OPTICAL INTERFEROMETRIC AND FIBER OPTIC TECHNIQUES FOR HIGH PRESSURE IMPACT STUDIES

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Abstract: Two optical techniques are experimentally investigated to measure the shock wave velocity and particle velocity in metals subjected to hyper velocity impacts. Fabry-Perot interferometer based optical system has been developed and used to measure the interface velocity profile of impacted Tantalum-Glass and Aluminum-Glass targets. Optical fibers coupled to fast photodiodes are implemented to measure the shock wave velocity in stepped copper targets. Experimentally measured particle velocity and shock wave velocity are found to be in close agreement with the reported equation of state data.

1. INTRODUCTION

Hyper velocity projectiles are frequently involved in studies related to shock physics [1, 2]. These projectiles, on impact with target can generate pressures in Mbar regime. Study of equation of state of materials at such high pressures requires the knowledge of projectile velocity as well as the particle velocity or shock wave velocity in target material. The time scale of these experiments lies between tens of nanoseconds to few microseconds and when pulsed power sources are involved, large electromagnetic (EM) interference is also generated. Precise measurement of velocities in such conditions necessitates the use of optical techniques which are highly sensitive and inherently immune to EM interference. To measure the projectile and particle velocity of impacted targets optical interferometric techniques have proven to be more useful. These techniques are based on measuring the Doppler shift in the light reflected from the moving surface. Many optical interferometric systems [3, 4, 5] based on this concept have been developed to measure the velocity histories of projectiles and impacted targets. Fabry-Perot velocimeter (FPV) is one such potential technique for high velocity measurements. This technique utilizes the property of Fabry-Perot interferometer that its fringe diameters are decided by the wavelength of the incident light. Therefore, time evolution of fringe diameters can be used to calculate the velocity profile of the moving surface by knowing the relations of Fabry-Perot interferometer and Doppler shift. To measure the projectile as well as the particle velocity of impacted targets we have developed a Fabry-Perot velocimeter in our laboratory. This velocimeter is designed to measure the velocities in the range of 0.2-10 km/s with a resolution of 0.2 km/s. The technical details of this technique are discussed in this article.

Another crucial diagnostic in shock wave research is the measurement of shock wave velocity in the targets impacted by a well characterized projectile. Shock wave velocity measurements are commonly performed by using arrival time gauges which generate a detectable signal on the arrival of shock wave at known distance of target. Commonly used fiber optic pins [6] have a micro balloon filled with argon gas attached to one end of an optical fiber. When this micro-balloon interacts with the shock wave, a light flash is generated and gets recorded in the oscilloscope through a photo detector. This technique is quite sensitive and immune to EM interference but requires special techniques to manufacture the probes. At high pressures, the arrival of shock wave also generates a weak luminescence due to sudden change in temperature near the free surface. To experimentally detect these light signals at different target steps, we have utilized the large diameter polymer optical fibers with fast photodiodes. Time delay between the generations of shock luminescence at consecutive steps is then used to compute the shock wave velocity in the impacted targets.

Technical details and design aspects of optical measurement techniques developed in our laboratory are described in the following sections. Shock wave studies have been carried out on tantalum, aluminum, and copper targets and results of these experiments with a comparison to known EOS data are presented in the later sections.

2. FABRY-PEROT VELOCIMETER

It is a well known fact that the radiation reflected from a moving surface experience a Doppler shift in its frequency. The most common and accurate way in optics to measure this change is to apply interferometric techniques. Fabry-Perot interferometer works on the principle of multiple
beam interference and its fringe diameters are decided by the wavelength of the incident light. Hence if the incident light is reflected from a moving surface then by considering the equation for relativistic Doppler shift and the equations of Fabry-Perot interferometer, velocity of the projectile may be written in terms of the instantaneous diameter of Fabry-Perot fringes \[4\].

\[
v = \frac{c\lambda L_0}{4d\mu} \left( 1 + \frac{D^2_{L0} - D^2_{L1}}{D^2_{L0} - D^2_{L1}} \right)
\]  

Where \(\mu\) is the refractive index of the material present between the two mirrors of Fabry-Perot interferometer, which are separated by a distance \('d'\), and \('i'\) represent the total number of new fringes moved out from the center of the fringe pattern. \(D_{L0}\) and \(D_{L1}\) are the diameters of the innermost and next to innermost bright fringes produced by the Fabry-Perot interferometer when flyer is at rest. \(D_{L0}\) is the instantaneous diameter of the innermost bright fringe while flyer is in motion. Therefore if fringe diameters are known at different time instances velocity profile can be obtained by this relation.

![Fig.1. Schematic of Fabry-Perot velocimeter](image)

The experimental configuration of Fabry-Perot velocimeter is shown in Fig.1. A narrow linewidth (5 MHz), 350mW frequency doubled Nd:YVO\(_4\) CW laser is used to illuminate the target. Light reflected from the target is collected and collimated by a lens and directed towards a Fabry-Perot etalon having a finesse of 80 and FSR 0.57cm\(^{-1}\). The various design parameters are chosen to measure velocity in the range of 0.2-10 km/s. The laser linewidth is decided in such a manner that it is much smaller than the expected minimum Doppler shift in wavelength. Cylindrical lens placed before Fabry-Perot etalon introduces one dimensional convergence in the incident light due to which interference fringes appears as dot pattern instead of normal ring like structure. The Fabry-Perot interferometer is followed by a good quality spherical lens, which focuses the interference pattern on to the camera slit, placed perpendicular to the axis of cylindrical lens. To avoid the exposure to the broadband background light generated by the projectile launcher an optical filter is placed before Fabry-Perot interferometer. The number of fringes observed in the streak camera is determined by the focal length of cylindrical lens, and fringe diameter is decided by the focal length of spherical lens. IMACON-790 camera with slits of width 100-200\(\mu\)m is used in streak mode to record the time history of interference fringes.

### 3. Fiber Optic Probe for Shock Detection

When a shock wave propagating through a material encounters a free surface, the air near the surface gets ionized and weak luminescence is generated. If stepped targets of predefined thicknesses are used for impact studies, shock wave velocity can be calculated by measuring the time delays between the generations of shock luminescence at consecutive steps. To measure the shock wave velocity in copper, stepped targets have been prepared by controlled chemical etching process. Two polymer optical fibers of core diameter 1.0 mm have been placed in a Perspex holder over the stepped target. These fibers have been coupled to Hamamatsu make S2383 fast avalanche photodiodes at other end and their output has been recorded on an oscilloscope. Avalanche photodiodes have been reverse biased near the breakdown region, and have a rise time of approximately 4 ns. Avalanche photodiodes are preferred because of their faster response time and better light detection efficiency as the light signals are generally weak and time delay between two fiber signals is of the order of few nano-sec’s.

### 4. Experimental Results

In our laboratory we have utilized a low energy portable electrically exploding foil accelerator (also known as electric gun) \[7\] for high pressure studies. The principle of electrically exploding foil accelerator (EEFA) is to use the energy initially stored in a fast capacitor bank to explode a thin metallic bridge foil sandwiched in between two dielectric sheets backed by a heavy tamper on one side and an appropriate size barrel on the other. Due to fast explosion, foil material expands and punches out a section of the dielectric sheet (flyer) positioned adjacent to it and drives it up in the barrel to suitably high velocities. The present system is capable in accelerating 10 mm diameter and 125 \(\mu\) thick projectiles of Kapton polyimide to a velocity of 3.2 km/s as characterized by the present Fabry-Perot velocimeter. The repeatability of flyer velocity profiles has been verified in three similar experiments and the variation in measured velocity profiles is found to be within 10%.
To study the impact characteristics, interface velocities of the tantalum and aluminum target have been measured with Fabry-Perot velocimeter. Schematic of experimental assembly is shown in Fig.2. A 25 µm thick foil of target material has been placed over the barrel and a 1mm thick glass plate was used to hold and maintain its planarity till the time of impact. The laser light is launched through the glass plate and reflected light is collected back and focused on the FPV. The obtained streak records and computed velocity profiles for Ta-glass interface are shown Fig.3 (a). A sharp jump observed in the interface velocity indicates the arrival of shock wave, after which the velocity remains constant for approximately 24 ns and then slowly decreases back to zero value after the arrival and overtaking of rarefaction wave generated at the rear free surface of the flyer. The measured peak interface velocity in this case is 0.8 km/s, which matches well with the theoretical expectations of 0.72 km/s based on known Hugoniot data [8]. Due to the availability of single beam FPV, the flyer velocity has not been measured in-situ and taken as 3.2 km/s at the time of impact as measured in earlier experiments. Similar results obtained for aluminum are shown in Fig.3 (b). The intensity of the reflected light was reduced considerably, due to higher shock velocity in aluminum and lesser contrast is obtained in the streak record. Here the peak interface velocity of 1.3 km/s is recorded, which is in good agreement with the theoretically expected value of 1.26 km/s for a flyer velocity of 3.2 km/s.

Shock wave velocity measurements are performed on step targets of copper with thickness of 50 µm. Due to small projectile diameter only targets with one step are prepared by controlled chemical etching process. Two polymer optical fibers with 1.0 mm core diameter are placed in a Perspex target holder over the steps. The experimental assembly is similar to that shown in Fig.2 except the metal-glass target has been replaced by stepped target assembly. The results obtained in one of the experiment are shown in Fig.4. A voltage pulse in the photodiode output indicates the arrival of shock wave and delay between two such signals yields the shock travel time between two steps. It can be observed from the oscilloscope records that the rise time of the light pulse for the fiber at second step is slower than that for the fiber at first step. The possible cause for this could be the reduction in shock strength due to arrival of rarefaction wave from the free boundary at the step. Another interesting phenomenon observed in the fiber signals is their two step behavior. The first light signals are due to the shock luminescence at steps and later fast rising signals appears to be due to the impact of metal free surfaces to the tip of optical fibers placed in close vicinity.

Using the time delay between the two light signals, measured shock wave velocity in 50 µm thick step target of copper is found to be 4.38 km/s. In this experiment also the flyer velocity is taken as 3.2 km/s from previous measurements as the placement of target obstruct the flyer view and made it difficult to launch laser light. Theoretically shock wave velocity
of 5.0 km/s is expected in copper target impacted by a Kapton flyer moving with velocity of 3.2 km/s. The possible reasons for this mismatch could be the errors involved in measuring the step heights or the generation of rarefaction wave near the target steps which reduces the strength of shock wave in the material.

5. CONCLUSIONS

Two optical techniques are described to measure the particle and shock velocity in materials impacted by hyper velocity projectiles. Kapton flyers have been launched to a velocity of 3.2 km/s by an electrically exploding foil accelerator and made to impact on tantalum and aluminum targets supported by a glass plate. Fabry-Perot interferometer based optical velocimeter has been developed and implemented to measure the metal glass interface velocity profiles. The measured peak velocities (0.83 km/s for tantalum and 1.3 km/s for aluminum) are found to be in good agreement with the known equation of state data. In another diagnostic technique optical fibers coupled to fast photodiodes are used to directly detect the shock luminescence generated at the steps of impacted copper target.

Measured shock wave velocity (4.38 km/s) has been found reasonably in agreement with the equation of state data. Further work is in progress for in-situ measurement of projectile as well as particle or shock wave velocity in impacted targets, to generate more reliable equation of state data.

6. REFERENCES