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Interferometric Measurement Techniques for Small Diameter Kolsky Bars

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ABSTRACT

The use of optical measuring techniques for small diameter Kolsky bar experiments is discussed. The goal is to develop methods that can eliminate the need for more commonly used strain gages which become impractical as bar sizes decrease. The basic approach taken here is to adapt interferometer-based methods, used commonly in pressure-shear plate impact experiments, to high-rate Kolsky bar experiments. A Normal Displacement Interferometer (NDI) is used to measure the motion of the free end of the transmitter bar and provide a measurement of the transmitted pulse. Similarly, the incident and reflected pulses are measured with a Transverse Displacement Interferometer (TDI) utilizing a diffraction grating at the midpoint of the incident bar. Both techniques are applied to 1.59 mm diameter steel pressure bars. In the case of the transmitter bar, measurements are also made with the traditional strain gage instrumentation and comparisons between the two are made. The incident bar measurements made via TDI are validated with a simple bar impact against a single incident bar, i.e., without a specimen or transmitter bar. The possible application of these methods to smaller systems is also discussed.

INTRODUCTION

The Split Hopkinson Pressure Bar (SHPB), or Kolsky Bar [1, 2], is a device commonly used for determining the stress-strain response of materials in the strain-rate range of 10^3-10^4/s. The most common arrangement, used for compression testing, is shown in Fig. 1. A specimen is placed between two long, thin, linear elastic bars, known as the *incident bar* and the *transmitter bar*. A projectile impacts the incident bar, which generates a stress wave (the *incident pulse*) that travels down the bar where it is measured by a set of strain gages at the mid-point. It then continues to the end of the bar where it begins to compress the specimen. The impedance mismatch at the specimen results in the creation of a *reflected pulse* which travels back up the incident bar where it is measured by the same set of strain gages used to measure the incident pulse. As the specimen is compressed, a third pulse, called the *transmitted pulse,* propagates into the transmitter bar where it is measured by a set of strain gages at that bar's midpoint. It is assumed that the incident and reflected pulses are short enough that they do

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not overlap at the measurement location. Similarly, the transmitted pulse must be short enough that it does not interfere with its own reflection from the free end of the transmitter bar.

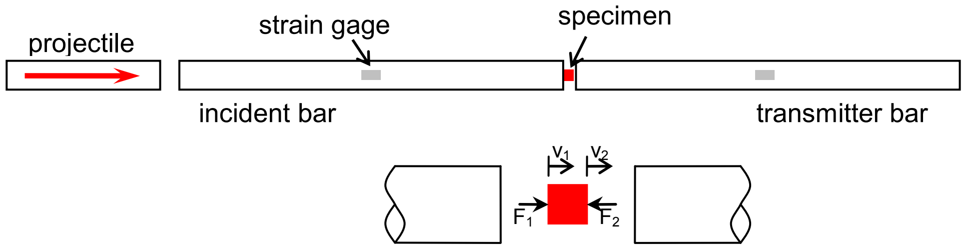


Figure 1 – A basic compressive Kolsky bar.

The force and motion at the interfaces between the bars and specimen can be found from the measured strain signals using the following equations.

$$F_1 = (\varepsilon_i + \varepsilon_r) E A_b \tag{1}$$

$$F_2 = \varepsilon_t E A_b \tag{2}$$

$$v_1 = (\varepsilon_i - \varepsilon_r) c_0 \tag{3}$$

$$v_2 = \varepsilon_t c_0 \tag{4}$$

Here A_b and c_0 are the cross-sectional area and wave speed of the bars. ε_i, ε_r, and ε_t, are the compressive strains due to the incident, reflected, and transmitted pulses at the time at which they act at the specimen. This requires translating the signals in time by the transit times between the specimen and gages, or possibly a frequency-based dispersion correction [3-5]. As long as the specimen remains in contact with the bars, these forces and velocities also act at the ends of specimen. If the specimen is in equilibrium (i.e., the effect of wave propagation in the specimen is negligible), we have the condition that $F_1 = F_2$ and from eqns. (1) and (2)

$$\varepsilon_i + \varepsilon_r = \varepsilon_t \,. \tag{5}$$

In the case of straightforward stress-strain testing, the engineering stress and strain-rate in the specimen can be determined:

$$\sigma_S = \frac{F_1}{A_0} \tag{6}$$

$$\dot{\varepsilon}_S = \frac{v_1 - v_2}{L_0} \tag{7}$$

Specimen strain is determined by integrating the strain-rate with time. Further simplifications are available but these are the basic equations needed for the analysis. Also note that under the assumption of equilibrium, only two of the three pulse are required to determine the response of the specimen. In practice, ε_r and ε_t are preferred. However, if all three pulses are measured independently, specimen equilibrium ($F_1 = F_2$) can be confirmed.

Two factors limit the maximum strain-rate that can be achieved during a given test. The first is related to the time required for a specimen to reach quasi-static equilibrium. As a general rule, smaller specimens equilibrate faster than larger specimens [6]. The second has to do with the dispersion characteristics of the bars. In the analysis of pressure bar signals, it is assumed that the wave propagation within the bars is one-dimensional. For pulses with wavelengths that are short in comparison to the diameter of the bar, this assumption is increasingly violated. This leads to an effective rise-time that limits the temporal resolution of measurements made by the bars [7]. Since high rate tests result in high frequency, short duration signals, this ultimately limits the maximum strain-rates that can be performed with a given bar diameter while maintaining a sufficiently one-dimensional state of stress in the bars.

It is clear that by reducing bar size, and correspondingly the specimen size, higher rate tests can be achieved. This has been recognized by numerous researchers who have built small systems based on this idea, both as Kolsky bar systems and also in Direct Impact (DI) configurations [8-14]. One difficulty encountered with this approach is the use of strain gages. As bar sizes decrease, their use becomes less practical for a variety of reasons, e.g., gage installation and alignment, decreased sensitivity associated with lower bridge excitations, and electrical connections becoming more cumbersome. For this reason we are adapting interferometer-based techniques used commonly in pressure-shear plate impact experiments [15] to the Kolsky bar method. These methods provide robust, non-contact measurements of the bar displacement that can be used to replace the strain-gage measurements under conditions encountered with miniaturized systems. Two applications of these techniques to 1.59 mm diameter steel pressure bars[1] are described in the following sections. In the first case, a Normal Displacement Interferometer (NDI) is used to measure the motion of the free end of the transmitter bar and provide a measurement of the transmitted pulse. In a second application, the incident and reflected pulses are measured with a Transverse Displacement Interferometer (TDI) utilizing a diffraction grating at the midpoint of the incident bar.

TRANSMITTER BAR – NDI MEASUREMENTS OF THE TRANSMITTED PULSE

In most cases with a Kolsky Bar, the end of the transmitter bar can be left free for the duration of the test. Therefore the motion at that free-surface can be measured with an NDI. The optical setup is shown in Fig. 2. The end of the transmitter bar is polished to a reflective finish and serves as the moving mirror in the interferometer. The interference of a laser beam reflected from the transmitter bar combined with a beam reflected from stationary mirrors produces an intensity variation that can be monitored with photodetectors. An example NDI signal from a Kolsky bar test is shown in Fig. 3. A displacement equal to half of the laser wavelength produces a 2π phase variation in the signal, or one fringe. The distance, d, that the free surface of the transmitter bar travels is therefore given by

$$d = \frac{\lambda}{2} n \, , \tag{8}$$

where λ is the wavelength of the laser and n is the number of fringes observed. The velocity of the free-end of the bar can be determined by differentiating with respect to time. The particle velocity due to the transmitted pulse is half the measured free-surface velocity,

$$v_t = \frac{1}{2} \dot{d} \, . \tag{9}$$

This velocity is related to the strain in the transmitted pulse by

$$\varepsilon_t = v_t / c_0 \, . \tag{10}$$

Thus the measurement made with the NDI can be used to replace the strain gage measurement of the transmitted pulse.

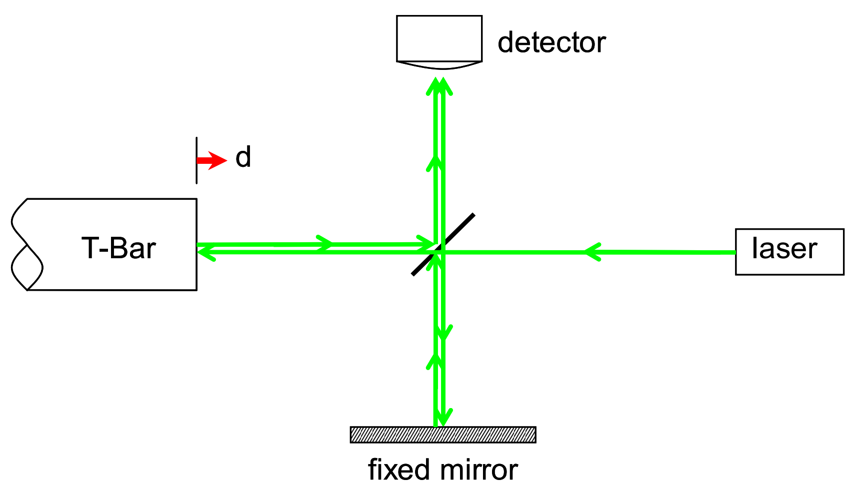


Figure 2 - An NDI used to measure the displacement of the end of the transmitter bar.

[1] Specific details of the Kolsky bar used during this research can be found in [8].

In a preliminary test on a copper alloy, the transmitted pulse was measured using the standard strain gage arrangement and an NDI simultaneously. A 5 mW HeNe laser with a 632 nm wavelength was used as a light source and the detector was an Electro-Optics Technology, Inc. model ET-2020 with a 200 MHz bandwidth. Figure 4a shows the strain signals measured using the strain gages during the test. The corresponding stress-strain curve is plotted with the strain-rate in Fig. 4b. The measurement of the transmitted pulse with both the NDI and the transmitter bar strain gage is shown in Fig. 5. Good agreement is obtained.

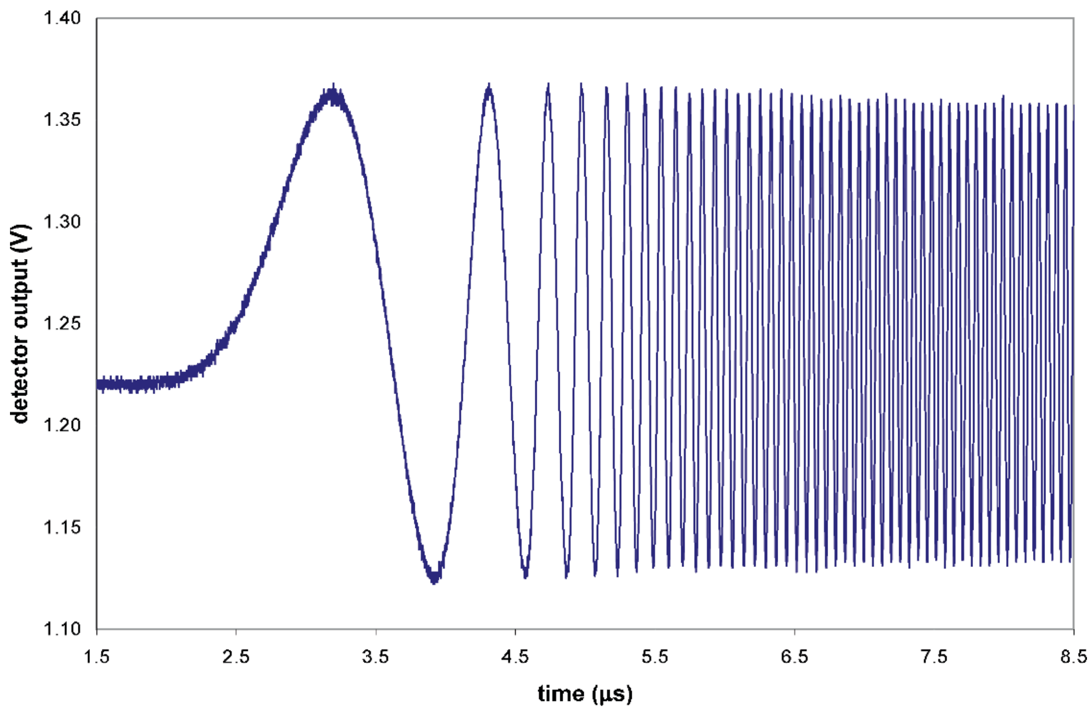
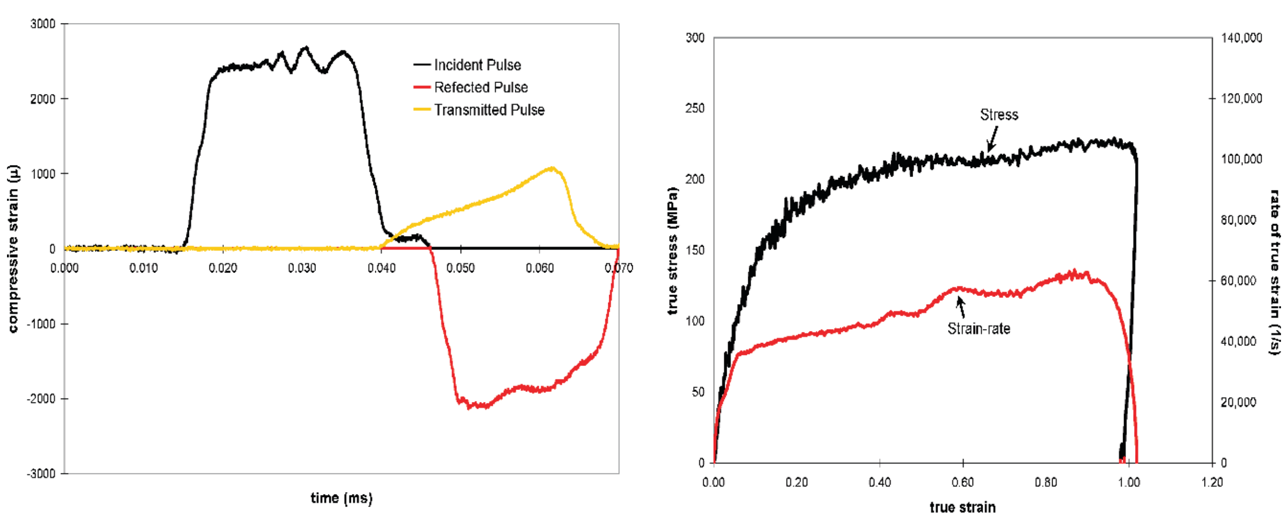


Figure 3 - Photodetector output from an NDI measuring the free-surface motion of the transmitter bar.



(a) (b)

Figure 4 - (a) Strain signals from an experiment with a 1.59 mm SHPB, and (b) the resulting stress-strain curve (black) and strain-rate (red).

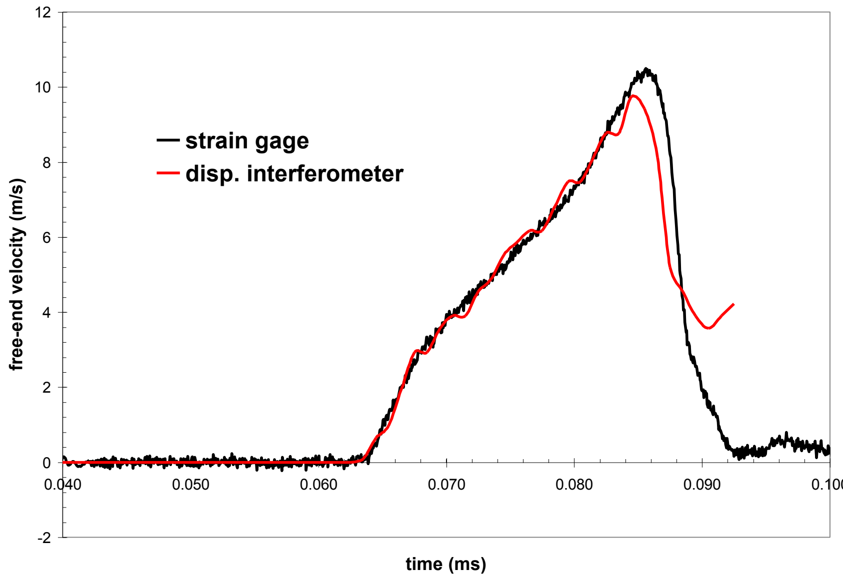


Figure 5 - The particle velocity due the transmitted pulse measured by the strain gage (black) and the NDI (red).

INCIDENT BAR – TDI MEASUREMENTS OF THE INCIDENT AND REFLECTED PULSES

Since no free-end of the incident bar is available during a Kolsky bar test, another NDI cannot be readily used. As an alternative, a TDI measurement near the midpoint of the bar (i.e., traditional strain gage location) allows the measurement of the bar displacement due to the incident and reflected pulses. Differentiation of the displacement over time leads to the particle velocity due to these pulses, v_i and v_r, respectively. These quantities are related to the traditional strain measurements by

$$v_i = \varepsilon_i c_0 \tag{11}$$

$$v_r = -\varepsilon_r c_0 \tag{12}$$

where v_i and v_r are positive for "down-range" motions of the bar. These equations can be then used in eqns. (1) and (3) to calculate the force and motion at the specimen/incident bar interface. The TDI is formed by combining two beams diffracted off a grating. Figure 6 shows the basic optical setup.

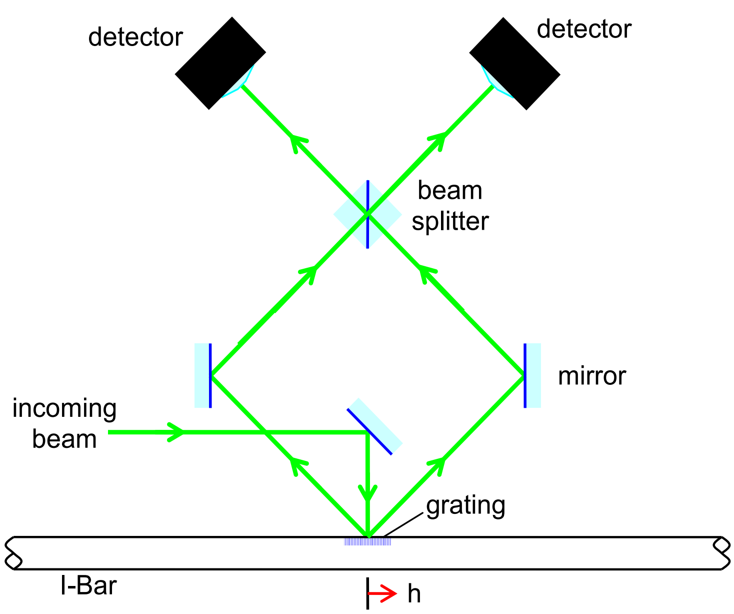


Figure 6 - An incident bar with a TDI.

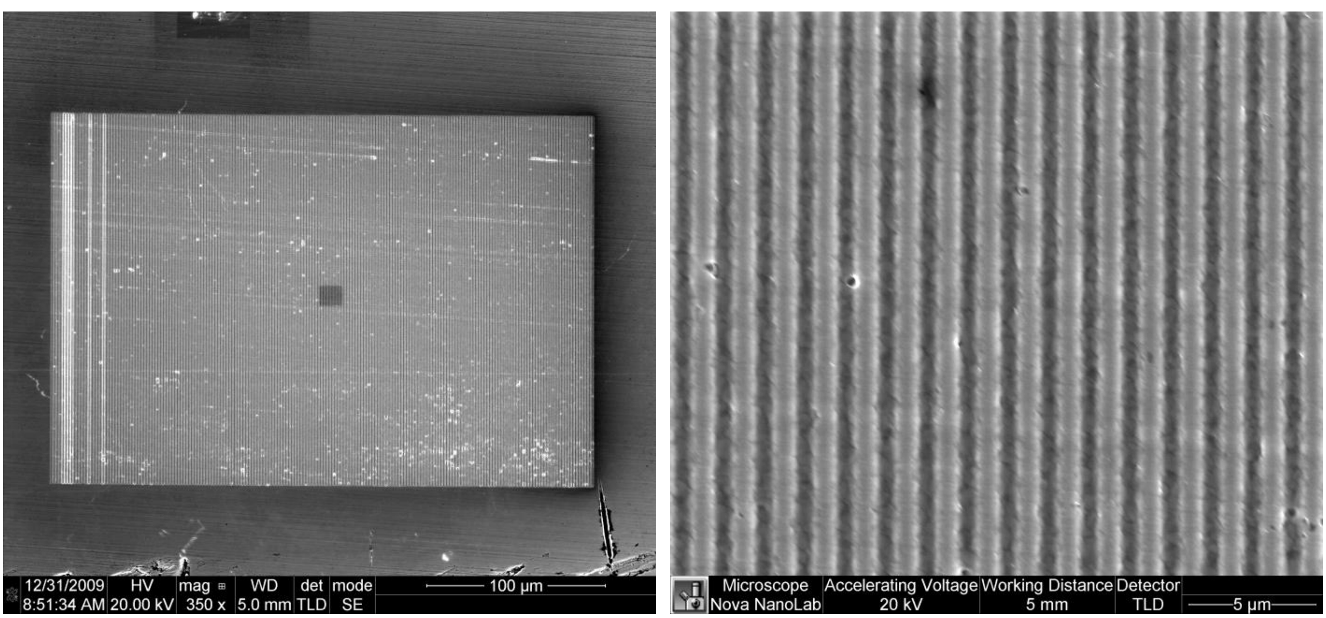
Motion of the incident bar (in the direction along the axis of the bar) equal to half of the line spacing of the grating will produce a 2π phase variation in the signal, or one fringe. The distance, h, that the grating on the incident bar travels is given by

$$h = \frac{p}{2} n , \tag{13}$$

where p is the line spacing of the grating and n is the number of fringes. More details about the TDI can be found in [16].

To demonstrate the use of the TDI, a simple bar impact experiment was performed. An aluminum striker bar (15.2 mm long, 1.59 mm diameter) impacts the steel incident bar described above (47.6 mm long). There is no specimen or transmitter bar in this experiment, i.e., the end of the bar is free. For this preliminary investigation, a ~300 micron wide flat was polished onto the side of the incident bar. The grating was then machined directly into the bar with a Focused Ion Beam (FIB) at an accelerating voltage of 30kV and a beam current of 1nA. Figure 7 shows SEM images of the grating. The line spacing is 1.6 μm, and each individual line is 0.5 μm wide and 0.5 μm deep. The removed material is minimal and the grating has essentially no effect on the wave propagation in the bar. Note that the flat extends the entire length of the bar, so that the entire bar has a uniform impedance. A 5W $Nd{:}YVO_4$ Coherent VERDI laser, with a 532nm wavelength, and Thorlabs PDA10A silicon amplified detectors, with 150 MHz bandwidths, were used in the optical setup of the TDI. The grating was located 20 mm from the free-end. Therefore two square pulses with durations of 6.0 μs were expected, separated by 2.1 μs.

Figure 8 shows the particle velocity measured by the TDI, along with the TDI trace signal used in its calculation. The square profiles due to the incident pulse and its reflection can be clearly seen, along with the familiar Pochhammer-Chree oscillations that arise due to dispersion. Note that this experiment required the use of rather large polycarbonate sabots on the projectile to fit a 3.85 mm bore gun. The effect of these sabots leads to further deviations from the expected incident pulse.



(a) (b)

Figure 7 - SEM images of the grating used for the TDI. (a) A view of the entire grating area, and (b) a close up of the individual lines.

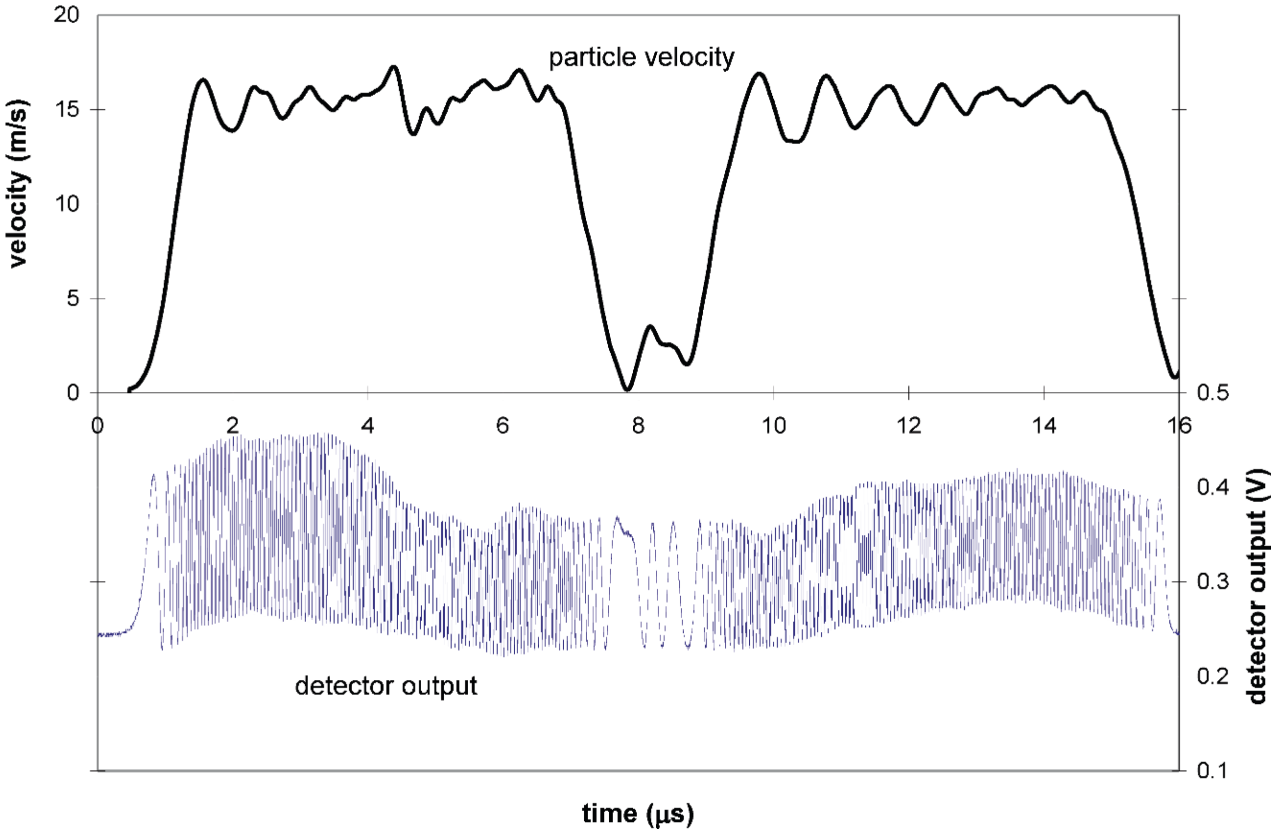


Figure 8 - Particle velocity at the grating as measured by the TDI. The detector output is also shown.

DISCUSSION AND CONCLUSION

This preliminary investigation has shown that optical techniques (NDI and TDI) can be used to replace strain gages as a means to measure the necessary pulses for a Kolsky bar analysis. These techniques have been applied to 1.59 mm diameter bars. Although this was shown in two separate examples, both methods can easily be applied simultaneously. A more rigorous investigation is underway to further validate the data acquired with these techniques.

As a practical matter, the use of standard strain gage techniques is limited to bar diameters of ~ 1.5 mm or greater. However, the use of these optical techniques can permit further miniaturization. Although additional complications due to bar manufacturing, alignment, and specimen preparation may arise, it is expected that the current instrumentation should be sufficient for application to bars as small as 0.4 mm diameter. This would permit testing of specimens as small as 100 μm at rates as high as 500k/s.

As a final note, consideration has been given to the application of these methods to various direct impact configurations, which also use pressure bars to measure specimen response. However, the Kolsky bar method is superior for in several respects given that it provides a more direct verification of specimen equilibrium, simplifies specimen recovery, and also permits the use of pulse shapers. For these reasons, future work will emphasize the Kolsky bar method.

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