Laser Vapour Screen Visualisation of Three-Dimensional Compressible Flow Fields

N. Menon[1] and B.W. Skews[2]

A Laser Vapour Screen (LVS) system has been designed and implemented in the supersonic wind tunnel at the Mechanical Engineering Laboratories, University of the Witwatersrand. The settling chamber of the wind tunnel is seeded with micron size droplets of water that evaporate in the settling chamber and subsequently condense out into a fog upon expansion through the converging-diverging nozzle of the wind tunnel. The fog in the test section is illuminated by means of a laser sheet generated by passing the beam from an argon-ion laser through a series of cylindrical lenses. Any disturbance in the flow field modifies the uniform concentration of fog particles in the plane of the laser sheet. In this manner, shock waves can be visualised and photographed. The ability of the technique to take multiple two-dimensional slices of the flow field lends itself to being ideally suited for visualising compressible and highly 3- dimensional flow fields. The double wedge models tested in the supersonic wind tunnel consisted of two sets of 27° wedges (having aspect ratios of AR = 0.5 and AR = 0.75). The AR = 0.75 model displayed Mach reflection at the centreline of the model, while the AR = 0.5 model displayed regular reflection at the centreline. The Mach stem surfaces on both models developed a prominent outward bulge and grew in size downstream of the models.

Nomenclature

s = wedge span
c = wedge length
δ = wedge angle, or flow deflection angle
i = Incident shockwave
r = Reflected shockwave
m = Mach stem
sl = slip layer
γ = specific heat ratio

1. Introduction

Reflection of shockwaves

There are two commonly encountered types of shockwave reflection patterns; they are Regular Reflection and Mach Reflection. Shockwave reflection studies are performed by placing two finite width wedges such as shown in Fig. 1, a set vertical distance apart from each other in a supersonic flow field.

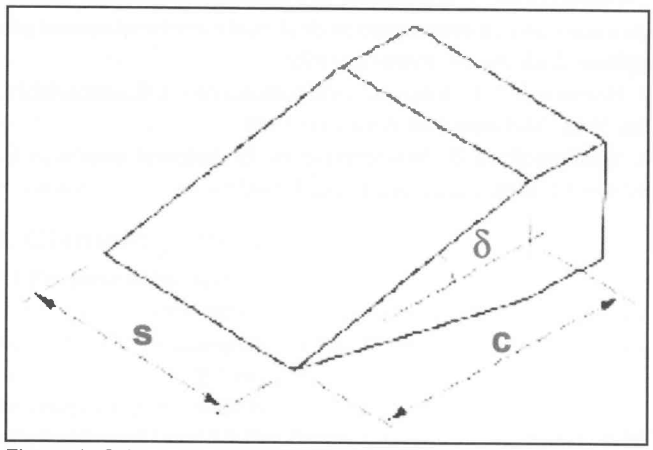


Figure 1: Schematic of a finite width wedge

Fig. 1 shows the sketch of a finite width wedge typically utilised in the supersonic wind tunnel. Two wedges of this nature placed a set distance apart from each other will generate shockwaves in a supersonic free stream that will interact with each other. The span of the wedge is denoted by *s*, the length of the wedge is denoted by *c*, and the flow deflection angle is denoted by δ. An important consideration during the experimental analysis of oblique shockwave reflection is the need to have a perfect reflecting boundary that would be adiabatic, impervious and rigid in nature. Such a boundary cannot be obtained through the use of physical reflecting surfaces such as wind tunnel walls for instance, due to the presence of a boundary layer along the wall. A surface of this nature can however be achieved by allowing oblique shock waves from two wedges (placed a set distance away from each other with a central plane of symmetry) to reflect off each other. The plane of reflection then behaves as an adiabatic, impervious and rigid surface.

Considering the two-dimensional regular reflection case shown in Fig. 2, the flow is turned parallel to the surface of the wedges by the first shockwave, denoted by *'i'*, the incident shockwave. The flow passing through the incident shockwave

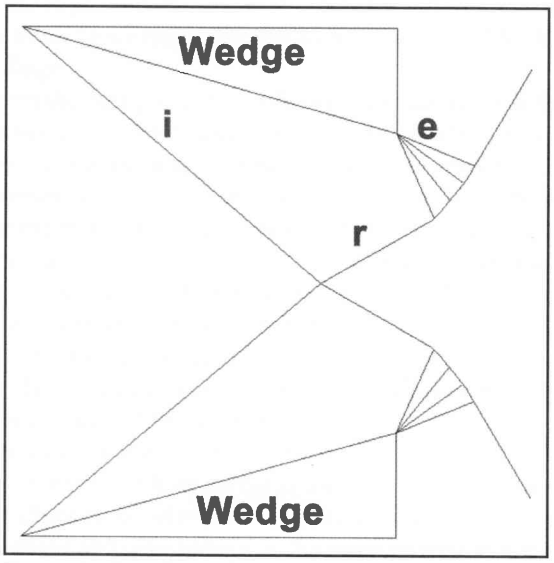


Figure 2: Two-dimensional regular reflection pattern between wedges (the flow is from left to right)

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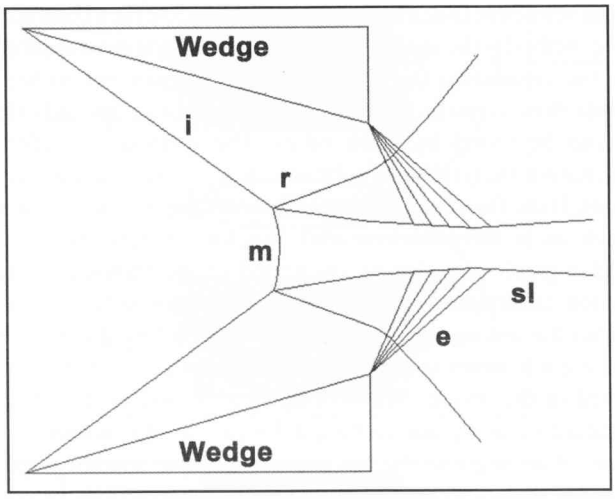


Figure 3: Two-dimensional Mach reflection between two wedges

experiences an instantaneous change in direction, turning it parallel to the surface of the wedge. The incident shockwaves from the two wedges then reflect at the plane of symmetry. The flow passing through the reflected shockwave, denoted by *'r'* is then turned instantaneously back to the original flow direction. The reflected shockwave undergoes a curvature as it meets the expansion fan that is created at the trailing edge of the wedge. The expansion fan serves to turn the flow over the trailing edge of the wedge. It is denoted by *'e'*.

The angles of incidence and reflection of the incident and reflected waves are not the same, as the relations governing the phenomena are non-linear. The reflection is not specular. If the wedge angle is increased, keeping the Mach number of the flow constant; a different reflection pattern is encountered. The reflection pattern is irregular and is known as Mach reflection. It consists of a three shock system, as can be seen in Fig. 3. The reflection point now moves away from the plane of symmetry, into a three-shock system, consisting of the incident shockwave, the reflected shockwave and the Mach stem, denoted as *'m'*. Unlike the incident and reflected shockwaves the Mach stem is a normal shockwave and the flow through it does not experience a change in direction. Hence the flow passing through the reflected shockwave and the Mach stem are at different velocities, and are separated by a shear layer known as the slip layer, denoted by *'s'*. The flow in these two regions is at the same pressure, but there is a temperature and density discontinuity between them.

The reflected shockwave curves as it encounters the expansion fan at the trailing edge of the wedge. The expansion fan also causes the slip layer to curve into the shape of a converging-diverging duct. The subsonic flow behind the Mach stem hence accelerates to supersonic conditions once again through this converging-diverging slip layer.

Three-dimensional shockwave reflection

Studies investigating the transition from regular to Mach reflection in shockwaves, performed in wind tunnels using wedges having a finite span were performed under the assumption that if the wedges had a span much greater than the separation between them, the flow on the centerline of the wedges would be two-dimensional. Skews[7] used oblique shadowgraphs to identify the interactions in the complex three-dimensional flow field present between two finite span wedges in a supersonic free stream. The effect of the aspect ratio of the wedges was looked at in detail. The effect of the corner signal emanating from the edge of the wedges and their effects on the shock reflection patterns obtained between two finite span wedges were investigated. The flow field near the leading edge of the model is still two-dimensional in nature owing to the fact that the flow field in this region does know of the existence of the edges of the model (in a completely supersonic flow field). It was discovered that the effect of the edges of the finite wedges were bounded within the Mach cone emanating from the corner of the wedge. The corner signal causes the incident shock wave between the two wedges to become curved. Sudani et al.[8] concluded that these three-dimensional effects promoted regular reflection between wedges. Hence two-dimensional results cannot be used to describe three-dimensional flow fields and that apparently two-dimensional flows which are perturbed to a small extent by three-dimensional effects could have very different effects on transition and hysteresis than the theoretical expectations. Skews[7] suggests that the subsonic condition prevalent behind the Mach stem allows for perturbations to creep up onto the incident wave system from the rear. This has a significant influence on the results obtained while investigating the hysteresis phenomena in shockwave reflection. Skews[7] also noticed signs of instability near the mechanical equilibrium point (where the regular reflection meets the Mach reflection) by taking oblique shadowgraphs of the flow field. A section was noticed near the transition point between regular and Mach reflection where there is a rapid reduction in the height of the Mach stem followed by a recovery in width before it collapsed into regular reflection. Tunnel noise and flow unsteadiness has been suggested to be a likely cause of transition in flows

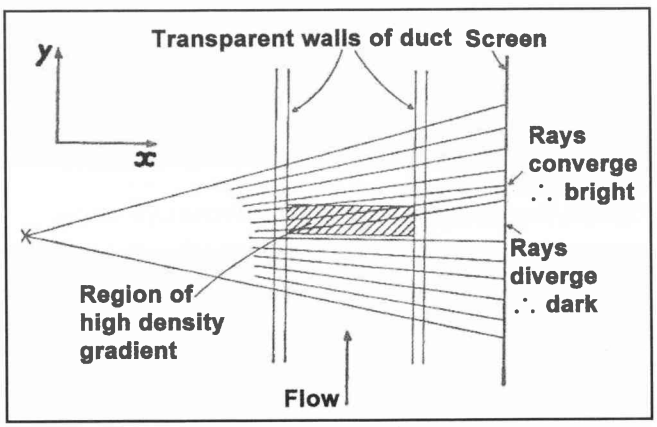


Figure 4: Schematic of the shadowgraph system

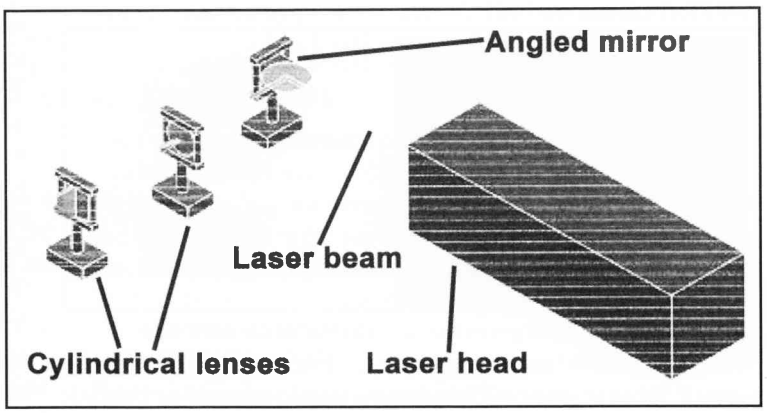
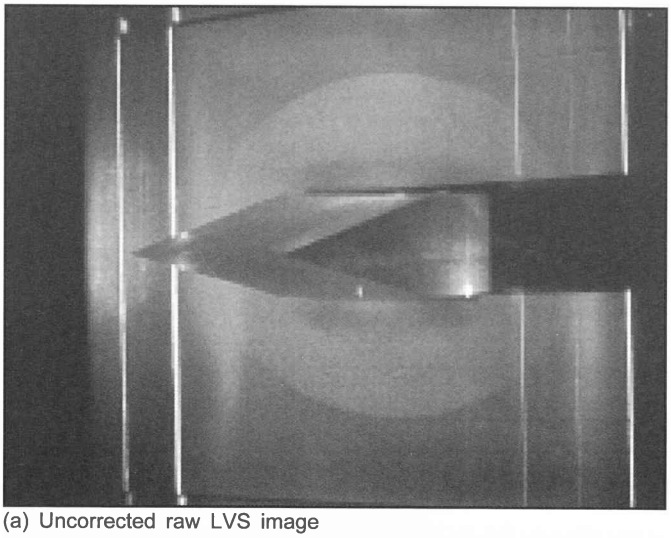


Figure 5: Schematic of the laser sheet

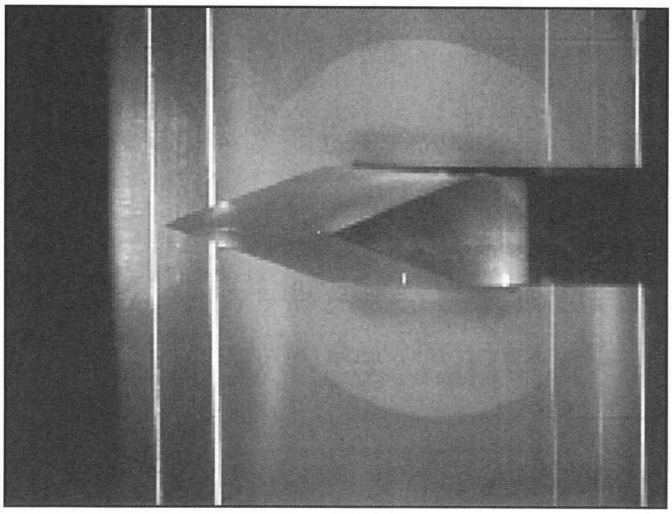
investigated by Skews[7].

The shadowgraph technique

A light beam that is transmitted through a flow with varying fluid density is disturbed owing to the inhomogeneous distribution of the refractive index in the flowing fluid. One such commonly used method is the shadowgraph (Fig. 4). This is most appropriate for visualizing the geometry of shock patterns, either in steady flow as can be found in wind tunnels or an unsteady flow as can be found in shock tubes. The method is useful in qualitative analysis of two-dimensional or axisymmetric flow fields. If the flow field is markedly three-dimensional in nature (such as a three-dimensional shockwave reflection), the shadowgraph provides an integrated image through the test section. Information of the interactions at any particular plane within the test section are superimposed on top of each other making it at times impossible to decipher the information obtained in the image. Skews[9] employed a modification to the standard shadowgraph technique by yawing the incident light beam at an angle to the test section (oblique shadowgraphs). Shadow images of the three-dimensional interactions can thus be captured from different angles. With the aid of 3-D reconstruction software packages the structure of the various shock interactions can then be recreated as surface models. A simpler and more direct method for studying three-dimensional flows is hence required.



(a) Uncorrected raw LVS image



(b) Corrected LVS image

Figure 6: Example of uncorrected and corrected LVS images

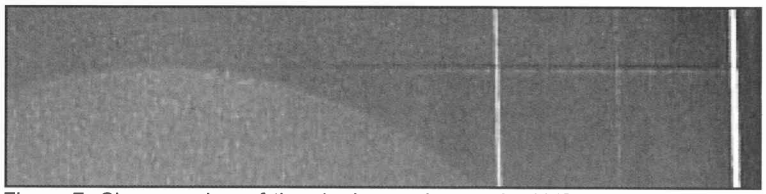
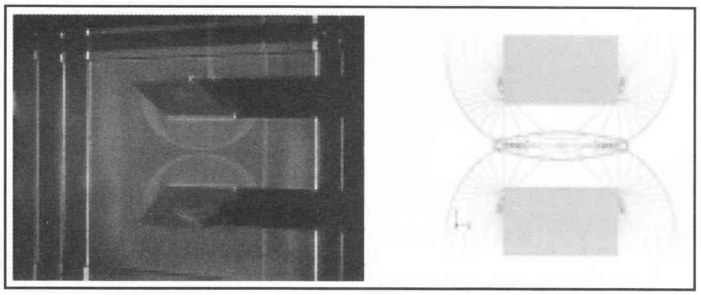


Figure 7: Close up view of the shadow region on the LVS images of the 20° wedge



(a) LVS image

(b) Numerical simulation, Mach number contours

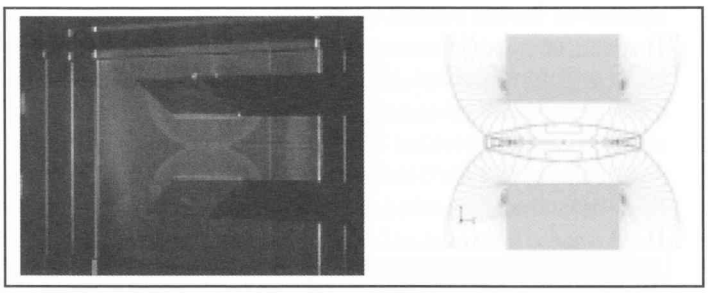
Figure 8: Shock structure at 32mm from the leading edge of the model (AR = 0.75)

Laser Vapour Screen

The LVS method of flow visualisation was first employed in 1951 in the National Advisory Committee on Aeronautics (NACA) 1 x 3ft supersonic wind tunnel at the Ames Aeronautical Laboratory to study the vorticial flows about slender inclined bodies of revolution at high angles of attack[2]. The method involved 'seeding' the flow in the wind tunnel with a small amount of liquid with a low latent heat of evaporation. The most commonly used seeding agent was water, but mixtures of alcohol and CCl_4 were also experimented with[6]. The water vapour present in the air in the tunnel condenses into a fog upon expansion through the supersonic converging-diverging nozzle, which leads to the test section of the supersonic tunnel. This fog is then illuminated by an intense sheet of light, and any disturbance in the flow field results in dark or brighter patches, which can be photographed. The method was used in the middle of the last century primarily to visualize vorticial flows[1,6]. Since these pioneering efforts, a number of researchers have utilised the technique to visualize shockwave interactions with great success[4,5,8]. Allen and Perkins[1] injected a small amount of water down stream of the converging diverging nozzle of the supersonic tunnel (Ames Aeronautical laboratory). The vaporisation was almost instantaneous and the temperature drop in the test section caused the moisture present in the air to condense out into a fog, which was illuminated by means of a light sheet generated from a mercury lamp. A similar technique was utilised by McGregor[6] to generate the LVS system of flow visualisation in the RAE (Royal Aeronautical Establishment) 3ft supersonic wind tunnel. McGregor[6] reasoned that a careful control on the humidity in the wind tunnel was required to produce the optimum fog in the test section of the wind tunnel. A procedure specific to the RAE, Bedford wind tunnel has been outlined by him. The water was introduced into the tunnel slightly upstream of the test section through static pressure tapings. The vaporisation was noticed to be instantaneous.

Humidity effects on the test section pressure and Mach number

McGregor[6] discovered that the degree of condensation was



(a) LVS image (b) Numerical simulation, Mach number contours

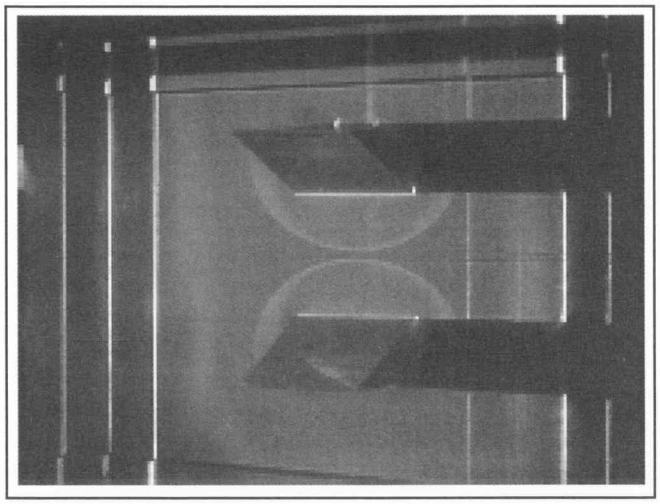
Figure 9: Shock structure at 34mm from the leading edge of the model (AR = 0.75)

not entirely dependent on the total pressure at which the tunnel was being run, but essentially on the amount on water present in the tunnel and not on the air/water mixture. The stagnation relative humidity is independent of the stagnation pressure, but is a function of the stagnation temperature and was found to be unsuitable for the purposes of analyzing the effect of humidity on the fog density. The frost point, which defines a unique relationship between the quantity of the water vapour and the volume of the tunnel, was found to be more appropriate as it is independent of the stagnation conditions. The optimum fog density was found by injecting measured quantities of water into the wind tunnel and photographing the resulting vapour screen. This detailed examination was only performed for Mach numbers of 1.51 and 1.81, while for other Mach numbers, the range of humidity over which a satisfactory screen was produced was examined visually[6]. The range of humidity required to produce a satisfactory fog is quite small; the humidity at which the fog density tends to be too thick is only some 20-30 % greater than at that which it tends to be too thin. Secondly there is a rapid increase in the humidity required at Mach numbers less than 1.5. The quantity of water required to saturate a given volume increases rapidly with temperature at low temperatures, and the working section temperature at the lower Mach numbers is sufficient to cause a large increase in the humidity required for saturated flow in the test section[6].

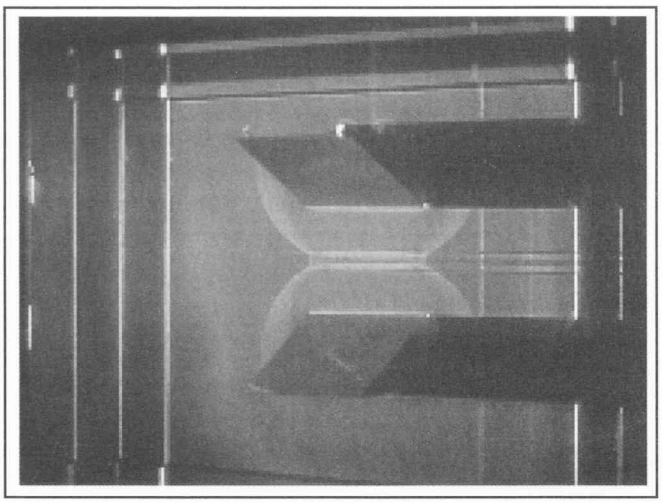
The humidity required reaches a maximum value at a Mach number of 1.6. It seems likely that all the water added to the tunnel is condensed out, so that if the fog is to be of constant density then the stagnation humidity must increase to allow for the greater expansion of the flow with increasing Mach number; ie, the amount of water added to the tunnel will vary inversely with the density in the test section[6].

Mechanism of condensation

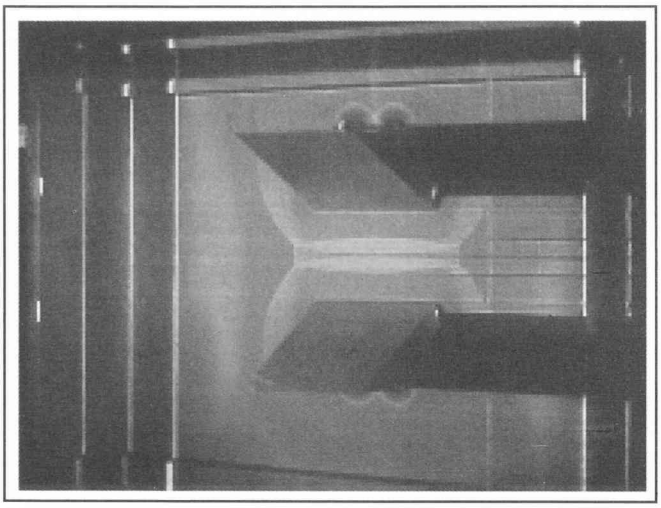
A saturated or supersaturated vapour will only condense if there are condensation nuclei present. These nuclei can be of two types — minute particles of dust or other foreign particles, and nuclei that are generated spontaneously in the vapour by random molecular aggregation. Nuclei of the former type are invariably present to a greater or lesser degree in all wind tunnels, whilst groups of molecules that are constantly forming in any vapour or gas are unstable and immediately break up again, so cannot form condensation nuclei unless the gas is heavily supersaturated. McGregor[6] has reasoned that for Mach numbers below 1.5 the condensation takes place on foreign nuclei, while at higher Mach numbers the condensation occurs by means of self-generating nuclei. In the case of higher Mach numbers, the number of nuclei per unit volume can reach astronomical figures and condensation can occur rapidly, leading to a condensation shock being formed[6]. It has to be emphasized that this was noted to be a factor in the LVS system implemented at the RAE Wind tunnel. McGregor[6] has concluded that in smaller tunnels a greater stagnation humidity will be required to produce a satisfactory vapour screen in the test section of the wind tunnel.



(A) 32 mm



(b) 36 mm



(c) 40 mm

Figure 10: LVS images of the flow field around the double wedge model at various distances from the leading edge of the model (AR = 0.75)

Use of LVS in visualizing three-dimensional flow fields

The work carried out by Allen and Perkins[1], Erickson and Inenaga[2] and McGregor[6] were limited to utilizing the LVS system to visualize the vortex flows over bodies at high angles of attack. The presence of the vortex region as a 'dark' patch in the image allowed for accurate visualisation of the presence and shape of the vorticial structures around such bodies. The LVS system can also be used extremely effectively in visualizing shockwave interactions in complex three-dimensional flows. Garrison et al.[4] utilised the LVS system successfully to visualize three intersecting oblique shockwaves interacting with a turbulent boundary layer. The system utilised was similar in nature to that used by Allen and Perkins[1] and McGregor[6], the only difference being that the light sheet was generated by passing a laser beam from a 4W Argon-Ion laser through a series of spherical and cylindrical lenses. The laser sheet was approximately 1mm thick as it entered the test section of the wind tunnel. Ivanov et al.[5] used a novel modification of the LVS system to photograph the interactions between the shockwaves coming off two finite span wedges placed a certain distance apart. The work was carried out in the 600mm x 600mm T-313 wind tunnel at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences at a Mach number of 4. The laser sheet was oriented streamwise to the flow in the test section by means of a narrow mirror placed upstream of the test section. The mirror could be rotated through an arc of 3.8°. Sudani et al.[8] used the LVS system to investigate the effects of three dimensionality and asymmetry on the transition to Mach reflection. The laser sheet was introduced perpendicular to the flow field and was used to obtain images of the flow field slightly behind the initial interaction between the shockwaves. Sudani et al.[8] concluded that the presence of the condensation in the wind tunnel promoted transition to Mach reflection.

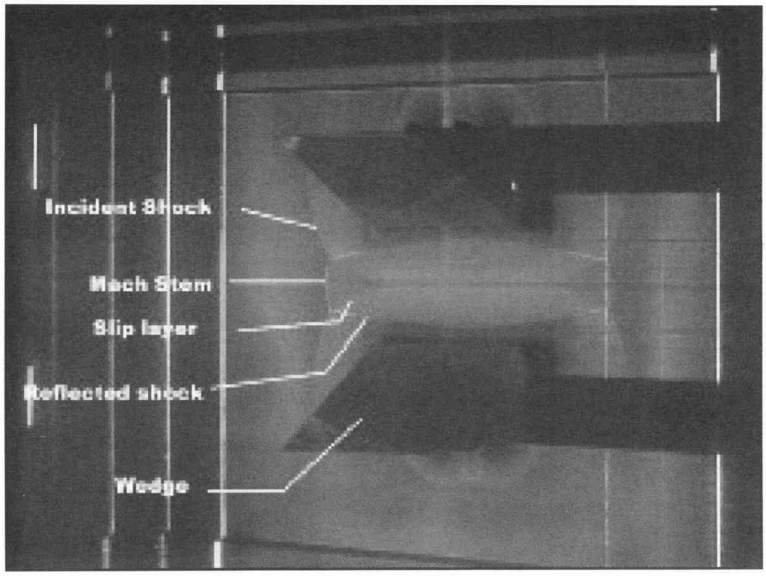


Figure 11: Figure 11: Explanation of the different features in the LVS image for the double wedge model (AR = 0.75)

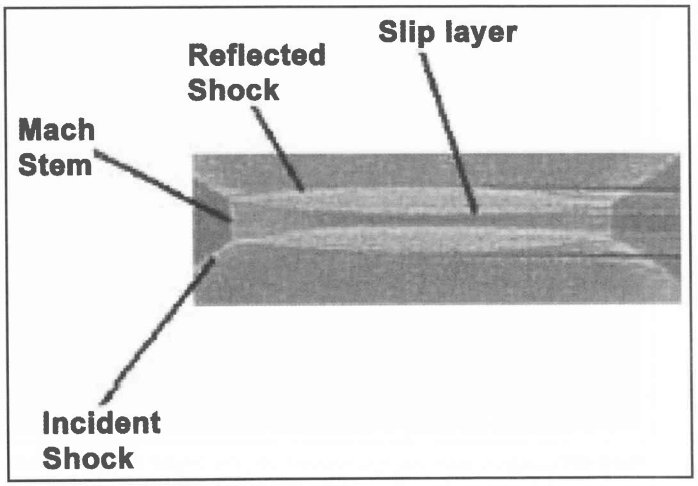


Figure 12: Figure 12: Close up of the reflection flow field at 34mm from the leading edge of the model (AR = 0.75)

2. Experimental Apparatus

The facility used for setting up the Laser Vapour Screen method of flow visualization was the 4" x 4" supersonic wind tunnel in the Mechanical Engineering Laboratory, at the University of the Witwatersrand, Johannesburg. The tunnel is a blow down type and can achieve Mach numbers in the range of 1.5 to 3.5. The tunnel is fitted with a sliding block first throat, which gives the tunnel a step-less change in Mach number from 1.5 to 3.5. The adjustment is achieved by a set of two blocks, an upper block, which is fixed to the tunnel, and a sliding lower block. The test section is 4" or 101.6mm square. A digital camera was used to capture the still images and short video clips for the project. The images in this paper were captured at 1200 x 780 pixel resolution. The laser beam emerging from an Argon-Ion laser was turned through an angle of 90° (using a 45° angled mirror) such that it was perpendicular to the walls of the tunnel test section windows. The laser beam was then passed through a series of cylindrical lenses that fanned the laser beam into a sheet of constant thickness at the wind tunnel test section. The optics for generating the laser sheet was placed on a specially constructed optical table, which was capable of traversing the sheet along the length of the test section allowing for the slicing of the flow field in the experiments. The schematic for the setup is shown in Fig. 5.

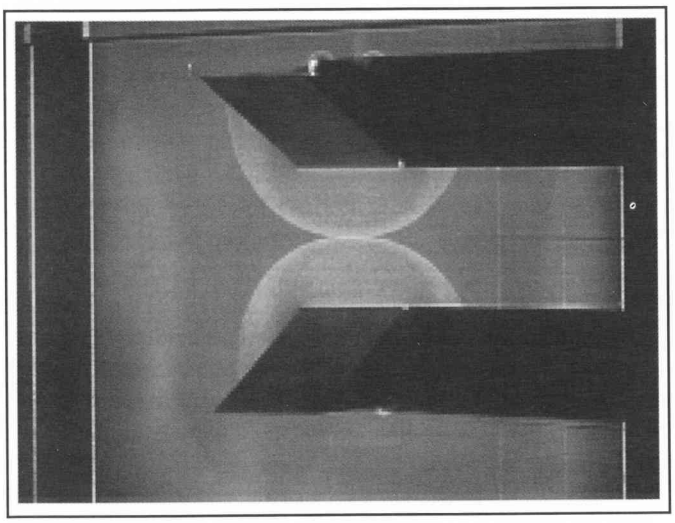
The settling chamber of the wind tunnel was seeded with a fine spray of water through a spray nozzle. The spray nozzle delivered water droplets at an average diameter of 50 μm into the settling chamber

Three models were tested in the supersonic wind tunnel. A single 20° wedge and two double wedge models. The wedges had a flow deflection angle of 27°, and the aspect ratios of the wedges were 0.5 and 0.75 (wedge span/wedge length). Only the double wedge results will be discussed in this paper. Numerical simulation of the flow field was performed using the commercially available CFD code Fluent 6.1.22. The simulations were performed as inviscid simulations. Two symmetry planes were used to reduce the size of the computational domain. The flow direction is orthogonal to the page for all of the numerical images presented in this paper.

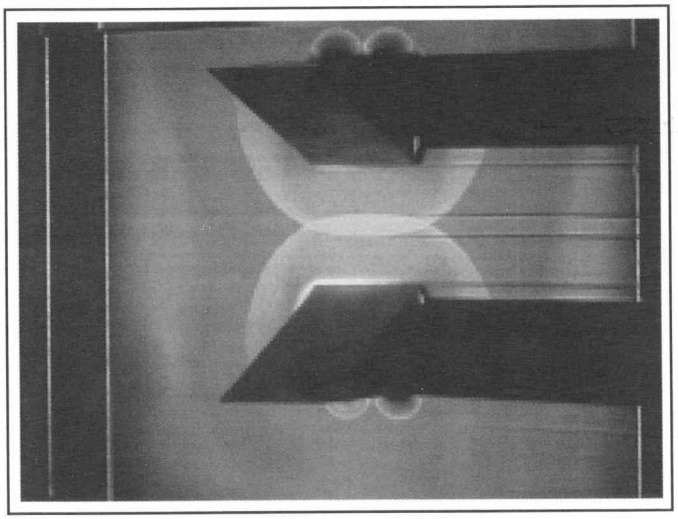
3. Results and discussion

The major aim of the project was to develop the system to visualize three-dimensional compressible flow fields in the supersonic wind tunnel. The seeding of the flow to generate an appropriate amount of condensation in the tunnel test section was the major problem encountered during the project. The spray nozzle chosen to seed the settling chamber with

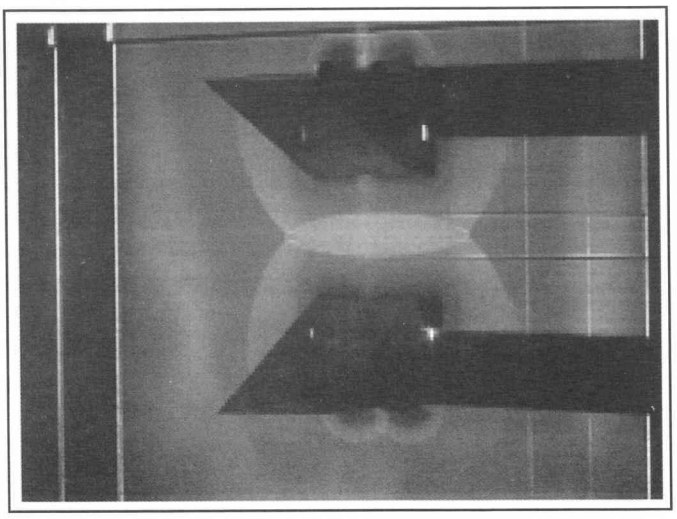
water particles has been identified as being a critical component in the LVS system. The size of the water droplets being sprayed into the tunnel cannot be determined, but is assumed to be on average 50 μm in diameter as suggested by the manufacturer. The initial design of the setup did not take into account the possibility of the nozzle getting blocked. When this did inadvertently occur, due to sediments in the water supply, the measures taken to clear the nozzle led to its damage. A more detailed explanation of this can be found in Hood[3]. Subsequent changes to the design such as feeding water into the settling chamber using a modified venturi system (Hood[3]) also proved to be unsuccessful. This system tended to seed the settling chamber with too much water resulting in either the formation of a condensation shock in the throat of the wind tunnel or the condensation pattern observed was streaky and inadequate for visualization purposes even if the tunnel was operating at the desired Mach number. The presence of the shock in the throat was inferred from the output of the test section pressure transducer. A new spray nozzle (of the original type) was hence installed. This proved to be the correct solution as the condensation in the tunnel was uniform and allowed for the images presented to be captured.



(a) 36 mm



(b) 40 mm



(c) 44 mm

Figure 13: LVS images of the flow field around the double wedge model at various distances from the leading edge of the model (AR = 0.5)

Perspective correction and salient features in the images

The images shown in the following figures are the raw images captured during the tests. The orientation of the camera to the image plane caused perspective distortions. There are also a number of prominent features present in the images that are a result of the laser sheet entering the test section, rather than from the flow field itself. A sample image of a 20° wedge in a Mach 2.93 free stream is provided to highlight the differences and provide an explanation of the various extraneous features present in the LVS images.

The most striking feature of all the images obtained for the models tested in the wind tunnel is the amount of detail and the contrast present in the image. Certain features have been noted to be common to all the images captured in the wind tunnel tests. The series of vertical lines present in the 20° wedge images (Fig. 6) are a result of the reflection of the laser sheet from the inner and outer walls of the tunnel far side test section window. The fainter lines to the right of the model are due to the reflection of the laser sheet from the near side test section window. The bright vertical lines that can be noticed on the extreme left of the image are due to the glare from the far side test section window (inner and outer surfaces) as the laser sheet enters the test section. Between the two bright vertical lines to the right of the model, there exists a third faint but visible vertical line. This is a reflection of the laser sheet from the test section windows but out of the plane of the laser sheet. Each image also contains two horizontal lines emanating from the bow shock as the laser sheet meets the shockwave along its most curved section. The laser sheet (see Fig. 7), finds the density gradients in the flow field acting in a manner such that the light sheet is unable to penetrate it (i.e. total internal reflection from the shock surface). This results in a shadow region directly behind it along the path of the laser sheet. These lines are not parallel in the raw images (Fig. 6(a)) and are used as guidelines for the perspective correction. In the corrected image (Fig 6(b)) these lines are parallel and the shape of the shock is more circular as is expected for a fully three-dimensional supersonic flow field over a finite wedge.

Effects on Mach number

From the images for the double wedge obtained experimentally (Fig. 8(a) and Fig. 9(a)) the reflection pattern first appears between 32 and 34mm from the leading edge of the double wedge model. The simulations performed for a Mach number of 2.93, (Figs. 8(b) and 9(b)) suggest that the reflection pattern first appears between 24 and 28mm from the leading edge of the

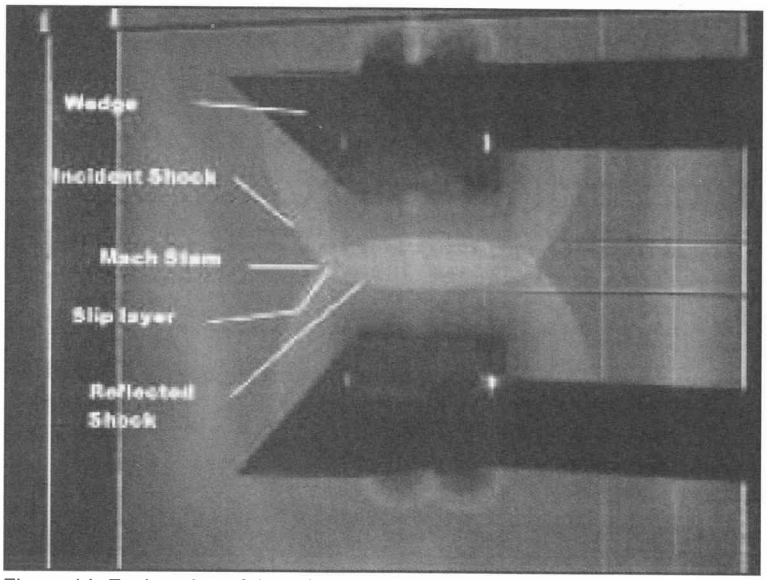


Figure 14: Explanation of the different features in the LVS image for the double wedge model (AR = 5)

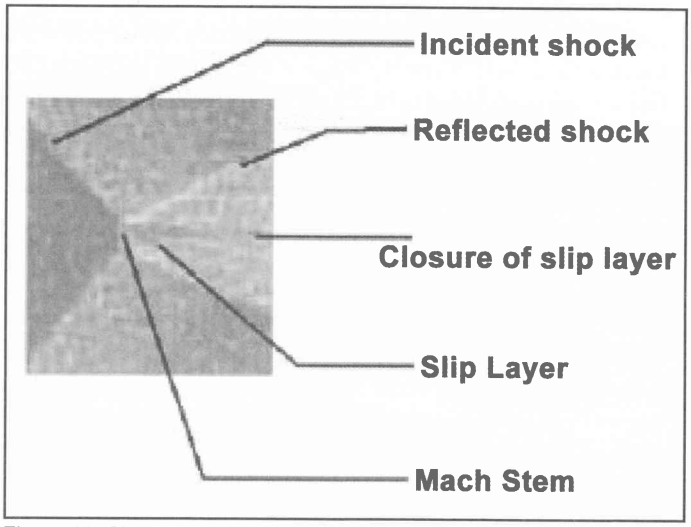


Figure 15: Close up section of the reflection flow field at 42mm from the leading edge of the model (AR = 0.5)

double wedge model. This seems to suggest that the shock angle on the experimental model is lower than that in the simulation (as the spacing between the wedges is the same for the experiment and the simulation), suggesting a higher experimental Mach number. McGregor[6], however, working under the assumption that a condensation shock was present in the nozzle leading to the test section, worked out that the test section Mach number would be lower than that for 'dry' conditions. The assumption of the formation of a condensation shock does not seem to be appropriate for the work undertaken in the current project. The presence of a condensation shock upstream of the test section would result in subsonic flow through the test section of the wind tunnel.

The presence of the boundary layer in the tunnel has an effect on the tunnel test section Mach number. If operating under 'dry' conditions' (i.e. no seeding of water), the displacement thickness of the boundary layer on the roof and the floor of the wind tunnel will cause the apparent angle of the model to seem higher relative to the free stream flow than it actually is, resulting in a smaller shock angle on the model for the same Mach number.

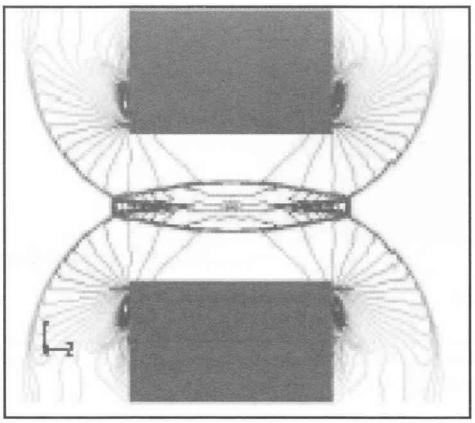
The water sprayed into the settling chamber evaporates in the settling chamber before it reaches the entrance of the nozzle. As it expands through the nozzle into the test section the vapour then condenses out into a fog. The local static temperature from isentropic relations would be 2.71 (at a Mach number of 2.93, according to the throat counter setting) times lower than the temperature in the settling chamber, which is assumed to be the same as the local temperature. The average temperature during the tests was approximately 25° C (298.15 K). Thus according to isentropic relations the temperature in the test section would be 109.73 K (-163.41° C). The change of phase, occurring as the water droplets evaporate in the settling chamber, would remove latent heat from the air in the settling chamber hence dropping the local test section temperature further as the flow expands isentropically. This would result in a lower sonic speed and hence a higher Mach number for the same free stream velocity. The value of γ is no longer 1.4 as the humidity of the air is increased due to the seeding of the settling chamber of air with water. This is still only a hypothesis on what might be occurring experimentally in the test section. It is the author's belief that both the boundary layer and the seeding of the flow with water have a combined effect on the apparent Mach number in the test section. This is very probably the reason why the numerical images suggest the various shock interactions to be occurring earlier than the corresponding experimental images obtained from the LVS system in the wind tunnel. Other workers examining supersonic flows all appear to have assumed that there is no effect on the test section Mach number. The numerical analysis was performed for all of the test cases at an assumed Mach number of 2.93. This has now proved to be questionable, and hence the numerical results are only qualitatively similar to the experimental LVS images obtained from the wind tunnel. Work is currently being carried out to calibrate the wind tunnel for various Mach numbers (according to the throat counter) and seeding rates.

Formation of the vapour screen image

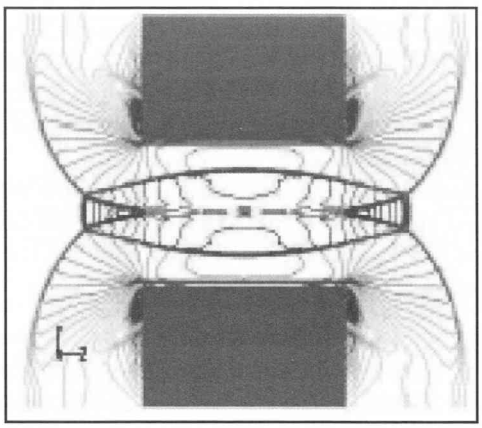
The shockwaves in the images taken for all of the models are rendered visible due to the change of density across them. McGregor[6] suggests that at Mach numbers above 2, the condensation is complete and the number of particles (condensed water droplets) will be directly proportional to the local air density. On passing through the shockwave the air undergoes a rapid deceleration, which the fog particles cannot follow owing to their higher inertia. A relative velocity hence exists between the fog particle and the local free stream. This will be quickly reduced to zero due to the action of viscosity and due to the very small particle size. A short distance after passing through the shock steady state conditions will be achieved, and the fog density will once again be proportional to the local air density. At the shock there is an increase in density and the vapour screen appears lighter due to the larger concentration of fog particles. The position of the shock is hence at the boundary between the lighter and the darker regions.

Shock structure between the double wedges

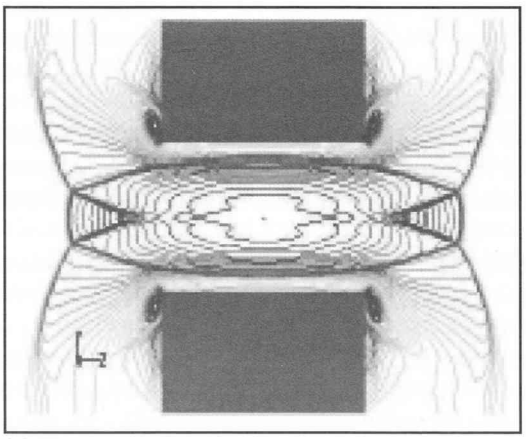
The shape and structure of the shockwaves and their interactions between two wedges of finite span is well documented. The LVS system however allows for the structure to be analyzed in much greater detail and much more simply than traditional density based visualisation techniques. The LVS images of the



(a) 32 mm



(b) 36 mm



(c) 40 mm

Figure 16: Mach number contours of the flow field around the double wedge model at various distances from the leading edge of the model (AR = 0.75)

flow field around the double wedge model (AR = 0.75) were spaced at streamwise distances of 4mm until the interactions between the incident shockwaves was first witnessed. The reflection of the incident waves is irregular from the outset. A finite span Mach stem can be seen in the LVS image taken at 36mm from the leading edge of the model (Fig. 10(b)). The

Mach stem can be seen to grow in width and develops a prominent outward bulge as it grows larger downstream of the model. The features that are prominent in these interactions are explained in Fig. 11. Fig. 12 shows a close up section of the flow field. The usefulness of the LVS system is apparent in that detailed information of the shock structure in three-dimensional flow fields can be easily obtained at any plane in the flow field. A regular reflection pattern is observed when the wedge width is reduced (Aspect ratio = 0.5).

The shockwaves from the narrower wedges undergo regular reflection at the centerline, which develops into a peripheral Mach stem as the sections further downstream are viewed (Figs. 13(a) to 13(c)). This corresponds to the hypothesis put forward by Sudani et al.[8] that a wider region of the flow field is influenced by the model three-dimensionality, especially for lower aspect ratio models. For a free stream Mach number of 2.93 over a wedge of 27°, two-dimensional theory suggests the interaction to be in the Mach reflection domain. The effect of the three-dimensionality is hence to promote regular reflection between the incident shockwaves.

Considering an enlarged view of the flow field (Fig. 15) around the interaction point 42mm from the leading edge of the model (AR = 0.5), the salient features visible are again the incident shock, the reflected shock, the slip layer, and a small Mach stem. The slip layers seem to close up toward the center of the image and disappear. It is more likely that the combined slip layers from the two triple points have merged into a shear layer having a finite thickness.

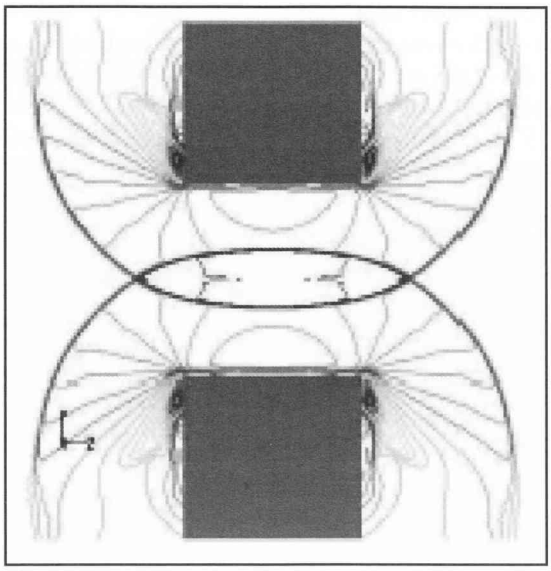
The CFD prediction of the interactions is qualitatively similar to the experimental results. An exact correlation to the experiment was not observed, as the Mach number of the experimental flow was most likely higher than expected, as mentioned earlier in this paper. The numerical result does not show two distinct shear layers for the AR = 0.75 model. The shear layers from the Mach reflection have been resolved quite clearly from the start of the Mach stem, but seem to merge into a finite thickness shear layer toward the center (Fig. 16(a) to 16(c)). The numerical prediction of the flow field around the AR = 0.5 model is also similar in nature to the experimental images although not exact. This is also as a result of the Mach number discrepancy discussed earlier. The reflection pattern around the AR = 0.5 model is definitely regular in nature, with the formation of a Mach stem being visible at 36mm from the leading edge of the model (Fig. 17(a) to 17(c)).

Fig. 18 shows a close up of the shockwave interaction between the screws holding the wedge onto its sting. An image such as this only serves to emphasize the phenomenal ability provided by the LVS system to understand complex three-dimensional flow fields. The screws are cap head screws and hence have a depression on the head. The screw acts as a cylinder in a supersonic free stream and hence the incident shock will be detached from the screw. As the flow passes over the top of the screw the presence of the depression on the head of the screw causes the flow to expand into the depression. The expansion fan generated by this can be seen in Fig. 18 as dark patches marked by points A and A'. The bow shocks from the screws undergo Mach reflection at their point of intersection.

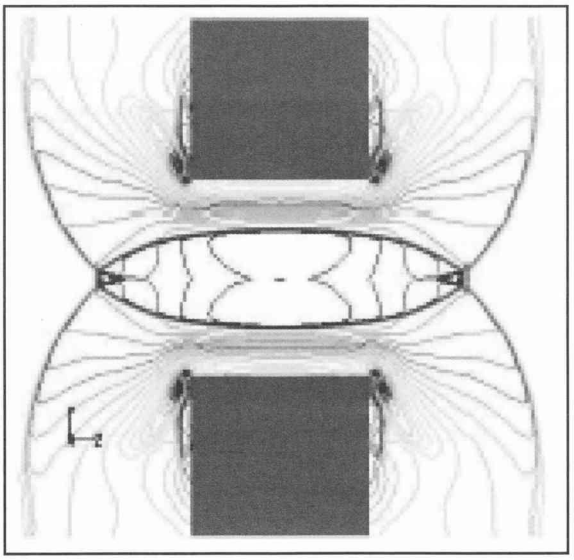
4. Conclusions

The following conclusions could be drawn from the work performed for this project:

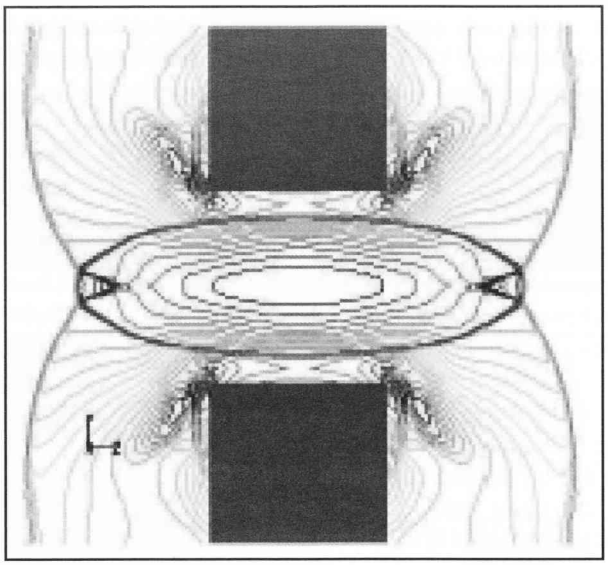
- The Laser Vapour Screen (LVS) system has been designed and implemented in the supersonic wind tunnel at the School of Mechanical, Industrial and Aeronautical Engineering.
- The shock structure around a double wedge model in a Mach 2.93 free stream has been visualized using the LVS system in the supersonic wind tunnel. A three-dimensional model of the flow field has been developed from the LVS images. The LVS slices



(a) 36 mm



(b) 40 mm



(c) 44 mm

Figure 17: Mach number contours of the flow field around the double wedge model at various distances from the leading edge of the model (AR = 0.5)

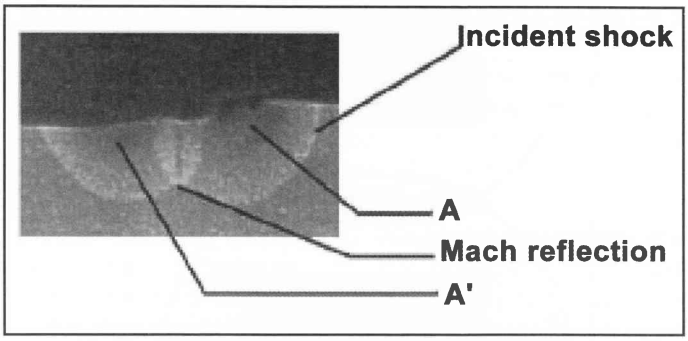


Figure 18: Close-up section of the flow field around the screws holding the wedge onto the sting

accurately allow for quantitative information to be established on the behavior of the shear layers, which has not been done to date. three-dimensional effects influence a greater region of the flow field between the wedges in the lower aspect ratio wedges, promoting regular reflection. This result confirms the observation made by Sudani et al.[8].

❑ It has been noticed that the seeding of the flow with water has an effect on the free stream Mach number. The calibration of the wind tunnel for different seeding rates and test section Mach numbers is being performed.

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