Damage Delineation in Structures Using Laser Vibrometry And Remote Excitation

Peter Swanson[1] and **John Rettkowski**[2]

[1]Research Geophysicist (pswanson@cdc.gov), [2]Engineering Technician

National Institute for Occupational Safety and Health
Spokane Research Laboratory
315 E. Montgomery Ave.
Spokane, WA 99207
USA

ABSTRACT

As part of a research program to reduce injuries and fatalities in the U.S. mining workforce, NIOSH is investigating the potential use of noncontact vibration measurements to identify hazardous ground fall conditions. In the present study, the effectiveness of *remote* vibration sources in exciting resonant responses in damaged structures is examined. Initial experiments were performed on a damaged concrete slab in a controlled environment. Vibration response was measured with a laser Doppler vibrometer using both single-point and two-dimensional array recordings. Excitation sources included direct mechanical impacts to remote portions of the slab and a remotely located industrial demolition hammer. Surficial damage was effectively delineated with both sources through visualization of vibration response in spectral bands selected to discriminate wave propagation from large-scale slab resonance effects.

INTRODUCTION

The unexpected fall of ground remains one of the largest sources of injuries and fatalities in underground mines [1]. Visual inspection, followed by roof "sounding," are the primary means by which miners evaluate the stability of overhead rock structures in their workplaces. As part of NIOSH's mission to find ways to reduce hazards to workers, the feasibility of measuring remote vibrations using laser techniques is being explored as a means of improving, expanding, and automating procedures for mine roof inspection.

With the age-old method of roof sounding, miners provide direct mechanical impacts to roof rock and listen for the hollow drummy sound that indicates the presence of a loose block of rock. As impact-generated vibrations interact with nearby low-stiffness fracture interfaces and imperfect interfaces between rock layers, loose blocks of rock resonate weakly and produce airborne sound through seismic-acoustic wave conversion. Removing a miner from beneath the hazard requires not only measurements of remote (noncontact) responses, but also remote vibration stimulation. The feasibility of delineating damaged structures through the combination of remote stimulation and remote (noncontact) response measurements is the focus of this investigation. For operational ease in developing and testing the proposed methods, a damaged concrete slab was selected to serve as a convenient analog to the blocky roof rock structure encountered in underground mines.

Additional background information on previous studies of loose roof rock vibrations in underground mines, analyses of expected low-order resonant frequencies of slabs with varying boundary conditions, and reviews of laser Doppler and full-field vibration techniques applied to large structures can be found in [2].

Techniques for detecting defects in concrete structures include impulse response (IR) [3] and impact-echo (IE) [4] testing and modal analysis. The impulse-response and impact-echo techniques are both essentially drive-point response measurements, as is the miners' roof sounding, where a stimulus is applied and a response is measured in the same, or nearly same, location. IE uses a low-amplitude, high-frequency source (often a spring-loaded or solenoid-driven ball bearing) to obtain a frequency-domain measure of the compression wave's travel time between the outer surface and internal planar discontinuities or external boundaries that exhibit an acoustic impedance mismatch. IR uses a larger amplitude, lower frequency impact source (e.g., instrumented hammer) that stimulates more of a low-frequency global deformation response. Determination of this global response through identification of the structure's natural frequencies, mode shapes, and damping forms the basis of experimental modal analysis [5].

Both the IR and IE methods can be used to characterize the vibration response over two-dimensional surface structures by making measurements over a two-dimensional grid. Damaged areas, or regions requiring further investigation, can readily be recognized through anomalies in vibration response. This same approach is applied in this study to evaluate the integrity of a concrete slab. However, the advantage we seek is elimination of the requirement to occupy each target site physically for both source and response measurements by using a single, remote, excitation point and numerous noncontact response measurements.

INSTRUMENTATION

Vibration response was measured with a portable, battery-powered, laser Doppler vibrometer (Figure 1). The vibrometer (LDV) is an optical interferometer that measures relative motion between the LDV and target via a Doppler shift carried by the scattered return signal. The unit outputs analog and digital measures of ground velocity over a frequency range of 0 to 22 kHz with a resolution of 0.05 mm/s. Unlike automated scanning vibrometers, the portable LDV does not have a speckle tracking feature to help compensate for the poor reflective qualities of rough surfaces. Speckle tracking helps maintain high signal-to-noise ratios to reduce momentary signal dropouts [6]. To minimize the time required to collect suitable time periods of dropout-free data, each target site was given a small area of retro-reflective treatment.

Figure 1.–Portable laser vibrometer, dynamic signal analyzer, battery pack, and data collection computer.

To detect and be able to compensate for movement of the tripod-mounted LDV, an accelerometer was attached to the unit in line with the beam direction. The accelerometer outputs a velocity signal that is recorded with the LDV signal. However, none of the data presented in this paper were actually corrected for tripod motion.

A 1.4-kg hammer with an integrated load cell was used as the first impact source. A 0- to 2-kHz force signal is typically generated by the hammer when equipped with a hard plastic tip. The second vibration source was a standard industrial-grade demolition hammer (5 kg) equipped with a 7.5-cm diameter flat steel bit. It was used to strike a 2.5-cm-thick steel plate at the bottom of a 25-cm hole dug into the loose soil at a distance of 4 m from the edge of the slab.

Signals were recorded with a 24-bit, 4-channel dynamic signal analyzer powered by the laptop data acquisition computer's USB port. Data collection windows for the sources investigated in this study ranged from 5 to 10 seconds with sampling rates of 48.8 microseconds.

CONCRETE SLAB TEST STRUCTURE

The 1.8- by 1.9- by 0.25-m concrete slab was about 23 years old at the time of the experiments. It was located on the shady north side of a building where most of it was exposed to snow and rain. Surficial damage was obvious in places where a thin outer layer

Figure 2.–(a) Concrete damage that has penetrated through to the slab's surface, exposing more-competent material (field of view is 90 cm across). (b) Near-surface damage and aggregate characteristics exposed at edge of slab (penny for scale)

had become completely detached from the bulk of the slab (Figure 2a) and exposed a deeper, more-competent, rough concrete surface. The thickness of the detached layer in the exposed area was up to one to two aggregate particle diameters. Figure 2b shows a closeup of similar damage on the edge of the slab outside the measurement array.

The relative positions of the slab, LDV, and two different vibration source locations (A, B) are shown in Figure 3. Source location B is positioned 4 m from the edge and 1 m below the top of the slab. Each test sequence utilized a single stationary source position and roving response measurements. The angle between the slab normal and direction of the LDV measurements varied as a function of target position on the slab. Consequently, uncorrected measured velocities contain systematic variations in relative amounts of vertical and horizontal motion.

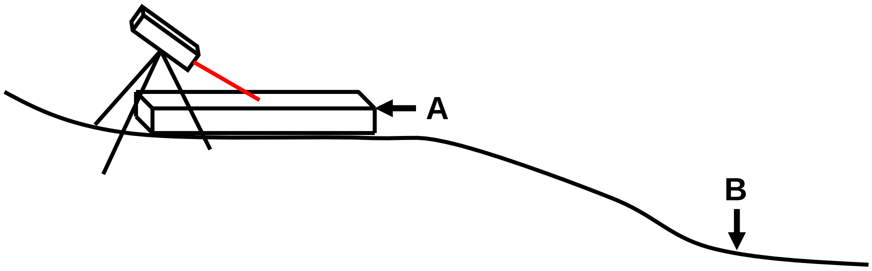


Figure 3.—Slab test setup with LDV and source positions A, B

RESULTS

Qualitative Sounding Test

A conventional qualitative sounding test was first used to assess the spatial variation in apparent slab competence. A 1.5-m-square measurement grid was laid out with target points spaced every 0.15 m. Grid points are indicated in Figure 4 as alpha-numeric row-column pairs (e.g., F6). Each target position was repeatedly tapped with a wooden rod or other suitable object. The acoustic response was separated into three categories—S, L, and H. The S category corresponded to what was perceived as being unquestionably solid and competent. L referred to a marked low-frequency response, and H was intermediate where the response was perceived to contain relatively high frequencies in comparison to L. An H designation encompassed a surprisingly wide range in acoustic response. Such an evaluation is very qualitative and is biased by an individual's tendency to use the most recent sounding measurements as a reference point instead of an absolute reference. S (solid) and L (loose) targets are marked in Figure 4 with white and black circles, respectively, and H (intermediate) targets are not marked.

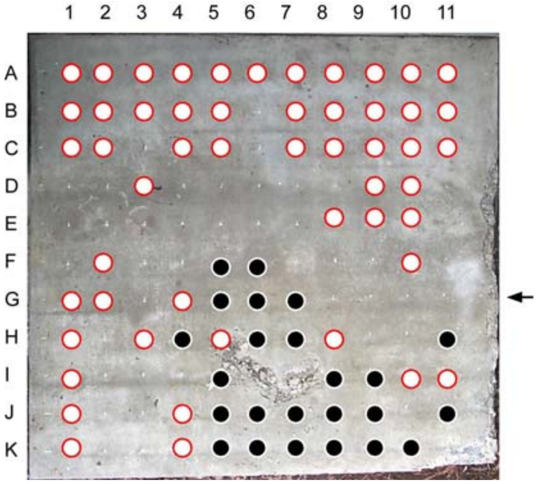


Figure 4—Manual sounding results. Competent (S) sites (white symbols), damaged/loose (L) sites (black symbols), intermediate (H) response (no symbols)

The lowest frequency audible response (L) was observed in the vicinity of visual slab damage. However, in places where the surface layer of concrete was totally removed by the damage to expose a deeper, more-competent surface, the sounding response was more intermediate. The area of slab exhibiting predominately solid (S) response (rows A-C) was under the protective roof overhang of an adjacent building.

Impact Hammer Applied to Edge of Slab

Examples of transient vibrations recorded by the LDV as a result of four sequential hammer impacts at source site A (Figure 3) are shown in Figure 5. J4 and J5 target locations were denoted as competent and damaged sites, respectively, in the manual sounding tests. The raw velocity response consists of an initial high-amplitude, high-frequency phase with abrupt first arrival followed by a decaying low-frequency phase. The effect of damage is manifested as an enhancement of the transient high-frequency response.

Figure 5—LDV vibration signals from hammer impacts on competent (S) and damaged (L) targets J4 and J5.

The velocity of propagation of the initial phase was estimated to be ~2800 m/s from the slope of plots of measured travel time versus propagation distance. Such a value is less than the compressional, or longitudinal, wave velocities typically reported for good-quality concrete (3500-4500 m/s). As the predominant amount of energy recorded at the targets is less than 2 kHz, the longitudinal wavelengths are long compared to slab thickness. Therefore, the measured first-arrival likely represents a guided wave mode; however, a longitudinal plate wave in poor-quality concrete cannot be ruled out. The initial transient phase is herein referred to as a propagation phase to distinguish it from the energy of larger-scale resonant modes that continue through later times.

Signals from sequential impacts were observed to be very repeatable at a given target site, but the response from target to target exhibited significant variation. To illustrate the spatial variation in the time domain response, velocity waveform profiles were obtained over two grid lines (column 4, row J). Each waveform in Figure 6 represents a time-domain averaged stack of 10 individual impacts, each with a duration of 0.04 s. Note that this time window is a factor of 40 less than that shown in Figure 5 and therefore primarily represents the initial propagation phase.

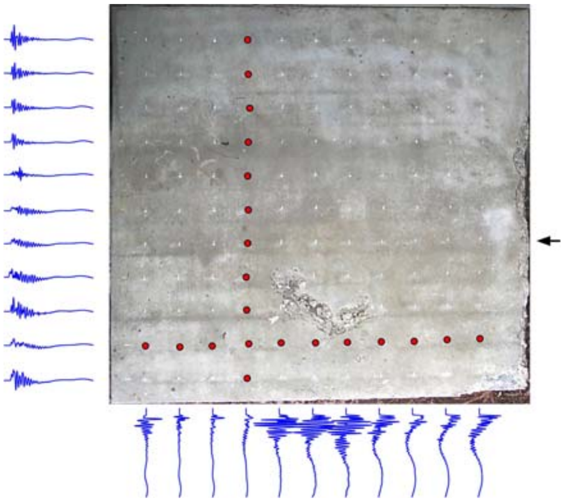


Figure 6—Profiles showing time series for column 4 and row J targets for impact hammer at position (A)

A general correlation is apparent between locations of significant damage, as indicated visually and by the sounding results, and enhanced vibration response. The highest amplitudes are observed in the area (J5, J6, J7) immediately surrounding the region where damage has breached the surface to reveal the more-competent concrete structure below.

A comparison of raw velocity spectra observed at competent and damaged targets J4 and J5 is shown in Figure 7. A notably elevated response is observed at the damaged site, in comparison to the solid target, over the frequency band of 600 to 1500 Hz. To account for variation in the source input, frequency response, or mobility, functions were created using the measured excitation and response signals for the J4 and J5 targets (Figure 8). The mobility shows regions of both high-frequency and low-frequency response. The 600- to- 3000-Hz band is largely produced by the initial transient propagation, while the 10- to 100-Hz band is mostly due to larger-scale resonant response. As was apparent in the time-domain signals and raw spectra, waveforms measured at the J5 damage site show an elevated high-frequency response in comparison to the more competent J4 target. A less notable, but still significant, elevated response is also apparent in the low-frequency portion of the spectrum.

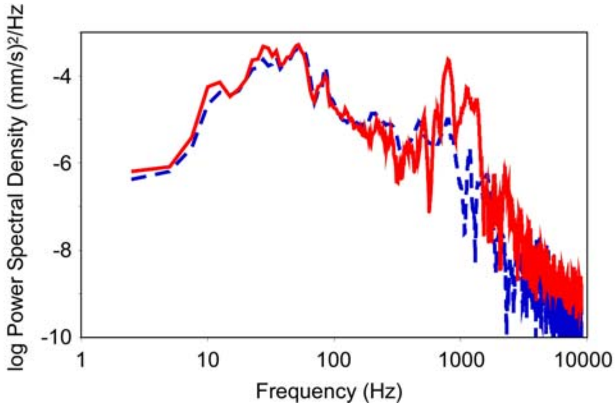


Figure 7—Power spectra for LDV signals recorded at targets J4 (competent = dashed line) and J5 (damaged = continuous line)

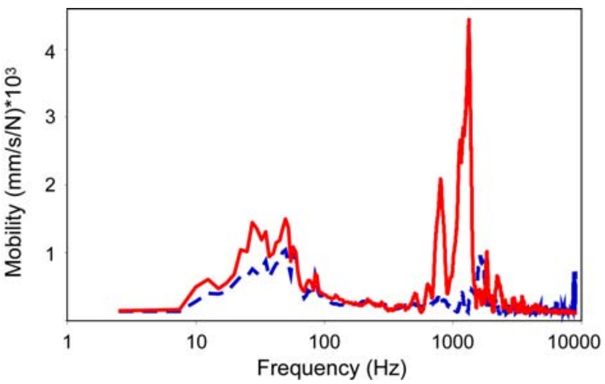


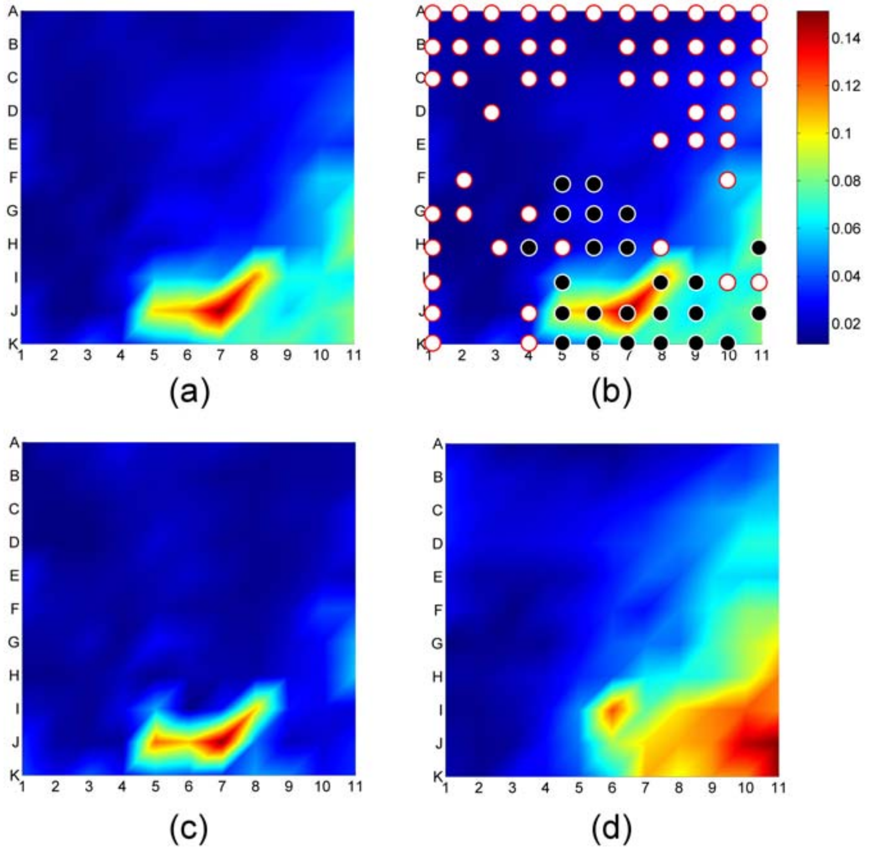
Figure 8—Mobility for targets J4 (competent = dashed line) and J5 (damaged = continuous line)

One way to visualize the spatial variation in damage is to map some measure of vibration response into a color scheme and superimpose it onto the grid/object. For example, the measure could be simple RMS average particle velocity values from the time series or various band-restricted spectral measures of amplitude, power, mobility, etc. In general, high values of these response measures correspond to areas that sound hollow with tapping, and low values correspond to areas that sound most competent. Figure 9a shows such a map produced using power spectral density (PSD) integrated over a range of 10 to 5000 Hz. The maximum spread in response values in each image of Figure 9 is mapped into the full color spectrum. The results from the manual sounding map from Figure 4 are also superimposed on Figure 9a and reproduced in Figure 9b.

The area of highest vibration response is not found at sites of greatest damage. The area of greatest damage, where the surface has been breached to reveal the more-competent underlying structure (H5, I5-7), exhibits an intermediate vibration response. Immediately adjacent to this area is a region that displays no obvious visual signs of damage, yet has the greatest velocity response (e.g., rows I-K). This region is interpreted as an area where delamination has taken place, but the damage has not yet breached the surface.

The region above the area of greatest damage (rows F-H), which contains L response targets from manual sounding, does not exhibit as strong an anomalous vibration response. The reason for this discrepancy is likely attributable to bias in the qualitative and cursory sounding measurements and points to the need for independent measures of material damage.

A broad area of elevated response is also observed over the entire lower right-hand corner of the slab (Figure 9a). From the time series (Figure 6), it is quite apparent that the elevated response in this area is low frequency in nature. By integrating the power over different passbands, we can largely isolate the propagation phase (200 to 5000 Hz) (Figure 9c) from lower-frequency slab resonance modes (10 to 200 Hz) (Figure 9d). Corrections for geometric spreading, attenuation, and source radiation pattern were not applied to any of the data in this paper. The high-amplitude, low-frequency velocity response is enriched in the 30- to 40-Hz band compared to other slab quadrants. From its lack of symmetry, it is not thought to represent a typical low-order resonance mode in a uniform plate. Possible explanations for this anomalous response include (i) the slab is not uniformly supported on, or



(a) (b)

(c) (d)

Figure 9─Vibration response due to impact hammer excitation. (a) Summation of PSD over 10 Hz to 5000 Hz, (b) correlation with manual sounding results, (c) summation over 200- to 5000- Hz, (d) summation over 10- to 200-Hz band.

attached to, its underlying foundation, (ii) the foundation material is more compliant in this corner, (iii) slab thickness is reduced, (iv) large-scale delamination yielding an effective reduced slab thickness, and (v) reduced confinement at slab edges in this corner. Several of these explanations (i, ii, v) may apply as the slab is on a steep hillside with bedrock exposed, and the high-response area of the slab lies on the outer downhill corner.

By processing response data over different spectral bands, different scales of anomalous dynamic response can be identified and analyzed with respect to structural health and performance.

Demolition Hammer at Remote Soil Location

Figure 10─Demolition hammer vibration source

The demolition hammer source (Figure 10) was applied at source position B (Figure 3) for a duration of 5 s for each LDV target position. Raw velocity spectra from the J4 and J5 target positions are shown in Figure 11. The 43-Hz percussion frequency is clearly seen in the dominant 43.6-Hz spectral peak along with its associated harmonics. Notable elevation in velocity response over the frequency range of 200 to 2000 Hz was observed at J5 and other damaged target sites in comparison to competent targets such as J4.

Power spectral density values across the measurement grid were integrated over the 200- to 2000-Hz frequency band and mapped into a color scheme (Figure 12). Good agreement with the results shown in Figure 9c is apparent. Exceptions are evident at certain damaged target positions. These positions experienced additional permanent damage during a series of direct target impact tests conducted in between the impact-hammer and demolition-hammer tests. These direct impact response tests are still being analyzed and will be reported elsewhere. The measured vibration amplitudes produced by the demolition hammer source were significantly lower than those produced by the impact hammer. As a result, analysis of the low-frequency response (10 to 200 Hz) did not reveal the same broad asymmetric response pattern in the lower right corner as was observed with the demolition hammer. Other sources of vibration, such as tripod motion, dominated and obscured any such pattern if present. A problem that developed with the LDV-mounted accelerometer data during these tests did not allow compensation for tripod motion.

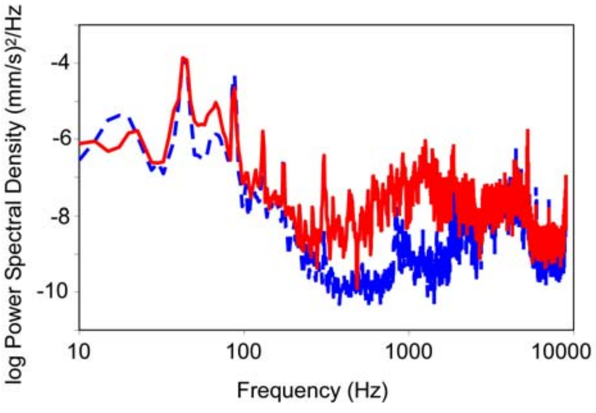


Figure 11─Vibration response at solid (J4, dashed line) and loose (J5, continuous line) targets due to demolition hammer excitation at source position (B)

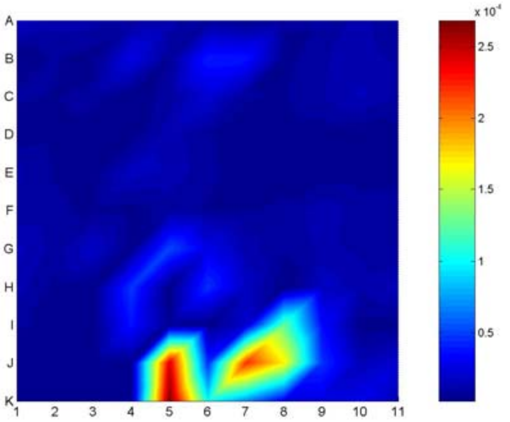


Figure 12─Vibration response (200 to 2000 Hz) due to demolition hammer excitation

SUMMARY AND CONCLUSIONS

A series of experiments was performed on a concrete slab to (i) determine the suitability of laser vibrometry to identify anomalous dynamic properties indicative of material/structural damage and (ii) determine whether remote vibration excitation sources are able to stimulate such anomalous responses. Vibration sources included an instrumented impact hammer striking the edge of the slab away from target locations and an industrial demolition hammer striking a metal plate in soil several meters away from the slab. Responses were measured with a portable, tripod-mounted laser vibrometer manually scanned across a two-dimensional grid over a range of several meters. Due to the poorly reflecting surface set at oblique angles to the beam, a reflective treatment was used on target locations to maintain a sufficient signal-to-noise ratio to minimize signal dropouts. The speckle tracking feature of automated scanning vibrometer systems and/or signal processing methods have not yet been evaluated to determine to what extent this barrier to more practical applications can be overcome. Spatial variation in vibration response was analyzed by overlaying two-dimensional velocity response maps over the structure image and comparing the results with a similar map of qualitative sounding measurements.

The LDV response measurements from the impact hammer tests were loosely interpreted in terms of a propagation phase and a resonance phase, where the initial elastic transient provided a relatively high-frequency excitation compared to the later arriving, lower frequency modal response. By separating the vibration response into low- (10 to 200 Hz) and high- (200 to 5000 Hz) frequency bands, two types of anomalous vibration signatures were observed. Surficial material damage was delineated in the high-frequency band. In the low-frequency band, an area of unusually high response was observed that may reflect an anomaly in slab foundation support. High-frequency response maps obtained with the impact and demolition hammers were in agreement and largely consistent with qualitative sounding results and areas of damage.

ACKNOWLEDGMENTS

The authors would like to acknowledge the able assistance of Andy Caley (NIOSH) in both collecting the field data used in this study and in performing experiments during the course of technique development.

REFERENCES

[1] Bauer, E., D. Pappas, D. Dolinar, F. McCall, and D. Babich, Skin failure of roof and rib in underground coal mines. Proceedings, 18th Inter. Conf. on Ground Control in Mining, Morgantown, WV, pp. 108-114, 1999.

[2] Swanson, P., Feasibility of using laser-based vibration measurements to detect roof fall hazards in underground mines. Fifth Inter. Conf. on Vibration Measurements by Laser Techniques: Advances and Applications, Proceedings. SPIE, ed. by E. P. Tomasini, Vol. 4827, pp. 541-552, 2002.

[3] Davis, A.G., and C.G. Peterson, Nondestructive evaluation of prestressed concrete bridges using impulse response. Proceedings,. Inter. Symp. on Non-Destructive Testing in Civil Engineering (NDT-CE 2003) (Berlin, Sept. 16-19, 2003). Deutsche Gesellschaft Für Zerstörungsfreie Prüfung E.V., Vol. 013, 2003.

[4] Sansalone, M. J., and W. B. Streett, *Impact-Echo: Nondestructive Evaluation of Concrete and Masonry*. Bullbrier Press, Ithaca, NY, 339 pp., 1997.

[5] Ewins, D. J., *Modal Testing: Theory, Practice and Applicatio*n”, 2nd ed., Research Studies Press, UK, 562 pp., 2000.

[6] Erfurt, W., J. Stark, and W. Köhler, The application of laser techniques in the non-contacting excitation and recording of sound waves. Proceedings, Inter. Symp. Non-Destructive Testing in Civil Engineering (NDT-CE 2003) (Berlin, Sept. 16-19, 2003). Deutsche Gesellschaft Für Zerstörungsfreie Prüfung E.V., Vol. 014, 2003.