Gazi University Journal of Science
GU J Sci
23(4):401-411 (2010)

www.gujs.org

Non-Linear Behavior of Blasting Noticed on Seismic Signals

Guzin Gulsev UYAR ALDAS[1♠]

[1]Ankara University, Faculty of Engineering, Department of Geophysics, Besevler, Ankara, 06100, Turkey

Received: 21.05.2010 Accepted: 13.07.2010

ABSTRACT

In mining operations, it is necessary to remove the overburden in order to uncover the mineral deposits. When the overburden consists of highly consolidated materials, blasting should be performed to fragment the rocks. Blasting introduces extensive impulsive energy into the surrounding earth. It is expected that most of the explosive energy is used for rock fragmentation. However, part of this energy is transmitted away from the blasting point as ground vibrations. Mitigation of ground vibrations has been discussed by many researchers and their waveform models of blast vibration typically consider a linear superposition of characteristic waveforms. However, blasting produces large strains in the surrounding medium, which implies a non-linear response of the material. It is therefore questionable to use a linear superposition scheme in analyzing waveform. This study aims to investigate the non-linear behavior of blasting phenomena. Therefore, studies for mitigation of ground vibration can be performed more realistic way.

Key Words: *Non-linear behavior, blasting, vibration, elastic wave, plastic deformation..*

1. INTRODUCTION

The classical approach in minimizing blast-induced ground vibration is: a) measuring the peak particle velocities by seismograph b) determining the filed-constants between blast-location and target c) finding the empirical formula which establish the propagation rule of the vibration and d) determining the maximum amount of explosive per delay by using this empirical formula ([1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], and many others).

Aldas et al. ([15], and Aldas and Ecevitoglu [16]) proposed a new methodology to minimize the blast-induced vibration. The most important finding of this methodology is the use of "Pilot-Blast Signal", which embraces the seismic properties of all complex geology between the blast and target locations, to model the "Group-Blast Signal". The aim is to minimize the "Group-Blast Signal" by using appropriate delay elements. The main assumption of this newly developed methodology is "Linear-Behavior" of blasting process. Every blast in the Group-Blast" is assumed to be the

♠Corresponding author, e-mail: aldas@eng.ankara.edu.tr

same as "Pilot-Blast". Therefore, "Superposition Principle" is valid ([17], [18], [19]). Although the blasting event is non-linear in its nature, linear behavior may still be acceptable for practical reasons. Explosion phenomena are not completely non-linear all the time. If, say, a whole explosion event takes 50ms, at least the first half of the time, prior to the demolishing of the rocks, creates elastic waveforms mostly due to the linear behavior of the explosion. If the rocks are plastically deformed from the very early stage of the blasting, there would be no seismic wave generation. Rocks are stretched before fracturing. With this stretching event, seismic wave propagation starts. In other words, at this stage, most of the elastic waves are generated where linear assumptions are holds. These very first elastic waves are not affected by the fracturing process occurring later.

This principle is applicable when the vibrations are measured at a certain distance (Far-Field) from blast-location. However, it loses its validity at the blasting point and Near-Field. At the blasting point rock fragmentation (plastic deformation) occurs, as it is aimed, and blasting process shows non-linear behavior.

The subject of this work is to investigate the effects of Non-Linear Behavior of blasting on seismic signals. The work may provide crucial information about the nature of the blasting phenomenon. If we know the non-linear behavior of blasting process by analyzing the blast-signal, we can revise the vibration-mitigation studies. Moreover, we can control the ratio of Linear / Non-linear behavior and direct the large portion of the explosive energy to the rock fragmentation, and just small portion of it to the elastic wave propagation (vibrations). Hence, while the blast productivity is increased, the environmental effects of seismic vibrations are mitigated.

2. TEORY

The classical approach in seismic and seismology is using spectral ratio of seismic signals belong to same source but different station and depth levels. This ratio removes both the source-dependent effects and common-path effects of signals. The remaining from the spectral ratio is the picture and physical properties of the field between related stations [20].

In this work, mathematical formulation of above mentioned classical approach is interpreted by different point of view. Knowing that both Pilot-Blast Signal and Group-Blast Signals follow the same route from blast-location and record station (target), spectral ratio of Group and Pilot-Blast Signal is taken. This ratio is then transformed back to the time domain. Therefore, all the effects related to the geologic-path, time-delays and convolution effects, resulting in seismic signal stretch are removed. The remaining from this spectral ratio is Non-Linear Behavior of Group Blast. The signal, named as Non-Linear Behavior Response Signal *h(t),* is equivalent of "Source-Time function" in seismology. The following part gives this mathematical formulations and relating explanations.

2.1 Derivation of Non-linear Behavior Response Signal, h(t)

Although the seismic data is recorded in the time domain, it is practical to study the mathematical formulation in the frequency domain (Formula 1). Assuming the Linear-Behavior of blasting phenomena, every blast in the Group-Blast is the frequency-independent h_1, h_2, h_3...constants of Pilot-Blast, occurred in Δ_{t1}, Δ_{t2}, Δ_{t3}, ...time-delays (Formula 2). In this condition, rocks behave elastically (no fragmentation) and only produce seismic wave.

If a blast shows Non-Linear Behavior, every blast in the Group-Blast is the frequency-dependent $H_1(\omega)$, $H_2(\omega)$, $H_3(\omega)$, ... functions of Pilot-Blast, occurs in Δt_1, Δt_2, Δt_3, ... time-delays (Formula 3). In this condition, rocks behave plastically. Energy is used mostly for fragmentation. Small portion of this energy is spent as seismic wave.

Formula 4 is the general form of Formula 3. In the case of *n* blasts in a Group, *H(ω)* is defined as in Formula 5 and by this way, we obtained Formula 6. Extracting the *H(ω)* from Formula 6, we got Formula 7. Response signal of Non-Linear Behavior of blasting phenomena, *h(t)* is acquired by inverse Fourier Transform of Formula 7 (Formula 8).

Time domain to frequency domain:

$$f(t) \xrightarrow{FT^{-1}} F(\omega) \qquad g(t) \xrightarrow{FT^{-1}} G(\omega) \tag{1}$$

Statement of Linear Behavior:

$$G(\omega) = F(\omega)\left(h_1 e^{-i\omega\Delta t_1} + h_2 e^{-i\omega\Delta t_2} + h_3 e^{-i\omega\Delta t_3} + \cdots\right) \tag{2}$$

Statement of Non-Linear Behavior:

$$G(\omega) = F(\omega)[H_1(\omega)\, e^{-i\omega\Delta t_1} + H_2(\omega)\, e^{-i\omega\Delta t_2} + H_3(\omega)\, e^{-i\omega\Delta t_3} + \cdots] \tag{3}$$

General Statement:

$$G(\omega) = F(\omega)\sum_{j=1}^{n} H_j(\omega)\, e^{-i\omega\Delta t_j} \tag{4}$$

$$H(\omega) = \sum_{j=1}^{n} H_j(\omega)\, e^{-i\omega \Delta t_j} \tag{5}$$

$$G(\omega) = F(\omega)\, H(\omega) \tag{6}$$

$$H(\omega) = \frac{G(\omega)}{F(\omega)} \tag{7}$$

Frequency domain to time domain:

$$H(\omega) \xrightarrow{FT^{+1}} h(t) \tag{8}$$

Where, t is time; ω is angular frequency; FT^{-1} is normal Fourier Transfom; FT^{+1} is inverse Fourier Transform; i is imaginary variable; ∑ is addition sign; j is counter; n is number of terms added; f(t) is pilot-signal at time domain; F(ω) is pilot-signal at frequency domain; g(t) is group-signal at time domain; G(ω) is group-signal at frequency domain; h_1, h_2, h_3, is linear-behavior terms (frequency-independent); $H_1(\omega)$, $H_2(\omega)$, $H_3(\omega)$, is non-linear behavior terms (frequency-dependent); Δt_1, Δt_2, Δt_3, is time-delays belong to linear-non-linear terms; Δt_j is general form of Δt_1, Δt_2, Δt_3; $H_j(\omega)$ is general form of $H_1(\omega)$, $H_2(\omega)$, $H_3(\omega)$; H(ω is non-linear behavior response signal at frequency domain; h(t) is non-linear behavior response signal at time domain.

Details of above mentioned formulas are explained graphically in following section

2.2. Impacts of Non-Linear Behavior on Seismic Signals (Graphical Representations)

In order to investigate the non-linear behavior response signal at time and frequency domain, I used the blast-signal obtained from the blasts at TKI GELI Eskihisar Lignite Mine [16]. Gray-colored signal, *f(t),* is the vertical component of a real Pilot-Blast Signal (Figure 1). Using this Pilot-Signal, a Group-Signal (summation of 0ms, 300ms and 600ms time-delayed Pilot-signal) was modeled. Red-signal in Figure 1 illustrates Linear-Behavior of modeled Group-Blast signal, *g(t).* As a result of Linear-Behavior, gray-colored real signal overlaps with red-colored signal in first 300ms. Blue-colored signal belongs to Non-Linear Behavior of modeled Group-Blast signal. As a result of Non-Linear Behavior, blue-colored signal does not overlapped with the other two signals.

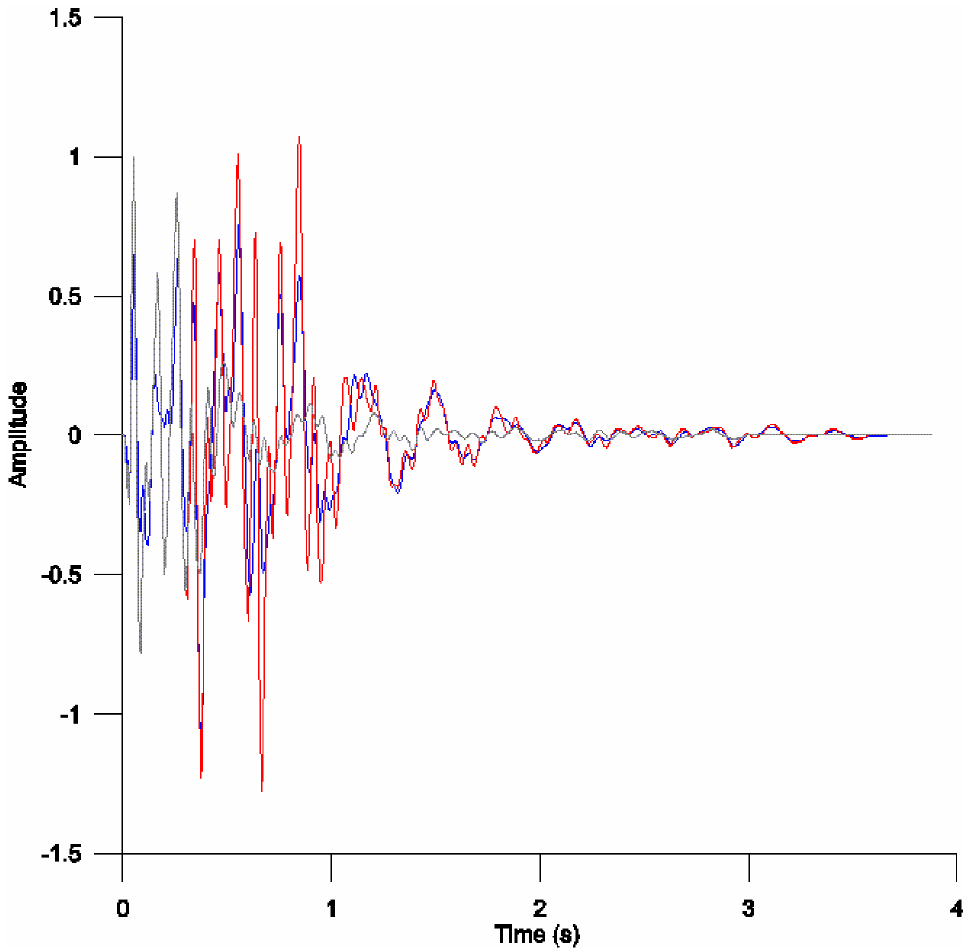

Figure 1. Representation of Pilot-signal and modelled group blast signal obtained at TKI GELI Lignite mine's blast at time domain. Gray signal is vertical component of the Pilot-signal. Red signal is Linear-Behavior Group-Signal obtained by superposition of pilot-signal. Blue signal is Non-Linear Behavior of Group-Signal obtained by Formula 8.

Figure 2 demonstrates the amplitude spectrums (*F(ω)* and G(ω)) of the time-domain signals given in Figure 1.

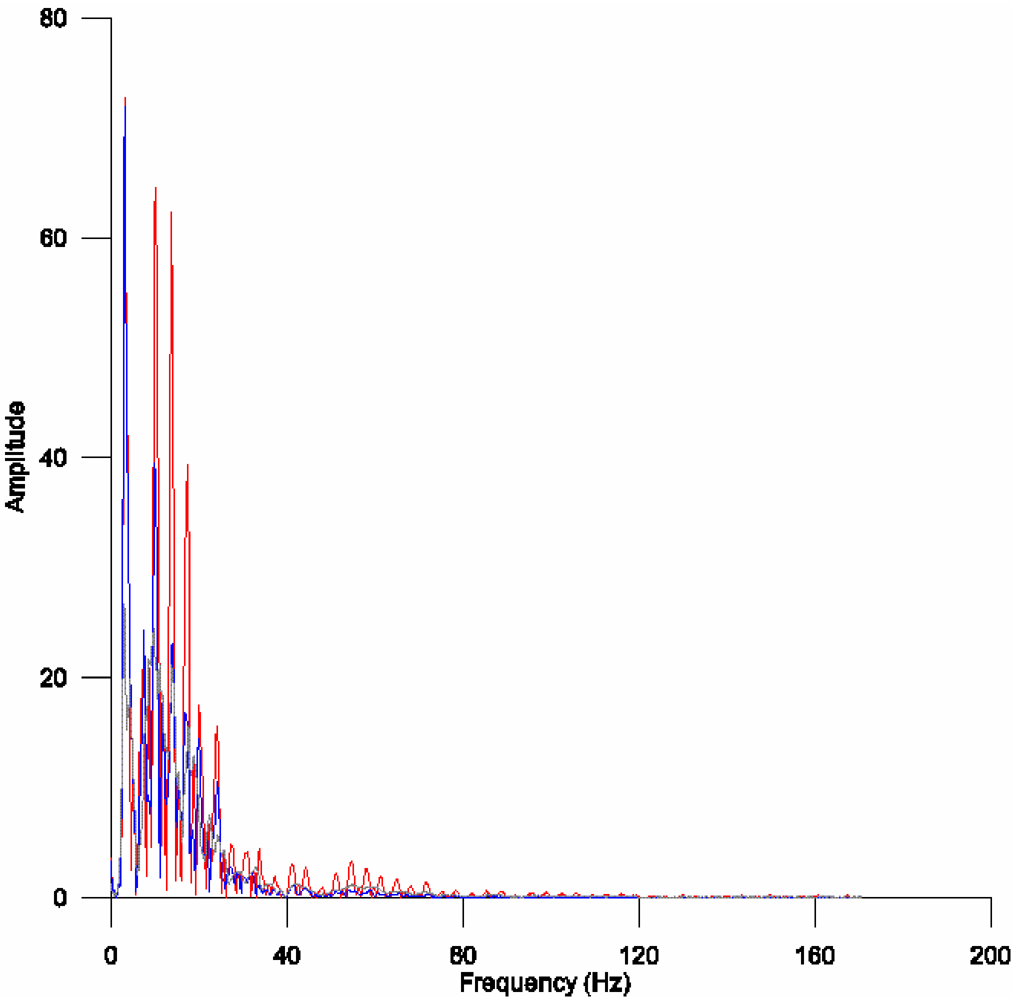

Figure 2. Representation of Pilot-signal and modelled group blast signal obtained at TKI GELI Lignite mine's blast at frequency domain. Gray: Pilot-signal, Red: Linear-Behavior Group signal, Blue: Non-Linear Behavior Group-Signal.

Comb-like structures (comb is a series of equally spaced unit impulses) of red-colored Linear-Behavior Group-Signal and blue-colored Non-Linear Behavior Group-Signal (in Figure 2) are related with gray-colored Linear-Behavior response signal and red-colored Non-Linear Behavior response signal (in Figure 4).

Figure 3 explains Linear and Non-Linear Behavior of blast-signals. Spikes, having unit-amplitude, at 0ms, 300ms and 600ms (gray-color) symbolize Linear-Behavior. In this case, Group blast makes the rocks behave only elastically (no fragmentation). Therefore, it provides seismic wave propagation.

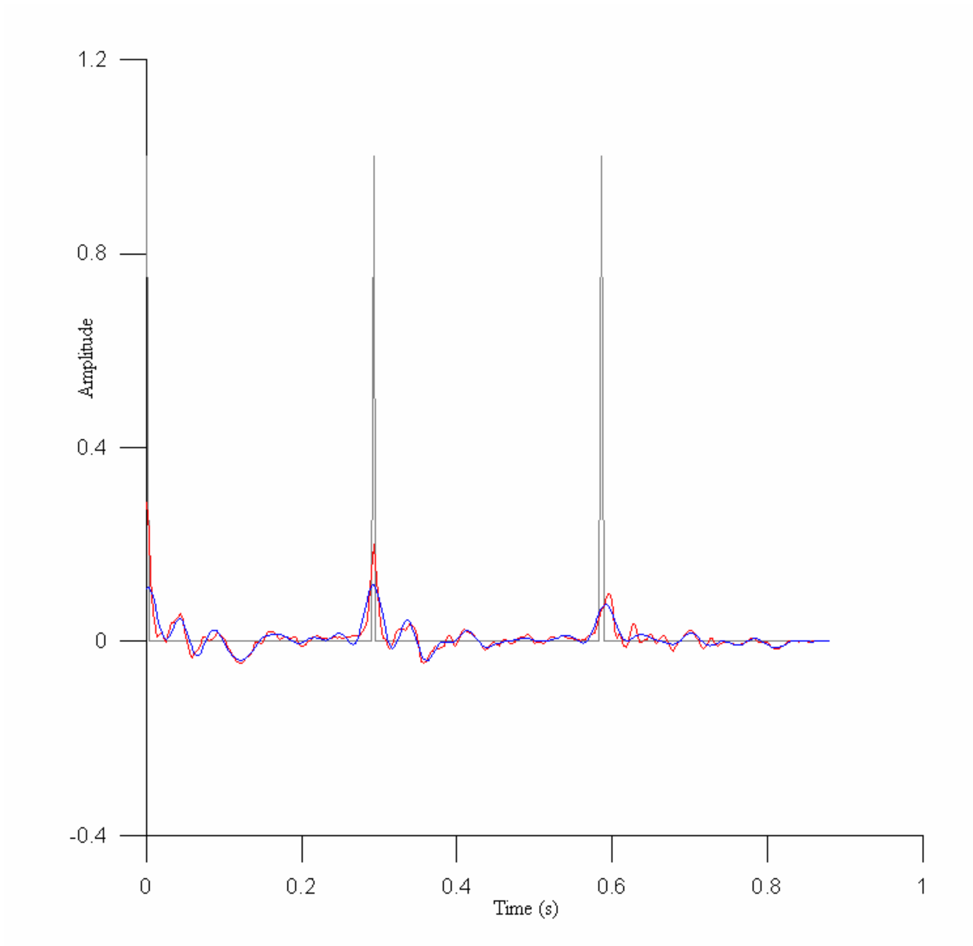

Figure 3. Linear and Non-Linear behavior response signal at time-domain. Gray: Linear-behavior response signal. Red: Non-linear behavior response signal. Blue: Non-linear behavior response signal (25 Hz cut-off frequency).

Red-colored time-series, delayed at 0ms, 300ms and 600ms, symbolize the Non-Linear Behavior. It is seen that amplitudes of this time series is decreasing by doing small oscillations. In this case, Group blast causes the rocks behave plastically. Therefore, most of the energy is used for rock fragmentation and small portion of it is lost as seismic wave propagation.

With blasting process, rock fragmentations occur in various shapes and dimensions. All those fragments cause seismic signals having different amplitudes and frequencies. High-frequency and low-amplitude waves are absorbed easily while traveling and their amplitudes decrease under noise-level. Those frequencies, below noise level, are not reliable. For this reason, instead of red-color signal (Non-Linear Behavior signal, *h(t)* , up to 170 Hz), blue-color signal (Non-Linear Behavior signal, *h(t)*, up to 25 Hz) should be preferred.

Figure 4 shows the amplitude spectrums of response signals given in Figure 3. Gray-colored signal illustrates typical amplitude spectrums of a time-series composed of unit impulses (Linear Behavior). Red-colored signal shows amplitude spectrum, *H(ω),* of Non-Linear Behavior response signal, under ideal condition (no-noise). Blue-colored signal shows amplitude spectrum, *H(ω),* of Non-Linear Behavior response signal, at cut-off frequency 25 Hz.

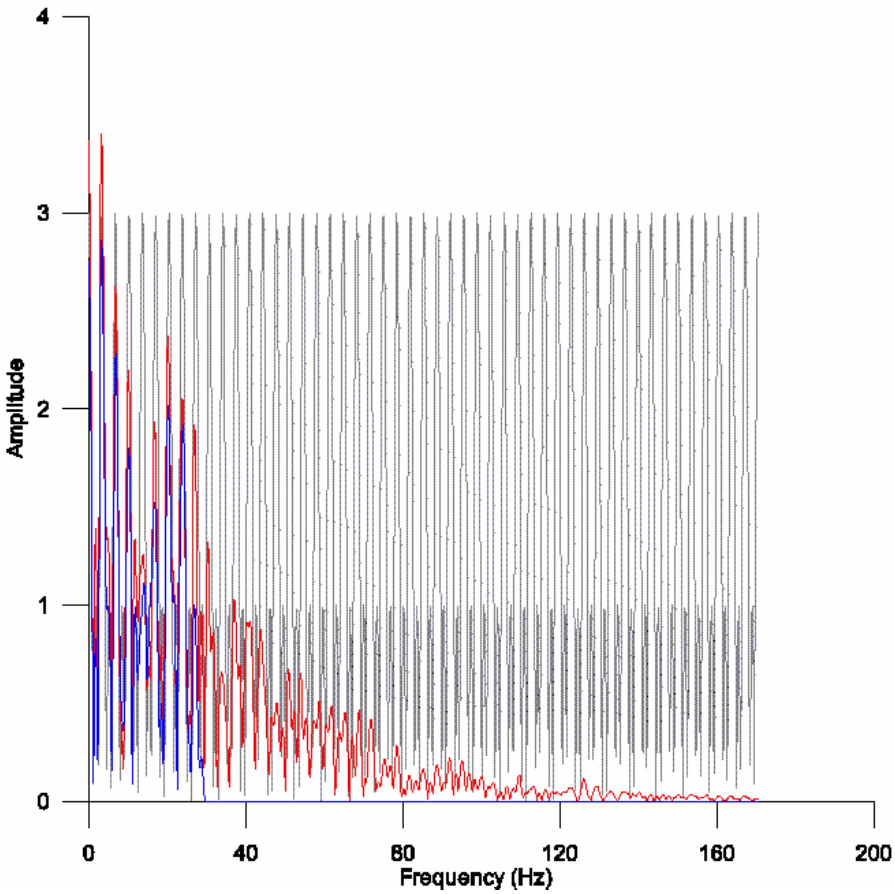

Figure 4. Linear and Non-Linear behavior response signal at frequency-domain. Gray: Linear-behavior response signal. Red: Non-linear behavior response signal. Blue: Non-linear behavior response signal (25 Hz cut-off frequency).

3. EXPERIMENTAL STUDY

The newly developed theory was tested by field-experiment. Figure 5 shows the experiment set. At the Group-blast, distances between blast-holes control the interaction between blast-holes. Group-blast signal generated by blasting of individual-blast-holes (interacted with each other) is different than the summation of individual blast-hole's signal. This is the case due to Non-Linear Behavior of blasting process. In the experiment, two pair of blast-holes (4 -5 and 1-8) was filled with same amount of explosive. Drilling diameter and depth of the holes were also same. Firstly, blast holes 4-5 (distance between them was 3m) were fired at the same time and seismic signals were recorded at two station called near-field and far-field in Figure 5. Then, blast-holes 1-8 (distance between them was 21m) were fired at the same time. Similarly, seismic waves were recorded at near and far-field stations.

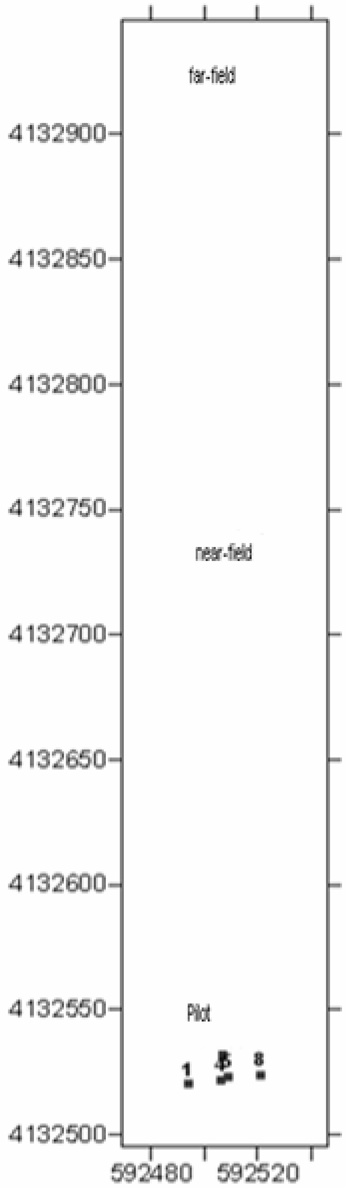

Figure 5. Experiment set to show the interaction between blast-holes: Far-Field: Far-field measurement station, Near-Field: Near-field measurement station. Pilot: Pilot blast. Distance between blast holes 4-5 is 3m. Distance between blast holes 1-8 is 21m.

Figure 6 and 7 demonstrate three-component records of Non-Linear Behavior response signal *h(t),* which was determined by spectral ratio of Group-Blast Signal and Pilot-Blast Signal (those signals were real field records, not synthetic). As it is seen, near-field record in Figure 6 and 7 has no longitudinal component due to geophone breakdown.

Figure 6. Experiment on interaction between blast-holes: Non-linear behavior response signals belong to blast-holes 4-5 (distance between them is 3 m). The signals were recorded in three component, transversal, vertical, longitudinal. Near: Signals belong to near field seismometer.. Far: Signals belong to far-field seismometer. (record length is1.313 s).

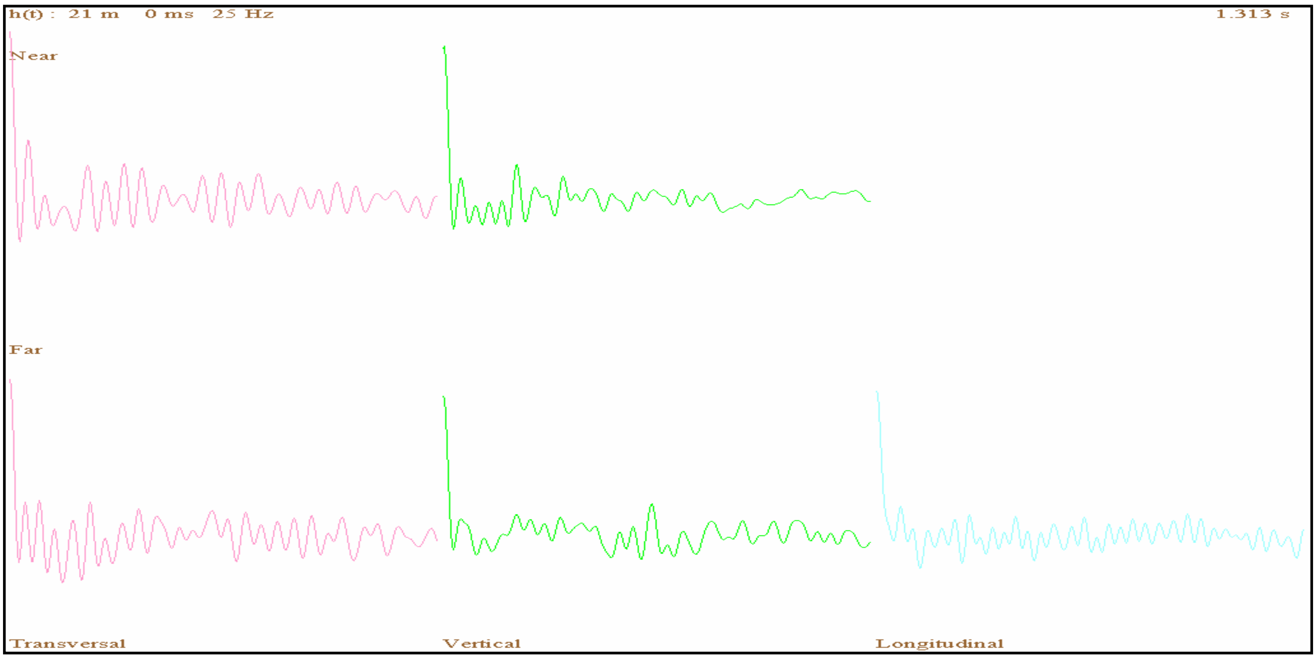

Figure 7. Experiment on interaction between blast-holes: Non-linear behavior response signals belong to blast-holes 1-8 (distance between them is 21 m). The signals were recorded in three component, transversal, vertical, longitudinal. Near: Signals belong to near field seismometer. Far: Signals belong to far-field seismometer. (record length is1.313 s).

4. DISCUSSION AND CONCLUSION

In this study, Non-Linear Behavior response signal, *h(t),* was determined by spectral ratio of Group-Blast Signal and Pilot-Blast Signal. Non-Linear Behavior of Blasting, which is hidden in seismic signals, was investigated.

In Linear-Behavior case, time series includes an impulse followed by zeros. However, in Non-Linear Behavior case, the impulse at the start position collapsed and time series show decreasing behavior (there is also small oscillation) with time (Figure 3). As in the case in Figure 6, blast-hole interaction increases when the distance between holes is short (3m between blast holes 4 and 5). For example, at about 0.6 second in Figure 6, there is a long period event which may be the ground vibration following the blast. The short-period events collapsed over this long period may show the fragmentation process. The picks scattered may represent the fly-rocks. These details can gain certain means when they are evaluated with high-speed video camera images. If the distance between blast-holes are long (21m between blast hole 1 and 8), interaction impacts cannot seen easily (Figure 7).

This type of seismic signal analysis enlightens us about the nature of rock fragmentation process. It is also helpful in selection process of optimal blasting parameters. For example, if the interaction between blast-holes could be analyzed in terms of non-linear behavior, distance between blast-holes in the group-blast can be arranged. In our experiments, the analysis of signal in terms of nonlinearity shows that, distance between blast-holes 4 and 5, which is 3m, is more suitable than that between blast-holes 1 and 8, which is 21m. Moreover, if one increases the interaction between blast-holes in the group, he/she increases the nonlinearity. Consequently, the fragmentation is enhanced and ground vibration is mitigated.

In order to explain Non-Linear Behavior of Blasting in detail, the author proposes the comparison of seismic signal and related high-speed video camera images.

ACKNOWLEDGEMENTS

I am grateful to Turkish Coal Company (TKI) for their continuous support to this project during two full years. I would like to thank to Prof. Dr. Berkan Ecevitoglu for his valuable advises. I would also thank to Asli Can, Betul Unucok and Ozgur Sagol for their generous assistance throughout the study. This study was supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under grant no 108M359.

REFERENCES

[1] Bollinger, G.A., "Blast Vibration Analysis", S***outhern Illinois University Press***, 132 (1971).

[2] Siskind, D.E., Stagg, M.S., Kopp, J.W., Dowding, C.H., "Structure response and damage produced by ground vibrations from surface mine blasting", RI 8507, 75 (1980).

[3] Anderson, D.A., Winzer, S.R., Ritter, A.P., "Blast Design for Optimising Fragmentation While Controlling Frequency of Ground Vibration", ***Proceedings of the 8th Conference on Explosives and Blasting Technique***, New Orleans, 69–89 (1982).

[4] Dowding, C.H., "Blast Vibration Monitoring and Control", ***Prentice-Hall, Inc.***, Englewood Cliffs, NJ, (1985).

[5] Siskind, D.E., Crum, S.V., Otterness, R.E., Kopp, J.W., "Comperative study of blasting vibrations from Indiana surface coal mine", ***USBM RI***, 922 (1989).

[6] Anderson, D.A., "Blast Monitoring: Regulations, Methods and Control Techniques", ***In: J.A. Hudson (ed.): Comprehensive Rock Engineering***, ***Pergamon Press***, 4: 95–110 (1993).

[7] Persson, P.A., Holmberg, R., Lee, J., "Rock Blasting and Explosives Engineering", ***CRC Press, Inc.***: 365-367 (1994).

[8] Muller, B., "Adapting blasting technologies to the characteristics of rock masses in order to improve blasting results and reduce blasting vibrations", ***FRAGBLAST***, 1: 361-378 (1997).

[9] Muller, B., Hohlfeld, Th., "New possibility of reducing blasting vibrations with an improved prognosi", ***FRAGBLAST,*** 1: 379-392 (1997).

[10] Hoshino, T., Mogi, G., Shaoquan, K., "Optimum delay interval design in delay blasting", F***RAGBLAST – International Journal of Blasting and Fragmentation,*** 4: 139–148 (2000).

[11] Siskind, D.E., "Vibrations from blasting, International Society of Explosives Engineers", 120 (2000).

[12] Chen, G., Huang, S., "Analysis of Ground Vibrations Caused by Open Pit Production Blasts: A Case Study", ***FRAGBLAST – International Journal of Blasting and Fragmentation,*** 5(1): 1-2, 91-107 (2001).

[13] Tripathy, G., Gupta, I.D., "Prediction of Ground Vibrations due to Construction Blasts in Different Types of Rock", ***Rock Mech. Rock Eng***, 35 (3): 195–204 (2002).

[14] Adhikari, G.R., Theresraj, A.I., Venkatesh, S., Balachander, R., Gupta, R.N., "Ground Vibration due to Blasting in Limestone Quarries", ***FRAGBLAST – International Journal of Blasting and Fragmentation***, 8 (2): 85–94 (2004).

[15] Aldas, G.G.U., Ecevitoglu, B., Can, A., Unucok, B., Sagol, O., "Minimization of Blasting Induced Ground Vibrations at TKI GELI Eskihisar Lignite Mine", ***Final Report in Turkish***, (2005).

[16] Aldas, G.G.U., Ecevitoglu, B., "Waveform analysis in mitigation of blast-vibration", ***Journal of Applied Geophysics***, 66:25-30 (2008).

[17] Bullen, K.E., "Introduction to the Theory of Seismology", ***Cambridge University Press***, 381 (1963).

[18] Oppenheim A.V., Schafer R.W., "Digital Signal Processing", ***Prentice Hall***, 585 (1975).

[19] Karu, Z.Z., "Signals and Systems Made Ridiculously Simple", ISBN 0-9633752-1-4, ZiZi Press, 124 (2002).

[20] Shearer, P.M., Introduction to Seismology, ***Cambridge University Press***, 260 (1999).