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HIGH PRESSURE HUGONIOT MEASUREMENTS USING MACH WAVES

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Abstract. Traditionally, most dynamic shock compression experiments are conducted using a plane one-dimensional wave of uniaxial strain. In this case, the evaluation of the equation of state is simplified due to the geometry, but the amplitude of the induced shock wave is limited by the magnitude of the input load. In an effort to dramatically increase the range of pressures that can be accessed by traditional loading methods, a composite target assembly is examined. The target consists of two concentric cylinders aligned with the axial direction parallel to the loading. The target is designed such that on initial loading, the outer cylinder will have a higher shock velocity than the inner material of interest. Conically converging shocks will be generated at the interface between the two materials due to the impedance mismatch. Upon convergence, an irregular reflection occurs and the conical analog of a Mach reflection develops. The Mach reflection will grow until it reaches a steady state, at which point the wave configuration becomes self similar. The resulting high pressure Hugoniot state can then be measured using velocity interferometry and impedance matching. The technique is demonstrated using a planar mechanical impact generated by a powder gun to study the shock response of copper. Two systems are examined which utilize either a low impedance (6061-T6 aluminum) or a high impedance (molybdenum) outer cylinder. A multipoint VISAR experiment will be presented to validate the technique, and will be compared to numerical simulations. The feasibility of measuring an entire Hugoniot curve using full field velocity interferometry (ORVIS) will also be discussed.

Keywords: Hugoniot, Mach reflection, converging shocks.
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INTRODUCTION

Generally, Hugoniot measurements are made using well-controlled one-dimensional shocks. Plate impact experiments, for example, provide avenues for extremely accurate equation of state (EOS) measurements. The maximum achievable impact velocity, however, limits the magnitude of the induced shock. In an effort to increase the pressures accessible with a given impact velocity, converging shock waves are generated through a composite target consisting of two concentric cylinders. This configuration was originally examined for a solid material confined by a high explosive [1, 2]. Later, the method was extended to mechanical impact testing, where the outer explosive was replaced by a solid material [3] and shocks are generated by a standard plate impact. Recently, this target assembly has been shown to produce a high-pressure planar shock at the center of the inner cylinder for which Hugoniot measurements can be made [4].

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EXPERIMENTAL SETUP

The Mach lens target configuration is shown in Fig.1. A normal plate impact generates a plane shock on one surface of the composite target assembly. The target materials are selected such that the shock speed in the outer cylinder is higher than that in the inner cylinder. Under this condition, converging shocks are generated at the material interface due to the impedance mismatch. Upon convergence, the geometry forces an irregular reflection, and the conical analog of a Mach reflection occurs. After some transient build up, the Mach reflection becomes steady in time and the Mach reflection approaches a self-similar solution. The axisymmetric nature of the target results in a normal Mach stem at the center of the inner cylinder. Thus, in the steady state, the configuration essentially produces a plane shock traveling at the shock speed of the outer cylinder, and a single measurement of the particle velocity results in an estimate of the shocked state behind the Mach stem.

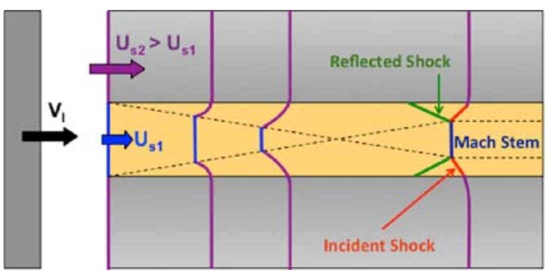

Figure 1. Mach lens target assembly. A plane shock is generated at the left of the target with a normal plate impact.

NUMERICAL SIMULATIONS

Numerical simulations, the details of which can be found elsewhere [4, 5], were performed with the CTH hyrdrocode [6] to properly design the experiments. The results of a typical simulation are shown in Fig. 2. In this simulation a thick aluminum flyer impacts an aluminum outer cylinder and copper inner cylinder 6.4 mm in diameter at 1.6 km/s. Fig. 2(a) – (d) illustrate the initial converging shocks in the inner cylinder, iirregular reflection, growth of the Mach wave, and finally the steady state Mach reflection. A more quantitative view of the simulation is taken in Fig. 2(e) where equally spaced Lagrangian tracers along the center of the inner cylinder illustrate the behavior of the interacting shocks. At early times the axial particle velocity trace represents what would be typical of a standard plate impact. At ~1 µs, the converging shocks arrive at the centerline, and the particle velocity begins to increase. The transient build up of the Mach reflection is captured until at ~4.5 µs, the wave profile becomes steady in time. As shown, the corresponding length-to-diameter ratio (L/D) associated with this point in time is ~4. This provides the effective design criteria for the experiment. Thus, in this case, the length of the assembly must be at least 4 times larger than the inner cylinder diameter while the outer cylinder diameter must be large enough such that any edge effects can be neglected.

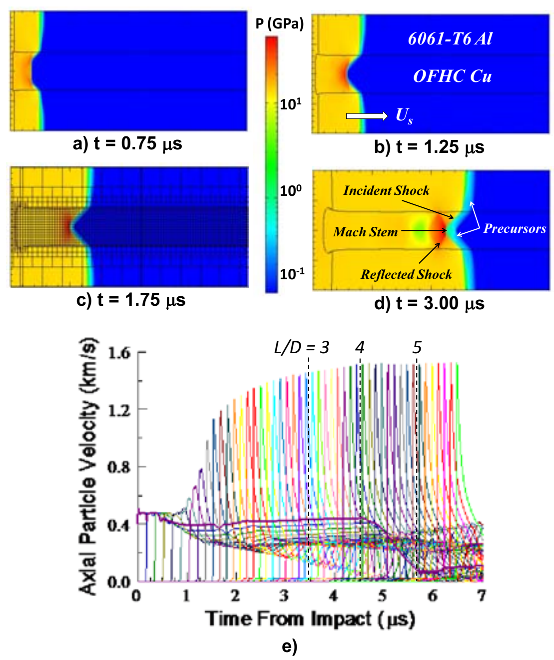

Figure 2. Pressure contours for a typical simulation at various stages of the Mach reflection (time from impact) are shown in (a)–(d). Equally spaced axial velocity traces along the center of the target are shown in (e).

It should be noted that simple analytic methods can be used to determine the nature of the steady state Mach reflection. The methods are based on the shock polar framework commonly used in gas dynamics but generalized for an arbitrary EOS [7].

These shock polar solutions can be used to provide useful physical insights and have been shown to be in excellent agreement with the numerical simulations [4, 5].

EXPERIMENTAL RESULTS AND DISCUSSION

In an attempt to validate the experimental method, an experiment which utilized multiple VISAR [8] measurements will be discussed in detail. In this experiment, an aluminum flyer 13 mm thick and 89 mm in diameter impacted an aluminum outer cylinder and copper inner cylinder at 1.59 km/s. The outer diameters of the inner and outer cylinders were 76 mm and 6.4 mm, respectively. The length of the target was 22 mm. As shown in the insert in Fig. 3, probes were used to monitor the rear free surface of the target at radii of 0, 1.35mm, 2.69 mm, and 7.21 mm.

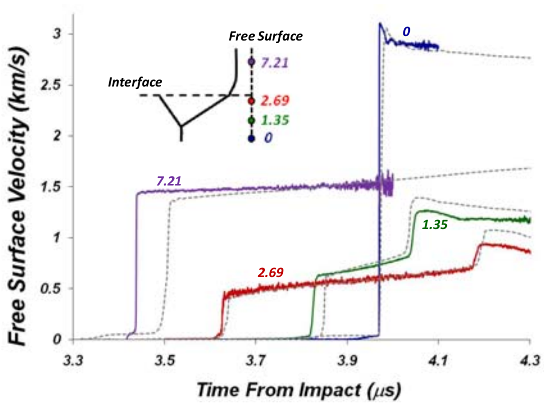

Figure 3. Experimental free surface velocities measured in an aluminum / copper Mach lens. The traces are color coded to the probe locations shown in the inset. The dashed gray traces are the corresponding numerical profiles.

Results of the experiment, along with the corresponding simulated waveforms, are shown in Fig. 3. As shown, the experiment agrees well with the expected Mach wave profile shown in the inset. The outer most probe corresponds to the plane wave corresponding to the shock in the outer cylinder. The discrepancy between the simulation and experiment is thought to be a result of the impactor tilt which was ~2 mrad. The probe near the cylinder's interface, at 2.69 mm, illustrates the two-shock structure corresponding to the incident shock followed by the reflected shock. The gradient in the measured particle velocity between these two shocks is thought to be a result of the curvature of the wave front [9]. The probe at 1.35 mm represents a point close to half the radius of the inner cylinder and exhibits a similar double shock structure. The higher initial particle illustrates the increase in pressure due to the gradient along the Mach wave while the shorter spacing between the two shocks is simply a function of the geometry of the reflection. Finally, at the center of the inner cylinder, the Mach stem is monitored where the single shock exhibits the dramatic pressure increase in this portion of the Mach reflection.

As alluded to previously, a shocked state can be calculated easily for the profile measured at the center of the target. Given the measured impact velocity, impedance matching [10] can be used to determine the shocked state in the outer cylinder as long as the impactor and outer cylinder material Hugoniots are well known. Thus, assuming the Mach wave has reached a steady state, the axial wave velocity of the entire Mach reflection is known. Making a free surface approximation, the axial particle velocity can be estimated to be half of the measured free surface velocity. The conservation equations can then be used to calculate the rest of the mechanical variables associated with the shocked state behind the Mach stem.

Technically, the Mach reflection provides a continuous pressure gradient between the state at the interface to the center of the inner cylinder. Hence, a full field measurement of the particle velocity distribution along the entire reflection can theoretically be used to calculate the entire Hugoniot curve between these two points. As a rough illustration of the idea, the two profiles monitoring the two-shock regime can be used to estimate an average shocked state. Given the radial position of each measurement and the time of arrival of the initial shock, the average incident shock angle can be calculated through the known axial wave speed for which the average normal shock and particle velocities can then be calculated [4]. The calculated shocked states are shown in Fig. 4 along with the copper Hugoniot measured using conventional methods [11]. As shown, the measured points are in good agreement with the literature. Further, the high pressure point represents a gain in pressure of approximately 4.4 when compared to the equivalent plate impact experiment.

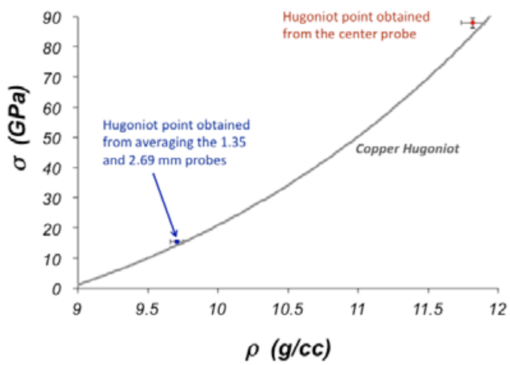

Figure 4. Shocked states calculated from the experimental profiles shown in Fig. 3 along with the copper Hugoniot from [11].

CONCLUSIONS

In the present study, the feasibility of using a simple composite target to generate a steady Mach reflection is examined. Numerical simulations are used to gain insights into the problem and design the experiments. The experiment presented here illustrates the ability to calculate a shocked state using a single measurement of the free surface velocity at the center of the cylinder. In this case, the Mach stem is monitored for which an extremely high-pressure state exists. Further experiments have shown repeatability [4, 5] and suggest this target configuration may be used to greatly extend the capabilities of existing shock compression techniques. The experiment also demonstrates the ability to calculate multiple Hugoniot points in the same experiment. Given quality data with both a high temporal and spatial resolution, such as that provided by ORVIS [12], it should be possible to calculate a significant portion of the Hugoniot in a single experiment.

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