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MEASUREMENT OF WAVE PROFILES IN
SHOCK-LOADED SOLIDS*

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ABSTRACT

The evolution of the numerous detectors which measure wave profiles in solids subjected to rapid impulsive loading is traced and principal trends are identified. Recent capabilities for the measurement of transverse or higher-order motions (acceleration and velocity gradient) are described.

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INTRODUCTION

Those of us whose technical interest concerns the response of solids to shock-wave loading feel quite at home with nanoseconds and GPa's. Nevertheless, the nonlinear and largely irreversible events which take place under such short durations and high pressures are not available for direct examination with our human senses and we rely on our instruments for scientific descriptions of the processes. Since our experience is so limited under these conditions, experiments have played a leading role in the development of the field and the fidelity of our instruments and the validity of our experiments are crucial elements in our understanding of shock processes.

What I want to do in this paper is to take a brief critical look at the characteristics of our detectors as they affect our ability to picture conditions in the shocked state from measurements of wave profiles in shock-loaded solids. We will then identify some critical characteristics and important trends. Finally, new developments which promise to significantly influence future experimental capabilities will be described. Because the length allocated for this paper is short, I will draw heavily from a more detailed description of technique published by Asay and me,¹ and to the text of a paper presented at a recent workshop on nonlinear waves in solids.²

CONSERVATION RELATIONS

In a shock-loading experiment stress-volume relations and the kinetic effects associated with the loading are deduced from the measurements of the reaction of the sample to the loading. This usually involves measurements of characteristics of the wave profiles. Conservation relations are utilized to relate the measured variables to the desired mechanical effects.

For a steady shock wave of fixed amplitude there are discontinuous jumps in particle velocity, u , and longitudinal component of stress, σ_x , and the conservation relations are:

$$\sigma_x = \rho_0 uU$$

$$V/V_0 = 1 - u/U \quad (1)$$

$$E - E_0 = \frac{1}{2}(V_0 - V)(\sigma_x)$$

where ρ_0 is the initial density, U is the shock velocity, V is the specific volume of the compressed material, V_0 is the initial specific volume, E and E_0 are the internal energies per unit mass of the shocked and unshocked materials, respectively. The propagation direction is along the x -axis. According to Eqs. 1, if we wish to characterize the mechanical state of the material, a measurement of the jump in particle velocity and the shock velocity gives sufficient information to specify the average thermodynamic conditions behind the shock.

On the other hand, if the propagating wave is not a shock, the conservation relations for an arbitrary wave profile are, in material coordinates:³

$$\rho_o(\partial v/\partial t) - \partial u/\partial h = 0$$

$$\rho_o(\partial u/\partial t) + \partial \sigma/\partial h = 0 \quad (2)$$

$$\partial E/\partial t + (\sigma/\rho_o)\partial u/\partial h = 0$$

where h is the material position, t is time, and other symbols are as defined in Eqs. 1. Fowles has shown that in a general unsteady wave the speed of particle velocity, stress and density waves are not the same. In special cases of steady waves or centered waves Eqs. 2 are simplified but in general the information called for from the measurements is no longer particle velocity and shock velocity but higher order terms, acceleration, $\partial u/\partial t$, velocity gradient $\partial u/\partial h$ or stress gradient, $\partial \sigma/\partial h$. Thus, if we wish to measure the appropriate variables directly, the analysis of wave profiles requires higher-order information than the analysis of shock waves. We will return to this point later.

CHARACTERISTICS OF DETECTORS

Measurements of motions in shock-loaded solids require response times which can only be obtained with active elements which are in principle massless and in practice approach a massless condition. Thus, mechanical detectors are inadequate and shock detectors utilize either electrical or optical effects to achieve adequate response time. We can make a first order estimate of the effect of a finite mass in the detector by considering the time for mechanical equilibrium to be established.

The detectors which have been used for wave profile measurements have a variety of operating principles and characteristics which affect the choice of a particular detector for a particular measurement. This choice is based on a number of considerations which cannot be neatly characterized, but once the data are obtained, we can characterize detectors on the common ground of the measured parameter. On that basis, we characterize detectors on the basis of whether they provide a discrete or continuous measure of displacement, stress, or particle velocity versus time.

The conservation relations for shock waves, Eqs. 1, require information on particle velocity and the measured displacement-time data must be differentiated before the data specify material response. Likewise, the conservation relations for continuous wave profiles, Eqs. 2, require information on acceleration, velocity gradient or stress gradient and time-resolved displacement or velocity data must be doubly or singly differentiated respectively to obtain data to specify material response.

Trends in Detector Development

Evidence for trends and the activity in detector development is shown in Table I which lists the principal detectors, categorizes them according to the measurement they provide and dates the first report of their development. References to the individual papers describing these detectors are given in reference 1. Reviews of operating principles are given by Fowles (3), McQueen, et al. (4), and Doran (5).

The information in Table I indicates that early measurements of particle velocity and shock arrival were made with charged electrical pins or with flash gaps (argon gas chambers which luminesce when shocked at high pressure). These techniques are used to the present time and offer the advantage of simplicity and fast data return but their use is limited to very high pressure and circumstances in which there is little evidence for or interest in details of the wave profile.

Continuous displacement-time detectors provide more data than the discrete detectors and the continuous record assures that there are no undetected discontinuous behaviors. Numerous continuous displacement-time detectors were developed in the period from 1957 to 1970. With one minor exception there has been no further development of this class of detector since 1970. The end of this development trend no doubt results from the techniques for direct measurement of velocity or stress which have proceeded more or less continuously since about 1960.

As indicated in Table I, the trend toward direct measurement of velocity or stress is apparent. This trend is apparently in response to the recognition of the importance of improved time resolution in changes in

velocity, increased interest in details and interest in more refined models of material response.

Time Resolution

The significant influence of time-resolution of detectors has been somewhat clouded in the past because of a lack of definition of the term which could be used to quantify the response of the detectors. Consider for a moment the time resolution problem posed by measurements on a shock followed by a constant particle velocity. In this case, if detail of the rise time of the shock is not desired, detectors with limited time resolution can provide an accurate measure of the particle velocity since it is constant for a relatively long time.

If finite accelerations occur the ability to accurately record a velocity depends on the time resolution of the detector. Accordingly, a measure of velocity time resolution is proposed based on the response of a detector to a step in velocity followed by an exponential decay in time. Presuming that our prime interest is in providing an accurate measure of the peak velocity a time resolution is assigned based on a response whose peak is within 3% of the peak input velocity.

The determination of a time resolution is performed by the following process. A detector is subjected to a series of step loadings each followed by a different exponential decay as indicated in Fig. 1a. In each case a different response will be measured as indicated in Fig. 1b. The time resolution is specified by noting the time after initial loading at which the peak velocity is detected to an accuracy of 3%.

Although this procedure is conceptually straightforward and would provide unequivocal results if we had a machine to generate our loading functions, we do not have such a machine nor has there been any concerted effort to precisely measure response functions.* Nevertheless, we can make a first-order determination based on our knowledge of the physical processes affecting rise times and observations of the measurements of various wave profiles with the different detectors.

To assign values to time resolution I have collected a number of observations of the same or similar profiles and have examined most of the wave profile measurements published in the literature. Those measurements on the same or similar wave profiles which have been collected and compared include: On the elastic wave in 4340 steel, charged pins, Minshall;⁶ displacement capacitor, Minshall;⁶ inclined resistance wire, Butcher and Canon;⁷ velocity interferometer, Tuler;⁸ quartz gauge, Benedick;⁹ solid dielectric gauge, Graham and Ingram.¹⁰ On elastic-plastic wave profiles in Armco Iron, velocity capacitor, Taylor and Rice;¹¹ quartz gauge, Jones, et al.;¹² VISAR, Barker and Hollenbach.¹³ On elastic-plastic wave profiles in 1060 aluminum by Karnes¹⁴ displacement interferometer, and quartz gauge. On elastic-plastic wave profiles in a tungsten carbide by Karnes,¹⁵ displacement interferometer, inclined resistance wire, velocity interferometer and quartz gauge.[†] On elastic-plastic wave profiles in [100] MgO by Grady,¹⁶ Manganin gauge, quartz gauge and VISAR.

*⁶Minshall is the only investigator I am aware of who has attempted a formal measure of a response function. He attempted this on his displacement capacitor with a quartz gauge as the standard and the elastic wave in 4340 steel as his forcing function.

[†]The elastic wave in this material is a shock followed by an increase in stress in time. The time resolution directly affects the value chosen for the Hugoniot elastic limit. Values obtained were: inclined resistance wire 5 GPa, displacement interferometer 4.0 GPa, quartz gauge, 3.65 GPa, velocity interferometer, 3.49 GPa.

The time resolutions derived from these specific measurements, from other individual measurements in the literature and consideration of the physical mechanisms limiting time resolution are listed in Table II. Comparison of these time resolutions with the trends in detector development shown in Table I indicates that the principal change introduced by the direct measurements of velocity or stress is an improvement in time resolution of at least two orders of magnitude. These direct measurements eliminate the need for differentiation of data, a process which degrades resolution and accuracy, and provide information on acceleration which can be used to judge whether the velocity is sufficiently constant for accurate measurement. Although all of the detectors provide information on the next higher derivative of the measured data, certainly very limited information is provided on the second derivative of the measured data.

NEW DEVELOPMENTS

New detectors, loading methods and improved experimental capabilities have provided an almost continuous change in the directions of research on materials under shock-wave loading. Today, it appears that there are a number of new developments that have potential for significant influences on directions of future research. Two of these developments which I will discuss include transverse motion measurements and higher-order motion measurements.

Transverse Motion Measurements

Shock compression experiments have traditionally been limited to measurement and analysis of motions along the direction of propagation. Although this condition forces the material into a well-defined mechanical state, longitudinal motion alone does not differentiate between deformations accompanying isotropic compression and deformations accompanying shear. Since the shear strength of shock loaded solids is not well understood, the limitation to longitudinal motions has greatly restricted experimental studies of the effects of shear. Furthermore, shock-loading techniques have been used to determine longitudinal third- and fourth-order elastic constants of solids and capability for measuring transverse motions promises to permit determination of additional constants involving shear deformations.

Transverse motion measurements and loading techniques have now been accomplished by three different groups. Clifton and his associates at Brown University¹⁷⁻¹⁹ developed a shadow technique for the measurement of transverse displacement. A stationary optical grating is placed at a distance from the surface to be monitored and a similar grating is placed on

the sample surface. A laser beam is passed through the master grating onto the sample grating then back through the reference grating to a photodiode which monitors the intensity of the diffracted beams. Normal velocity measurements are accomplished with the VISAR optical interferometer system. The transverse displacement measurements are then differentiated to obtain velocity.

An oblique impact loading technique is used to produce both normal and transverse motions into the impact face of the sample. If slip does not occur on the impact surface, the relative amplitudes of the normal and transverse motions are controlled by the angle of impact. Rotation of the projectile is prevented by a keyway machined into the inside of the barrel. These authors reported measurements on transverse, and normal motions on fused quartz.

In further work, Kim, et al.²⁰ have reported development of a transverse displacement interferometer which monitors a laser beam reflected from a single diffraction grating on the surface of the sample. These authors monitored normal and transverse motions in impact loaded Y-cut quartz samples which are produced in normal impact configuration due to the crystal anisotropy.

Gupta²¹ and Fowles²² have reported adaptation of the electromagnetic velocity gauge to measure transverse and normal velocities. Thin metallic foils are embedded in nonconducting samples and aligned at an angle to the magnetic field. According to Faraday's law, the motion of the foil in the magnetic field produces an emf which is sensitive to both normal and transverse motions. Measurements are reported for polymethyl methacrylate.²¹

The embedded electromagnetic velocity gauge is limited to nonconductors and the optical grating techniques may be limited at large deformations due

to integrity of the gratings but both techniques offer considerable promise and should stimulate additional activity in this new area of shear measurements. Loading may be simplified to the conventional normal impacts if impactors of Y-cut quartz or other nonspecific crystal cuts are utilized.²³

Higher-Order Measurements

In Section II we pointed out that the conservation relations for arbitrary wave profiles involve acceleration and velocity gradient. Hence, if we wish to provide a direct measure of the parameters used in analysis we need to devise means for higher-order measurements. Acceleration measurements can now be made in a reasonably routine fashion and a proposal for velocity gradient measurements will be described here.

Acceleration. It has been shown that a direct measure of acceleration can be provided by measurement of the rate-of-change of short-circuited piezoelectric current from a piezoelectric current-mode gauge whose active element is quartz or lithium niotat.²⁴ In a linear approximation,

$$a(t) = \frac{1}{e_{ii}} \frac{\ell}{A} \Delta(t) , \quad (3)$$

where a is acceleration, e_{ii} the longitudinal second-order piezoelectric constant of the active element, ℓ the thickness of the active element, A the charge-collecting area of the active element and Δ is the rate-of-change of current (hereafter called the current rate). For x-cut quartz²⁵ $e_{11} = 0.171 \text{ C/m}^2$ and for Z-cut lithium niobate²² $e_{33} = 1.82 \text{ C/m}^2$.

The current rate is measured by a simple electronic differentiation of the current pulse. In a manner analogous to optical velocity interferometers, which optically differentiate a Doppler shifted laser beam by superposing the

beam and the same beam delayed by an optical delay leg, the accelerometer superposes a current pulse and the same pulse delayed by an electronic delay leg provided by a low-loss coaxial cable. (Since speeds of electromagnetic waves in good coaxial cables are close to those in air, similar delay times and delay lengths may be employed in both optical and electronic delay legs.)

An experimental arrangement for a combined velocimeter/accelerometer is schematically shown in Fig. 2. The active area of a piezoelectric current-mode gauge is connected to a number of low-loss coaxial cables, each terminated in their characteristic impedance. In the arrangement shown in Fig. 2, three cables are used; one cable transmits the velocity signal in the usual manner^{27,28} and the remaining two cables transmit and differentiate the velocity signal to provide an acceleration signal. One of the two acceleration cables is selected to be somewhat longer than its companion cable and the longer travel distance delays the current pulse a fixed time relative to the current pulse in the direct cable. These two acceleration cables are connected to a high frequency differential preamplifier* which measures the difference between the two signals and provides an output proportional to the difference in current over the delay time. With the three cable configuration a simultaneous measure of both velocity and acceleration is obtained. We have found a 13.5 ns delay leg (~ 3 m) to provide an acceptable compromise between time resolution and signal level.

To investigate the feasibility of our accelerometer, acceleration waves produced by impact loading of vitreous silica and propagation through various

* We are currently using Tektronix 7A13 differential amplifiers with Tektronix 7903 oscilloscopes.

sample thicknesses were applied to quartz accelerometers. Vitreous silica, both GE 151 and Dynasil 1000, has been carefully studied by Barker and Hollenbach,²⁹ Barker,³⁰ Asay³¹ and by the present author. Acceleration pulses are produced with impact loading since the positive third-order longitudinal elastic constant of vitreous silica causes a shock to decay to an acceleration. The magnitude of the acceleration depends only on the sample thickness up to an input stress of about 3 GPa.

The results of previous determinations of accelerations from velocity measurements and direct acceleration measurements are shown in Fig. 3. The solid line is a fit to the original data of Barker and Hollenbach²⁹ on GE 151. The measurements on Dynasil 1000 show that the accelerations from that material are slightly higher* than in GE 151.

The value of the acceleration determined from the accelerometer on Experiment 1248 is in excellent agreement with the acceleration derived from previous velocity measurements and from the simultaneous velocity measurement on Experiments 1248. Experiment 1249 was not as successful since bonding problems between the sample and the gauge caused a poorly defined acceleration pulse. Nevertheless the results were reasonable.

In order to examine the entire acceleration pulse, the nonlinear theory of the accelerometer is employed.²⁴ In this theory the third-order piezoelectric constants of the active elements are accounted for† and

*The density of Dynasil 1000 is 2.2015 Mg/m^3 and the speed of an acceleration wave at zero stress is 5.95 km/s .³⁰ The best fit to the acceleration versus thickness for Dynasil 1000 is $a = \frac{6.9}{l} \times 10^9 \text{ m/s}^2$, where l is the sample thickness in mm.

†For X-cut quartz $c_{111} = 2.62 \text{ C/m}^2$ and for Z-cut lithium niobate $e_{333} = 21 \text{ C/m}^2$.

provide acceleration versus time records such as that obtained from Experiment 1248 and shown in Fig. 4. A well-defined constant acceleration is noted after an initial rise caused by tilt, bonding and amplifier rise time. The capability to measure jerk, the derivative of acceleration, is clearly demonstrated by the data of Fig. 4. The data show that the jerk is zero for the full acceleration pulse length. The present measurement is believed to be the first determination of jerk on a wave profile.

We have performed about twenty acceleration measurements on different materials, in different gauge configurations and with both quartz and lithium niobate as active elements. The principal problems encountered were bonding of the gauges to the samples and limitations imposed by the differential amplifiers.

The bonding problem is more severe for acceleration measurements than for velocity measurements due to the increased sensitivity of the acceleration measurements. In addition to the usual care taken to achieve optical flatness for the surfaces to be bonded, care must be taken not to stress either the sample or gauge after the gauge is bonded to the sample.

The principal limitations to acceleration measurements lie with the differential amplifier. Our investigations lead us to believe that the rise time of our 7A13 amplifier in the differential mode is about 25 ns. However, rise times of a few nanoseconds can be achieved in differential systems for direct deflection of the plates of either Hewlett Packard 183 or Tektronix 7903 oscilloscopes. We have made direct deflection measurements with an HP 183 system. The 7903 system is apparently the most practical to use since the HP 183 system requires 100 Ω cable which is not standard. Improved rise time is achieved at the expense of vertical sensitivity. For

direct deflection the sensitivity of the 7903 oscilloscope is about 7 volts per division. The maximum acceleration signal that can be generated is about 5 volts so fast rise time measurements will provide small vertical deflections. For general use the 25 ns rise time which provides much more flexibility in vertical sensitivity should prove satisfactory.

Noise is a definite problem in the differential mode. What appears to be minor noise on a conventional velocity versus time record can become a serious problem when electronically differentiated. Usually the effect of noise is to limit the definition of the acceleration signal but if the differential signal is driven well beyond full deflection on the oscilloscope, the amplifier can become saturated and a finite time is required for recovery. In spite of these difficulties, measurement of both velocity and acceleration can eliminate any ambiguity in interpreting the acceleration records.

Acceleration Loading Methods. The ability to measure accelerations makes the study of material properties from acceleration pulses considerably more attractive. Herrmann³² has pointed out the role that acceleration measurements can play in characterizing viscous flow in metals. Nunziato, et al.³³ have summarized acceleration experiments in nonlinear viscoelastics. In typical acceleration experiments samples of various thicknesses are loaded with acceleration pulses and the output accelerations are measured. The effect of material properties on acceleration is to increase or decrease the acceleration depending upon the competition between nonlinear elastic and viscous effects.

Several typical experimental configurations for acceleration loading are shown in Fig. 5. In these configurations shock loading is applied to vitreous silica acceleration pulse generators and these accelerations are

propagated into the samples. Since the accelerations produced by the acceleration pulse generators are more reproducible than we can measure at present, it is not necessary to measure their output accelerations. Various accelerations are achieved by the use of different thicknesses of vitreous silica. (See Fig. 3.)

In previous work projectile impacts from guns have been used for controlled shock loading of samples and explosive loading has not been an effective method of loading for experiments at low stresses. The use of acceleration wave generators makes explosive loading entirely feasible since the acceleration loading is controlled by the thickness of the vitreous silica and the first 2 GPa of the output pulses are independent of driving pressure up to 35 GPa.³⁴ For higher pressure investigations, Benedick and Asay³⁵ have shown that shock-loaded glass ceramic produce an output acceleration up to pressures of about 30 GPa.

Measurement of Velocity Gradient. Although we have not yet made velocity gradient measurements, our proposed configuration is similar enough to the acceleration configuration that we feel confident that the measurement is feasible. The proposed configuration is shown schematically in Fig. 6. A sample with two discrete thicknesses is used and gauges are placed on parallel planes about 0.25 to 0.5 mm apart. The output from the two gauges spaced at known Lagrangian positions are connected to a differential pre-amplifier and the difference in particle velocity between the two stations is directly recorded. Since the spacing h is small the measurement accurately approaches a measurement at fixed time.

In the configuration shown in Fig. 6 the use of six coaxial cables provides measurements of acceleration, velocity gradient and tilt. This

configuration provides a valuable set of measurements, and since the particle velocity speed, C_u , is given by

$$C_u = \partial u / \partial t / \partial u / \partial h ,$$

the measurements provide sufficient data to complete the material description.

The principal difficulty in taking the measurement is in the control and correction for tilt which acts as an error in h . With good tilt control and an active measure of tilt at the gauge, it appears likely that good velocity gradient measurements can be made. Other similar configurations seem feasible.

Both the acceleration and velocity gradient measurements are typical of a class in which the gauge may introduce a significant perturbation to the wave in the bulk. The question of how to best manage this perturbation remains a significant problem.

CLOSURE

In this review I have attempted to stimulate consideration of response characteristics of the instrumentation and consideration of how these response characteristics affect the present understanding of the properties of solids under shock-wave loading. The summary presented indicates that considerable progress has been made in improving instrumentation and that the description of processes occurring under shock-loading is critically dependent on experimental capabilities. The critical importance of instrumentation requires that we exert considerable effort in the study of the response of the instrumentation before being satisfied with material property measurements.

Transverse and higher-order measurements provide qualitatively different capabilities for probing material response than we have had before. Investigations with these new tools have the potential for a significantly improved picture of material response. The continual development of new experimental capabilities is essential if we are to continue to improve our understanding of shock processes.

Finally, consideration of the general conservation relations by Fowles³ indicates that the measurement of stress and its higher derivatives is of considerable value and that stress and particle velocity waves may have different characteristics. Nevertheless, in the case of a single piezoelectric gauge, the two measurements cannot be distinguished since they are directly related by the elastic constants of the gauge. If stress and particle velocity are separately distinguishable in the sample, complex coupling must be postulated between the gauge and the sample. Such complex coupling

would affect interactions between samples and all gauges. It seems difficult to devise an experiment which can distinguish between inherent differences in response to stress and particle velocity, and the question of whether we can provide a measure of stress in-situ seems significant.

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TABLE I

DATES OF DEVELOPMENT OF DETECTORS

	<u>Displacement vs. Time</u>		<u>Velocity or Stress-Time</u>
	<u>Discrete</u>	<u>Continuous</u>	
1945	pins	---	---
~	~	~	~
1955	flash gap	---	---
1956	---	---	---
1957	pins	capacitor	---
1958	---	---	---
1959	---	---	---
1960	---	---	electromagnetic velocity capacitor
1961	---	optical image	quartz piezoelectric
1962	---	---	Manganin piezoresistance
1963	---	inclined mirror	optical lever
1964	pins	inclined resistor inclined prism	---
1965	pins	displacement interferometer	---
1966	---	---	---
1967	---	---	velocity interferometer
1968	pins	---	sapphire solid dielectric
1969	---	---	---
1970	---	electromagnetic stress integral	---
1971	pins	---	---
1972	---	---	VISAR
1973	---	---	LiNbO ₃ piezoelectric axisymmetric magnetic
1974	---	---	---
1975	---	---	---
1976	pins	---	---

TABLE II

STRESS/VELOCITY TIME RESOLUTION OF VARIOUS GROUPS OF DETECTORS

<u>Detectors</u>	<u>Resolution</u>
Discrete Displacement-Time Detectors	~ 200 ns
Continuous Displacement-Time Detectors	~ 100 ns
Optical lever, electromagnetic velocity gauge	50 - 100 ns
Manganin gauge, velocity capacitor	25 - 50 ns
Displacement interferometer	10 - 25 ns
Piezoelectric current-mode gauge, velocity interferometer, VISAR, sapphire gauge	1 - 5 ns

FIGURE CAPTIONS

- Figure 1. The specification of time resolution of particle velocity measurements with a detector is defined in terms of its responses to a series of step loadings followed by exponential decays as indicated in (a). The measured responses, indicated in (b), are used to specify the time at which the peak measured output equals 97% in the peak input.
- Figure 2. Experimental configuration for the simultaneous measurement of acceleration and velocity with a piezoelectric detector. The acceleration measurement utilizes an electronic delay leg furnished by an added length of coaxial cable.
- Figure 3. Output accelerations observed for input shock waves which have traversed different thicknesses of vitreous silica.
- Figure 4. Acceleration versus time pulse for an acceleration pulse produced by vitreous silica. The capability for measuring jerk, the derivative of acceleration, is clearly indicated.
- Figure 5. Acceleration loadings are accomplished by output waves from vitreous silica disks whose thicknesses are varied to achieve the desired acceleration.
- Figure 6. Experimental configuration for simultaneous measurement of particle velocity gradient, $g(t)$, acceleration, $a(t)$, particle velocity, $u(t)$, and tilt. The distance between measuring stations, Δh , is exaggerated for clarity. Each line shown connected to the guard-ringed electrodes of the piezoelectric disk, P, is a low-loss coaxial cable. The cable lengths are matched except

for the delay leg used for the acceleration measurements.

All cables except the velocity cable are connected to differential preamplifiers which measure the differences between the current pulses.

Figure 2 of 6
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Figure 3 of 6
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(a)

(b)

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