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EFFECTS OF OBSTRUCTIONS, SAMPLE SIZE AND SAMPLE RATE ON ULTRASONIC ANEMOMETER MEASUREMENTS UNDERGROUND

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ABSTRACT

In fluctuating airflow, continuous air velocity recording is the most reliable method of air velocity measurement. It allows for fast recognition of changes and the calculation of long-term averages. Also, it enables the mine operator to identify when the airflow has decreased to a point requiring action. Using ultrasonic anemometers provides an accurate option for continuous air velocity monitoring.

This paper provides information about the effect of common obstructions in underground mining on air velocity readings. Stationary and moving obstructions are used to represent workers and equipment that would cause discrepancies in measured airflow. Also, it is important to know how large of a sample size is required to ensure reasonable accuracy of results. Statistical analysis is used to evaluate the required sample size. The sampling procedure is further studied by comparing two different sample rates.

The results show that obstructions provide noticeable differences in air velocity measurements. Also, movement of obstructions can be recognized from changes in results. Surprisingly small sample sizes provide reliable air velocity information. Standard sample rates are found to be suitable for the underground environment.

INTRODUCTION

Ultrasonic velocity transducers have been used extensively in fluid flow applications but are a relatively new addition to the underground mine environment. The operation of an ultrasonic instrument is based on the principle that the speed of a sound pressure wave varies with the local air speed. The air velocity is calculated from measurements of air-pulse transit times between sound transmitter and receiver (Hall et al., 2007). Ultrasonic anemometers have a linear response to airflow and an absolute calibration that depends only on sensor spacing and transit time measurement accuracy (Taylor et al., 2004). As opposed to conventional forms of velocity measurement, this technique requires no correction for air density, there are no moving parts to wear, and there are no start-up friction or inertial problems when the air velocity changes rapidly (Casten et al., 1995). An important advantage of this method is the ability to provide a directional sign to the air velocity.

Ultrasonic instruments fall into two distinct categories: variable distance instruments and fixed single-point instruments (Casten et al., 1995). Variable distance instruments consist of two ultrasonic transceivers mounted on each side of an airway, pointed axially towards each other and measuring the difference in time of flight. Variable distance instruments are limited to one-axis measurements, but are often capable of calculating airflow for a known area. Fixed distance units operate on the same principle as variable distance units, but the measurement is performed inside one unit, with a typical sensor array of about 0.2 m (0.7 ft). Fixed distance ultrasonic anemometers are categorized as one-, two- and three-axis.

From the fixed distance ultrasonic anemometer options available, the one-axis instrument measures flow in one direction, the direction of instrument orientation. Thus, it has the same limitations as the current standard vane anemometer, which is dependent upon orientation with respect to airflow. The two-axis instrument measures flow velocity in a plane defined by the U and V flow components in a direction relative to a reference direction. The three-axis instrument measures flow in a three-dimensional space defined by the U, V, and W components of flow.

Some new additions to the variable distance instrument category have been developed recently in Canada for fan airflow monitoring in underground mines (Synergy Controls Corporation, 2010; Accutron Instruments, 2010). Fixed, single-point instruments currently available are primarily for meteorological and research purposes (R. M. Young Company, 2009; Gill Instruments, 2009; Vaisala, 2009).

Coal mine operators can use an ultrasonic instrument to help them comply with ventilation requirements such as air velocity and direction in the belt entry, and total air quantity in the belt entry and primary escapeway (Martikainen et al, 2010). However, ultimate compliance is determined by the Mine Safety and Health Administration (MSHA) by taking traverse velocity measurements in the entries using a vane anemometer. Currently, some ultrasonic anemometer manufacturers have either applied for or are looking into applying for MSHA certification for permissibility as defined under 30 CFR § 75.506 to enable the use of their instruments in the US underground coal mines. Several instruments have been classified as intrinsically safe based on other certifications in countries including Poland, Canada and the UK. Permissible, MSHA certified instruments could be used in return airways of coal mines in the US instead of only in fresh air.

This study evaluates the feasibility of single-point 2-axis and 3-axis ultrasonic anemometers for air velocity measurements in underground coal mines. The specific issues addressed by the study are the effects of common obstructions underground, required sample size to achieve accurate results, and an adequate sample rate.

TEST SETTING

Tests were performed underground in three locations of the NIOSH Bruceton Experimental Mine, which is driven into the Pittsburgh coal seam. The first location (location 1) is in a long, straight section of a tunnel with a cross-sectional area of 5.3 m^2 (57 ft^2). The second test location (location 2) is in a curve of about 45°. The cross-sectional area of the tunnel is about 7.7 m^2 (83 ft^2). Locations 1 and 2 were chosen to represent airflow in a straight and curved tunnel and because of instrument cable length restrictions. Location 3 is in an entry to an opening used to run cables through a bulkhead. The cables block part of the opening, causing a very uneven airflow. The cross-sectional area of location 3 is 3.0 m^2 (32 ft^2) and the cross-sectional area of the opening is 0.7 m^2 (7.5 ft^2). The testing locations are shown in Figure 1. Air velocity was varied in the mine by opening and closing doors and changing fan settings.

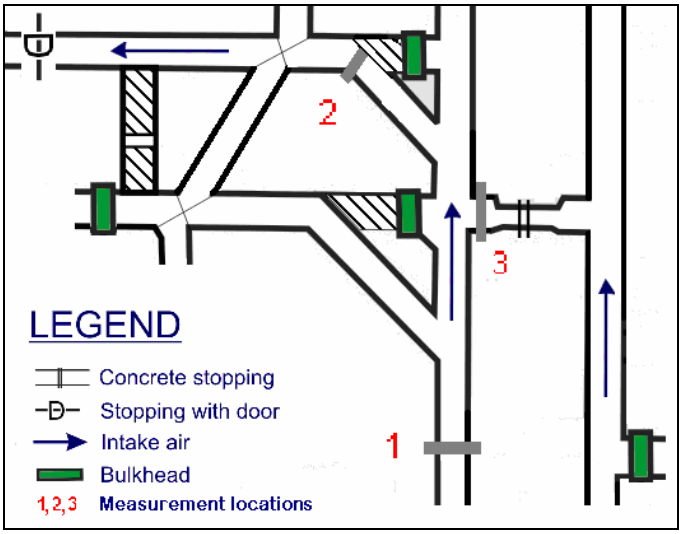

Figure 1. Underground Test Locations.

At all three test locations, the ultrasonic anemometers were set up in the tunnels with the 3-axis instrument positioned between the 2-axis instruments. The 3-axis anemometer was kept stationary throughout the measurements in all locations, while the 2-axis instruments were attached to adjustable poles with swinging arms. This allowed for point measurements to be taken at several spots across the entry. A total of six measurements were taken across the entry with both 2-axis instruments at locations 1 and 2. Figure 2 shows the ultrasonic anemometer set-up for testing in locations 1 and 2. The same set-up was used during a previous study (Martikainen et al, 2010). A similar set-up was used at location 3, but due to a smaller cross-sectional area the swinging arms were not turned and only two heights, high and low, were used for the 2-axis instruments. As a result, only five measurements were taken over the cross-section at location 3 (two-two axis measurements on each side plus a three axis measurement in the middle) while in locations 1 and 2 the number of measurements was 13.

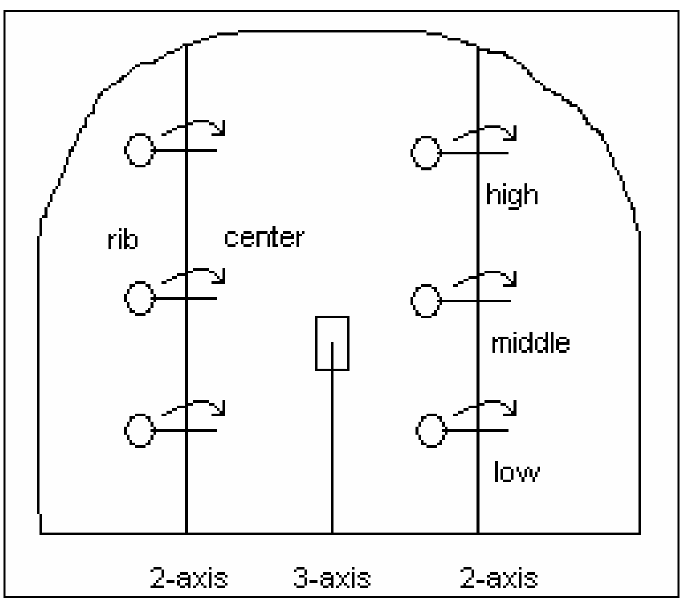

Figure 2. Anemometer Placement for Locations 1 and 2.

A 180-s data collection time was used with the ultrasonic anemometers. The sample rate used was 1 sample/s except for the sample rate study, during which a sample rate of 4 samples/s was used. These sample rates were readily available in all measurement instruments.

Davis rotating vane anemometers were used to measure air velocities for comparison. Three vane anemometer traverses of 60 s were taken in all locations to compare with the averages of the 180 s data measured by the ultrasonic anemometers. The vane anemometer was used with an extension rod to minimize errors caused by measurement-taker proximity. The averages of the vane anemometer readings were compared with the averages of the results obtained by the ultrasonic anemometers.

OBSTRUCTION ANALYSIS

Obstruction test set-up

A potential difficulty with continuous airflow monitoring may arise with the presence of obstructions (i.e. equipment and personnel) upstream of an anemometer station. Depending upon the distance from the anemometer, such obstructions can interfere with the flow around the sensor head and may generate vortices and eddies that seriously impact the accuracy and stability of the output of this instrument. A series of evaluations were conducted to examine the impacts of both stationary and mobile obstruction at two different distances from the instrument location.

Two different stationary obstructions were tested with two airflows at locations 1 and 2. The first obstruction (stationary obstruction 1) was a test subject with a height of 1.75 m (5.9 ft) and an approximate average width of about 0.4 m (1.3 ft) in full mine gear. Stationary obstruction 1 was placed between the instrument poles. To distribute the effect evenly between instruments, the obstruction was moved to four locations from left to right in the entry, as follows:

(1) between rib and left pole,
(2) between left pole and the 3-axis instrument,
(3) between the 3-axis instrument and right pole (Figure 3), and
(4) between right pole and rib.

Stationary obstruction 2, an electrician's personnel and equipment carrier cart was placed in front of the instrument set-up, 3.0 m (10 ft) upstream from the instruments. The height of this cart is about 1.17 m (46 in) and the width is 1.14 m (45 in). The cart is shown in Figure 4.

Figure 3. Stationary Obstruction 1 between 2-axis and 3-axis Ultrasonic Anemometers in Location 2.

The test subject was also used as a moving obstruction. The test subject moved with a steady pace of about 0.25 m/s (50 fpm) back and forth across the entry at two different distances, first at 1.2 m (4 ft) (moving obstruction 1) and then at 3.0 m (10 ft) (moving obstruction 2) upstream from the instruments. Tests were performed at locations 1 and 2 with two different airflows.

Results of obstruction testing

With both airflows in location 1, stationary obstruction 1 increased the average air velocity measured across the entry by about 15%. An air velocity increase was also observed at location 2. The change in air velocity corresponds to an area decrease of about 0.7 m^2 (7.2 ft^2) at both locations, which correlated well with the size of the obstruction.

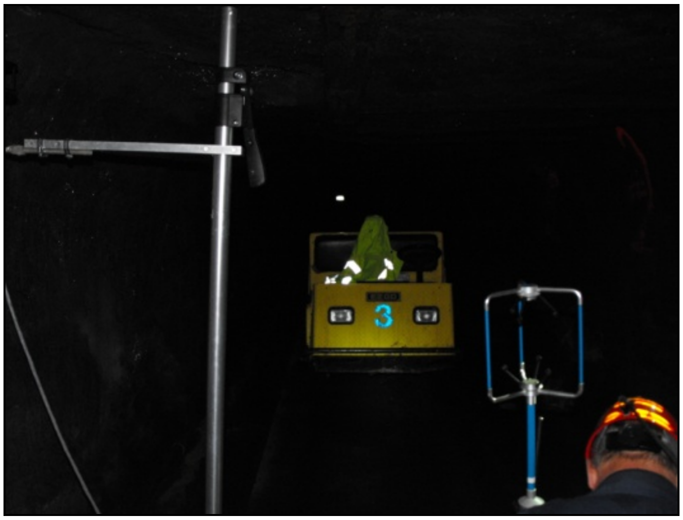

Figure 4. Stationary Obstruction 2 Upwind of Location 1.

Similar air velocity differences due to the effect of stationary obstruction 1 were observed in previous tests when comparing the results of a rotating vane anemometer to the results obtained by the ultrasonic anemometer set-up (Martikainen et al., 2010). Even when an extension rod was used according to the suggested practice of keeping a minimum distance of 0.9 to 1.2 m (3 to 4 ft) between operator and instrument (Boshkov and Wane, 1955), with care taken to keep the anemometer upstream of the measurement taker, all the vane anemometer readings were significantly higher than the velocities recorded by the ultrasonic anemometers. These differences were recognized to correlate well with the size of the measurement taker and were comparable to the effect of stationary obstruction 1 on the ultrasonic anemometer measurement results.

Stationary obstruction 2 affected the airflow in location 1 in the same way as stationary obstruction 1. In this case the measured change in air velocity was about 22%. The expected air velocity increase from the free cross-sectional area decrease caused by the obstruction based on a calculation was 1.4 m^2 (14.9 ft^2) and the measured was 1.3 m^2 (14.4 ft^2). This discrepancy can be explained by the circumstances in location 2 being more complicated. The average change in air velocity was different for every instrument. In some cases a slight decrease in air velocity was observed instead of an increase. It was determined that the stationary obstruction caused an air velocity distribution change over the entry cross-section, moving higher airflow from the left side of the entry to the right. Also, the 3-axis instrument recorded noticeable W-axis values (air moving up- or downwards).

Moving obstruction 1 decreased the average air velocity values in comparison to the air velocity with no obstruction. Comparison of the ultrasonic anemometer outputs with the positions of the obstruction showed a significant decrease of airflow immediately after moving obstruction 1 had passed the instrument. After this disturbance, the air velocity quickly returned to slightly above that measured with no obstruction. The disturbances are easily recognizable in comparison to the undisturbed airflow and the results and are shown in Figure 5. In this figure, the impact of the obstruction on the airflow can be clearly seen as pronounced dips in the plot. It is important to realize that the readings returned to near normal, unobstructed levels once the obstruction passed the anemometer.

Similar results were observed for moving obstruction 2. In this case, however, the average air velocities were approximately the same as with no obstruction. The disturbances caused by the obstruction moving further away from the instruments were not long enough or large enough to affect the averages. An example of the air velocity averages with no obstruction and with obstructions from all three instruments is shown in Figure 6.

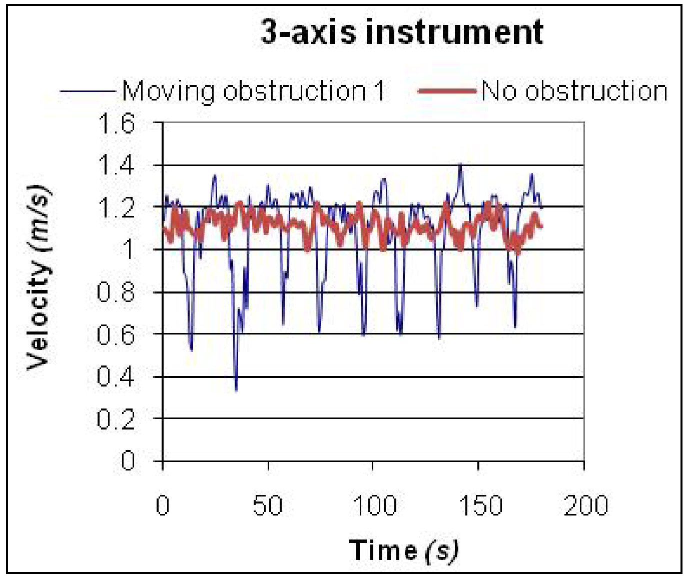

Figure 5. Airflow with no Obstruction Compared to Airflow Disturbed by Moving Obstruction 1 at Location 1.

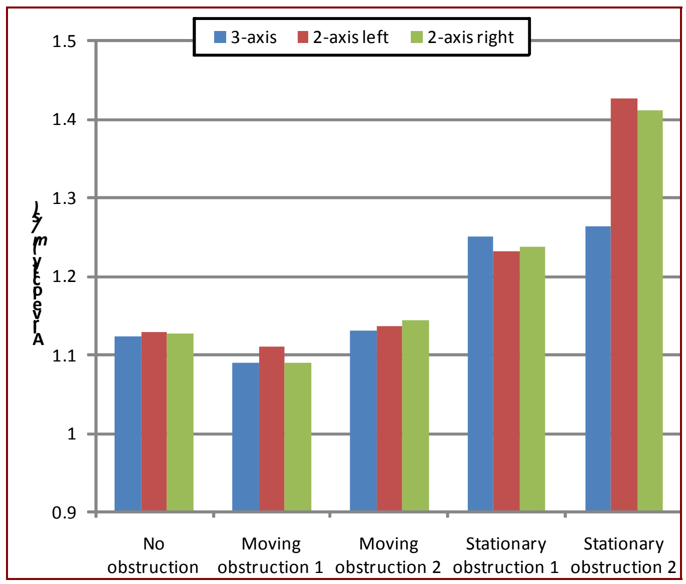

Figure 6. An Example of Air Velocity Averages with Obstructions and with No Obstructions in Location 1.

SAMPLE SIZE AND SAMPLE RATE

Testing

Measurements to evaluate the required sample size to obtain a reasonable accuracy of results with the ultrasonic anemometers were taken at all three locations. For a rotating vane anemometer, a recommended minimum traverse time is 60 s (McPherson, 2009). A minimum number of three measurements with results within 5% of each other are suggested. To ensure easy comparison of results, a 180-s data collection time was used with the ultrasonic anemometers. The collected data was then analyzed statistically to determine adequate sample sizes for different measurement conditions.

The rotating vane anemometer commonly used to measure air velocity in underground coal mines is known to suffer from erroneous readings in turbulent airflow. Also, vortex-shedding anemometers often used for fixed point measurements perform well in laminar flow only (Thimons & Kohler, 1985). For these reasons, ultrasonic anemometer performance in a highly turbulent airflow was tested. The required sample size was expected to be very different in such a case. Location 3, which was close to an opening used to run cables through a bulkhead, was chosen for these tests because it was expected to have an extremely turbulent airflow. All three ultrasonic anemometers were used for testing in location 3 (Figure 7).

Figure 7. Test Set-up at Location 3 with the 2-axis Instruments at Low Position.

Only two sample rates, 1 sample/s and 4 samples/s, were readily available for both 2-axis and 3-axis ultrasonic anemometers. Twelve tests were performed in location 1 with these two sample rates. Location 1 was chosen for these tests due to its similarity to typically-accepted underground velocity measurement locations. The obtained results were compared to define an appropriate sample rate for underground use.

Results

Statistical calculation was used to evaluate the required sample size. Adequate sample size was calculated by using the following equation:

$$n = \frac{\sigma^2 z_0^2}{e^2}$$

In which n is the desired sample size, z_0 is the z-value corresponding to the desired confidence, σ^2 is the population variance, and e is the maximum allowable error of estimate (Hoel, 1960). Confidence intervals of 95% and 98% with an error value of 0.01 were used to determine the sample size. An example data set from location 2 is shown in Figure 8.

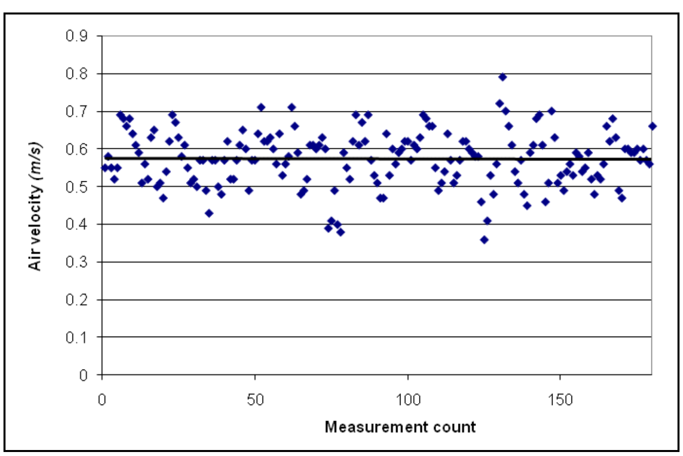

Figure 8. An Example Data Set from Location 2 Showing a Rather Stable Airflow and a Trendline.

The results showed that the smallest sample size was required for location 1 with a stable airflow. In that case, only 1 sample, taken in the middle of the airway, was sufficient to satisfy both confidence intervals, while two to six samples were required to reach 95% and 98% confidence intervals in the middle of the entry at location 2, respectively. However, when samples were taken close to the rib, the more turbulent airflow resulted in larger sample sizes: 2 to 9 samples for location 1 and up to 16 samples for location 2 were required.

On the other hand, calculations for location 3 with a turbulent airflow and a high air velocity showed extremely large sample sizes ranging from 9 to 1180, with most sizes falling between 200 and 550 samples. For the 3-axis instrument, fluctuating values for the vertical velocity component (W-values) also were observed.

The averages from the sample rate tests were calculated and then compared for both sample rates of 4 samples/s and 1 sample/s. The comparison showed that identical values were obtained with the 3-axis instrument. Also, the results were very close to each other when using the 2-axis instruments. The largest air velocity average difference over the cross-section was less than 3%. For turbulent airflow conditions, however, the faster sample rate of 4 samples/s is beneficial because it results in a shorter required measurement time, in that the same number of samples are gathered in one-fourth of the time.

CONCLUSIONS

Ultrasonic anemometers show tremendous potential to become an accurate air velocity measurement instrument for use in underground mining environments. There are several possible applications that can be considered such as integrating 3-axis instruments on mining machines, using hand-held instruments with displays for ventilation surveys, using intrinsically safe instruments in return airways, and using 2-axis instruments for continuous flow and direction monitoring in straight entries. This series of tests evaluated the impacts of obstructions, sample size, and sample collection rate on the ability of ultrasonic anemometers to accurately measure ventilation air velocities.

This study shows that the effects of moving obstructions are easily recognizable in continuous measurement data. If these types of changes are seen in data, the measurement location can be checked for unexpected activity. Also, the effects of stationary obstructions in a straight entry can be seen in the collected data set and found to correlate well with the cross-sectional area of the obstruction. The effects of stationary obstructions can be seen similarly in air velocity values recorded by vane anemometer traverses.

To achieve 95% and 98% confidence in the results, the required sample sizes when using 2 or 3-axis anemometers in a relatively straight airway (location 1) with a nearly stable airflow are surprisingly low. Only a few measurements are needed for an accurate air velocity value, assuming that the measurements are not taken too close to the rib. In the case of a less-than-optimal measurement location, 15 data points are recommended. With a typical sample rate of 1 sample/s, this standard results in a 15-s measurement time. In comparison to the recommended practice of a minimum of three 60-s traverses with rotating vane anemometer surveys, using an ultrasonic anemometer significantly shortens the required measurement times resulting in increased surveying efficiency.

In very turbulent airflow, accurate results require extremely large sample sizes, which are not necessarily feasible in an underground environment. If measurements have to be taken in such circumstances, long measurement times or continuous measurement stations are recommended for higher reliability of results. Location 3 with its turbulent airflow conditions required nearly 1180 samples which, at a rate of 1 sample/s, would result in a sample time of almost 20 minutes.

The typical sample rate of 1 sample/s is adequate and easily achievable for underground air velocity measurements. In comparison to the sample rate of 4 samples/s, the greatest difference in air velocity values was less than 3%. This is well below the 5% error value viewed as acceptable air velocity measurement error in an underground mine.

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