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Wireless real-time sensing platform using vibrating wire-based geotechnical sensor for underground coal mines

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ABSTRACT

Continuous, real-time and remote measurement of stress in underground coal mines plays a vital role in the safety of the mines. Vibrating wire-based geotechnical sensors are widely used for stress measurement of strata in underground coal mines. These types of sensors have several advantages over other geotechnical sensors. However, the measurements from these sensors are taken in-situ using conventional readout unit manually till date even in the case of deep underground coal mines where the depth of cover is more than 300 m. When sensor site moves to inaccessible places due to dynamic nature of mining, then the measurement is discontinued and instruments become abandoned. Also, sensors connected through wire get disconnected during movement of machinery, roof falls, and other associated hazards. Therefore, there is a need for wireless sensing platform for vibrating wire-based geotechnical sensors which can assess the stress on a real-time basis and obviate the impending mishap associated with the strata failure. Hence, in the present paper, authors have designed a prototype wireless real-time sensing platform for vibrating wire-based geotechnical sensors for continuous, real-time and remote monitoring of strata behavior. The laboratory trial and the field demonstration of the same have been carried out and compared with conventional readout. The results are in agreement.

1. Introduction

Underground coal mining by its inherent features is perilous in nature. The dynamic nature of coal mining may disturb the overburden strata and the surface area above the mine; resulting in a continuous change of different geotechnical parameters. Moreover, underground coal mining operations are becoming more difficult day by day due to adverse geo-mining conditions; like winning of thick as well as complex deposits, winning of seams under surface/sub-surface constraints, increasing the depth of mining, etc. [1]. The hazardous situation of underground mining demands continuous, real-time and remote observation of strata in and around the working for the safety of mine and miner. Strata control is a vital part of successful implementation of a mining method during underground extraction of coal seams. Measurement of mining-induced stress is one of the most important parameters for strata control [2,3]. The redistribution of stress over the pillars during underground mining is monitored with the help of stress meters. The trend and pattern of redistribution of stress in the rock mass/coal around an excavation are monitored in terms of the changes in stress levels. The study of mining-induced stress developed over the pillars for the varying dimension of excavation becomes an important issue to understand the interaction between the natural support like pillars and overlying strata during mining [4]. However, if the stress coming from the roof on the pillars exceeds its strength, the pillars fail; leading to failure of roof strata, and potentially resulting in an accident due to spalling, roof fall and/or crushing of pillars [5]. Continuous, online and remote monitoring of strata permit real-time detection of changing ground conditions during mining and an immediate response to any impending ground control hazard [6]. With usual method of instrumentation, readings are taken in hours, shifts or days, which fail to evaluate the limiting or strategic values. Thus, suitable guidelines with respect to the safety of the workers and the workings cannot be framed.

In underground coal mines, the vibrating wire (VW) based geotechnical sensors are commonly used for measuring the stress on the strata. These types of sensors have several advantages over other geotechnical sensors which are primarily used in underground mines. In general, geotechnical sensors are based on following four principles: i) Linear variable differential transformer (LVDT), ii) Strain gauge, iii) Resonant/variable resistance, and iv)

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Vibrating wire [1]. LVDT, strain gauge and resonant types of sensors have an analog output, whereas VW based geotechnical sensors provide output in terms of frequency and, therefore, there is less dilapidation of the signal. It is easy to transmit the output of the VW based sensors i.e. frequency to a remote and safe place without much noise and distortion. LVDT is an inductive transducer which is sensitive to stray magnetic fields and requires a setup to protect them. Further, the strain gauge and resonant sensors operate on the basis of the change in internal resistance. These sensors have a temperature effect due to their small size [7]. Therefore, the most appropriate solution turns out to be VW based geotechnical sensors for monitoring of strata behavior, due to not only its ease of installation and cost effectiveness but also reliability, endurance, lesser drift, and stability [8–10]. However, despite increasing depth of underground mine excavations, in-situ measurements are performed manually through these sensors by conventional readout unit till date. Further, depending upon the strata condition, the measurements are taken either shift wise or with a time interval. The time gap between the measurements can pose an impending strata failure because of the stress developed on the roof and pillar due to the continuous excavation of coal, which puts the miners and personnel in trouble. When sensor location moves to inaccessible places due to dynamic nature of mining, then the measurement discontinue and instruments become abandoned. Also, the sensors connected through wire get disconnected during movement of machinery, roof fall, and other associated hazards [11]. Therefore, in the present paper, attempts have been made to develop a prototype wireless real-time sensing platform using VW based geotechnical sensors for data transmission from strategic locations of an underground coal mine to a remote and safer place for continuous monitoring of strata behavior to ensure the safety of the mines and miners. The modules for exciting the VW and counting the resonant frequency (output) before and after applying stress are completely programming based. The laboratory trial and the field demonstrations of the same have been carried out as well. The results obtained during the trials are compared with the results obtained from the conventional readout units to show the effectiveness of the developed system, which is also presented in this paper.

2. Overview of vibrating wire-based geotechnical sensor

VW based geotechnical sensor measures stress exerted by the strata during extraction of coal. It mainly consists of a tensioned steel wire that vibrates initially at its natural frequency (without stress) and then at a varying frequency when stress is applied. This wire is hermetically sealed and is coupled with an electromagnetic coil and anchored diametrically across a robust hollow metallic cylinder. The stress meter is easily embedded in rock mass through a hole and wedge-platen system, fastened in a simple mechanical setting tool unit. The changes in rock stresses enforce the change in load over sensor body causing the body to deflect. This deflection is noted as a change in tension and the resonant frequency of vibration of the vibrating wire element. A plucking coil and a magnet assembly, located close to the tensioned wire as shown in Fig. 1, are used to excite the wire and to sense the resultant frequency of vibration with the help of readout unit. It also consists of a sensor cable which is mainly used i) to excite the vibrating wire, and ii) to obtain the output signal in terms of resonant frequency. The natural frequency of vibrating wire changes due to change in length of wire while stress is applied and is given as [12–14]:

$$f = \frac{1}{2L}\sqrt{\frac{\sigma}{\rho}} = \frac{1}{2L}\sqrt{\frac{E\varepsilon g}{\rho}} \quad (1)$$

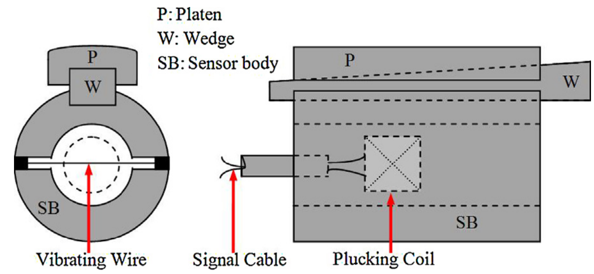

Fig. 1. VW based sensor's cross-sectional and side view.

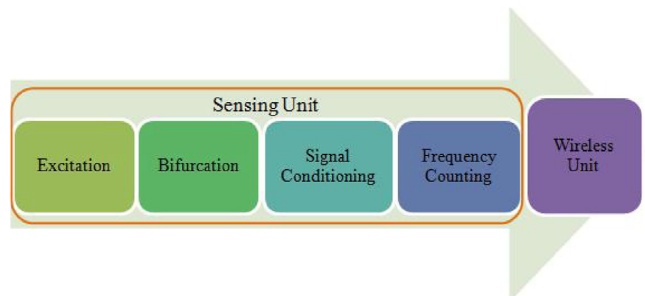

Fig. 2. Block diagram of VW based wireless sensing platform.

Where f = natural frequency of the wire, L = length of wire, σ = stress, ρ = mass density, E = modulus of elasticity, ε = strain of wire, and g = gravitational acceleration.

Change of stress in the rock causes a small change in the diameter of the gauge cylinder which results in the elongation or compression of vibrating wire. These changes are measured in terms of the change in the frequency of vibrations as shown in (1). The stress change from σ1 to σ2 is related to this frequency as follows [15]:

$$\sigma_1 - \sigma_2 = \frac{4\left(f_1^2 - f_2^2\right) L^2 \rho \alpha}{g} = k\left(f_1^2 - f_2^2\right) \quad (2)$$

Where, f_1 = natural frequency of VW at σ_1 stress level, f_2 = natural frequency of VW at σ_2 stress level, L = wire length, ρ = density of the wire material, g = acceleration due to gravity, α = calibration constant, and k = gauge factor.

3. Design of wireless sensing platform

In the present development, the VW based wireless sensing platform consists of two sub-units a) sensing unit and b) wireless communication unit (Fig. 2). The sensing unit consists of four sub-modules for different functions such as excitation, bifurcation, signal conditioning, and counting of the resonant frequency.

The excitation module mainly consists of microcontroller board designed and developed by authors (Fig. 3) which mainly comprises of microcontroller IC of Atmel family, diode safety barriers and protection fuse to prevent against the breakthrough of dangerous voltages in hazardous area, and the sockets available for the transceivers (such as XBee series/nRF family).

It has been observed that the frequency of the VW based sensors for monitoring the strata of an underground coal mine mostly varies up to 6 kHz. Therefore, the excitation module excites the VW by sending a group of frequencies starting from the lowest frequency i.e. 50 Hz to the highest frequency i.e. 6 kHz with a definite group interval of 50 Hz generated by programmable microcontroller board instead of triggering by electric power/single frequency or by an RC circuit as done by earlier workers [16,17].

When the natural frequency of the VW based sensor matches with the frequency being applied then the resonance phenomenon