On the Structure of Three-Dimensional Shock-Induced Separated Flow Regions

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A study is made of existing experimental data on three-dimemsional skewed shock-wave interactions with both laminar and turbulent boundary layers and recent results in which extensive regions of turbulent separation were obtained. Comparisons show that the structure of three-dimensional shock-wave/boundary-layer interactions is not fundamentally different for laminar or turbulent flow; it is primarily dependent on the extent of separation. A qualitative description is given for the flow structure from incipient to large extents of separation. For the latter, a secondary incipient condition arises within the primary separation vortex. For still larger extents of separation it is deduced that a secondary vortex arises adjacent to the surface and totally embedded in the primary separation vortex.

I. Introduction

IN recent years much progress has been made toward the understanding of three-dimensional shock-wave/boundary-layer interactions through studies on such models as blunt protuberances-fins, cylinders, etc.—mounted on flat plates (varying shock strength), and streamwise compression corners made up of sharp-edged intersecting wedges or of single wedges on flat plates (constant shock strength).[1,2]

Strong similarities have been noted between the characteristics of two- and three-dimensional shock induced regions of separation. In the case of blunt protuberances, several investigators have pointed to the strong resemblance of the flow structure in the plane of symmetry to that of two-dimensional interactions.[1] In the case of a streamwise compression corner, a more recent investigation[3] shows that spanwise pressure distributions and the extent of separation for both laminar and turbulent flow strongly resemble those for the respective two-dimensional cases. These observations have suggested that three-dimensional shock-wave/boundary-layer interactions could be viewed locally as equivalent to two-dimensional ones with strong crossflow and mass suction[1,3] (to account for the scavenging by vortices generated in the separated region in the the three-dimensional case).

Also identified recently is the effect of boundary-layer transition along a zone of three-dimensional shock interaction, whereby the extensive separation of a laminar boundary layer collapses through the transition region to the smaller one of a turbulent boundary layer.[4] It could, in fact, collapse entirely if the pressure rise were not sufficient to sustain turbulent separation. In both cases the excess vorticity is presumably carried downstream by the flow, eventually to dissipate.

Evidence of multiple vortices in regions of three-dimensional separation abounds for the interaction of the bow shock of a blunt protuberance with laminar or turbulent boundary layers.[5-7] For this configuration, one has locally the very strong interaction of a normal shock with the boundary layer in the plane of symmetry.

In the case of a streamwise compression corner, multiple vortices have been mainly found for shock interactions with laminar boundary layers for which regions of separation are invariable large.[8,9] Lack of evidence of multiple vortices for the turbulent case prompted two investigations[10,11] of sharp wedges mounted normal to planar surfaces in a supersonic stream, whereby the wedge angles were varied from low values (relatively weak shock strengths) to high values (strong shocks) which resulted in extensive turbulent separation and the appearance of more than one vortex.[11] It should be mentioned that some years ago McCabe[12] noted "a tendency towards a second separation in the dead air region" for large wedge incidences.

With the information presently available on three-dimensional shock-wave/boundary-layer interactions much is now known at least qualitatively about the physical aspects of the flow. It is the purpose of this paper to describe the structure of three-dimensional separated flow regions from incipient to extensive separation. Specifically discussed is separation due to a plane-skewed shock wave interacting with a boundary layer on a planar surface as a step in the understanding of the more general case of three-dimensional separation due to shocks whose strengths vary along lines of interaction.

II. Definition of Flow Model

The interaction flow model, shown in Fig. 1, represents a single axial compression corner (wedge on flat plate). The model could also be a double compression corner (axial intersection of two wedges) which has a more complex shock structure.[3] The common feature of these models is that in both cases a skewed shock interacts with the boundary layer on a planar surface. In the experimental data presented further on, no distinction is made between these two models. The

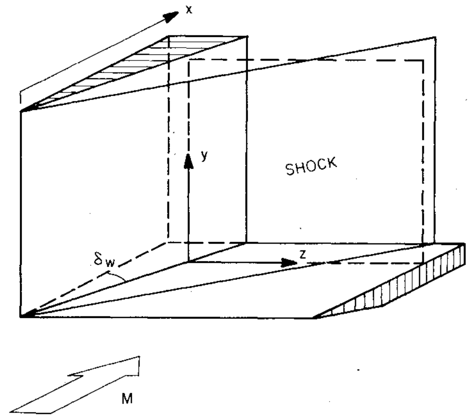

Fig. 1 Flow model.

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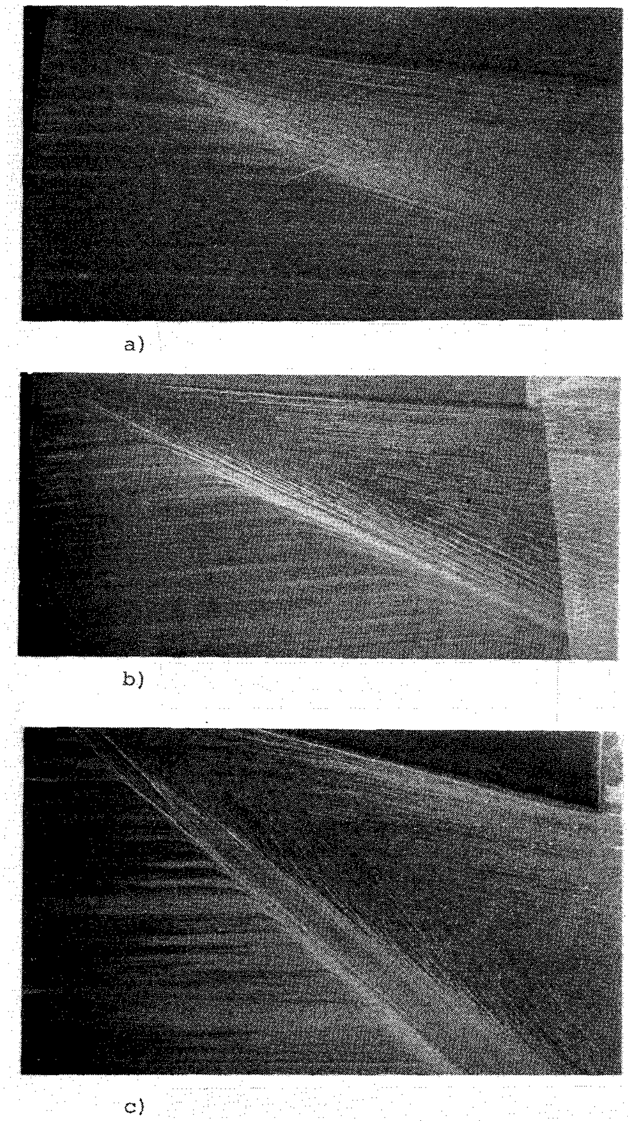

Fig. 2 Skewed shock interaction with a turbulent boundary layer at $M=2.5$ (from Ref. 10). a) Unseparated $\delta_w = 6\frac{1}{2}°$; b) small separation $\delta_w = 10°$; c) extensive separation $\delta_w = 17°$.

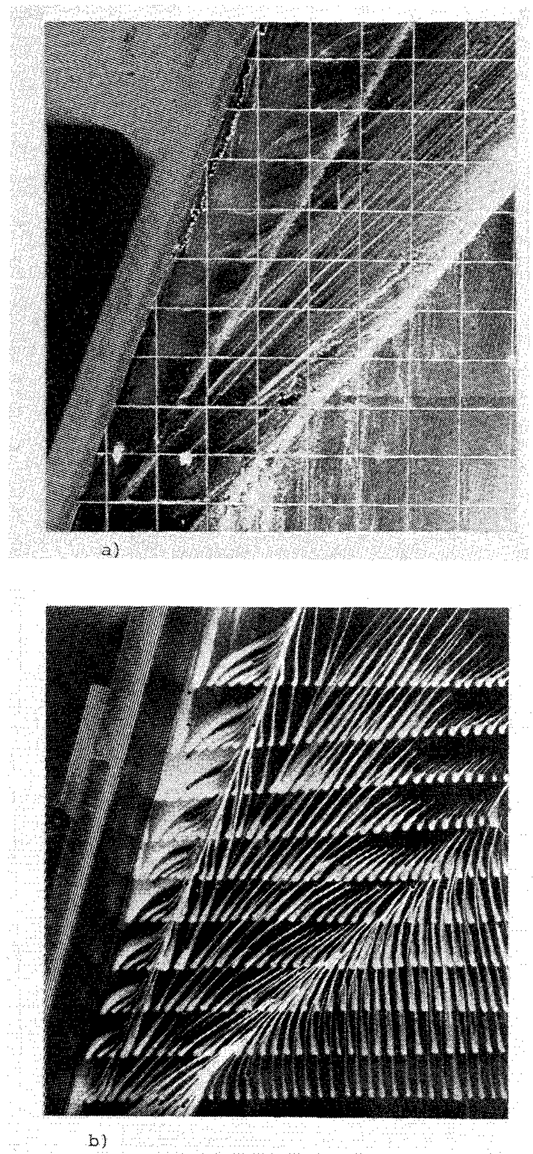

Fig. 3 Skewed shock interactions with secondary separation. a) Turbulent $\delta_w = 20°$, $M=6$ (courtesy of C. H. Law[11]); b) laminar $\delta_w = 15°$, $M=12.5$ (from Ref. 9).

coordinate system used in subsequent figures is also defined in Fig. 1.

The terms "separation" and "reattachment" for the three-dimensional case are used in a broader sense than in the two-dimensional case in which they are conventionally associated with a point (or line) at which the surface shear vanishes. In the three-dimensional case, separation is associated with a line or envelope of limiting streamlines.[13] From a physical, though perhaps less precise standpoint, separation may be viewed as a line along which the flow lifts off a continuous solid surface, and reattachment, a line of flow impingement onto a continuous solid surface. Only the component of surface shear normal to these lines vanishes; but the tangential component is finite except at singular points such as in the plane of symmetry of a continuous separation line. An extensive discussion of three-dimensional separation is given by Wang.[13]

III. Comparison of Laminar and Turbulent Interactions

All laminar data known to the author, for a skewed shock interaction, show extensive three-dimensional separation.[8,9,14] Recent experimental data for the turbulent case have extended skewed shock strengths (wedge angles) to large values,[10,11,15] thus generating sizeable regions of separation comparable with the laminar ones.

A. Surface Flow Patterns

Figure 2 shows a sequence of oil flow photographs from Ref. 10 for progressively larger wedge angles at Mach number 2.5 and Reynolds number based on chord length of 20×10^6 so that the boundary layer is turbulent over almost the entirety of the surface. The pattern is essentially conical as observed in other skewed shock interaction studies for either laminar or turbulent boundary layers.

In Fig. 2a the shock strength is insufficient to separate the flow as indicated by the oil lines (approximately surface shear lines) which are simply deflected by the shock wave. In Fig. 2b there is a small separated region as indicated by the oil accumulation line (approximate location of separation) and the less-well-defined inboard line along which the oil flow lines diverge (approximate location of reattachment). This separated region comprises a single vortex. In Fig. 2c the separated region is seen to be quite extensive and the oil flow lines exhibit a secondary inflection near the center of this region below which (lighter area) they again turn toward the oil accumulation line. This inflection is interpreted as the approach, with increasing shock strength, to a secondary separation within the primary vortex. The study of Ref. 10 does not quite extend that far.

For very strong skewed shock interactions with turbulent boundary layers, one does indeed obtain a second oil accumulation line indicative of secondary separation as shown in Fig. 3a (from the study of Ref. 11, courtesy of C.H. Law). The features of the oil flow pattern are virtually identical to those for the laminar case as illustrated in Fig. 3b taken from Ref. 9. In both Figs. 3a and 3b the reattachment line associated with the primary vortex is very near the corner formed by the vertical wedge and the plate as the Mach numbers in both cases are relatively high. The secondary reattachment line, just to the right of the secondary separation line for the laminar case of Fig. 3b, does not clearly appear in the turbulent case of Fig. 3a, most probably because of the effect of much higher shear rates for the latter, combined with a relatively large oil accumulation bubble.

B. Pressure Distributions

Further evidence of similarity between extensive turbulent and laminar separation due to a skewed shock interaction is given in Fig. 4 which shows a spanwise pressure distribution for each case. In each figure, going from right to left, the pressure rises from its undisturbed flow value just prior to separation (beginning of interaction), to a plateau beyond which it exhibits a dip and then a large pressure rise and overshoot associated with reattachment. The dip appears to be associated with the secondary separation. The overshoot is due to the high momentum of the reattaching flow after a long stretch of separation and mixing with the outer stream. It should be noted that a dip is also found, and is even more pronounced, in the plane of symmetry upstream of a blunt protuberance in supersonic flow,[6] for which case strong secondary vortices appear near the base of the protuberance.

C. Heat Transfer

Heat transfer rates, which are classically known to peak at reattachment following a region of separation in two-dimensional flow, exhibit two peaks in the case of laminar[8,13] and extensive turbulent separation[11,14] caused by skewed shock interaction. The two peaks are associated with the two reattachment lines as observed elsewhere,[1,9] and shown in Fig. 5 for the laminar case. It should be noted that the turbulent case does not exhibit an initial drop in heat rates below the undisturbed flow value following primary separation, but rather, has an immediate rise above this value.[15] This observation is consistent with the similarity pointed out elsewhere[1,3] between crossflow in three-dimensional separation and streamwise flow in the two-dimensional case.

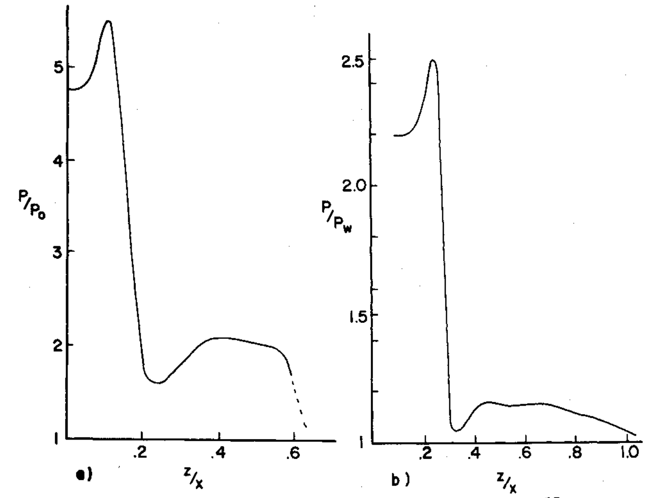

Fig. 4 Spanwise pressure distributions. a) Turbulent,[15] $M=3.7$, $\delta_w=20°$; b) laminar,[14] $M=3.64$, $\delta_w=12.2°$.

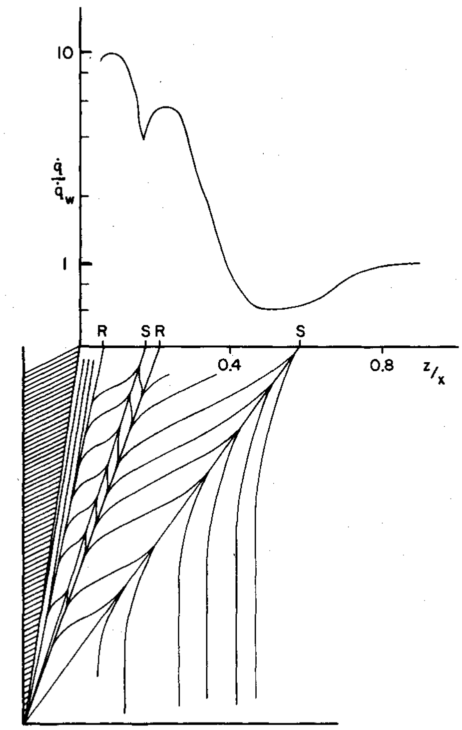

Fig. 5 Spanwise heat transfer for laminar flow, $M=20$, $\delta_w=10°$ (data from Ref. 8).

IV. Flow Structure

From these comparisons it seems quite clear that the characteristics of skewed shock-induced separated regions do not exhibit any basic difference between laminar and turbulent flow for comparable extents of separation. The shock intensities needed for extensive separation, however are clearly much larger for turbulent than for laminar flow, and the detail of the flow structure differs because of turbulent mixing in the one case and molecular mixing in the other. One can conjecture with a high degree of confidence that these similarities also prevail for two-dimensional flow separation.

From the evidence previously mentioned, it is now possible to define the structure of the separated flow region resulting from the interaction of a skewed shock wave with either a laminar or turbulent boundary layer since, basically, the two differ only in the intensity of the shock wave required to produce a certain extent of separation.

Figure 6 shows qualitatively a sequence of flow characteristics from unseparated flow to extensive separation on a planar surface caused by a wedge-induced shock wave of progressively increasing strength. The lines of interaction on the surface are essentially conical, as noted in virtually all experimental investigations of this axial corner configuration.

In Fig. 6a the wedge angle or shock strength is small and the boundary layer flow across the shock wave is fully attached, as indicated by the mild turning of the surface shear lines through a slight inflection before assuming their new direction parallel to the wedge face some distance downstream after the disturbed boundary layer has fully relaxed to its new condition. The symbol Sh indicates the location of the wedge-induced shock wave, and B, the beginning of interaction, or the line along which the boundary layer begins to respond to the pressure jump generated by the shock wave. As shown in Fig. 6a (2), τ_n, the component of surface shear normal to the lines of interaction generally decreases in absolute value, with a slight dip at the approximate shock location in traversing the region of interaction from right to left.

In Fig. 6b the wedge angle has been increased to the point where the boundary layer is on the verge of separating as indicated by the tangency of the surface shear lines at their point of inflection, to the approximate shock wave direction (indicated by I for incipient separation). At this point τ_n just equals zero.

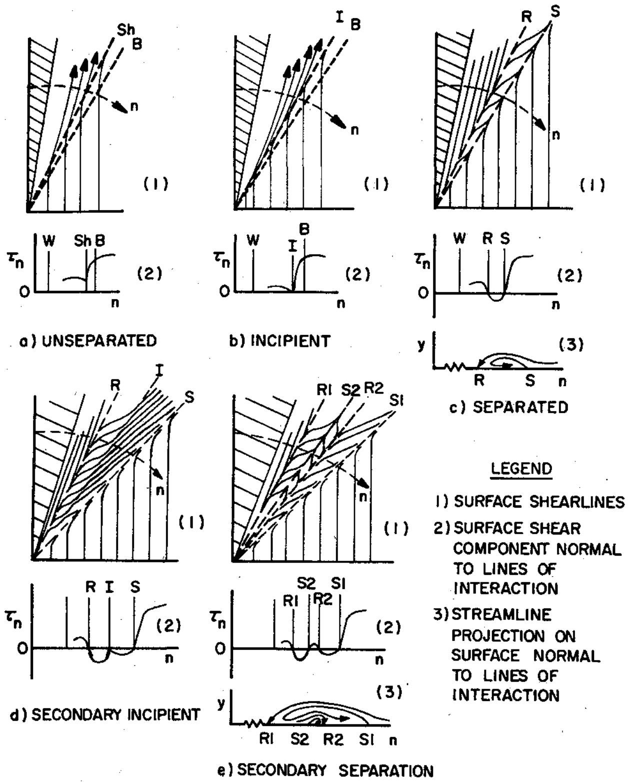

Fig. 6 Structure of three-dimensional shock-induced separation.

In Fig. 6c, for a still larger wedge angle, there is a small region of separation comprised of a counter-clockwise vortex as viewed from upstream. The line along which surface shear lines converge is indicative of separation S, and the line along which they diverge, of reattachment R. τ_n undergoes a change in sign, going through zero at separation and again at reattachment. The streamline projection in the region of separation, sketched in Fig. 6c (3) shows that the separating and reattaching streamlines are not the same, but rather, that there is scavenging of the oncoming flow by the vortex. The two-dimensional equivalent would be mass-suction in the separated region.

As the separated region grows in size due to a progressively stronger shock, the "reverse flow" itself is on the verge of separating, as indicated by the reversal of the surface shear lines to tangency with the line I in Fig. 6d (1). This condition can be viewed as a secondary incipient separation of the flow along which line τ_n is zero as well as at the original separation and reattachment lines, shown in Fig. 6d (2). Note that the doubledip of the shear has also been found for extensive regions of separation in two-dimensional flow.[16]

With further increase in shock strength a secondary separation region develops within the primary one as shown in Fig. 6e. S1 and R1 are respectively the primary separation and reattachment lines, and S2 and R2 the secondary ones. The surface shear component τ_n undergoes three reversals in sign as shown in Fig. 6e(2). The flow structure is deduced to consist of a secondary vortex embedded in the primary one as shown in Fig. 6e (3). The secondary vortex scavenges flow from the primary vortex, as does the primary vortex from the oncoming boundary layer. Justification for this model stems from the fact that the secondary incipient condition and secondary separation occur gradually near the middle of the primary vortex and not as a departure in either separation or reattachment conditions of the vortex. Furthermore, the inner heat peak (see Fig. 5), associated with reattachment of the primary vortex, is clearly larger than the outer one which is associated with reattachment of the secondary vortex.

V. Conclusions

With reference to previous investigations of the interaction of a skewed shock with a boundary layer, the following observations were made: 1) For the laminar three-dimensional case, as for the two-dimensional case, a small shock-induced pressure rise causes extensive separation; 2) For the turbulent three-dimensional case, a pressure rise greater than 1.5 is required to induce separation, and a considerably greater pressure rise is necessary to produce extensive separation; 3) In a transverse plane, three-dimensional separation is similar to two-dimensional separation with mass transfer.

From the present study, the following conclusions arise: 1) The structure of the three-dimensional interaction is not fundamentally different for laminar or turbulent flow; it is primarily dependent on the extent of separation; 2) For large extents of separation due to a skewed shock interaction, a secondary incipient condition arises within the primary separation region following which a secondary separation arises for still larger extents of separation. It is deduced that the latter flow structure takes the form of a secondary surface vortex embedded in the primary one; the secondary vortex scavenges flow from the primary vortex which, in turn, scavenges flow from the oncoming boundary layer.

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