Effective installation of rock bolts is highly dependent on correct identification of the geological conditions, including discontinuities because they tend to vary, even within a short distance (Gu, 2003). Currently, many drilling parameters are being collected and processed that can potentially be utilized to estimate the geological conditions at the jobsite (Peng, 2003). A series of studies has demonstrated the potential for analyzing drilling parameters from roof bolters to estimate rock properties and to identify discontinuities (Ichihara, Deguchi, and Itakura, 1995; Itakura et al., 1997a; Itakura et al., 1997b; Itakura, 1998; Itakura et al., 2001; Itakura et al., 2008).

Itakura et al. (1995, 1997a) employed a portable pneumatic roof bolter with the ability to record torque, thrust, revolution, and stroke. Torque and thrust were monitored by using strain gauges installed on the surface of the drilling rod, while penetration and rotation rate were kept constant during the tests. The manufactured blocks included sandstone, sandy shale, and coal samples with three different discontinuity angles of 0 degrees, 30 degrees, and 60 degrees and three types of discontinuities, namely cracks, boundary, and separation of layers. Cracks are discontinuities within a layer. Boundary and bed separation are discontinuities between the layers and often feature an aperture between layers in the rock mass, often intersected by joints. The average value of torque and/or thrust was found to be an indicative index to allow for classification of the rock layers along the borehole. Furthermore, It has been proposed that patterns of thrust or torque along with neural network algorithms may be used to categorize the discontinuities, but the resulting error was rather large (Itakura, 1998; Itakura et al., 2001). Itakura et al. (2008) reported feasibility studies for rock mass characterization while drilling for roof bolts in an underground coal mine in Queensland, Australia. In these studies, 48 holes were drilled using the instrumented drill unit, and one hole was cored in the test area. The system successfully showed the distribution of discontinuities and layer boundaries using the ratio of recorded parameters of torque and thrust.

In a similar work, J. H. Fletcher & Co. developed a system that monitors drilling operations. Fletcher® has been a pioneer in developing instrumented roof bolters to monitor and process drilling parameters, including thrust (obtained from feed pressure), torque (obtained from rotation pressure), rotation rate, and bit position (Gu, 2003). The Fletcher system has been employed to...
detect different kinds of discontinuities including voids, fractures, and bed separations, and to estimate the relative hardness of the rock mass (Finfinger et al., 2000). Variation of thrust or feed pressure had been found to be the most suitable identifier of discontinuities (Finfinger, 2003; Gu, 2003; Mirabile, 2003; Tang, 2006; Finfinger et al., 2000; Luo, Peng, and Wilson, 2003; Luo et al., 2002; Peng et al., 2003). For example, Finfinger (2003) proposed a thrust valley concept by which the presence and the size of discontinuities, such as fractures, joints, and voids in the rock, can be evaluated. Based on this concept, thrust decreases rapidly after reaching a void and increases rapidly again when it goes through the discontinuity to keep the preset level of penetration constant. A drop of more than 50% was then considered as an index to detect discontinuity. The distance between the two sides of the valley was also used to measure the discontinuity aperture. Two models were offered for estimating the size of discontinuity.

A secondary parameter of rotational acceleration was also proposed to detect beddings. This parameter could detect 70% of the interfaces designed in the experimental program using layered blocks. The location of 57% of these interfaces was predicted within 2 inches of the actual locations. This system is further developed by Gu (2003, 2005) with the introduction of the drilling hardness (DH) parameter. The DH parameter considers the geometry of the drill bit and contact area between the drill bit and rock, the friction between the drill bit and rock, and the energy lost in kinetic energy, potential, and torsion energies. The slope of the drilling hardness curve and its peak values are used to determine the location of discontinuities and interfaces. Discontinuities were detected using threshold-based algorithms that need to be adjusted for different rock types. This limits the applicability of the system for deployment and utilization in different mining locations. For example, Gu (2003) mentioned that, in one mine site, only 25.86% of the discontinuities were detected by DH method within an acceptable error window. He explains that this failure stems from the fact that the rocks encountered were not weak enough to be detected by the DH slope approach. More recent studies show that the feed pressure is the most indicative parameter for identifying discontinuities, provided that the penetration and rotation rates are constant or under control (Tang, 2006). Tang (2006) developed a method that is able to detect fractures with an aperture of 1/8 inch or larger. However, this approach was found to be somewhat ineffective for discontinuities of 1/16-inch aperture or smaller. Moreover, the accuracy of the drilling parameters recorded by the available system was insufficient to determine the size of discontinuities smaller than 1/2 inch.

Although the instrumented system has been improved to a great extent, there are still some inaccuracies in detecting the location and, especially, the size of discontinuities. Collins, et al. (2004) explained that some voids could not initially be detected by the system during a series of field experiments in a limestone mine, mainly, because of the difference between the hardness of concrete used in the laboratory and the limestone at the roof of the mine. It was found that unlike the usual pattern observed in the laboratory, in which both thrust and torque would drop simultaneously, a sudden rise in the rotation torque happened just before encountering the voids. Meanwhile, the thrust did not have a consistent reaction. New theories were developed later to describe the observed trends. Another problem was reported by Anderson and Prosser (2007), in which the hairline and vertical cracks along with layers of the rocks were not correctly identified. Moreover, as mentioned before, Tang (2006) elaborated that the applicability of the developed system is limited to voids with size of 1/8 inch or larger.

All the developed methods discussed in this section utilize the drilling parameters to locate discontinuities and estimate rock hardness, which may be affected by many other factors, such as drill size, bit wear and geometry, drill machine mechanisms, etc. (Anderson and Prosser, 2007). In this paper, the installation of new sensors on the Fletcher unit for collecting additional data and monitoring the drill head vibration will be discussed. The initial results will be reviewed and, in particular, the feasibility of using vibration and acoustic signal for void detection, which are independent of the drill unit control system, will be examined. The results of our preliminary analysis indicate that these two parameters are, indeed, informative and can potentially improve the performance of void detection and rock characterization. This refers to increasing the possibility of accurate detection of the discontinuities and reducing the frequency of false detection.

The paper will briefly cover the capabilities of the existing Fletcher roof mapping system. Newly installed vibration and acoustic sensors will be explained, and the results of preliminary testing and data analysis using signal processing tools will be discussed. Finally, some concluding remarks and discussion of future plans for continuation of the research, including full-scale laboratory and field testing will be provided.

FLETCHER INFORMATION DISPLAY SYSTEM

J. H. Fletcher & Co. has developed the Fletcher Information Display System, which uses a programmable logic controller to monitor drilling operations. This system features a drill control unit (DCU) to automate the cycle of drilling and bolting for safety and productivity reasons (Anderson and Prosser, 2007). The DCU processes the drilling parameters including torque, thrust, rotation rate, and position, along with vacuum or water pressure used for flushing, bit breakage, or bending of the drill by controlling the drilling parameters without deteriorating the optimum drilling operation (Anderson and Prosser, 2007). Several modifications have been made to improve the accuracy of measuring bit position and torque (Gu, 2003). The Information Display System was modified to communicate with the DCU to display the information from four separate drill holes side-by-side so that trends could be easily observed in real time. These graphs can show the material hardness and can display the location of voids or other discontinuities in the mine roof structure. Also, rotation events, like stalls, and water events, which may indicate that the drill steel is being plugged with soft material, are marked with colored lines and letters (Anderson and Prosser, 2007). The new Information Display System features a rugged touch screen panel, a solid state flash memory for better durability, uninterrupted power supply, a virtual keyboard for entering additional information to the files, a back-up video display, and a print function (Anderson and Prosser, 2007). The sampling interval in this system is 10 Hz or 0.1 second time interval.

INSTALLATION OF NEW SENSORS

As discussed earlier, a set of vibration and acoustic sensors was installed on the Fletcher drill unit, as shown in Figure 1. An experienced operator can notice changes in vibration of the drill
rod and noise amplitude when the rock strength changes. Previous studies have also examined the advantages of using vibration and acoustic sensors for rock characterization while drilling (Gradl et al (2012), Celada et al, (2012)). Therefore, the drill unit was equipped with additional vibration and acoustic sensors to study the suitability of these sensors for void detection. We will also use the data from these instruments for rock strength characterization in future research.

The additional vibration sensor is a PiezoStar accelerometer with frequency range of 1 to 5KHz with high sensitivity (50 mV/g). The acoustic sensor is a Piezo disc, also known as a contact microphone. It is a small ceramic wafer on a thin metal disc that can be used for acoustic measurements. The sensors are glued to the drilling unit as shown in the Figure 1 to avoid the need for additional machining and to save time. The initial testing and calibration shows that this type of mounting has not impacted the performance of the sensors, but for field deployment, their location should be optimized and a more permanent arrangement should be used to protect the sensors. The sensors, including the accelerometer and microphone, are monitored in parallel to the existing data acquisition device at a high sampling rate of 1KHz. This is done by using a separate data acquisition system (DAQ). The wires from new sensors are directly connected to the new DAQ for excitation and data channels. Also, data from the original sensors of the Fletcher drill void detection system are collected by the new DAQ as analog input from the wiring terminal of the existing Programmable Logic Controller (PLC) of the machine.

The signals from the two data acquisition devises are further synchronized using a relay. However, since the objective of this paper is to illustrate the application of vibration and acoustic sensors for void detection, the data that are usually monitored by Fletcher in their existing roof mapping algorithm are not analyzed here. The two systems will ultimately be integrated to develop a “measurement while drilling” system. This will allow for a better characterization of the rocks and will facilitate optimized ground support design for safe underground mining and tunneling operation. The following section contains the discussion of the preliminary results of data analysis based on the application of acoustic and vibration sensors for void detection.

**REVIEW OF THE RESULTS OF PRELIMINARY TESTING PROGRAM**

This section offers the review of the results of the preliminary experiments performed at the Fletcher testing facility in Huntington, WV, on selected concrete blocks. For this purpose, a set of 16 concrete blocks with different strength were poured and allowed to cure for more than 28 days. The blocks are approximately 0.5 x 0.5 x 0.75 m (~20 x 20 x 30 inches), and the concrete mix was designed for various strengths: low (~20 MPa or 3,000 psi), medium (50 MPa or 7,500 psi), and high (70 MPa or 10,000 psi). In this setup, a hard (high-strength) concrete block was placed on top of a soft (low-strength) concrete block. There was a small gap, less than a couple of millimeters, between the two concrete blocks that was considered to simulate a “void” in this study.

**VIBRATION SENSOR**

As noted earlier, specialized vibration sensors were installed on the drive unit of the roof bolting machine and were monitored with the new DAQ at a sampling rate of 1 kHz. Figure 2 shows the plot of position and vibration signal obtained while drilling a hole with a void. The drill was set with penetration rate of 1 inch per second and a rotation rate of 400 rpm. During the first ~3 seconds of the data collected, bit and drill string is in rotation, as indicated by rotation pressure, and the feed pressure gradually increases. In this part of the test, the position signal shows almost constant value (no actual drilling), and the vibration amplitude is low. As the bits gets in touch with the sample and drilling starts, the amplitude of the vibration increases, as expected. The vibration signal is not a uniform periodic signal because the concrete block is not homogeneous material. However, 26 seconds into the test, where the drill bit reaches the void located 39 inches into the block, the amplitude of the vibration signals decreases. It is logical to anticipate a reduction in the vibration signal when no rock/concrete is being drilled, and the bit runs through the void.

Figure 2. Position and vibration signal obtained from drilling a hole with a void.

This signal provides a measure that is directly correlated with existence of the void, and it is independent of the closed loop control unit of the drill machine. This is the main incentive in using the vibration signal for void detection, rather than using a
Figure 3. Feed pressure signal corresponding to the data shown in figure 2.

Figure 4. Spectrogram of the vibration signal.

Figure 5. Filtered vibration signal and detected void.

ACOUSTIC SENSOR

Figure 6 shows the acoustic signal during the same experiment where the vibration signal was studied. In contrast to the vibration, the amplitude of the acoustic signal does not change significantly between the first 3 seconds (when no actual drilling is performed) and the rest of the test. The reason for this is that, even if drill bit is not moving forward, the drill bit is rotating and, therefore, generating noise. Thus, it might seem that the acoustic signal cannot be utilized for the purpose of void detection. However, this is not true, which became clear in subsequent analysis. Figure 7 shows the frequency response of the signal, which illustrates that the acoustic signal is, indeed, periodic with important components at a frequency close to 6.6 Hz. This is justified by the fact that the RPM of the drill machine was set to 400 during the drilling of the hole. This is equivalent to almost 6.6 turns a second. This periodic signal exists the whole time the drill bit is rotating, and its amplitude was very big, masking other important information embedded in the signal, including the void information. Therefore, to utilize the acoustic signal for void detection, the signal should be treated with a high pass filter. This is better illustrated in Figure 8, which shows the spectrogram of the signal in the frequency domain. The high value (red part) of the spectrogram at low frequencies demonstrates the same information shown in Figure 6. If this low frequency component is removed, the rest of the spectrogram clearly shows the same two bands observed on the vibration signal. Having a nonlinear filter to further isolate these two bands and reconstructing the signal results in the filtered acoustic signal is shown in Figure 9. This clearly demonstrates the success in the application of the acoustic signal for void detection. Further testing, possibly with different drill strings and with multiple drilling rods in the field would allow for expansion of these measurement to more complex cases and related algorithms for detection should be modified accordingly. It should be emphasized that high frequency components of the acoustic signals are more informative for the application of the void detection than the low frequency components, as discussed here. Therefore, a higher sampling rate than the current 10 Hz would be necessary in identifying voids using acoustic signal. As mentioned earlier, sampling rate of 1 KHz was used in the testing program and the sampling rate will be optimized based on the adopted data analysis algorithm.
Figure 6. Acoustic signal obtained by drilling a hole with a void.

Figure 7. Absolute values of the Fourier components for the acoustic signal.

Figure 8. Spectrogram of the acoustic signal.

Figure 9. Filter acoustic signal with void detected.

CONCLUSION

The results of the preliminary analysis of the data from the vibration sensor and the microphone indicate that they can provide a void detection system, which is independent of the existing algorithm that is installed on the J. H. Fletcher & Co. roof bolters with capability of void detection. This allows for the improved detection capabilities of the Fletcher void detection system, which can reduce false detections if used in combination with the existing system. Further testing in a variety of block strengths and also in conditions where the interface between the different layers are at an angle with the drilling path will be examined to further refine the proposed void detection system based on the vibration and noise signals. The developed routine can be programmed as an executable module to allow for installation on various roof bolter units. This allows for the extending the ability for void detection to older units, where, with the addition of an accelerometer and a microphone, the machine can be retrofitted with a PLC or an onboard computer to sense the formations and identify voids. The higher data-sampling rate, which is needed for this type of detection, could create file management problems. Thus a real-time analysis capability within the data acquisition program can facilitate the implementation of the required data filtering and required analysis to convert the high volume of data to a smaller, more manageable set of physical characteristics of the rock formation.

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REFERENCES


