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Experimental Investigation of Three-Dimensional Vortex-Airfoil Interaction in A Supersonic Stream

by

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I. ABSTRACT

An experimental study involving interaction between streamwise wing-tip vortices and a two-dimensional lifting surface in a supersonic stream was conducted. The experiments were designed to simulate interaction of supersonic vortices with aerodynamic surfaces of high-speed aircraft and missiles. The experimental scheme involves positioning an instrumented two-dimensional wedge downstream of a semi-span wing so that the trailing tip-vortex from the wing interacts with the aerodynamic surface. Experimental results indicate that the interaction strongly depends on the vortex strength and vortex proximity to the wedge leading edge. In their most organized form, distortion of streamwise vortices upon interacting with the wedge was found to result in formation of symmetric detached shock fronts far upstream of the wedge leading edge followed by an apparent slip surface separating a subsonic region from a supersonic zone. Interaction of vortices with oblique shock wave over the wedge section indicates that interaction of a relatively weak vortex with a moderate strength oblique shock does not lead to significant changes in the vortex structure. On the other hand, interaction of a moderate strength vortex with a strong oblique shock results in the formation of a detached shock wave upstream of the oblique shock front.

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Nomenclature

c	Airfoil chord
Cp	Pressure coefficient$=(p-p_\infty)/q_\infty$
h	Distance between the airfoil leading edge and the vortex generator tip (Fig. 3)
H	Enthalpy
L	Characteristic length
M	Mach number
p	Pressure
q	Dynamic pressure
Re	Reynolds number
s	Entropy
t	Time
T	Temperature
V	Velocity
X,Y,Z	Cartesian coordinates
α	Vortex-generator angle of attack
Γ	Circulation

Subscript

0	Stagnation condition
1	Condition ahead of the shock
2	Condition behind the shock
t	Tangential
VG	Vortex-generator
∞	Free stream

II. INTRODUCTION

Understanding the dynamics and behavior of stream-wise vortices is an important yet challenging task in the design of aerospace vehicles. At sufficiently high angles of attack the vortex sheet generated by sharp leading-edge wing sections; or the vorticity field found near the tip section of lifting surfaces, roll up into organized concentrated vortices which convect downstream and may interact with other components of the vehicle. Such interactions may occur as a result of canard-shed vortices striking wing or aft control surfaces of an aircraft or as a result of forward fin/body shed vortices interacting with aft control surfaces in a missile. Examples of such flow fields are shown in Fig. 1. In general, these interactions are three-dimensional and unsteady and they may lead to a loss of lift, an increase in drag, and sudden changes in the pitching moment characteristics of the vehicle thus limiting maneuverability and influencing stability and control characteristics. Beyond a critical angle of attack, vortices formed over highly swept sharp leading edges are known to undergo a drastic change in structure in a phenomenon called "vortex breakdown" or "vortex bursting".[1-5] It is also well established that vortex breakdown in incompressible flows may occur for example if stream-wise vortices are subjected to sufficiently strong adverse pressure gradients. The vortex breakdown phenomenon cited in the low-speed literature is in general characterized by a sudden growth of the vortex size followed by a region of highly turbulent flow and formation of local stagnation zones and regions of reversed axial flow.

Although the vortex breakdown phenomenon in supersonic flows has been examined by a few investigators, the problem has only recently attracted serious consideration. Previous numerical and experimental studies relevant to the vortex breakdown phenomenon in supersonic flows have mainly concentrated on investigating the behavior of stream-wise vortices as a result of a shock wave-vortex interaction and attempts have been made to develop a vortex breakdown criterion based on vortex swirl rate and shock wave strength.[6,7]

Previous experimental and numerical studies relevant to the interaction problem have focused on understanding the physics of shock wave-vortex interaction and development of the vortex breakdown phenomenon in supersonic flows. Moreover, such studies have mainly concentrated on interaction of streamwise vortices with normal shock waves. To the author's knowledge, the only systematic study of the oblique shock wave-vortex interaction problem were reported in Ref. 8 where Copening and Anderson used the three-dimensional Euler equations to study interaction of vortices with oblique shock waves at Mach numbers of 2.28 and 5. They observed no vortex breakdown or appreciable alteration of vortex strength as a result of interactions; however, they reported regions of reversed flow as well as convex-concave shock shape. On the experimental side, interaction of wing tip vortices with oblique shock waves formed over a two-dimensional wedge surface was reported in Ref. 9. In this study, the interaction was found to be a strong function of the vortex strength. Interaction of strong vortices with oblique shock fronts resulted in formation of locally detached shock waves followed by a distorted vortex pattern resembling a body of revolution placed in a supersonic flow. Other experimental and computational efforts pertinent to the proposed research program available in the literature have considered interaction of streamwise vortices with normal shock waves. Delery et al[6] carried out a wind tunnel study of the interaction of streamwise vortices with normal shock waves and reported some shock-induced modifications to both structure and trajectory of vortices. Moreover, they established a vortex-breakdown criteria as a function of vortex swirl rate and shock intensity for the case of nearly uniform axial velocity distribution in the vortex core. Their results also indicated that interactions with vortex breakdown leads to negative axial velocity at the vortex axis, a considerable reduction in maximum tangential velocity, and an increase in the radius of the vortex viscous core; all characteristics of low speed vortex breakdown. Dissipation of streamwise vortices as a result of interaction with normal shock waves in an inlet type configuration was investigated by Zatoloka et al[10] who also reported development of a stagnation zone as well as distorted shock pattern as a result of such encounters. Interaction of vortices with normal shock waves was also experimentally studied by Metwally et al[7] and Cattafesta et al,[11] who reported a strong influence of vortex swirl rate and Mach number on the interaction, a vortex breakdown, and an upstream shock propagation. The experimental results of Refs. 7 and 11 revealed a hypothetical supersonic vortex breakdown model consisting of a region of reversed flow as well as a stagnation point downstream of a bulged-forward shock wave. Head-on interaction of tip vortices with a wedge surface in a Mach 3 flow was reported in Ref. 12 where the encounter resulted in formation of a locally detached shock front far upstream of the wedge leading edge. In addition, the distorted vortex structure was reported to form a slip surface separating a subsonic zone from a supersonic region.

A simple dimensional analysis of the shock wave-vortex interaction problem indicates that the governing simulation parameters are the flow Mach number, M_∞, Reynolds number, Re, a shock wave strength parameter, p_2/p_1, and a vortex intensity parameter defined by $\Gamma/V_\infty L$, where L is a characteristic length.[12] Although the shock strength parameter defined by p_2/p_1 accounts for the pressure jump imposed upon the vortex by the shock wave, a more appropriate parameter will include the shock inclination angle since in addition to the shock strength, the vorticity jump across a shock wave is influenced by the shock curvature and the magnitude of the velocity component tangent to the shock.[16] For the case of an axi-symmetric vortex frequently used in numerical modeling of vortex flows, the interaction of vortices with normal shocks in the absence of vortex breakdown is governed by the axial Mach number distribution in the vortex core and the flow condition downstream of the shock. On the other hand, the interaction of axisymmetric vortices with two-dimensional oblique shocks is influenced by both axial and tangential components of velocity and downstream influences are not present during such encounters. As a result, depending on the shock wave inclination angle relative to the free stream direction, two types of interactions are of interest; a normal shock wave-vortex interaction and an oblique shock wave vortex interaction. The two types of interactions are schematically shown in Fig. 2. Fundamental theoretical studies of Hays[13] demonstrated that the vorticity jump across a shock discontinuity is given by:

$$\delta\zeta_{\mathbf{n}} = 0 \tag{1}$$

$$\delta\zeta_t = \mathbf{n} \times [\nabla_t(\rho V_n)\delta\rho^{-1} - (\rho V_n)^{-1}\, \mathbf{V}_t \cdot \nabla_t \mathbf{V}_t \delta(\rho)] \tag{2}$$

where **n** is the unit vector normal to the discontinuity surface and t is a two-dimensional vector tangent to the shock surface with the velocity vector **V** for the flow field given by:

$$\mathbf{V} = \mathbf{n}V_n + \mathbf{V}_t \tag{3}$$

Thus, a streamwise vortex will experience no jump in vorticity across a normal shock; while the same vortex will experience a finite jump in its vorticity when crossing a planar oblique shock front. In practice however, introduction of a vortex filament in a uniform free stream upstream of an otherwise planar shock will give rise to a locally deformed and curved shock structure leading to a jump in the tangential component of vorticity across the shock as given by Eq. 2 for both types of interactions.

The vortex breakdown phenomenon of low-speed flows has been examined by several investigators and comprehensive surveys of vortex breakdown are presented by Hall,[14] Benjamin,[15] and Leibovich.[16] Leibovich[16], for example, describes vortex breakdown to be a discontinuous transition between two flows with very different characteristics: a supercritical region incapable of admitting upstream propagating waves and a subcritical state which admits upstream propagating waves. In a sense, such description of the vortex breakdown is reminiscent of normal shocks in gas dynamics.[16] An interesting aspect of this description of vortex breakdown involves passing a stream-wise vortex through a shock wave. Interaction of a vortex with a normal shock wave always results in a super-critical (supersonic flow ahead of the shock) to subcritical (subsonic flow behind the shock), while crossing a vortex through an oblique shock wave does not necessarily involve a supercritical to subcritical transition.

An important issue to be addressed in the study of shock wave-vortex interaction problem is how the vortex and the shock wave mutually influence one another. To date, flow visualization taken during shock wave-vortex interaction experiments[9-12] with apparent vortex breakdown, have indicated some form of a three-dimensional curved shock structure leading portion of which is normal to the axial flow direction with a limited region of subsonic flow downstream of the shock wave. These observations suggest that encounters, at least leading to drastic changes in the vortex structure, are affected by both the upstream and the downstream flow conditions. Furthermore, since a planar shock wave is only possible for uniform entropy distribution upstream of the shock, it is evident that introducing a concentrated vorticity field in an otherwise uniform flow ahead of a planar shock wave (oblique or normal shock), will result in a locally non-uniform flow upstream of the shock leading to some form of distorted shock pattern. Crocco's theorem for a steady inviscid flow is:

$$T\nabla s = \nabla H_0 - \mathbf{V} \times (\nabla \times \mathbf{V}) \qquad (4)$$

which states that a vortex filament of limited spatial extent immersed in a uniform irrotational flow ahead of a planar shock wave will lead to non-uniform entropy distribution upstream of the shock, giving rise to formation of a locally distorted curved shock structure. On the other hand, behavior of vortices upon crossing shock fronts is not well understood at the present time.

III. INTERACTION STUDIES IN MACH 3

Experimental studies involving interaction of concentrated, streamwise vortices with a 27° wedge surface is currently being carried out in Polytechnic University's newly installed blowdown supersonic wind tunnel facility. The experiments are currently being conducted in a Mach 2.5 stream. Prior to these experiments, interaction studies performed in a Mach 3 flow revealed many interesting and unexpected results which will be briefly discussed in the following section.

A schematic of the experimental arrangement is shown in Fig. 3. A two-dimensional shock generator having a wedge angle of 27° and a chord length of 3.81 cm was placed 15.7 cm (4.1 vortex generator chord lengths) downstream of the vortex generator wing section. The wedge section was capable of being traversed in the vertical direction so that the vortex height relative to the wedge leading edge could be adjusted. The wedge surface was equipped with 18 pressure taps at three equally spaced span-wise rows at $Y/c = -0.13$, 0, and 0.13 ($Y = 0$ is the wedge mid-span location) and six equally spaced chord-wise locations from $X/c = 0.13$ to $X/c = 0.80$. Further details of the experimental arrangement may be found in Refs. 9 and 12. Flow diagnostic techniques included simultaneous wedge surface pressure measurements and multiple spark shadow photograph of micro-second spark duration. Typical wind tunnel running times were 3 seconds and pressure data at the rate of 250 Hz for a period of 2 seconds during the steady state portion of a run was acquired. Interaction experiments were carried out for three vortex-generator angles of attack of $VG = 5^{\circ}$, 7.5°, and 10° for several vortex-wedge separation distances. Details of the parametric study may be found in Ref. 9.

i. Head-on interaction of a vortex with a wedge

A typical spark shadowgraph of the flow field during a head-on interaction of a relatively weak vortex with the wedge is shown in Fig. 4. The flow is from left to right, and the aft segment of the vortex generator may be seen in the upper left portion of the photograph. The wedge section is located at the lower right of the shadowgraph with the inclined portion of the wedge terminating exactly at the edge of the picture. The flow field was generated by interaction of a tip vortex created by placing the vortex-generator at an angle of attack of 5°. The picture clearly indicates a concentrated trailing tip vortex originating at the vortex-generator tip, convecting downstream and intersecting the wedge surface with the vortex core very close to the airfoil leading edge. Extensive multiple spark shadowgraphs (generally four per run) taken during the encounter indicated an unsteady movement of the vortex core during the interaction process thus, the head-on collision of the vortex core and the wedge leading edge occurred only in a transient manner. Study of shadowgraphs similar to the one shown in Fig. 4, indicated only a slight modification to the wedge shock wave while the main features of the flow field appeared to remain unchanged.

Interaction experiments incorporating stronger tip vortices were carried out by placing the vortex generator at an angle of attack of $7.5.^{\circ}$ Successive spark shadowgraphs of the flow field during a typical run for this encounter are presented in Figs. 5a-5c. These figures show temporal shadow photographs taken at $t = 0.52$, $t = 1.15$, and $t = 1.85$ sec, where $t = 0$ is approximately the wind tunnel starting time. An unsteady movement of the vortex core may be seen by comparing Figs. 5a and 5c. Figure 5a clearly shows the vortex core passing over the wedge leading edge while in Fig. 5c the vortex is seen to pass below the wedge leading edge. Figure 5b on the other hand, represents a head-on collision of the vortex and the wedge leading edge as a result of which formation of a "detached" shock upstream of the airfoil leading edge is observed. Behind the detached shock wave, the flow shown in Fig. 5b may be seen to consist of two distinct regions (also see for example Fig. 6); a central zone characterized by a darkly shaded conical region with its vertex situated at the vortex center, and a lighter area between the shock and the central conical region. The detached shock wave is seen to be strongly curved in the vicinity of the vortex core, while outside of the vortex core the shock is straight. Behind the curved portion of the shock, the vortex grows in size to form a central conical region. The rapid radial expansion of the vortex core in crossing the detached shock wave may be seen to have a strong visual resemblance to the incompressible B-breakdown reported in the literature. Although the generated flow field in this study leading to formation of these shock patterns occurred in a transient manner, the detached shock fronts were observed in all shadowgraphs taken during the head-on encounter of the vortex and the wedge leading edge.

Comparison of Figs. 5a and 5b reveals another important feature of the vortex-wedge interaction. These figures indicate that the encounter can lead to formation of a locally detached shock wave (Fig. 5b) which implies a local region of subsonic flow ahead of the wedge. This is similar to the flow field downstream of a detached shock wave formed in front of a blunt body placed in a supersonic stream. Moreover, the leading portion of the detached shock is normal to the axial flow direction and since at the vortex center the tangential velocity is negligible, the flow immediately downstream of the normal portion of the shock wave is necessarily subsonic.

These observations lead to a vortex distortion model as presented in Fig. 6. This hypothetical flow model suggests that distortion of supersonic vortices upon encountering a strong pressure jump, at least in their most organized form, consists of flow regimes with two distinct entropies separated by a slip surface; a central subsonic region containing the distorted vortex structure; and a supersonic outer region downstream of the straight portion of the detached shock wave. The subsonic conical region is formed as a result of vortex distortion and acts as a solid conical body for the supersonic incoming flow as a result of which a detached shock wave is formed. This shock wave bears a strong similarity to the shock wave formed over a conical surface placed in a supersonic stream with one notable exception, i.e., at the apex where the observed detached shock in the present problem has a strong curvature. This difference may be explained by the non-uniform vortex core Mach number distribution approaching the slip surface which forms in the region between the shock and the wedge. However, since the spatial extent of the vortex core is small in comparison to the outer irrotational flow, the main features of the flow leading to formation of the detached shock wave is governed by the uniform free stream flow outside of the vortex core and presence of the vortex only modifies the leading portion of the shock wave. The generated flow field may be seen to have striking similarities to the incompressible "B-breakdown" model which as described by Leibovich,[16] resembles a body of revolution placed in the flow.

Another important aspect of the interaction is the mechanism behind generation of these detached shock waves. Although the exact cause of this phenomenon is not well understood at the present time, a candidate mechanism to explain this behavior is the inability of the wedge to support an attached shock wave as a result of the vortex core Mach number distribution. A detached shock may develop due to either low Mach number or high flow deflection angle created by vortex-induced flow angularity. This will result in formation of a locally detached shock front leading portion of which is a normal shock wave with a subsonic flow just downstream. The strong pressure jump across the normal portion of this detached shock wave will then be responsible for distortion of the vortex possibly in a manner similar to the subsonic vortex breakdown. Furthermore, the subsonic region just downstream of the normal portion of the shock will then justify further upstream propagation of the detached shock wave. Additional information concerning the flow field generated by the strong interaction may be gained by considering simultaneous shadowgraphs along with the wedge surface pressure data. Figure 7a shows the time history plot of chord-wise pressure distribution and the shadow photograph taken at t=1.28 sec during the same run is shown in Fig. 7b. Figure 7a shows yet another important aspect of the interaction problem. This figure illustrates the time history of the pressure coefficients at two chord-wise locations along the wedge surface for a period of 1.5 seconds. Although the use of finite length tubing from pressure ports to the pressure transducers does not permit time accurate analysis of pressure traces, these trends provide certain information concerning mean characteristics of the interaction process. Two points concerning time history variation of the wedge pressure distribution are immediately obvious. First, higher amplitude pressure fluctuations are seen near the airfoil leading edge at X/c=0.13 in comparison with pressure variations at X/c=0.80. Second, on the average, higher vortex-induced suction pressures may be seen near the wedge leading edge than further downstream. Experimental studies are currently being carried out where high-frequency surface mounted pressure transducers are used to time accurately characterize the observed unsteadiness.

ii. Oblique shock wave-vortex interaction

Interaction experiments with a vortex-wedge vertical separation distance of h/c=0.40 (Fig. 3) resulted in encounters with the vortex passing over the wedge leading edge thus creating an oblique shock wave-vortex interaction. It should be noted that the non-dimensional separation distance parameter, h/c, is a reference geometric parameter defined by the distance between the vortex-generator tip and the wedge leading edge, and in general does not represent the actual vortex height relative to the wedge leading edge. Figure 8 illustrates sequential spark shadowgraphs of the flow field for one test case of h/c = 0.40. This case represents a situation in which the vortex passes over the airfoil surface and intersects the oblique shock wave, a classic example of an oblique shock wave-vortex interaction. Figure 8a indicates formation of a compression wave just downstream of the oblique shock, while figure 8b, taken a distinct time later, shows formation of a detached shock wave with its vertex situated at the vortex center and above the airfoil leading edge. The aforementioned picture also clearly indicates a growth of the vortex size behind the detached shock wave, situation similar to that found in vortex breakdown phenomenon. A closer examination of Fig. 8b reveals a strong shock curvature at the apex with the leading portion of the shock being normal to the axial flow direction. Consequently, the flow represents a situation in which an oblique shock wave-vortex interaction leads to a normal shock wave-vortex interaction with a subsonic flow downstream of the detached shock. Such observation suggests an important aspect of supersonic vortex breakdown that may be expected during oblique shock wave vortex interaction, i.e. presence of a local subsonic region. To the author's knowledge, a vortex distortion as a result of oblique shock wave vortex interaction similar to that seen in Fig. 8b has not been reported in the past. Similar results were observed for a vortex-wedge vertical separation distance of h/c = 0.067. Repeatability runs, however, indicated formation of different size detached waves and the flow field was found to be highly unsteady.

IV. INTERACTION STUDIES IN MACH 2.5

This investigation is being conducted in Polytechnic University's 15 x 15 in^2 supersonic blow down wind tunnel facility[17]. The facility is an intermittent blowdown wind tunnel with a square test section of 38.1 cm x 38.1 cm (15 in x 15 in) and is capable of producing unit Reynolds numbers in the range of 26 x 10^6 to 22 x 10^7 per meter (8 x 10^6 to 66 x 10^6 per foot) over a Mach number range from 1.75 to 4.0. The tunnel utilizes fixed, contoured-nozzle-blocks to produce Mach numbers of 1.75, 2.0, 2.5, 3.0, 3.5 and 4.0.

The current experimental set-up is similar to the arrangement used in earlier studies of the problem in the Mach 3 wind tunnel.[8] A generic illustration of the experimental arrangement is shown in Fig. 9. The vortex-generator is a semi-span wing having a diamond shape airfoil section with a chord length of 50.8 mm (2 in), a half angle of 8,^{o} and angle of attack capability from 0 to 10 degrees. The vortex-generator shape and the angle of attack ranges were selected so that the difficulties associated with the shock/expansion wave structure emanating from the vortex generator or their reflection from test section walls would not adversely influence the interaction problem. A shock wave-generator in the form of a wedge section with a wedge angle of 20^o, a chord length of 71.6 mm(2.82 in) and variable angle of attack capability from 0 to 10 degrees is used in order to investigate the influence of shock strength on the interaction. The shock-generator section is equipped with a 6 x 3 matrix of 18 equally spaced pressure ports behind which miniature high-frequency pressure transducers can be mounted. The 6 chord-wise rows are equally spaced between X/c = 0.18 and X/c = 0.80 (where X is chordwise distance from the leading edge), and 3 span-wise rows are at Y/c=-0.124, Y/c=0, Y/c=0.124 (where Y=0 is the wedge mid-span location). For these experiments the shock wave generator is placed 15.2 cm (6 in; 3 vortex-generator chords) downstream of the vortex-generator wing section.

Initial experiments were performed to investigate the feasibility of using wing tip vortices to effectively simulate the interaction problem. Figure 10 shows a shadowgraph of the flow field generated in the absence of the vortex generator wing section. The picture shows the wedge at 5^{o} angle of attack (25^{o} flow deflection angle) with an oblique shock at an angle which compares favorably with the two-dimensional theoretical prediction of 50.5^{o}. It should be noted that the shock generating wedge does not span the entire width of the test section and some three-dimensional effects at the tip regions are present. For example in Fig. 10 a relatively strong shock wave appears in the shadowgraph image beginning at about the 80 percent chord location. This is believed to be due to a mismatch between the wedge surface angle and the surface angle of the wedge supports, a discrepancy which will be corrected in future studies of the problem. On the other hand, such effects are confined to the tip region and are not expected to influence the interaction phenomenon. Time history of the wedge surface pressure distribution for the same flow condition at several arbitrary chord-wise and span-wise locations are compared to the theoretical prediction in Fig. 11 with good agreement and little three-dimensional effects influencing the measured quantities.

Initially, the interaction experiments were designed to clarify certain behavior of the flow field which were observed in the 10 x 10 in^2 Mach 3 wind tunnel. In previous experiments[9,12] conducted in the Mach 3 tunnel only a limited tests were performed on the oblique shock wave-vortex interaction. Moreover, in those experiments the geometry of the experimental set-up was such that the vortex intersected the shock front very close to the wedge surface. As a result, situations leading to vortex distortion with limited subsonic region downstream of the shock was speculated to have been influenced by the wedge surface boundary layer. In the present configuration the geometry of the interaction was arranged such that the intersection point is sufficiently far from the wedge surface. Figure 12 illustrates a typical shadowgraph of the flow field generated during the interaction of a relatively weak vortex and a weak oblique shock wave. The vortex is generated by placing the vortex-generator at an angle of attack of 5^{o} and the shock-generator is at a 5^{o} angle of attack. The flow is from left to right with the vortex-generator at the lower left portion of the picture while the wedge section may be seen at the right of the picture. The picture clearly indicates a concentrated tip vortex convecting downstream which intersects the oblique shock wave creating a classic oblique shock wave-vortex interaction. Although the above picture does not indicate an appreciable alteration to the vortex structure in crossing the oblique shock front, a sensible deflection of the vortex in the general direction of the flow behind the shock is evident.

Interaction experiments incorporating stronger vortices resulted in a more pronounced alterations to the vortex structure as a result of the encounter. Figure 14 shows a shadowgraph of the flow field generated by placing the vortex generator at an angle of attack of 6.5° (a moderately strong vortex) and a wedge angle of 10° (a strong shock). The 30° flow deflection angle for the wedge at a Mach 2.48 stream is slightly higher than the wedge shock detachment angle. This is evident in the shadowgraph of Fig. 13 from the highly curved and detached shock structure. The above picture indicates that the vortex has been drastically distorted as a result of the encounter to form a "two-zone" region form very similar in structure to the results of vortex-wedge interaction studies reported in Ref. 12. Moreover, as already stated, the interaction point may be seen to be sufficiently far from the wedge surface so that the flow does not seem to have been influenced by the wedge boundary layer. This was of great concern in the interaction studies reported in Ref. 9. An interpretation of the observed phenomenon based on the vortex distortion model of Ref. 12 is illustrated in Fig. 14 where appearance of a slip surface as a result of vortex distortion is believed to be responsible for formation of the observed locally detached shock structure in the interaction region.

V. RECOMMENDATIONS FOR FUTURE WORK

All of the data generated and analyzed in the present investigation point to the fact that more detailed study of the interaction problem is required in order to gain a better understanding of the complex flow field. Detailed measurements of flow properties in the vortex core and interaction region are needed in order to more clearly characterize vortex-breakdown phenomenon in supersonic flows. Such measurements should be non-intrusive in nature without altering the natural environment of the flow field. Although the results of present study indicate some similarities between incompressible "B-breakdown" and supersonic vortex distortion, detail measurements in the breakdown region should be made in order to determine whether a reversed flow region and a stagnation point (both characteristics of incompressible vortex breakdown) are present. A systematic study of the oblique shock wave-vortex interaction is necessary in order to establish criteria based on vortex strength and shock wave intensity which may lead to vortex breakdown in supersonic flows. In order to gain a better understanding of the unsteady nature of the flow, wedge surface pressure measurements using high-frequency detectors are needed. Wedge surface pressure measurements incorporating high-frequency sensors are currently being carried out the results of which will be presented in future work.

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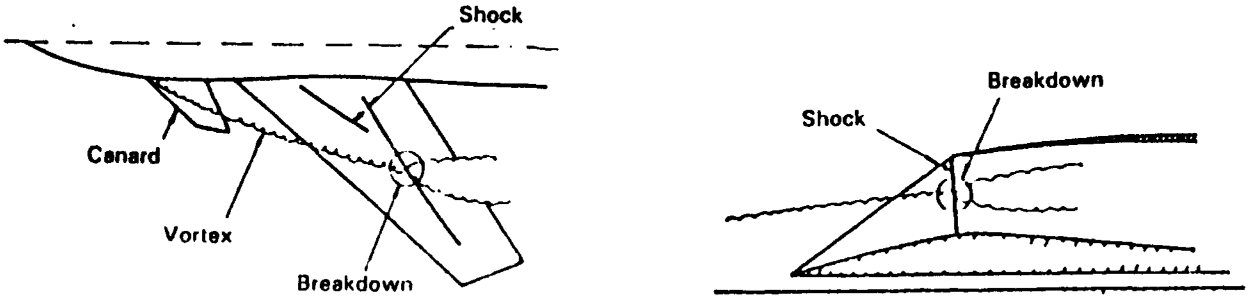
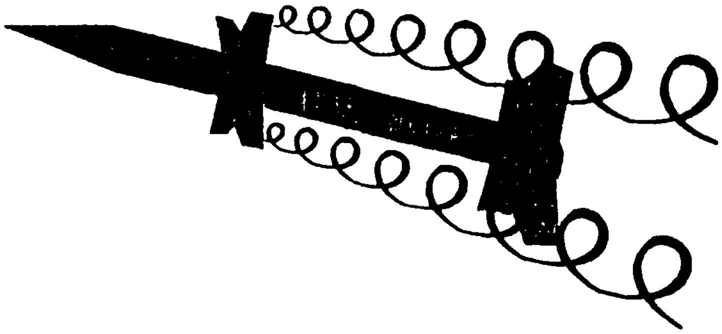


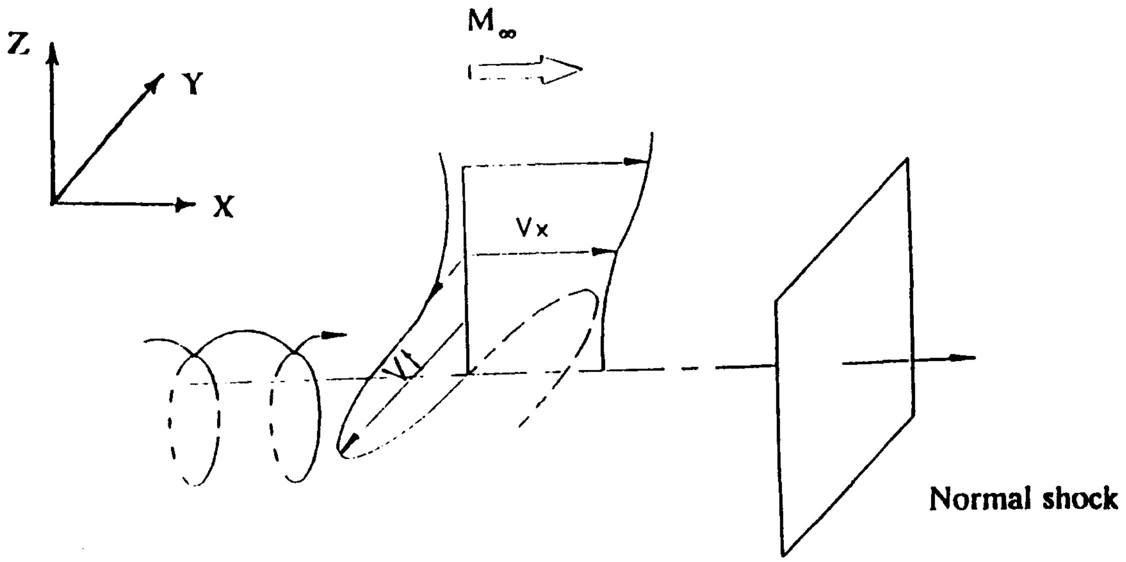
a. Canard vortex-wing shock wave interaction (from Ref. 6)

b. Supersonic inlet

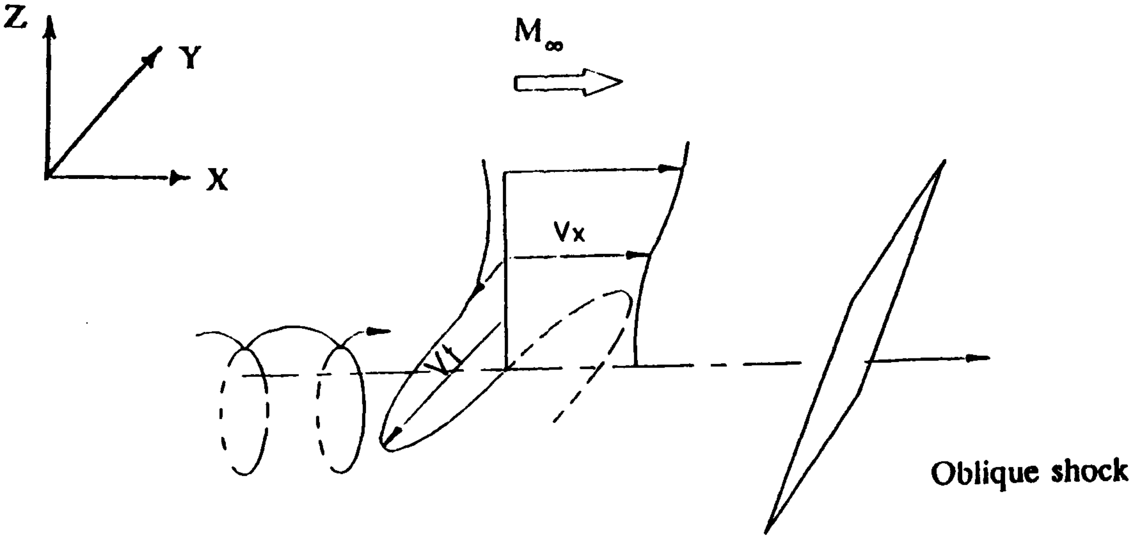


c. Typical vortex-surface interaction on missile configuration

Figure 1 Examples of shock wave-vortex interaction



(a) Normal shock wave-vortex interaction



(b) Oblique shock wave-vortex interaction

Figure 2. Normal and oblique shock wave vortex interactions

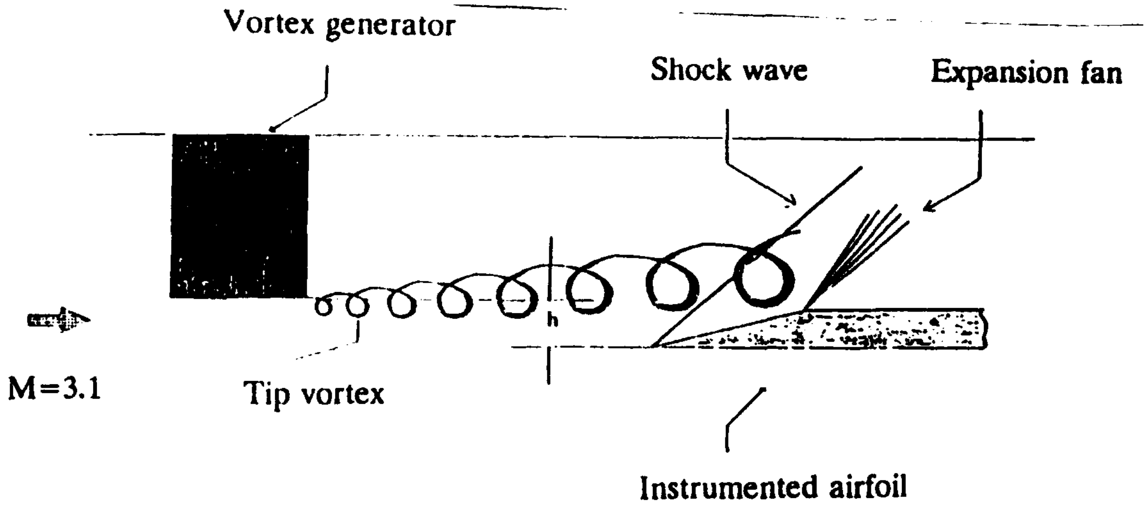


Figure 3. Schematic of the experimental arrangement

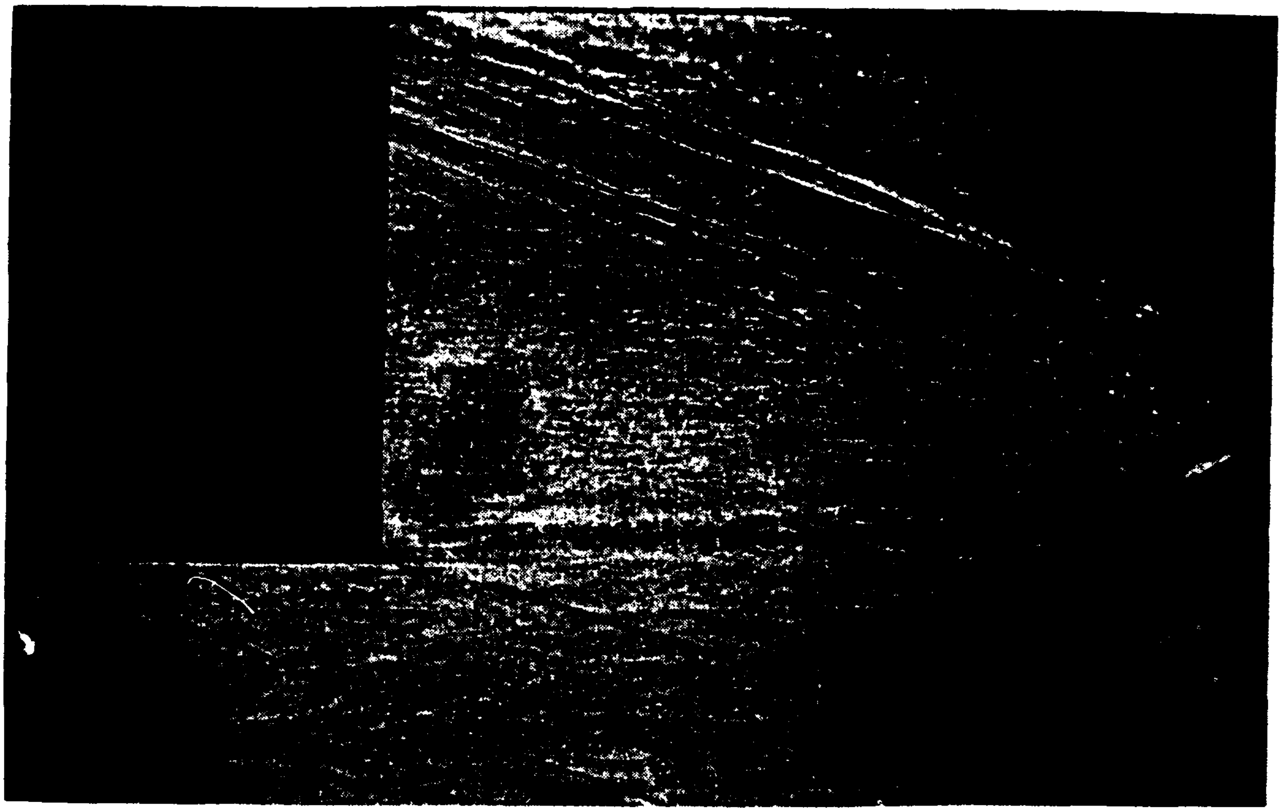


Figure 4. Shadowgraph of the flow field generated during the head-on interaction of the vortex and the wedge

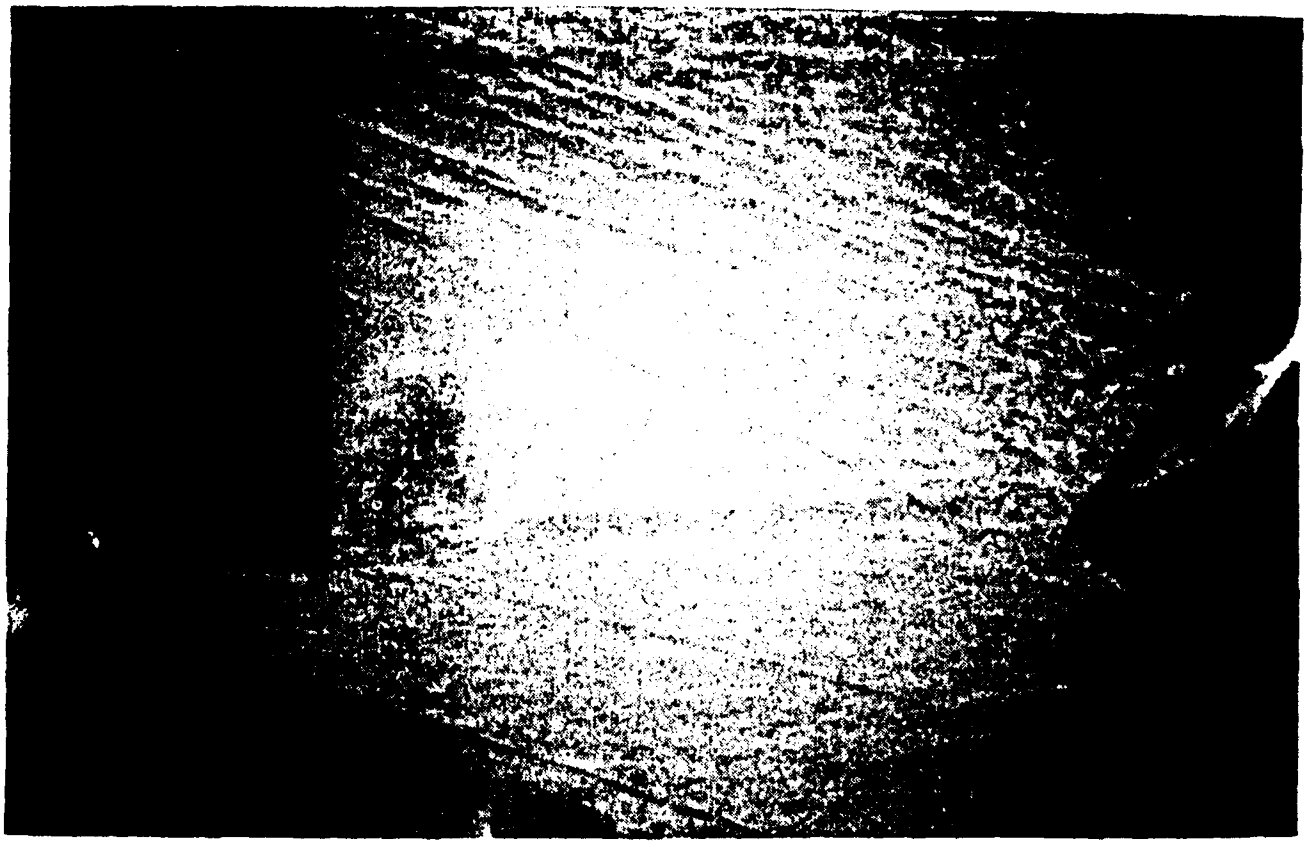


Figure 5a t=0.52

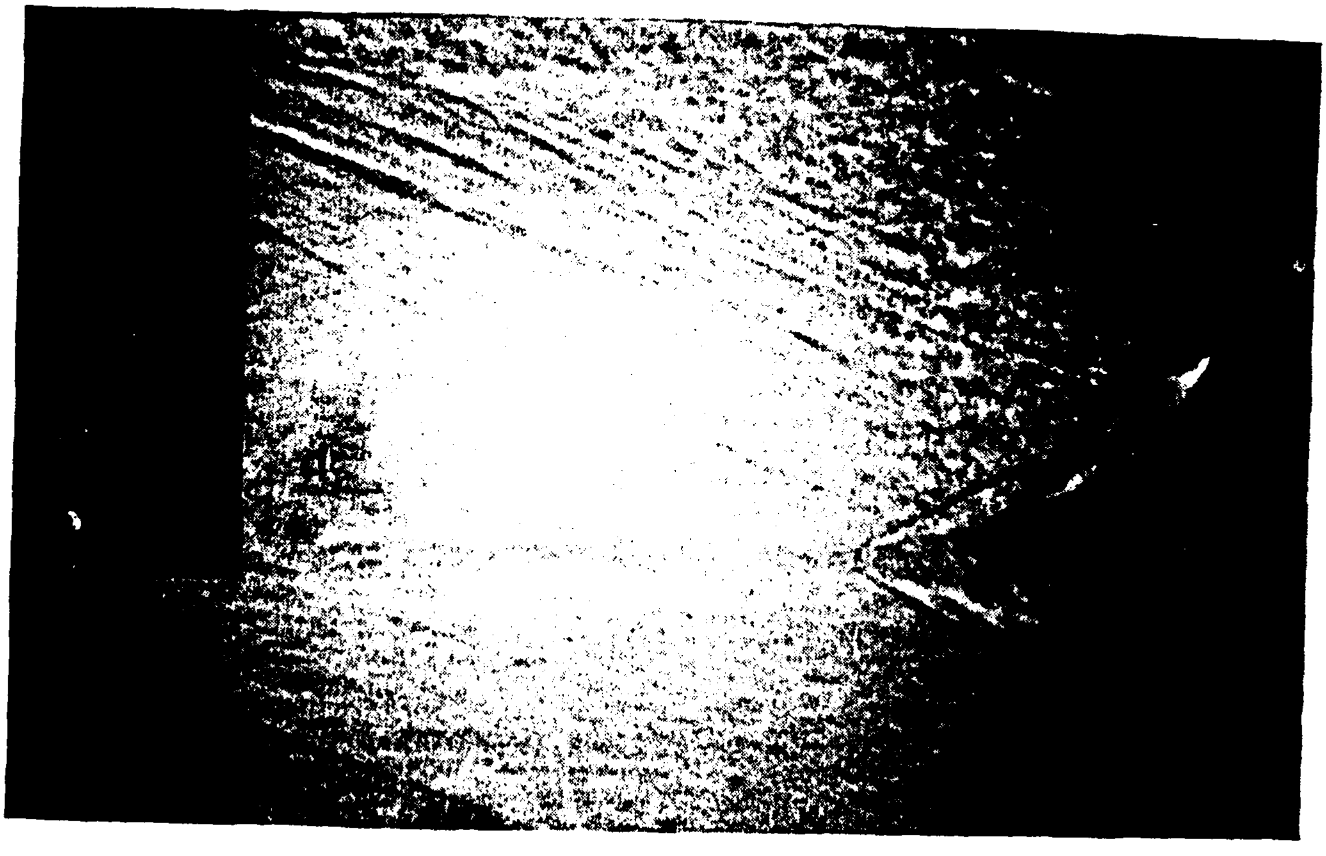


Figure 5b t=1.15

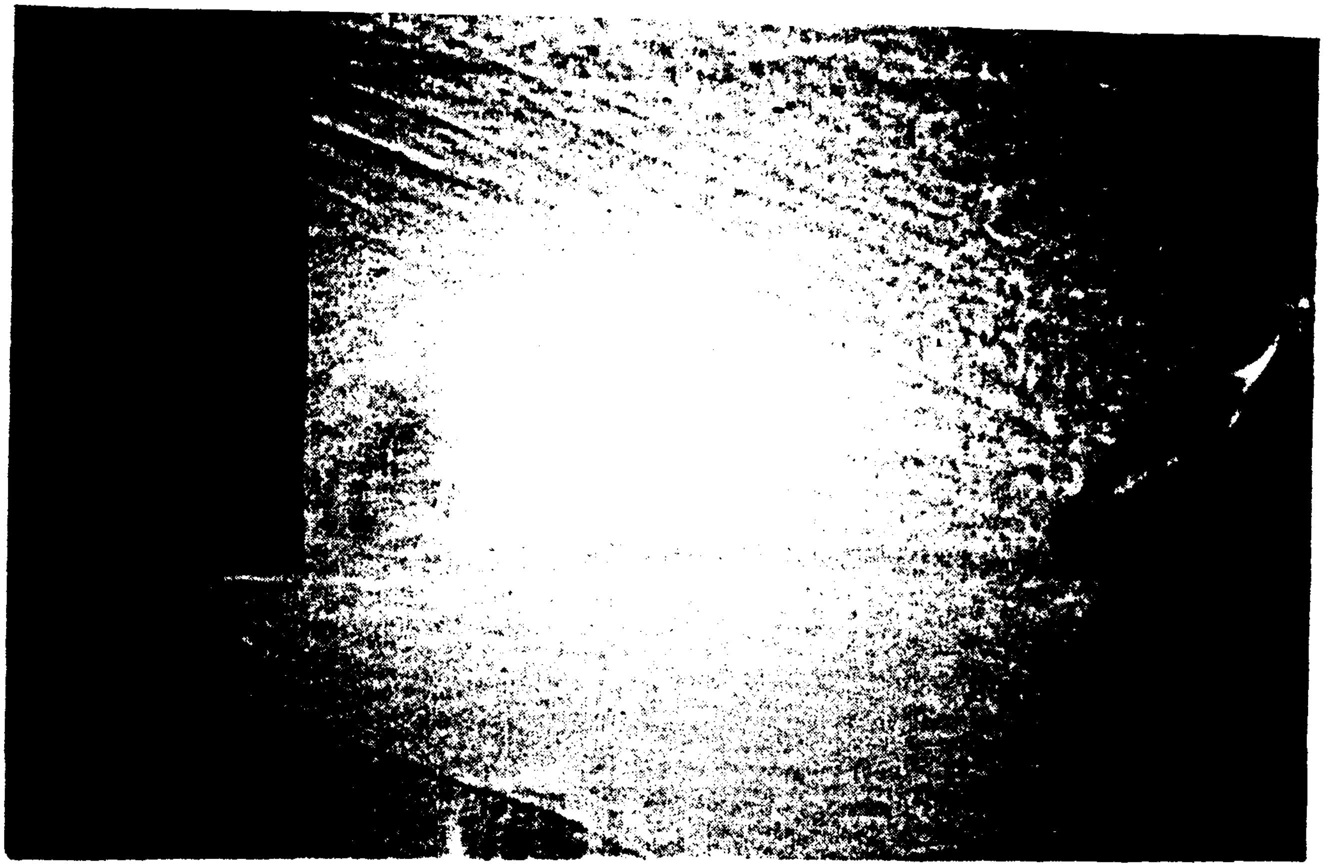


Figure 5c t=1.85

Figure 5. Shadowgraph of the flow field generated during the head-on interaction of the vortex and the wedge for $\alpha_{VG}=7.5^{o}$

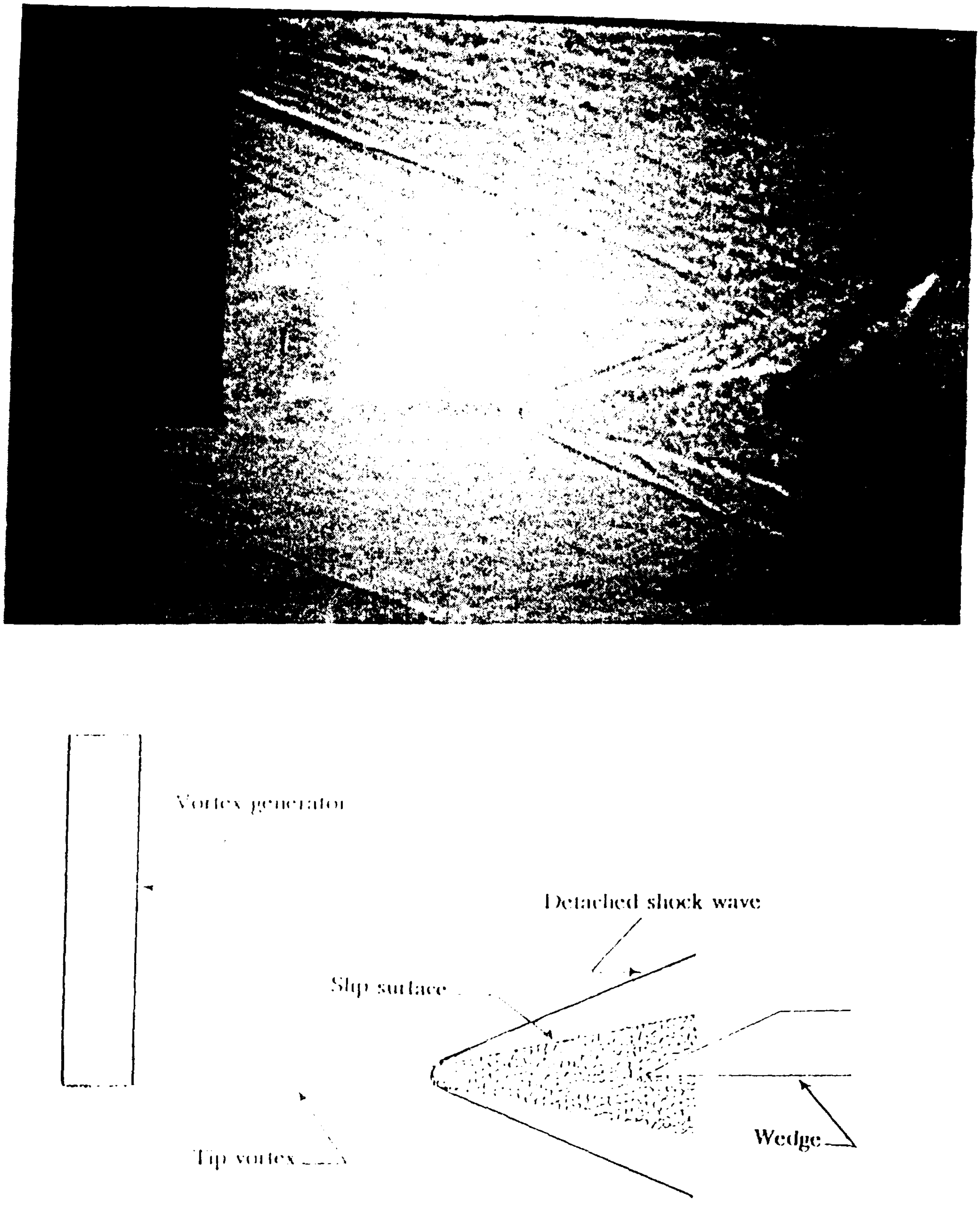


Figure 6. Shadowgraph of the flow field generated during the head-on interaction of the vortex and the wedge for $\alpha_{VG}=7.5^{0}$

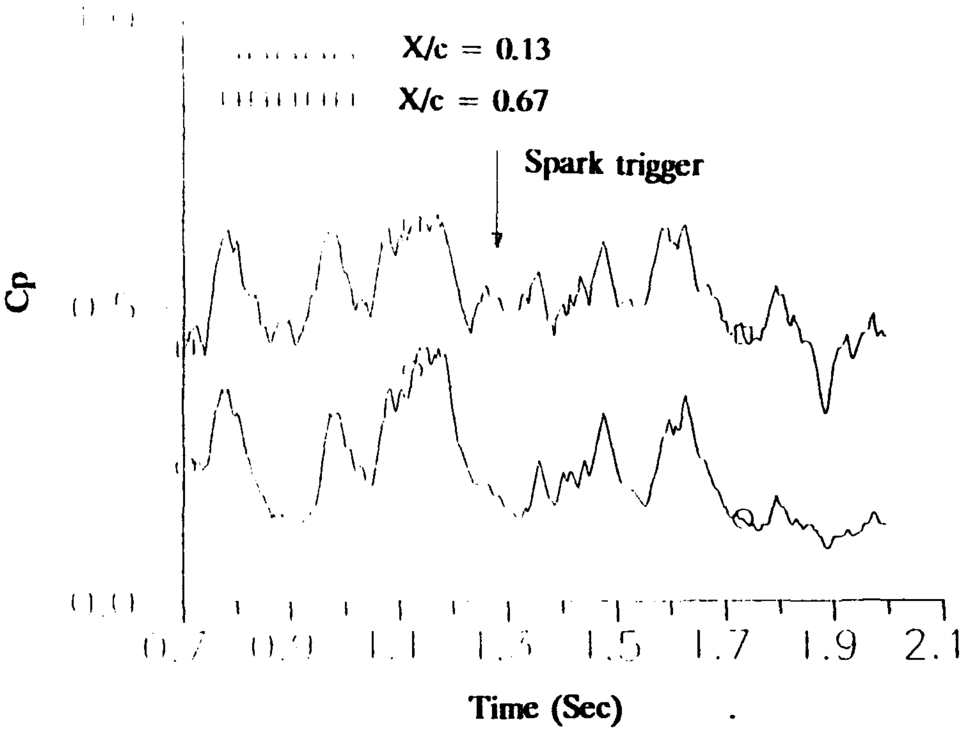


Figure 7a. Time history of the wedge pressure coefficient during the strong interaction

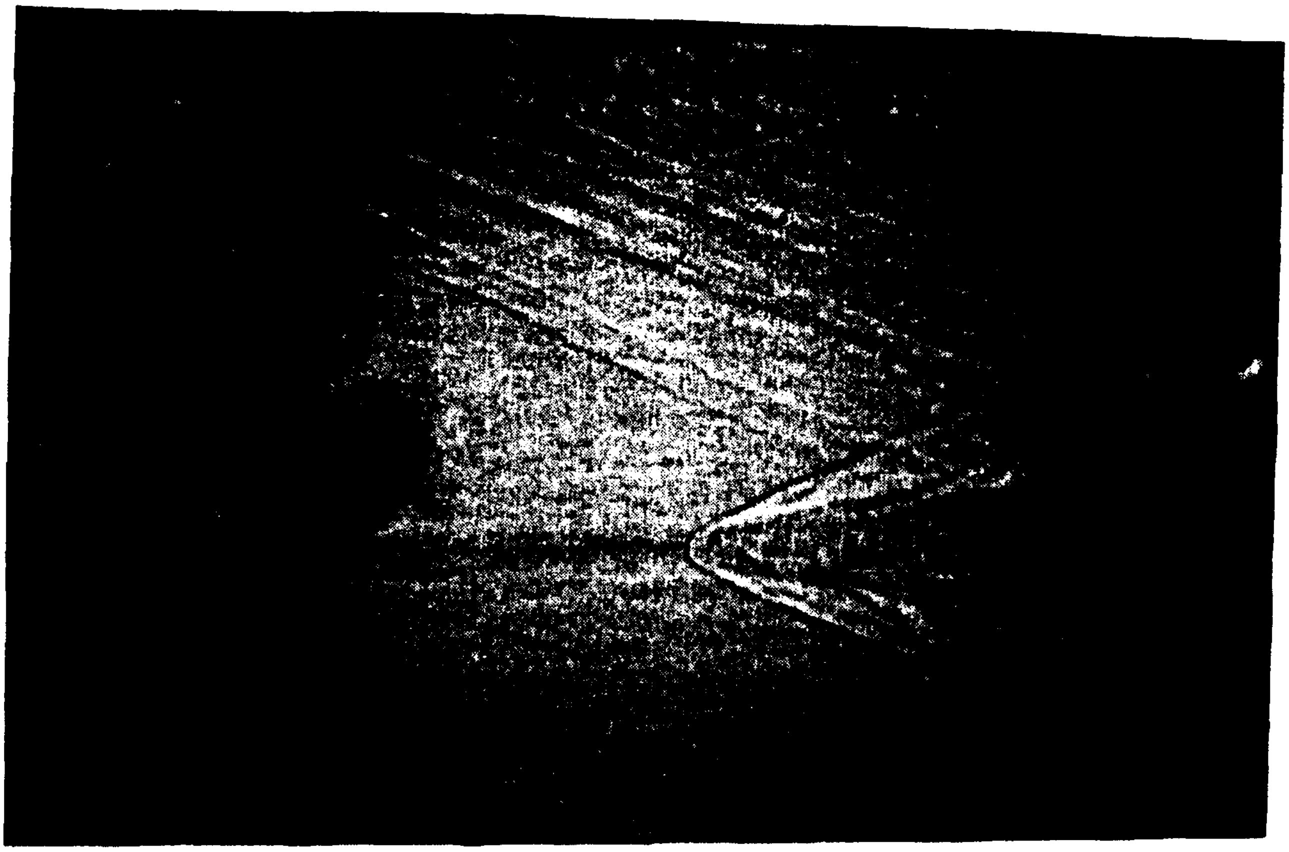


Figure 7b. Shadowgraph of the flow field generated during the strong interaction at t=1.28 sec.

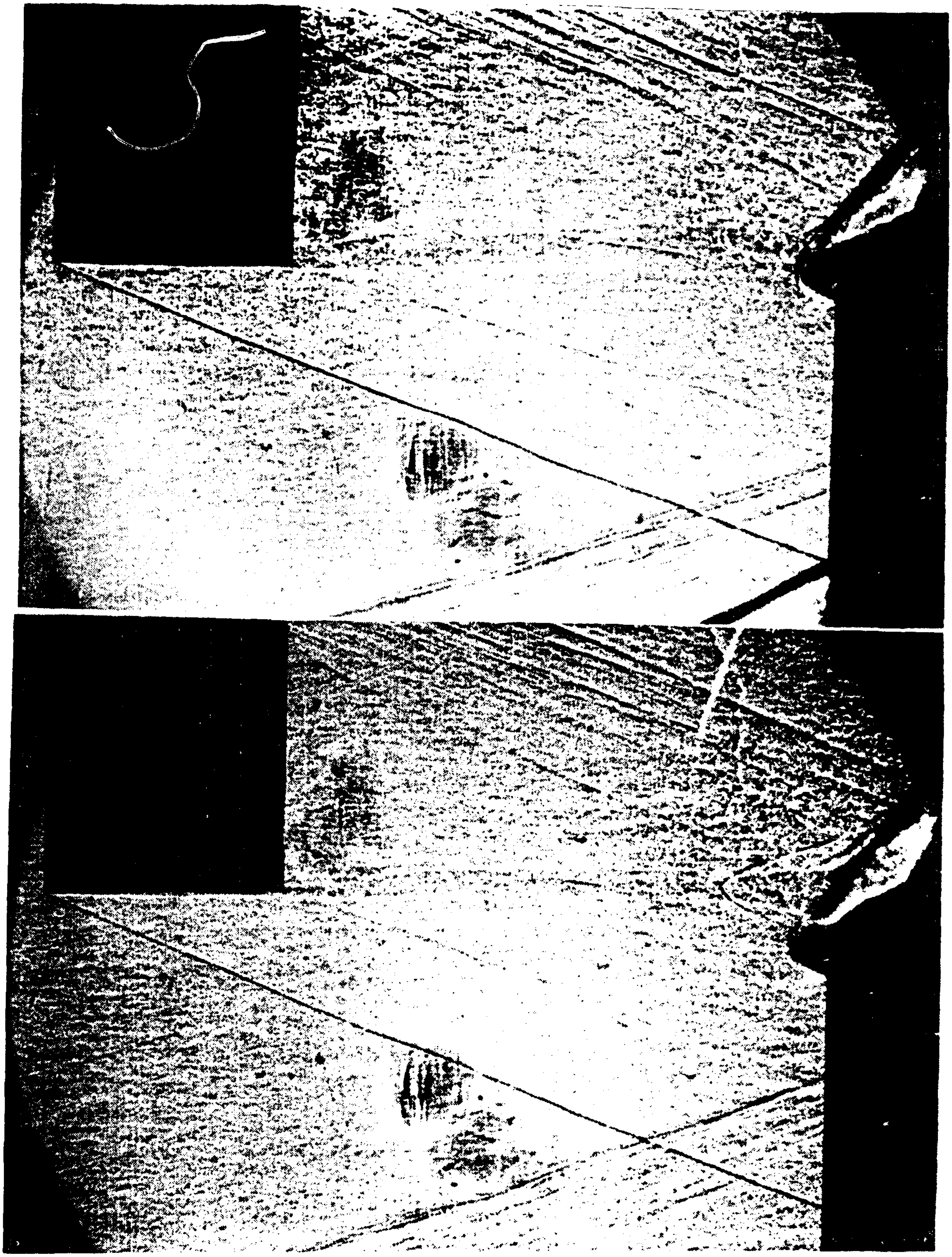


Figure 8. Sequential shadowgraphs of the flow field generated during the oblique shock wave-vortex interaction for $\alpha_{VG}=10^{\circ}$, h/C=-0.10

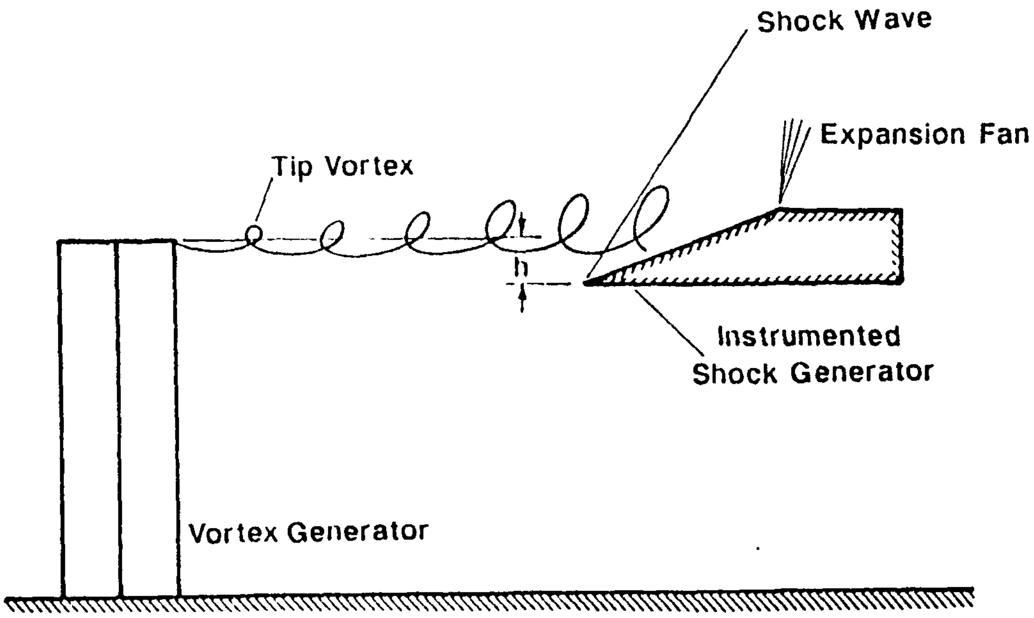


Figure 9. Schematic of the experimental set-up in the Mach 2.5 tunnel

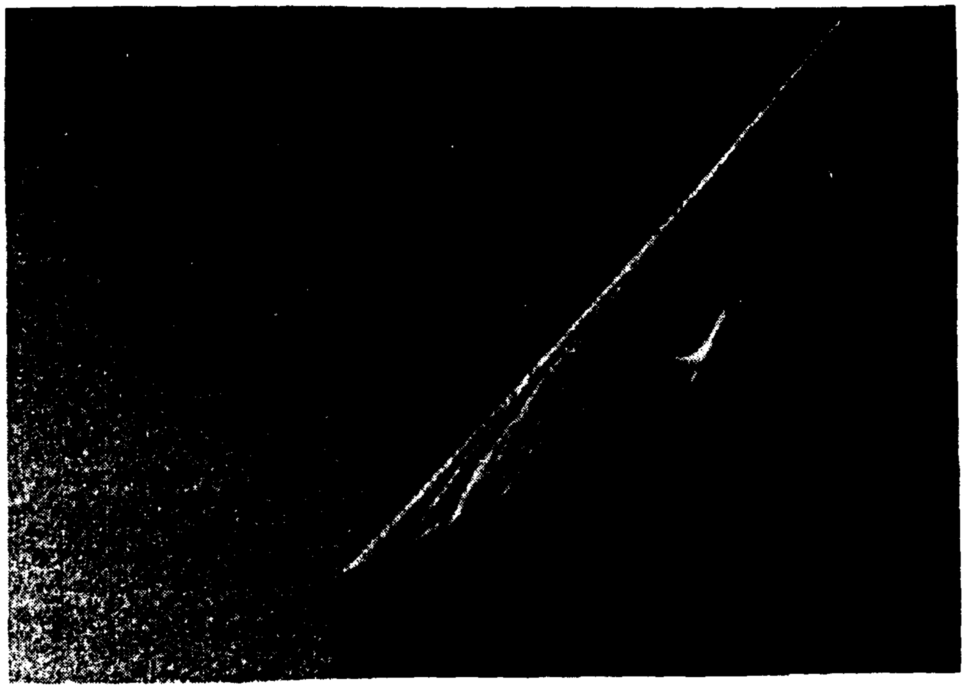


Figure 10. Shadowgraph of the flow over the 20° wedge at 5° angle of attack

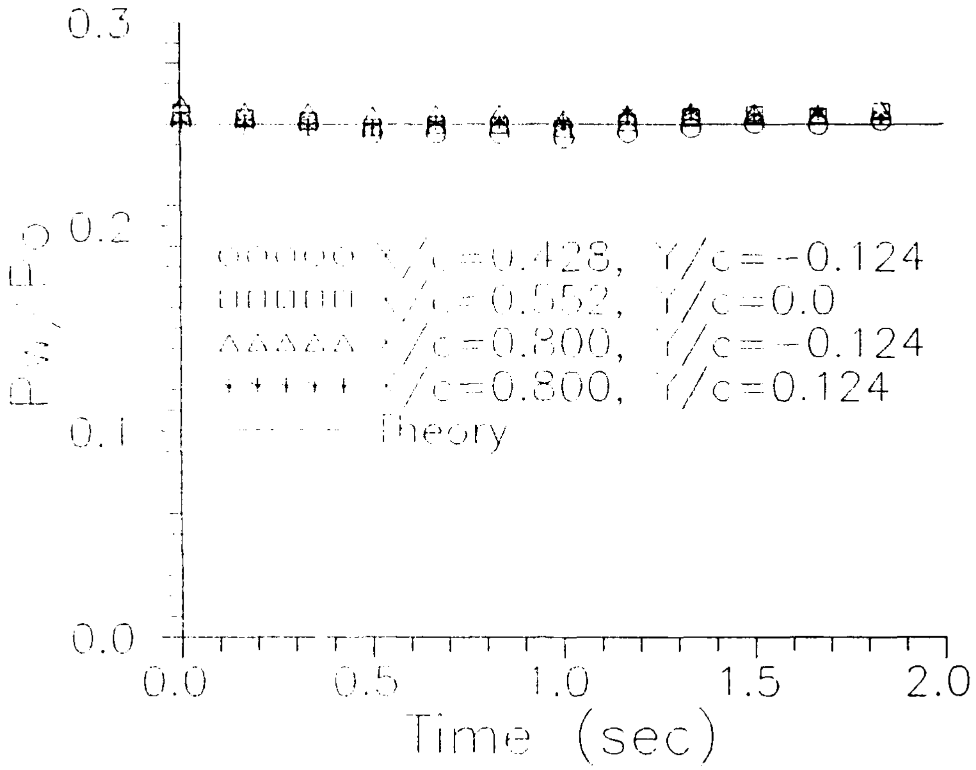


Figure 11. Comparison of wedge surface pressure with theory

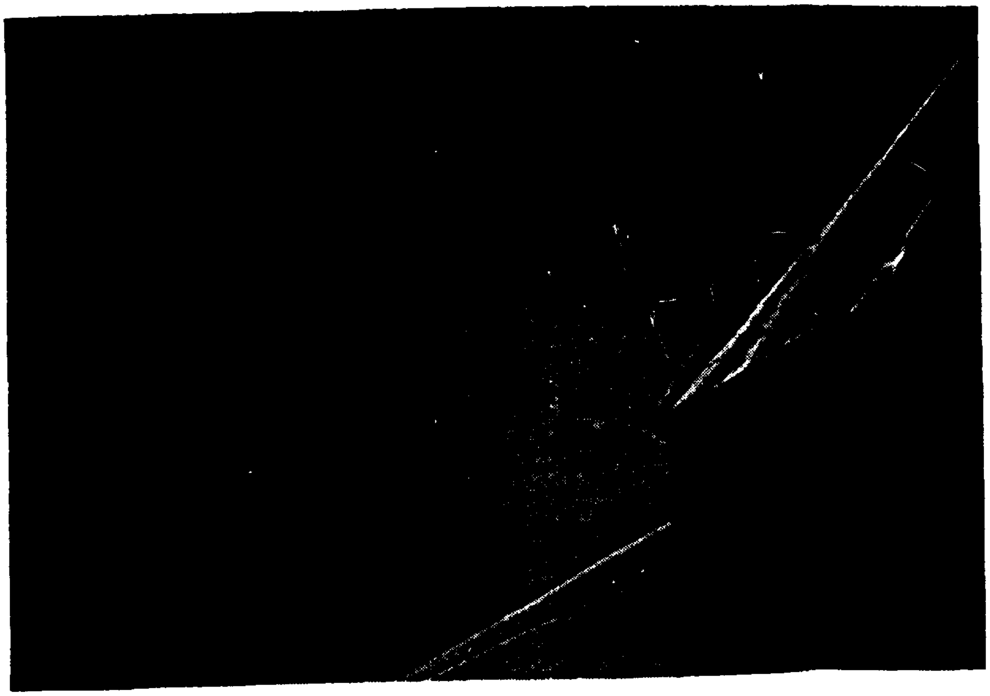


Figure 12. Shadowgraph of the flow during a weak interaction

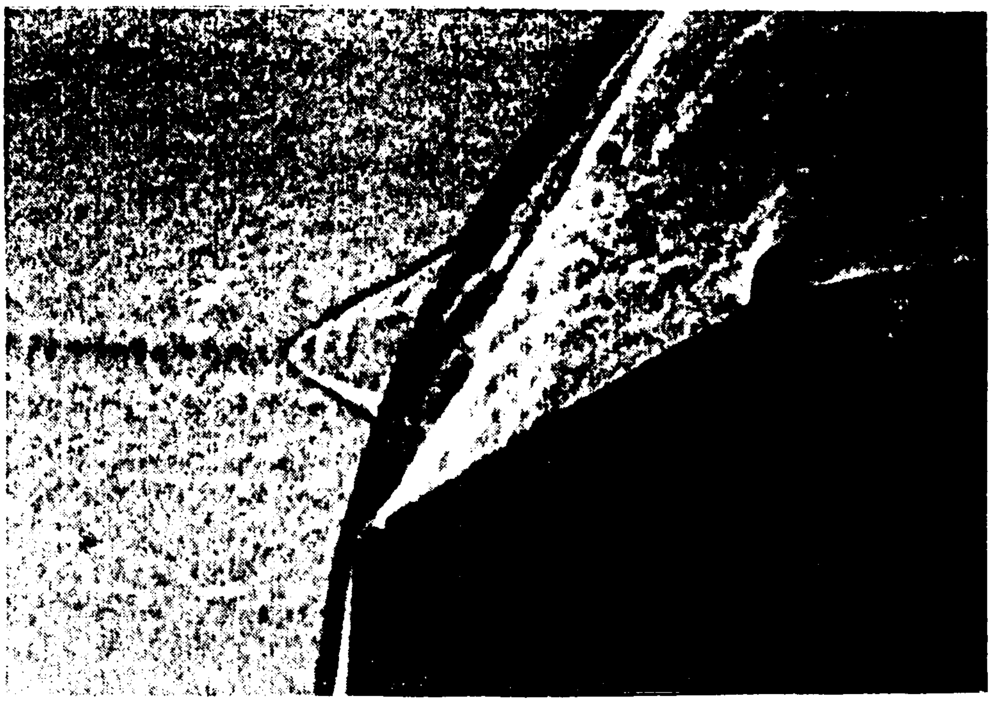


Figure 13. Shadowgraph of the flow during a strong interaction

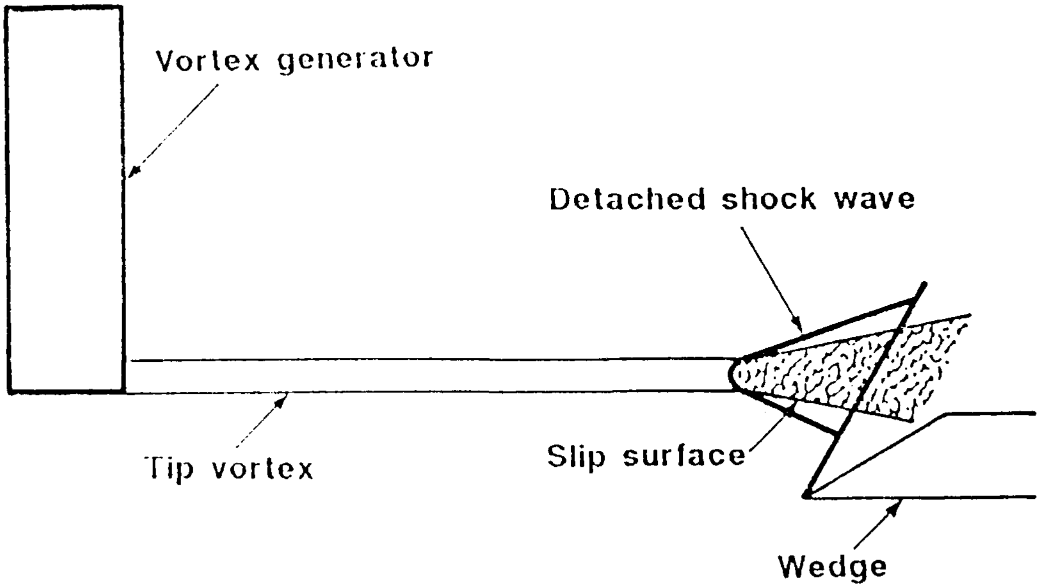


Figure 14. Interpretation of the observed flow field in Fig 13

VII. APPENDIX A

Abstracts of Journal publications during funding period

Accepted for publication in the AIAA Journal

Vortex Distortion During Vortex-Surface Interaction in a Mach 3 Stream

Iraj M. Kalkhoran*

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Abstract

An experimental study has been conducted in a Mach 3 wind tunnel to investigate the behavior of supersonic vortices as they interact with a wedge surface placed in their passage. The experimental setup was arranged so that interactions resulted in a close encounter of the vortex core and the wedge leading edge. Spark shadow photographs of the flow field along with pressure measurements on the wedge surface were used to study the interaction problem. In their most organized form, distortion of stream-wise vortices upon interacting with the wedge was found to result in formation of symmetric detached shock fronts far upstream of the wedge leading edge followed by an apparent slip surface separating a subsonic region from a supersonic zone. Interaction experiments leading to substantial changes in the structure of vortices revealed that the supersonic vortex distortion has strong resemblances to the incompressible "B-breakdown" reported in the literature. Experimental results also indicate that the interaction strongly depends on the vortex strength and vortex proximity to the wedge leading edge and the generated flow field was found to be highly unsteady. Interaction of concentrated stream-wise vortices with the oblique shock formed over the wedge surface resulted in formation of a locally three-dimensional shock wave with a limited subsonic region downstream of the shock.

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Aerospace Engineering Department, Member AIAA

Accepted for publication in the AIAA Journal

AIRFOIL PRESSURE MEASUREMENTS DURING OBLIQUE SHOCK WAVE-VORTEX INTERACTION IN A MACH 3 STREAM

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Aerospace Engineering Department
Polytechnic University, Brooklyn , New York, 11201

Abstract

An experimental investigation of the interaction between streamwise discrete vortices and oblique shocks formed over a two-dimensional wedge surface was conducted in a Mach 3 blowdown wind tunnel. An instrumented two-dimensional wedge section was placed downstream of a semi-span wing so that the trailing tip vortex would arbitrarily interact with the shock wave formed over the wedge surface. The experiments were designed to simulate interaction of streamwise vortices from upstream bodies with shock waves formed over aft surfaces as might be encountered in supersonic flight of aircraft and missiles. The influence of vortex strength and vortex-airfoil vertical separation distance on the interaction was examined. The flow field generated was found to be highly unsteady and a substantial change in the pressure distribution on the downstream airfoil was observed. The interaction of a strong vortex with the oblique shock wave over the downstream wedge section resulted in formation of an unsteady detached shock wave upstream of the wedge leading edge. Furthermore, when the vortex approached the wedge leading edge, formation of detached shock wave occurred further upstream of the section leading edge.

Presented as Paper 92-2631, AIAA 10th Applied Aerodynamics Conference, Palo Alto, CA, June 22-24, 1992

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** Professor and Head, Associate Fellow AIAA