Feasibility of using laser-based vibration measurements to detect roof fall hazards in underground mines[†]

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ABSTRACT

One of the primary methods for analyzing roof stability in underground mines is the age-old method of “roof sounding” where a miner taps on the roof and listens for the hollow sound of loose blocks of rock. This paper looks at the feasibility of using noncontact laser-based vibration measurements to detect roof fall hazards with the ultimate vision of improving, expanding and automating procedures for mine roof inspection. Vibration measurements made on loose blocks of rock in underground mines are summarized and compared to estimates of fundamental resonance frequencies for rock slabs of the size responsible for highly hazardous “skin failures.” Both laser Doppler vibrometry and full-field interferometric methods are examined and are considered to be feasible methods for detecting anomalous vibrations in loose roof rocks. Results from simple laboratory experiments using laser vibrometry demonstrate some of the proposed application concepts. While considered a challenge to move these techniques from the laboratory to heavy industrial or outdoor environments, the potential for success in the current application is enhanced by the reduced requirements of *qualitative* analyses.

Keywords: Roof falls, ground falls, ESPI, laser vibrometry, mining, roof sounding, TV holography

1. INTRODUCTION

Unexpected falls of ground remain one of the largest sources of injuries and fatalities in underground mines throughout the world. While safety statistics reveal that U.S. mines are among the safest, there are still approximately 10 to 15 fatalities and 700 to 1000 injuries each year due to ground falls.[1,2] This feasibility assessment is being conducted as part of the mission of the National Institute for Occupational Safety and Health (NIOSH) to find ways to reduce hazards to worker populations.

The first part of the paper describes mine roof conditions, roof falls, vibration characteristics of loose roof rocks, and some of the accelerometer-based tools that have been used to probe and identify them. The vibration response of loose slabs composed of different common rock types is estimated and compared to observations. A number of laser-based vibration and deformation measurement studies pertinent to the present application are reviewed. The last part presents the results of simple laboratory tests to demonstrate the application concepts and outlines proposed optical methods to delineate regions of anomalous vibration associated with loose roof rock.

2. THE UNDERGROUND WORKPLACE

2.1 The nature of mine roof

Mine roof conditions vary significantly because of differences in mining methods and geology. For example, roof heights can range from 1 to 30 m high (2 to 4 m is typical), and roof spans can extend from 1 m to greater than 20 m. Roof surfaces can range from flat, smooth, and of a single composition requiring no support to incompetent, unconsolidated material requiring steel arches and lagging or complete suspension through installation of mesh and roof bolts. In many U.S. mines, typical support is provided by 1- to 2-m-long roof bolts installed every 1 to 1.5 m. Metal straps and timber are added where supplemental support is required. As mining is an evolutionary process and rock

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properties are rate sensitive, mine roof can deform and fail in a time-dependent fashion. Roof conditions in certain geologic structures also exhibit sensitivity to weathering and seasonal variations in moisture content. Thus, mine roof that is safe today is not necessarily safe tomorrow.

2.2 Roof fall characteristics

Gravity-driven mine roof failure results from the time-dependent loss of cohesion across fracture, joint, and geologic interfaces. Roof fall volumes range from small pieces of rock to complete failure of the roof and roof-support system. Several studies have documented how fatality and injury rates relate to roof fall characteristics. Ninety-eight percent of the roof fall injuries in U.S. coal mines in 1997 involved failure with a thickness, or extent into the roof, of 0.3±0.2 m.[1] These are termed "skin failures" and often involve failure of the roof between roof supports. Fatalities, however, occurred more often with massive roof falls (2.8±2.3 m thick) during this study period. More than 70% of all roof falls, as well as 70% of the roof falls associated with fatalities, in S. African coal mines had a thickness of 0.5 m or less.[3] Thus, in this initial study, the emphasis is on detecting loose blocks of roof rock with thicknesses of 0.5 m or less.

3. ANOMALOUS VIBRATION BEHAVIOR OF LOOSE ROOF ROCKS

3.1 Methods used to assess roof stability

Visual examination is the primary method used to assess the condition of a mine roof, followed by roof sounding. In conventional roof sounding, a miner taps the roof with a scaling bar, sounding tool, or other object and listens to the response. Elastic waves generated by the tap interact with the near-surface roof rock and are converted back into sound waves through seismic-acoustic coupling. Roof response may also be felt with the fingertips if the roof is within reach. There are two end-member responses: (1) the rock mass is competent and acts like a stiff infinite half-space and (2) a wholly or partially detached block of rock resonates like a free body. The "drummy" or hollow response that the miner uses to identify and eliminate loose blocks of roof rock is closer to the latter. Reduced stiffness (acoustic impedance) along the loose block boundaries provides the flexibility (reflection) that allows the loose rock mass to resonate for a short time upon excitation.

This manual inspection method takes place as new roof surfaces are created. With time, however, roof conditions can deteriorate. A noncontact inspection tool for imaging anomalous roof vibrations from a remote location could help identify dangerous conditions in this work environment and lead to improvements in mine safety. A two-dimensional map showing qualitative relative surface displacements, or vibration amplitudes, may allow loose blocks of rock to be identified in a manner similar to the empirical way a miner contrasts the sound of safe and unsafe roof.

3.2 Vibration characteristics of loose roof rocks

Several attempts have been made to quantify the vibration characteristics of safe and unsafe roof. In these studies, an accelerometer or geophone (velocity sensor) was mounted to the mine roof, an impact was applied to the roof up to several tens of centimeters away from the sensor, and the signals were recorded for analysis. Measurements on both competent and drummy roof were then compared. These studies showed that vibration frequency was lower, amplitude was greater, and duration was longer than for competent mine roof.

Summerfield[4] investigated coal mine roof and found that drummy-sounding roof rock generated low-frequency vibration amplitudes that were twice as large as observed in solid roof. This effect was most pronounced between 200 and 1000 Hz. Similarly, the duration of vibration in drummy roof was found to be roughly twice that for solid roof. de Montille and Weber[5] found loose slabs to vibrate at frequencies ranging from several to 450 Hz. Palmer and Czirr[6] examined vibration spectra from loose slabs in a coal mine and found enhanced spectral peaks in the 200- to 600-Hz range with some response below 200 Hz as well. Hanson[7] investigated vibration characteristics of loose roof rocks in both hard rock and coal mines. A notable increase in response in the 0.2- to 1-kHz range was observed in the hard rock mines and from a few to 250 Hz in a coal mine. Most of these studies noted the influence of sensor mounting and details of the impact force on the results.

A slightly different approach was used by Brennecke and Gallagher.[8] Following Obert,[9] their method inolved a single fixed geophone recording site and multiple tap/impact sites. The geophone was attached to solid roof rock and located as far away as 75 m from an impact site. Impacts on solid rock produced signal amplitudes that were up to 10 times as high as impacts on loose rock. Instead of recording the anomalous vibration response of the loose rock directly (drive-point response), these measurements sensed the reduced ability to transmit seismic energy into the surrounding medium due to the rock mass decoupling (transmittance).

Use of sound wave recordings to discriminate between competent and loose roof rock has been investigated[4,5] and rejected[5] as microphone data were difficult to interpret due to extraneous airborne noise in the confines of underground space. It is worth noting that the seismic-to-acoustic coupling in this process is very inefficient. Because of the large acoustic impedance mismatch between air and rock, the signal heard by a miner has less than 0.05% of the energy reflected back into the rock. Thus, there would appear to be advantages to recording surface vibrations directly.

The effect of crack-like defects on the low-frequency vibration response of mining structures has been investigated using both physical and numerical models.[10,11] With the introduction of defects, nodal frequencies shift to lower values, which is consistent with field observations and the expected effect of a reduction in system stiffness.

3.2 Instruments to detect loose roof rock

Several attempts have been made to construct an instrument for industrial use by nonexperts to detect loose blocks of rock. They consist of a sensor, a method of applying a nearby impact, and circuitry connected to the sensor to discriminate the signal. Hanson[7] developed a prototype that compared vibration power spectra in the 200- to-1000-Hz band and the 3000- to 3500-Hz band. Field tests in which the sensor was held against the rock with a spring-loaded pole showed that large values of this ratio are indicative of roof rock instability. A similar instrument was developed and tested by Siva Kumar et al.[12] They contrasted relative amounts of energy in three different bands (600-1200, 1800-2400, 3000-3600 Hz). In both of these studies, a silicon-based couplant was used between the sensor and the roof. Altounyan and Minney[13] reported on trials of a similar prototype that was based on the rate of decay of impact-induced vibrations. Following an area-specific calibration, these data were used to indicate questionable roof sites.

With each of these approaches, there is essentially a duplication of the same procedures that a miner follows in a conventional sounding test (manual handling of a tool, local application of an impact, and subsequent sensing of the local response). As the most sophisticated hardware and software available are still no match for the powerful integrating process carried out by a miner's senses and brain, and as this natural data collection and processing would still automatically be used by a miner during operation of such electronic systems, it is difficult to foresee widespread adoption of this approach.

3.4 Slab resonance frequencies

We estimated the frequencies of the lowest order resonance mode of rock slabs to determine their sensitivity to rock composition and boundary conditions and to compare with field observations. Figure 1 shows several possible loose roof rock configurations and their approximate boundary conditions. These include (1) a slab completely separated from the host rock and held in place solely by geometrical constraints, (2) a cantilevered slab attached by only one of its four lateral edges, and (3) a slab formed by separation along a bedding plane but still attached on all four edges.

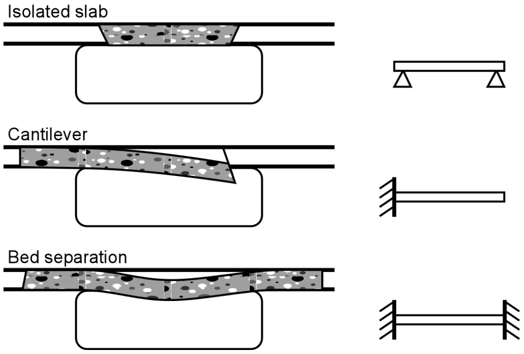

Figure 1.–Three types of loose slabs that pose a roof fall hazard and their approximate boundary conditions.

For simplicity, we consider a square plate with edge length a and uniform thickness h. The frequency of the first bending mode (n = 1) is given by[14]

$$F = (K_1/2\pi)*\sqrt{(D/\rho*h*a^4)}, \qquad (1)$$

where D, plate stiffness, is given by

$$D = Eh^3/12(1-\nu^2).$$

E is Young's modulus, ν is Poisson's ratio, ρ is mass density, and K_1 is a constant for the first bending mode. Values of K_1 for the boundary conditions of Figure 1 are 19.74, 3.49, and 35.98, respectively.

Table 1. Properties of roof rock

Rock type	E (GN/m^2)	ν	ρ (kg/m^3)
Quartzite	65	0.16	2700
Limestone	50	0.25	2400
Sandstone	30	0.22	2250
Shale	15	0.27	2100
Coal	3.5	0.40	1500

Equation 1 is evaluated for several common types of roof rock with properties listed in Table 1. Due to natural variability, material properties for specific rock types can vary significantly. Specific values in Table 1 were chosen to help identify the range of expected vibration behavior. Fundamental frequencies are plotted against plate thickness in Figure 2 for a range of slab sizes expected in underground environments. Data for the different rock types are shown in hachured bands for each slab size. Quartzite and coal values are found on the upper and lower bounds, respectively. For a given slab size, the first mode frequency varies by a factor of three for the common roof rock materials. Variation due to the different boundary conditions (not shown) is one order of magnitude.

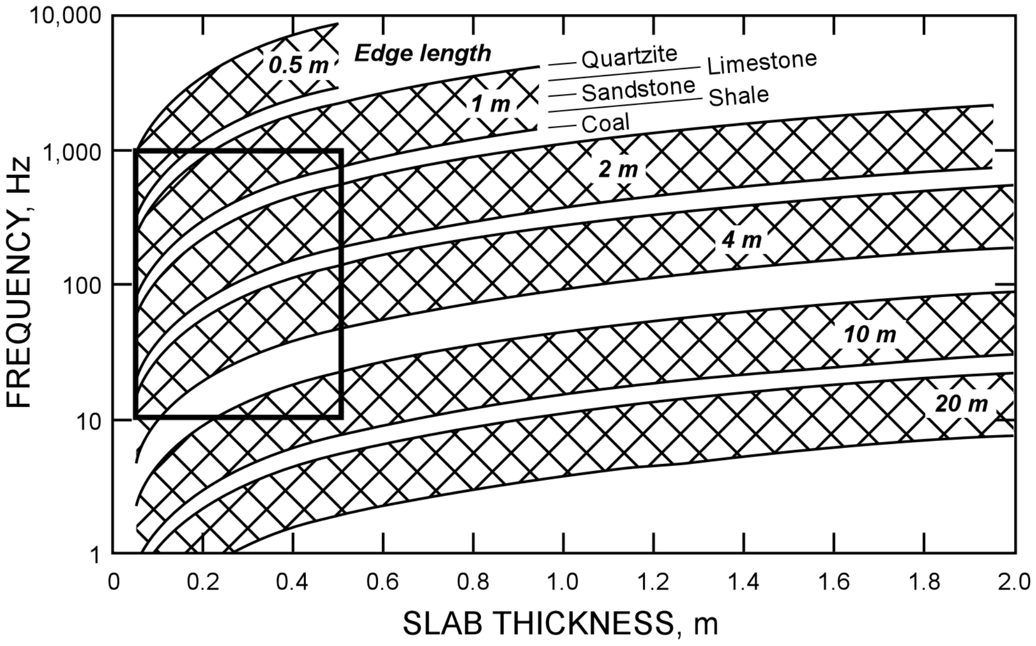

Figure 2.–Resonance frequencies of roof slabs (simply supported plates)

With such variation, it is not likely that frequency measurements alone will allow loose block dimensions to be estimated accurately. A similar conclusion was reached in several of the roof vibration measurement studies. The frequencies reported in those field observations and the most commonly observed roof fall slab thicknesses are highlighted in the box in Figure 2. The slabs within this box represent reasonable estimates of the sizes of actual roof falls.

The estimates of slab vibration frequencies delineate the range to be expected in the field and provide a constraint for the laser vibration measurement and forced-vibration excitation procedures.

4. VIBRATION EXCITATION SOURCES

Three basic types of excitation are considered: impact, forced vibration, and ambient vibration.

Miners' mechanical impacts are known to be effective in exciting anomalous vibrations. While response amplitudes vary considerably from blow to blow, the frequency content remains similar.[4,7] For remote operation and automation of this inspection process, other impulsive sources should be explored, such as dynamic pulses from water jets, lasers, and/or compressed air.

For discussion purposes, the following distinction is made between forced and ambient vibrations. A forced vibration is a continuous, periodic vibration specifically imposed to assist in roof and rib inspection. Ambient vibration includes background earth noise as well as all other continuous and discontinuous sources of ground vibration in the mining environment. The latter include conveyor belts, mining machinery (mobile and fixed), light and heavy diesel-powered mobile equipment, trains, hoists, drilling equipment, ventilation fans, motors, and pumps. Many of these noise sources are in proximity to active mining areas where the greatest number of roof fall injuries and fatalities occur. At close range, most of these sources are likely to provide effective excitation. A number of these ambient sources could be utilized as controlled forced-vibration sources. Other sources to consider include arrays of loudspeakers that take advantage of enclosed-space resonance, pneumatic-powered hammers, rotating eccentric masses, etc.

Certain types of mining machinery produce low-frequency vibrations that travel much farther than those produced by higher frequency sources. As an example, ground velocity was measured at a longwall mine with and without the longwall operating. Amplitude spectra for signals recorded at an underground site 600 m from the longwall are shown in Figure 3. Signals were obtained using a local microearthquake monitoring system.[15] The two large peaks at ~4 Hz dominated the spectra at surface and underground sites separated by as much as 2.5 km. This long wavelength excitation source operates for long periods of time and affects large areas. While such low frequencies may excite low-order resonance modes in very large but thin slabs, another potential use is in providing small periodic strains to examine quasi-static deformation response.

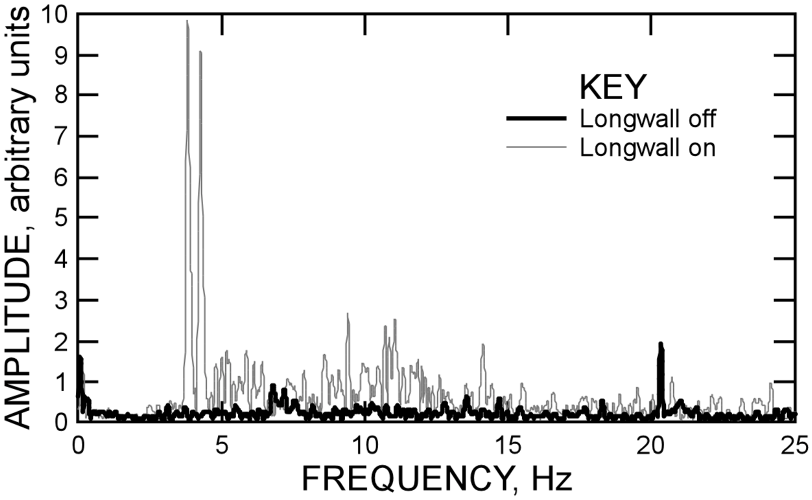

Figure 3.–In-mine ambient background vibration spectra. Longwall on (gray line) and off (black line).

5. LASER-BASED VIBRATION MEASUREMENT METHODS

5.1 Potential advantages of noncontact vibration sensing

Noncontacting laser vibration methods offer several potential advantages: (1) The miner does not have to stand immediately below hazardous roof to measure vibration response, (2) vibration response can be measured on roofs that exceed the miner's reach, (3) wide areas can be scanned or imaged instead of having to be measured at a single point, yielding a much more effective, timely, and thorough evaluation of the workplace, (4) stability evaluations can conceivably be made automatically and continually updated in the most dangerous areas while a miner continues to work, (5) large areas of a mine may be evaluated on a regular or less frequent basis at a small fraction of the effort required to do the same job by conventional sounding techniques, and (6) periodic surveys can be made at the same location without sensor contact repeatability problems.

5.2 Lasers and mine safety

One issue that should be considered in methane-rich mining environments is the possibility of laser-induced ignition. Experiments conducted by NIOSH examined minimum power levels required to ignite methane-air mixtures.[16] While U.S. federal safety regulations that govern intrinsically safe equipment in underground mines do not contain specific guidance on lasers and other optoelectronic components, the European Committee for Electrotechnical Standardization (CENELEC) has suggested limits of 150 mW or 20 mW/mm^2 for open-beam lasers where methane gas and coal dust mixtures may be present.[17] Higher-power lasers can stay below these limits through beam expansion. As with all electronic equipment, issues related to permissibility, or operation of electronic devices within potentially explosive environments, must be addressed before such technology can be used within exhaust airflows in methane-rich and coal-dust-laden mine atmospheres.

5.3 Previous work on application to large surfaces in industrial environments

5.3.1 Scanning laser Doppler vibrometry: Numerous examples of the use of laser Doppler vibrometry (LDV) in analyzing the response of large structures are found in the literature and are not reviewed here. However, two recent studies with particular relevance to the present evaluation are noted. Scanning LDV systems (SLDV) have been demonstrated to be effective in identifying buried land mines. Sabatier and Xiang[18] irradiated a soil- and gravel-covered land mine target area with pseudorandom 80- to 300-Hz acoustic waves. The mismatch in elastic properties between soil/gravel and buried land mines resulted in an anomalous vibration response that was detected by the SLDV.

In the second study, large controlled defects beneath a plaster surface on a brick wall were identified by Drdacky et al.[19] through excitation by forced vibration and sensing with a SLDV. Smaller defects, which have reduced flexibility, were more difficult to detect through excitation of the wall via mechanical shaking.

5.3.2 Full-field interferometric techniques: Key considerations[20-22] in moving full-field laser interferometric systems from measurements of small objects in the laboratory to large surfaces in industrial or outdoor environments are (1) maximization of available laser light and (2) minimization of extraneous vibration during recording. High-power lasers, reflective coatings, and more sensitive cameras help achieve the former, while stable optics, common path interferometers, short exposures using pulsed or chopped continuous wave (CW) lasers, and synchronization of object illumination and camera exposure with object vibration help achieve the latter.

Several studies in which full-field techniques were applied to large surfaces and/or which sought to identify anomalous vibration characteristics are described below. Unless otherwise indicated, use of the general term ESPI[23] (electronic speckle pattern interferometry) implies TV holography or the 25 to 30 frames per second recording of speckle interference patterns by video or CCD camera. This form of ESPI is most suitable for mine safety inspections.

Buried land mine targets have also been detected using full-field interferometric techniques. Gaul and Plenge[24] recorded distortions of transient elastic wave fields as they interacted with simulated land mine targets buried in sand. A 1-joule pulsed ruby laser illuminated a 4-m^2 area in double-exposure holographic interferometry. Both mechanical impacts and forced vibration (100 to 500 Hz) were used as excitation sources. Christnacher et al.[25] also imaged impact-excited land mine targets buried in sand with holographic interferometry and pulsed ESPI.

Several studies have examined deformation of plaster walls. Facchini[22] analyzed quasi-static deformation in a 10-m^2 section of a plaster wall using a CW laser with 1 to 2 W output. Shearing, out-of-plane, and in-plane configurations were used. A desensitized in-plane ESPI arrangement (60 micrometers per fringe) was used by Jacquot et al.[26] to characterize quasi-static rotational movements in a similar wall. An area of approximately 12 m^2 was illuminated using a CW laser with 800-mW output. Plaster detachments in large historical murals were identified by Gülker et al.[27] using acoustic stimulation and ESPI. A 150-mW diode laser was used to illuminate a 2-m^2 area. Vibration frequencies were swept from 50 to 700 Hz in 10-Hz steps. Vibration amplitudes were kept as small as 10 nm to avoid damaging the murals, and reference beam modulation was used to increase measurement sensitivity. Anomalous vibration areas were highlighted on the monitor with time-varying brightness (i.e., flickering).

A 3-m^2 area of a reinforced concrete wall containing defects was subjected to vibration excitation and studied with ESPI by Facchini[22] using a 1- to 2-W CW laser. Christnacher[28] used a 1-joule pulsed laser to analyze deformation in a cracked, reinforced-concrete wall with double-exposure holography and pulsed ESPI. Surface displacements were generated through impact excitation.

Vibration modes of a 3.4-m-tall liquid storage tank were recorded using holographic interferometry by Trolinger et al.[29] A 1-joule pulsed ruby laser was used at distances ranging from 6 to 20 m. Forced vibration utilized sinusoidal and white noise signals. When the excitation frequency was equal to a specified resonance frequency, the nodal/fringe patterns were reproducible. A variable fringe pattern was observed when the excitation frequency was other than a resonant frequency. White-noise excitation produced a fringe pattern dominated by a prominent resonant mode.

Periodic deformation of solid earth due to tidal forces was recorded with real-time holographic interferometry by Takemoto.[30] A 1-m^2 surface area of a wall in an underground tunnel was coated with a retro-reflective substance and illuminated continuously with a 50-mW He-Ne laser. After the initial hologram film plate was developed and returned to its original position, a CCD video camera and a time-lapse video tape recorder were used to record the real-time fringe patterns. The conditions were observatory quality with the optical elements affixed to massive steel supports attached to concrete footings. Temperature, pressure, and humidity variations were minimal. An updated version of the system uses ESPI.

An example of clear sharp holographic interferometry fringes obtained on a large vibrating steel railway bridge is given in Steinbichler et al.[31]

Active compensation for movements of a real-time ESPI system was demonstrated by Galanulis et al.[32] The method uses a compact Michelson inteferometer to determine relative motion between the ESPI head and the object. This information is then used to modify reference phase shifting in the real-time out-of-plane ESPI system. The ability to compensate for instrument movement is critical to moving ESPI and SLDV systems toward being practical industrial inspection tools. However, when only qualitative comparisons are required, such as in delineation of spatial variations in vibration response, compensation may not be as critical.

These studies document the feasibility of using full-field interferometric methods on large surfaces outside of the laboratory environment. Although many of these examples use holographic interferometry with pulsed lasers, the number of CW ESPI applications on large surfaces continues to increase.

6. DEMONSTRATION OF MEASUREMENT CONCEPTS

A series of vibration measurements was made in the laboratory using an LDV to illustrate a few of the concepts to be evaluated in the underground environment. The first test contrasted the impact response of competent mine roof (Figure 4*A*) with that of roof with loose rock (Figure 4*B*). A geophone (velocity sensor G1) was attached to the concrete model roof for comparison. Low-amplitude movements recorded by a geophone (G2) placed on the LDV support structure (Figure 4*A*) indicated the source of the low-frequency rumble in the LDV output.

The second lab test illustrates a slightly different approach to sensing the presence of loose roof rock. In this case, the recording site was stationary and multiple impact sites were distributed about an area. As a convenient analog to roof sounding, we conducted a common stud-finding test by knocking on a wooden frame wall covered with gypsum board (Figure 5). The difference in sound when tapping at stud locations (the analogy to stiff, competent roof) and locations without studs (less stiff, loose rock) was not unlike the differences heard in mine roof sounding tests. In both cases, the differences were sometimes subtle but recognizable. Tapping on the wall directly above a stud resulted in signals (Figure 5*A*) that were higher in frequency, lower in amplitude, and shorter in duration compared to impact sites between the studs (Figure 5*B*). This result paralleled the audible response. As the distance between the impact and LDV measurement site increased, signal amplitude decreased. However, the contrast in relative signal amplitude, frequency, and duration between taps at stud and nonstud locations persisted. In this test, the zones of low stiffness were well coupled with the rest of the structure. If impacts are made directly on a zone of low stiffness that is also decoupled from the rest of the structure (e.g.,

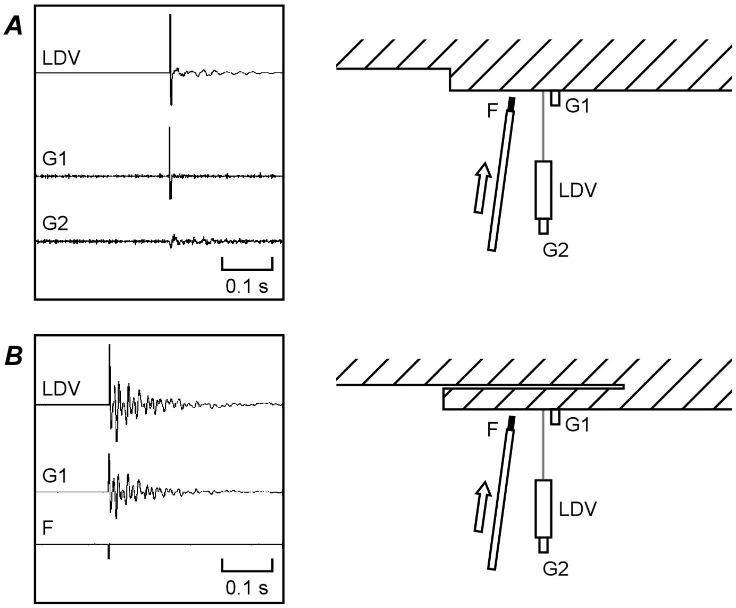

Figure 4.–Vibration response due to impact on (*A*) competent (simulated) roof and (*B*) loose roof. Signals are from laser vibrometer (LDV), geophones (G1, G2), and impact hammer (F).

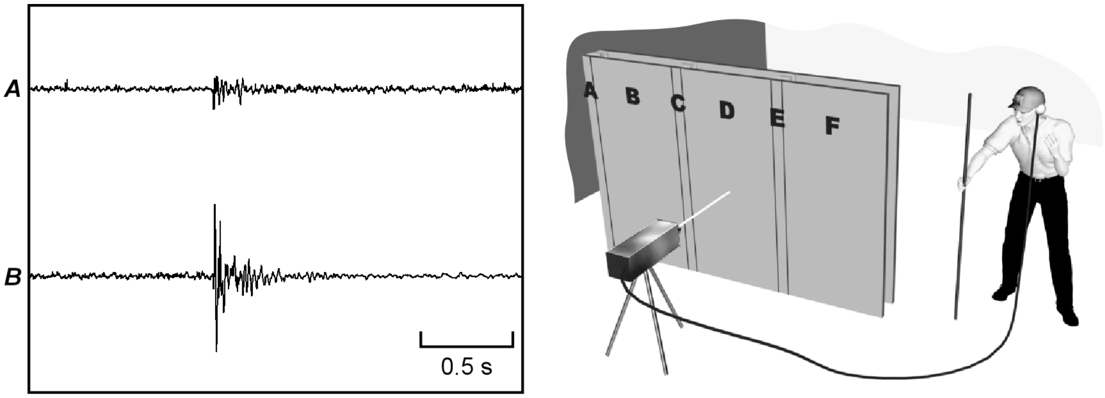

Figure 5.–Time-series response measured with LDV at a single site due to impacts at multiple sites. Gypsum covered wooden stud wall used as analog of mine roof with spatial distribution of competent and loose rocks. (*A*) Impact on stud (stiff competent roof) and (*B*) impact between studs (low stiffness loose rock). Similar results were observed with LDV aimed at stud and nonstud sites.

Figure 1), then overall signal amplitudes measured away from the impact site are expected to be much smaller than amplitudes for impacts at competent sites. This behavior was observed in mine roof sounding tests in the field.[8]

When the LDV signals in these simple analog tests had high signal-to-noise ratios, it was fairly easy to discriminate between "loose slab" and "competent roof" by simple visual examination of the time series. However, as the signal-to-noise ratio decreased, it became more difficult. The same was not true with the audible signal. Thus, the LDV signal was converted back into an audible signal to see if the processing available in the ear and brain allowed continued discrimination at low signal-to-noise ratios. After amplifying the LDV output and using it to drive audio speakers, the stud finder test was repeated. The resulting output provided a sufficient reproduction of the sound such that blindfolded listeners could recognize the type of impact (stud or nonstud) with high accuracy, even with low-amplitude signals in a noisy environment.

7. DISCUSSION

Field measurements demonstrate that loose roof rocks exhibit anomalous vibrations during conventional roof sounding tests. The vibrations have larger amplitude, lower frequency, and longer duration in comparison to measurements made on competent roof. LDV and full-field interferometric techniques are well suited to delineating anomalous vibration conditions. To the extent that such anomalies identify hazardous ground conditions, these techniques can be used to recognize these hazards. The real issues are practical matters. Which method of stimulation should be used? Should LDV, ESPI, or holographic interferometry be used as the measurement method? How do we develop practical methods of inspection for the mine environment?

Conventional film-based double-exposure holographic interferometry with a pulsed laser can produce acceptable results on large surfaces under any excitation conditions, but the delayed feedback of film-based processing is not a realistic choice for this application. On the other hand, a single-point LDV used in conjunction with a miner manually striking the roof meets no operational or engineering barriers, but it does not significantly improve a miner's own ability to assess roof hazards.

Selection of an optical vibration measurement technique is usually based upon on the type of excitation to be used. Vibrations of interest are typically inherent in the structure or easy to excite in a controllable fashion. In the current application, there is uncertainty as to which method of stimulation would be most effective. While roof impacts are clearly effective in discriminating between competent and loose roof rock, the rapid transient response limits the use of available optical vibration measurement methods. Ambient ground motion resulting from drilling and other nearby vibration sources is no doubt of sufficient amplitude and of appropriate frequency to be useful in discriminating loose roof rocks. However, control over amplitude, frequency, duration, and positioning of vibration sources during inspection is highly desirable. Forced-vibration sources provide this control. Additional work is clearly needed to characterize the vibration response of ambient sources as well as potential active forced-vibration sources in the mine environment.

We briefly consider possible measurement methods to use with the different vibration sources.

7.1 Laser vibrometry

A single-point LDV can sense and discriminate the response of a miner's localized mechanical impact. Of all the potential advantages of noncontact vibration measurements, removing the miner from underneath potentially loose roof rock is most critical. The simple laboratory tests described here suggest that if LDV signals are converted to audible signals, they can be used to discriminate between loose roof rock and competent roof, just as stud and nonstud locations behind drywall can be discriminated. Therefore, without any sophisticated data processing, use of an LDV would allow a miner to be removed from beneath hazardous roof, at least for the purpose of *sensing* vibration response. Special conditions such as high roof and high-noise areas could benefit from this simple application of LDV and extend a miner's ability to evaluate roof stability.

To move toward improving and automating the inspection process, the response should be obtained over a field of view that is larger than that sampled by an individual roof tap. Two possible configurations to increase the sampling area include use of a single, fixed impact site with multiple scanned response sites and a fixed response measurement site with multiple impact sites (e.g., Figure 5). Use of manual or automated scans with an LDV in conjunction with a forced-vibration source could increase inspection coverage and rate of inspection.

LDV units are now being manufactured in fairly durable portable configurations. With the handy point-and-shoot measurement style and the ability to determine impact response, LDV is likely to find some role in mine safety inspections. However, collecting vibration response data over large surfaces is likely faster with full-field interferometric techniques.

7.2 ESPI

From an inspection standpoint, the ability to visualize full-field vibration patterns using the TV holographic form of ESPI is very attractive. In addition, simple qualitative analyses are adequate for this application. The main practical issue relates to laser power and the size of the inspected area. A pulsed laser provides sufficient light to record vibration mode shapes on large surfaces, even those lacking retro-reflective treatments. They also produce extremely short light pulses capable of capturing impact response. However, their use may be limited to off-shift inspections or limited-access areas because of safety considerations. High cost further limits their use in many practical applications.

Vibrations can still be recorded on large surfaces at long distances using CW lasers as reported in the studies cited earlier. Of course, the greater the surface reflectivity, the larger the view area. Because of the speed with which ESPI images are obtained, large areas can be covered rapidly with a roving CW laser system even if the individual areas are smaller than areas scanned with a pulsed laser.

Forced vibration is the preferred method of excitation so that frequencies can be swept through a range that includes resonance frequencies of loose blocks. At resonance, the contrast between the vibration response of loose blocks and that of surrounding competent rock is maximized. A dynamic shearography[33] configuration may allow such contrasting behavior to be delineated in a qualitative fashion while minimizing the influence of extraneous vibrations.

Since ambient vibrations are omnipresent, a significant benefit would be derived from their use as an excitation source. ESPI's ability to adjust fringe sensitivity[23] to the level of vibration amplitude and phase provides a way of adapting to the diverse and time-varying character of ambient mine vibration. To take full advantage of ESPI's flexibility requires a signal synchronized to the object vibration. As this signal is not generally available with ambient vibration, the analog output from an LDV or electromechanical transducer may be used to provide this synchronization.

7.3 Limitations

While numerous examples of the use of ESPI and holographic interferometry outside of the laboratory environment were described, these environments were quite tame compared to certain areas of active mining operations. These mine areas and their attendant activities are associated with elevated levels of dust, dripping water, strong air turbulence, and fog. The performance of optical measurement methods is adversely affected by these conditions, and these techniques would not be expected to be applied in such areas or during these activities.

8. CONCLUSIONS

Loose roof rocks associated with roof fall hazards in underground mines exhibit anomalous vibration characteristics. Laser vibrometry and full-field interferometric techniques are well suited to delineating regions of anomalous vibrations. To the extent such anomalies identify hazardous ground conditions, these techniques could be used to recognize these hazards. Ambient ground motions and potential sources of forced vibration excitation in mining environments need further characterization prior to field evaluation tests. While there are many difficulties in extending these techniques from the laboratory to larger surfaces in industrial or outdoor environments, the potential for success in the current application is enhanced by the reduced requirements of *qualitative* analyses.

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