

WEAK SHOCK WAVE REFLECTIONS FROM CONCAVE CURVED SURFACES

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DECLARATION

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

Signed this ____ day of _____ 20__

Sebastien Gruber.

ABSTRACT

The reflection of very weak shock waves from concave curved surfaces has not been well documented in the past and recent studies have shown the possible existence of a variation in the reflection configuration evolution as a very weak shock wave encounters an increasing gradient on the reflecting surface. The current study set out to investigate this anomaly using high resolution photography and numerical simulations. Shock tube tests were done on various concave circular and parabolic geometries, all with zero initial ramp angle. Unlike for the stronger shock wave case, the results showed that for very weak Mach numbers, $M_s < 1.1$, there is a region in which the reflection configuration resembles that of a regular reflection. This region exists after the triple point of the Mach reflection meets the reflecting surface and prior to the formation of the additional shock structures that represent a transitioned regular reflection. The Mach and transitioned regular reflections at $1.03 < M_s < 1.05$ also exhibited no signs of a shear layer, possibly due to the lack of a clear discontinuity at the triple point.

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LIST OF SYMBOLS AND ABBREVIATIONS

RR	Regular reflection
MR	Mach reflection
InMR	Inverse Mach reflection
StMR	Stationary Mach reflection
DiMR	Direct Mach reflection
TRR	Transitioned regular reflection
M	Mach number
M_s	Incident shock wave Mach number
U_{gas}	Gas velocity
U_{shock}	Shock velocity
P	Pressure
ρ	Density
T	Temperature
A	Area
c	Sonic velocity
γ	Specific heat ratio for a gas
θ_w^{tr}	Wall angle at MR-TRR transition
θ_w	Wall angle
χ^{tr}	Triple point trajectory angle

1 INTRODUCTION

The purpose of this section is to introduce the topic being studied in this dissertation. It starts with a brief background to shock wave reflection and weak shock waves to provide context for the reason this study was pursued. The propagation of shock waves in gases is then explained in more detail, and the equations that govern this field derived. An overview of the phenomenon of shock wave reflection is covered, starting with the different types of reflections and then going into detail on the evolution of the reflection configurations that are found when a transient shock wave encounters a curved reflecting surface of increasing gradient. Much of the material introduced in this section is common knowledge in the field of shock wave research, except where specifically referenced, and can be found in more detail in (Krehl, 2001), (Henderson, 2001) and (Ben-Dor, 2007).

1.1 Background and Motivation

The reflection of shockwaves has been well documented since its discovery by Ernst Mach in 1878. Early analytical and empirical work focused primarily on characterising the reflection of very strong shock waves which, in this investigation, we shall deem to be those with a Mach number far greater than 1.1. This focus on strong shock waves, which is a linear system up to the point that the flow becomes hypersonic, has been strongly motivated by its relevance to the aerodynamics of supersonic aircraft and ballistics. Using schlieren methods, it is easy to visualise such interactions, and today there is a wealth of understanding on the topic. Using very different methods of study, the reflection characteristics of acoustic waves (shock waves which travel at Mach 1, the local speed of sound) have been extensively analysed, and found to be consistently regular when meeting a reflecting surface obliquely.

Weak shock waves, which we shall define here as those having a Mach number of less than 1.1, have received far less attention in terms of research. This may be in part due to the fine pressure gradients that characterise weak shock waves requiring highly sensitive imaging systems. At the acoustic limit the reflection is always regular, and it has been assumed that any shock with a Mach number greater than one will have the possibility of reflecting irregularly and should be predicted by the current two-shock and three-shock theories. First indications that there was some deviation from these theories for the case of weak incident shock waves came in the form of the von Neumann paradox.

Advances in computing power and the subsequent development of advanced numerical methods for shock wave study as well as the advent of high resolution digital photography has allowed further investigation into flow regimes that were previously limited to empirical methods. New and emerging applications of shock wave research outside the fields of aerodynamics and ballistics has further motivated new interest into the study of weak shock waves. This study aims to improve on the understanding of weak shock wave reflection dynamics, specifically for the unsteady case of a propagating shock wave moving along a reflecting surface of continuously increasing gradient.

1.2 Propagation of Shock Waves in Gases

A shock wave can be described as a disturbance propagating through matter caused by a sudden compression of particles (Krehl, 2001). Most people have experienced a shock wave as a loud bang, such as that coming from the firing of a weapon, or as a moving shock front - seen on video footage of large explosions. The individual particles of the fluid in which the shock wave is passing are forced closer to one another in the vicinity of the shock wave, creating a discontinuity, shown as the darker particles in Figure 1.1, through which the velocity, density, pressure and temperature of the medium change.

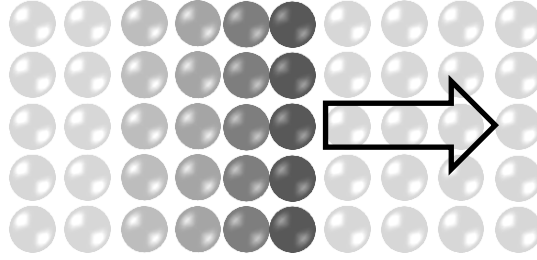


Figure 1.1: Illustration of uniformly distributed fluid particles being compressed by the passing of a shock wave

The shock wave can either be stationary, such as the shock wave produced on an aircraft that is moving supersonically relative to the air around it, or can be propagating through a medium, like that produced from a large explosion. To study a propagating shock wave in the laboratory, a disturbance is introduced into the fluid being studied. This is typically done using a shock tube and although a variety of methods are employed to create this disturbance, let us consider the simple case of a shock wave produced from a piston suddenly pushing a compressible gas within an enclosed space as shown in Figure 1.2. This derivation has been adapted from (Skews, 2007).

The force of the piston will push the gas in front of it at a finite velocity U_{gas} , producing a disturbance, or shock wave, which will move into the gas at a finite velocity of U_{shock} . Due to the compressibility of the gas, U_{shock} will not be the same as U_{gas} . The gas ahead of the shock wave remains stationary.

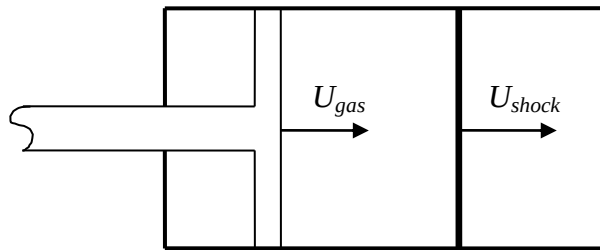


Figure 1.2: Illustration of a propagating shock wave with velocity U_{shock} moving ahead of gas displaced by a piston moving into an enclosed space with velocity U_{gas}

By considering the shock wave in this manner, we are using a laboratory-frame coordinate system where we see the shock wave as a propagating disturbance. In this coordinate system, classifying P_{gas} as the pressure of the gas in the region between the piston and the shock wave, and P_o and ρ_o as the pressure and density of the gas in the undisturbed region ahead of the shock wave, we can apply the conservation of momentum equation to obtain:

$$P_{gas} - P_o = \rho_o U_{shock} U_{gas} \quad (1)$$

The properties within a control volume defined with this coordinate system vary with time, resulting in an unsteady analysis. It is also often difficult to determine the velocity of the gas behind the shock wave, so we instead change to a shock-fixed coordinate system by defining a control volume around the moving shock wave which allows a steady analysis to be applied. As Figure 1.3 shows, we define a control volume which moves at the same velocity of the shock wave, U_{shock} . For simplicity, we now redefine the region of gas ahead of the shock wave as *region 1* and that behind the shock wave as *region 2*.

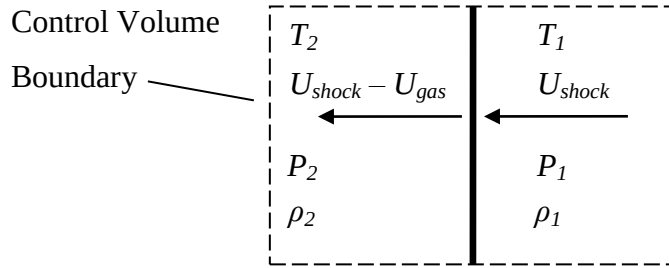


Figure 1.3: Illustration of a shock-fixed control volume where the shock sees the oncoming gas approaching at velocity U_{shock}

The shock wave now sees the gas in *region 1* coming toward it at velocity U_{shock} with temperature, pressure and density of T_1 , P_1 and ρ_1 respectively. Applying the continuity equation ($\rho_1 U_1 = \rho_2 U_2$) to this control volume, we obtain:

$$\rho_1 U_{shock} = \rho_2 (U_{shock} - U_{gas}) \quad (2)$$

The conservation of momentum equation ($P_1 + \rho_1 U_1^2 = P_2 + \rho_2 U_2^2$) can also be applied to the control volume and neglecting the effect of friction with the walls of the shock tube, this gives:

$$P_1 + \rho_1 (U_{shock})^2 = P_2 + \rho_2 (U_{shock} - U_{gas})^2 \quad (3)$$

Re-organising equation (2) to make $(U_{shock} - U_{gas})$ the subject of the formula, and substituting it into the conservation of momentum equation above allows us to eliminate U_{gas} . We can then re-organise equation (3) to get an expression that describes the shock wave velocity in terms of only the pressure and density changes across the shock wave, as shown in equation (4).

$$U_{shock}^2 = \left(\frac{\rho_2}{\rho_1} \right) \left(\frac{P_2 - P_1}{\rho_2 - \rho_1} \right) \quad (4)$$

While the density of the gas ahead of the shock wave is easily calculated by measuring the gas temperature in the shock tube, the density of the air immediately behind it is far more difficult to obtain, so it is desirable to remove it from the above expression. To do this, we assume the gas is an ideal gas and invoke the fact that for a sufficiently large shock tube such as that used for this research, where wall friction and heat transfer is negligible, the shock wave can be seen as an adiabatic process. Hence:

$$\frac{\rho_2}{\rho_1} = \left(\frac{P_2}{P_1} \right)^{\frac{1}{\gamma}} \quad (5)$$

where γ is the specific heat ratio for the gas, which for dry air (the gas used in this study) is 1.4 at a room temperature of 20 °C. Reorganising equation (5) and substituting it into equation (4) gives an expression to calculate the velocity of the shock wave in terms of only the pressure ratio across it and the thermodynamic state of the gas.

$$U_{shock} = \sqrt{\frac{1}{2\rho_1} (P_2(\gamma + 1) + P_1(\gamma - 1))} \quad (6)$$

The Mach number, M , can now be defined as the ratio of the fluid velocity to the local sonic velocity. The sonic velocity, c , of a compressible gas is independent of density and can be obtained using:

$$c = \sqrt{\gamma RT} \quad (7)$$

where R is the specific gas constant (which for dry air is 287.05 J/(kg·K)) and T is the absolute temperature of the gas in Kelvin. Thus, the Mach number of the shock wave is defined as:

$$M = \frac{U_{shock}}{c} \quad (8)$$

The propagation velocity of the shock wave moving down the shock tube can be calculated in two ways. The first uses equation (6), whereby the pressure change across the shock wave is obtained using a single calibrated pressure transducer placed into the wall of the shock tube. Then ρ_1 is obtained by measuring the temperature of the gas in the tube and, knowing the pressure, implementing the perfect gas law. In this case, the shock wave velocity is highly reliant on the calibration of the transducer, therefore a method involving two transducers placed a known distance apart is also used to obtain the shock wave velocity. In this method, the time difference between the shock wave triggering each transducer as it propagates down the tube is measured. The distance between the transducers is then divided by the time difference to obtain the shock wave velocity which can then be substituted into equation (8).

1.3 Shock Wave Reflection

If a shock wave encounters an obstacle obliquely, it will reflect off it. This obstacle can be any medium with a density different to that of the fluid in which the shock

wave is travelling. Because at supersonic speeds, the flow has no way of communicating upstream the state change caused by the obstacle, the structures of a shock wave reflection serve the purpose of correcting the flow once it encounters the obstacle. Unlike light reflecting from an oblique surface, the reflection of a shock wave can be more complex than just a regular reflection (RR).

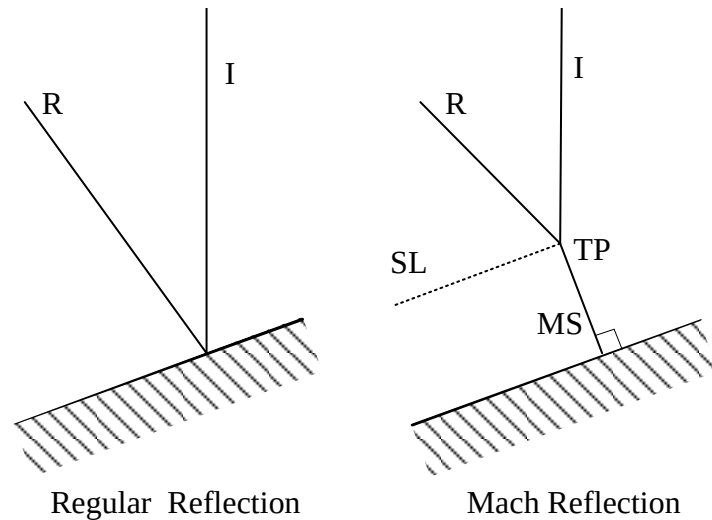


Figure 1.4: Schematic illustration of the two shock structure of a regular reflection (left) and the three shock structure of a Mach reflection (right)

Shown in Figure 1.4, the RR is made up of two shock waves - the incident shock wave (I) and reflected shock wave (R) which meet at the reflecting surface. Ernst Mach was the first to identify a second type of reflection made up of three shock waves, and this type of reflection was subsequently named after him - the Mach reflection (MR). In the case of a MR, the reflected shock wave (R) meets the incident shock wave (I) not at the surface, but rather at a discontinuity on the incident shock wave known as a triple point (TP). From the triple point, a third shock wave – the Mach stem (MS) – extends down to the reflecting surface and meets it perpendicularly. All three shock waves are plane when they meet at the triple point (von Neumann, 1963). A slipstream (SL) also extends back from the triple point because of the difference in velocities between the flow that has passed through the

Mach stem only and that which has passed through both the incident shock wave and the reflected shock wave. The SL also gives an indication of the trajectory of the TP in non-steady flows.

Further studies have found that under varying flow conditions, different configurations of the MR can exist. The simple structure of the MR shown in Figure 1.4 was further broken down into direct (DiMR), stationary (StMR) and inverse (InMR) Mach reflections, depending on the angle that the slipstream makes with the reflecting surface. The case of the tail of the SL pointing toward the reflecting surface is termed a DiMR, and in a non-steady flow, indicates that the TP is moving away from the reflecting surface with time. A StMR has the SL parallel to the reflecting surface. An InMR describes the case where the tail of the SL points away from the reflecting surface, indicating a TP which is converging on the reflecting surface.

Depending on the initial conditions when the reflection forms, further shock wave configurations are possible, and thus far a total of 13 different shock wave reflections configurations have been identified by (Ben-Dor, 2007) as shown in Figure 1.5. Most of these reflection configurations are not relevant to this study, and have been subsequently greyed out but the unique case of the von Neumann reflection (vNR) is discussed further in Section 2.2 as part of the research that has been done into weak shock wave reflections.

When a propagating shock wave encounters a flat reflecting surface obliquely, it is considered to be a pseudosteady flow since the geometry does not change with time. The reflection of the incident shock wave off the reflecting surface will change over time as the incident shock wave moves along it. The flow equations can be applied to the shock wave reflection at a particular point in time and position, and because the incident shock wave is always meeting the reflecting surface at the same angle, the changes in the reflection configuration as it travels can be considered to be self-

similar and dependant only on the initial conditions at which the incident shock wave first encounters the reflecting surface.

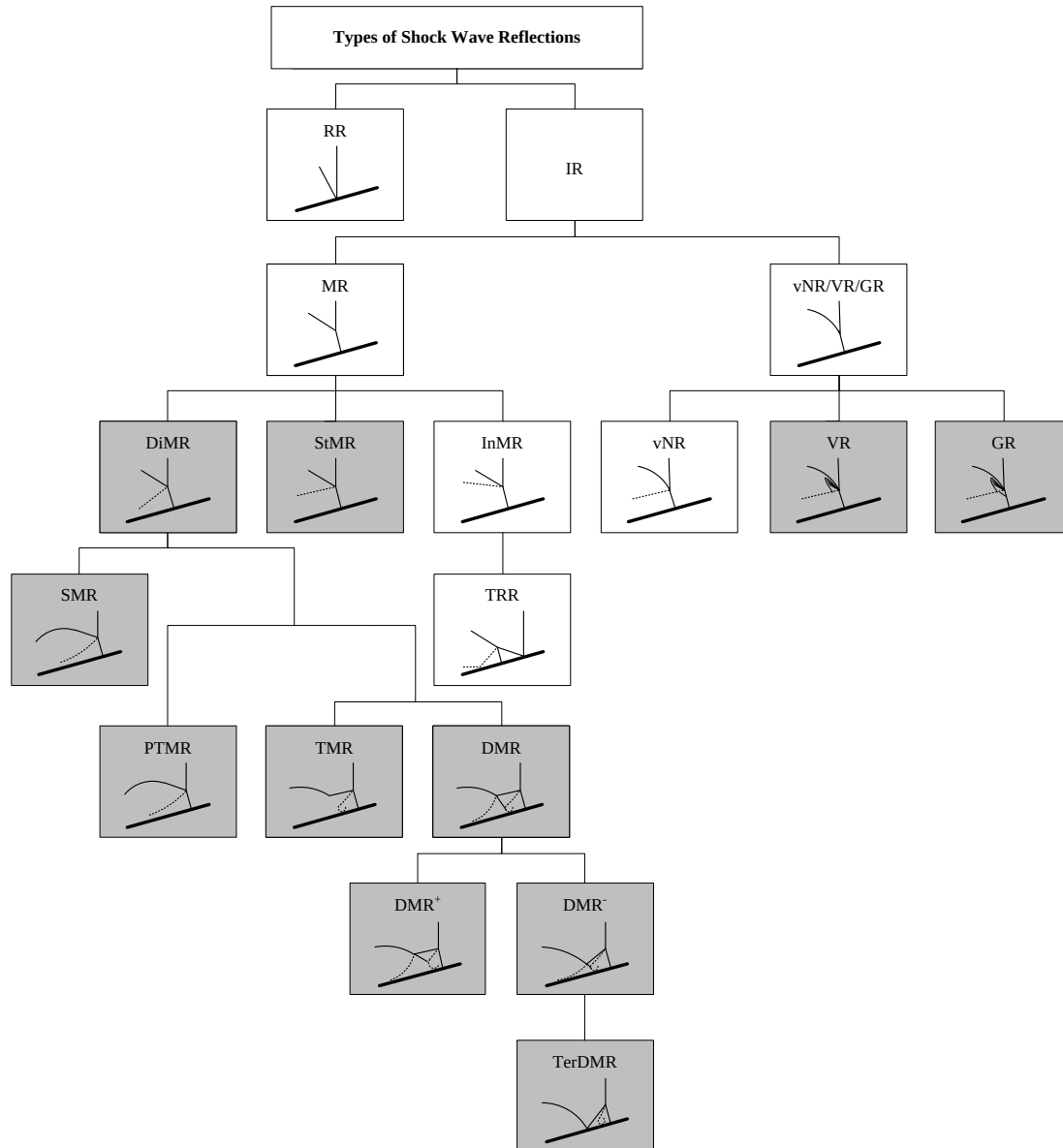


Figure 1.5: The possible shock wave reflection configurations that have been identified (adapted from (Ben-Dor, 2007)) with those not pertinent to this study highlighted in grey

For the case of a propagating shock wave moving along a curved surface, the fluid that is close to the reflecting surface meets the incident shock wave at a continually

varying angle and is thus considered an unsteady flow. Oblique shock equations can only be applied to a known reflection configuration at a particular point in time. To analytically predict the flow through the shockwave, the oblique shock equations need to be calculated for each previous time instant, which makes analysis of unsteady flows a prime candidate for computerised numerical analysis. Empirical studies have however been done to describe the reflection configurations that are created in many unsteady flows.

The initial reflection is determined by the attributes of the flow behind the reflected shock wave of the initial reflection. These attributes are determined by both the initial wedge angle, θ_w , at which the shock wave meets the surface and the Mach number of the incident shock wave. Considering the reflection configuration defined in Figure 1.5, (Ben-Dor, 2007) explains that if the flow behind the reflected shock wave is subsonic, then the reflection configuration will start out as a SMR. Should the initial θ_w or M_s or combination of the two be great enough such that the flow behind the reflected shock wave is supersonic, then the reflection configuration may start out initially as a DMR, TMR or RR. Should the initial reflection be irregular, the triple point will eventually converge onto the reflecting surface as the incident shock wave progress along the concave curvature, and will transition to a RR.

Should the initial wedge angle be approximately zero, i.e. a case of glancing incidence, then there will initially be no reflection at all. This case is discussed in detail in Section 2.2, but is summarised here. The flow at the surface will encounter the incident shock wave at an increasing angle as the gradient increases and the incident shock will curve in the vicinity of the reflecting surface to ensure, like the Mach stem of a MR, that its foot meets it perpendicularly. This curvature is due to strengthening of the incident shock wave at the surface caused by compression waves in the wake of the shock wave (Skews et al., 2008). As the gradient increases, the compression waves merge to form a shock wave which intersects the incident shock wave at its point of maximum curvature. This point subsequently becomes the triple

point of an InMR when a slipstream is produced from it. The InMR configuration remains until the triple point ultimately meets the reflecting surface, at which point it becomes regular.

To support the sudden pressure drop at the surface caused by the transition to regular reflection, an additional shock wave (S), as shown in Figure 1.6, is formed in the wake of the reflected shock wave (R) (Henderson and Lozzi, 1975)). The additional shock wave remains perpendicular to the reflecting surface and meets the new reflected shock wave as well as the original reflected shock wave that existed prior to transition (R^*) at a new triple point (TP), which produces a shear layer (SL) that meets the reflecting surface. These additional structures differentiate it from a regular reflection configuration and it is thus termed a transitioned regular reflection (TRR).

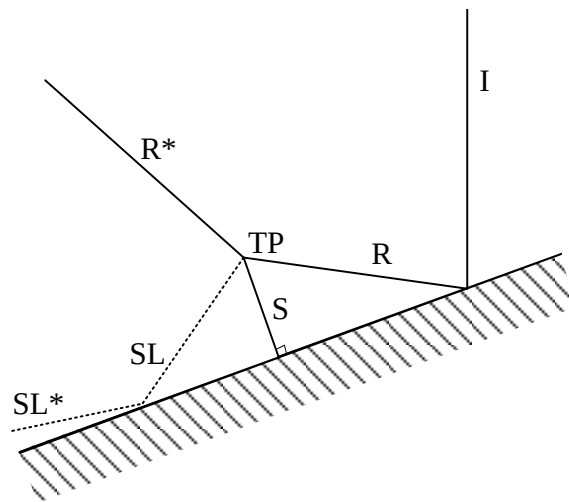


Figure 1.6: Schematic illustration of the multi shock wave structure that is identified as a transitioned regular reflection (TRR)

2 LITERATURE REVIEW

This section summarises the major studies that have been done into shock wave reflection in unsteady flows as well as studies that have been done into weak shock wave reflection specifically. This is the main body of existing research that is relevant to this current study.

2.1 Shock Wave Reflections over Curved Concave Surfaces

When a constant velocity shock wave encounters a surface that is curved, the angle of incidence of the oncoming flow to the incident shock wave close to the surface changes continuously, therefore the initial pattern of reflection is not only dependant on the incident Mach number, M_s , and the initial wedge angle, it can also change as it progresses along the curved surface. This flow regime is therefore considered unsteady, and has not been studied as extensively as the steady and pseudo-steady regimes. The main focus of research in this area has been on the transition of Mach reflection to a transitioned regular reflection as well as on shock wave focusing using concave cavities. Focusing involves study of the shock wave reflection at much steeper wall angles than required by this study, so most of the available literature reviewed here covers that which was done on the MR-TRR transition.

Some of the first studies into shock wave reflection off curved surfaces were done by (Henderson and Lozzi, 1975). In their study into MR – RR and RR – MR transition criteria, they observed the additional shock wave formed in the TRR, and hypothesised that its existence was to support the pressure drop caused by the sudden absence of the Mach stem (Ben-Dor, 2007). In a re-examination of the MR $\leftrightarrow$ RR transition criteria by (Ben-Dor, Takayama and Kawauchi, 1980), a concave cylindrical model with zero initial ramp angle was used to show the full transition of

the reflection from MR to RR. At this point, a TRR was still considered a RR with no specific name being given to the additional wave structure behind the RR.

(Takayama and Sasaki, 1983) then did research into the specific effect that the radius of curvature and initial wedge angle had on the MR-TRR transition. In this paper, the transition from MR to TRR is studied far more aggressively, and they suggest that as the initial triple point of the MR meets the wall, the flow behind it becomes supersonic, allowing a second shock wave to exist which meets at the secondary triple point on the reflected shock wave. This situation also implies that the disturbance from the leading edge (not necessarily a discontinuity, but rather the point at which curvature starts) of the concave wall can reach, at most, to this secondary shock which forms. The slipstream from the initial MR cannot be extinguished by the transition, and is instead transferred to the secondary triple point on the reflected shock. (Takayama and Sasaki, 1983) also conducted weak shock tests on the same cylindrical models, and the schlieren images at $M_s = 1.08$ on the 50mm and 160mm radius models showed that for the weaker case, the transition wedge angle, θ_w^{tr} , (the gradient of the wall at which MR-TRR transition takes place) was smaller than expected, and approached the detachment criterion.

However, for a cylindrical model of 300mm radius and $M_s = 1.05$, they found that the MR-TRR transition never appeared, but instead a RR remained from the leading edge of the model. Instead of seeing the second triple point of a TRR form, a kink appeared on the reflected shock in a situation similar to the generation of complex Mach reflection (CMR) in a truly non-stationary flow. From this, they concluded that as the radius of curvature of the wall grows, the wedge angle at which MR-TRR transition takes place becomes smaller, until it eventually reaches the detachment criterion for weak shock waves as proposed by (von Neumann, 1963).

(Takayama and Ben-Dor, 1986) followed on from (Takayama and Sasaki, 1983) by performing a detailed study of shock wave reflections along concave circular walls of

130mm radius and developed an approximate analytical prediction of θ_w^{tr} for a circular concave wall. This prediction (outlined below) was based on assumptions that the corner signal could reach at most to the point of transition and could not bypass the incident shock wave. The transition angles obtained by this analysis then showed good correlation with their experimentation. These assumptions also indicated that the point of transition occurred when the corner signal produced by the start of curvature met the triple point at the circular concave wall, and that the triple point followed a linear trajectory to the point of transition as shown in Figure 2.1.

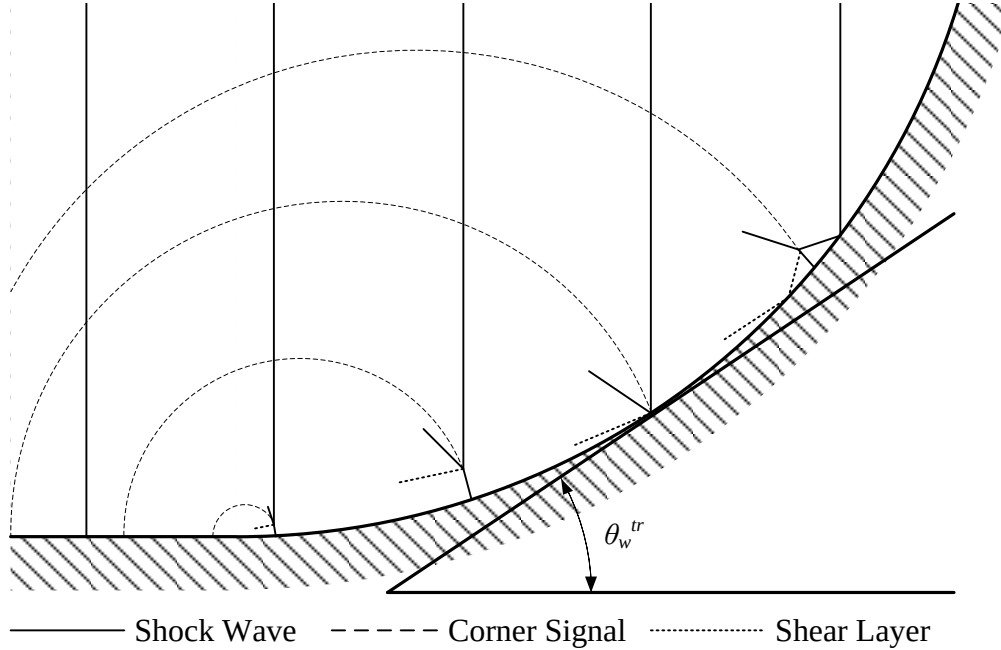


Figure 2.1: Evolution of the reflection of a propagating shock wave as it encounters a circular wall predicted by (Takayama and Sasaki, 1983)

Two different trajectories of the triple point were assumed, and these led to two different formulas for deriving the critical angle θ_w^{tr} at which transition from MR to TRR occurs. If the trajectory of the triple point is assumed to be along the reflecting surface, then Equation (9) is obtained:

$$\frac{\sin \theta_{trans}}{\theta_{trans}} = \frac{U_{shock}}{U_1 + c_1} \quad (9)$$

where U_1 and c_1 are the flow velocity and local sonic velocity, respectively, behind the incident shock wave. If, however, the trajectory of the triple point is assumed to be a straight line joining the leading edge and triple point, and the length of the Mach stem is assumed to be much shorter than the radius of curvature of the wall, then:

$$\cos \frac{\theta_{trans}}{2} = \frac{U_{shock}}{U_1 + c_1} \quad (10)$$

Though both these equations are independent of the radius of the cavity, Takayama and Ben-Dor's experiments also show that this has some influence on the actual transition point as found by (Takayama and Sasaki, 1983). The radius of curvature was later included in another analytical consideration suggested by (Ben-Dor and Takayama, 1986/7). However this analysis is incomplete, requiring further information on the shock wave reflection.

By adding very weak perturbation sources to the reflecting surface, (Skews and Kleine, 2009a) were able to study the behaviour of the flow behind the shock wave reflection. This is because as the incident shock wave moves over the perturbation source, a very weak disturbance is generated which propagates into the flow at sonic velocity – much like the corner signal produced from the start of curvature. Using time resolved photography to track the propagation of this weak shock wave, its influence on any particular part of the flow in the wake of the incident shock wave may then be determined. Using this technique, a variety of unsteady reflecting surfaces were studied and experimental results for $M_s = 1.33$ shock wave reflections off concave walls showed some differences with previously mentioned studies, which were then studied in further detail in the following papers.

(Skews and Kleine, 2009b) conducted experiments over a wider range of Mach numbers and showed definitively that the triple point trajectory does not start from the point of initial curvature as a Mach reflection does not in fact form until further

up along the reflecting surface. Instead, a series of compression waves arising from the increasing slope of the wall accumulate behind the incident shock wave resulting in part of the shock wave that is close to the wall to strengthen and bend forward to remain perpendicular to the wall. These compression waves eventually coalesce into a shock wave which meets the incident shock wave and creates a kink in it at a point just above the point of maximum curvature on the incident shock wave. The formation of this kink is the first indication of a MR as the reflected shock wave grows from this kink, and is the point at which the triple point trajectory starts. The evolution of the reflection then continues as previously described with the triple point moving closer to the reflecting surface as the incident shock wave progresses until it intersects the reflecting surface and a TRR is formed.

In (Takayama and Ben-Dor, 1986), it was suggested that the corner signal could reach at most to the triple point of the MR, and that transition from MR to TRR happened when the corner signal could no longer keep up with the triple point. Using the weak perturbation method described previously, (Skews et al., 2008) showed that the corner signal produced from the start of curvature of the reflecting surface did not in fact have any effect on the point of transition from MR to TRR. The experimental results showed that at the point in time that the MR initially forms, the corner signal meets the incident shock wave above the triple point, and at the point of MR to TRR transition, the corner signal has already fallen behind the triple point and is instead intersecting the reflected wave. This was shown to be valid on both cylindrical and parabolic surfaces. This new understanding of the shock wave reflection evolution as an incident shock wave moves along a concave, curved surface is summarised in Figure 2.2.

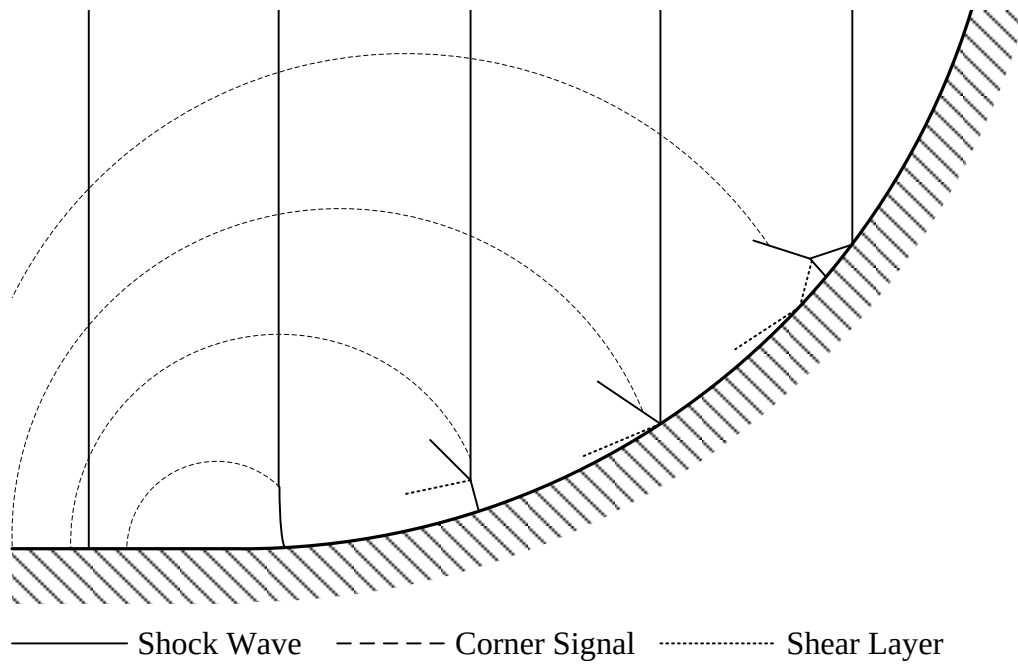


Figure 2.2: Evolution of the reflection of a propagating shock wave as it encounters a circular wall shown by (Skews et al., 2008)

Other studies with some bearing on this research include (Shugaev and Shtemenko, 1998), which is a summary of work done on shock wave reflection. It included a large section focusing on shock wave reflector cavities, which inherently covers unsteady reflections from concave surfaces, but was limited in detail on the earlier reflection configuration and mainly focused on strong shock waves. (Ivanov et al., 2009) demonstrated numerical simulations of weak steady shock reflections. This study provides a numerical solution under the von Neumann paradox conditions, at an M_s of 1.5, which is far stronger than the shock waves being studied here, but shows the development of numerical analysis for the weaker shocks waves. (Ben-Dor, 2007) is the most comprehensive summary of work done on shock wave reflection in unsteady flows and has 32 pages dedicated to reflection from concave surfaces.

2.2 Weak Shock Wave Reflection

John von Neumann did some of the first analytical studies into shock wave reflections, starting in 1943. He developed a theory, listed in (von Neumann, 1963),

for shock waves in air which was assumed to be a perfect gas, and based on the Rankine – Hugoniot jump conditions was able to deduce algebraic equations which solved the problems of both regular and Mach reflection for steady flow regimes. Subsequent experiments found that this theory found agreement with both strong and weak regular reflection, and also for strong Mach reflection, but there were large discrepancies for the weak Mach reflection. These experiments showed that a Mach reflection, or something that looked very much like it, existed even when the von Neumann theory had no physical solution for very weak incident shock waves. This discrepancy was named the von Neumann paradox of weak shock reflection by (Birkoff, 1950).

Using improved optical and experimental techniques, as well as numerical simulations, (Sakurai et al., 1989) showed that for the cases where the von Neumann theory failed to give a solution, a type of Mach reflection existed that looked somewhat different from the usual Mach reflection. In this case, the incident shock wave and Mach stem appeared to be part of a single shock wave front with a continuous curving tangent instead of the triple point seen for the stronger shock case. They also suggested that some of the reasons for the failure of the von Neumann theory for weak Mach reflection may be due to the effects of viscosity and non-uniformities in the flow, effects that von Neumann considered negligible in his theory.

(Colella and Henderson, 1990) studied the von Neumann paradox with particular attention to the weak Mach reflection using numerical simulations and shock tube tests at $M_s = 1.47$ and $M_s = 1.035$. Their results present evidence that there does indeed exist a different type of irregular reflection for the case of weaker incident shock wave, and that this type of reflection has a reflected shock wave which instead of meeting the incident shock wave, breaks down into a series of unsteady, self-similar compression waves close to incident shock wave - Mach stem intersection. This causes the curvature as seen in (Sakurai et al., 1989). They named this type of

specific weak shock wave reflection, the von Neumann reflection (vNR), and the differences between it and a Mach reflection can be seen in Figure 2.3.

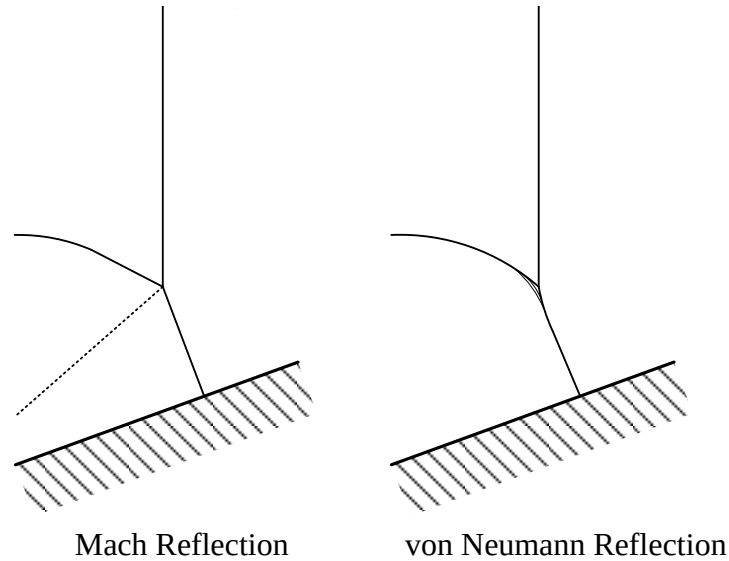


Figure 2.3: Schematic illustration of a Mach reflection with shear layer (left) compared to the shock structure of a von Neumann reflection (right)

Between 1990 and 2008, many further numerical and experimental studies were done on the existence of the vNR, trying to further refine the understanding of it. Most of these studies however focused on the very weak reflection of the vNR for the pseudo-steady flow regime, that is, of an incident shock wave propagating along an oblique but straight wedge. (Hunter and Moysey, 2000) presented the first numerical evidence of the existence of a supersonic patch and very small scale multi-wave structure immediately behind the three-shock intersection of the vNR, as first suggested by (Guderley, 1962). This was followed by experimental confirmation of Guderley's suggestions by (Skews and Ashworth, 2005) and a shock wave reflection structure that included these features was subsequently renamed the Guderley reflection, but it is still to be confirmed whether this phenomenon applies to all very weak irregular reflections. There have however been far fewer studies done into the unsteady case of a very weak incident shock wave propagating along a reflecting surface of

continuously changing gradient, particularly of the concave type and with a zero initial wedge angle.

The following studies included research into weak shock wave reflection off curved surfaces of increasing gradient. (Ben-Dor, Takayama and Dewey, 1987) expanded on the analytical predictions made by (Takayama and Ben-Dor, 1986) and applied them to a very weak planar shock wave encountering a curved concave reflecting surface. Using this, they developed a differential equation for the triple point trajectory angle, χ^{tr} , (assumed linear) for the range $1.01 < M_s < 1.15$. Solving for the point at which the triple point trajectory intersected the reflecting surface using numerical analysis, they were able to calculate θ_w^{tr} as shown in Table 2.1.

Table 2.1: Wedge angles (θ_w^{tr}) and TP trajectory angles (χ^{tr}) for various shock wave Mach numbers (M_s) at glancing incidence (adapted from (Ben-Dor, Takayama and Dewey, 1987))

M_s	θ_w^{tr} [°]	χ^{tr} [°]
1.01	15.89	7.93
1.02	21.95	10.99
1.03	26.37	13.21
1.04	29.88	15.00
1.05	32.81	16.49
1.06	35.32	17.79
1.07	37.52	18.94
1.08	39.47	19.98
1.09	41.22	20.92
1.10	42.80	21.78
1.11	44.24	22.57
1.12	45.55	23.31
1.13	46.76	24.00
1.14	47.88	24.65
1.15	48.92	25.26

In a study by (Skews and Kleine, 2007) into the flow features resulting from $1.04 < M_s < 1.36$ shock waves impacting a cylindrical cavity with zero initial ramp angle, new flow features were found mainly in the focus as the two reflected shockwaves

from each side of the cavity meet. For the weaker shock wave case, an omnidirectional schlieren system with a circular cut-off was used, which made it difficult to distinguish the flow features of the reflection pattern in the vicinity of the triple point due to the high pressure gradients in the wake of the reflection. The main point raised on the weaker shock wave case was that the corner signal produced from the leading edge of the reflecting surface does not affect the formation of the TRR, as confirmed for the strong shock wave case in (Skews et al., 2008).

Further focus was given to the weak incident shock wave reflection off curved surfaces in (Skews, Kleine and Barber, 2007), with both schlieren images and shadowgrams being taken of a $M_s = 1.04$ shock wave reflecting off circular and parabolic geometries with zero initial ramp angle. Their shadowgrams show a reflection prior to the TRR formation that is lacking a shear layer, although the resolution of the images was insufficient to say with certainty that the reflection was regular. In later images of the TRR, there is also no shear layer visible and the original reflected shock wave, the new reflected shock wave and additional shock wave of the TRR all appear to be curved and meet tangentially instead of at a well-defined secondary triple point. (Skews, Kleine and Barber, 2007) suggest that this reflection may be more similar in nature to that of a von Neumann reflection.

Using the weak-perturbation visualisation technique mentioned previously, (Skews et al., 2008) attempted to determine the type of reflection that (Skews, Kleine and Barber, 2007) described for weak incident Mach numbers. However, because of the very weak incident shock waves used, of only $M_s = 1.03$, the perturbations were much weaker still and required image processing to visualise clearly. The flow features of the resulting reflection were very small and at their camera's resolution, it appeared that there may be a very quick compression wave to MR transition, as described for stronger shock waves, before transitioning to a RR followed later by the appearance of the additional structures of a TRR. This ambiguity and the apparent presence of a regular reflection is what motivated the study undertaken in this report.

Most of the studies listed above were started in the field of strong shock dynamics, and the results for weak shock waves were obtained as they approached the lower limit of the compressible flow regime. At the other end of the spectrum, the field in which (Marchiano, Coulouvrat and Baskar, 2007) operate is within acoustics. However, their study also showed a deviation from regular, or “mirror”, reflection in nonlinear acoustics. They found that for ultrasonic shock waves in water with very small grazing angles (the equivalent of very small initial ramp angles described here), a three shock wave structure was present which looked very similar to a vNR.

(Izumi, Aso and Nishida, 1994) concerned an experimental and numerical study into shock wave focusing processes using parabolic reflectors. Although a weak incident Mach number of 1.1 was used for some tests, very little attention was paid to the early shock reflection, and their models have finite ramp angles. (Takayama et al., 2008) mentions that “in weak shock reflections, Mach reflection patterns do not necessarily accompany distinct triple points, which is named a Neumann reflection.” His tests, done on a concave circular wall of 150mm radius, are however at M_s of 1.5, which he considered weak as the flow behind the reflected shock wave is subsonic. He shows a von Neumann reflection to be the configuration where the base of the shock wave is curved slightly forward with converging pressure signals behind it. According to (Skews et al., 2008), this is considered to be the pre-MR curvature of the incident shock wave close to the reflecting surface, and not a distinct reflection configuration.

(Hakkaki-Fard and Timofeev, 2011) presented very high resolution numerical results of an incident shock wave encountering a convex circular cylinder which showed that transition on circular models occurs at the same point as off a plane wall. Their grid was sufficiently resolved to the physical thickness of the shock wave and this high resolution allowed a magnified view at instances when the reflection geometry is changing. Their results showed that for inviscid simulations, the sonic point (instance when the flow behind the reflected shock wave becomes sonic) coincided with the

catch-up point (instance when disturbances in the wake of the incident shock wave first catch up with the reflection point) and both converge on the theoretical sonic point as the grid is refined further. For viscid simulations, the sonic point and catch-up points were still found to coincide but were reached later. This study was done after the experiments for the current discussion were completed.

3 OBJECTIVES

Investigate the reflection characteristics of a weak transient shock wave ($M_s < 1.1$) impacting curved, concave reflecting surfaces with zero initial ramp angle. Specifically, investigate whether there exists a regular reflection (RR) prior to the formation of a transitioned regular reflection (TRR), unlike for the immediate MR-TRR transition predicted by current theory for stronger shock waves.

4 METHOD

To meet the objects outlined in the previous section, a primarily experimental study was decided upon. The reason for this over a purely numerical study was due to the ready availability of excellent experimental facilities at the institution and the concern that numerical solvers available at the institution would not be able generate well resolved shock waves of such a low Mach number due to being so close to the acoustic limit - whereby shock waves, by their very definition, would cease to exist. Numerical simulation was thus chosen as a second, additive - but not primary - means of study that would seek to confirm the experimental results if at all possible.

Confirmation of the experimental results by (Skews et al., 2008) required very high resolution images to be taken of the shock wave reflection during MR-TRR transition. Due to processing limitations, the fastest high speed cameras currently used for this type of research are currently limited to capturing images of about 4 megapixels resolution at the frame rates required for this study. Considering the relative size of the shock wave reflections that would be created by the available experimental facilities and the limitations provided by the available optics, it was decided that the resolution requirements exceeded that provided by current high speed cameras. Still, flash-based imaging using high resolution SLR cameras was thus decided upon as the method of image capture. Shadowgraphy was chosen over schlieren methods because only the actual reflection structure was being studied and information on the surrounding flow field was not required.

The exact Mach numbers chosen to be studied were defined by the diaphragm materials available, provided that they generated consistent weak Mach numbers below $M_s = 1.1$, with a preference for Mach numbers that were as close as possible to those tested by (Skews et al., 2008) for comparison purposes.

In order to determine whether a regular reflection existed between MR-TRR transition required that the reflection at each stage of the reflection evolution was conclusively identified. A TRR is easily distinguished by its additional shock wave structures in the wake of the incident shock wave, but the only differentiating element between a MR and RR is the presence of a Mach stem and shear layer. Criteria were thus chosen by which to test each shock wave reflection that was captured. These criteria included looking for signs of a shear layer, position of the intersection point, and the angle with which the incident shock met the reflecting surface.

5 EXPERIMENTAL FACILITIES

This section describes the apparatus used to carry out the experimental part of this study. The Seitz shock tube is introduced, followed by a description of the instrumentation and visualisation setup used to record the test results. The selected models that were tested and their associated dimensions are then explained. This section is concluded with a description of how the numerical solver works, used to run finite element simulations in parallel to the experimentation. Detailed specification of the equipment used can be found in Appendix A.

5.1 Experimental Data: The Shock Tube

5.1.1 Introduction

To generate shock waves in the laboratory in a controlled manner, a diaphragm driven shock tube was employed for the experimentation part of this study. This type of shock tube typically consists of a long tube, divided into two chambers, a compression chamber and an expansion chamber. The two chambers are separated by a gas-tight diaphragm. To generate a shock wave, the compression chamber is pressurised, creating a pressure difference across the diaphragm. The diaphragm eventually ruptures due to the pressure force applied to it exceeding its design stress, at which point there is immediately a pressure discontinuity created within the shock tube. To equalise this discontinuity, a series of compression waves move down into the expansion chamber (which at that point of time is at a lower pressure), ahead of the pressurised gas from the compression chamber. These compression waves merge to form a planar shock wave which continues to move down the expansion chamber to a test section where the shock wave can be studied. The strength of the shock wave

produced is controlled by varying the thickness of diaphragm used and the pressure difference that is applied to it.

The Michael W. Seitz Shock Tube was selected for this study because of its ease of use and appropriate test section size. This shock tube was designed and commissioned by Michael W. Seitz for the purposes of shock wave research within the Flow Research Unit of the University of the Witwatersrand, and details of its design and initial study can be found in (Seitz, 2001). It is of a double diaphragm design, using two diaphragms separated by an intermediate chamber to obtain a greater range of shock wave Mach numbers and negating the need for a “pricker” to burst the diaphragm as is used in some other conventional single diaphragm shock tubes. Initially designed to be fully automated in order to facilitate rapid testing within the incident Mach number range of $1.2 < M_s < 1.5$, the operation of the shock tube had to be modified as the very weak Mach numbers required by this study fell outside of the original design specification of the shock tube. The basic layout of the relevant components of the shock tube can be seen in Figure 5.1.

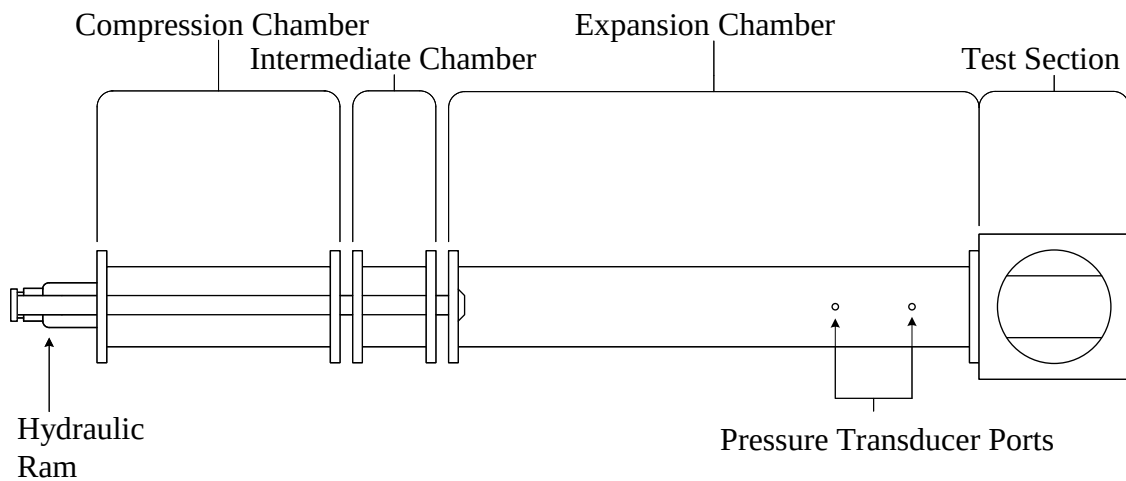


Figure 5.1: Schematic illustration of the various components and layout of the Michael W. Seitz Shock Tube

5.1.2 The driver section

Because this shock tube is of the double-diaphragm type, the driver section is made of two sections - the compression chamber and the intermediate chamber. The compression chamber is made of steel, has an initial diameter of 300mm and is 2080mm long. Internally, there is a contraction from the 300mm diameter at the back of the chamber, to a square cross section of 180mm by 180mm at the front. This contraction exists to increase the bursting pressure of the diaphragm placed in the upstream position. The compression chamber is pressurised by a series of high pressure air lines placed evenly along its length to give an even pressurisation. A diaphragm is placed between the compression and intermediate chambers.

The intermediate chamber is 215mm long and has a cross section of 180mm by 180mm at the back where it meets the compression chamber, and narrows to 76mm by 180mm at the front to match the cross-section of the expansion chamber. Pressurisation of the intermediate chamber is by means of a single high pressure air line which can also act as a vent for the chamber. A second diaphragm is then placed between the intermediate and expansion chambers, as shown in Figure 5.2.

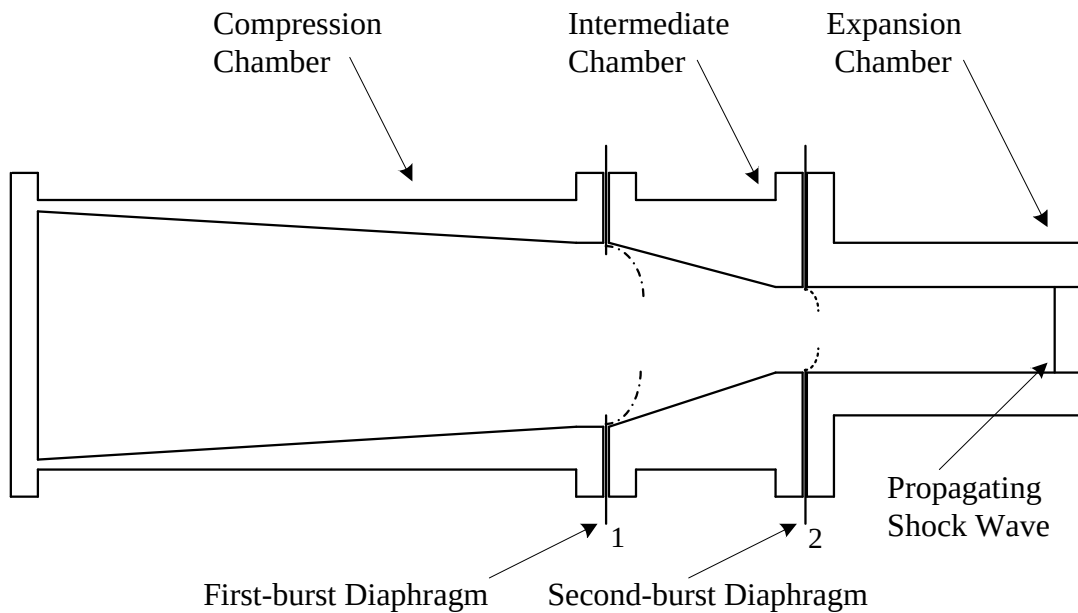


Figure 5.2: Schematic illustration of the inside of the driver section of the Michael W. Seitz Shock Tube showing the diaphragm positions and change in cross sectional area

A hydraulic cylinder, as shown in Figure 5.1, powered by a squirrel cage induction motor and hydraulic pump is used to close and seal the driver section by pushing the compression and intermediate chamber along two guides to meet the expansion chamber. Once diaphragms are inserted and the driver section is closed to perform a shock tube test, both the intermediate and compression chambers are pressurised to the same pressure. This first pressurisation is to just below the natural burst pressure of the diaphragm placed at position 2 in Figure 5.2, henceforth referred to as the second diaphragm. The pressure required to burst a particular diaphragm is obtained by doing a burst-pressure calibration test. The intermediate chamber is then vented to atmosphere, which rapidly increases the pressure difference across the first diaphragm to beyond its natural burst pressure, causing the first diaphragm to rupture. As a result of the sudden pressure increase in the intermediate chamber due to the rupture of the first diaphragm, the second diaphragm bursts, resulting in a series of compression waves from both ruptures to move down into the expansion chamber and eventually coalesce to form a propagating shock wave which travels into the test section.

5.1.3 The expansion chamber and test section

The expansion chamber is 6 metres long, and is made of 13 identical 450mm long cast iron sections. Each individual section has a transducer port in its centre and is made from cast iron due to the material's superior vibration damping properties when compared to steel or aluminium. The internal cross section of the expansion chamber is a continuous 76mm wide by 180mm high and has carpet felt mounted to approximately the first 60cm of its top and bottom walls to reduce transverse waves in the wake of the propagating shock wave.

When a shock wave propagates down the shock tube, it should be developed to the point of being fully planar before entering the test section. To this end, extra 450mm sections can be added or removed from the expansion chamber section. The test

section of the shock tube at the end of the expansion chamber is 350 mm long and has the same cross-section of 180mm by 76mm. Its vertical walls are made of two large aluminium doors, each with a 255mm diameter, 55mm thick borosilicate glass window at its centre. This gives an effective viewing area of approximately 250mm by 180mm. The doors allow access to the inside of the test section so that different test pieces can be positioned and secured by means of tappings along the centreline of the bottom, top and rear walls of the test section. These tappings, all 30mm apart from one another can also be used to place pressure transducers inside the test section for the collection of data. The test section is sealed for a test by clamping the doors shut using four large bolts.

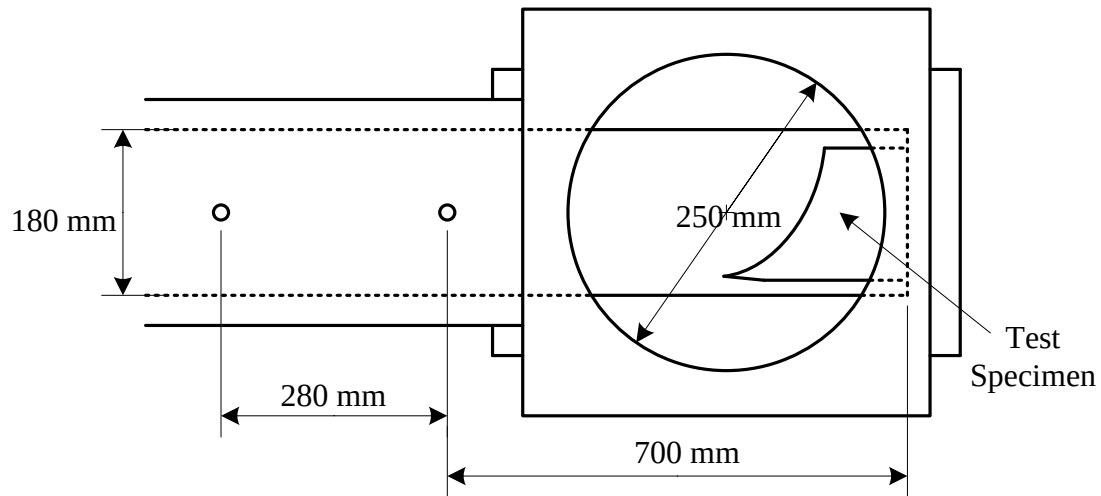


Figure 5.3: Schematic illustration of the test section of the Michael W. Seitz Shock Tube showing the relevant dimensions and test specimen placement

Two pressure tappings in the expansion chamber, 700mm and 980mm (280mm apart) from the rear wall of the test section have pressure transducers mounted in them to calculate the velocity of the incident shock wave just before it enters the test section.

5.1.4 Diaphragm material

This study required incident Mach numbers in the $1.01 < M_s < 1.1$ range. To achieve this, a large variety of new diaphragm materials were tested in order to find a

diaphragm suitable enough to produce consistent weak incident Mach numbers. Eventually it was found that aluminium foil was the best diaphragm to use for the selected shock tube to produce the required Mach numbers. Two types were tested, both commercially available in local convenience stores. The “regular” or standard gauge foils and “heavy duty” or heavy gauge foils, whose average thicknesses are summarised in Table 5.1, gave slightly different Mach numbers. Because the foils ruptured at such a low pressure, the resulting signal created by the pressure transducers was too weak to trigger the original shock-sensing system of the Michael W. Seitz Shock Tube. Instead of the automated control system, the pressurisation of the chambers was controlled manually and the recording of the pressure trace was done by connecting the two downstream pressure transducers directly to the data acquisition system.

Table 5.1: Details of the types and average thicknesses of the aluminium foil used in this study

Aluminium foil type	Thickness
Standard Gauge (SG)	15 μ m
Heavy Gauge (HG)	22 μ m

Although different combinations of foil were tried in both diaphragm positions 1 and 2, as described in Figure 5.2, it was found that in position 1, all tested foils ruptured inconsistently and at too low a pressure to produce a shock wave. Thus for all tests, diaphragms were only placed at position 2, making the shock tube run as a single-diaphragm type. Both the intermediate and compression chambers pressurised equally until a natural burst of the diaphragm was achieved as a “pricker” could not be inserted to control the burst of the diaphragm. There was also some variation of the incident Mach number due to slight variations and defects in the foil used for each test causing not all the diaphragms to have natural burst at exactly the same pressure. A summary of the types of foil used, their thickness, and the resulting Mach number can be seen in Table 5.2.

Table 5.2: Resulting shock Mach numbers produced from various diaphragm combinations and positions

Diaphragm Combination	Diaphragm Position	Approximate Resulting M_s
2 x HG	2	1.075
2 x SG	2	1.055
1 x HG	2	1.035

5.1.5 Control system

The Michael Seitz Shock Tube currently has a computer-based data acquisition and control system developed by TLC Software CC. This software allows diaphragms to be burst-pressure tested and calibrated, manages the running of tests, records data for each test, triggers the flash for flow visualisation, and controls the opening, closing and pressurisation of the pressure chambers. However, because the software was made to the original design specification of $1.2 < M_s < 1.5$, it is unable to facilitate the generation of shock wave Mach numbers below 1.1. For this reason, the manually-operated control system as originally designed by (Seitz, 2001) was used. This consisted of a series of ball valves to control the pressurisation and venting of the compression and intermediate chambers, and displayed the pressures in each chamber via a pair of large static pressure gauges in the control room. Operation of the hydraulic pump for the opening and closing of the driver section was also controlled from the same position.

5.2 Instrumentation

As the incident shock wave moved down the tube toward the test section, it passed two pressure transducers described in Section 5.1.3. These transducers were used to measure the Mach number of the shock wave, as well as to trigger the light source. For this purpose, two fast response PCB piezoelectric pressure transducers were used, each with a rise time of $1\mu\text{s}$. As the shock wave passed each transducer, it created a

voltage change and this output signal, in the order of millivolts, was amplified by a pair of PCB (Model 482A10) ICP inline amplifiers.

Initial shock tube tests used a Yokogawa DL1200A 4-channel digital oscilloscope to analyse signals from the pressure transducers. A shock wave passing the first transducer would trigger the oscilloscope to record the voltage rise across each transducer. Manual measurement of these voltage rises and the time differential between them allowed the velocity of the incident shock wave to be measured.

The majority of the shock tube tests used a digital data acquisition system to record and analyse the signals from the pressure transducers. The amplified signal from the pressure transducers was fed into a Graphtec GL1000 Hard Disk Logger which was able to record the high speed pressure fluctuations being experienced by the pressure transducers. A USB cable connected the data logger to a dedicated laptop computer which was running Graphtec's "Hard disk logger software" (version 1.00) in real time to record and display the output from each transducer. This software allowed preliminary analysis of the shock wave velocity and saved data files for each test in a .csv format.

The signal from the pressure transducer closest to the test section was used to trigger the light source. Its amplified signal was branched and sent to an Electro DI programmable time delay unit. This device added a user-defined time delay (in μs) to the transducers amplified output signal before it triggered the light source. The layout of the shock sensing system can be seen in Figure 5.4.

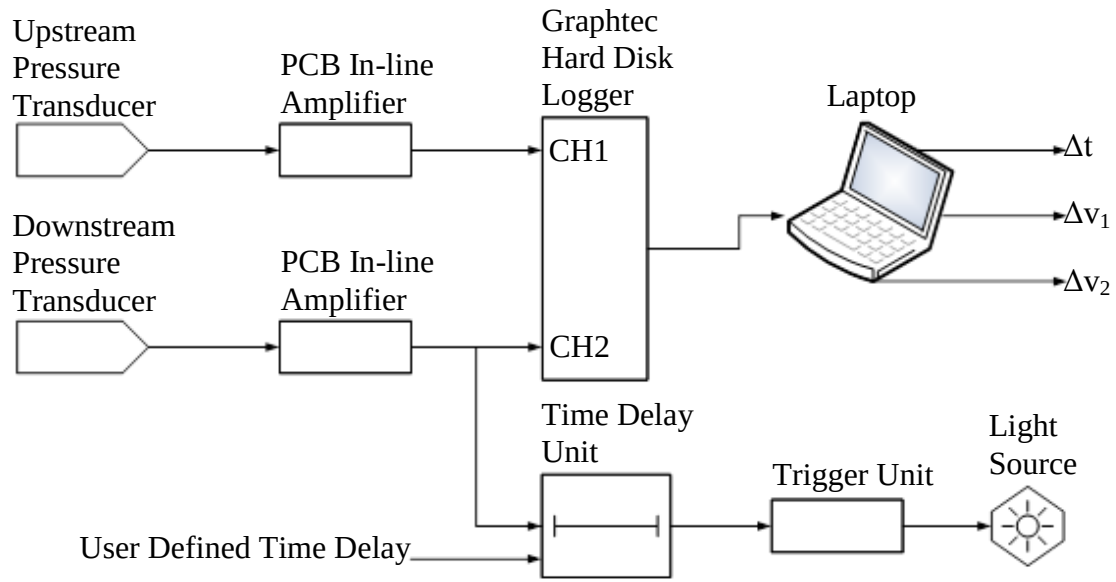


Figure 5.4: Schematic illustration of the components and layout of the shock wave sensing and light source triggering system

A Brannan 76mm immersion mercury laboratory thermometer was used to measure the temperature of the air for the sake of calculating the local sound velocity. To get an accurate reading, the thermometer bulb was mounted against the expansion chamber, close to the test section, and its value was checked every time a shock tube test was run.

Atmospheric pressure in the laboratory was also recorded during testing. A Halstrup-Walcher AD1000 Absolute Pressure Sensor, mounted in the main laboratory of the mechanical engineering laboratory was checked three times a day during testing to determine the absolute atmospheric pressure. The shock tube laboratory was in the same building as the sensor, on the same level and only separated by open doors and windows, thus the atmospheric pressure at the shock tube's location was assumed approximately equal to that at the sensors location.

5.3 Flow Visualisation

Compressible flow features such as shock waves, compression waves and expansion fans are defined by density gradients in gaseous media. These gradients cannot easily be seen with the human eye or photographed using normal techniques, therefore specialised visualisation methods must be employed to image them. Light is refracted when it encounters regions of differing density and recording the amount by which light is refracted forms the basis for the schlieren and shadowgraph techniques used for this study.

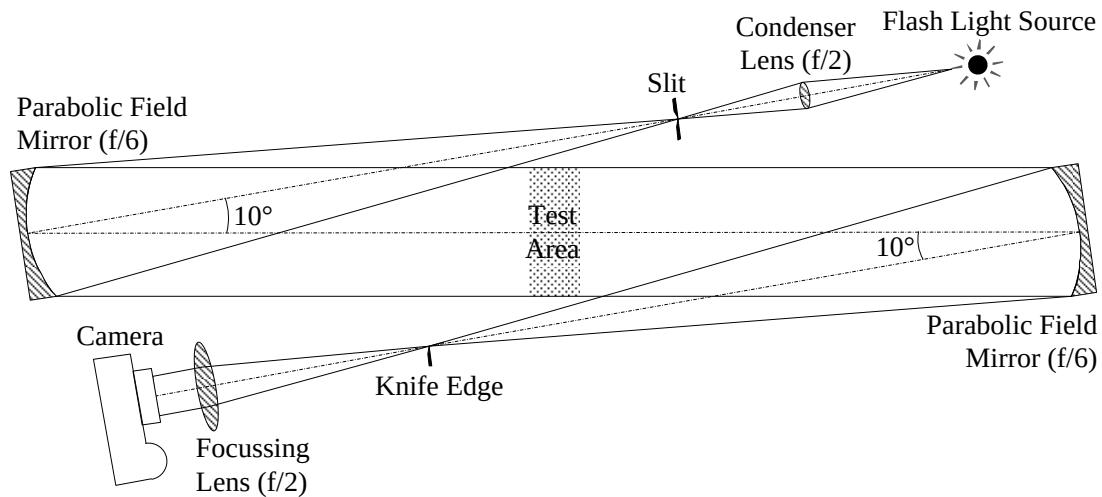


Figure 5.5: Schematic illustration of the components and layout of the Z-type schlieren system used to visualise the shock waves in this study (adapted from (Settles, 2001))

A simple Z-type schlieren, or “focused”, shadowgraph system was used as the chosen setup. The basic layout of the system can be seen in Figure 5.5. A Hamamatsu xenon flash lamp was used as the light source. The spread of the light from the lamp was reduced by placing a circular cut-off of approximately 5 mm directly in front of the lamp and any stray light from the lamp that did not go through the converging lens was minimised by shrouding the lamp and converging lens in an opaque tube. An Edmund Optics achromatic (f/2) converging lens, 40 mm in diameter, was then used to focus the light onto the slit. The size of the focal point was equivalent in size to the lamps filament.

To correct for astigmatism caused by the z-arrangement of the optical setup, a cylindrical lens was placed after the slit to create a second virtual focal point on the illuminator side of the test area. This cylindrical lens dispersed the light, obviating the need for a neutral density filter to reduce the intensity of the light passing through the test section.

This light filled the first parabolic field mirror on the illuminator side of the test area. The function of the parabolic mirrors is to take the divergent light coming from the slit and make it parallel as it passes through the test area. Due to the light being parallel, any refraction caused by density gradients in the test area can easily be seen. The parabolic mirrors had an f-number of $f/6$ and a 255mm diameter, matching that of the effective viewing area of the test section. Their centre lines were placed in a plane perpendicular to and 1718mm from the test section windows. Once the light had passed through the test section, it was focused to point by a second parabolic field mirror on the analyser side of the test area. If required, a commercially available razor blade was used as a knife edge at the focal point to adjust the sensitivity when schlieren photography was used. For tests where shadowgrams were required, the knife edge was removed completely.

The resulting image was focused using a 60mm convergent lens with an f-number of approximately $f/2$. The use of a large lens in this position allowed for greater magnification of the focused image that was projected onto the charge coupled device (CCD) of the digital camera, as required for this study. A Fujifilm S3 Pro with a 12 megapixel CDD was used to capture both the schlieren images and shadowgrams. To do this it was set in bulb mode to allow manual control of the shutter, with an ISO setting of 1600. Images were recorded in the RAW image format which, unlike JPEG, does no processing or compression on the image file before saving it. This was done so that the maximum amount of data could be extracted for each image and post-processed as required at a later stage.

For some tests, a grid was mounted to the test section to allow for quantitative measurements to be made from the images as well as to check for any distortion in the image. The grid was made from 250 μ m brass wire and the grid spacing was 25mm.

5.4 Test Specimens

The focus of this study is reflection of shock waves off curved concave surfaces and for this, two types of curved surfaces were selected. Reflections off cylindrical surfaces have been well documented, so two cylindrical models were selected. The first, with a radius of 130mm was selected to compare to previous studies by (Skews et al., 2008). The very small scale of the flow features being studied meant that either an optics set-up with high magnification or a very large model would be required to maximise the size of the reflection that was captured by the camera's CCD. Therefore a second cylindrical model was selected to take maximum advantage of the size of the test section. CFD simulations were run to determine the largest possible radius that would fit into the test section and still show MR-TRR transition within the $1.03 < M_s < 1.5$ range, and this was found to be 260mm for the second cylindrical model.

Concave parabolic reflecting surfaces have also been studied extensively, primarily for their shock focusing characteristics. Three parabolic models were selected for study, all divergent in nature and with the shock wave initially intersecting the parabola at its vertex where the gradient is zero. A very steep parabola of equation $y = 6x^2$, similar to that studied by (Skews et al., 2008), was chosen and scaled to fit the test section. This model would show MR-TRR transition happening very quickly. To determine the difference that just the type of curvature has (constant versus variable), a shallow parabola of equation $y = 2x^2$, similar in shape to the cylindrical model of radius 260mm was selected as the second parabolic model. A final parabolic model of

equation $y = 4x^2$ was chosen as its coefficient was between the other two parabolas. All the model geometries were tested using CFD prior to manufacture and their depths optimised to ensure MR-TRR transition occurred within the viewable area of the test section, except for the $y = 2x^2$ parabolic model.

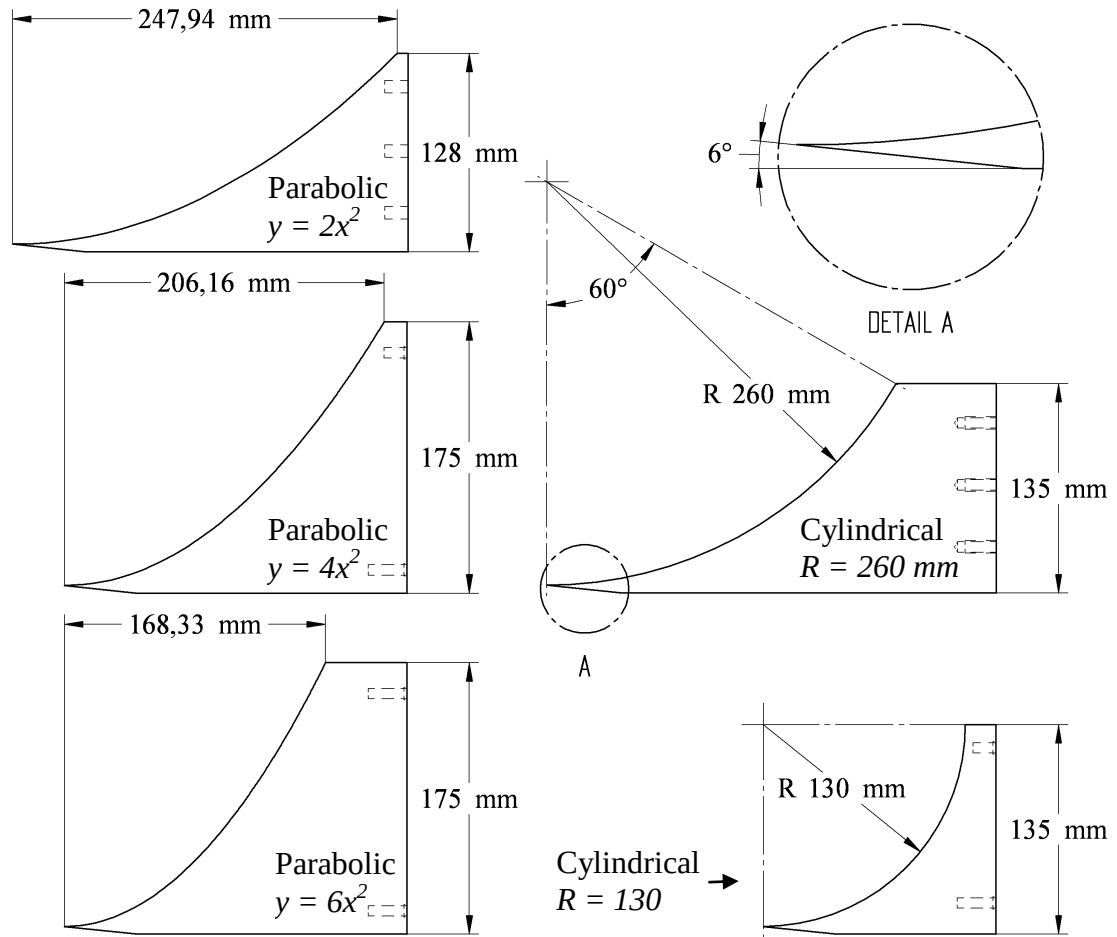


Figure 5.6: Specifications of the five different 75mm wide models tested in this study showing details of their dimensions and relative size

The $y = 4x^2$ and $y = 6x^2$ parabolic models as well as the 130mm radius cylindrical model were CNC machined from solid billets of aluminium, while the $y = 2x^2$ and 260 mm radius models were made from PVC. To avoid possible boundary layer interactions, a minimum 10mm gap beneath the model was imposed, constraining the maximum height of each model to 170mm. To ensure a smooth entry, all models

were designed to have a zero initial ramp angle so that the shock initially met the reflecting surface perpendicularly. Due to physical and machining limitations, a perfectly sharp leading edge could not be obtained and so each model had a 6° external ramp. Mounting holes were tapped into the back of each model so that it could be mounted to either the back wall of the test section or a spacer block, as required. The general arrangement of each type of model can be seen in Figure 5.6 and more detailed manufacturing drawings of the models can be found in Appendix B.

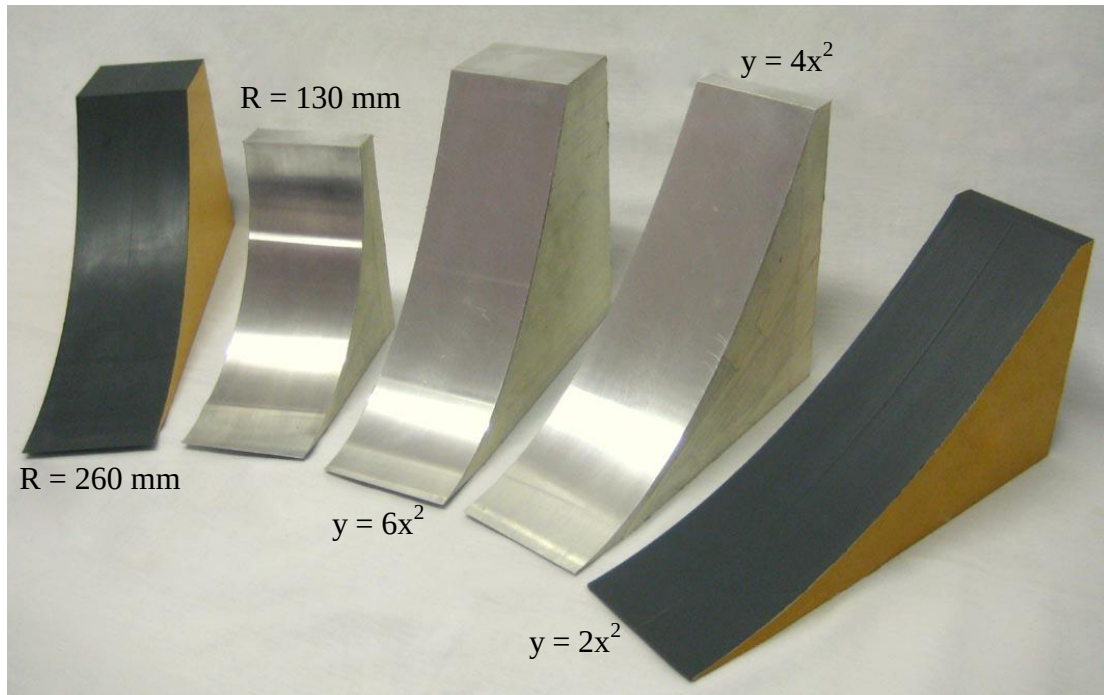


Figure 5.7: Image showing the material and finish of the five models tested in this study

All the models were manufactured to be 75mm wide and lined with sealing tape on their sides to avoid any gap between it and the test section windows. This was done so that the resulting shock wave interactions were essentially two dimensional.

A spacer was also manufactured to push the models further forward into the test section. Its dimensions were 50mm x 75mm x 160mm, and it attached to the models

by means of four M10 bolts before being mounted to the back of the test section using three M8 bolts. Detailed drawings of the spacer block can also be found in Appendix B.

For tests in which the weak perturbation method was used, ten strips of 46 μ m thick, 12mm wide Scotch® tape were placed in 20mm even intervals across the surface of the model being tested. This resulted in a gap of 8mm between each piece of tape.

5.5 Numerical Data: Computational Fluid Dynamics

Simulations of the flow features were performed using a Computational Fluid Dynamics (CFD) solver developed at the University of the Witwatersrand by (Felthun, 2002). The code is written in the C++ programming language and solves the Euler equations for the given flow domain. Because it is an Euler code, it does not consider viscous effects such as boundary layers but is very effective at modelling compressible flows. To pick up specific flow features, the code has a mesh adaptation algorithm based on the required pressure gradient of the flow feature being studied. An example of the code setup used in this study can be seen in Appendix E.

5.5.1 Geometry

The geometry of the mesh was created by specifying the vertices of the flow field in the code and then curve-fitting boundaries between them. For the continuous parabolic geometries (those that did not have simulated perturbation sources), a three-point interpolating spline was used to generate the parabolic curves. To ensure a zero initial wedge angle on the continuous cylindrical geometries, the arc was divided into 10 points and three separate, tangentially-conjoined four-point interpolating splines were used to generate the full arc along these 10 points.

The discontinuous geometries (those that included simulated perturbation sources) were generated by dividing the arc by $(i + 2)$, where i is the number of perturbation sources required along the arc. The arc was then generated by joining each point with a straight line. This meant of course that the geometries were not strictly curves, but rather polygons. However, using a high enough number of perturbations sources resulted in an approximation of the desired curve deemed sufficient for this study. The characteristic length, L , for the simulation and was then defined as the maximum depth of the model being tested. The domain can be seen in Figure 5.8.

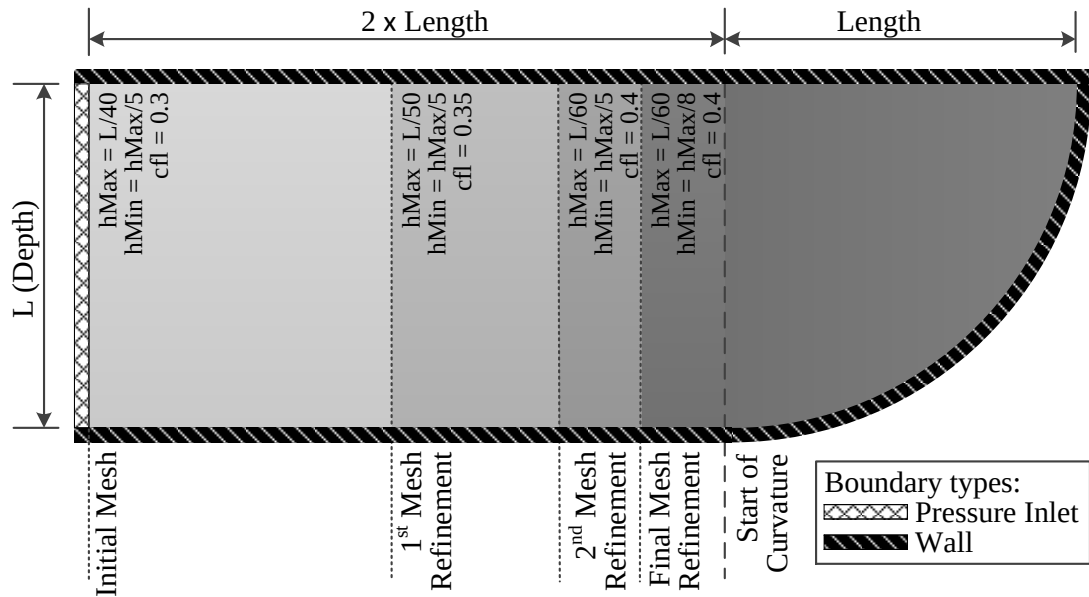


Figure 5.8: Schematic illustration of the design of the mesh used for CFD analysis showing boundary types, relative sizes and mesh refinement stages

To give the shock wave sufficient time to develop, the inlet was defined two characteristic lengths upstream of the leading edge of the model. Between each vertex, all the boundaries with the exception of the inlet were defined as straight, perfectly solid walls with no heat transfer. Because the flow domain being studied was assumed to be compressible and inviscid, no slip conditions or turbulence models were applied and the walls are considered to be perfectly smooth. The inlet, seen as the boundary on the far left of Figure 5.8, was defined as a pressure inlet. An initially

unstructured mesh made up cells of size $L/20$ was created between the vertices that defined the corners of the domain.

5.5.2 Initialisation

To generate a clean, infinitesimal shock that would pass through the flow field, a shock was generated by specifying a high pressure gradient at the inlet position for the first time step, the details of which can be seen in Appendix E.

After the first time step, the mesh adaption algorithm began structuring the mesh by dividing cells where a specified pressure gradient was found into cells half the initial size. This created a structured mesh of triangular cells that had the smallest cells where the pressure gradients were being studied but kept the rest of the cells in the mesh at a much larger size to improve calculation speed. The minimum cell size at this point was defined as one third of the maximum cell size of $L/40$.

The mesh then went through three further mesh refinements as the shock wave progressed across the domain. Once the shock wave reached one characteristic length into the shock initialisation volume, the maximum cell size was reduced to $L/50$ and the Courant number (cfl) increased to 0.35 from an initial 0.3. At 1.5 characteristic lengths, the maximum cell size was reduced further to $L/60$ and the cfl changed to 4. In the final mesh refinement at 1.7 characteristic lengths from the inlet, the minimum cell size was reduced further to one eighth of the maximum cell size. This size was chosen as it was determined to be the maximum cell size that would be able to resolve the small details of the flow features being studied.

These successive mesh refinements allowed the initial part of the simulation, prior to the shock meeting the curved surface, to run faster and ensured that at the time step when the shock started encountering the curve, the mesh was sufficiently refined to capture the required flow features. Because the flow domain is unsteady, mesh

dependence could not be determined by studying convergence of deltas on known variables in the flow domain. Mesh dependence for this study was instead determined by computing the numerical simulation on a sequence of finer and finer meshes until the solution did not change significantly. This is an acceptable method for unsteady domains as described by (Durbin and Medic, 2007).

Running on a 2.8GHz Pentium D (dual-core) processor with 2 Gb or RAM, the simulations typically took about 72 hours to complete with an initial mesh size of about 3,000 cells and a fully resolved mesh after the successive mesh refinements of about 130,000 cells. The resulting .plt files that the simulation created were then analysed using Tecplot® 360 (2009).

6 EXPERIMENTATION

This section provides a detailed step-by-step explanation of the experimental procedure that was followed in doing the experimental tests. It covers how the shock tube was run manually and how the shock sensing system was setup. Precautions that were taken at each step are also listed.

6.1 Experimental Procedure

6.1.1 Shock tube operational procedure

All shock tube tests were performed using the Michael Seitz Automated Shock tube in the School of Mechanical, Industrial and Aeronautical Engineering's laboratory. Although designed to be a fully automated process, the generation of very weak shock waves were not part of its original design brief and as such, a slightly different operational procedure had to be followed to capture the weak shocks required. The steps taken to obtain an image of a weak shock wave are outlined below.

1. The supply pressure in the receiver tank was checked to be sufficient for the required shock tube test. If found to be insufficient, the compressor was run to fill the receiver (see Compressor Procedure below).
2. One of the test section doors was then opened and the compression and expansion chambers blown clear by inserting a pressurised air hose into the chambers. This ensured that loose pieces of diaphragm from a previous test would not influence the next test.
3. Before returning to the control room, the required diaphragm was placed between the expansion and intermediate chambers and held in position with a piece of masking tape.

4. The required model was then mounted in the test section and the test section was sealed by closing the test section doors and tightening the 3 large bolts.
5. The inlet supply pressure to the compression and intermediate chambers was set to 2 bar.
6. All respective power supplies to the transducers, light source, oscilloscope, hydraulic pump, and computer were switched on.
7. All lens and mirror covers were removed, and lenses and mirrors were checked for any dust accumulation on their surfaces.
8. The optics set-up was checked by setting the light source's power supply to be internally triggered, creating a strobe effect. The camera was turned on and a sample image was taken. If required, the optics were then adjusted.
9. The delay box was then switched on and set to the required delay.
10. a) For tests using the oscilloscope, the settings shown in Table 6.1. were dialled into the oscilloscope to correctly capture the shock wave as it passed the two pressure transducers.

Table 6.1 Selected settings used on the oscilloscope to enable the capture of the shock wave passing both pressure transducers

Trigger Mode	Trigger Source	Trigger Level	Resolution CH1	Resolution CH2	Resolution Δt
"Single L"	CH1	35 mV	20mV/div	20mV/div	100 μ s

- b) For tests using the DAQ, settings in the "HARD DISK LOGGER Software" were adjusted to ensure the passing of the shock wave past the two pressure transducers would be correctly captured. Details of these settings can be found in Appendix F.
11. When ready to test, the green button on the panel labelled "Hydraulic Motor" was pressed to start the hydraulic motor. With the switch for "Mode of Opening and Closing" set to manual, the switch labelled "Open, Close HP Chamber" was turned to the close position. This closed the compression and intermediate chambers, clamping the diaphragm between them.

12.
 - a) For tests using the oscilloscope, the system was set to receive the trigger signal by pressing the “Start/Stop” button, and the delay box was armed.
 - b) For tests using the DAQ, “F7” was then pressed on the laptop keyboard, which readied the hard disk logger to capture the passing of the shock wave, and the delay box was armed.
13. The lights in the control room were switched off and the shutter on the camera was opened by squeezing the air bulb.
14. The yellow valve supplying high pressure air to the compression chamber was slowly opened, resulting in the pressurisation of the compression and intermediate chambers until the diaphragm burst naturally.
15. Once the diaphragm had burst the bulb was released, closing the camera’s shutter, and the lights in the control room switched on. The yellow valve was also closed to stop the supply of high pressure air to the compression chamber.
16. If the test was successful, the ambient pressure and temperature in the room was recorded along with the “ Δv ” values for each transducer channel. This information was then later used to work out the Mach number of the shock wave produced by the test. For tests using the DAQ, the data file generated by the test was also saved in the .csv format for later analysis.

This procedure was repeated for different time delays and on different models so that the entire spectrum of reflections could be captured as the shock wave moved through the test section.

6.1.2 Shock tube operational precautions

1. Cover the sides of the test pieces that will be in contact with the glass windows of the test section with either masking tape or double-sided tape to prevent scratching the window and to avoid 3D effects.

2. Ensure that all the smaller frame-support bolts on the test section door are tight and flush against the window frame.
3. Take care not to touch or bump any of the optics components when moving around in the control room, as this will cause misalignment in the optics setup.

6.1.3 Compressor operational procedure

1. On the dryer, ensure that both the valves at the top and bottom are closed (horizontal position) and that the heater is turned off at the orange control box below the dryer.
2. At the compressor, switch the compressor's circuit breaker - located on the side of the electrical control box - to the up (on) position.
3. Turn on the water supply by turning the red tap on the green water supply line by one revolution (located on the support column next to the electrical box).
4. On the front of the electrical box, turn the red emergency shut off switch (at bottom right) clockwise. It should spring back and the compressor should start.
5. When the receiver reaches maximum pressure (15 bar), the compressor will automatically turn off. At any point, the compressor can also be turned off by pressing the red emergency shut off switch. Turn off the compressors circuit breaker on the side of the electrical box (to the down position), then close the water supply tap by turning clockwise until tight.
6. To heat and dry the silicone crystals in the dryer that were used to remove moisture from the air going into the receiver, slowly open the valve found on top of the dryer followed by the valve found below the dryer and turn on the heater. The heater will then turn off automatically when the dryer reaches the required heat.

6.1.4 Compressor operational precautions

1. Although the compressor will turn off when the maximum pressure in the receiver is reached, it is advisable to check when this happens so that the water supply can be turned off and the heater started.
2. It is highly recommended to wear hearing protection when opening the valves on the dryer, as the air rushing out of the valve produces a very high pitch and can damage your hearing.

7 DATA PROCESSING

This section details how the data files produced by the simulations were analysed as well as what post-processing and analysis was done on the images obtained from the experimental results. The method for calculating the strength of the shock wave is described last.

7.1 Simulation Data

Running the simulations produced a set of 200 data files, each capturing the fluid properties at each node in the mesh at 200 different instances of time as the shock wave progressed across the flow field. Tecplot 360 (2009, Release 1) was then used to process these *.plt* data files. Because this study is primarily focused on visualising the physical structure of the shock wave reflections, emphasis was placed on processing the data in such a way that best showed these reflection structures. It was only desired to see the actual shock structures and no other details, thus an edge detection algorithm was required for post-processing. To this end, the shadowgram facility of Tecplot 360 was used to create numerical shadowgrams that could subsequently be compared directly to the shadowgrams obtained from experimental analysis.

To create a shadowgram from the numerical data, Tecplot 360 calculates the second spatial derivative - also known as the Laplace operator (Δ) or Del-Squared (∇^2) - of density for each cell in the mesh. This is equivalent to the ray displacement resulting from the deflection caused by density gradients in the flow that is normally captured by experimental shadowgraphy (Settles, 2001).

To compare to the shadowgrams captured experimentally, a greyscale flood plot of the second spatial derivative variable was created. Initially, this applies the colour gradient between black and white across the entire density range of the mesh, with pure white being allocated to the cells of highest density and pure black being applied to cells of lowest density.

If the region of interest is not the only part of the mesh with high density gradients, then this can sometimes lead to only a small colour gradient being applied across the area of interest. For this reason, the density range across which the colour density is applied was adjusted for each numerical shadowgram, effectively modifying the sensitivity of the shadowgram in much the same way that adjusting the amount of light cut off by the first slit in the experimental setup has. The detailed procedure taken to generate these shadowgrams in Tecplot 360 can be seen in Appendix C.

7.2 Experimental Data

7.2.1 Image processing

Two forms of data were extracted from each shock tube test - a pressure reading from each transducer and a .raw image. RAW format shooting on the camera was chosen over black and white JPEG shooting as the RAW format contains all the data received by the CCD, and does not pre-process and compress the image before saving to disk as JPEG image compression does. As a result, there is no loss of detail in the images due to processing at the time of the image capture. The RAW format images that were obtained were very dark and had a low contrast due to the low amount of light falling onto the CCD in the experimental setup. Fine details, like the shear layer of a MR, were also difficult to make out so post processing was done on all experimental results so that they could be analysed.

Post-processing of the images was done primarily in Adobe Photoshop CS5. Due to all the shadowgrams being of very similar brightness and contrast, an action was recorded in Photoshop which could then be applied equally to all the images, ensuring the processing was uniform across all results. The details of this action can be seen in Appendix D. The initial RAW image can be seen in Figure 7.1a), in which the shear layer is very hard to discern. The post-processed image can be seen in Figure 7.1b), where the shear layer can be clearly made out. For the purposes of this report, the post-processed images were then desaturated to a greyscale image as can be seen in Figure 7.1c). This was done by applying the “Black and White” image adjustment in Photoshop and selecting “Auto” on the levels. This action produced images with the incident shock wave and its reflection contrasted correctly, and made the shear layer clearly visible where it existed.

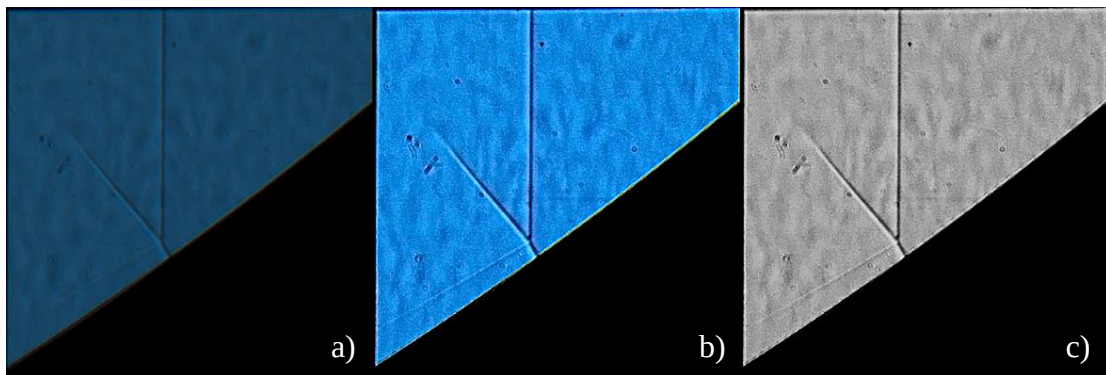


Figure 7.1 : Comparison of shock detail enhanced by image processing (b) and desaturation (c) done on the RAW images (a) obtained from experimentation

To visualise the change in the reflection configuration as the shock wave progressed along the reflecting surface using still imaging, images of the position of the shock wave at different instances of time were captured. Once post-processed using the method described above, the images were spliced together in such a way that the progression of the shock wave could be seen on a single image. This was possible because the sets of images taken for a particular test case were all taken within a small space of time, and the imaging system was not adjusted between tests, resulting in exactly the same field of view for each image. It is however important to note that

while the resulting spliced images shown in Section 8 give the impression of a single shock wave from a single test moving along the reflecting surface, it is in fact made up of many different tests each with slightly varying Mach numbers.

Quantitative measurements were made on the images by using a known dimension in the image and scaling according to it. The known dimension was provided by the grid spacing, with the spacing between any intersection of two wires on the grid being 25mm. Once the length between two intersections was measured, a scale could be calculated for that region of the image, and applied to any measurements made in the same region of the image. To make the measurements, a CAD program – Solid Edge V19 – was used. The images were inserted onto a draft sheet in the program and end points placed onto the flow feature being measured, between which dimensions could be placed. This method allowed relatively accurate measurements of the flow features to be made.

7.2.2 Calculation of M_s

For the shock tube tests, M_s was calculated using equation (8). The velocity of the incident shock wave was obtained by measuring the time delta between the triggering of each pressure transducer and dividing it by the known distance between them. To measure the time delta between the triggering of each pressure transducer, the voltage trace recorded by either the oscilloscope or the DAQ was studied. This recorded the voltage change across each pressure transducer caused by the passing of the incident shock wave and can be seen in Figure 7.2 as the pair of sudden, sharp rises in voltage. This figure is an example of one of the trace's recorded during testing for a $M_s = 1.05$ incident shock wave and the horizontal axis does not start at zero due to the system being set to record with a 10% pre-trigger. The change in voltage shown is directly proportional to the change in pressure, with the calibration factor of the pressure transducer being used as the constant.

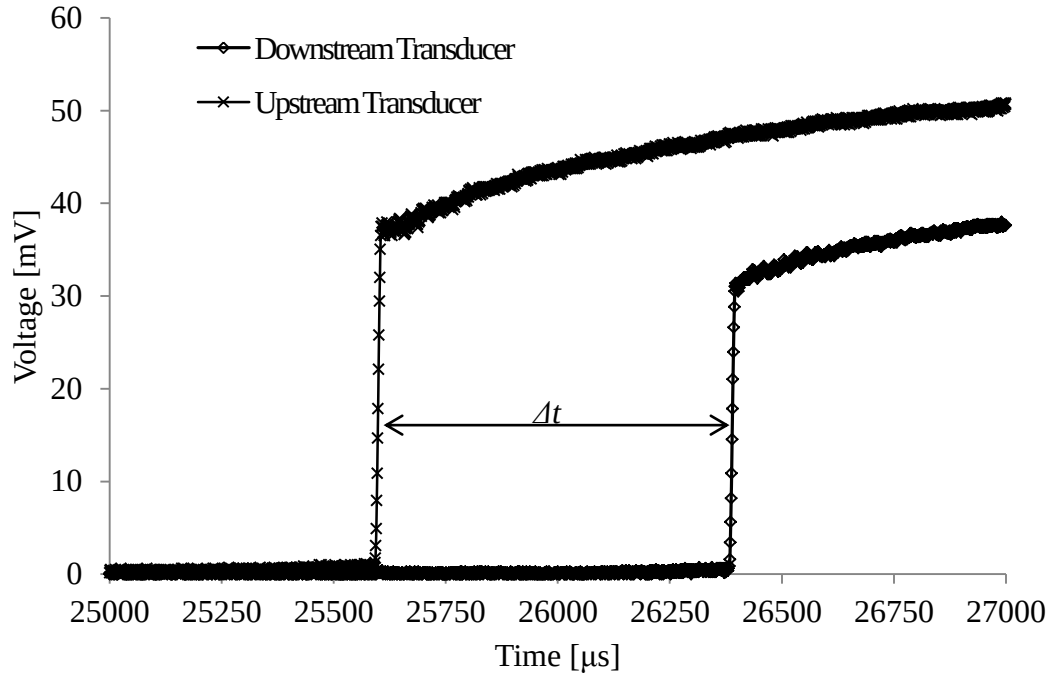


Figure 7.2: Example of a typical trace picked up by the shock sensing system during a shock tube test, $M_s = 1.05$

Measurements of the time delta, Δt , were taken from the midpoint of steepest part of the voltage rise on each pressure transducer. This was then divided by the distance between the two transducers, 280mm, to obtain U_{shock} . The local sonic velocity, c , was obtained using equation (7) with the room temperature of the laboratory as an input.

The uncertainty of the Mach number due to propagation of error from the measurements taken was calculated to be a maximum of 0.0052, which is at most 5.4% when compared against the lowest Mach number measured.

8 RESULTS

Included in this section is first a description of what was captured by the typical shadowgram recorded in this study, followed by a selection of the results that best illustrate what is trying to be determined by this study. The shadowgrams obtained from the experimental results showed the shock waves and their reflections structures far more clearly than the schlieren images, and therefore only the post-processed and spliced shadowgrams for each test case are shown here. The results from the numerical simulations and a discussion of their validity are included in Section 9.

8.1 Description of Results

In all the images, one can see the alignment grid, or rather its shadow, as the series of well-defined vertical and horizontal black lines. This grid is used to get quantitative measurements from the images as well as to check for optical aberrations. The grid has a spacing of 25mm and using this known dimension, the lengths in the image can be measured and scaled. Combining this with the known time delta between images, approximate velocities can also be measured.

The dark shape that takes up the lower right portion of each image is the shadow of the test model, the upper surface of which is the reflecting surface. It is designed to be perpendicular to the image plane, so that what is seen in the image is as close to two dimensional as possible.

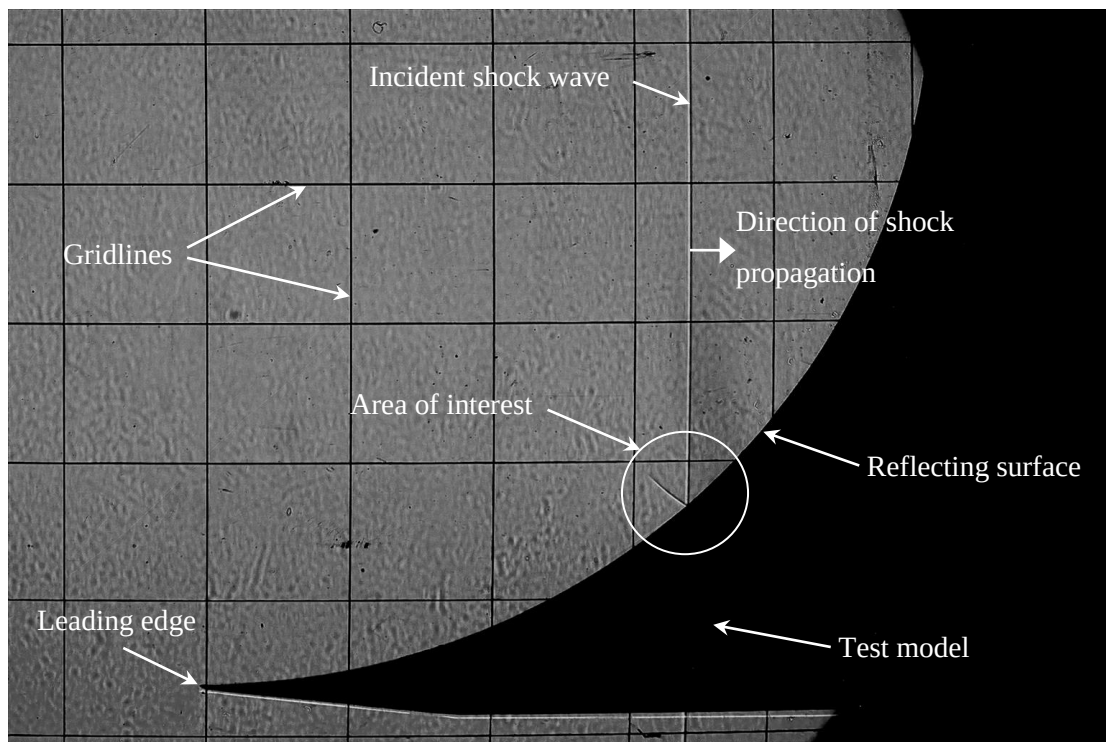


Figure 8.1: Description of elements found in a typical shadowgram captured during experimentation for this study

The incident shock wave comes in from the left of the image and progresses along the wedge toward the right. It can be distinguished as the well-defined vertical line which intersects the reflecting surface of the wedge. Because the shock wave is a pressure gradient, it can be distinguished from the dark vertical grid lines by it having a gradient across its width, going from a dark black to white, depending on the direction in which the pressure increases.

The focus of this study is the reflection structure of the shock wave and can be found where the incident shock wave intersects the reflecting surface. In all the images, there is at first no shock reflection as the shock wave comes in from the left and the gradient of the reflecting surface is small. However, as the shock progress towards the right and the gradient of the reflecting surface increases, different shock structures appear.

Tests were done on both models with a smooth surface and models with perturbation sources. It was however found that for the tests with perturbation sources, the disturbance caused by the shock wave passing over the perturbation source was so weak that it could not be visualised. This was expected as the incident shock wave itself was already so weak that it was barely visible, and thus any weaker disturbance produced by it would be very difficult to visualise. Other than the initial tests using perturbation sources on the $y=2x^2$ parabolic model, no other tests were therefore done with perturbations and the results are not included here as they do not add any additional insight to the study.

8.2 Shadowgraphy Results

It is important to reiterate that the following images do not show a single shock wave captured at various times along the model but rather a combination of shock waves of similar Mach numbers at different positions along the reflecting model. Because of the slight variation of Mach number between each shock tube test, an average Mach number is giving for each image, as well as each images actual Mach number for reference purposes.

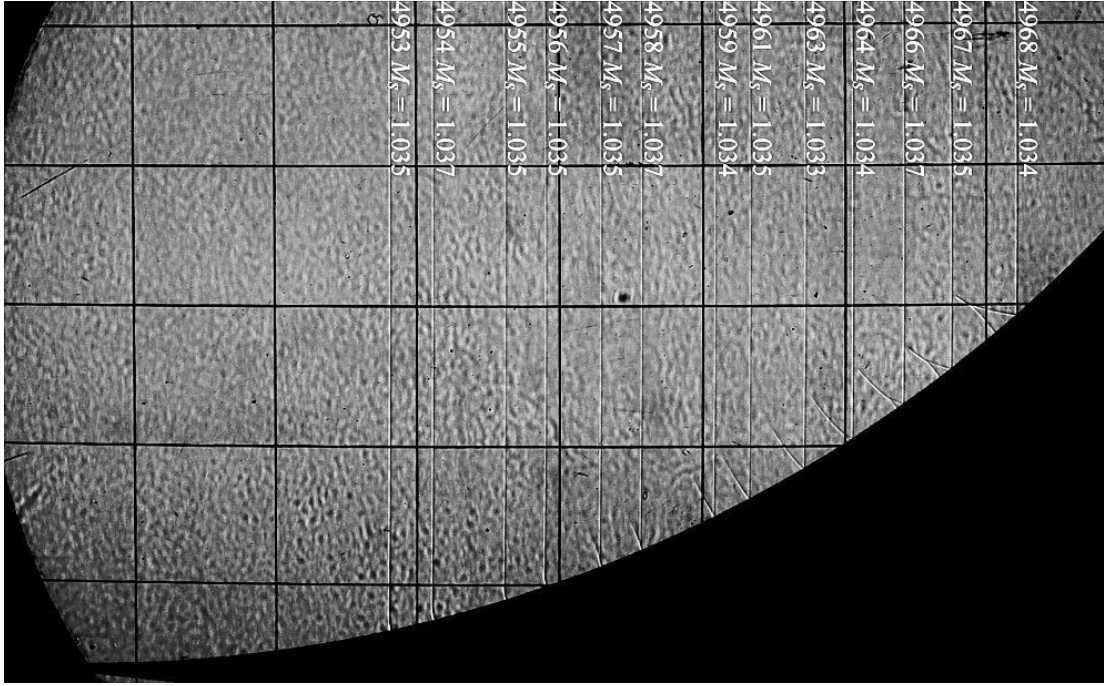


Figure 8.2: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.035$ encountering a circular model of 260mm radius at 25 μ s intervals

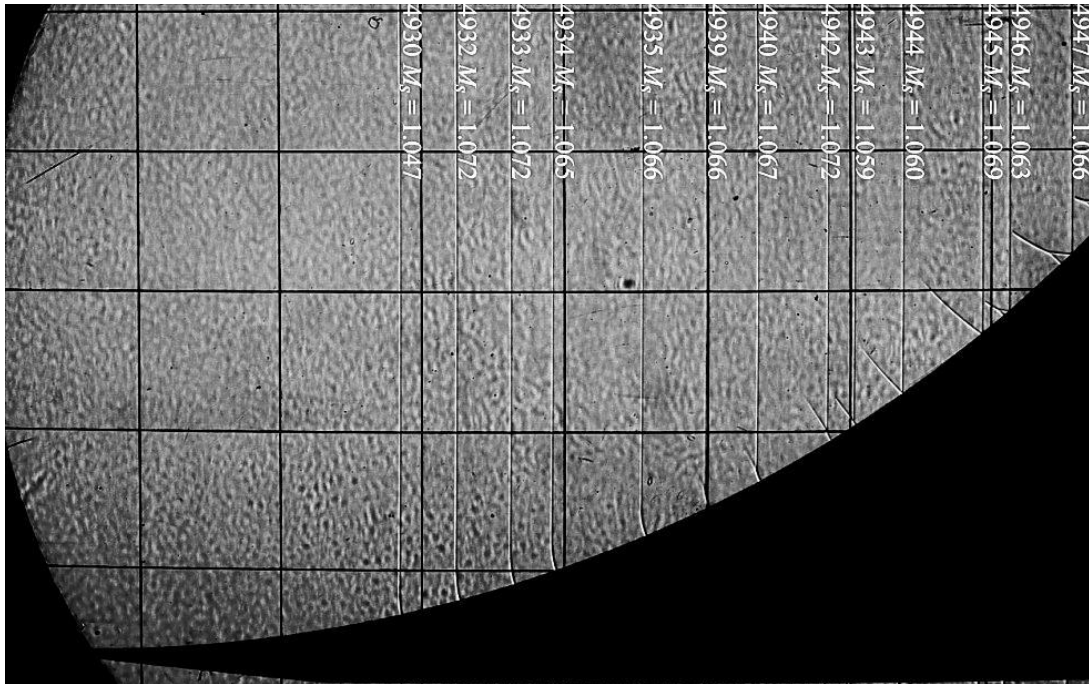


Figure 8.3: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.065$ encountering a circular model of 260mm radius at 25 μ s intervals

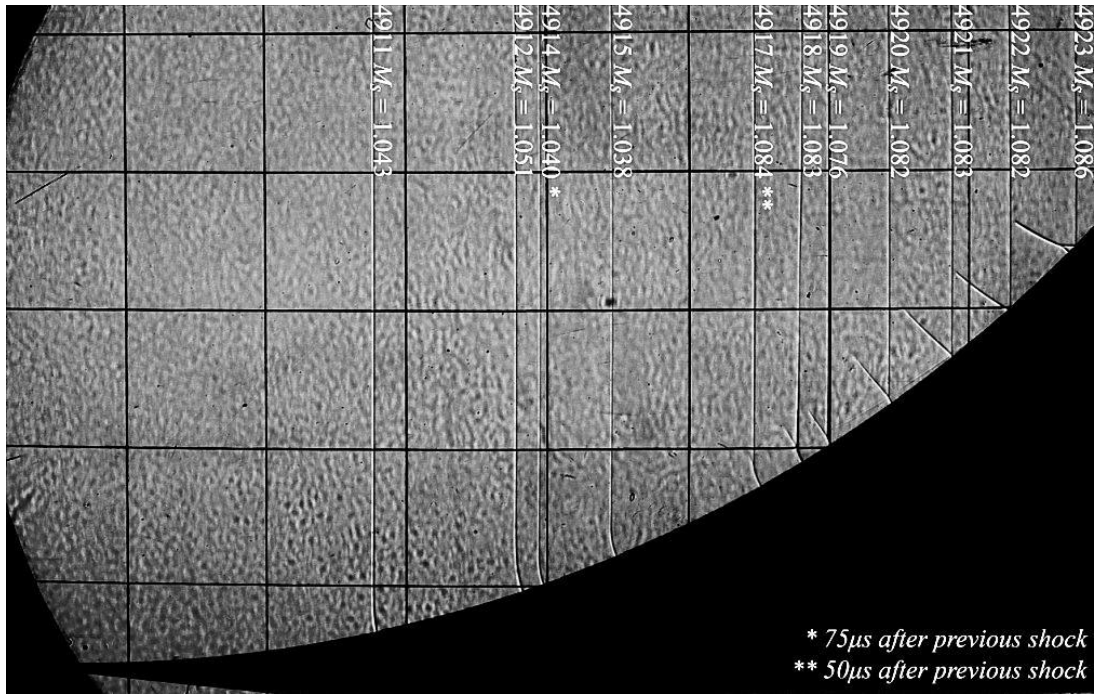


Figure 8.4: Combined shadowgrams of multiple shock waves of average $\bar{M}_s = 1.068$ encountering a circular model of 260mm radius at 25μs intervals

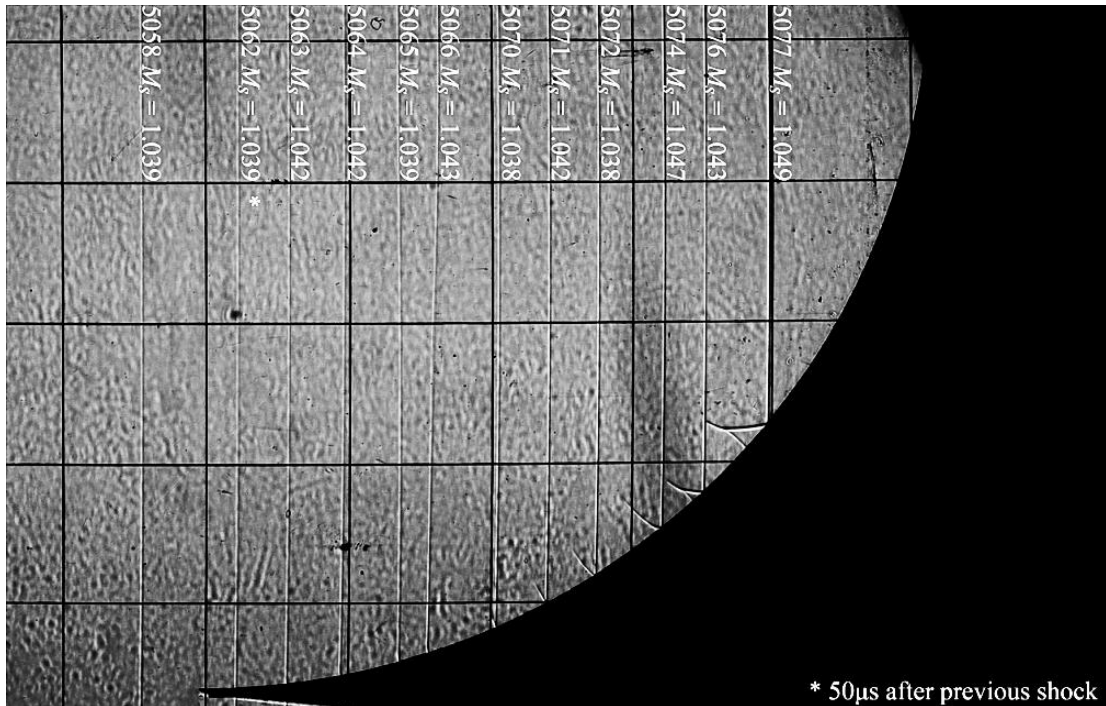


Figure 8.5: Combined shadowgrams of multiple shock waves of average $\bar{M}_s = 1.042$ encountering a circular model of 130mm radius at 25μs intervals

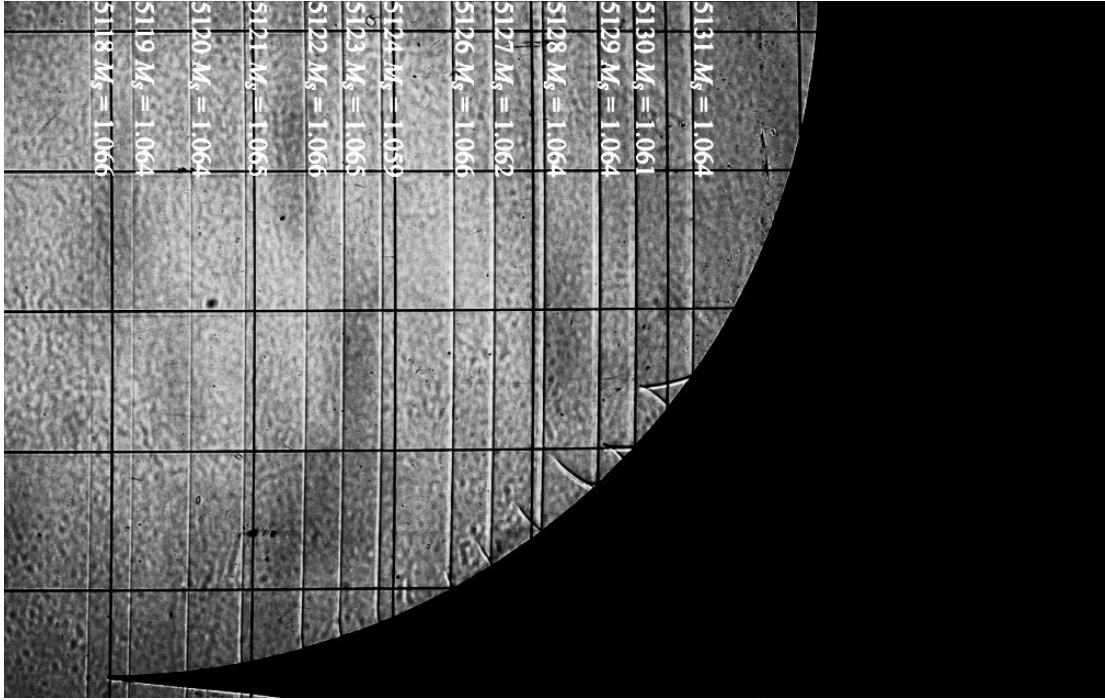


Figure 8.6: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.064$ encountering a circular model of 130mm radius at 25 μ s intervals

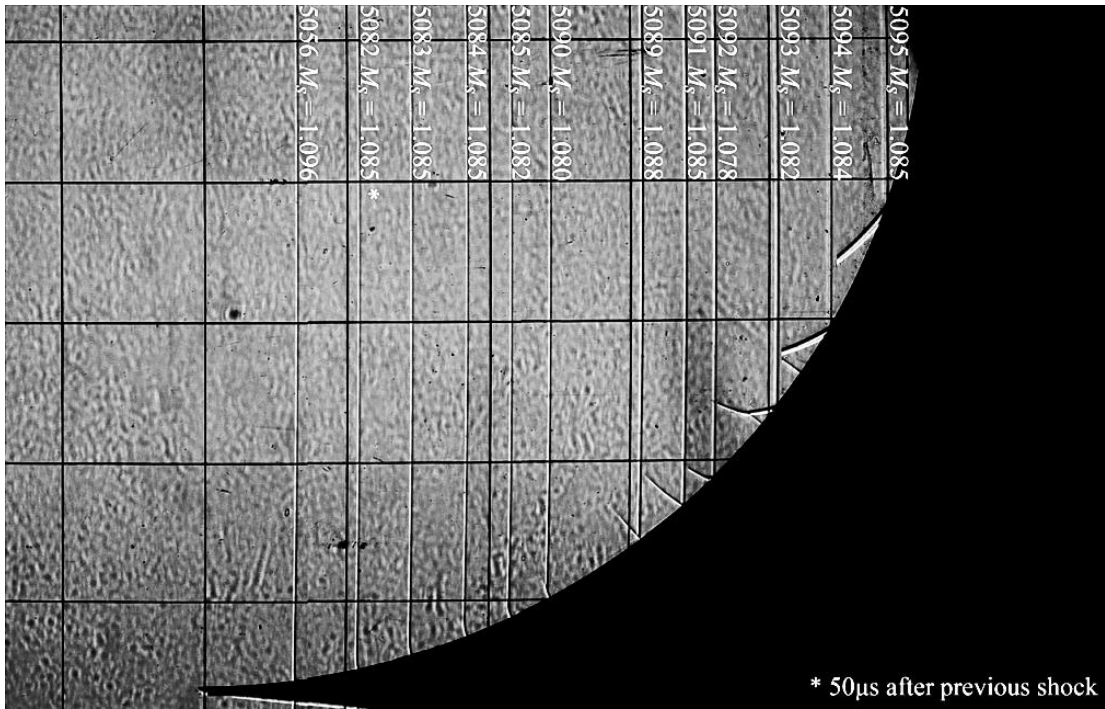


Figure 8.7: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.085$ encountering a circular model of 130mm radius at 25 μ s intervals

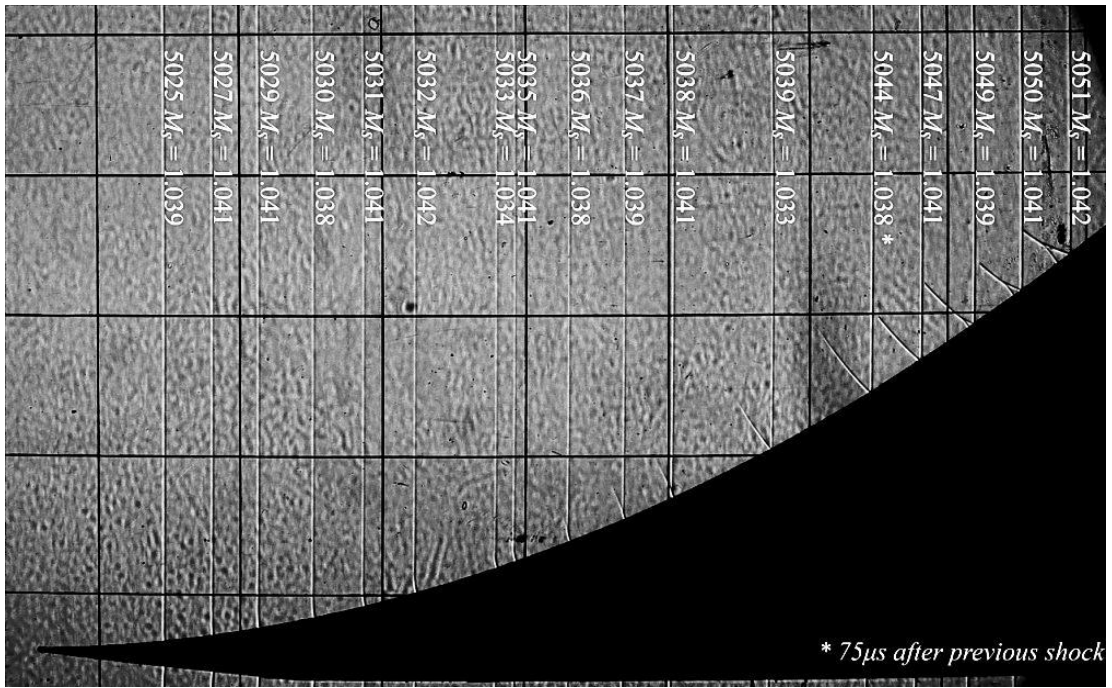


Figure 8.8: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.039$ encountering a parabolic model of equation $y = 2x^2$ at $25\mu s$ intervals

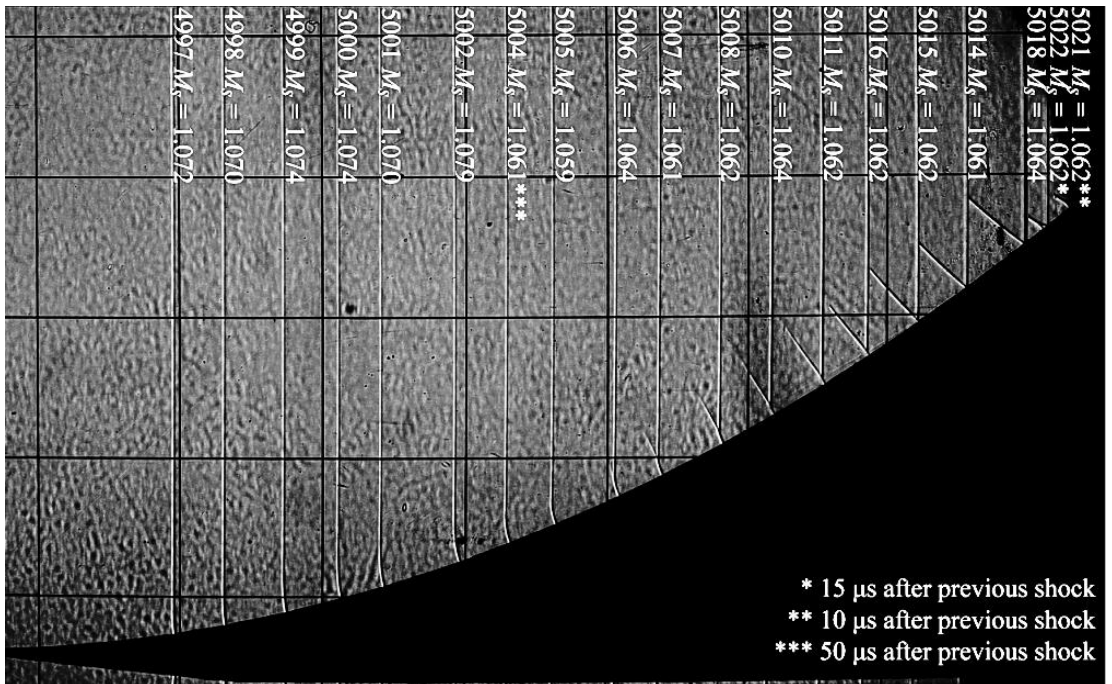


Figure 8.9: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.066$ encountering a parabolic model of equation $y = 2x^2$ at $25\mu s$ intervals

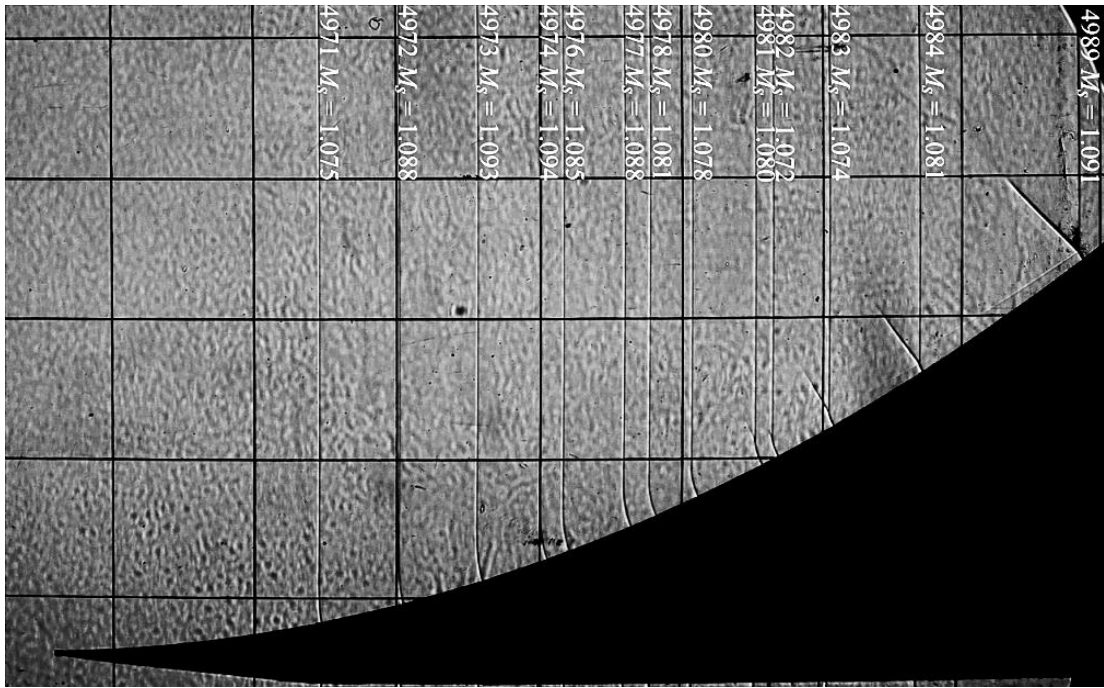


Figure 8.10: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.082$ encountering a parabolic model of equation $y = 2x^2$ at $25\mu s$ intervals

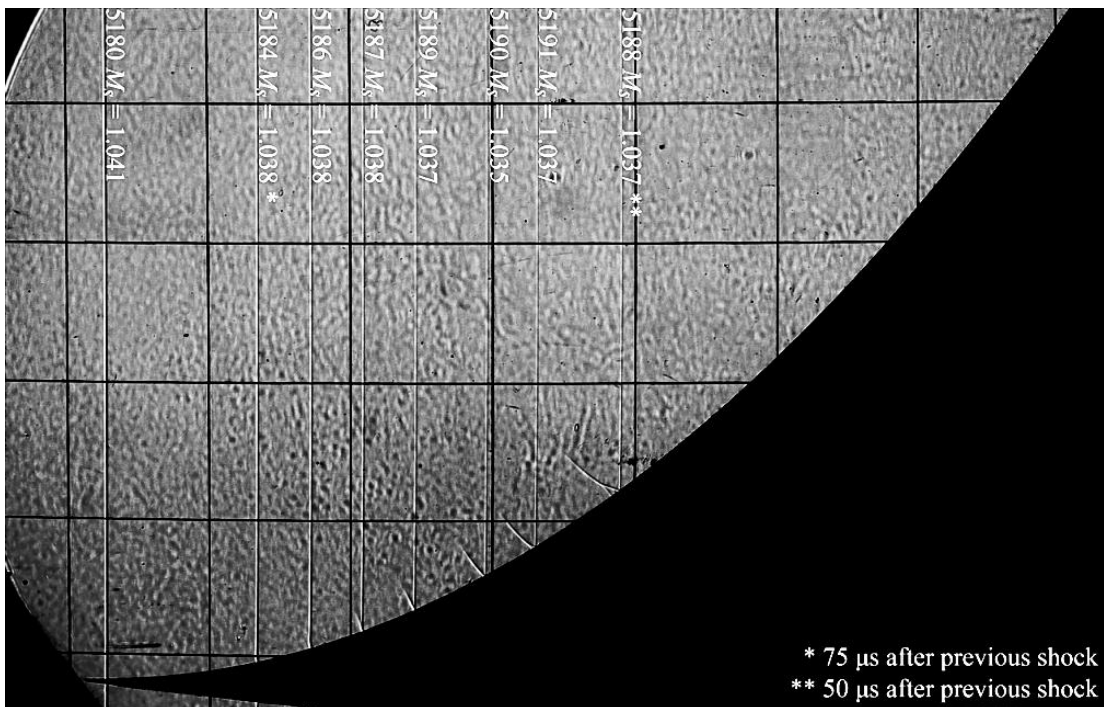


Figure 8.11: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.037$ encountering a parabolic model of equation $y = 4x^2$ at $25\mu s$ intervals

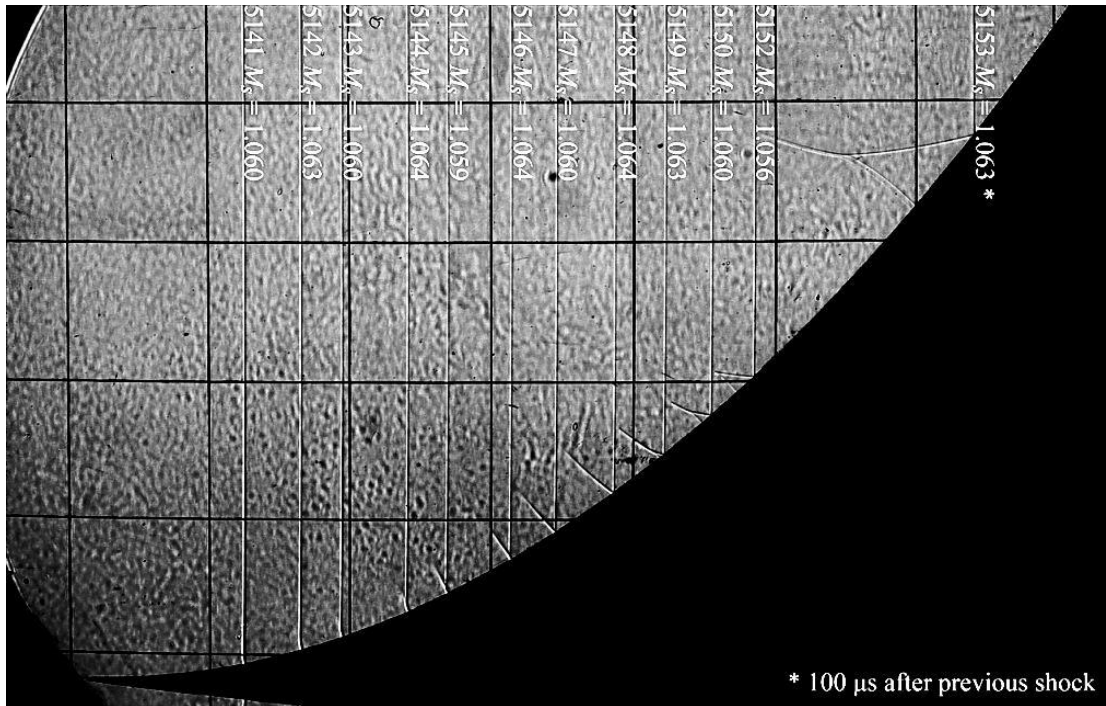


Figure 8.12: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.062$ encountering a parabolic model of equation $y = 4x^2$ at 25μ s intervals

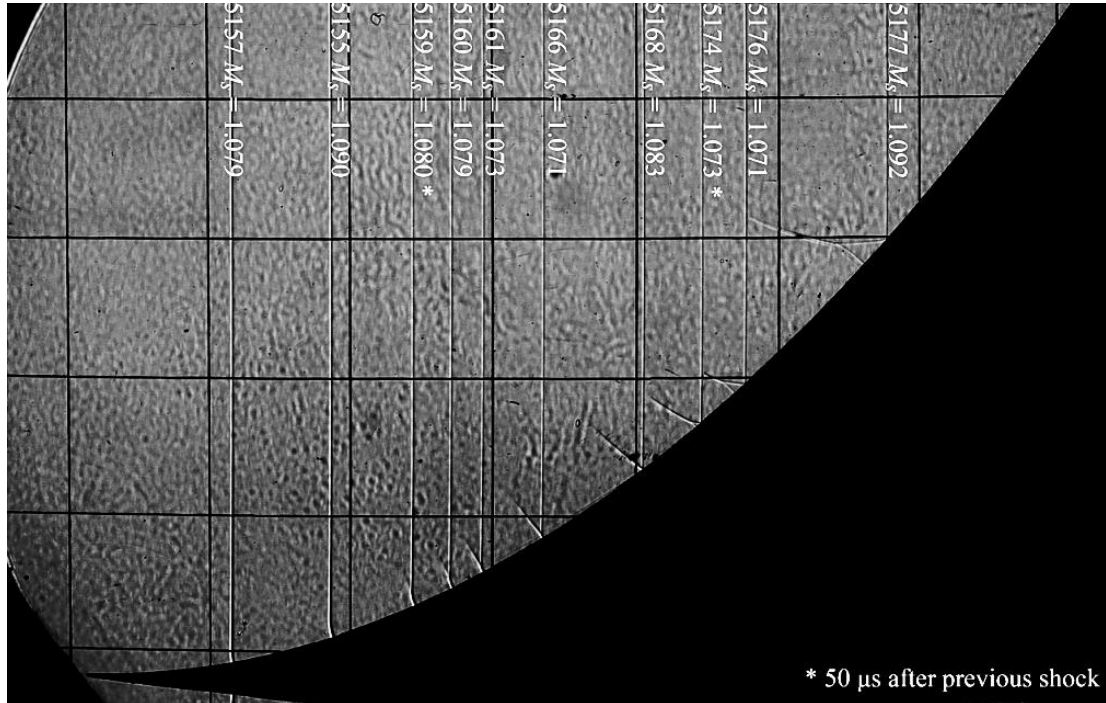


Figure 8.13: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.079$ encountering a parabolic model of equation $y = 4x^2$ at 25μ s intervals

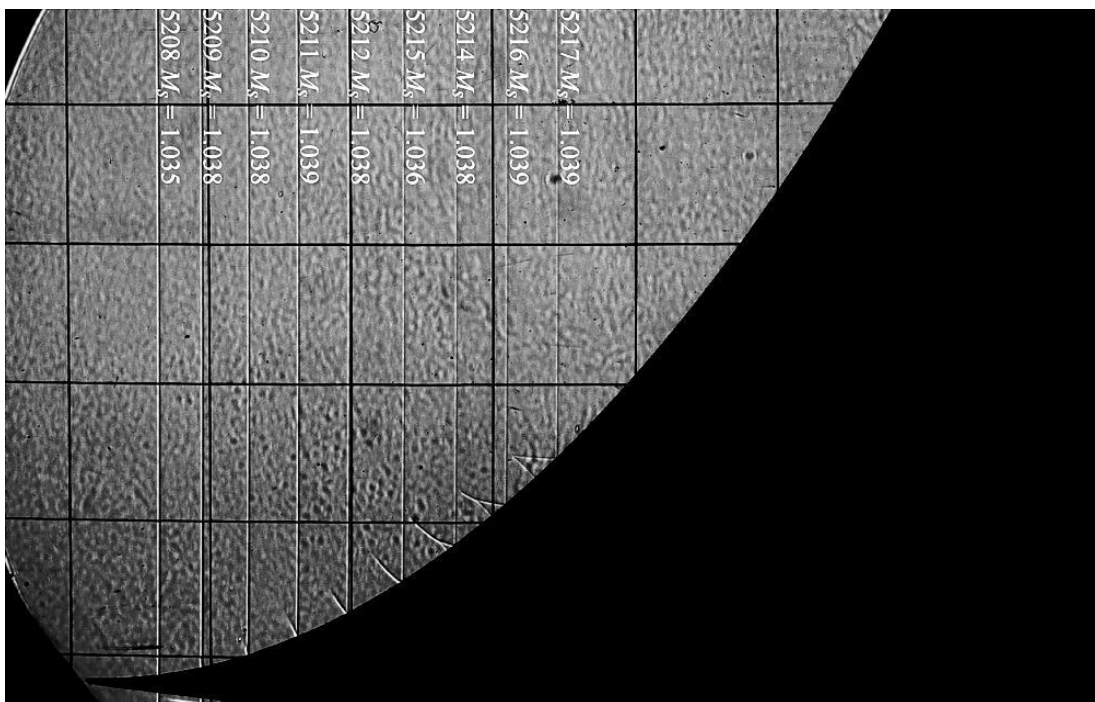


Figure 8.14: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.038$ encountering a parabolic model of equation $y = 6x^2$ at $25\mu s$ intervals

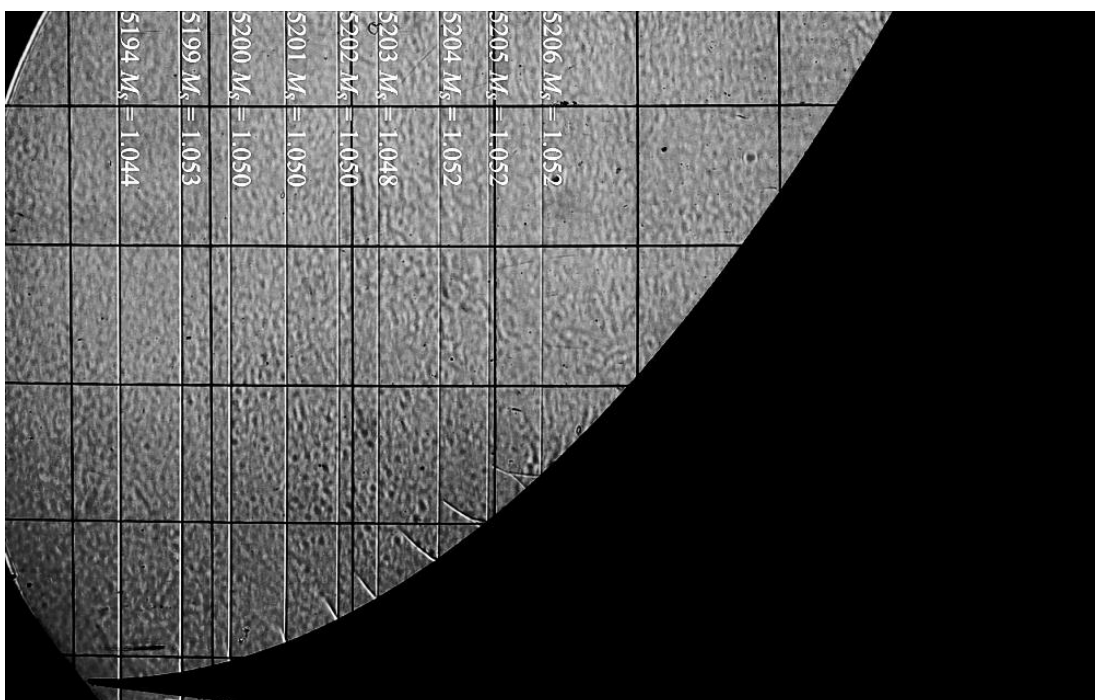


Figure 8.15: Combined shadowgrams of multiple shock waves of average $\bar{M}_S = 1.050$ encountering a parabolic model of equation $y = 6x^2$ at $25\mu s$ intervals

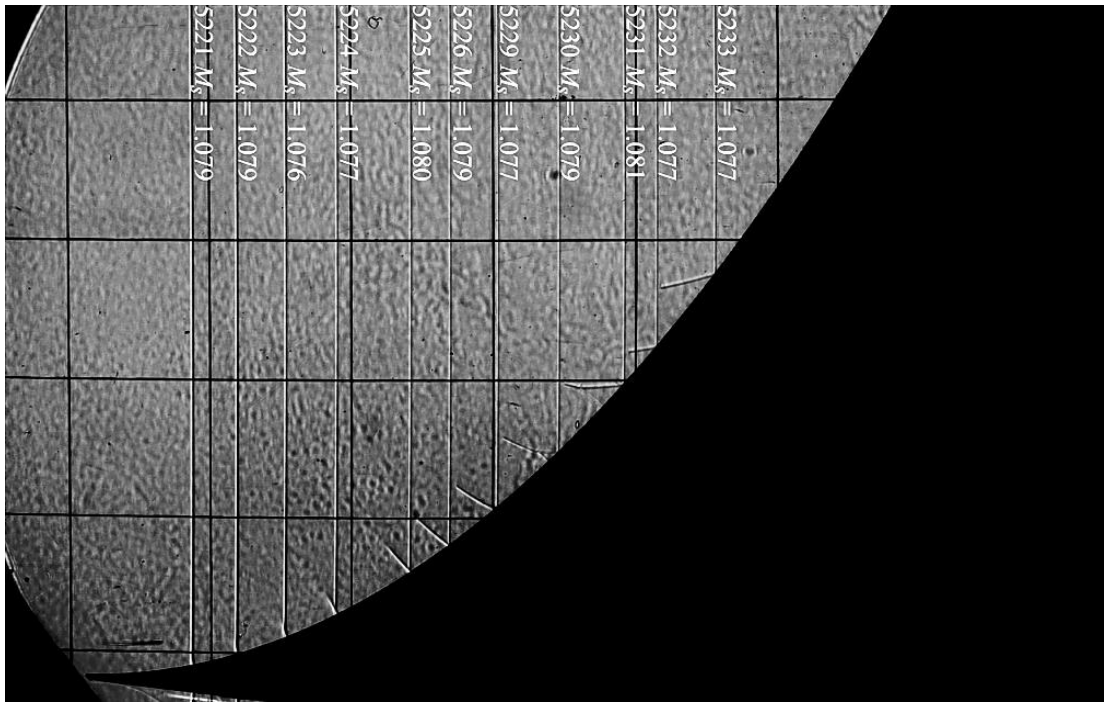


Figure 8.16: Combined shadowgrams of multiple shock waves of average $\bar{M}_s = 1.078$ encountering a parabolic model of equation $y = 6x^2$ at $25\mu s$ intervals

9 DISCUSSION

The purpose of this section is to provide a critical analysis of the results, highlighting areas of interest with specific images and figures. It begins with a description of the experimental results, followed by analysis of them. The numerical results and their validity are discussed at the end.

9.1 Reflections from Circular Models

For the circular geometry, the reflection evolution should be the same, regardless of radius. The size of the reflection and the point at which it transitions should just scale linearly with radius size, and is thus self-similar. The most pertinent results for this study would therefore be those done on the largest radius circular models, which in this case are 260mm, the largest radius which would fit in the test section of the shock tube used.

This study is also focused specifically on weak shock wave reflection. We know that at the acoustic limit, the reflection is always regular. Thus, most relevant are those tests achieved closest to the acoustic limit, in this case in the range: $1.03 < M_s < 1.04$. The results of the 260mm circular geometry tests at this incident Mach number are described first and in most detail, followed by the test results on the $y=2x^2$ parabolic geometry at the same Mach number. The remainder of the tests on the other geometries and at higher Mach numbers did not show significantly different results except where discussed, and these are together covered in later sections.

9.1.1 Circular model tests at the weakest Mach number

Figure 9.1 shows a series of shock wave reflections taken from multiple shock tests, all at approximately the same incident Mach number, with $25\mu s$ increments in the

delay between consecutive images. The average Mach number of all the shock waves shown in the image, $\bar{M}_S$, is 1.035 with a minimum variation of 0.0002 and maximum variation of 0.0024. The exact M_s for each individual shock wave can be found in Figure 8.2.

At the point that the incident shock first meets the reflecting surface (out of view in Figure 9.1), it is perpendicular to the reflecting surface and at first there is no reflection. As the gradient of the reflecting surface increases, the incident shock wave meets the reflecting surface at a progressively greater angle. To adjust for this, the shock wave curves in an attempt to remain perpendicular to the reflecting surface, shown by a), b), c) and d) in the pre-reflection region of Figure 9.1 and as described in Section 1.3. This curvature at the root of the shock wave increases as the shock wave progresses along the reflecting surface until a discontinuity forms where the curvature on the shock is the greatest.

Up until this point, the shock wave interaction with the reflecting surface has been the same as that for the stronger shock case as described by (Skews et al., 2008). The shock at position e) of the MR reflection region of Figure 9.1 shows the point at which a discontinuity on the shock forms and a reflected shock is shown to emanate from it. Unlike the stronger shock case, there is no evident shear layer produced from this triple point. Even as the shock wave progress further along the surface to points f), there is still no evidence of a shear layer. At both of these points, the reflected shock meets the incident shock not at the reflecting surface but at some distance from it. The shock that joins this triple point to the reflecting surface would thus be a Mach stem, but the lack of a shear layer casts some doubt as to whether this reflection structure is that of genuine Mach reflection or something more akin to a von Neumann reflection. The identity of this reflection is discussed further in Section 9.2.

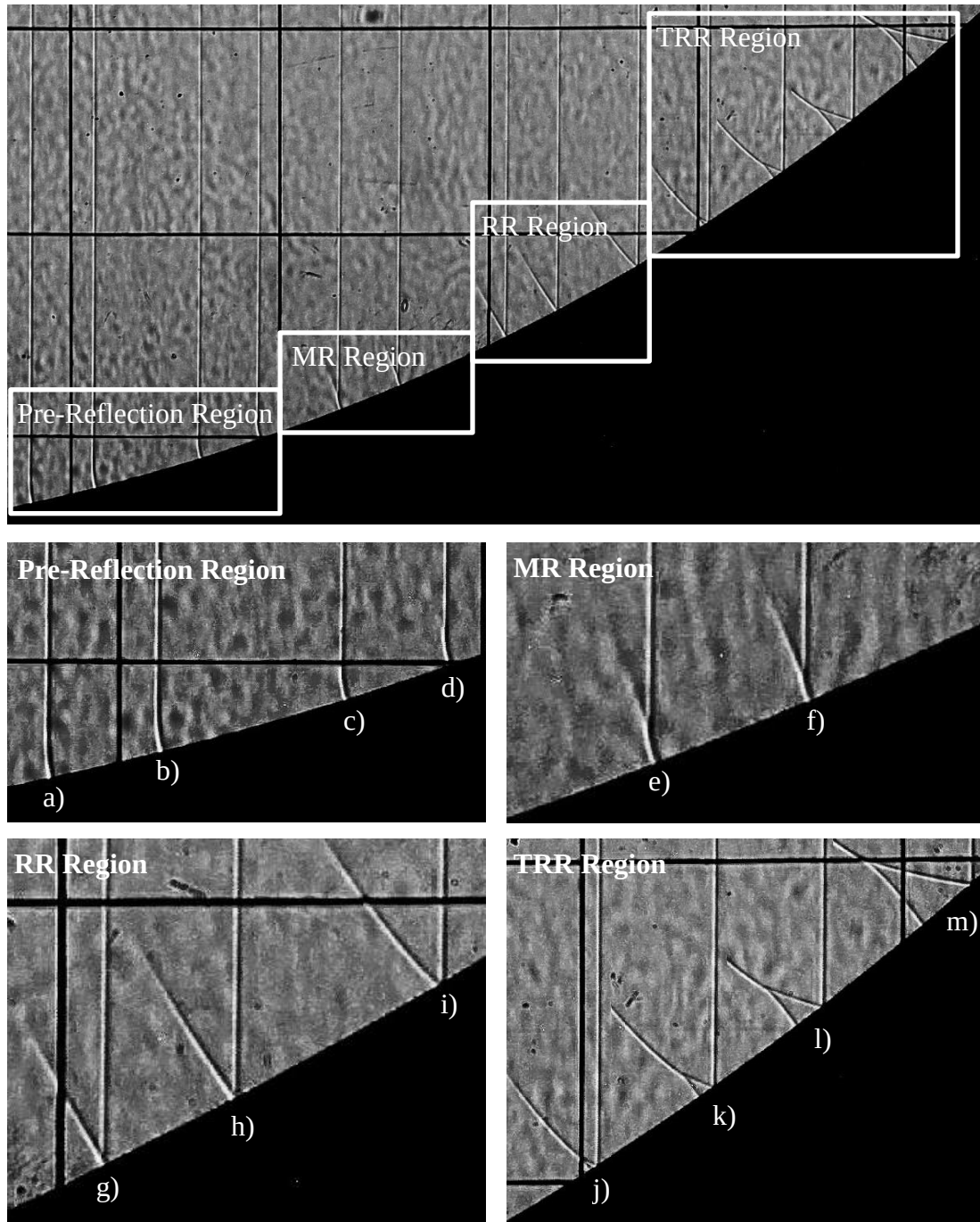


Figure 9.1: A composite image made up of shadowgrams taken from multiple tests at an average $\bar{M}_S$ of 1.035, each 25 μ s apart, encountering a circular model of 260mm radius, with close-ups of the regions of interest shown below.

For the strong shock case, once the triple point of the MR meets the reflecting surface, the reflection structure should immediately evolve into that of a TRR, with

an additional shock wave emerging from the reflection point and meeting the reflected shock wave at a new triple point. The dynamics shown in Figure 9.1 show that for the weak shock case, it appears that the transition to a TRR is not immediate. The shock wave at positions g), h) and i) of the RR region show that once the triple point of the MR has intersected the reflecting surface soon after f), a reflection structure that looks very much like that of RR persists for some time before the second shock wave and triple point, characteristic of a TRR, appear at position j) of the TRR region.

Like the supposed MR seen at e) and f), the TRR has no noticeable shear layer emanating from the triple point, and the reflected shock wave and additional shock wave seem to meet almost tangentially instead of at well-defined discontinuity as in the strong shock case. This is discussed further in Section 9.2. Another notable feature of these weak shock wave reflections is that the reflected shock is curved, unlike for strong shock wave reflections which have a straight reflected shock wave.

The shadowgrams obtained for the smaller radius circular model demonstrated similar characteristics. The smaller circular model had a radius of 130mm, half that of the model discussed above, resulting in the size of the reflections being scaled to half the size of those in image Figure 9.1. At this scale, the difference between a MR and RR was not clear as the Mach stem could not easily be differentiated from the incident shock wave, as discussed further in Section 9.2.

9.1.2 Circular model tests at other Mach numbers

Generating a higher Mach number of between $1.05 < M_s < 1.08$ in the shock tube required using two pieces of diaphragm material as described in Section 5.1.4. The diaphragm combination using two pieces of SG tinfoil did not generate very consistent Mach numbers. For the case of tests done on the circular model of 260mm radius, the mean M_s from this combination was 1.065 compared with a mean M_s of

1.068 for the combination of two HG tinfoil diaphragms. The results from these two sets of tests are therefore discussed together as their Mach numbers and results are very similar.

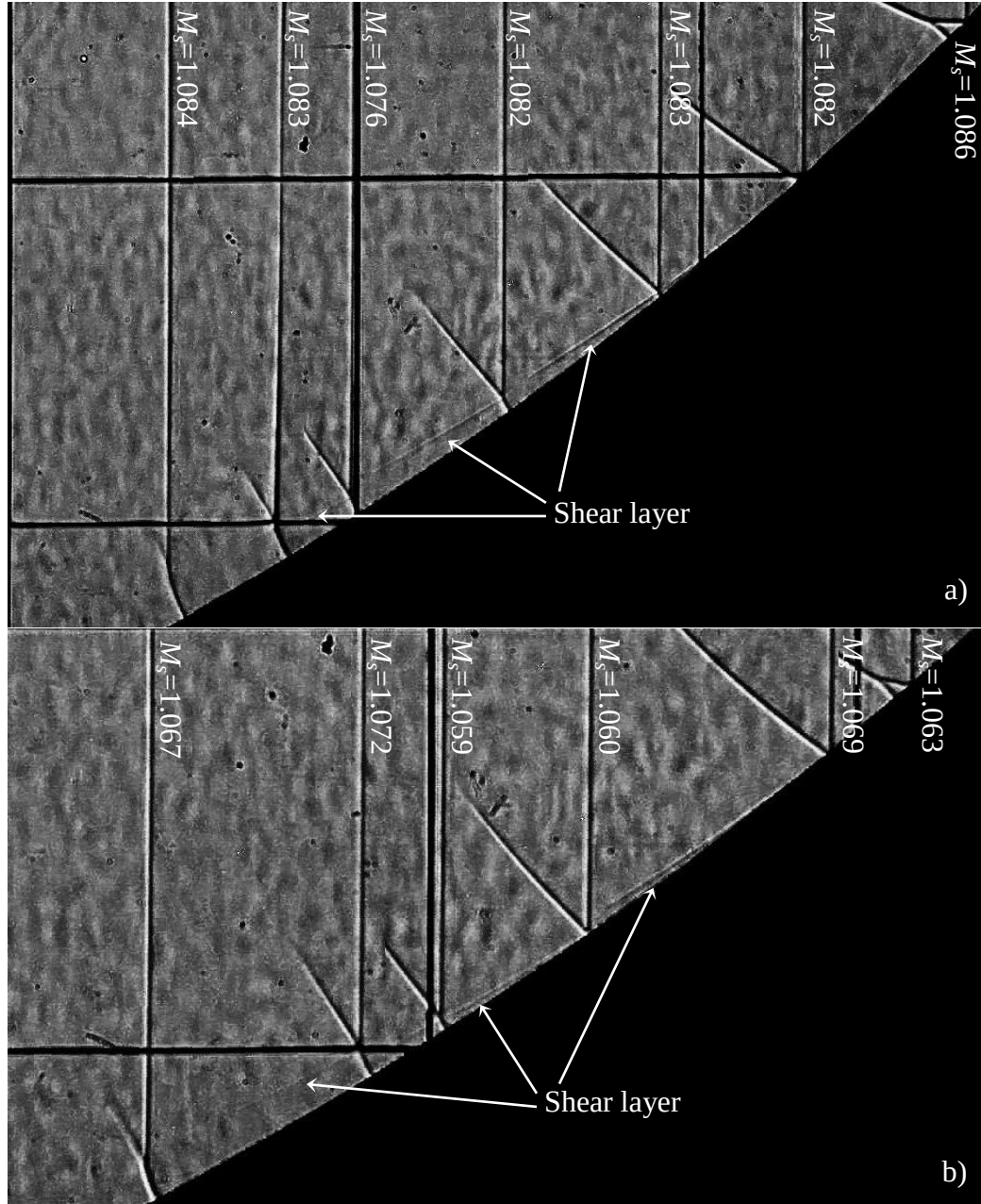


Figure 9.2: Shadowgrams of shockwave reflections off a circular model of 260mm radius at an average $\bar{M}_s$ of 1.082 a) and $\bar{M}_s = 1.065$ b), highlighting the presence of shear layer in the MR at higher Mach numbers

The transition of the reflection for the slightly higher Mach number shock waves can be seen in Figure 9.2. Although out of shot, the initial interaction is the same as for the weaker shock wave case, with the shock wave curving in the vicinity of the reflecting surface. We first see the shock from the point where the discontinuity and reflected shock forms.

For these higher Mach numbers, a shear layer can clearly be seen emanating from the triple point, implying that the initial reflection in the $1.059 < M_s < 1.085$ range is indeed a true MR. The triple point then meets the reflecting surface and unlike the $\bar{M}_s = 1.035$ case, the formation of the TRR is immediate, with the extra structures of the TRR appearing in the frame immediately following the frame at which the triple point can be seen meeting the reflecting surface.

Like the $\bar{M}_s = 1.035$ case, the reflected shock wave and additional shock wave of the TRR's in Figure 9.2 a) and b) appear to meet not at a discontinuous triple point but rather tangentially. For Figure 9.2b), although there is a shear layer produced from the triple point in the Mach reflections, there is no shear layer produced from the triple point of the TRR's which are captured at an M_s of 1.069, 1.063 and 1.066. However, in Figure 9.2a) a faint white line is seen connecting the triple point of the TRR to the surface at an M_s of 1.086, although much weaker in strength and less defined than the shear layers seen in the earlier Mach reflections.

9.2 Identification of the Shock Reflection

It is well known that the reflection structure at the acoustic limit is always regular, but it is unknown how far away from the acoustic limit the standard MR-TRR transition starts to appear. It has been assumed up until now that any shock wave strength above the acoustic limit follows the standard transition. One of the defining points of this study is therefore to determine the existence of a regular reflection at very weak

incident Mach number as one approaches the acoustic limit. To do this, it has to be differentiated from a Mach reflection.

As mentioned previously, the relatively small size of the reflection structures at the selected Mach number, combined with the resolution of the images made this differentiation not as straight forward as initially thought. For those cases where it was difficult to distinguish between a Mach and a regular reflection, three criteria were chosen to distinguish, with some degree of certainty, the existence of a Mach reflection. If any of these criteria were met it would indicate the existence of a Mach reflection.

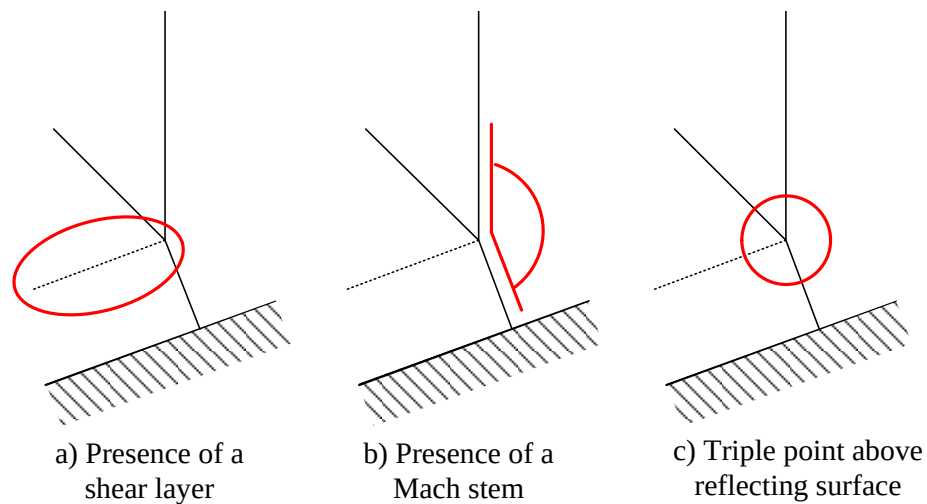


Figure 9.3: Schematic illustration of the three selected criteria used to distinguish a Mach reflection from regular reflection – presence of a shear layer (a) and/or Mach stem (b) and triple point above the reflecting surface (c)

The first and simplest criterion involved establishing the presence of a shear layer emanating from the incident shock wave at a visibly discernible distance from the reflecting surface. This would signify the presence of a discontinuity on the incident shock wave, most probably caused by a reflected shock meeting the incident shock wave at the triple point of a Mach reflection. The angle of the knife edge was oriented in the same plane as the incident shock wave in order to capture the shock wave and the predominantly vertically oriented flow features. With the shear layer typically being perpendicular to the shock waves being studied, the knife edge orientation had

the effect of reducing visibility of the shear layer. The faint features of a shear layer were therefore difficult to identify, but after some post-processing of the images, shear layers could be found in some of the reflections at the two higher chosen Mach numbers, but never in the reflections of the weakest Mach number tested.

The second criterion used to distinguish a MR from a regular reflection was to check whether the portion of the incident shock wave closest to the reflecting surface met it obliquely or perpendicularly. As shown in Figure 9.4, the Mach stem of a Mach reflection joins the incident shock to the reflecting surface, meeting it perpendicularly. If there is no Mach stem present, then the incident shock wave extends all the way to the reflecting surface, meeting it obliquely. Thus, if there is no sharp change in direction of the incident shock wave as it meets the surface, the reflection would be considered to be regular.

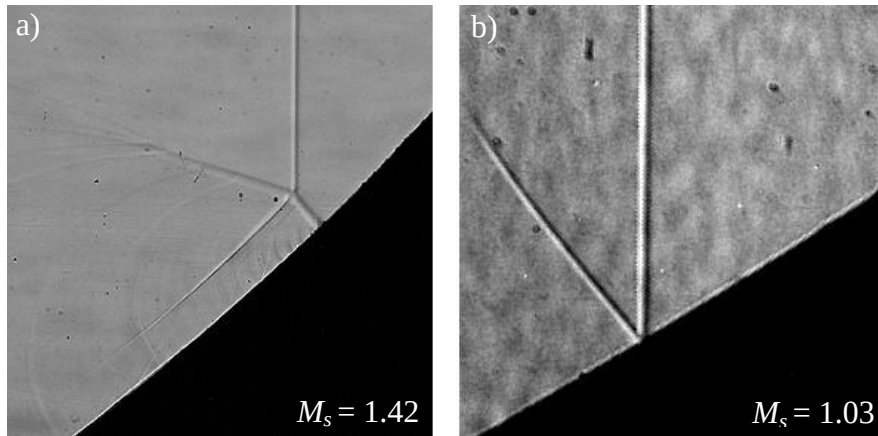


Figure 9.4: Typical examples of shadowgrams captured of a strong Mach reflection (a) and a strong regular reflection (b)

To determine if a particular shock reflection satisfied the second criterion, its image was digitally magnified until the individual pixels that made up the image could be seen. Because there is a sharp gradient across the shock wave, at this magnification, a line can easily be drawn between the two pixels of greatest colour gradient and projected down, representing the plane of the incident shock wave. Any pixels

deviating forward from this line would indicate the presence of some sort of a Mach stem, therefore indicating a Mach reflection.

The final criterion used to distinguish a Mach reflection from a regular reflection was identifying the presence of a reflected shock wave meeting the incident shock not at the reflecting surface, but at a clearly distinguished triple point. As shown in Figure 9.5a), the angle between the incident shock wave and the reflected shock wave in a MR for a strong incident shock wave is much greater than that for a weak reflection, showing a clear discontinuity at their intersection. The angle between the Mach stem and reflected shock wave is also clearly visible for the stronger shock, but for the weaker shock wave, the reflected shock wave appears to merge with the incident shock wave almost tangentially, so that a clearly defined triple point or discontinuity is not as easy to discern. This is especially true if there is no visible shear layer present as in Figure 9.5b), which was the case for all the tests at the weakest Mach number of $M_s = 1.03$.

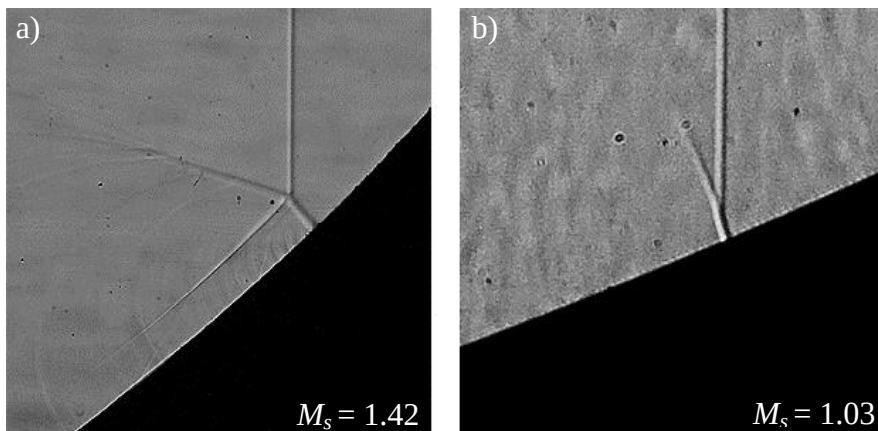


Figure 9.5: Typical examples of shadowgrams captured of a strong Mach reflection (a) and a very weak Mach reflection (b)

Establishing the third criterion on the models of greatest radius (circular model of 260mm radius and parabolic model of equation $y = 2x^2$) was less difficult than for the rest of the models. On the smaller radius models, the reflections were much smaller because of the smaller radius and having less time to develop. As such, the reflection

itself is captured by fewer pixels on the camera sensor than for the larger models. This, along with the very acute angle between the incident shock wave and reflected shock at weak Mach numbers, made it very difficult to establish the third criterion for the smaller models. Because of this, an investigation was done to determine at what resolution a clearly defined MR without a slipstream would start to look like a RR like those found for smaller models.

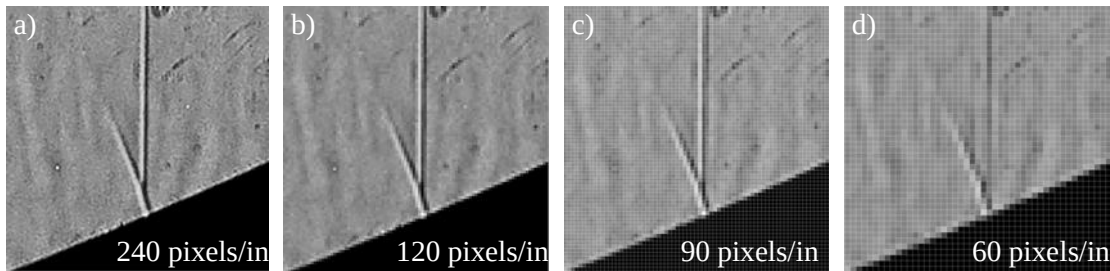


Figure 9.6: Multiple instances of the same image at various resolutions demonstrating the effect that decreasing resolution has on MR classification

Figure 9.6a) shows a shadowgram of a MR that was captured in this study. It is at the native resolution, 240 pixels per inch, at which all pictures in the study were captured with the 12.1 megapixel CCD of the Fujifilm S3 Pro camera. At this resolution, the incident shock wave is approximately 6 pixels in thickness, and the flow features are clearly defined. At half the resolution shown in Figure 9.6b), the incident shock is about 4 pixels thick followed by 3 pixels thick at 90 pixels per inch for Figure 9.6c) and 1 pixel thick at 60 pixels per inch respectively in the last image. In Figure 9.6d), it is difficult to distinguish where the reflected shock wave is meeting the incident shock wave and the reflection could be mistaken for a RR. Thus it can be deduced that any flow features equal in size or smaller than the pixel size of the image cannot be distinguished with any certainty. With the imaging system laid out as it was, the physical size of the area covered by a single pixel in the images captured for this study is approximately 0.0625mm by 0.0625mm. This limitation also implies that any deviation in angle, such as the angle of the Mach stem, smaller than the thickness of the shockwave, would not be clearly distinguishable.

Similar investigation on the images used in (Skews et al., 2008) shows them to have a resolution of 72 pixels per inch. Figure 9.7b) shows an example of an image taken from (Skews et al., 2008), magnified to the point at which you can see the individual pixels that make up the image. The incident shock wave is approximately 2 pixels thick, and as such, any detail in the region of the triple point is very close to being lost at this resolution.

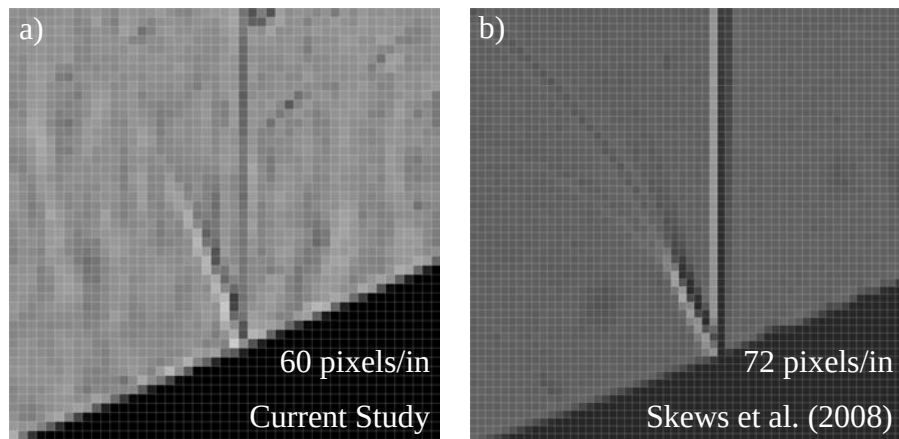


Figure 9.7: Magnified shadowgram (a) of a MR from the current study reduced in resolution enough to resemble an RR compared to a shadowgram (b) at full resolution captured by Skews et al. (2008)

9.3 Reflection Classification

Using the three previously mentioned criteria, the shock waves in each of the images contained in Section 8 were analysed and the reflection structure termed as either having no reflection where the shock wave was bending forward, a MR, a RR or a TRR. The distance from the leading edge of each model to the position of the incident shock wave at which each of these reflection structures exist was then measured, and defined here as the shock waves penetration. Normalising these results by dividing all the penetrations on circular models with their respective radius and plotting the result

against the M_s at which they occurred can be seen in Figure 9.8. Results from the parabolic models were not included as they could not be normalised using a common scaling factor in the same way that results from the circular models were done.

As expected, there is initially no reflection configuration where the shock wave is curving forward to remain perpendicular to the reflecting surface. The region over which this occurs increases with increased Mach number. A region then exists in which a MR configuration exists, before becoming a RR.

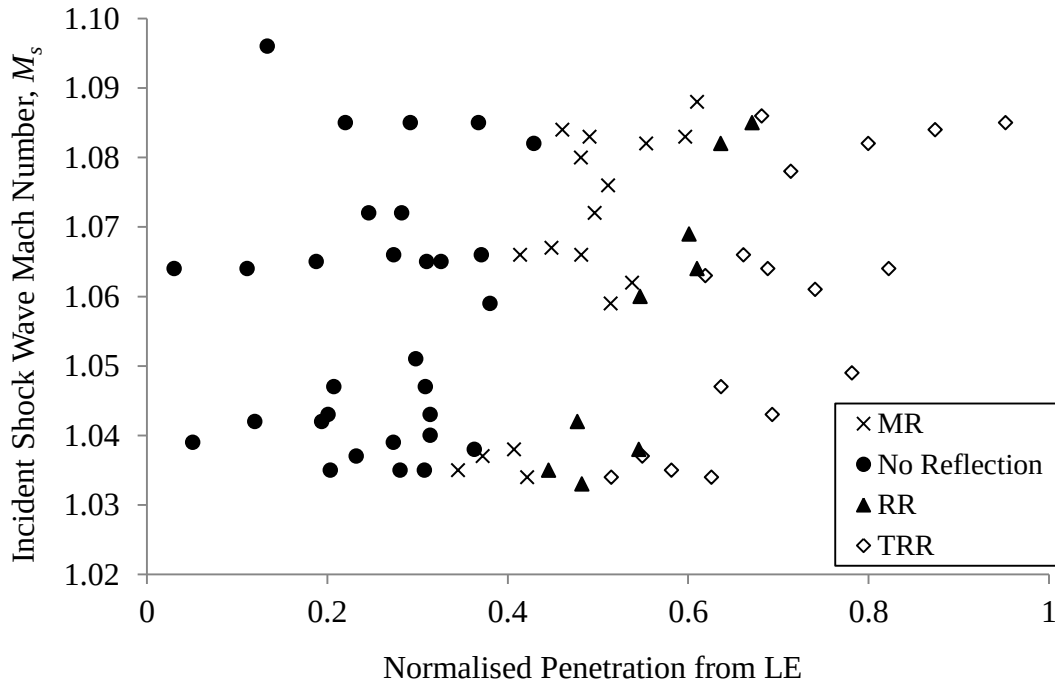


Figure 9.8: Scatter plot summarising the reflection configurations after classification for all circular models tested

Although termed a RR here, for stronger Mach numbers this may instead be an instant in time at which the transition from MR to TRR exists and just takes on the appearance of an RR. This can be seen at the higher Mach numbers where only a single penetration shows a RR configuration for a given Mach number. However, at the weaker Mach numbers, there is more scatter for the region in which a RR configuration is seen, and a range of penetrations exist for a given Mach number.

Error bands on the measured penetration of the shock wave were less than 1.9% and for the region in which the RR exists, the error bands do not overlap into the other regions, showing confidently that the transition to TRR is not instantaneous at the lower Mach numbers. The scatter also shows, as expected, that the appearance of the MR and the transition to TRR is increasingly delayed as the Mach number is increased. This is due to the strength of the shock wave being able to maintain its initial curvature for longer.

9.4 Trajectory of the Triple Point

To confirm the existence of a region in which the RR persists prior to TRR formation, the trajectory of the triple points were studied. Projecting the trajectory of the triple points allows us to estimate where they will terminate or emerge from the reflecting surface. To project a triple point trajectory onto the spliced images, a set was required that exhibited at least 3 instances of a MR and 3 instances of a TRR. This would allow a curve to be fitted between the triple points of each type of reflection to determine where the triple point trajectory meets the reflecting surface. Due to their shallower gradient, only the largest of the circular and parabolic models, $R = 260\text{mm}$ and $y = 2x^2$ satisfied these requirements and the triple point trajectories were projected onto them and are shown in Figure 9.9.

For the case of a strong shock wave, the transition from MR to TRR should be instantaneous, therefore the trajectory of the triple points, shown as the yellow lines in Figure 9.9, for the MR and TRR should meet at the reflecting surface at the instance that transition takes place. However, what we see in Figure 9.9 for the case of very weak shock wave reflections is that the triple point trajectories of the MR and TRR do not meet for both parabolic and circular geometries.

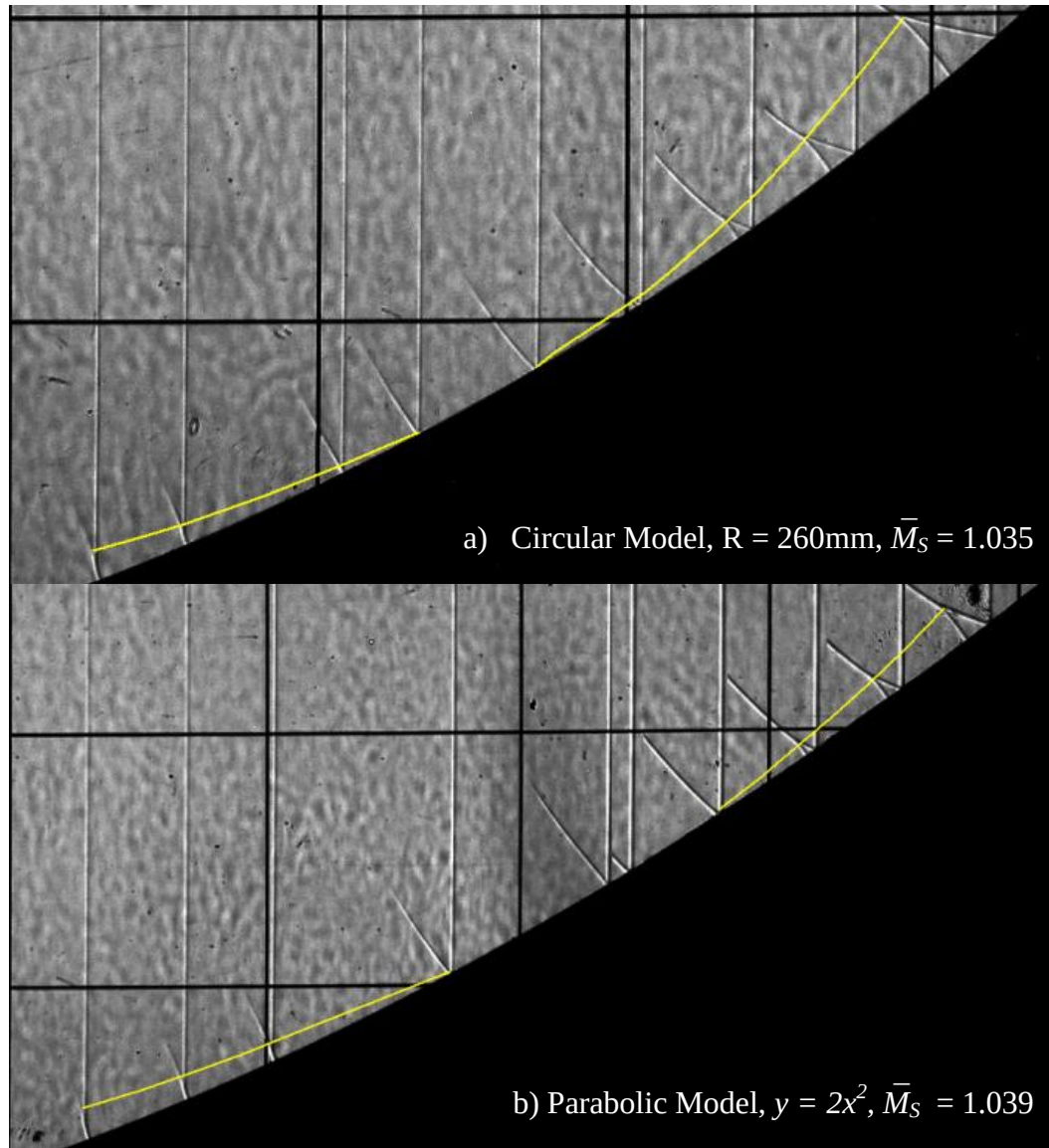


Figure 9.9: Superposition of the triple point trajectories onto combined shadowgrams for the largest circular (a) and parabolic (b) models

In both Figure 9.9a) and b), the trajectory of the triple point of the MR terminates on the reflecting surface and only at some distance later does the triple point of the TRR emerge. Even though the average Mach number for Figure 9.9b) is slightly higher, the emergence of the triple point is more delayed than for Figure 9.9a), which is expected because the parabolic geometry has a slower gradient increase. It must be noted however that the effect of Mach number variation for each consecutive image means that the triple point trajectories are not sharply defined lines as shown here, but

are instead thicker bands in which the triple point could lie for the given range of Mach numbers denoted by the average.

9.5 Mach Stem Length

An analysis of the Mach stem length at the point at which the MR first appeared was then done. Considering the criterion used to distinguish the RR from a MR, the first appearance of the MR was deemed to be the first point at which a discontinuity on the incident shock wave could be seen. The perpendicular distance from this discontinuity to the reflecting surface was then measured. For the case of a concave curved reflecting surface, the MR would be of the InMR type from its creation to the point at which it transitions, and thus the Mach stem would have its maximum length at the point at which it first appears. The results of these measurements can be seen in Figure 9.10.

Considering the point made in Section 9.2 regarding the ability to distinguish very small features at the set resolution, a Mach stem smaller than the thickness of the shock wave as it is captured in the shadowgram would be indistinguishable from the incident shock wave itself. We can see in Figure 9.10 that Mach stems measured off the smaller circular model and the two steeper parabolic models were typically 2mm or less and thus very difficult to distinguish.

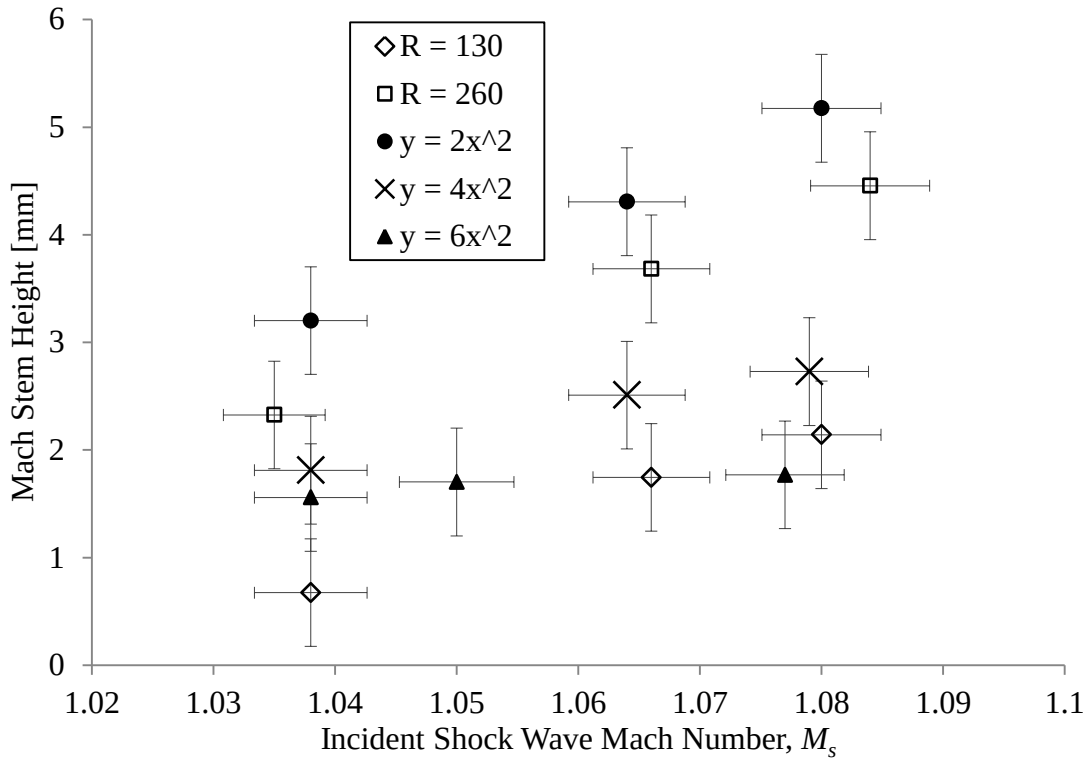


Figure 9.10: Scatter plot summarising the length of the Mach stems measured on all Mach reflections picked up in the experimental results plotted against M_s

As seen in Figure 9.6, at these sub 1.1 Mach numbers, the angle that the reflected shock wave made with the incident shock wave was almost collinear with the Mach stem, making determination of the locus of the triple point more difficult. Therefore, the first sign of a discontinuity on the incident shock wave was used as the point from which to measure the Mach stem length and as a result, the propagation of error in the measurement of the error band, on average close to half a millimetre, was however relatively large compared to the measured length.

The short length of the Mach stem combined with the angle of the reflected shock wave make distinguishing a MR from a RR even more difficult on the smaller models, suggesting that the persistence of the RR would more likely be seen on the smaller models. However, it is on the larger models that the persisting RR is most evident at the lowest Mach number. These models have the largest initial Mach stem

height and the most number of shock waves captured prior to transition, making the existence of a delayed TRR transition very clear.

9.6 Transition Wedge Angle

As mentioned in Section 2.2, (Ben-Dor, Takayama and Dewey, 1987) give an analytical prediction of the wedge angle at transition, θ_w^{tr} , over a range of $1 < M_s < 1.15$ for a shock wave with glancing incidence, as is the case in this study. Measurements of the wedge angle for each of the instances of RR determined previously were made and compared to the wedge angles at transition calculated by (Ben-Dor, Takayama and Dewey, 1987). Only the circular models can be compared resulting in very few data points, but the comparison, seen in Figure 9.11., shows that for the higher Mach numbers, the RR is occurring very close to the wedge angle at which normal MR-TRR transition should occur. This is expected because as mentioned previously, the RR seen here is the instant of MR-TRR transition. The uncertainty in measurement of the angle was small in comparison to the measurement itself, less than 0.8%, and therefore would have little effect on the scatter of the measured results. Conversely, the propagated uncertainty in the measure of the shock waves Mach number can be clearly seen on the figure to be significant enough that the measured angle could be predicted by the analytical solution.

However, at the lower Mach numbers, there is more deviation of the wedge angle from the analytical prediction, which is due to the wide range of wedge angles over which the RR persisted before transitioning to a TRR.

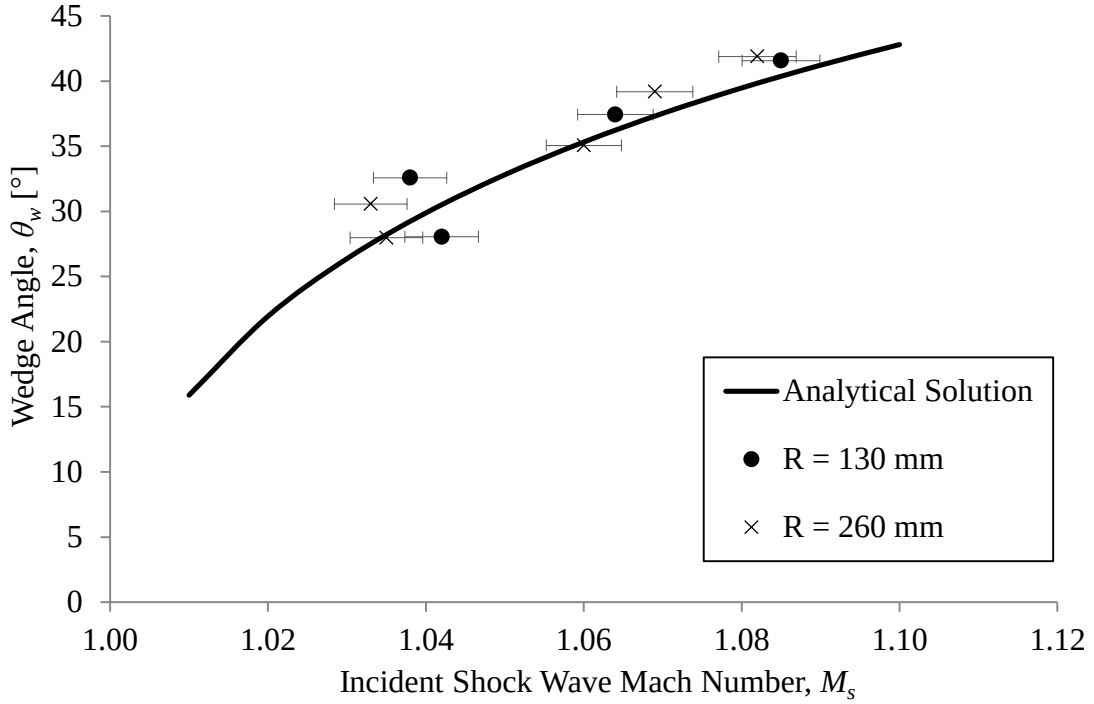


Figure 9.11: Scatter plot of measured wedge angle (θ_w^{tr}) for regular reflections seen in this study compared to the analytical solution for θ_w^{tr}

9.7 Absence of a Shear Layer

The persistence of the RR before transformation to TRR may in part be explained by the same reason that there is no visible shear layer in the wake of the triple point. (Henderson and Lozzi, 1975) hypothesized the need for the additional shock wave in wake of the triple point to adjust for the sudden pressure drop caused by the sudden transition from MR to TRR. The lack of a visible shear layer may indicate the absence of a sharp slope discontinuity on the incident shock wave, but rather a finite region over which the reflected and incident shock waves merge. This is further supported by the very small acute angle between the reflected and incident shock waves, as well as the difficulty in distinguishing a clearly defined termination of the Mach stem.

As mentioned in Section 9.1.1, the lack of a shear layer is akin to another very weak shock wave reflection, the vNR. The likeness to a vNR is further supported by the lack of a clear slope discontinuity between the incident shock wave and Mach stem. The images captured at the lowest Mach numbers show what looks rather like a single shock wave front with a smoothly turning tangent near the triple point, as described for a vNR in (Ben-Dor, 2001). (Ben-Dor, 2001) goes further to say that for the case of a vNR, the point at which the three shocks meet is not a well-defined triple point, as seen here.

9.8 Effect of Optical Misalignment

Another possible hypothesis for the existence of the RR is that the instantaneous transition from MR to TRR is masked by a very small misalignment in the optical setup for the experimental results. As described in Section 9.10, the numerical results are unable to clearly resolve the triple point in the vicinity of the reflecting surface, and the large amount of noise in the simulations aggravates this further. This study is therefore heavily reliant on the experimental results. With the parabolic mirrors being almost two metres from the test section, a slight misalignment will be greatly amplified. The hypothesis is that should the beam of parallel light passing through the test section not be perfectly collinear with the plane of the reflecting surface then a small shadow might be created by the model which may obscure the Mach stem as it gets shorter and approaches the reflecting surface. If the beam was misaligned in the vertical plane, this shadow would have greatest effect on the region of the model with the lowest gradient. For these weak Mach numbers, the transition should indeed occur much earlier than for stronger Mach numbers, at a much lower gradient, and the Mach stem when it forms has already been shown to be very short. An exaggerated example of the effect of such a misalignment can be seen in Figure 9.12.

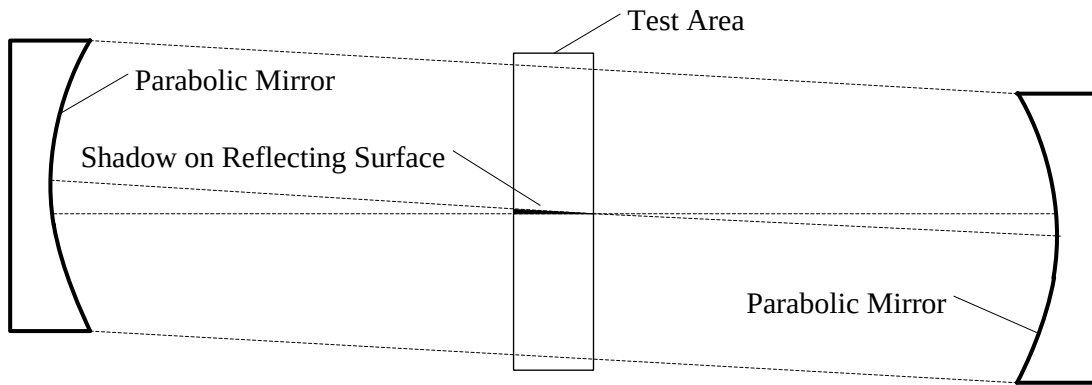


Figure 9.12: Schematic illustration of the effect that a small optical misalignment can have on creating a shadow that could partially obscure the Mach stem of a MR

With the mirrors at 1718mm from the test section, a 1mm high shadow would be produced by the mirror being 22.29mm off the centre plane. A misalignment of just 5mm on the mirror would produce a shadow 0.22mm in height. This would be enough to mask the very short Mach stem of the weak reflections as it approached the reflecting surface and make it appear as if the transition to RR reflection is delayed. A possible check for this would be to see if the incident and reflected shock waves of the TRR meet on the surface, however the appearance of the TRR is often at a point of higher gradient, where the shadow would have reduced effect. To try and minimise the effect of misalignment during testing, the alignment of the test section with the parabolic mirrors was checked with a self-levelling laser sheet as well as with plumb lines and spirit levels strung from the centre lines of the mirror and test section window. The possibility of the same optical misalignment being present in both this study, and that done by (Skews et al., 2008) is however unlikely.

9.9 Comparison with Parabolic Models

For the models with parabolic geometries, the increase in gradient is constant, unlike for the circular geometries. Parabolas are self-similar, the coefficient a in the Cartesian equation of the parabola $y = ax^2$ is merely a scaling factor which scales the parabola without distortion. Decreasing the coefficient between the models tested has the same effect as increasing radius on the circular models; it zooms into a section of

curvature. The parabolic model with the smallest coefficient, $y=2x^2$, should therefore offer the most detailed view on evolution of the shock wave reflection.

As for the circular model case, the tests done at the weakest Mach number are discussed in detail first, as they are most relevant to this study. This is followed by discussion of the tests at higher Mach numbers and on other parabolic geometries.

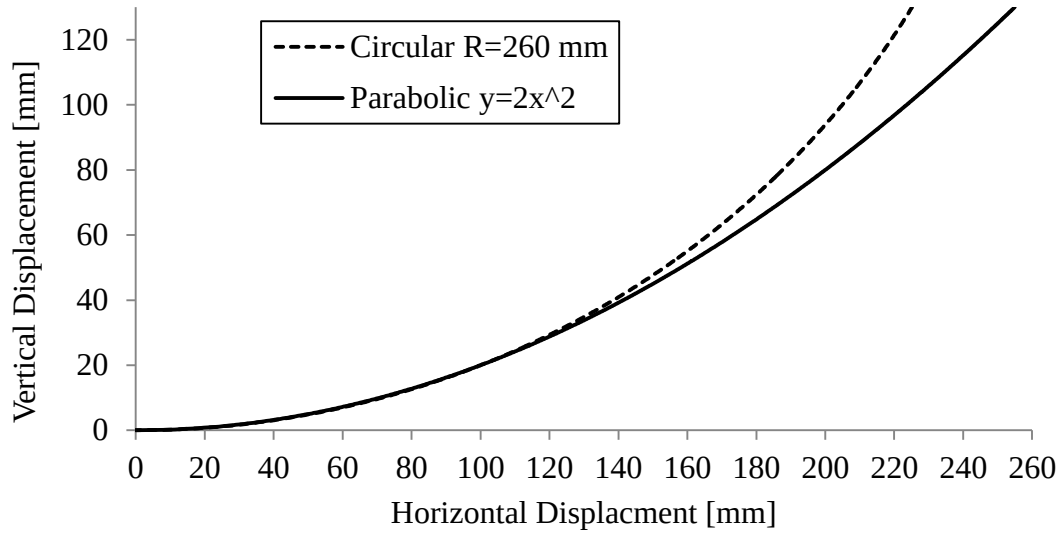


Figure 9.13: Diagram highlighting how similar the gradient of both the shallow circular and parabolic geometries are for the first 120mm of penetration

As Figure 9.13 shows, the difference between the parabolic geometry of equation $y=2x^2$ and the circular geometry of 260mm radius is minimal. Up until a penetration of approximately 120mm, the incident shock wave should exhibit approximately the same reflection evolution as the circular case. From 120mm onward, the reflection from this point should evolve slower for the parabolic case when compared to the circular geometry due to the shallower gradient. For the circular geometry of 260mm, the RR for the $\bar{M}_S = 1.035$ was first seen at approximately 91mm penetration and the first appearance of a TRR at approximately 136mm. (approximate figures given because the leading edge of the model for the 260mm radius model was out of view). The gradients of the two different geometries start visibly diverging soon after the

point of appearance of the first RR on the circular model, so for the parabolic geometry it would be expected that due to the slower gradient change of the parabola, the appearance of the TRR would be delayed by a small margin when compared to the 260mm geometry. This is confirmed by Figure 9.9.

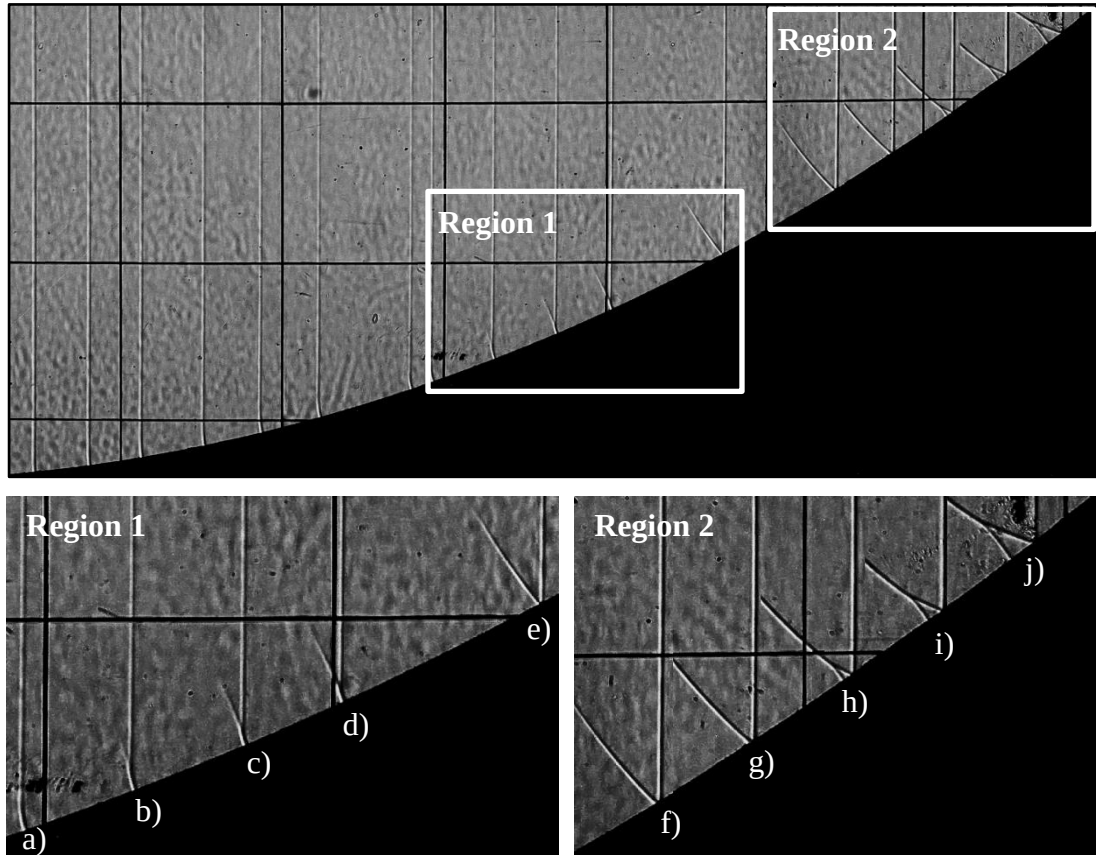


Figure 9.14: Two close-ups showing reflection details for a set of combined shadowgrams of multiple shock waves with an average $\bar{M}_S = 1.039$ at $25\mu s$ intervals reflecting off a parabolic model of equation $y=2x^2$

The shock wave evolution for an average $\bar{M}_S = 1.039$ shock wave reflecting off a parabolic model of equation $y = 2x^2$ is shown in Figure 9.14. It exhibits an almost identical evolution as the average $\bar{M}_S = 1.035$ case reflecting off a circular model of 260mm radius. Upon initially meeting the reflecting surface of the model, the incident shock wave remains planar before curving forward slightly in the region close to the reflecting surface so as to remain perpendicular to it. At a), a

discontinuity begins to form on the incident shock wave at the point of greatest curvature. As the shock progresses to b), c) and d), this discontinuity develops into a reflected shock wave meeting the incident shock wave at some distance away from the reflecting surface, and is thus termed a MR. The triple point of the Mach reflection intersects the reflecting surface at e), and the reflection configuration takes on the appearance of a RR. This RR persists until h) where the additional structures of a TRR can be seen to be emerging in the wake of the reflected shock wave.

For the tests done at higher Mach numbers on the parabolic model of equation $y = 2x^2$, the results were not markedly different to those done at the higher Mach numbers on the circular model of 260mm radius. For a shock wave of average $\bar{M}_S = 1.066$ shown in Figure 8.9, the slower gradient change gives the MR more time to develop, and at this speed, a shear layer can be seen to have developed before the triple point intersects the surface. The emergence of the TRR is still delayed at this Mach number until the incident shock wave is almost out of frame. At a slightly higher average Mach number of $\bar{M}_S = 1.082$ shown in Figure 8.10, the triple point of the MR does not have enough time to intersect the reflecting surface before going out of frame. The incident shock wave captured with the greatest delay had a slightly higher average $\bar{M}_S = 1.091$ and exhibits a clear shear layer along with a straight reflected shock and Mach stem, indicative of the InMR seen for stronger shock cases.

The tests done on the other parabolic models of coefficient 4 and 6 exhibited a far more rapid reflection evolution than for the coefficient of 2. The MR exists for a very short time, with the Mach stems being barely long enough to measure, making them very difficult to distinguish from a RR. Because the reflection evolution transitioned to TRR very rapidly, it was possible to capture a well-developed TRR produced from a weak shock wave. Figure 9.15 shows the TRR caused by a $\bar{M}_S = 1.063$ shock wave on a parabolic model of equation $y = 4x^2$.

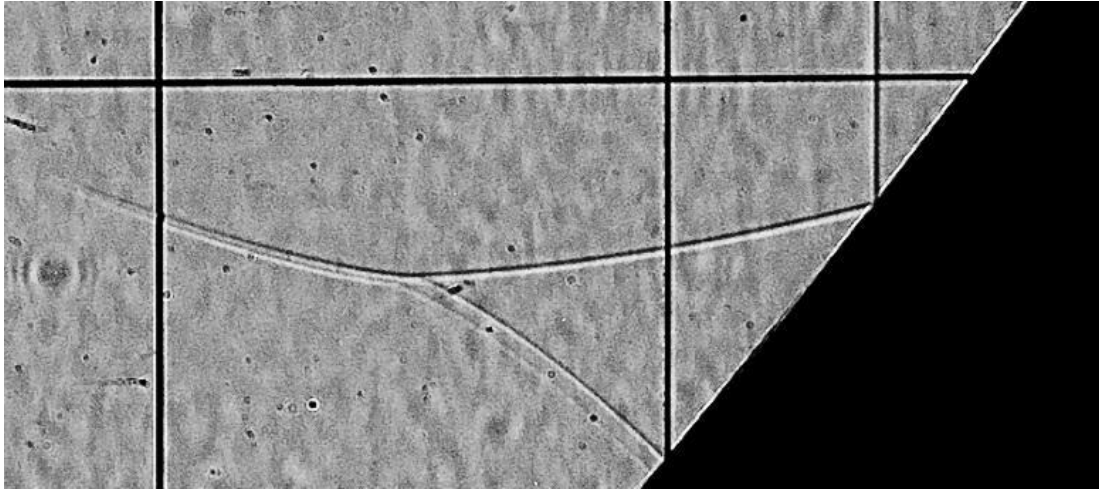


Figure 9.15: Shadowgram depicting the curved wave structures of a very late TRR produced from a $M_s = 1.063$ shock wave encountering a $y = 4x^2$ parabolic model

Unlike the depiction of the TRR shown in (Ben-Dor, 2007), all the shock waves other than the planar incident shock wave are non-straight as described by (Skews, Kleine and Barber, 2007). The reflected shock wave and the additional shock wave of the TRR also do not meet at a slope discontinuity, but seem instead to merge into one another tangentially, very much like the Mach stem and the reflected shock waves seen on the very weak reflection on the larger radius models. Rotating the image ninety degrees anti clockwise and cutting out the incident shock wave and reflecting surface produces an image very similar to the depiction of a vNR as shown in (Ben-Dor, 2001), with a single shock wave front, turned smoothly forward in the vicinity of the triple point. The double image of the additional shock wave and part of the reflected shock wave imply that the additional shock wave might not be entirely perpendicular to the viewing plane.

9.10 Numerical Results

Due to the difficulty in producing very weak shock waves of a consistent Mach number and the requirement for a very sensitive imaging system to pick up the even weaker shock reflections, it was determined to see if numerical simulations could be run of the same test case as the experimental tests. The numerical code, developed in

the flow research unit by (Felthun, 2002), was designed to simulate compressible flows in the $1.1 < M_s < 1.5$ range, so there was some question before starting as to how successful it would be at solving weak flow domains of $M_s < 1.1$.

The resolution of the simulation is determined by the cell size of the mesh, and the flow features it resolves is determined by a user defined minimum density gradient between two neighbouring cells in the mesh. If this density gradient is found between two cells, then that cell is split a user defined number of times per pass and the flow equations for that cell are recalculated a user defined number of times in that same pass. Any pair of cells with a density gradient less than that predefined minimum is not analysed further and is essentially filtered out. For the weakest case to be tested, an incident shock wave of $M_s = 1.03$, 0.006 was selected as the density gradient between two cells of the mesh. This gradient was at the bottom limit of what could be used, anything lower and the amount of noise resolved in the simulation made it almost impossible to distinguish the flow features from the noise in the vicinity of the shock wave.

To compare to the experimental results shown by (Skews et al., 2008), initial simulations were performed using the same M_s of 1.025, and atmospheric conditions as those recorded for their shock tests which showed the RR. By taking the second derivative of the density in the cells of the mesh, numerical shadowgrams were produced from the simulation's data files for comparison with the experimental shadowgrams and are shown in Figure 9.16.

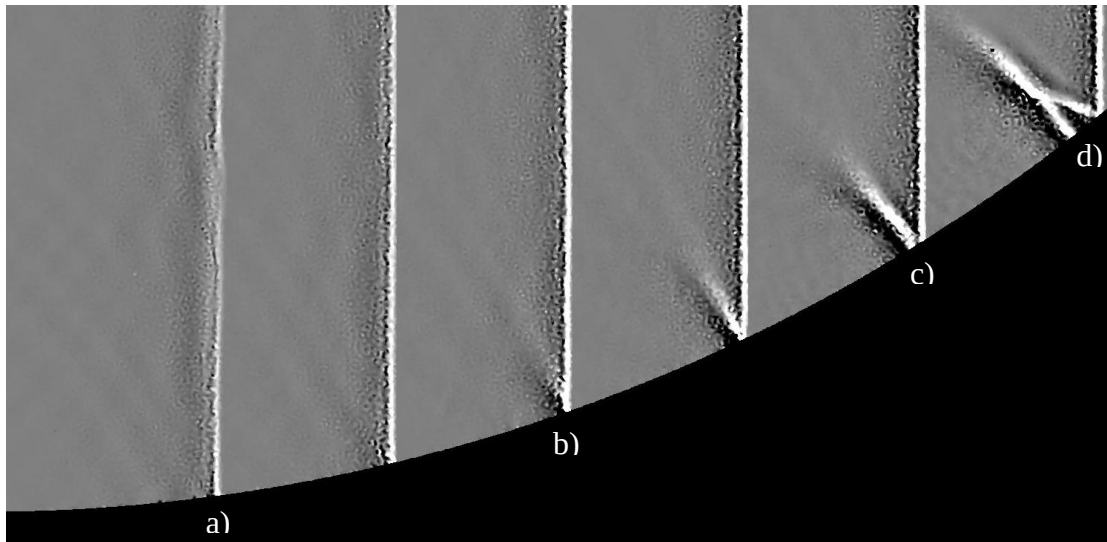


Figure 9.16: Numerical shadowgram of a $M_s = 1.025$ shock wave encountering a circular model of radius 260mm, showing the inability to resolve a sharply defined shock wave at the lowest tested Mach numbers

Despite allowing two characteristics lengths and three mesh refinements for the incident shock wave to develop, it was still not fully formed upon reaching the circular model as seen at a). It resolves soon after that, but remains too thick to see any development of curvature near the reflecting surface as seen at b). The large amount of numerical noise hides any small flow feature in the wake of the incident shock wave. A reflected shock wave is resolved at c) but is too thick to identify the reflection as either MR or RR. The additional shock wave of the TRR is seen at d), but is again too thick to clearly resolve a defined triple point.

Simulations done of an $M_s = 1.03$ incident shock wave showed an almost identical result, but at an M_s of 1.05, the incident shock wave had fully formed before intersecting the model and had better resolved flow features than for the $M_s = 1.03$ case. An example of the shock wave reflection evolution can be seen in Figure 9.17

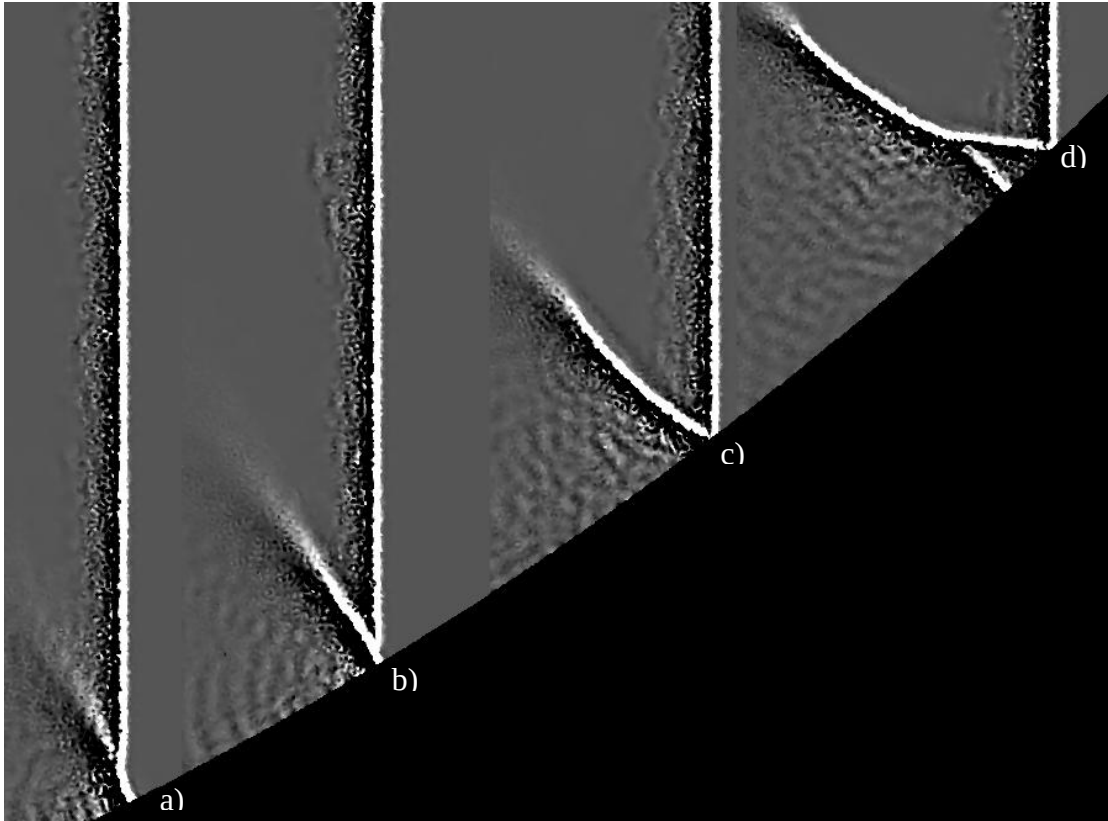


Figure 9.17: Numerical shadowgram of a $M_s = 1.05$ shock wave encountering a $y=4x^2$ parabolic model, showing the sharper defined shock features at higher Mach numbers

The start of a MR and a Mach stem that is not collinear with the incident shock wave can clearly be seen at a). The MR at position b) appears to be very close to have having its triple point intersect the surface, and at c) a reflection configuration resembling that of RR is seen before transitioning to a TRR at d). Although difficult to discern the difference between a MR and RR in the simulations, applying the second criterion described in Section 9.2 by checking to see if the incident shock wave was planar all the way down to the surface showed that the appearance of the additional shock of the TRR was not immediately after the instance in time that the incident shock wave was found to be planar all the way down to the reflecting surface, supporting the observations made by the experimental results. This was true for all the Mach numbers tested in the simulations.

Another notable observation from looking at the simulations is the shape of the reflected shock wave. The reflected shock which develops in the Mach reflection remains straight until the triple point intersects the reflecting surface. Over the region in which the RR is seen to exist, the reflected shock wave is seen to start curving toward the incident shock wave, similar to the kink in the reflected shock wave that is described by (Takayama and Sasaki, 1983). This curvature increases until the additional shock wave of the TRR appears.

Simulations of $M_s = 1.08$ incident shock waves showed very similar results to the $M_s = 1.05$ case albeit for a later transition to TRR. None of the simulations at any of the Mach numbers tested resolved a shear layer in the wake of the MR or TRR. Velocity contours of the data files show no discontinuous change in the wake of the reflection indicative of a shear layer.

In Figure 9.17b), a small indentation can be seen in the incident shock wave close to the triple point. Closer inspection of the resolution of the shock wave showed this indentation to be the breaking down of the incident shock wave where it met the reflected shock wave as the triple point approached the surface. This breakdown can be seen in the contours of constant density shown in Figure 9.18.

The density contours that define the incident shock wave start to diverge as the incident shock wave is about to meet the reflecting surface. The point at which the reflected shock wave meets the surface is directly below where the incident shock wave should meet the surface if one projects a line straight down following the plane of the incident shock wave, indicating that this is at or very close to the point of transition. The breakdown of the incident shock wave makes it ambiguous as to whether the reflection is a RR or a MR at the instances for which it exists.

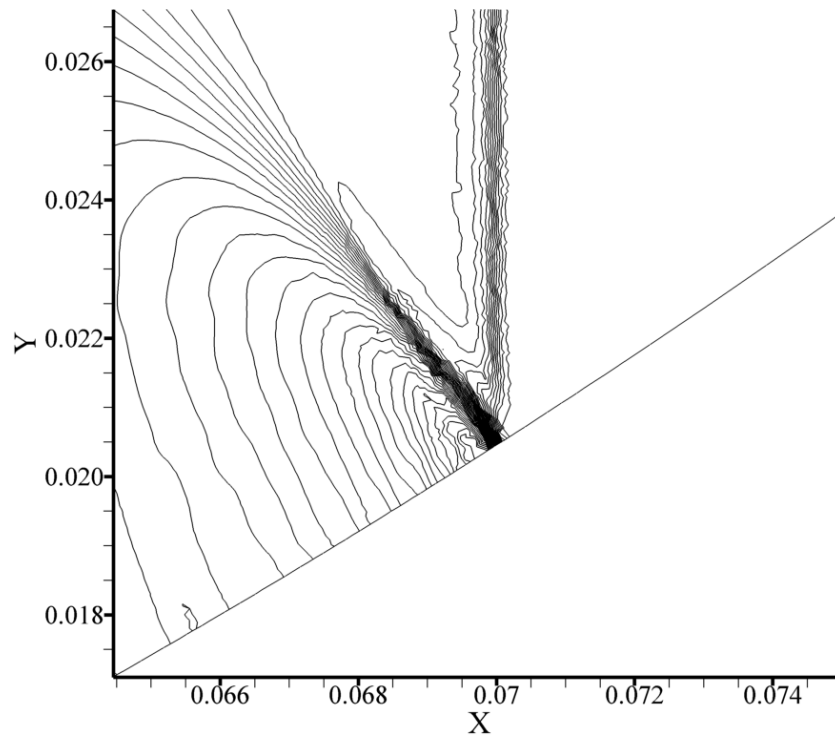


Figure 9.18: Plot of numerical constant density contours around a MR just before transition, showing the breakdown of the shock wave close to the reflecting surface

Due to the inability of the simulations to clearly resolve the shock wave and reflections at the lowest Mach number of $M_s = 1.03$, the breakdown of the triple point as it approached the surface, and the large amount of numerical noise obscuring the flow features being studied, it was deemed that the numerical simulations did not add sufficient detail to the study to provide information in addition to that which was already provided by the experimental testing.

Ultra high resolution simulations were performed by (Hakkaki-Fard and Timofeev, 2011) after the results of this study were completed. They produced both viscous and inviscid solutions of shock waves encountering convex surfaces, with the grid refined enough to resolve to the physical thickness of the incident shock wave. Although for the convex case, their inviscid solutions showed that the instance in time at which the flow just behind the reflected shock wave becomes sonic coincided with the instance in time at which disturbances in the wake of the incident shock wave catch up to the

reflection point. This would confirm the suggestion by (Ben-Dor, 2001) that the transition from MR to TRR occurs when the corner signal met the triple point of the MR at the reflecting surface. These inviscid results also contradict the findings of (Skews et al., 2008) – that disturbances in the wake of the incident shock wave have no influence on the transition from MR to TRR.

(Hakkaki-Fard and Timofeev, 2011) go further to say that the finite shock wave thickness observed in experimental results, which is a few orders of magnitude thicker than the physical shock wave thickness, may lead to a delay in the detection of the sonic point in experimental studies. Their own viscous solutions with a finite shock wave thickness show that although the sonic and catch-up points still coincide, they are delayed. This is comparable to the results of the current study discussed in Section 9.2 wherein it is explained how the effect of the thickness of the shock wave and the number of image pixels that captures it has an effect on the classification of the reflection geometry and could ultimately lead to a MR being misclassified as a RR. Viscous solutions by (Hakkaki-Fard and Timofeev, 2011) that included the no-slip boundary condition show the sonic and catch-up point to be even further delayed when compared to those with the slip condition, implying that boundary layer effects could have an effect on transition for concave surfaces. In the current study, boundary layer growth in the region immediately behind the primary reflection point may therefore also have an influence on the delay in transition from MR to TRR, especially at such low M_s .

10 CONCLUSION

Shock wave reflection configurations were investigated for the case of very weak shock waves reflecting off curved, concave wedges with zero initial wedge angle. This was done primarily to investigate the possible existence of a pure regular reflection prior to the formation of additional shock waves associated with a transitioned regular reflection as one approaches the acoustic limit where reflection is always regular.

The Michael Seitz Automated Shock Tube was selected as the apparatus for this study, although shock waves of $M_s < 1.1$ had never before been generated in this shock tube. A variety of different diaphragms and diaphragm combinations were tested to find a way to generate constantly weak Mach numbers. Commercially available tin foil was found to give the best results, and various combinations of it could be used to generate shock waves ranging from $1.03 < M_s < 1.09$. The most consistent results however came from the use of a single piece of tin foil as a diaphragm.

Originally designed to generate much higher Mach numbers, the fully automated design of the shock tube was found to be inadequate for this study. The pressurisation was too rapid, causing the diaphragm to rupture prematurely and the shock sensing system could not pick up the very weak pressure gradient across the weak shock waves. The operational procedure was modified to be run fully manually, with a very slow and gradual pressurisation of the compression chamber. To sense the passing of the shock wave, pressure transducers in the walls of the expansion chamber were connected to a data acquisition system set to be triggered by a very small voltage change.

To capture the fine details of the reflection structure, a shadowgram setup was selected as the most ideal imaging technique. The optics were setup with great precision and tested by focusing on the individual strands of an unravelled thread of wool placed in the test section. This was done to both ensure that the very small features of the very weak shock waves reflections could be pictured as well to try and avoid the details of the shock from being masked by tiny shadows caused by misalignment of the optics.

Initial experimental results showed that as the weak shock wave first meets the reflecting surface, there is no reflection. As the shock wave progresses along it, a section of the shock wave close to the reflecting surface grows stronger and curves forward to remain perpendicular to the surface which increases in gradient. The curvature of the incident shock wave increases until a discontinuity forms on it. This discontinuity develops into the triple point of a Mach reflection with the initially curved part of the incident shock wave becoming a Mach stem and a reflected shock wave growing in length in the wake of the incident shock wave. The Mach stem shortens as the incident shock wave progresses until the triple point intersects the reflecting surface.

Up until this point, the evolution of the reflection is the same as that for a stronger shock wave. For the strong shock wave case, immediately following the intersection of the triple point with the reflecting surface, an additional shock wave should emerge from the reflection point, indicating the transformation to a transitioned regular reflection. However, the experimental results showed that as the acoustic limit was approached, the transformation to a TRR did not occur immediately, but rather the reflection remained in a regular reflection configuration for some time before transitioning to a TRR.

This region of RR existence was most noticeable on the largest circular model of 260mm radius and the shallowest parabolic model of equation $y=2x^2$, due to the MR

having sufficient time to develop and the slower gradient change of these models within the confines of the test section.

Image enhancement further resolved the features of the reflections and allowed some quantitative analysis on the images to be done. Projecting the triple point trajectories of both the MR and the TRR onto images of the shock wave at different instances of time superimposed on top of one another confirmed that there is definitely a delay between the triple point of the MR intersecting the surface and the triple point of the TRR appearing. The wedge angles at which the TRR was first seen to appear also conform fairly well to the analytical predictions made in previous studies.

Variations in the structure of the reflections from the stronger shock wave case were also noted. For shock waves of $M_s < 1.05$, no shear layer could be identified emanating from the triple points of the MR or the TRR. Even at $M_s > 1.05$, the shear layer was still absent in the TRR. The reflected and incident shock waves of the MR appeared not to meet at a clear discontinuity but rather merged together tangentially at the triple point. The reflected and additional shock waves of the TRR were also all curved, and also merged tangentially rather than meeting at a clear triple point.

Numerical simulations were done to try and confirm the experimental results. At such a low Mach number, the density gradients required to be resolved resulted in a large amount of noise being generated in the wake of the shock, obscuring much of the features of the reflection. The shock wave itself was also not resolved to a sufficiently thin discontinuity and was shown to decompose in the vicinity of the triple point as it approached the reflecting surface. The numerical results did however show the reflected shock wave to be straight in the MR configuration, and after the triple point intersected the reflecting surface, the reflected shock wave gradually grew in curvature until the triple point of the TRR emerged.

RECOMMENDATIONS

This study highlighted the small size of the reflection configurations at transition for very weak shock waves. The resolution of the shock wave structure can be improved in one of two ways. A camera with a higher pixel density can be used in parallel with an optical system which focuses on a smaller area of the test section instead of capturing the entire test section in the image. Alternatively, larger radius models can be tested. It has been shown that the RR only appears at about 50% penetration of the circular models at the very weak Mach numbers, and it is not necessary to see the initial reflection of the shock wave or the reflection after the initial formation of the TRR. A much larger radius model can thus be tested which only has the RR region visible in the test section.

Further testing should be done in the $1.01 < M_s < 1.05$ range to further clarify configurations for very weak Mach numbers. It is known that acoustic reflection is always regular, but such testing will allow the point at which the MR starts appearing to be determined.

To ensure more consistent and repeatable shock waves in the very low Mach number range, as well as to possibly provide a greater range of Mach numbers to test at, it is recommended to install a “pricker” to rupture the diaphragm instead of allowing natural burst of the diaphragm.

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APPENDICES

Appendix A - Specification and Performance of Apparatus

Shock-Tube:

Compression chamber dimensions:	2080mm X 300mm (internal Ø)
Compression chamber:	
Design pressure:	2000 kPa
Hydrostatic pressure tested to:	3000 kPa
Design temperature:	50° C
Capacity:	0.155 m ³
Expansion chamber dimensions:	6000mm X 180mm X 76mm
Test-section dimensions:	350mm X 180mm X 76mm
Viewing windows material:	Borosilicate glass
Viewing windows diameter and thickness:	250mm and 55mm

Optical Setup:

Light Source:

Manufacturer:	Hamamatsu
Model:	Xenon Flash Lamp Unit
Components:	L2437 Lamp
	Arc Size: 1.5 mm
	Min λ : 240 nm,
	Max λ : 2000 nm
	Max Avg Input Power: 15 W
	Max Rate of Repetition: 100 Hz
	Jitter: 200 ns
	Output Fluctuation: 3.5 %
	E2438 Socket
	C3684 Power Supply
	S/N: 91050364
	Input: 24V DC

Output:	H.V. 0.3-1 kVdc
Maximum Output:	15W Max
Trigger Voltage:	140 V

E2608 Shield Box

Power converter for light source:

Manufacturer:	Trip Tech
Input Voltage:	220V AC
Output Voltage:	24V DC

Parabolic mirrors:

Diameter:	254mm
F-number:	(f/6)

Camera:

Manufacturer:	Fujifilm
Model:	S3 Pro
S/N:	62903532
Max. Resolution:	12 megapixels

Convergent Lens:

Manufacturer:	Edmund Optics
Model:	Achromat
Diameter:	40 mm
F-number:	(f/2)

Focusing Lens:

Manufacturer:	TSI
Model:	9917
Effective Diameter:	60 mm
Focal Distance:	121.5 mm
K number:	10.735

Opto-Mechanics:

Manufacturer:	Optosigma
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Components used: 2 x Optical rails, various posts, post holders and clamps, adjustable lens holders, 4 x Magnetic Low Profile Bases (used to secure rails to stands).

Shock Sensing Equipment:

Pressure Transducers:

Manufacturer:	PCB Piezotronics
Model:	113A21
S/N:	5924 (Upstream), 4817 (Downstream)

ICP Amplifier/power supply:

Manufacturer:	PCB Piezotronics
Model:	482A10
S/N:	661 and 662
Input Voltage:	230V
Output:	24V DC
Constant Current:	4mA

Delay Box:

Manufacturer:	Electro DI
Model:	Programmable Time Delay Unit
Trigger Level Range:	3.0V Max, 0.0V Min
Delay Range:	50 μ s - 99,998 μ s

4 Channel Digital Oscilloscope:

Manufacturer:	Yokogawa
Model:	DL1200A #7006 20-5/D/RS-232C
S/N:	21XF5178
Settings:	
Volts/div:	20 mV/div (CH1 and CH2)
Time/div:	100 μ s
Trigger Level:	20.8 Mv
Trigger Source:	Channel 1

Digital Data Acquisition System (DAQ):

4 Channel Hard Disk Logger:

Manufacturer: Graphtec
Model: GL1000
S/N: D8090037

Notebook for running data acquisition software:

Manufacturer: Hewlett-Packard Compaq
Model: 6735s Notebook
S/N: CNU838FG8

Specifications:

Processor: AMD Athlon X2 Dual Core (1.9 GHz)
RAM: 1GB DDR2
Operating System: Windows XP
Running: “Hard disk logger software” version 1.0

Temperature Measurement:

Mercury thermometer:

Manufacturer: Brannan
Product No: 40/408/0
Type: 76 mm immersion mercury laboratory thermometer
Length: 305 mm
Division: 1.0 °C
Range: $-10 < T \text{ (°C)} < 200$
Accuracy: $\pm 0.5^\circ\text{C}$

Ambient Pressure Measurement:

Atmospheric pressure sensor:

Manufacturer: Halstrup-Walcher AD1000
Type: Absolute Pressure Sensor
S/N: 270990100114

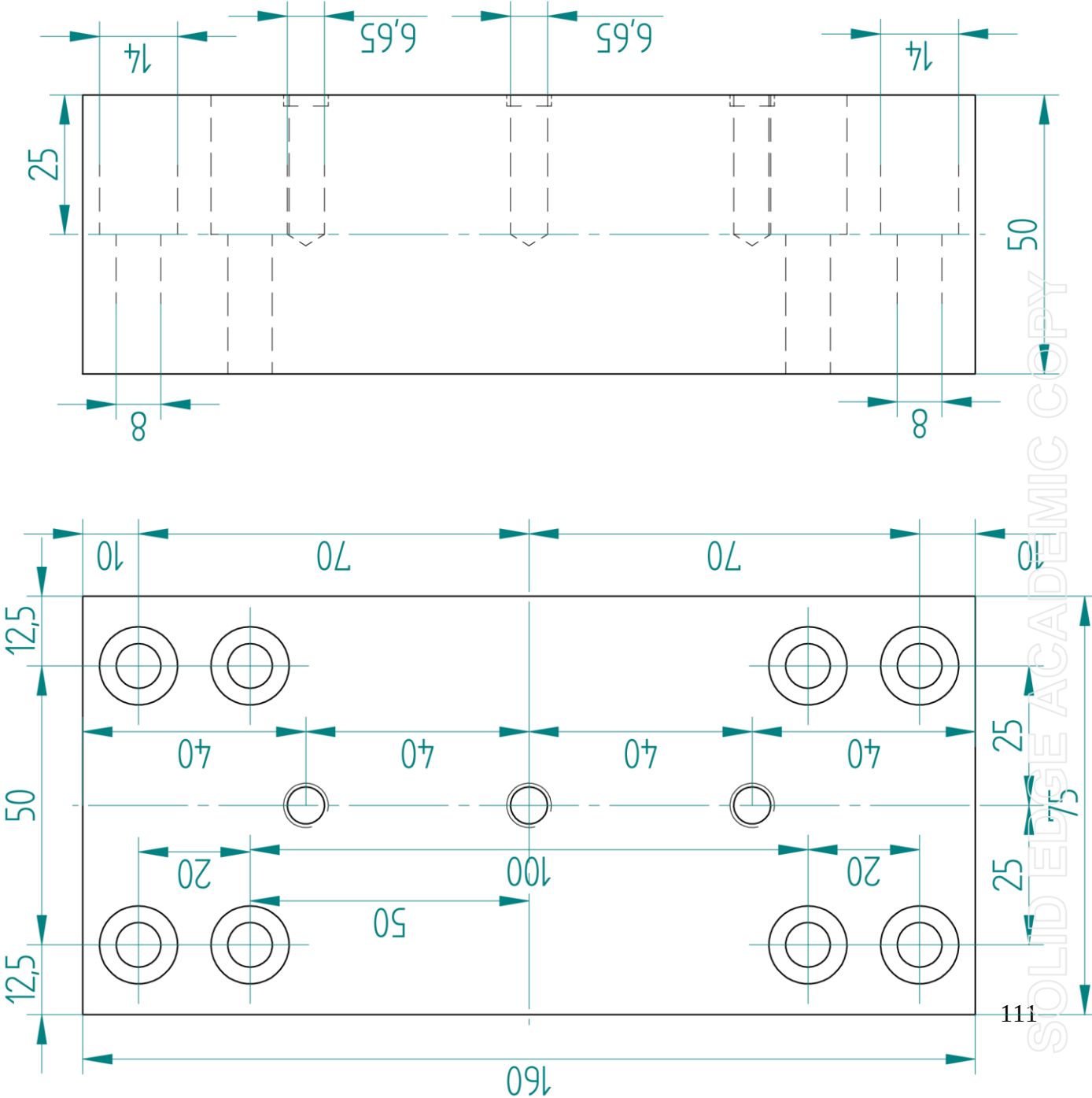
Range: 800-1000 mbar
Output Voltage: 0 – 10 V
Supply Voltage: 220 V AC
Accuracy: ± 0.05 mbar

Numerical Simulation Computer:

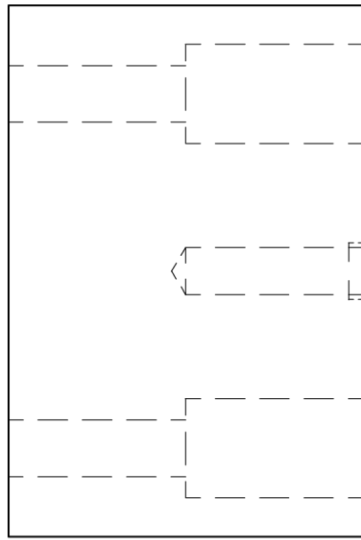
Manufacturer: Lenovo IBM
Model: ThinkCentre Tower 75G
S/N: LMFZN3M
Specifications:
Processor: Pentium D (2.8 GHz)
RAM: 2GB DDR2
Operating System: Windows XP
Running: Microsoft Visual C++ 6.0
Tecplot 360 Release 1

Appendix B - Engineering Drawings

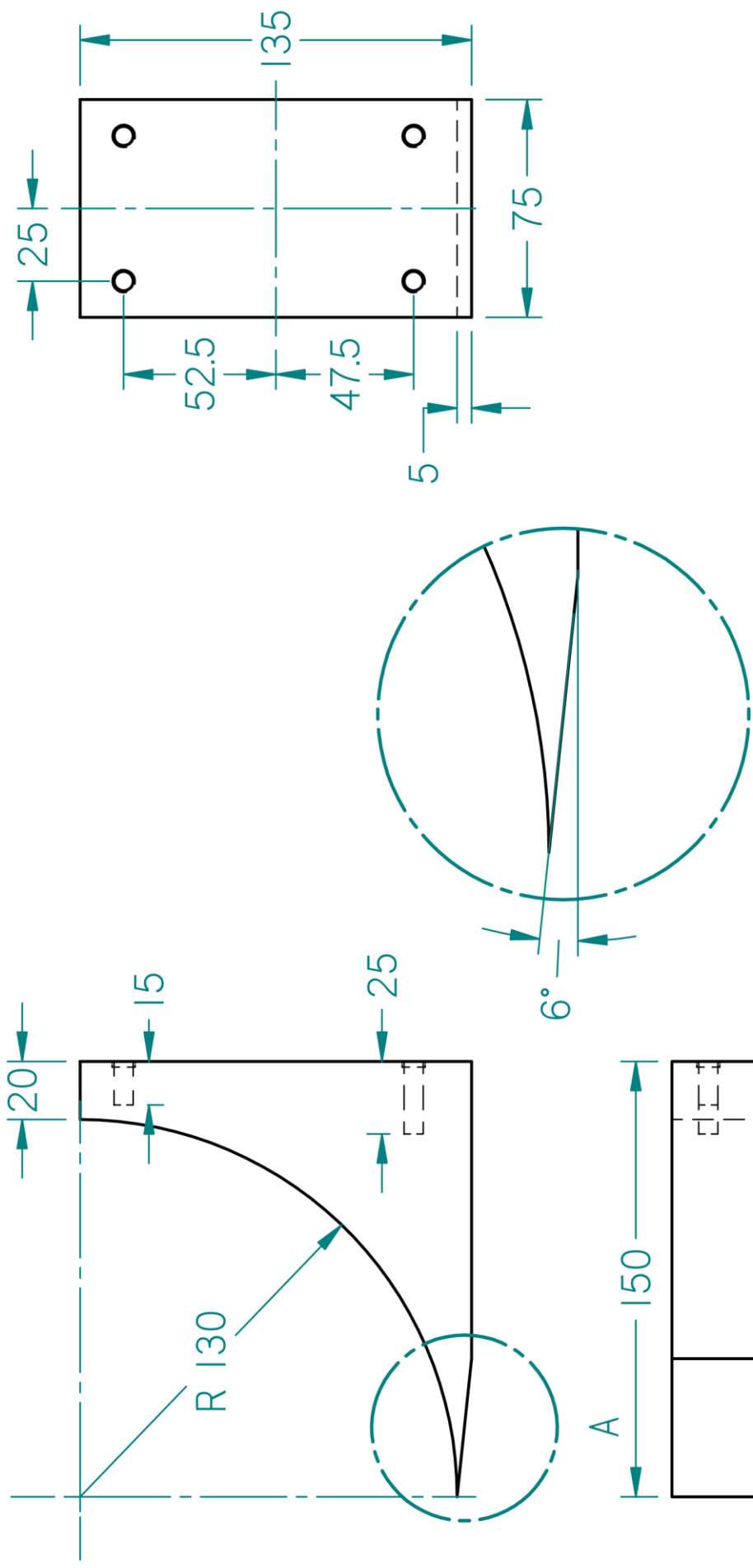
REVISION HISTORY		
REV	DESCRIPTION	DATE



Center holes to
be M8



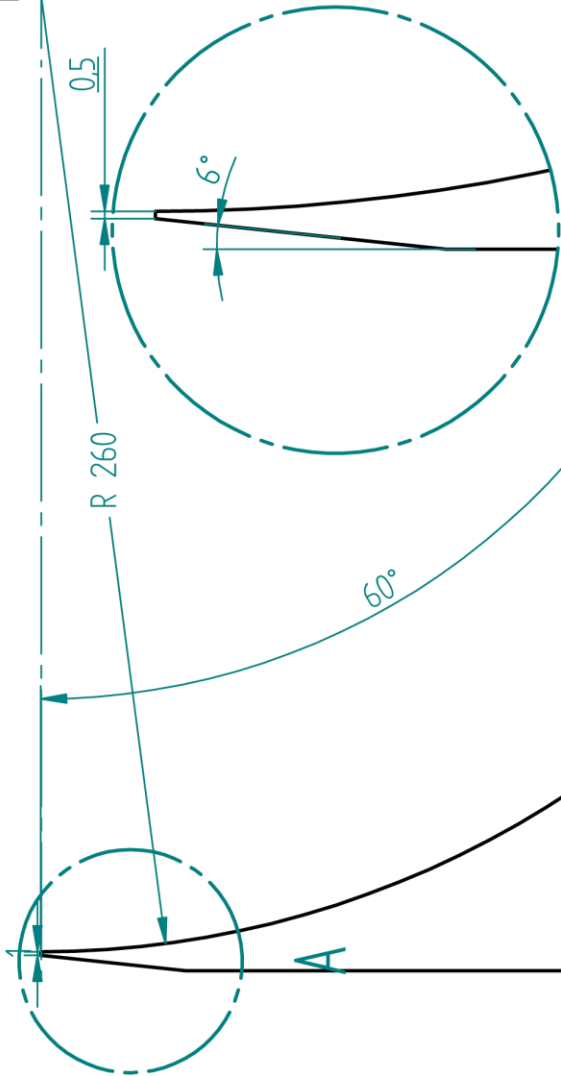
SOLID EDGE		
UGS - The PLM Company		
NAME	DATE	TITLE
DRAWN Sebastian E. 08/29/09		
CHECKED		
ENG APPR		
MGR APPR		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS ANGLES ±XX°		
SIZE	10x6x0	REV
FILE NAME	New SolidEdge.dft	
SCALE	2 PL ±XXX 3 PL ±XXXX	WEIGHT
SHEET 1 OF 1		



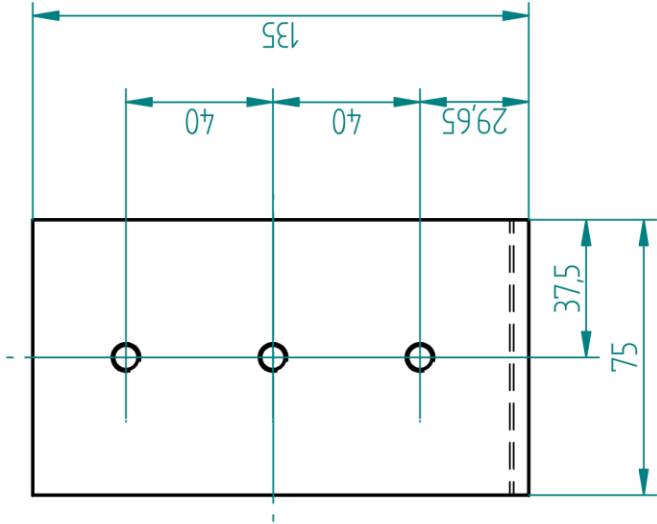
DETAIL A

Comments: All holes to be M8 Thread	TITLE: Circular Ramp Radius 130mm	
	NAME: Sebastien Gruber	
DATE: 05/29/09	CHECKED: / /	
File: R130 drawing		

MATERIAL: GREY PVC



DETAIL A

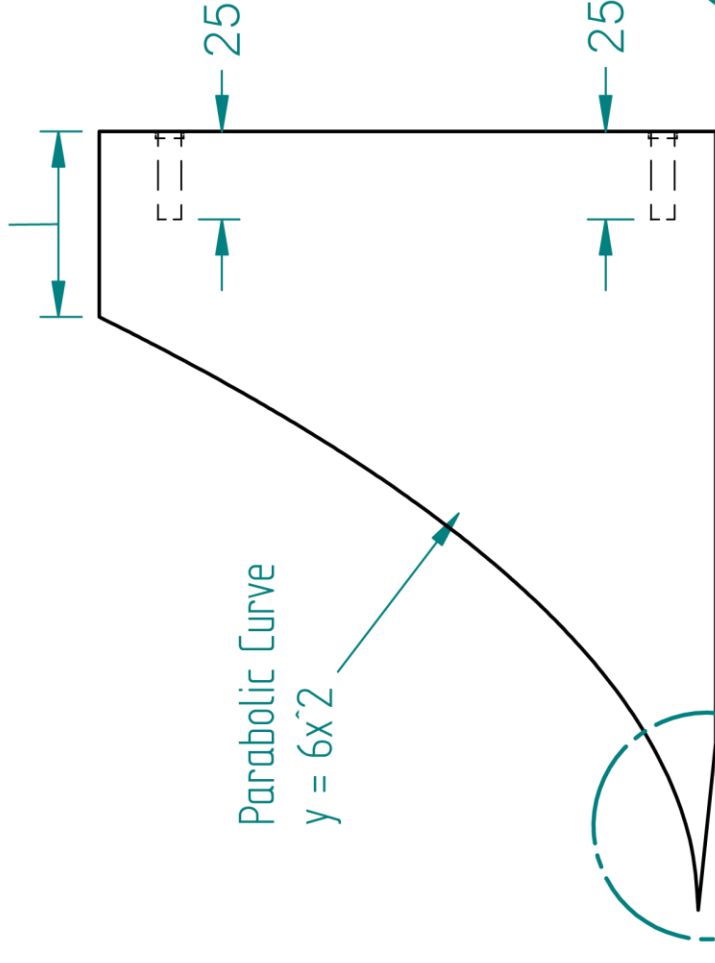


NOTE: ALL HOLES M8 STANDARD THREAD

DRAWN		NAME	DATE
CHECKED		S. Gruber	05/22/07
ENG APPR			
MGR APPR			
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MILLIMETERS ANGLES ±XX° 2 PL ±XX.XX 3 PL ±XXXX			
TITLE		SOLID EDGE UGS - The PLM Company	
SIZE		260mm Circular Wedge	
DWG NO		260C-01	
REV		REV	
FILE NAME: 260C_wedge.dft		SCALE:	
WEIGHT:		SHEET 1 OF 1	

52.72

Parabolic Curve
 $y = 6x^2$



221.05

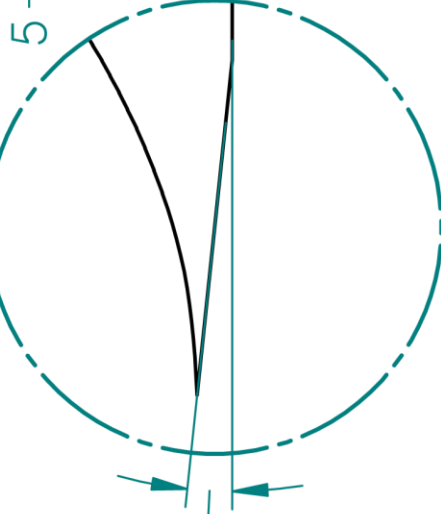
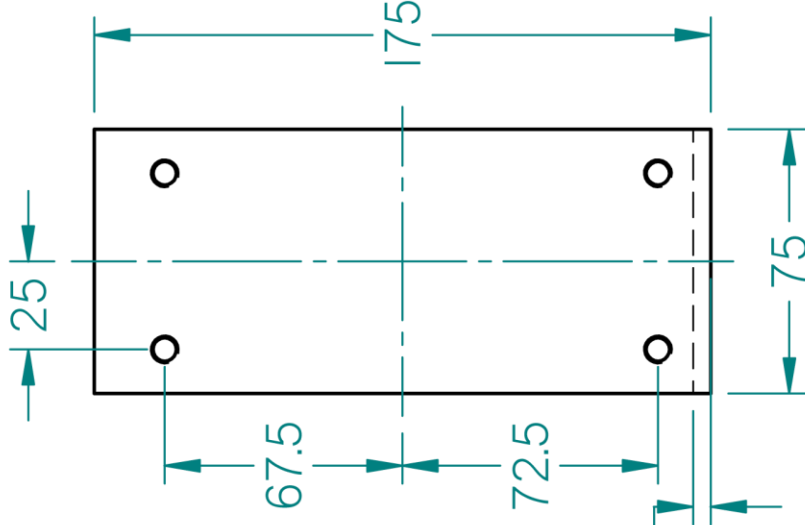
6°



114

173.48

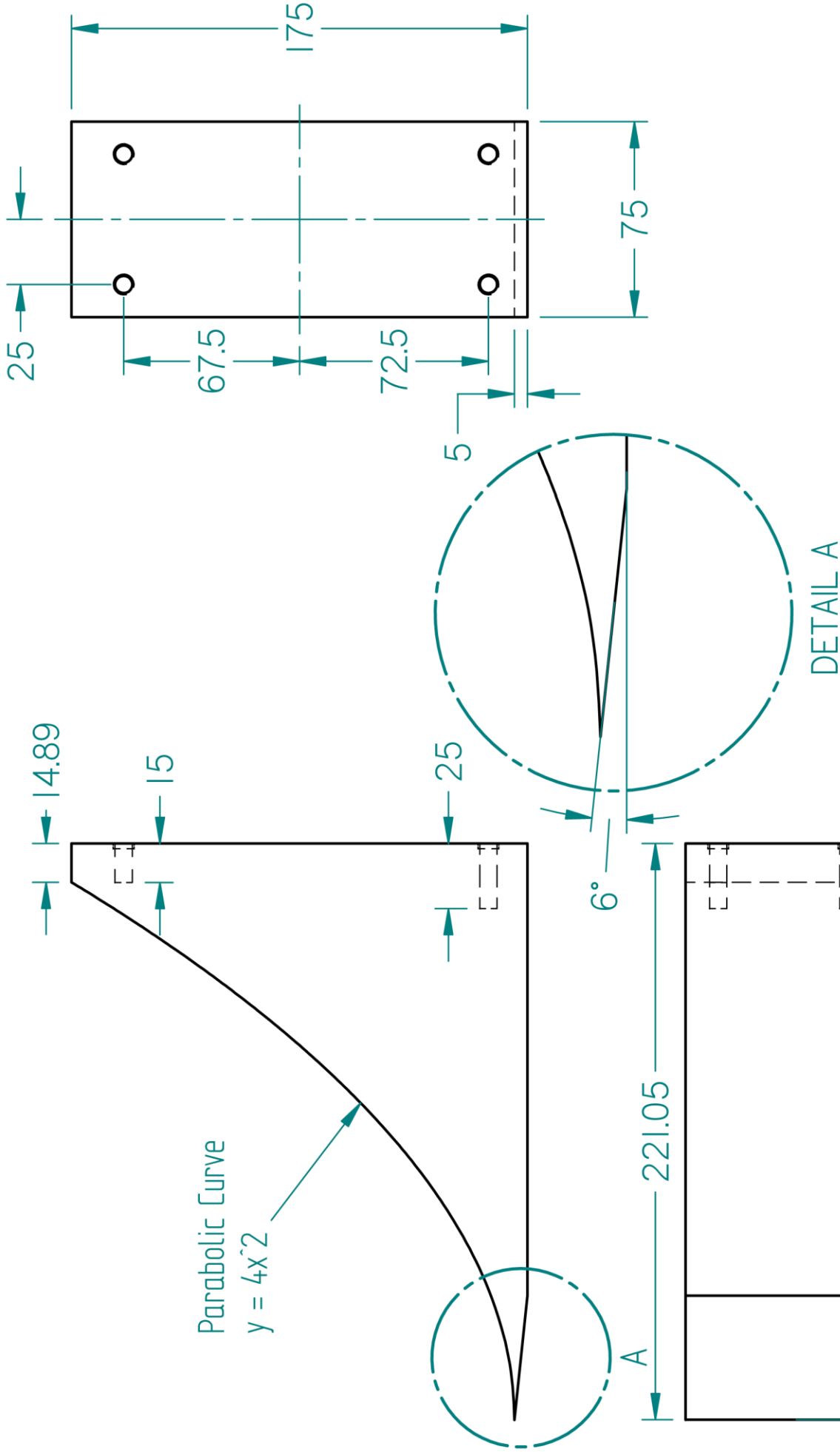
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±XX°



DETAIL A

SHEET 1 OF 1

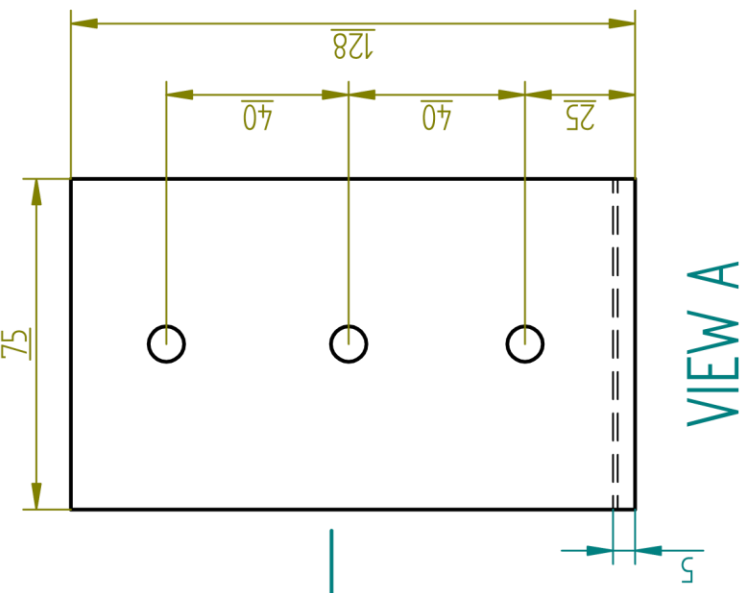
Comments: ALL holes to be M8 Thread		TITLE: Y=6x^2 Parabolic Ramp	
DATE: 05/29/09	CHECKED: / /	NAME: Sebastien Gruber	
File: y=6x2 drawing			



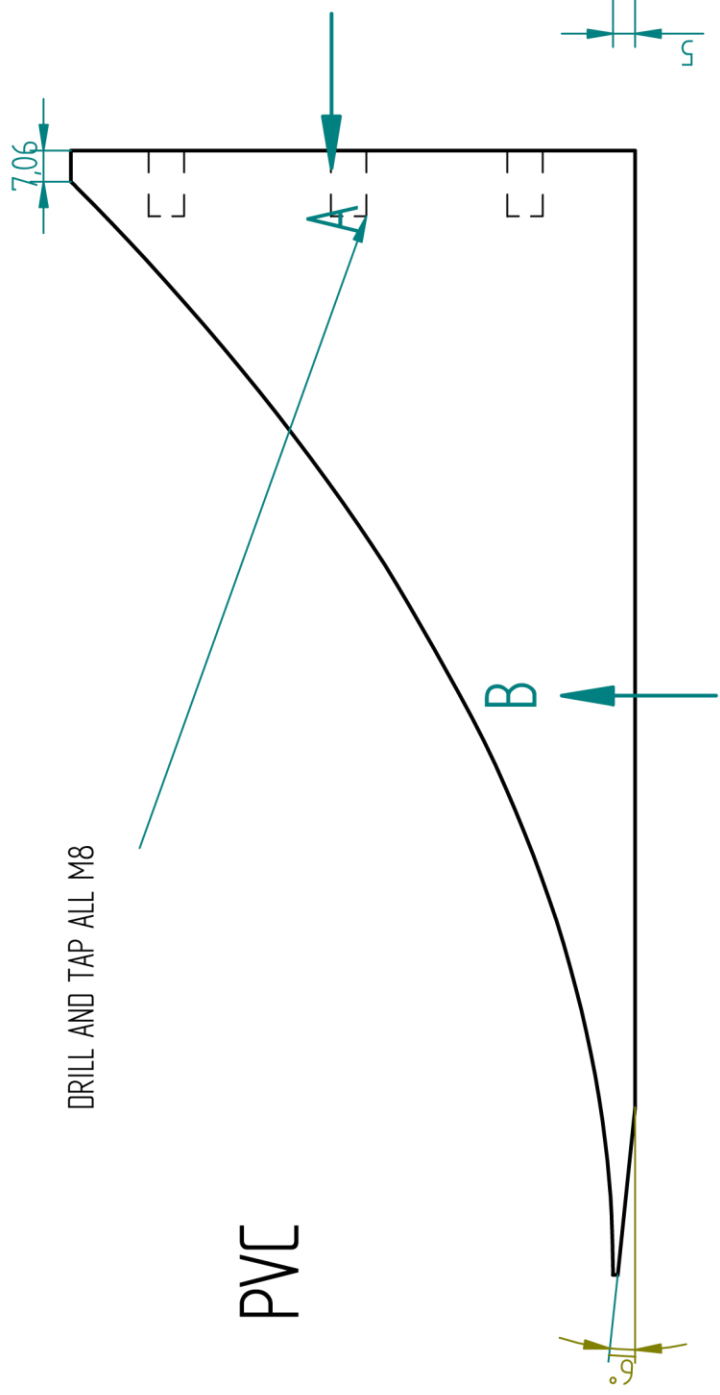
SHEET 1 OF 1

Comments: ALL holes to be M8 Thread		TITLE: Y=4x^2 Parabolic Ramp	
DATE: 05/29/09	CHECKED: / /	NAME: Sebastien Gruber	
File: y=4x2 drawing			

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MILLIMETERS
ANGLES ±XX°



VIEW A



PVC

DRILL AND TAP ALL M8



VIEW B

Ramp 1
 $y=2x^2$

TITLE		CHRISTIAAN		REV	
SIZE		A4		0300772J	
SCALE:		WEIGHT:		SHEET 1 OF 1	

Appendix C - Shadowgram Generation in Tecplot 360

To generate a numerical shadowgram, the following actions were taken:

1. Open the .plt data file in Tecplot 360.
2. Select “Field Variables” from the “Analyse” drop-down menu.
3. Check the “Velocity” checkbox and select only “U” and “V” as the convection variables for “U” and “V” by pressing the “Select” button.
4. Select “Pressure” and “Density” as the State Variables, and choose P and RHO as the Thermodynamic Variables by pressing the “Select” button.
5. Press “OK” to return to the main screen.
6. Then select “Calculate Variables” from the “Analyse” drop-down menu and choose “Shadowgraph” from the list by pressing the “Select” button.
7. Press “OK”, followed by the “Calculate” button and then the “Close” button. This will have calculated a new “Shadowgraph” variable for each node in the mesh, being the first derivative of gradient with respect to pressure.
8. The shadowgram variable can now be viewed by checking the “Contour” checkbox in the left sidebar, opening the contour settings from the button beside “Contour, and selecting “Shadowgraph” from the top right menu in the pop-up window.
9. For comparison to the experimental images, a two colour colour-map such as grayscale should be selected, and the colour distribution method set to “Continuous”. The contour values at the colour-map endpoints can then be adjusted according to how much contrast is required across the density gradient that the shock waves in the image covers.

Appendix D - Image Processing Actions

Using an automated action, the following processing steps were applied to each .RAW format image in Adobe Photoshop CS5.

Exposure:

Preset Kind: Custom

Exposure: 1.88

Offset: -0.051

Gamma Correction: 0.89

Brightness/Contrast:

Brightness: 32

Contrast: 14

Without Use Legacy

Artifact:

With: Channel Parameters list

Channel Parameters

Channel: composite channel

Strength: 7

Preserve Details: 60

Channel Parameters

Channel: green channel

Strength: 0

Channel Parameters:

Channel: blue channel

Strength: 0

Settings Name: "Default"

Colour Noise: 45%

Sharpen: 50%

Without Remove JPEG

Vibrance:

Vibrance: 36

Saturation: 34

Smart Sharpen:

Amount: 100%

Radius: 3.1 pixels

Angle: 0

Without More Accurate

Remove: Gaussian Blur

Settings Name: "Default"

Shadow: Parameters

Amount: 0%

Tone Width: 50%

Radius: 1

Highlight: Parameters

Amount: 0%

Tone Width: 50%

Radius: 1

Reduce Noise:

Appendix E - Simulation Code Setup

Below is an example of the C++ code that defined how a numerical simulation was setup.

```
#include <iostream.h>
#include <fstream.h>
#include "EulerDomain.h"
#include <stdio.h>
#include <string.h>
#include <math.h>
#include <stdlib.h>
#include "geometry.h"
/*****
// FUNCTION : CircularWedge

void CircularWedge(void)
{
    EulerDomain s(100000);
    double radius = 0.260;           //radius of circular wedge
    double arc = 90;                  //arc of circular wedge – do not exceed 90
    double arcrad = arc*3.14159/180; //converts arc to radians
    double ms = 1.025;                //Mach shock number
    double l = 2*radius*sin(arcrad/2)*sin(arcrad/2); //mesh dimension
    double a = 340.294;               //local sound speed
    double length = 2*radius*sin(arcrad/2)*cos(arcrad/2); //horizontal depth of curve

    //Geometry Creation

    Point p[20]; //creates an array for the vertices of the geometry

    int j = 1; //defines point 1 as the origin of the geometry
    for (int i = 0; i <= arc/2; i = i + arc/18)
    {
        double theta = (i)*3.14159/180; //creates 10 points along arc/9 deg intervals
        double R = 2*radius*sin(theta);
        p[j].set(R*cos(theta), R*sin(theta));
        j++;
    }

    p[11].set(-2*length, p[10].coord[2]); //top left corner at inlet
    p[12].set(p[11].coord[1], p[1].coord[2]); //bottom left corner at inlet

    for (int k = 1; k <= 15; k++) //puts vertex co-ords on screen on sim initialisation
    {
        cout << p[k].coord[1] << " " << p[k].coord[2] << endl;
    }

    ECurve curve1(&p[1], &p[2], &p[3], &p[4]); curve1.bCode[0] = 1; //1st arc curve
```

```

ECurve curve2(&p[4], &p[5], &p[6], &p[7]); curve2.bCode[0] = 1; //2nd arc curve
ECurve curve3(&p[7], &p[8], &p[9], &p[10]); curve3.bCode[0] = 1; //3rd arc curve
ECurve curve4(&p[10], &p[11]); curve4.bCode[0] = 1; //top wall
ECurve curve5(&p[11], &p[12]); curve5.bCode[0] = 3; //inlet
ECurve curve6(&p[12], &p[1]); curve6.bCode[0] = 1; //bottom wall

//Generate Initial Mesh

s.mesh(1/20.0, 6, &curve1, &curve2, &curve3, &curve4, &curve5, &curve6);

//Initial Flow Conditions

s.gamma = 1.4; //specific heat ratio
double rho = 0.972; // air density
double pr = 81489; //atmospheric pressure
double u = 0.0; //initial horizontal velocity
double v = 0.0; //initial vertical velocity
double e = pr/(rho*(s.gamma-1));
s.initialConditions(rho, u, v, e);
s.fs.rho = rho;
s.fs.u = u;
s.fs.v = v;
s.fs.e = e;

double lam = 6*ms*ms/(ms*ms+5);
double pratio = (6*lam-1)/(6-lam);
double ar = sqrt((6*lam-1)/(lam*(6-lam)));
double mss = sqrt(5)*(lam-1)/sqrt(6*lam-1);

curve5.bCode[1] = lam*rho;
curve5.bCode[2] = mss*a*ar;
curve5.bCode[3] = 0.0;
curve5.bCode[4] = pratio*pr/(lam*rho*(s.gamma-1)) + 0.5*mss*mss*a*ar*a*ar;

char name[30] = "R260_M1025 _"; //Name of output data files
s.outputData(name, "i");

s.hMax = 1/40.0; //Maximum cell size
s.hMin = s.hMax/3.0; //Minimum cell size

double outTime = length/(a*ms); //Time when shock is on reflecting surface
double Totaltime = 3*length/(a*ms); //Total run time
cout << "Run Time: " << Totaltime << " seconds" << endl;
double deltaOut = outTime/200; //How often to produce data files
cout << "Data files will be written every " << deltaOut << " seconds" << endl;
double nextOut = 2*length/(a*ms);
int lastout = 0.0;
int stepNo = 0;
double time = 0.0;
double cfl = 0.3; /**was 0.3

s.constructEdges();

```

```

while ( time <= Totaltime)
{
    stepNo++;
    double distCovered = ms*a*time; //How far the shock has travelled

    if (distCovered > length) //First mesh refinement
    {
        s.hMax = l/50.0;
        cfl = 0.35;
    }

    if (distCovered > 1.5*length) //Second mesh refinement
    {
        s.hMax = l/60.0;
        cfl = 0.4;
    }

    if (distCovered > 1.7*length) //Final mesh refinement
    {
        s.hMin = s.hMax/8.0;
    }

    s.deltaT(cfl, 0.0 );

    cout << "stepno = " << stepNo << " time = " << time << " Percentage complete = "
<< (time/Totaltime)*100 << " " << "\n";
    cout.flush();

    if (stepNo/10 == stepNo/10.0) //How often to refine the mesh
    {
        s.adaptMesh(0.008, 5, 3); //Min. density gradient, # of layers, # of levels
    }

    s.fvmcfd(); //Calls the actual solver algorithm
    time = time + s.dt; //Moves forward one time step

    if (distCovered > 2*length) //When to start generating data files
    {
        if (time >= nextOut)
        {
            char buffer[10];
            lastout++;
            itoa(lastout, buffer, 10);
            s.outputData(name, buffer);
            cout << "Output data file : " << lastout << endl;
            nextOut += deltaOut;
        }
    }
}
}

```

Appendix F - DAQ Settings

The following screenshots outline the settings that were selected on the DAQ to ensure that the passing of the incident shock wave was recorded on the hard disk logger.

1. With the hard disk logger connected to the laptop via USB, the capture settings button was selected to bring up a window where the data capture settings could be adjusted. Under the first tab, “AMP Settings”, the range for each channel was changed to 200Mv as shown in Figure F.1 below.

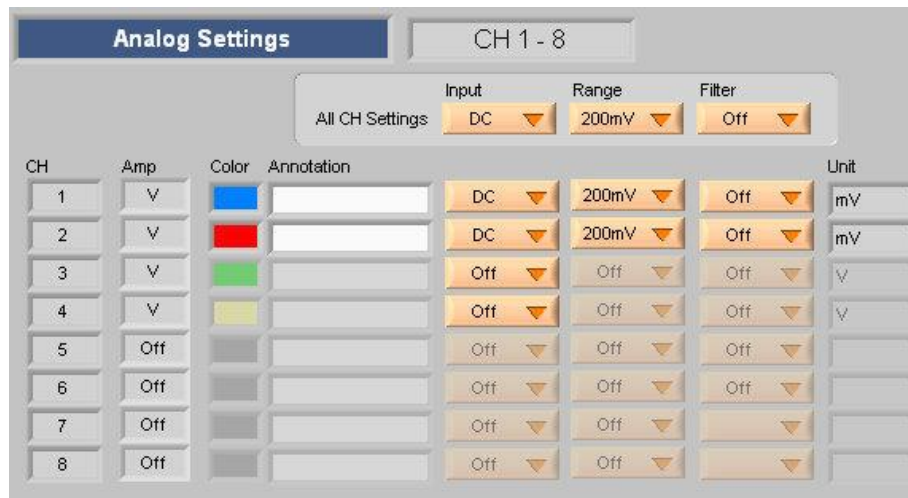


Figure F.1: Analog settings for the DAQ

2. The tab for “Capture/Trigger Settings” was then selected and the data capture settings adjusted. The sampling interval was set to its highest value of “1µsec” and the block size in the device memory set to “4kW x 128”, indicating that a block of 4000 samples would be taken. These settings are shown in Figure F.2.

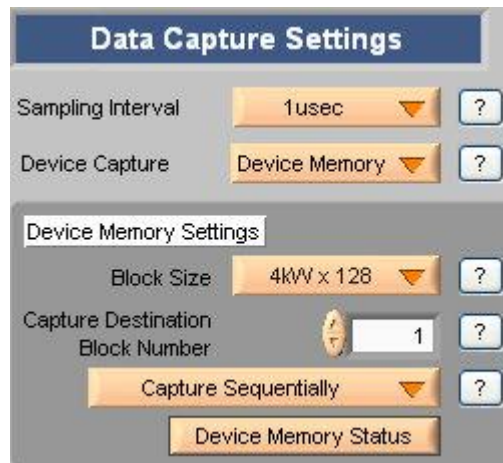


Figure F.2: Data capture settings for the DAQ

3. The trigger settings were then changed to have an “Internal” trigger start condition, and the “Internal Settings” adjusted to use a “Level AND” combination. Channel was selected to be the trigger, and its function was set to “Hi”, with a trigger start setting of 12% as shown in Figure F.3. This would cause the system to trigger if the voltage increased above twelve percent of the range (200mV). A 10% pre-trigger was also set, allowing the possibility to check the condition of the signal prior to the system triggering.



Figure F.3: Trigger start setting for the DAQ

4. These settings were then applied and once a test had been completed with the system successfully triggering, a preliminary check was done on the Mach number of the test to determine if it was within range for that case. To do this, immediately following a successful test, the time delta between the triggering of the two pressure transducers was measured by placing a measurement cursor on the midpoint of the rise on each channel, as shown in Figure F.4. The time delta could then be read off from in the bottom right of the screen and recorded.



Figure F.4: Time delta measurement using the DAQ