Piezoceramic Float Dust Deposition Meter: A Feasibility Study

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Abstract—The Bureau of Mines is exploring the possibility of designing a meter to measure the quantity of float dust deposited at various locations in a coal mine by using the change in the resonate frequency of a piezoceramic diaphragm. The results of the study have shown that dust deposited on a 0.9-in-diameter, 0.021-in-thick piezoceramic diaphragm with a natural frequency of about 2.5 kHz exhibits a linear frequency change of about 1 Hz for every mg/cm² of dust loaded on the diaphragm between 0 mg/cm² and 30 mg/cm² independent of the type of dust used (coal-dust or rock-dust), and 2 Hz/mg-cm⁻² between 30 mg/cm² and 100 mg/cm². The change from 1 Hz/mg-cm⁻² to 2 Hz/mg-cm⁻² at 30 mg/cm² is believed to be associated with a change in the contiguity of the dust deposit. Present results indicate that a float dust deposition meter based on this technology can measure dust loads to within ± 1 mg/cm² but cannot distinguish between the type of dust i.e., coal-dust or rock-dust.

INTRODUCTION

ONE OF the responsibilities of the U.S. Bureau of Mines is to conduct research toward making the Nation's underground coal mines safe. One of the many hazards associated with mining is related to the copious quantities of float coal dust[1] generated during coal cutting and handling operations. The large quantity of flammable coal dust deposited in mine entries is the primary reason coal mine explosions are so destructive.

Since removal of the coal dust by vacuuming the mine is uneconomical, current practice requires the mixing of the deposited coal dust with a flame inhibitor such as pulverized limestone, i.e., rock dust, to render it nonflammable. This requires the mine operator to periodically dust the mine with rock dust in sufficient quantities to ensure that the resulting coal dust-rock dust mixture is nonflammable. Most mine operators use machines that periodically dispense the pulverized rock dust into the ventilating air and deposit it on the coal mine surfaces.

Experiments at the Bureau's Pittsburgh, PA Research Center have established that to render a coal dust layer nonflammable, the total incombustible (ash, water, and rock dust) must constitute at least 80% by weight of the mixture. To determine the surface deposits of coal dust required to reach the lower flammability limit (50 mg/L) of coal dust when dispersed in air, the cross-sectional area of the mine entry must be considered. For example in a mine having a cross-sectional area similar to the Bureau's Experimental Mine, i.e., 54 ft², 9.0 mg/cm² of float coal dust will form a lower limit mixture with the air in the entry. Therefore, rock dusting would have to begin before the coal dust loading density reached 1 mg/cm² and could be stopped after the rock dust loading density reached 4 mg/cm². For economic reasons, the mine operator wants to operate as close to these two limits as possible. Too much rock dusting is expensive, and too little is hazardous. Other than taking a grab sample of the deposited dusts and sending it out for chemical analysis, there is no reliable means available for determining when to start and stop rock dusting. Presently, the mine operator determines when the rock dust-coal dust mixture is safe by observing the grayness of the dust surface layer. The purpose of this investigation is to determine the feasibility of using the change in frequency of a resonant diaphragm with dust loading to measure surface mass loading and establish the appropriate design parameters for the construction of a float dust deposition meter for use in coal mines. The change in frequency of piezoelectric quartz crystals with surface load has been used in the chemical industry to measure both microscopic dust deposits and chemical vapor detectors [1]. In the latter case the electrode region of the crystal surface is coated with a material that soaks up the vapor from the environment. An increase in the coating mass due to solution decreases the frequency of the crystal.

Apparatus

This particular research concerns the use of a horizontally positioned resonantly-driven piezoceramic diaphragm to measure the loading density of either coal dust or rock dust by measuring the decrease in the diaphragm's resonant frequency with increased mass deposited on the piezoceramic diaphragm. Fig. 1 shows the Electric Products, Inc. model 104-FB-00[2] piezoceramic diaphragm used in this study, and Fig. 2 shows the clear plastic holder for securely clamping the diaphragm. The annulus at which the diaphragm is clamped corresponds to the nodal ring for the diaphragm's fundamental resonate frequency which, for the diaphragm used in these studies, corresponds to about 2.5 kHz. Fig. 3 shows the circuit used for driving the diaphragm at its resonant frequency.

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[1] Float coal dust by definition is particles less than 75 μm in diameter.

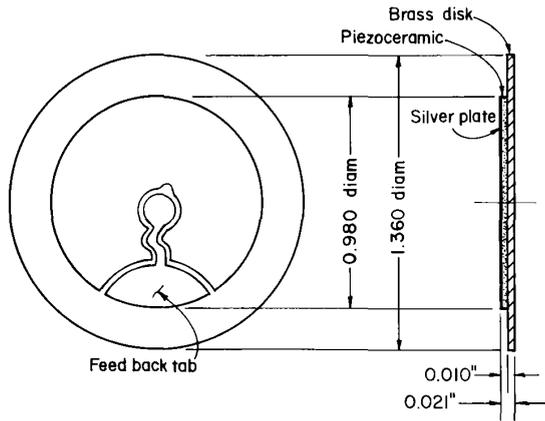[2] Reference to specific products does not imply endorsement by the Bureau of Mines.
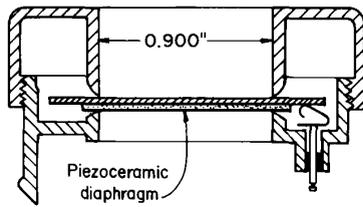
Fig. 1.   Piezoceramic diaphragm.

Fig. 2.   Plastic holder for piezoceramic diaphragm.
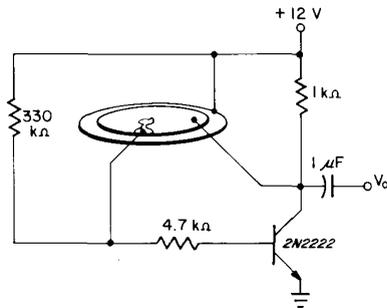
Fig. 3.   Circuit used to drive piezoceramic diaphragm at its resonate frequency.

Fig. 4.   Spectral response of piezoceramic diaphragm.

Fig. 5.   Circuit used to measure the shift in diaphragms resonate frequency with dust loading.

Fig. 6.   Typical heterodyne wave form.

frequency meter measures this difference frequency to the nearest 1 Hz.

Materials

The coal dust used in this study was prepared from bulk coal taken from the Pittsburgh coal seam; it was ground, sieved, passed through a 200-mesh (74 μm) screen, and stored in 5-gal steel drums. The rock dust used was obtained from a commercial source in which 80 wt pct of the particles were less than 74 μm. Particle size distribution of these two dusts was measured with a Coulter counter and by sonic seizing [2]. The surface weighted mean diameter [3] of coal dust calculated from these distributions is about 30 μm. The volatility of the Pittsburgh coal is 37 wt pct, the moisture is 2 wt pct, the ash is 6 wt pct, and the fixed carbon is 50 wt pct as measured by the standard ASTM [4] method. The rock dust has a surface weighted mean diameter of 5 μm.

Procedures and Results

To conduct an experiment, the unit was powered up, and the difference frequency for an unloaded diaphragm was recorded. Fig. 6 shows a typical heterodyne waveform for the unloaded pair of diaphragms. The beat frequency resulting from the diaphragms having slightly different frequencies, 2,429 Hz and 2678 Hz in this case, is very evident in the

Under the diaphragm is a resonant cavity, which, according to the manufacturer, is designed to increase the audio output of the unit. This is certainly a desirable feature when the unit is used for the purposes that the manufacturer intended, i.e., generating audible alarms, however, it may not be a desirable feature for the purposes for which it is being used in this study-this point remains to be explored. Fig. 4 shows the manufacturer's reported acoustical spectral response of the diaphragm mounted in the holder shown in Fig. 2.

To measure the change in frequency with dust loading and simultaneously provide temperature compensation (the diaphragm's resonant frequency changes with environmental temperature), a heterodyne configuration was used employing two units similar to that shown in Fig. 2. Fig. 5 shows the schematic for the complete circuit. The operational amplifier (mixer) generates the heterodyne signal, the low-pass active filter (3-dB cutoff frequency at 1 kHz, and a 6-dB bandwidth at 400 Hz) extracts the difference frequency component, and the
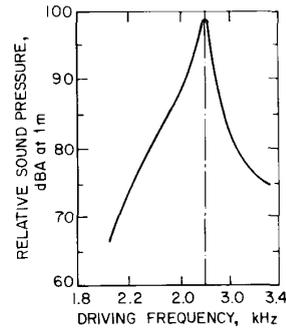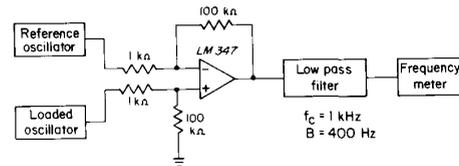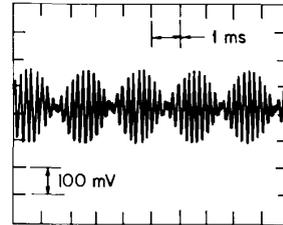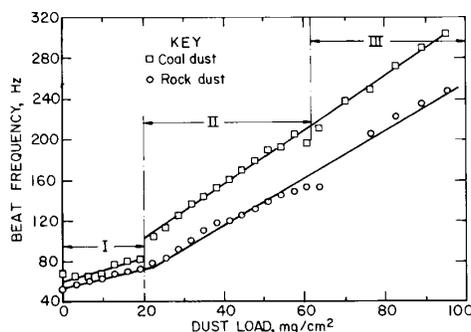
Fig. 7. Shift in diaphragm resonate frequency (beat frequency) of hetero-
dyne as function of dust loading.

figure. While the unit remained powered, dust in 1.8-mg increments (weighted to the nearest 0.1 mg) was sprinkled on the top of the test oscillator diaphragm; about 10 min was allowed between additions to establish equilibrium before the difference frequency was recorded. No measurable change in this frequency was observed after 10 min. The 10-min equilibration process is apparently associated with the redistribution of the dust over the surface of the vibrating diaphragm. Although the dust layer appeared contiguous, microjets of dust could be seen erupting from the surface at the rate of two or three/s. The mass increments of dust were added to the diaphragm until the oscillation stopped (usually near 100 mg/cm^2). Fig. 7 shows a plot of these measurements. The same diaphragm was used for all the runs and was carefully cleaned of any residual dust before each experiment. Initially, i.e., up to a loading of approximately 20 mg/cm^2, the frequency response shows the same slope of ≈ 1 Hz/mg-cm^2 for both types of dust. Above 20 mg/cm^2, the responses for the two dusts are obviously different and the line slopes are statistically not equal. The frequency response is 2.6 $\pm$ 0.1 Hz/mg-cm^2 for coal dust and 2.3 $\pm$ 0.1 Hz/mg-cm^2 for rock dust. At about 100 mg/cm^2, the load on the diaphragm becomes sufficient to stop vibration. It was found that the oscillatory range of the diaphragm could be extended by increasing the power to the diaphragm (by increasing the supply voltage); however, this is presently of no particular interest to this research.

The data suggest that there are three phases of operation (I, II, and III in Fig. 7). There is an obvious and abrupt change in the oscillatory behavior of the loaded diaphragm at 20 mg/cm^2 and possibly another, although less obvious, change near 60 mg/cm^2. In the latter case there does not appear to be a change in the slope of the curve. It is assumed that these changes are associated with a change in the mode of the diaphragms oscillation, although it could also be influenced by the changing characteristics, such as the porosity, of the dust layer with increasing load. Furthermore the device exhibits mild instability in the 0 to 20-mg/cm^2 range, although it is stable between 20 and 60 mg/cm^2. It is therefore desirable, in designing a dust deposition meter using this concept, to force the diaphragm to oscillate in the phase II region. Apparently, this will require preloading the diaphragm by coating it with a thin contiguous film equivalent to a 20-mg/cm^2 load, to get it

to start oscillating in the phase II region. Since the slope of two curves corresponds to a frequency shift of about 2 Hz/mg-cm^2, to construct a meter capable of accurately measuring dust loads to within ± 1 mg/cm^2, it is necessary to target the meter design to resolve surface dust loads to ± 0.1 mg/cm^2 or equivalent frequency shifts to within ± 0.2 Hz. However, even under the best conditions using the present apparatus, the minimal error in the loading density will be only 0.25 mg/cm^2 at a 95% confidence. Additional studies are in progress to determine if this minimal error can be further reduced, possibly by increasing the sensitivity of the diaphragm.

Conclusion

From these preliminary studies, the technique of using a self-resonant piezoceramic diaphragm to measure dust deposition loadings below 100 mg/cm^2 appears feasible. Since the lower explosive limit for coal dust-air mixtures is 50 mg/L, corresponding to a surface dust loading (for a typical mine cross section) of 10 mg/cm^2, a meter with an accuracy of 0.1 mg/cm^2 should be adequate for the detection of a hazardous accumulation of float coal dust. Unfortunately, the ultimate resolution of the present equipment appears to be near 0.25 mg/cm^2; although this is marginally adequate, an improvement in accuracy should be possible with hardware design modifications. Future work will be directed to designing a meter based on the results of this study and to extending this research to examine the physics of dust layers deposited on vibrating surfaces in more detail.

References

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