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Reflexion of an oblique shock wave by a turbulent boundary layer

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Measurements are presented of the reflected wave field produced by a plane oblique shock wave impinging on a turbulent boundary layer at an initial Mach number of 2·5. The outgoing waves are either a single shock, with the same deflexion as the incident shock, or a shock of approximately 10° deflexion followed by a region of compression in which is embedded an expansion fan having the same turning as the incident shock. The transition between these two types of wave field was not studied, but it is fairly abrupt and appears to be closely linked to the onset of boundary-layer separation. The observed wave systems broadly agree with the suggestions of a number of previous workers, but not with a recent theoretical treatment. Surface-pressure measurements and oil flow photographs are used to determine the onset of separation, and from these it is found that the overall pressure rise associated with incipient separation is rather smaller than previous work would suggest.

1. Introduction

The presence of a boundary layer causes an oblique shock to reflect from a solid surface as a complicated wave system rather than as a single shock. Most experimental studies of interactions between shock waves and boundary layers have yielded some information about this wave system but, since the information has been largely qualitative, our understanding of the structure of the system has remained qualitative also. Figure 1 shows a typical set of schematic interpretations of schlieren photographs made by Bogdonoff & Kepler (1955).

It is true that some authors have suggested quantitative models, but these have usually been as an aid to predicting boundary-layer growth and have been based more on intuitive reasoning than on experimental measurement. Figure 2 shows the model used by Lees & Reeves (1964). Recently, however, Henderson (1967) has made an ambitious theoretical attack on the problem. His approach has been to re-interpret the reflexion as a process of shock refraction by an inviscid shear layer. He has derived wave patterns for the interaction, including particularly the patterns inside the boundary layer, which are notable for their detail, complexity and variety. Figure 3 illustrates two classes of reflexion which he refers to as regular, the one with only compression, the other with both compression and expansion in the reflected wave pattern. In both cases the boundary layer is shown as separating.

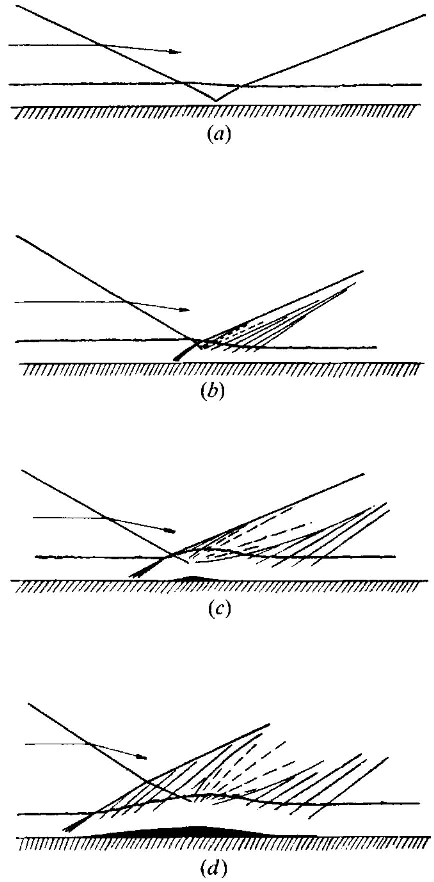


FIGURE 1. Reflexion of an oblique shock by a turbulent boundary layer. (Sketches by Bogdonoff & Kepler based on their schlieren photographs.) ——, edge of boundary layer; ——, compression; ----, expansion. (*a*) Weak incident shock $\alpha \leqslant 7°$. (*b*) Medium strength shock $\alpha \sim 9°$. (*c*) Medium strength shock $\alpha \sim 11°$. (*d*) Strong incident shock $\alpha \geqslant 13°$.

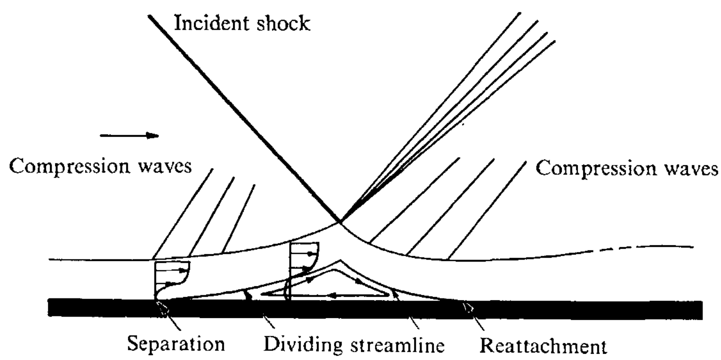
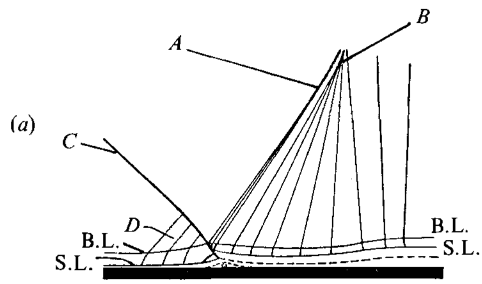


FIGURE 2. Flow model used by Lees & Reeves. (Laminar boundary layer.) Pressure drop through expansion equal to pressure rise through incident shock.



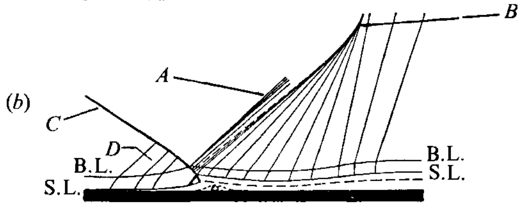


FIGURE 3. Wave fields calculated by Henderson. (*a*) Reflected waves, compression only. B.L., boundary layer; S.L., sonic line; *A*, envelope of compression waves from refraction of incident shock by outer part of boundary layer; *B*, envelope of downstream compression system; *C*, incident shock; *D*, upstream compression waves. (*b*) Reflected waves, expansion and compression. B.L., boundary layer; S.L., sonic line: *A*, expansion fan from first refractions of incident shock; *B*, envelope of downstream compression system; *C*, incident shock; *D*, upstream compression waves.

The purpose of this paper is to present some measurement of the reflected wave system in a flow with fully turbulent boundary layers. The main interest is in comparing the measured wave system with that envisaged by other workers. As a secondary issue, the results are discussed in the context of incipient separation.

2. Experimental results

The measurements which follow were obtained as a by-product of an experimental study (Green 1966) of boundary-layer development during and after interaction with an incident oblique shock. The experiments were performed at a Mach number of 2·5 in a wind tunnel $4\frac{1}{2}$ in. wide by $3\frac{1}{4}$ in. high. A plane shock generator of variable incidence, fully spanning the tunnel, produced an oblique shock which impinged on the boundary layer of the tunnel floor. The boundary layer was turbulent, with a Reynolds number based on its thickness just upstream of the interaction of approximately 4×10^5. The shock generator was sufficiently long for disturbances from its trailing edge to reach the tunnel floor well downstream of the interaction region.

Seven flow fields were investigated, for nominal deflexion angles through the incident shock ranging from 2 to 10·5 degrees. Measurements included surface-pressure distributions along the tunnel floor and Pitot traverses across the boundary layer, and the flow was visualized using surface oil and optical techniques.

Figure 4, plates 1 to 4, presents shadowgraph and schlieren photographs for every incident shock. The schlieren was cut off vertically, using a graded filter; exposure time was 0·01 sec. The shadowgraphs were illuminated by a spark of between 2 and 3 μsec duration. Each photograph contains some spurious detail. The dark patch at the right-hand side is due to pitting of the tunnel windows. The right-running wave in the top right of each photograph emanated from a joint between the front and interchangeable rear portion of the shock generator. The pattern following this wave in the case of the 9·5° and 10·5° shocks was produced by machining marks in the wooden rear portion of the generator used for these two shocks. Pitot traverses showed that the variation in free stream Mach number caused by these disturbances was less than 0·002.

The strengths of the various waves seen in the photographs were determined from Pitot traverses normal to the tunnel floor. The probe employed was circular with an outside diameter of 0·016 in. compared with a boundary-layer thickness of about 0·28 in. Traverses were made at a streamwise spacing of 0·25 in. Pitot pressure was measured by strain-gauge transducer and probe position by potentiometer. As the probe was being traversed across the boundary layer the outputs from these two instruments were plotted on an X–Y chart recorder as a continuous trace of Pitot pressure against probe position. Local Mach numbers outside the boundary layer were evaluated from the ratio of Pitot pressure to the estimated total pressure, the latter being obtained by subtracting the appropriate oblique shock losses from tunnel total pressure. No corrections were made for the probe being pitched relative to the local flow, but misalignment was generally, and in most cases appreciably, less than 10°. Since the Pitot traverses were recorded continuously, the position and strength of most components of the wave system could be determined from the local Mach numbers with reasonable accuracy. However, because the experiments were not planned to study the wave system, not every traverse position was ideal and in some cases it is not certain that the full range of a particular wave fan was measured.

Figure 5 is a sketch of the wave field derived from the present schlieren photographs. Its proportions are roughly those for a deflexion through the incident shock of 8°, for which case there was a separation bubble of length about twice the boundary-layer thickness. The flow field has been divided into seven regions which, apart from the expansion, region 5, appear from the schlieren photographs either to be regions of constant pressure or to contain weak, left-running compression systems. The boundaries dividing the regions are therefore, notionally, discontinuities either in pressure or in pressure gradient.

Figure 6 is a sketch of a sequence of traces from the X–Y chart recorder. It shows Pitot pressure distributions across the boundary layer obtained, for the 8° shock, at seven stations corresponding roughly to those labelled A to G in figure 5. Distance and pressure are normalized with respect to the thickness of the undisturbed boundary layer and total pressure in the tunnel settling chamber. On each traverse the regions and waves of figure 5 are identified. In this particular case, wave strengths were deduced as follows: deflexion α through the incident shock from the change in Mach number across RS, traverse B; deflexion β through the initial reflected shock from the change across LS, traverse C; compression in region 4 from the decrease in Mach number from its maximum, just inboard of LS on C, to its minimum at the pressure peak in 4 on D; expansion γ in 5 from the increase in Mach number between the pressure peak on D and

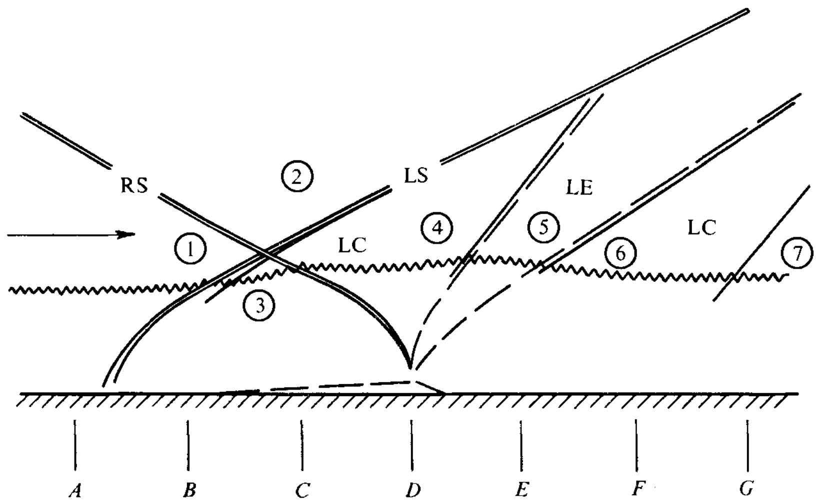


FIGURE 5. Schematic wave system for $\alpha \simeq 8°$. RS, right-running shock; LS, left-running shock; LC, left-running compression; LE, left-running expansion.

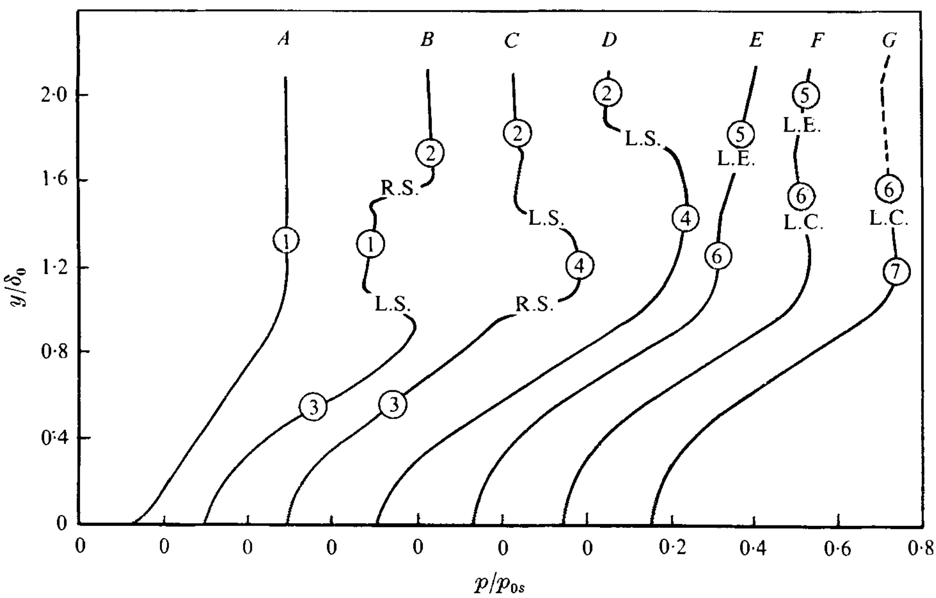


FIGURE 6. Pitot pressure distributions through the boundary layer ($\alpha_n = 8°$). Waves denoted by the convention of figure 5. Regions of figure 5 indicated by ringed numbers.

the junction between 5 and 6 on E or F; final compression in 6 from the deceleration between the 5 and 6 junction on F to the pressure peak at 7 on G. From this description some idea will be gained of how the uncertainty in finding the full extent of a wave fan arises—in this instance the boundary between 5 and 6 can be pinpointed, but not that between 4 and 5. Although each set of traverses has a highly individual character, depending on the position of the wave pattern relative to the traversing stations, problems of interpretation are generally similar to those found in figure 6.

Two further points may be noted on this figure. First, due to probe interference effects the incident and reflected shocks appear spread out over a distance of the same order as the probe diameter ($\simeq 0{\cdot}06\ \delta_0$). Secondly, it is necessary to distinguish between waves generated by the incident shock and waves which have been produced somewhere upstream by imperfections in the nozzle. The ripple apparent in region 1 on traverse B, region 2 on traverse C, and also faintly visible in some of the schlieren photographs, is one such spurious wave.

Deflexions through the various components of the wave system, measured as near as possible to the edge of the boundary layer, are given in table 1. These values are estimated to be accurate to $\pm\frac{1}{2}^{\circ}$.

Nominal deflexion through incident shock	α_n	2	3·5	5	6·5	8	9·5	10·5
Measured deflexion through incident shock	α	2·6	3·7	5·1	6·7	7·6	9·5	10·0
Deflexion through leading reflected shock	β	−2·9	−3·7	−5·4	−9·5	−9·4	−10·0	−10·0
Turning through compression regions 3 and 4		0	0	0	0	−1·2	−3·4	−3·3
Turning through expansion region 5	γ	0	0	0	6·7	8·0	9·9	10·5
Turning through compression region 6		0	0	0	−2·3	−2·6	−3·1	−4·3

TABLE 1. Wave deflexions in degrees measured immediately outside the boundary layer (deflexions towards the wall positive).

3. Discussion

3.1. *The reflected wave system*

The shadowgraph and schlieren photographs have features similar to those observed in this type of flow by other experimenters. The spark shadowgraphs indicate the turbulence within the boundary layer and the unsteady nature of the disturbances propagated from the interaction. The schlieren photographs suggest that the weakest shock reflects almost regularly as a single shock, while the strongest shock reflects as a shock-compression–expansion-compression system. In the latter case it also appears that the boundary layer separates. These photographs closely resemble the schematic wave fields sketched by Bogdonoff & Kepler (1955), figure 1, and are crudely similar to the pattern suggested by Lees & Reeves (1964), figure 2 (though the latter were concerned only with a laminar boundary layer). They differ appreciably, however, from the patterns derived by Henderson (1967), figure 3, in which any expansion waves present are upstream of the main reflected shock.

Of course it has already been tacitly assumed, in the schematic wave field of figure 5, that the sketches of Bogdonoff & Kepler contain all the essential features of the flow. The measured wave strengths given in table 1 reinforce this assumption. That is to say, apart from some spurious disturbances arising upstream in the nozzle, the Pitot traverses indicate no significant waves other than those sketched in figure 5. Furthermore, when deflexions through the various components of the reflected wave system are examined, a remarkably simple structure for this system suggests itself.

Table 1 shows that for the three weakest incident shocks the only reflected wave is a shock with deflexion angle equal, within experimental accuracy, to that through the incident shock. In effect, the reflexion is the same as that at a solid surface in the absence of a boundary layer.

For the four strongest shocks, in contrast, it is the expansion fan which has the same turning angle as the incident shock. This part of the reflected pattern is thus virtually the same as would be produced if the incident shock were reflected at a free, constant-pressure boundary in inviscid flow. Moreover, the shock which is the leading wave of the reflected system has a deflexion of approximately 10° irrespective of incident shock strength. This behaviour is characteristic of the shock associated with boundary-layer separation at a 'free interaction', as discussed for example by Chapman, Kuehn & Larson (1957).

It therefore appears that the seven flows studied can conveniently be classified as either 'separated' or 'unseparated', the two classes being distinguished by the marked difference in the character of their reflected wave systems. The two distinguishing parameters, the deflexions through the leading reflected shock and the reflected expansion, are plotted against deflexion through the incident shock in figure 7. The difference between the two classes of flow, and the abruptness of the transition from one to the other, are very noticeable in this figure.

The components of the wave system not yet discussed are the compressions in regions 4 and 6 of figure 5 which occur when the flow is 'separated'. Their total strength may be approximately inferred from the requirement that the free stream is turned back roughly parallel to the wall by the end of the interaction. The incident shock and reflected expansion turn the flow towards the wall through a total angle twice the deflexion through the incident shock alone. The nominally equal and opposite turning away from the wall is accomplished by the leading 'free interaction' shock, approximately 10°, plus the compressive turning in regions 4 and 6. In fact, for every 'separated' flow, table 1 shows the total turning towards the wall to be significantly greater than the turning away from the wall. The discrepancy arises because at the station labelled G, which has been taken as the downstream limit of the interaction region for the purpose of analyzing the wave field, the boundary-layer displacement surface is not parallel to the wall. For the 6·5, 8 and 9·5 degree shocks, displacement thicknesses in the vicinity of G were determined from the Pitot traverses. The values of $d\delta^*/dx$ at station G in these three cases were estimated to be $-0{\cdot}030$, $-0{\cdot}038$ and $-0{\cdot}056$ respectively. In figure 8 total deflexions towards and away from the wall are plotted against each other, and are seen to be consistent when $d\delta^*/dx$ is taken into account.†

† It may be wondered why measurements of the wave field were not extended downstream to the point where $d\delta^*/dx$ was zero. The reason is that the station here labelled G was roughly the rearward limit of two-dimensionality in the wave field. Downstream of station G the centre-line flow was influenced by transverse waves propagated from the interaction between the incident shock and the boundary layers on the tunnel sidewalls.

These results as a whole suggest that the outgoing wave system is produced primarily by a process of reflexion, or reflexion coupled with a strong interaction between boundary layer and free stream.

For the weakest incident shocks the measurements show, at the edge of the boundary layer, either a single reflected shock or a region of densely packed compression waves. Because of probe interference spreading the pressure jump, we cannot confidently distinguish between the two from Pitot traverses. However, we may interpret the schlieren photographs as indicating that it is indeed a shock, and that it is reflected from deep within the boundary layer in much the same way that a Mach line is reflected. Shocks appear spread in these photographs, primarily because non-uniformity of the tunnel flow produces slight transverse concavity in the incident shock. For the three weakest shocks, surface oil flows (figure 9, plate 5) indicate that the interaction regions (and therefore, probably, the reflected shocks) are concave upstream. Accordingly, for these three shocks, we should associate lines having the same relative streamwise position in the images of the incident and reflected shocks. If this view is correct, the photographs clearly indicate a reflexion similar to that of a Mach line. The conclusion we draw is that, for 'unseparated' flows, the fine structure at the shock foot which Henderson discusses is confined to a small region well within the boundary layer. Similarly, the region in which the subsonic part of the flow adjusts to accommodate the shock-induced pressure rise is small. The result is that outside the boundary layer there is little influence from either region, and the shock appears to have been reflected from a solid surface.

For the strongest incident shock the picture is rather different. The overall pressure rise is large enough to produce a long separation bubble, and there is a strong interaction between free stream and boundary layer which spreads out the pressure rise and generates an outgoing system of compression waves. The essential point here is that boundary-layer development and the outgoing compression system are mutually induced; i.e. the outgoing compressions are not reflexions or refractions of any incident waves. On the contrary the incident shock, penetrating the boundary layer at a point where it is separated, is reflected from the separated layer as an expansion fan. To a good first approximation this reflexion is as if at a constant-pressure boundary in uniform flow—any effects of shock refraction in the outer part of the layer appear to be lost in experimental error.

The total outgoing wave field may thus be seen as that of a strong compressive interaction between boundary layer and free stream—i.e. an oblique shock followed by a compression fan—in which is embedded an expansion fan which is the constant pressure reflexion of the incident shock. For strong shocks, where the separation bubble is large and the characteristic features of the interaction are some distance apart, several workers have postulated such a structure. If the present results are unexpected, it is because they show this structure when the deflexion through the incident shock is as little as $6{\cdot}5^{\circ}$, and indicate that transition from 'separated' to 'unseparated' behaviour is surprisingly abrupt.

As far as they go, the wave systems described or proposed by, for example, Bogdonoff & Kepler or Lees & Reeves conform with the present measurements and call for no further comment. On the other hand, the wave fields constructed by Henderson appear not to be consistent with certain aspects of these measurements, and it is worth considering the specific nature of the discrepancy.

From Henderson's analysis we should expect each of the seven flows reported here to resemble qualitatively the flow illustrated in figure 3(*b*), with a reflected wave system containing both expansion and compression waves. According to this analysis, the expansion waves are generated solely by refraction of the incident shock in the outer part of the boundary layer; the compression waves come partly from refraction of the incident shock in the central part of the boundary layer, partly from upstream influence thickening the subsonic, innermost part of the layer, and partly from a region downstream of the incident shock where the main stream is deflected until it is once again flowing parallel to the wall. The strength of those components of the system which arise from refraction of the incident shock may of course be determined from oblique shock tables. Typically, in the present flows, the deflexions through the outgoing expansion and (refracted) compression fans should be each of order one tenth the deflexion through the incident shock. Any upstream compression waves generated by thickening of the subsonic stream tubes adjacent to the wall (figure 3(*b*)) will interfere with this refraction process, strengthening the refracted compression system but weakening—possibly even cancelling completely—the refracted expansion fan.

The present measurements are clearly of no more than first-order accuracy and reveal the flow structure in outline only. Hence, for the 'unseparated' flows, the structure of the shock foot is too compact to be observable and the outgoing expansion fan predicted by Henderson's analysis is sufficiently weak to be lost in experimental scatter. Consequently, there appears to be no first-order inconsistency between Henderson's flow model and the observed 'unseparated' flows. The same is not true, however, of the 'separated' flows. In these, the observed deflexion through the outgoing expansion fan is an order of magnitude too great for this expansion to be attributed to refraction of the incident shock in the outer part of the boundary layer; on the contrary, it seems explicable only in terms of shock reflexion at a boundary of effectively constant pressure—such as might be provided by a separation bubble. The flow structure proposed by Henderson appears at present to preclude such behaviour, although this limitation is not fundamental to his analysis. It could probably be circumvented by adopting a different approach to the application of boundary conditions along the sonic line—in particular, by trying to ensure that these conditions were compatible with the behaviour of the subsonic portion of the flow, even when a separation bubble was present. Thus, if our understanding of these flows is to advance, further insight into the behaviour and influence of the subsonic region would seem to be essential. Indeed, in the present 'separated' flows it appears that the behaviour of the innermost, subsonic, viscous part of the boundary layer dominates the outgoing wave pattern, while the refraction phenomena considered by Henderson are of only secondary importance.

3.2. *Incipient separation*

We have yet to establish whether the words 'separated' and 'unseparated', as applied to the reflected wave system, can also be taken literally; i.e. whether the appearance of a reflected expansion fan coincides with the onset of separation as it is conventionally understood.

Figures 9 and 10 show surface oil flow patterns and static pressure distributions through the region of shock reflexion in the present experiments. The oil flow photographs were taken from directly above the wind-tunnel floor after it had been removed from the tunnel. The side-edges of the photographs correspond to the corners between the tunnel floor and sidewalls, so that in every case (except that of the 10·5° shock, where one side of the photograph has been trimmed) the flow pattern over the full tunnel span can be seen. The direction of the main stream was from top to bottom in the photographs. Every pattern is marred to some extent by oil blown downstream during tunnel shut down from an accumulation in the interaction region; this effect is particularly severe for the separated flows in which, during a run, the oil accumulation along the separation line was considerable. In general, those features of the pattern which indicate the nature of the steady airflow may be distinguished by their long, thin, continuous filaments.

The only photograph in which both the separation and reattachment lines are well defined is that for the 10·5° shock. The reattachment line, characterized by surface streamlines flowing out from it on either side, curves gently round to cross the centre line (marked by the line of pressure tappings) perpendicularly at about one third the height of the photograph. The separation line, somewhat bowed, is close to the top edge of the photograph. Although the line itself is slightly smudged, it is possible, particularly in the left-hand part of the photograph, to trace streamlines running into it from both sides and hence to define its position fairly closely. It appears to cross the centre line at, or very slightly upstream of, the edge of the photograph. For the shocks of 5° to 9·5° deflexion, the oil blown back during tunnel shut down obscures much of the separation region. Nevertheless, for both the 8° and 9·5° shocks the position at which the reattachment line crosses the tunnel axis can be estimated. For the 6·5° shock neither separation nor reattachment lines can be identified, but the shape and extent of the thick oil patch suggest that a short separation bubble was present in this case also.

The observed positions of separation and reattachment are marked on the surface pressure distributions, figure 10. Then, assuming the pressure rise up to separation to be in every case the same as that observed for the 10·5° shock, and taking the pressure rise downstream of reattachment for the 5° and 6·5° shocks to be the mean of the observed values for the three strongest shocks, positions of separation and reattachment are inferred for the cases masked by oil accumulation. Because the observed pressure rise downstream of reattachment decreases with decreasing shock strength, and the rise to separation may be expected to do the same (since the maximum pressure gradients are steeper for the weaker shocks), this procedure probably tends to underestimate the length of separation bubble for the weaker shocks.

We may therefore be fairly confident that there is an appreciable separation bubble beneath the 6·5° shock and that, for the boundary layer in these experiments, the incipient condition occurs at an incident shock deflexion of approximately 5°. That is, in every case except the borderline one of 5°, the surface flow

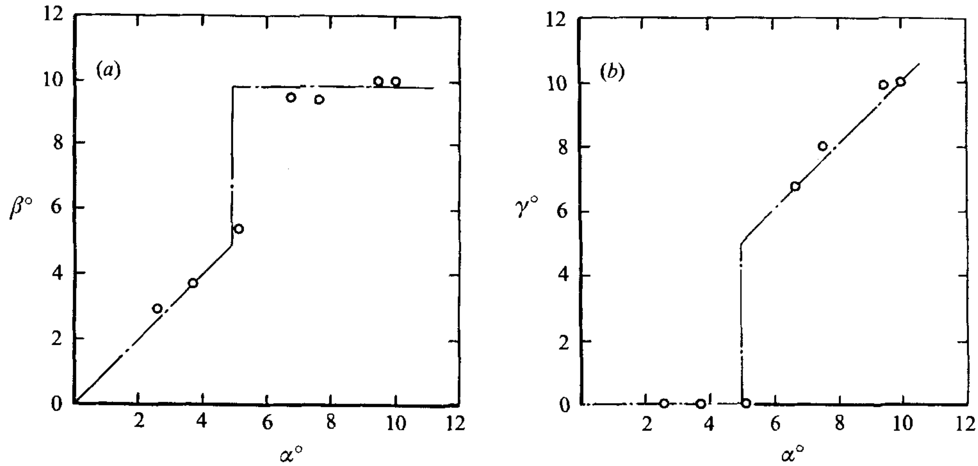


FIGURE 7. Deflexion through principal reflected waves. (*a*) Leading reflected shock. (*b*) Reflected expansion.

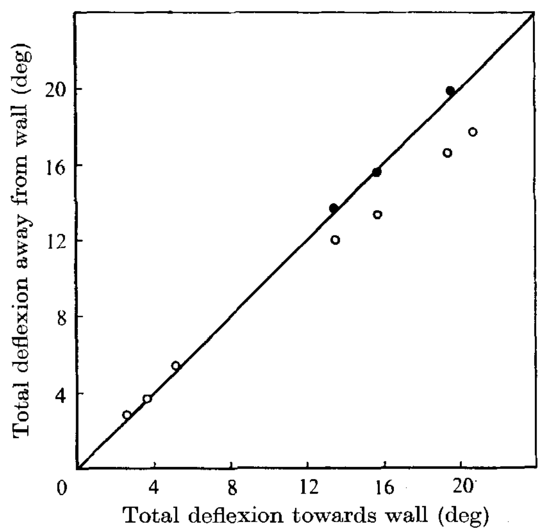


FIGURE 8. Total free stream deflexions. ○, outgoing compression system; ●, outgoing compression minus $(d\delta^*/dx)_G$.

and reflected wave fields correspond. What still remains unexplored is the transitional region between flows with 'separated' and 'unseparated' wave patterns, and where and how during the transition reversed flow becomes incipient.

A lower bound for the 'separated' wave pattern is an incident shock deflexion equal to half that through the 'free interaction' shock (net angular deflexion zero, no compression in regions 4 or 6 of figure 5). The lines drawn in figure 7 show the initial strengths of the reflected shock and expansion *if* transition between the 'separated' and 'unseparated' patterns were to occur as a sudden jump at this lower bound. In so far as surface pressure and oil observations indicate incipient separation at the same shock strength as this hypothetical jump, and since a reflected expansion fan is clearly visible in the corresponding schlieren photograph (figure 4(*e*)), the lines in figure 7 appear to have some justification. This agreement could well be fortuitous, however, and it would seem incautious to expect any widespread validity for so simple a model until we have evidence about the transition process over an appreciable range of flow conditions.

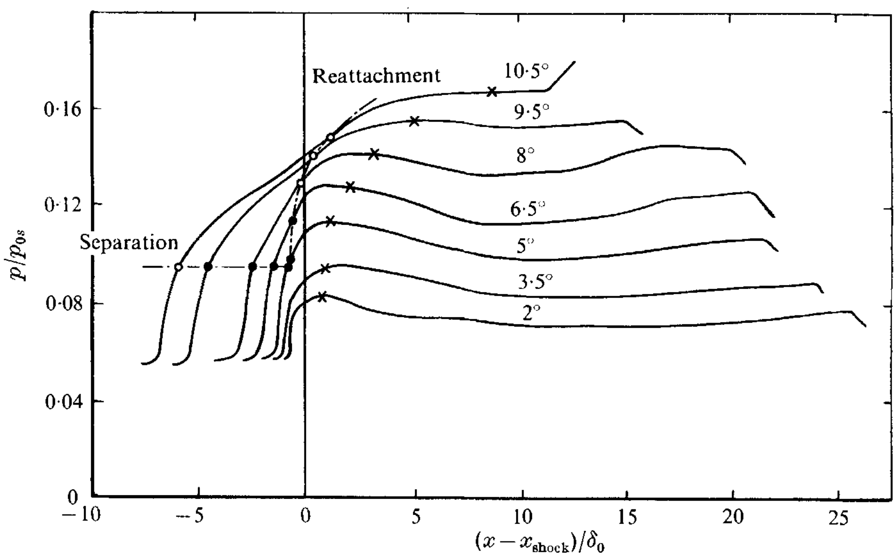


FIGURE 10. Surface pressure distributions showing separation and reattachment positions. ○, positions of separation and reattachment deduced from surface oil flows; ●, positions of separation and reattachment inferred from pressure rises; ×, station *G* of figure 5.

To date, the most extensive studies of incipient separation *per se* have been those of Kuehn (1959, 1961). In this work, the incipient condition was taken to be that at which the surface pressure distribution first showed three inflexion points (a hump). Kuehn found some indication that this hump first appeared when a small separation bubble was already present, but argued that small separation bubbles were 'primarily of academic interest'. The criterion which he proposed could, in his view, be associated with the more practically important condition at which the scale of the separation began to increase rapidly with further increase in overall pressure rise.

If this criterion were applied to the pressure distributions of the present experiments (figure 10), incipient separation would be associated with an incident shock of deflexion between 6·5° and 8°. This is consistent with Kuehn's extrapolation of his own experimental results from which, at the Reynolds number and Mach number of the present experiments, incipient separation would be predicted at a shock deflexion of 8°. Thus, although the pressure measurements of the present experiments are broadly in agreement with those of Kuehn, the use of surface oil flow has shown that the overall pressure rise which the boundary layer can withstand without separating is, in fact, less than two thirds the value we should deduce by following Kuehn. Consequently, some doubt is cast on the notion, which has become generally accepted since Keuhn's experiments, that the overall pressure rise associated with incipient separation appreciably exceeds that upstream of a forward-facing step. In the present experiments (and in a later and more extensive study of separation, which used surface oil flow and which agrees well with the present work) the reverse appears to be the case. This question is discussed at greater length in Green (1969). For the present, it is sufficient to note two points. First, for flows involving an incident oblique shock (and with the external stream everywhere supersonic), incipient separation seems more closely connected with the appearance of a strong reflected expansion than with the appearance of a hump in the pressure distribution. Secondly, because the onset of separation causes a pronounced change in the outgoing wave pattern, small separation bubbles in flows with incident oblique shocks are of more than academic interest. At the very least, the onset of separation is associated with a sudden doubling of the deflexion through the main reflected shock, and this in turn involves an almost eightfold increase in the total pressure loss through the shock. At the worst, in certain types of internal flow (supersonic air intakes, for example), a sudden change in the reflected wave system might well precipitate a drastic change in the entire flow pattern.

3.3. *Three-dimensionality*

The oil-flow photographs (figure 10) show the surface pattern in the interaction region to be far from two dimensional. Remembering that many previous, careful experiments have in one way or another been compromised by three-dimensional effects, we must ask how important such effects are to the present work.

The boundary layer under investigation grew on the plane floor of a single-sided (asymmetric) wind tunnel nozzle. Its origin was effectively at the tunnel throat, and its thickness therefore of the same order as that of the boundary layer on the sidewalls (approximately 0·27 in. compared with the tunnel span, 4·5 in. and height, 3·25 in.). Surface oil flow showed virtually parallel flow upstream of the interaction, and Pitot traverses showed the spanwise variation of integral parameters to be negligible over the central half of the undisturbed flow. The precise nature of the flow in the nozzle is therefore thought to have comparatively little relevance to the three-dimensional behaviour observed in the region of interaction.

The principal three-dimensional effects are believed to come from the interaction between the incident shock and the boundary layers on the tunnel sidewall and in the corner between sidewall and floor. Low energy air appears to be swept down the sidewall and in from the corner towards the centre of the floor. The precise mechanism by which this influences the region of supposedly two-dimensional interaction is not understood, but its main effect seems to be on the length of the separation bubble. (Measurements of bubble length at nominally the same flow conditions but with different experimental arrangements have on occasion been found to differ by almost an order of magnitude.)

In the present context, accepting from figure 10 that the flow is not two dimensional, we must assess the extent to which departures from two dimensionality compromise the results presented here and the conclusions drawn from them. The discussion in § 3.1 of the outline structure of the wave system—which is the central topic of the paper —is thought not to depend critically on the flow being two dimensional. The three simple properties which have been observed—'solid surface' reflexion in unseparated flows, 'constant pressure' reflexion in separated flows, and a leading shock of strength independent of the incident shock in separated flows—are essentially *qualitative* features which are not expected to be significantly affected by the kind of departure from two dimensionality present in these experiments.

On the question of incipient separation there is more room for doubt. It is known that, when the scale of separation is comparable with that of the wind tunnel, experimental geometry can have an appreciable influence on this scale, presumably through three-dimensional effects. Whether this influence is still to be found when the separation bubble is vanishingly small is at present difficult to say. In both the present experiments and those of Green (1969) there is no evidence that departures from two dimensionality in any way vitiate the conclusion that separation occurs when the overall pressure rise is appreciably less than the minimum required to produce three flexes in the pressure distribution. On the other hand, there might be some influence from the sidewall interactions on the value of the shock strength at which incipient separation occurs. There is, however, some evidence in the experiments of Bogdonoff & Kepler (1955), Kuehn (1959, 1961), Green (1969) and in the present paper that, provided a single criterion is used to define incipient separation, the discrepancies between different experiments is not large.

4. Conclusions

At a Mach number of 2·5 incident oblique shocks are found to reflect from a turbulent boundary layer in one of two essentially simple patterns.

For the weaker incident shocks the boundary layer remains unseparated and the reflected wave is a single shock with equal and opposite deflexion to the incident wave.

For the stronger incident shocks the boundary layer separates. The outgoing wave pattern is that of a strong compressive interaction between boundary layer and free stream—an oblique shock followed by a compression fan—embedded in which is an expansion fan with turning equal to that through the incident shock.

Transition between flows of these two types takes place over a narrow range of incident shock deflexion. Although no measurements have been obtained in this range, indirect evidence suggests that the transition is closely associated with the onset of separation. In the present flow it appears to occur when deflexion through the incident shock is half that (measured at the edge of the boundary layer) through the leading shock of a 'free' interaction. By this token incipient separation is provoked by an incident shock of approximately 5° deflexion.

Some uncertainties left by the present results are: the range of Mach number for which the behaviour described here is typical; the precise nature of the transition between 'unseparated' and 'separated' behaviour; the relation between this transition and the onset of separation proper; and the degree to which the refractive phenomena treated by Henderson contribute to the overall wave pattern. More extensive studies along similar lines to the present ones, perhaps using a refinement of the Pitot-traverse technique employed here, would help reduce these uncertainties.

The results presented here were obtained in the supersonic wind tunnel of the Aeronautics Sub-Department of the Cambridge University Engineering Laboratory during the author's tenure there of a D.S.I.R. Research Studentship.

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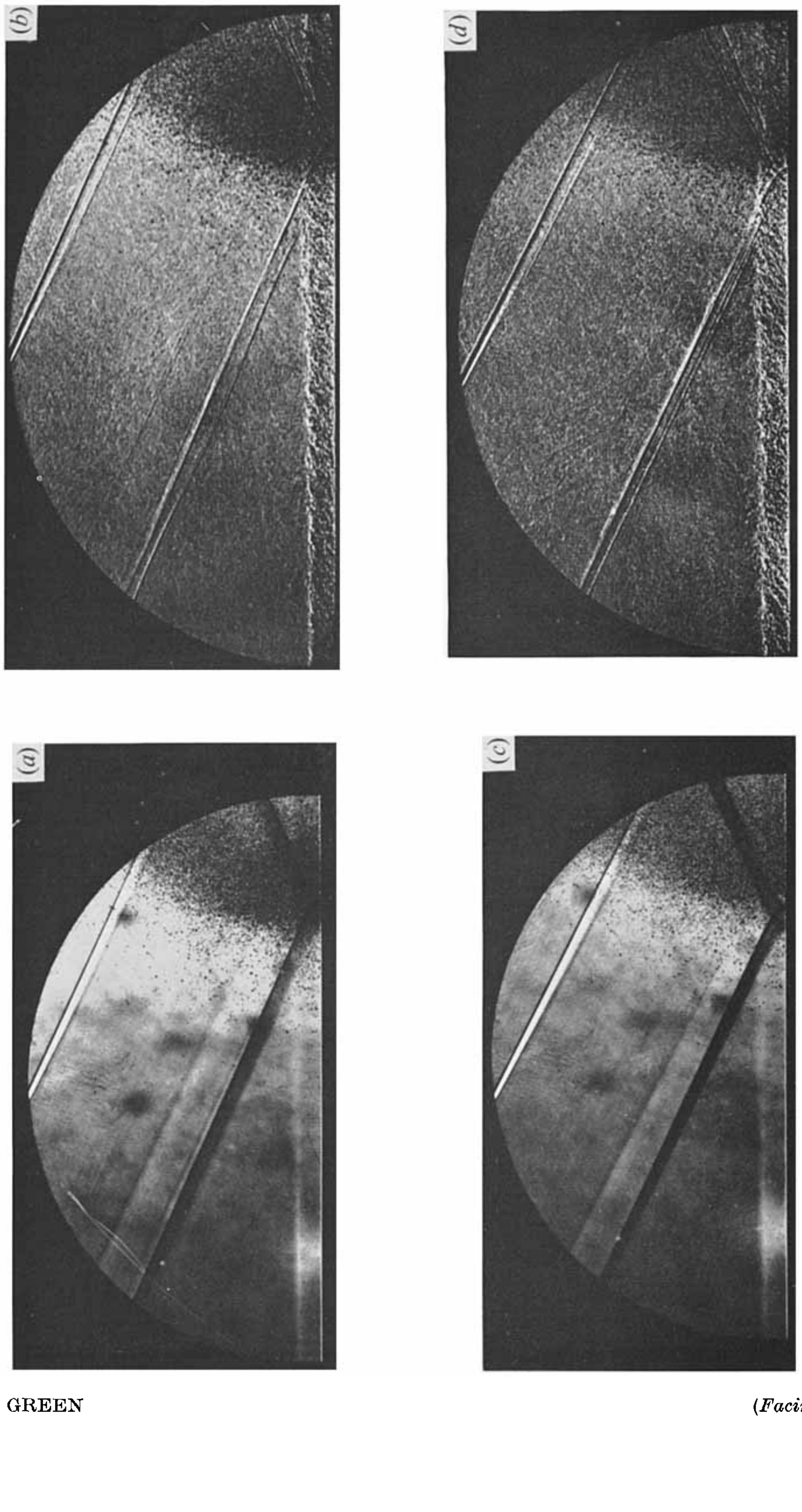


FIGURE 4. For legend see plate 4.

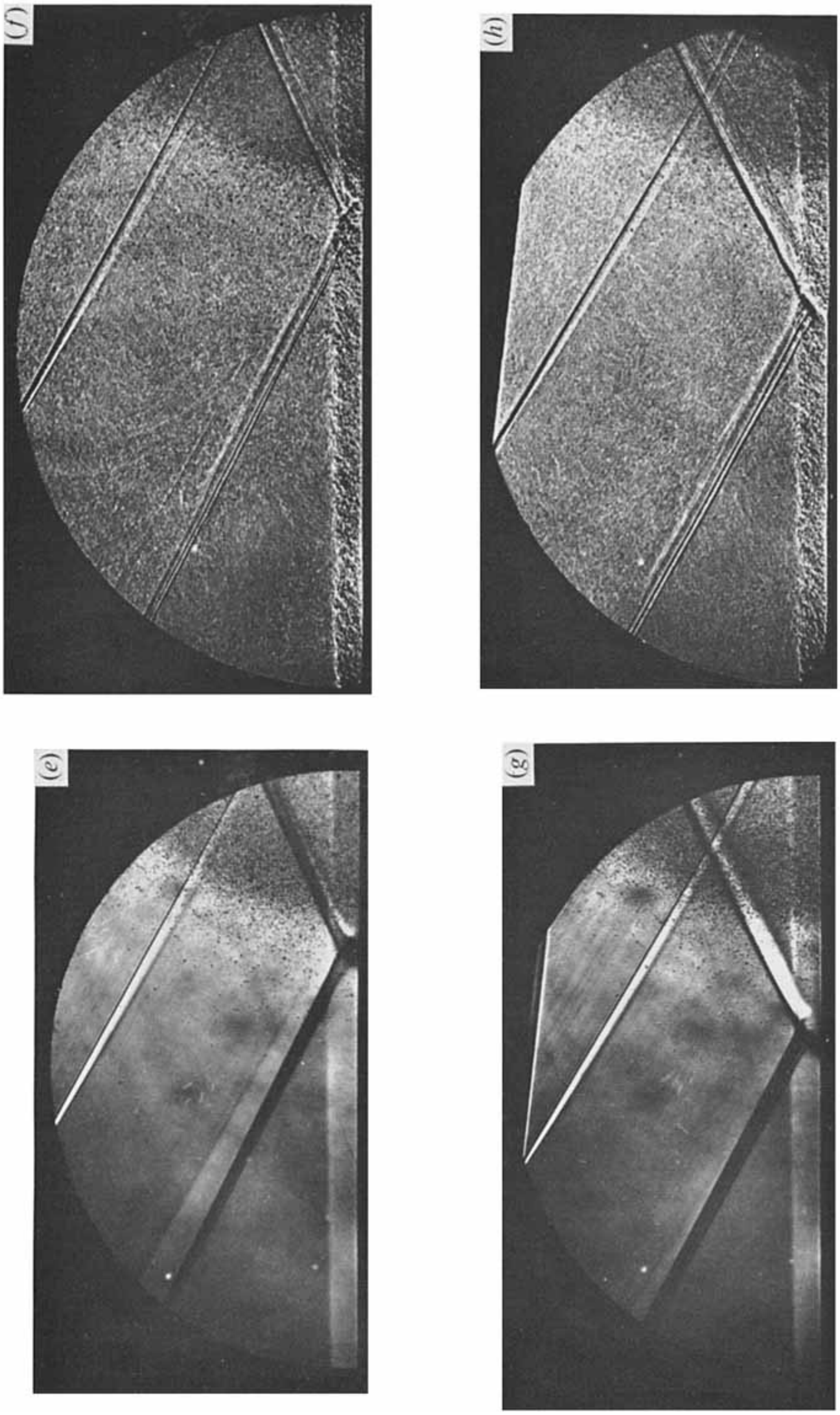


FIGURE 4. For legend see plate 4.

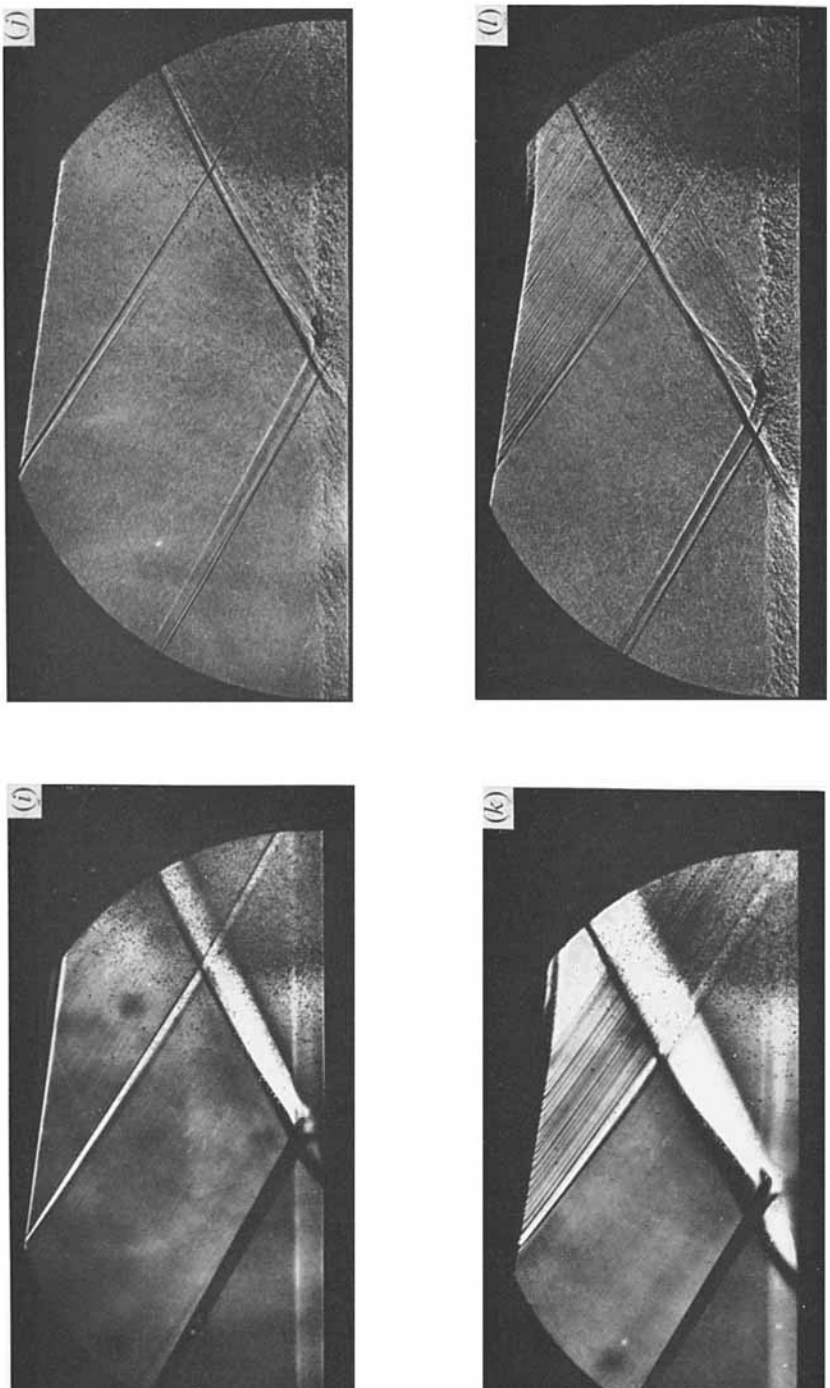
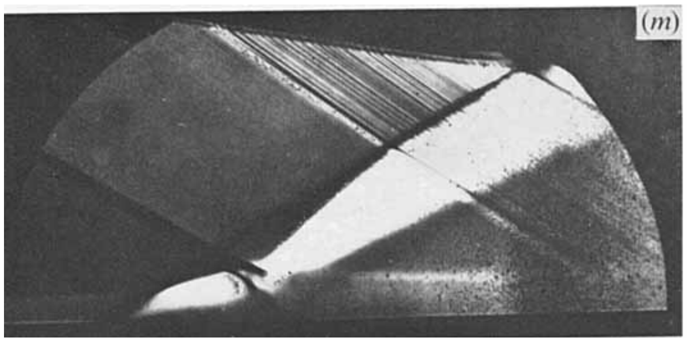


FIGURE 4. For legend see plate 4.



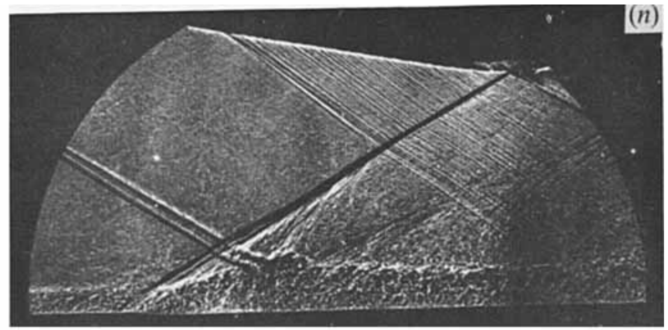


FIGURE 4. Optical studies of the wave system. Schlieren, vertical cut off, exposure 0·01 sec, (*a*), (*c*), (*e*), (*g*), (*i*), (*k*), (*m*). Shadowgraph, exposure 2–3 μsec, (*b*), (*d*), (*f*), (*h*), (*j*), (*l*), (*n*). (*a*), (*b*) $\alpha_n = 2°$; (*c*), (*d*) $\alpha_n = 3{\cdot}5°$; (*e*), (*f*) $\alpha_n = 5°$; (*g*), (*h*) $\alpha_n = 6{\cdot}5°$; (*i*), (*j*) $\alpha_n = 8°$; (*k*), (*l*) $\alpha_n = 9{\cdot}5°$; (*m*), (*n*) $\alpha_n = 10{\cdot}5°$.

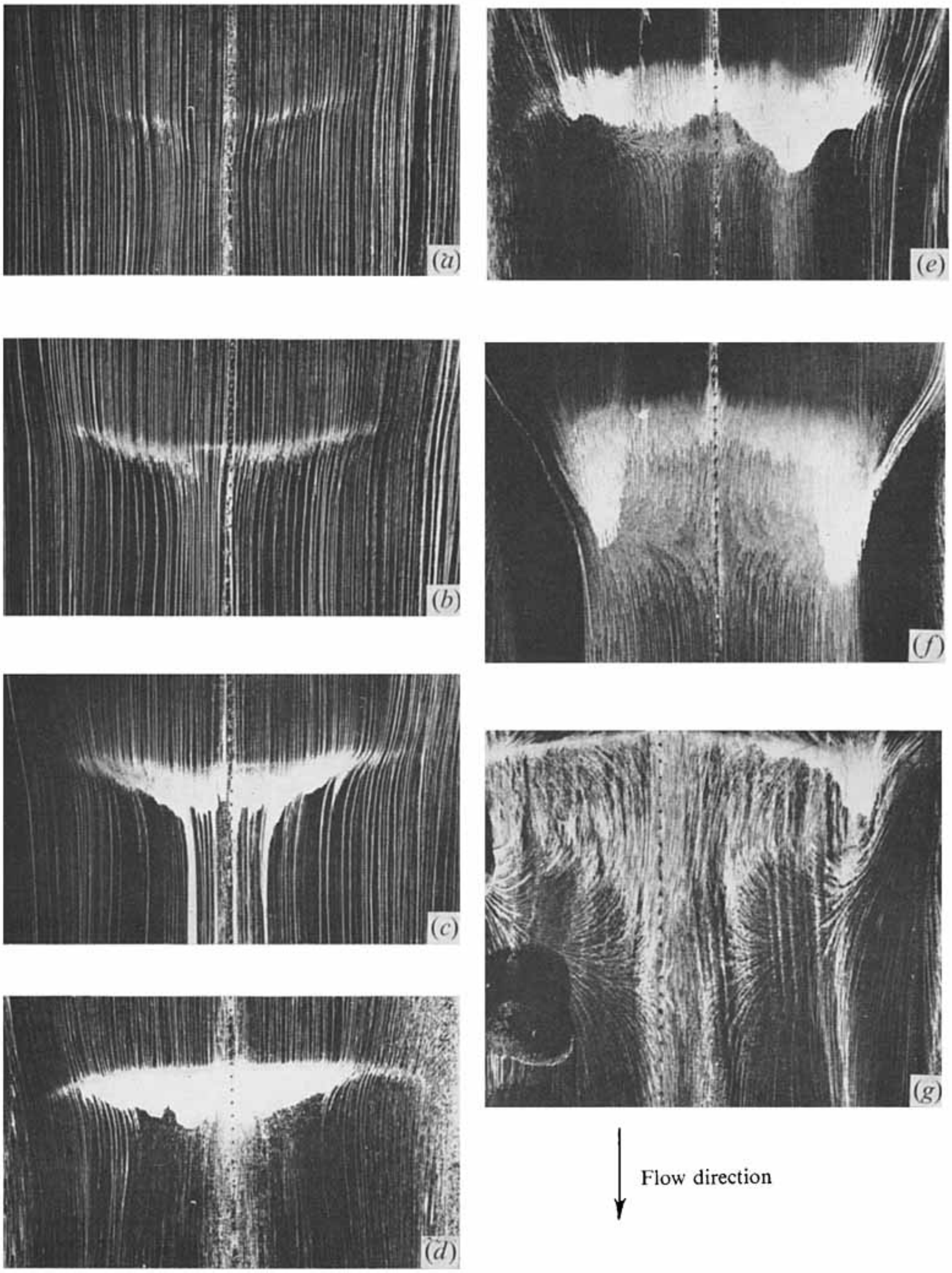


FIGURE 9. Surface oil flow patterns. (*a*) $\alpha_n = 2°$; (*b*) $\alpha_n = 3{\cdot}5°$; (*c*) $\alpha_n = 5°$; (*d*) $\alpha_n = 6{\cdot}5°$; (*e*) $\alpha_n = 8°$; (*f*) $\alpha_n = 9{\cdot}5°$; (*g*) $\alpha_n = 10{\cdot}5°$.

GREEN