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 to analyze 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 non-contact laser-based vibration measurements to detect roof fall hazards with the ultimate vision of improving, expanding and automating procedures of 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 viable methods for detecting anomalous vibration response of loose roof rocks. Results from simple laboratory experiments using laser vibrometry demonstrate some of the proposed applications 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

The unsuspecting fall of ground remains 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 10-15 fatalities and 700 to 1000 injuries each year due to ground falls[1,2]. This feasibility assessment is being conducted as part of NIOSH's mission 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 then estimated and compared to observations. A number of laser-based vibration and deformation measurement studies pertinent to the present application are then reviewed. The last part presents the results of simple lab 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 m to 30 m high (2-4 m 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 properties are rate sensitive, mine roof can deform and fail in a time-dependent fashion. Roof conditions in

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certain geologic structures also exhibit a 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 sizes 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 roof fall injuries in U.S. coal mines in 1997 involved failure with a thickness, or extent into the roof, of 0.3±0.2m[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±2.3m thickness) during this study period. More than 70% of roof falls and 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 thickness of the order 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 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: (i) the rock mass is competent and acts like a stiff infinite half space, and (ii) 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 non-contact 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 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 cm 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 larger, and duration was longer than that found 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 200-600 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 used 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 250 ft from impact sites. 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 audible sound wave recordings to discriminate between competent and loose roof rock has been investigated[4,5] and rejected[5] as microphone data was 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. Due to the large acoustic impedance mismatch between air and rock, the signal heard by the 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 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 non-experts 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 200-1000 Hz band and the 3000-3500 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 roof. Altounyan and Minney[13] report trials of a similar prototype that is based on the rate of decay of impact-induced vibrations. Following an area-specific calibration, this data is 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 the miner's senses and brain, and as this natural data collection and processing will still automatically occur by the operator during use of such electronic systems, it is difficult to foresee widespread adoption of this approach.

3.4 Slab resonance frequencies

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

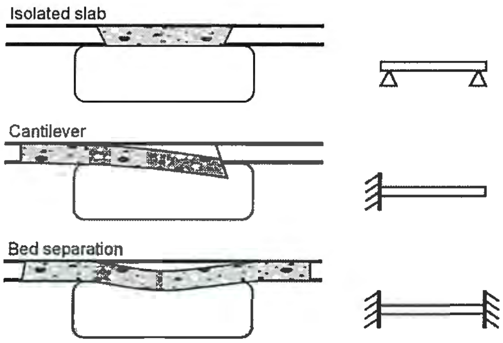

Figure 1 - Three types of loose slabs that pose a roof fall hazard, and their approximate boundary conditions.

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, the 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, respectively, 19.74, 3.49, and 35.98.

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 an order of magnitude.

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

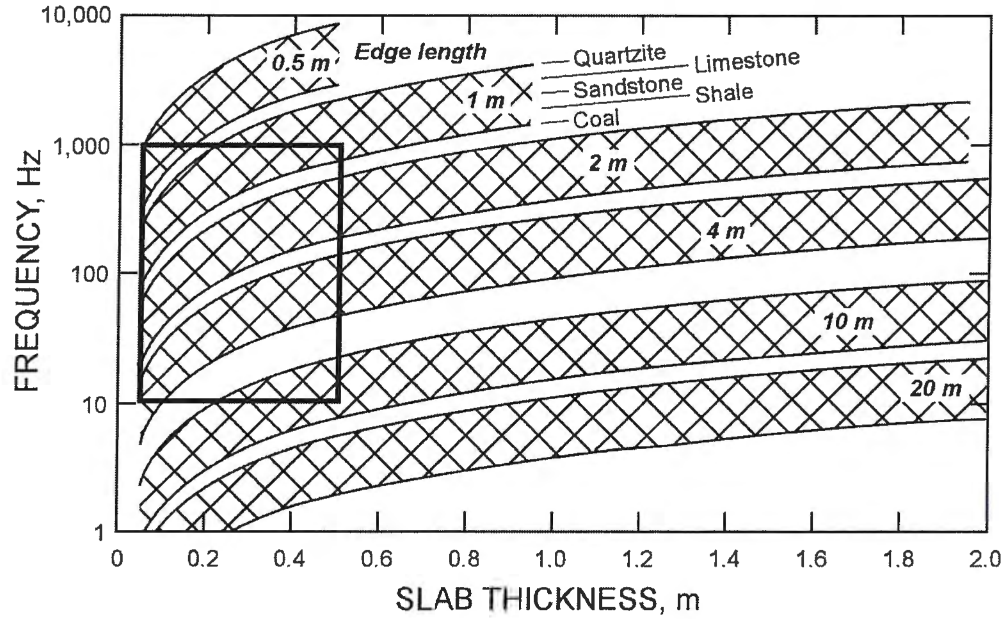

Figure 2 - Resonance frequencies of roof slabs (simply supported plates)

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 thickness are highlighted in the box in Figure 2. The slabs within this box represent reasonable size estimates 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.

The miners' mechanical impacts are known to be effective in exciting anomalous vibration response. 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 compressed air.

For discussion purposes, the following distinction is made between forced and ambient vibration. Forced vibration is that continuous periodic vibration that is specifically imposed to assist in roof and rib inspection. Ambient vibration includes background Earth noise as well as all other continuous and non-continuous sources of ground vibration in the mining environment. The latter includes 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 close 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 loud speakers 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 both 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.

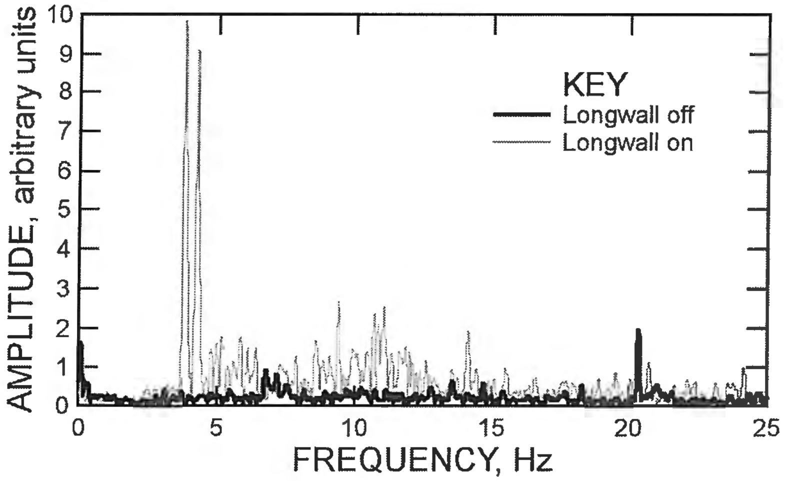

Figure 3 – In-mine ambient background vibration spectra. Longwall on (dashed) and off (solid).

5. LASER-BASED VIBRATION MEASUREMENT METHODS

5.1 Potential advantages of non-contact vibration sensing

Non-contacting 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 single-point measurements, 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 the 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 needs to 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-air flows in methane-rich and coal-dust laden mine atmospheres.

5.3 Application to large surfaces in industrial environments - Previous work

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 pseudo-random 80-300 Hz acoustic waves. The mismatch in elastic properties between soil/gravel and buried landmine results in an anomalous vibration response that is 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 measuring small objects in the laboratory to large surfaces in industrial or outdoor environments are (i) maximization of available laser light and (ii) 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 that applied full-field techniques to large surfaces and/or sought to identify anomalous vibration characteristics are described below. Unless otherwise indicated, in the following, use of the general term ESPI (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[23]. 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 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, 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 deformations 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 microns 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-scale 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 1-2 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 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 the solid earth due to tidal forces was recorded with real-time holographic interferometry by Takemoto[30]. A 1-m^2 surface 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 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 that were 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 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 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 used 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 contrasts the impact response of competent mine roof (Figure 4a) with that of roof with loose rock (Figure 4b). 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 4a) indicate 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 is stationary and multiple impact sites are distributed. 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 (stiff, competent roof analogy) and non-stud locations

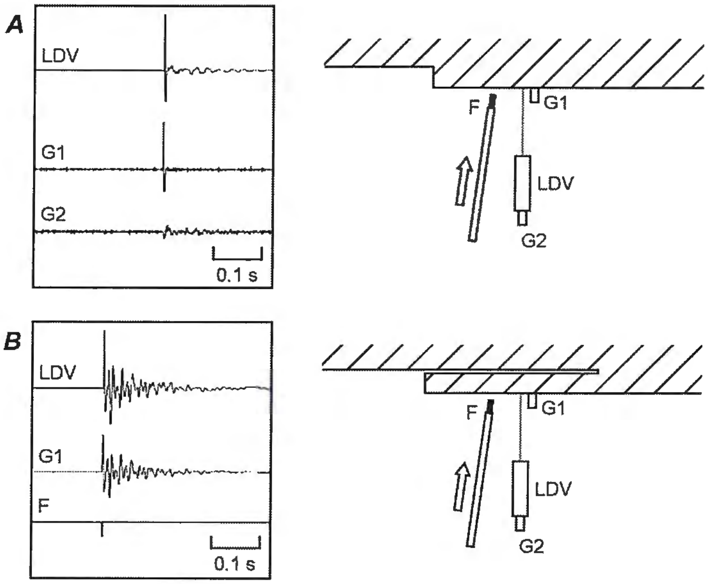

Figure 4 - Vibration response due to impact on (a) competent (simulated) roof and (b) loose roof. Signals are from laser vibrometer (LDV), geophones (G1, G2), and impact hammer (F).

(less stiff, loose rock) is not unlike the differences heard in mine roof sounding tests. In both cases the differences are sometimes subtle but recognizable. Tapping on the wall directly above a stud results in signals (Figure 5a) that are higher in frequency, lower in amplitude, and shorter in duration compared to impact sites between the studs (Figure 5b). This result parallels the audible response. As the distance between the impact and LDV measurement site increases, signal amplitudes decrease. However, the contrast in relative signal amplitude, frequency, and duration between taps at stud and non-stud locations persists. In this test, the zones of low stiffness are well coupled into 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 1a), then overall signal amplitudes measured away from the impact site are expected to be much smaller than for impacts at competent sites. This behavior was observed in mine roof sounding tests in the field[8].

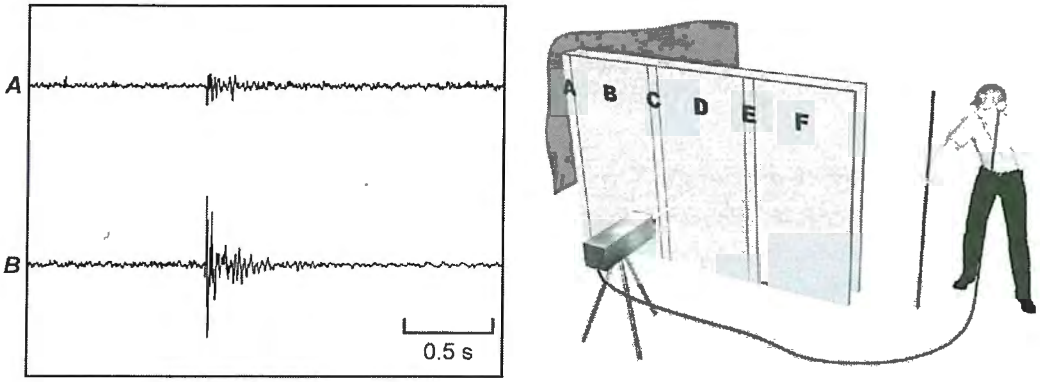

Figure 5 – Time series response measured with LDV at a single site due to impacts at multiple sites. Gypsum covered wooden stud wall used as analog of mine roof with spatial distribution of competent and loose rocks. (a) impact on stud (stiff competent roof), (b) impact between studs (low stiffness loose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

When the LDV signals in these simple analog tests have high signal-to-noise ratios it is 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 decreases it becomes more difficult. The same was not true with the audible sound. Thus, the LDV signal was converted back into an audible signal to see if the processing available in the ear and brain allows 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 provides a sufficient reproduction of the sound that blind-folded listeners can recognize the type of impact (stud or non-stud) with high accuracy, even with low amplitude signals in a noisy environment.

7. DISCUSSION

Field measurements demonstrate that loose roof rocks exhibit anomalous vibrations in 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's manual roof impact meets no operational or engineering barriers but it does not significantly improve the 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 either 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 will be most effective. While roof impacts are clearly effective in discriminating between competent and loose roof rock, the rapid transient response limits the available optical vibration measurement methods. Ambient ground motion due to 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 the 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 the miner's localized mechanical impact. Of the potential advantages of non-contact vibration measurements, removing the miner from underneath the potentially loose roof rock is most critical. The simple laboratory tests described here suggest that if LDV signals are converted to audible sounds they can be used to discriminate between loose roof rock and competent roof, just as stud and non-stud locations behind drywall can be discriminated. Therefore, without any sophisticated data processing, use of an LDV would allow the miner to be removed from beneath hazardous roof, at least for the purpose of *sensing* the vibration response. Special conditions like high roof and high noise areas could benefit from this simple application of LDV and extend the 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 area sampling include use of (i) a single fixed impact site with multiple scanned response sites, and (ii) 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 the 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 ability to determine impact response, they are 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 holography 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 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 individually imaged areas are smaller than 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 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 earlier, those environments are quite tame compared to certain areas of active mining operations. These mine areas, and specific 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 vibration response. To the extent such anomalies identify hazardous ground conditions, these techniques can 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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Paper #: 4827-44
Vibration measurements in a rotating blisk test rig using an LDV, pp.1-8

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Abstract: Three methods of using an LDV to measure the vibration of a bladed disc in a rotating rig are described: i.e. (1) The response of one blade is monitored continuously by diverting the laser beam via a small mirror on the rotating disc, and a fixed, annular, conical mirror. Any of the blades may be targeted, by indexing the rotating mirror. (2) Circular scans give circumferential response mode shapes directly, or (3) via spectra, as nodal diameter coefficients. Some natural modes of blisks (integral bladed discs) occur in isolated pairs, with amplitude distributions which are sinusoidal around a circular scan line. The natural frequencies increase with the number of sinusoids around the circumference, asymptotically to the cantilever blade frequency. Forced vibration of these modes, in a rotating situation, produces various combinations of standing and rotating waves. With a mistuned blisk, the close modes couple to create natural mode shapes which are very irregular. Excitation frequencies are at multiples of rotation speed, exciting modes with equivalent numbers of nodal diameters, sometimes aliased with the number of blisk blades. The LDV techniques described can cover all these effects, and some example measurements are included to illustrate their potential. !5

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A comprehensive velocity sensitivity model for scanning and tracking laser Doppler vibrometry on rotating structures, pp.9-21

Author(s): Ben Halkon, Loughborough Univ., Loughborough Leics, United Kingdom;

Paper #: 4827-28
Nondestructive testing technique combining ultrasonic Lamb waves and double-pulse TV holography, pp.530-540

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Abstract: The combination of ultrasonics with optics has led to the development of emergent technologies for non-destructive testing with outstanding capabilities. In this work we describe a combination that, in our knowledge, was up to now unexplored, directed to the detection of cracks and other types of flaws in metallic plates of medium thickness (several millimeters). We selected a special kind of surface acoustic waves, i.e. Lamb waves, to explore the volume of the plates in the search for flaws, while a whole field interferometric technique, namely double-pulse TV holography, is employed to generate a map of the surface displacements in which the signature of the defects can be seen as a perturbation of the initially smooth wavefronts. Several examples of detection of artificially generated flaws are presented. |13

Paper #: 4827-30
Feasibility of using laser-based vibration measurements to detect roof fall hazards in underground mines, pp.541-552

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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. |33