier about the

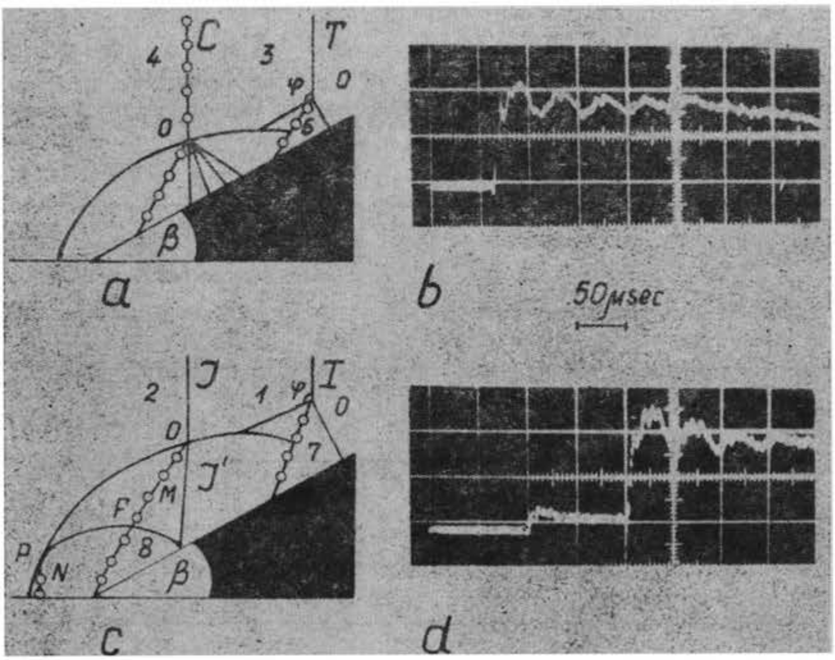

Fig. 6. The oscillograms showing the pressure change on the wedge surface under various interaction conditions.

a, b) the interaction of the *TC*-type
$\Delta\Pi^{th}_{60} = 12$ atm, $\varphi^{th} = 134.5°$,
$\Delta\Pi^{exp}_{60} = 28$ atm, $\varphi^{exp} = 133.5°$,
c, d) the interaction of the *IJ*-type
$\Delta\Pi^{th}_{70} = 4$ atm, $\varphi^{th} = 123.8°$,
$\Delta\Pi^{exp}_{70} = 7$ atm, $\Delta\Pi^{exp}_{87} = 30$ atm, $\varphi^{exp} = 123.5°$.

wave system forming at the interaction of the passing contact discontinuity C with the curved bow shock. In the present experiment the wave system being realized does not include the reflected shock wave r and thus the wedge is acted upon by the one shock wave T.

The measured gradients $\Delta\Pi^{exp}_{60}$, $\Delta\Pi^{exp}_{70}$, $\Delta\Pi^{exp}_{87}$ based on the signal maximum at the reflection of the shock waves T, I, J' and reflection angle φ^{exp}, are presented in Fig. 6.

The values of $\Delta\Pi^{th}_{60}$, $\Delta\Pi^{th}_{70}$ and the reflection angles φ^{th} calculated according to the Mach reflection theory [12] are presented here, too. The measured and calculated angle values agree within the measurement accuracy limits. The disagreement between the measured and calculated pressure gradients is due to the low spatial resolution of the pressure transducers (the diameter of the piezoelectric element is of the order of 5 mm). During the double Mach reflection of the shock wave T and I over the wedge surface (Fig. 6) there should be two pressure shocks [13]. The first corresponds to the change of pressure in the Mach wave ($\Delta\Pi^{th}_{60}$, $\Delta\Pi^{th}_{70}$), the second corresponds to the additional change of pressure in the secondary shock wave. In the present experiment (Fig. 6) at the reflection of the shock waves T and I the total pressure increase over the wedge surface is recorded following the circumstance indicated above.

4. Conclusions

Data are obtained as to the time development and pattern of the flow wave structures for different cases of the non-stationary interaction of two gasdynamic discontinuities with a wedge. These results may be used to estimate the accuracy of numerical methods applied for the solution of the non-stationary problem presented here.

It is shown that the interaction of the passing contact discontinuity with a body placed in the supersonic flow either induces the additional increase of pressure over the wedge surface or leads to a pressure decrease depending on what wave system will be formed at the point of the bow shock intersection with the passing contact discontinuity.

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