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Performance Analysis of Blast-Induced Ground Vibration Measuring Sensors at Low-Frequency Excitation

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Abstract

Measurement of ground vibration due to blasting is a mandatory practice in Indian surface mines. Three dominant sensors, namely Piezoelectric Accelerometers (PA), Micro-Electro-Mechanical Systems (MEMS) accelerometers and electro-magnetic Geophone, are, in general, used to measure the oscillation of the ground and thus record information related to the parameters associated with ground vibration. A controlled laboratory-based vibrational analysis is carried out with the help of a shaker table using a MEMS-based accelerometer and an electromagnetic-based Geophone at excitation signals of 3 Hz, 10 Hz, and 30 Hz frequencies. The excitation velocity for each frequency signal varies between 3 mm/s to 60 mm/s. The sensor's response, as output voltage, is found to vary from 10 mV to 400 mV for MEMS accelerometers and from 10 mV to 1600 mV for electromagnetic geophones. Deviation in the sensors' response in these frequencies is studied along with statistical analysis. The results revealed that the sensors responded properly above a certain excitation signal frequency. At lower frequencies, the response of the sensors is found to be inconsistent and affected by noise. For all the sensors, improved responses are observed with increasing frequency and peak amplitudes. Irrespective of various input amplitude velocities, the sensitivity remained constant for each fixed frequency; however, it increased proportionately with the rise in frequencies. In regression analysis, the geophone was proved to be more consistent than the MEMS accelerometer.

Keywords: *Accelerometer, Blast Vibration, Frequency Signal, Geophone, MEMS, Sensor Performance*

1.0 Introduction

Blasting is considered to be one of the most vital unit operations of the mining industry. It is the detonation of explosives, which fragments the rock mass into smaller sizes. Apart from the release of hot, dense, high-pressure gas, explosive detonation involves the uncontrollable release of shock energy that propagates as a shock wave outward and is called seismic or vibration waves resulting in ground vibration. Thus, ground vibration is an unavoidable effect of blasting. Due to fast-growing urbanisation, inhabitancy approaches at the proximity of the mines, along with the construction of household, office and other utility structures. Blast-induced ground vibration comprises frequencies ranging between 1 and 200 Hz and thus may become the prime reason for damage to nearby buildings and structures. Residents often complain about visible cracks found in their buildings and claim the blasting to be the prime reason. Hence, to prevent such claims and lawsuits and avoid any structure damage, measurement of ground vibration is needed on a day-to-day basis. Regular vibration monitoring also helps competent authorities monitor several aspects, namely, properties of rocks, structural and machine health conditions, human exposure to vibration dose, and environmental elements, all of which are done with the help of sensors. In this context, constant efforts are being made to improve the performance and efficiency of the sensors to meet versatile requirements at their best. As the types of sensors required are influenced by

their use in various fields, profound research on sensors deployed for measuring blast-induced ground vibration is felt essential to assemble accurate information about the frequency, magnitude and other important parameters associated with ground vibration. This study investigates the performance of geophone sensors and MEMS accelerometer sensors in terms of the response of the sensors concerning changes in frequency and amplitude and also presents a comparative analysis of the same.

1. Present Status

Two dominant sensors are mostly used to measure vibrations. One is a geophone sensor (electromagnetic-based), and the other one is an accelerometer (uniaxial/triaxial, piezo-based/MEMS-based). The responses of these sensors depend on their dynamic and electrical properties, which decide the domain of use in different fields. Significant research has been done to improve the sensitivity, resolution and frequency response of the sensors. Moreover, data retrieval is one of the important steps in any vibration-related study. For this, the use of appropriate data acquisition and analysis of the data becomes a challenging aspect.

Gabrielson (1993)[1] presented an equation to determine the Signal Noise Ratio (SNR) of a generic accelerometer sensor system for measuring the lowest detectable acceleration signal as given below -.

$$\text{SNR} = \frac{a^2 mQ}{4k_B T w_0} \quad (1)$$

where a = input acceleration in m s^{-2},
m = seismic mass in kg,
Q = quality factor of the sensor system
k_B = Boltzmann constant = $1.38064852 \times 10^{-23}$ m^2 kg s^{-2} K^{-1},
T = absolute temperature in K,
w_0 = resonance frequency in Hz.

For setting SNR to be 1, the input acceleration becomes,

$$a = \sqrt{\frac{4Tw_0k_B}{mQ}} \quad (2)$$

A similar statement was also proposed by Scheeper (1996)[2], which is that the minimum detectable acceleration can be determined by the mechanical-thermal noise of an accelerometer. Neimirovsky (1996)[3] designed a thin film Lead Zirconate Titanate (PZT) piezoelectric accelerometer and compared its performance with piezo-resistive and capacitive sensing accelerometers. PZT accelerometers showed a wide frequency response of up to 200 kHz (approx.) and a low-frequency response of 1 Hz or lower, along with a wide temperature range of up to 300°C. The calculated sensitivity was about 300mV/g, which was high, linear and independent of the dimensions of the piezoelectric material. Enhancement in the performance of a Geophone was accomplished by Bazilai *et al.* (1998)[4] through the measurement of proof mass displacement capacitively with the closed loop system. The advantage of this method is that it achieves improved low-frequency noise and wider bandwidth. The response of piezoelectric ceramic powder subjected to vibration of different frequencies at a set magnitude was studied by J. E. Holmes *et al.* (2000)[5]. The experimental set-up used was an electromagnetic shaker table driven by an analogue signal generated by a computer via a linear amplifier. A calibrated accelerometer was used to monitor vibrations. The output from the device under test was passed through an Analog Digital Converter (ADC) after proper amplification and filtration. It was found that the piezoelectric structure under test needs more optimization to allow it to respond the same as a moving coil geophone. Kim and Lee (2000)[6] studied the propagation and attenuation of various ground vibrations. It is stated that being a system with a single degree of freedom, a velocity transducer has a natural frequency, and the response becomes nonlinear at lower frequencies. Due to this, calibration is needed for voltage output with frequency[7]. A data acquisition system comprising vertical and horizontal geophones of 4.5 Hz standard frequency, data recording system and signal processing was used by M. Crispino *et al.* (2001)[8] to carry out data analysis. Tools used were – (i) Fourier Transform, (ii) Correction by the instrument calibration curve, (iii) integration/derivation in the frequency domain and (iv) inverse transform for arriving at a time history of acceleration/velocity/displacement. Chmielewski, Tadeusz, *et al.* (2005)[9] used high-sensitivity geophones that measured vibration velocities of tall industrial chimneys due to weak wind down to 0.2 Hz of frequencies.

The main technical specifications that help to decide the use of accelerometers were described in a comparative study of Integrated Circuit Piezoelectric (ICP)

accelerometers (Jyoti K. Sinha, 2005)[10]. The specifications should include –

"(a) Sensitivity, which relates the electrical signal [often expressed in Voltage (V)] to the amplitude of vibration in acceleration;

(b) Frequency range in which vibration measurement is useful.

(c) Amplitude limit that specifies the maximum range of acceleration that can be measured accurately.

(d) Shock limit is the maximum level of acceleration that the accelerometer can withstand without any damage.

(e) Linearity is the accuracy of the measured acceleration amplitude in the measuring Frequency range.

(f) Natural frequency, which is indirectly indicative of the measuring frequency range. The higher the natural frequency of an accelerometer, the larger the measuring frequency range in general."10

On subjecting the accelerometers to different kinds of excitations, it was found that all the accelerometers responded similarly with an error of 2 per cent when excited by sinusoidal inputs but did not respond accurately to impulse and random inputs. S. Thanagasundram (2006)[11] studied the performance of a MEMS accelerometer (ADXL105) with an ICP-type accelerometer (Bruel and Kjaer Piezo). The following formula was used to calculate Noise (N) (rms – root mean square)[12],

$$N = 225 \times \sqrt{K \times B} \text{ in } \mu g Hz^{-1/2} \quad (3)$$

where K = constant depending on the poles of the filter used,

B = frequency range of ADXL105 in Hz.

The noise level of the MEMS accelerometer was found to be 16 times greater than that of the ICP accelerometer, limiting its use in the detection of small values of acceleration. The sensitivity of the MEMS accelerometer is stated to be invariant with a temperature of about ± 1 per cent changes over the -40°C to + 85°C temperature range, whereas PA varied about ± 10 percent[13]. X. Meng *et al.* (2007)[14] stated that most accelerometers cannot measure low frequency accurately but are highly efficient in the measurement of high-frequency one. G.G.U Aldas *et al.* (2008)[15] proposed a new data acquisition system where two seismometers are combined with radio telecommunication units to give external triggering so that two seismometers start recording signals simultaneously in blast-induced ground vibration measurement. A software program for filtering signals, velocity measurements and delay were used. A bandpass filter was used to remove the mean or DC component in the lower frequencies. The surface wave velocities were calculated, and time delays between blast holes were adjusted by the delay program. A. Albarbar (2009)[16] evaluated the performance of a MEMS accelerometer and compared the results with a well-known commercial accelerometer. MEMS accelerometers performed well with shifts in phase for sinusoidal and random measurements. The frequency peak content was found to be the same as that of the conventional accelerometers. Liu Zhen–Dhong *et al.* (2012)[17] did detailed research on two types of geophones – a moving coil velocity and a piezoelectric acceleration type. A comparative analysis of velocity, acceleration and frequency response was carried out by using their frequency response function. The frequency response function used was as:

a) Piezoelectric acceleration geophones

$$H(j\omega) = \frac{X_o(\omega)}{A(\omega)} = \frac{1}{\omega_o{}^2} * \frac{-1}{\left[1-\left(\frac{\omega}{\omega_o}\right)^2+2j\zeta\left(\frac{\omega}{\omega_o}\right)\right]} \quad (4)$$

b) Electro-magnetic Induction moving coil velocity geophone

$$H(j\omega) = \frac{X_o(j\omega)}{\dot{X}_i(j\omega)} = \frac{\left(\frac{\omega}{\omega_o}\right)^2}{\left[1-\left(\frac{\omega}{\omega_o}\right)^2+2j\zeta\left(\frac{\omega}{\omega_o}\right)\right]} \quad (5)$$

where, $X_o(\omega)$ = Fourier transform of deformation (output) from the sensitive elements,

$A(\omega)$ = Fourier transform of vibration acceleration (input),

$X_o(j\omega)$ = Fourier transform of the relative movement velocity (output) of the inertia mass,

$\dot{X}_i(j\omega)$ = Fourier transform of the movement velocity (input),

ζ = critical damping ratio,

ω_o = natural frequency.

"The results show that the acceleration signal from the acceleration geophone has a better advantage in terms of high Signal-to-Noise Ratio (SNR), high accuracy, high resolution, and quantity of information"[17]

2.0 Experimentation and Analysis

A laboratory setup consisting of a Shaker Table, Data Acquisition System, and Signal Generator was used for the experimentation, as shown in Figure 1. The salient features of the experimental setup are given in Table 1. Two different types of sensors, namely MEMS-based ADXL335 accelerometer and HG-24 HS geophone, are used to generate data. The important characteristics of both the sensors are listed in Table 2. Both the sensors are mounted together on the shaker table and subjected to sinusoidal excitations at 3, 10, and 30 Hz frequencies to ensure equal and simultaneous excitations for both sensors. The experiment repeats for five to six peak amplitudes at each frequency of excitation. All the experiments are carried out for excitation towards the vertical direction. The shaker table, also used as a Geophone calibration table, gives a calibrated output in the unit of mm/sec displayed in the Geophone Master Unit (GMU) at 3 Hz, 10 Hz, and 30 Hz frequencies for vertical directions. The response of the sensors (in the form of voltage) is recorded in a Digital Storage Oscilloscope (DSO) at specified recording time and sample rate.

Altogether, eighteen sets of experiments are carried out with varying combinations of peak amplitudes and frequencies. The sample waveform obtained from geophone and MEMS sensors are shown in Figure 2. The recorded data are analyzed to observe the change in the sensor response with the variation in frequency and peak amplitude of the excitation. It is found that the minimum excitation velocity at which the sensors responded consistently decreased with increasing frequency. A positive correlation is also observed between the sensors' excitation velocity and voltage generation, as shown in Figure 3 and Figure 4. It is also observed that the output voltage increases with the increase in excitation frequency. The regression analysis (Table 3), shows a linear dependency model between the excitation velocity and output voltage of the sensors at individual frequencies. Analyzing the slope of the individual linear models, it can be inferred that, with increased frequency, the proportionate change in the output voltage concerning excitation velocity is increased. The sensitivity of the sensors, expressed as a ratio of output voltage and input excitation velocity[10] are analyzed for varying frequency and amplitude. It is found that the sensor's sensitivity increases with the increase in frequency, exhibiting a high pass nature of the sensor system. The same is presented in Figure 5, Figure 6 and Table 4.

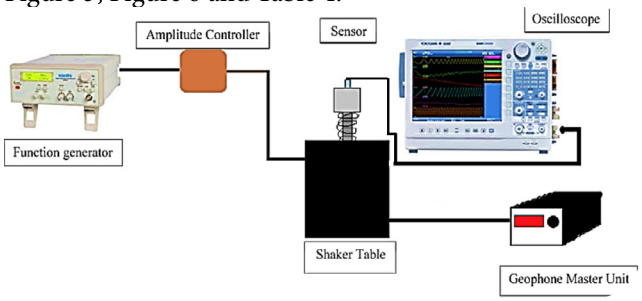


Figure 1. Laboratory experimental set-up.

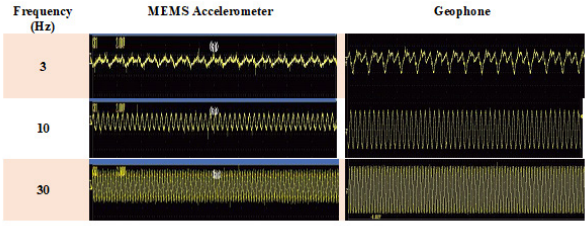


Figure 2. Waveforms in 3, 10, and 30 Hz excited at 59 mm/sec input velocity.

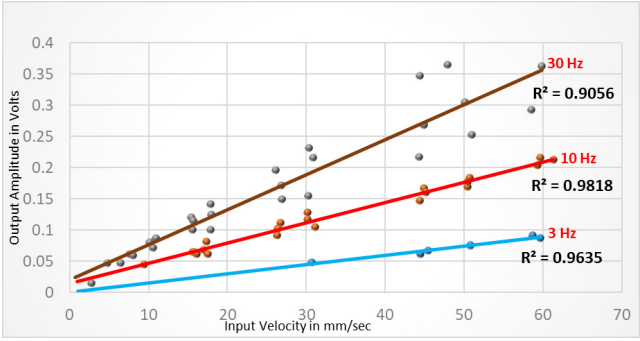


Figure 3. Output as peak amplitude voltage for varying excitation velocity in ADXL335.

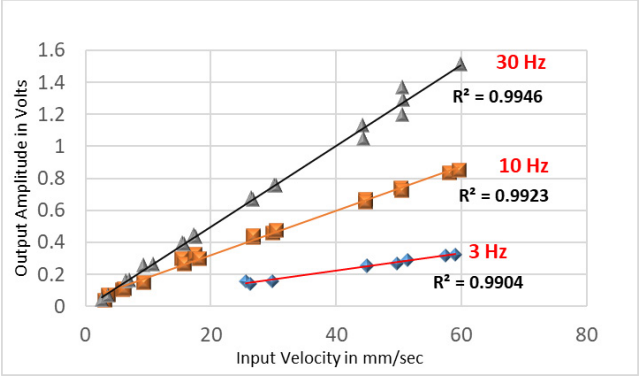


Figure 4. Output amplitude voltage for varying excitation velocity in HG-24 HS geophone.

Table 1. Specification of the instruments used in the study

Equipment	Function
Shaker Table	A vibrating table. Sensors under test are kept on the metallic table and subjected to vibration when acted upon by inputs.
Function Generator	Provides frequencies between 0.2 Hz and 3 MHz with varying amplitude of different types of inputs including Triangular, sinusoidal, Square and DC.
Digital Storage Oscilloscope (DSO)	A highly sensitive data acquisition system for recording and retrieving data along with inbuilt mathematical functions.

Table 2. Technical specification of sensors

MEMS Accelerometer		GEOPHONE	
Parameter (Units)	**Value**	**Parameters (Units)**	**Value**
Measurement Range (g)	±3.6	Natural Frequency (Hz)	10
Sensitivity (mv/g)	300	Sensitivity (V/mm/sec)	85.8
Bandwidth (Hz)	X, Y = 1600, Z = 550	Spurious Frequency (Hz)	>240
Cross-axis sensitivity (%)	±1	Damping Tolerance (%)	±3.5
Noise Density (μg/Hz$^{-1/2}$)	150	Moving Mass (gm)	11.8

Table 3. Linear dependency models for sensors at different excitation conditions

Frequency (Hz)	Accelerometer		Geophone	
	Regression Equation	R^2	Regression Equation	R^2
3	y = 0.0015x – 0.00002	0.9635	y = 0.0055x + 0.0032	0.9904
10	y = 0.0033x + 0.0143	0.9818	y = 0.0139x + 0.0428	0.9923
30	y = 0.0056x + 0.0208	0.9056	y = 0.0253x – 0.0073	0.9946

Table 4. Details of Sensitivity calculation for various input excitation velocities

Frequency (Hz)	Accelerometer		Geophone	
	Sensitivity (V/mm/sec)	Variance	Sensitivity (V/mm/sec)	Variance
3	0.001484697	4.033E-09	0.005573	5.492E-08
10	0.003803317	1.717E^{-07}	0.016332	4.215E-06
30	0.00679573	1.447E-06	0.0244	6.008E-06

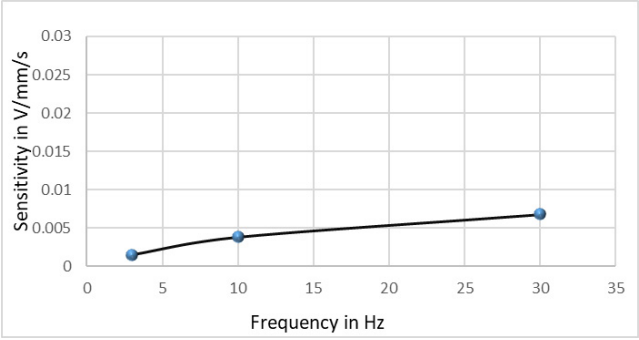


Figure 5. Sensitivity of ADXL335 sensor at different frequencies.

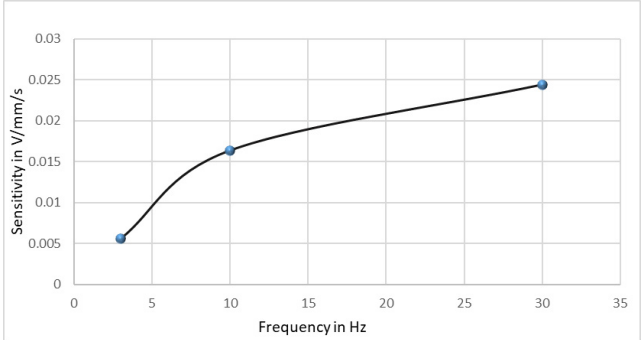


Figure 6. Sensitivity of HG-24 HS sensor at different frequencies.

3.0 Conclusions

This experiment aimed to analyze the performance of two types of sensors at excitation velocities varying concerning peak amplitudes and frequencies. The experimentation is carried out for 3, 10, and 30 Hz frequencies with varying excitation velocities ranging between 5 mm/sec to 60 mm/sec. The analysis of the waveforms for varying frequencies and exciting velocities reveals that the sensors' responses are poor with lower frequencies and amplitudes. The increment in output amplitude voltage of the sensor is dependent on the frequency of excitation, and the sensor response becomes consistent at higher frequencies. Apart from this, a strong coefficient of determination of the geophone sensors makes its response more accurate than MEMS-based accelerometers. Moreover, at the fixed frequency, the sensitivity, which relates the sensor's output to its input, is constant for various input excitation velocities for both accelerometer and geophone sensors and increases with increasing frequency.

Therefore, the selection of a vibration-measuring sensor is important, and the performance appraisal must be made prior to adopting the sensor. Commercial sensors often lack the performance guaranteed by suppliers. The linear dependency models should be established while the vibration measuring devices are designed.

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