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SUBMITTED TO XIV INTERNATIONAL CONFERENCE ON HIGH PRESSURE SCIENCE AND TECHNOLOGY AND 1993 TECHNICAL MEETING OF THE TOPICAL GROUP ON SHOCK COMPRESSION OF CONDENSED MATTER
JUNE 28-JULY 2, 1993
COLORADO SPRINGS, CO

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LIQUID SOUND SPEEDS AT PRESSURE
FROM THE OPTICAL ANALYZER TECHNIQUE*

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The optical analyzer technique has proved to be a useful means of obtaining wave velocities at high pressures. Stepped wedges of the investigated material emit shock, and later, rarefaction waves into a transparent analyzer covering the material. The time interval between shock and rarefaction plotted versus wedge thickness gives a linear plot whose intercept fixes the target/driver thickness ratio for exact wave overtake, and thus gives a relation between the shock velocity and overtaking wave velocity at pressure. The slope of this line is intimately related to the wave velocity at pressure of the analyzer in front of the wedge. This aspect of the technique has not yet been exploited. We present the appropriate analysis, some data on bromoform (one of the analyzers used), and discuss some possible applications of this technique.

INTRODUCTION

The optical analyzer technique has been used to measure release velocities in a variety of metals. Sound-speed accuracies of the order 1% allow determination of derivatives on the equation-of-state surface to the same level of accuracy as Hugoniot states. Several high-pressure phase transitions have been detected in metals that were not apparent from the Hugoniot data. We will show how the optical analyzer technique can be used to measure sound speeds in liquids. Accurate bulk moduli can be determined for validation of theoretical models, in addition to the possible detection of phase transitions such as shock-induced dissociation and ionization. In the conventional application of the optical analyzer technique, the overtake time in the liquid analyzer (usually bromoform) decreases linearly with increasing target thickness. From the intercept of this overtake curve on the target thickness axis the rarefaction velocity in the target can be determined. The information that hasn’t been exploited with this technique is the slope of the overtake curve. We will demonstrate that this slope is intimately related to the sound velocity in the liquid analyzer. Several shots have been analysed using stainless-steel targets to measure sound speeds in bromoform. These efforts were quite successful. We believe this technique can also be used on liquids at cryogenic temperatures. Because the liquid needs to radiate like a black body to simply correlate radiation records with wave arrival, high-pressure experiments are particularly suited to this technique.

WAVE RELATIONS

Our results will be obtained from an analysis of lead characteristics propagating into constant states. Fig. 1, in the time-Lagrangian coordinate \((t-y)\) plane shows the waves of interest. The dotted lines are applicable for impacts between the stainless steel driver and target that produce pressures less than those that result in melting on the Hugoniot \((P < 227 \text{ GPa})\). We analyze the fluid case (the solid lines) first.

Our direct observable \(\Delta t = t_{h}\) (we use \(x_{ij} \equiv x_{i} - x_{j}\)) is a function of the target thickness \(T = y_{1} = y_{6} = y_{h}\). Several target thicknesses from the step wedges in an experiment result in the \(\Delta t(T)\) shown in Fig. 2. From such a plot we get the intercept thickness \(T_{h}\) and a velocity from the

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*This work supported by the US Department of Energy.

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slope \(1/v^* = -d(\Delta t)/dT\). We have \(y_{98} = t_{CIc}t_{BG}\) and \(y_{BG} = u_{BG}t_{BG}\). Elimination of \(t_{BG}\) then implies 
\((y_{9} - T)(1/u_{BG} - 1/t_{CIc}) = t_{BG}\) and
\[t_{BG} = t_{BG}/(1 - u_{BG}/t_{CIc}) \]

Our information on the bromoform sound speed is contained in the second factor. We will be measuring the ratio of the shock and Lagrangian sound velocities. We now need to evaluate \(dS_{BG}/dT\).

Such derivations follow the above pattern; finding the intersections of straight characteristics. If the rarefaction from interaction 6 did not change the slopes of the lead characteristics we would have

\[t_{BG} = D\left(\frac{1}{u^*} + \frac{1}{t_{CIc}}\right) - T\left(\frac{1}{u^*} - \frac{1}{t_{CIc}}\right) \]

This assumption is valid for locating the intercept. When this time interval vanishes, we have \(R \equiv \)

\[t_{BG} = D\left(\frac{1}{u^*} + \frac{1}{t_{CIc}}\right) - T\left(\frac{1}{u^*} - \frac{1}{t_{CIc}}\right) \]

...
two state points on the isentrope representation in the $P-u_p$ plane. When we use eq. (4) in (3) we replace $c_B$ everywhere by its experimental equivalent $u_*(R + 1)/(R - 1)$. In order to evaluate the remaining terms in $f_{\text{fluid}}$, $c_B$ and $c_{\text{is}}$, we assume the usual $u_*(u_p)$ Hugoniot, a Mie-Grüneisen $E(P, V)$, and a constant $\rho \gamma$.

For the elastic-wave solution we slide interactions 7,8,9 down to the dotted line. The lead characteristics from 4 → 5 and 6 → 5 travel with velocity $c = u_*(R + 1)/(R - 1)$, the experimental longitudinal velocity given by the measured intercept $T_0$. The waves from 5 → 7 and 7 → 8 carry a release in material that has already been relieved elastically, so we assume that these waves travel with velocities $c_B$ and $c_{\text{is}}$, i.e., velocities appropriate to the bulk properties of the material. We are assuming that the initial elastic release drops the steel to its lower yield surface, and that the amplitude of this elastic release does not greatly change the bulk state (in particular its effect on calculating the $f$-factor), and that further wave propagation in the steel is at the bulk velocities. When we solve the $t-\gamma$ diagram for the elastic case we again get an equation similar to (2) with an $f$ given by

$$f_{\text{elastic}} = f_{\text{fluid}}(1 + \frac{c_B}{c_B})^2$$

In this case we will replace $c_B$ by its experimental equivalent $u_*(R + 1)/(R - 1)$ and use the EOS information for 316 stainless steel$^2$ and CHBr$_3$ to evaluate the intermediate velocities. The EOS's used for these two materials are: SS316($\rho_0 = 7.96, u_* = 4.64 + 1.544u_p, \rho \gamma = 17.27$) and CHBr$_3$($\rho_0 = 2.87, u_* = 1.50 + 1.38u_p$). Units are g/cm$^3$ and km/s. The SS316 EOS should be regarded as tentative, particularly if it is used above the melting transition.

**RESULTS**

Experimental values for $\nu^*$, $R$, and $u_*$ are used in eq. 3 to obtain $c_{\text{is}}$. The resulting sound speed at pressure in bromoform, $c_{\text{is}}(\rho) = \rho c_{\text{is}}(\rho)/\rho$, is shown in Fig. 3.

![Figure 3. Bromoform Sound Speed vs Density.](image)

When we measure sound speed in a liquid along the Hugoniot we also get the Grüneisen function. If $B = -VdP/dV$ for a curve, a convenient expression for $\gamma$ is:

$$\frac{\gamma}{2V}(V_0 - V) = \frac{B_h - B_s}{B_h - B_{\text{ch}}}$$

(6)

where the subscripts refer to the Hugoniot, isentrope, and Rayleigh ray. (An ambiguity exists for the chord slope; in writing the above form we have chosen $B_{\text{ch}} = V(P - P_0)(V_0 - V)$.) If the Hugoniot can be represented as a linear $u_*(u_p)$ a convenient computational form is:

$$\gamma(\frac{\rho}{\rho_0} - 1) = \frac{(c_0 + 2su_p) - c_0(u_*/u_p)^2}{su_p}$$

(7)

The results for $\gamma$ are shown in Fig. 4. The first and third data points are suspect. They lead to $\gamma$-values that are rather low. The linear fit to $c(\rho)$ shown is: $-1.21 + 1.21\rho$, and the scatter is such that $c(\rho_0) = 1.5$ readily fits within the uncertainty. Lowering the sound speed of the first
and third points (and increasing $\gamma$) is a move in the direction of a good linear $c(\rho)$ that would extend down to $\rho_0$.

The $\rho \gamma$ constant assumption is an approximation that is adequate for modest compression. It was never intended for the compressions achieved here. It may describe the initial drop from the thermodynamic $\gamma_0 = 1.2$. Even discounting the two lower values of $\gamma$, it seems to have dropped to 0.5, a low value perhaps induced by disassociation and the opening of miscellaneous energy sinks; and then has risen toward (and perhaps past) the value 2/3, a $\gamma$ characteristic of a hot electron gas.

Exceeding the value 2/3 may be a consequence of extrapolating the linear $u_s(u_p)$ fit of SS316 past its melting point. Some preliminary data exist that indicate this linear fit overestimates $u_s$ for a given $u_p$ for shock strengths beyond the melting point. Use of such a lowered Hugoniot could readily drop the $\gamma$-points from the melted regime (the last five points) toward 2/3 and lead to a constant $\gamma$ in this region.

**DISCUSSION**

This technique has the great advantage of not needing any structure in the liquid reservoir. Precision resides in the driver/target assembly. As our knowledge of driver/target behavior improves, we will be better able to estimate the $f$-factors required to implement this technique. For these experiments the $f$ values have been around 1.25. It is already a method that shows great promise for making these measurements in any transparent material that becomes sufficiently ionized in a shock.

We have not yet done an error analysis for this technique. Space available here precludes this. Because bromoform has been used as an analyzer on many different materials there are about a hundred or so shots waiting in the wings to be analyzed. Analysis of this wealth of data and the necessary error analysis is in progress. The bromoform high-pressure sound speed and its $\gamma(\rho)$ may turn out to be one of our most accurate high-pressure data curves; it will certainly be one with a high density of data points.

We have used this analysis for points where the driver/target is in the elastic regime (the lower six points) and where it has melted (the upper five). The bromoform data is smooth between these two data sets, even though the driver/target system exhibits a relative large discontinuity from one to the other. This is as it should be and lends some confidence to our use of the $f$-factors in the two different regimes.

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10/7/93