Signal Processing Computation based Seismic Energy Estimation of Blast induced Ground Vibration Waves

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***Abstract*—Study of ground vibrations resulted from blasting operations in mines and quarries is significant ecological aspect. In general, very lesser amount of explosive energy will be utilized in blasting process for breakage and creation of fragmentation, however the remaining will be squandered in the form of shock waves. Shock waves resulted from blasting operations cannot be entirely abolished, nonetheless can be lessened to the extent possible using an appropriate blasting methodology. Substantial work has been performed to detect ground vibrations for assessing the blast performance using the intensity of ground vibrations. Nevertheless, not much research has carried in the estimation of seismic energy and utilizing this energy for assessing the performance of blast rounds. In this paper, a Signal Processing based technique for the estimation of seismic energy dissipated at various distances is proposed. In total, 116 blast vibration events from Limestone Mines, 96 blast vibration events from Underground Coal Mine and 43 blast vibration events from Sandstone Mines were collected and respective signal processing analysis was carried out using Advanced Blastware and DADiSP software. Each vibration event in one direction carries about 2500 particle motion samples.**

Keywords—*Blast Vibrations, Seismic Energy, Signal Processing Approach, DADiSP, Advanced Blastware, Discrete Fourier Transformation (DFT), Power Spectrum Density, Angular Momentum, Rotational Kinetic Energy*

I. Introduction

When the explosive charge detonates in a blasthole under confinement, the chemical form of explosive energy is converted into gases and work to the surroundings with an enormous pressure according to the first principle of thermodynamics. Explosion of a spherical charge in an infinite rock medium result in three major zones (Fig. 1): (1) Explosion cavity - where explosion energy is liberated and the process is hydrodynamic; (2) Transition zone - where plastic flow, crushing and cracking occur; and (3) Seismic zone - where strain waves travel as seismic waves [4][7][9].

The partition of the explosive energy in a blast depends on the end effects involved. For instance, part of the fracture work is in its first stage intimately connected to the shock wave flow in the locality of the hole and, in the later stages, also to the rock movement, which begins as the fractures burst open. All other energy transfer takes place obviously, as follows: (a) expansion work of the fractures, that is absorbed as elastic and plastic deformation of the rock in the surface of the fractures as they are penetrated by the gases; (b) heat transferred to the rock from the hot detonation products; and (c) heat and work conveyed as enthalpy of the gases venting to the atmosphere through open fractures and stemming [8].

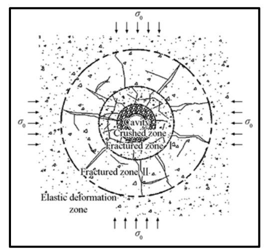

Fig. 1 Zones of rock deformation around a blasthole [4]

Therefore, the energy balance of the blast can thus be expressed by:

$$EE = EF + ES + EK + ENM$$

where,

EE	=	Explosive energy
EF	=	Fragmentation energy
ES	=	Seismic energy
EK	=	Kinetic energy
ENM	=	Energy forms not measured

Research studies carried out have indicated that in opencast mines there is a potential of seismic energy generation from 2-13J from a given blast. Also studies have indicated possible correlation between maximum charge per delay and the seismic energy. Therefore, a study leading to the possible estimation of energy dissipated at different distances from the blast site may be of industrial utility [11].

Seismic waves are classified as body waves and surface waves. Body waves travel through the interior of earth. Ground vibration waves are of two

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types, Primary (P-wave) and Secondary (S-wave). Surface waves generate when the radiating body waves impinge on a stress free plane, like surface or any discontinuity. These waves travel along the surface and discontinuities. Rayleigh waves are the best known surface waves and include both dilation and distortion of the medium. Surface waves carry maximum percentage of the radiated energy and are predominant at longer distances from the blast source, since their attenuation rate is slower than body waves. In addition, the frequency of surface waves is lower than body waves and frequently found to be in the range most favorable for structural response [5]. All these waves are characterized by exponential decrease in particle oscillation amplitude as distance from energy source increases [12]. Fig. 2 shows the characteristics of ground vibration waves on the structures.

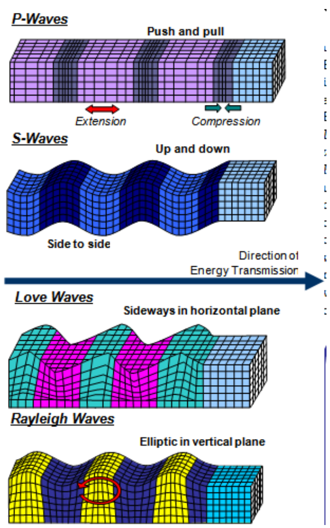

Fig. 2 Characteristics of Body Waves and Surface Waves

Vibration monitoring and recording instruments (Seismographs)

Many types of seismographs are available today. Each performs the basic function of measuring ground motion but supplies much additional information. Most seismographs are equipped with meters that register and hold the maximum value of the vibration components and the sound level. Other seismographs are equipped to produce a printout which gives a variety of information such as maximum value for each component, frequency of vibration for the maximum value, maximum displacement, maximum acceleration, vector sum, and sound level. Blast information such as date, blast number, time, location, job designation, and other pertinent information can also be added to the printout [6].

Normally, a seismograph record shows the following information (Fig. 3):

- Three lines or traces, one for each vibration component. A fourth line or trace for the acoustic or sound level.
- A calibration signal for each trace.
- Timing lines which appear as vertical lines running across all or part of the record.

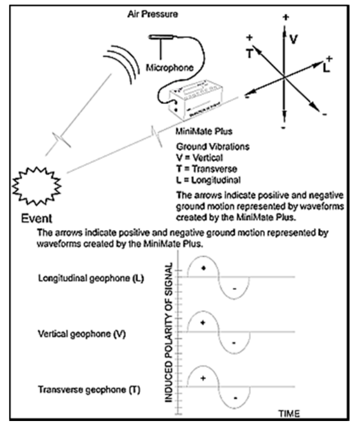

Fig. 3 A Seismograph record [3]

From the studies conducted by previous research [10], it is found that the actual utilization of explosive energy for the productive work is about 15-20%, and remaining energy is wasted in the form of unwanted side effects like ground vibrations. If the energy utilization could be improved even by 1%, there would be huge benefits to the industry, with much reduced environmental effects. In this paper, an attempt for the estimation of shock wave energy through the analysis of ground vibration waves generated from the blasts conducted in mines was made using signal processing techniques, in order to determine the energy carried / dissipated, later to be used in optimizing the blast design process.

II. Field Investigations

Initially for the assessment and estimation of seismic energy, blasts were conducted in three different mine formations in Southern part of India viz. Limestone, Underground Coal and Sandstone. For Signal Processing Analyses purpose, in total 116 blast vibration event samples were collected in three different Limestone Mines by conducting 32 opencast mine blast studies. Similarly, 96 blast vibration event samples were collected from Underground Coal Mine by conducting 34 blast studies. Further, 43 blast vibration event samples were collected in two different Sandstone Mines by conducting 16 opencast mine blast studies.

In Limestone formation, the distance between the monitoring point of vibration monitor (or seismograph) and blast site was varied from 30m to 485m. In Underground Coal formation, the vibration monitor (or seismograph) was placed both on surface (with about 65m parting) and in underground for finding the exact propagation of blast wave. The distance between vibrations monitor and blast location was varied from 15m to 111m in underground and from 54m to 122m on surface. Similarly, in Sandstone formation, the distances of monitoring instrument were varied as 100m to 2033m from the blast location.

III. RESEARCH METHODOLOGY

Vibrations induced from blasting operations were monitored using Ground Vibration Monitors. Ground vibrations generated from all the blasts were monitored at different distances and at specific structures using Microprocessor based Blast Vibration Monitors of Instantel, Canada. The geophone of the monitor was glued to the structure / ground with Plaster of Paris for effective tapping of ground vibration wave by geophone. Typical monitoring of ground vibrations is shown in Fig. 4. A typical wave form obtained is shown in Fig. 5. The typical vibration event samples were analyzed using Advanced Blastware Software.

Fig. 4 Ground vibratons monitoring at different locations during blast studies

The obtained vibration event samples data from Vibration Monitors were analyzed with the help of Advanced Blastware and DADiSP software using signal processing techniques. Initially, the vibration samples of ground vibration events were converted the into ASCII file using Advanced Blastware. The vibrations were analyzed using signal processing techniques available in the Advanced Blastware and found the intensity of blast waves (Fig. 6). The obtained ASCII values were imported into DADiSP for further signal processing analyses.

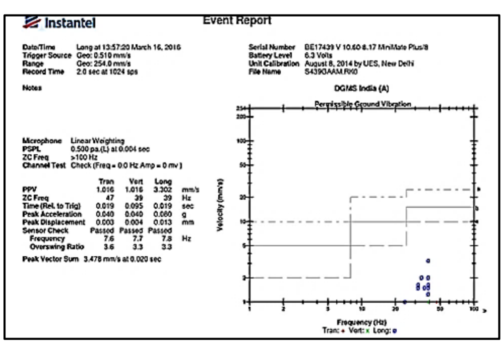

Fig. 5 Typical ground vibration event

Seismic energy can be obtained by considering area under the combination of three orthogonal vibration waves in frequency response.

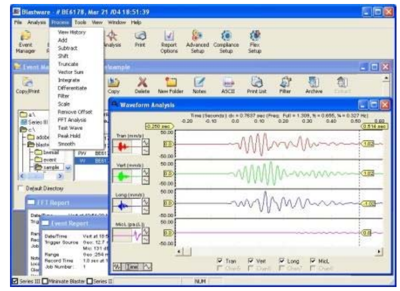

Fig. 6 Signal Processing Analysis of a blast vibration using Advanced Blastware

Initially, the discrete ASCII samples of Vibration wave obtained from Advanced Blastware are imported in DADiSP for reconstruction of Vibration wave which gives rise to quantized discrete signal (Fig. 7). *At about 2500 vibration samples were recorded for a vibration in one direction* and similarly vibrations in other two orthogonal directions were recorded with about 2100-2500 particle motion samples.

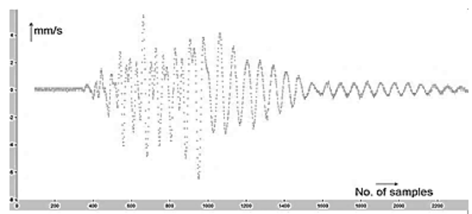

Fig. 7 Quantized discrete signal

The vibration samples were further processed to obtain a reconstructed vibration wave using reconstruction signal analysis available in DADiSP software in steps (Fig. 8). After the reconstruction process, the reconstructed sampled blast induced vibration analog waves were taken considering all three orthogonal directions for further signal processing computation (Fig. 9).

The waveforms which were in time domain were converted to frequency domain by applying Discrete Fourier Transformation (DFT). Since, Blast wave is a non-periodic discrete wave, application of direct Fourier Transformations for finding the frequency is not possible. Application of Discrete Fourier Transformation remains the system magnitude with same units but in frequency domain (Fig. 10).

This indicates no change in the state of the signal. After DFT using DADiSP package, the signals were further processed to find Power Spectrum Density. Power Spectral Density (PSD) is a measure of a signal's power intensity in the frequency domain. In practice, the PSD is computed from the DFT spectrum of a signal. The PSD provides a useful way to characterize the amplitude versus frequency content of a random signal [2].

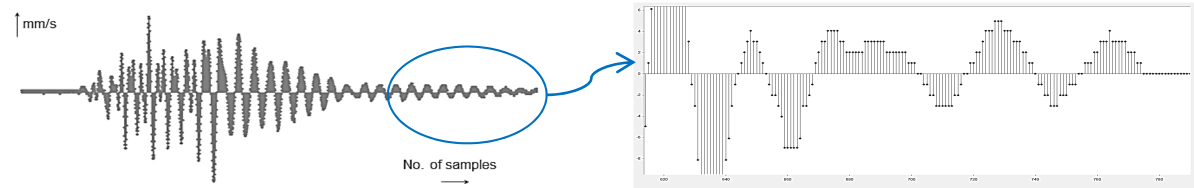

Fig. 8A Signal with discrete sample magnitudes

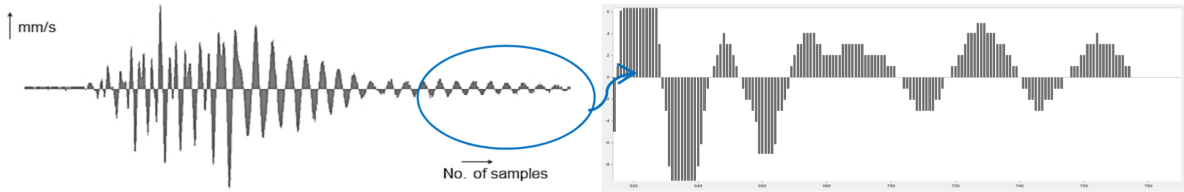

Fig. 8B Reconstruction of a signal with discrete samples

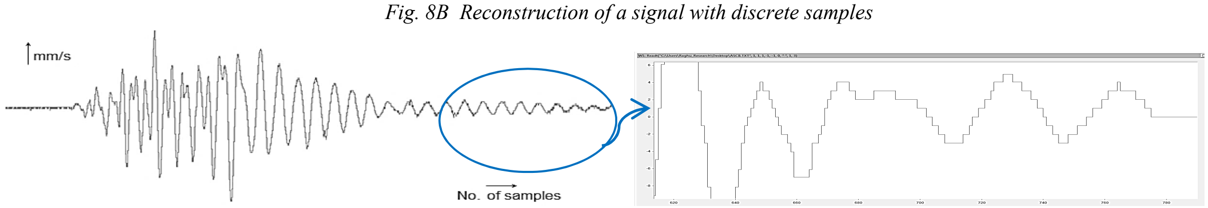

Fig. 8C Reconstructed quantized signal

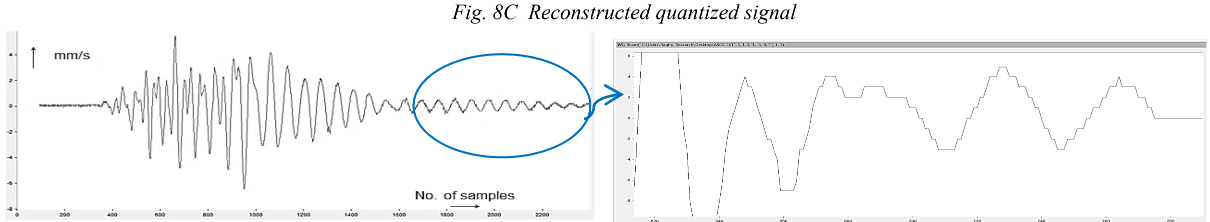

Fig. 8D Reconstructed discrete signal

Fig. 8 Reconstruction of Discrete Samples using DADiSP Package

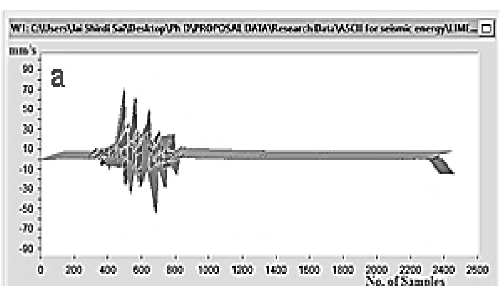

Fig. 9 Typical reconstructed vibration wave in three orthogonal directions

- Input (before DFT) – Vibration Velocity in time domain (mm/s)
- Output (after DFT) – Vibration Velocity in frequency domain (mm/s)

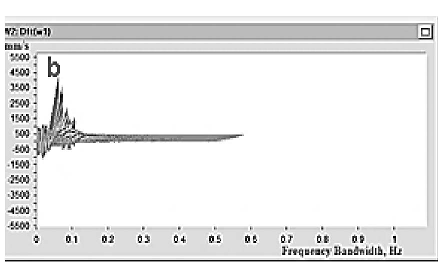

Fig. 10 Computation of DFT to random vibration signal aligned in three directions

When the input random vibration signal in frequency domain having units as ‘G’, the amplitude values of a PSD are normally expressed in ‘G^2/Hz’, where the term ‘G’ indicates units of the random vibration signal, mm/s, in frequency domain (Fig. 11). Therefore, application of PSD to the vibration signal gives rise to,

- Input (before PSD) – Vibration Velocity in frequency domain (mm/s)
- Output (after PSD) – $(mm/s)^2$/Hz → ($\mu m^2/s^2$)/Hz → $\mu m^2/s$

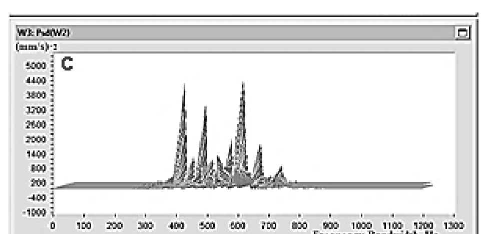

Fig. 11 Computation of Power Spectrum Density to the random vibration signal aligned in three directions after DFT operation

It was assumed that the vibration wave had a unit mass, M in kg. Therefore, the output after PSD operation was changed as μ ($kg.m^2/s$). Output is in the form of angular momentum (L). The angular momentum, L of a rigid body with moment of inertia I rotating with angular velocity ω, is given by:

$$L = I.\omega$$

where,

L = Angular momentum, kg-m^2/s
I = Moment of inertia, kg-m^2
ω = Angular Velocity, rad/s

The Rotational Kinetic Energy for a mechanical system considering the total mechanical energy of a rigid body is defined as,

$$KE_r = \int_0^{\omega} L\, d\omega = \int_0^{\omega} (I.\omega)\, d\omega = \frac{1}{2} I.\omega^2$$

where,

KE_r = Rotational Kinetic Energy, μ. Joules

Hence, from the above analysis, it is needed to apply integration to the output of vibration data after PSD operation. Since, Integration is applied only for continuous signals and for discrete signals application of integration is not possible. Hence, "Partial Sum" operation is computed for fining the Rotational Kinetic Energy available in the waveform [1]. Then the area under the vibration waves after "Partial Sum" were calculated which gives rise to the **Seismic Energy** of the blast induced vibration wave by using the command area(abs(w4)), which returns the area under the signal, seismic energy, at the left side bottom of the window (Fig. 12).

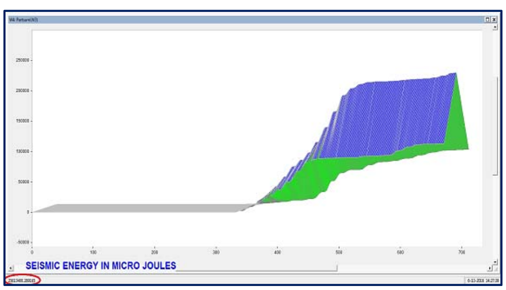

Fig. 12 Seismic Energy of the blast induced vibration wave

IV. CONCLUSIONS

From the studies conducted and analysis computed, the following conclusions are drawn:

- Analysis done in three different rock formations indicated that, the coefficient of determination, R^2, between Seismic Energy and Peak Particle Velocity is higher in the case of sandstone formation (about 95.19%) compared to the other two formations, with limestone formation of about 90.00%, coal formation of about 91.94%. This designates that there is a direct relationship between Seismic Energy and vibration intensity. Higher is the vibration intensity amplitude, more will be the seismic energy value.
- From the regression analysis made, it was observed that there is a proper correlation between Seismic Energy and Scaled Distance in all three different rock formations. In limestone formation it is about 83.92%, in coal formation it is about 81.76% and in sandstone formation it is about 85.68%.
- The minimum and maximum values of Seismic energies in three formations are 26762µJ and 111259278µJ, in Limestone formation, 4250µJ and 1904089µJ, in Coal formation, and 10311□J and 27388321□J, in Sandstone formation.
- The range of L-wave and T-wave velocities are 120m/s to 5,275m/s and 92m/s to 4,289m/s, respectively in Limestone formation, 79.44m/s to 10,10,800m/s and 1.19m/s to 1,01,080m/s, respectively in Coal formation and 109.05m/s to 75,000m/s and 108.70m/s to 20,000m/s, respectively in Sandstone formation.
- From the results, the velocity of ground vibrations is found to be lesser in case of limestone formation, which may be due to more discontinuities. Also it indicates relatively better utilization of explosive energy.

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