Development of a Blasting Vibration Monitoring System Based on Tri-axial Acceleration Sensor for Wireless Mesh Network Monitoring

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Abstract. Recently a variety of vibration monitoring devices based on MEMS (micro electro-mechanical system) 3-axis acceleration sensor has been introduced and is gradually replacing analog wire-type geophones for blasting vibration monitoring. Blasting vibration monitoring tasks generally require frequent movement of the monitoring devices. Since accurate device set along the vertical axis is essential at a new location, acceleration sensors sensitive to the gravitational acceleration are not suitable for accurate monitoring of the blasting vibration. In this study, the vibration monitoring system with a 3-axis MEMS acceleration sensor is developed for wireless mesh network monitoring. Individual monitoring units are equipped with an algorithm for reorientation along the direction of gravity once they are placed on a particular baseline. The algorithm aims at automatically adjusting the z-axis and resetting the zero offset value altered after each blasting vibration monitoring and relocation. With this feature, it shows individual unit can be applied as conventional portable devices as well. In addition, comparative studies are also carried out along with conventional units for 3-axis acceleration and primary frequency analysis. There are several advantages of the developed system. Firstly, this system has been designed for easy installation and wireless remote management to provide readings and alerts when the user-defined allowable limit is exceeded. Secondly, due to remote management, it can improve staff safety, reduce human resources, and save time and cost. Thirdly, this system can be positioned over a large area as each sensor can act as a repeater. Finally, multiple sensors can be installed to measure various locations monitoring at the same time. Furthermore, without the cables to interface with operations or accidental damage, this system improves safety and reduces maintenance costs. The readings from the multiple sensors deployed at target locations are transmitted to the management node connected to the PC. Thus, all the live data can be seen on the PC. This system is built to be deployed on mining and construction sites, tunnel, bridges, and other structures. The system is designed with the ultimate goal of

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understanding challenges and provide solutions to protect assets by the low-cost system with high accuracy and reliability.

Keywords: Blasting vibration · Vibration monitoring · MEMS · Zero offset · Wireless remote management

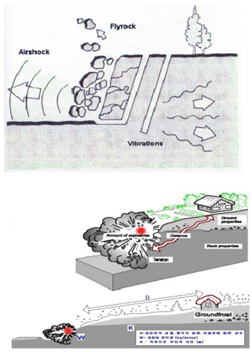
1 Backgrounds

Excavation using blasting is to remove rocks from the excavation section by using the impact and the gas pressure generated by the explosion of explosives. The impact and the gas pressure generated during blasting work spread deep into the rock in the form of elastic waves, causing ground vibrations and leading to the destruction of the rock. However, this vibration energy is not limited to rock destruction. However, only 5-20% of vibration energy is transmitted to the nearby ground in the form of elastic waves, which is called the vibration pollution caused by blasting. Table 1 shows the factors influencing blasting vibration.

To minimize vibration damage caused by blasting, each country regulates the allowable vibration limits to nearby target structures during blasting, and the criteria are listed in Table 2.

In Korea, since 2005, most of blasting vibration allowances have been limited under 0.3 cm/sec for any residential structures and also even strictly limited under 0.2 cm/sec in the urban area. And for a case of livestock (any animal), the usual limitation has been kept under 0.09 cm/sec. As shown in the table above, since countries around the world clearly define the acceptance criteria for vibration, accurate blasting vibration measurement is required for each blasting operation. However, internationally-renowned blasting vibration monitoring-only instruments are still expensive measurement procedures that are also laborious and time-consuming. Therefore, demands for wireless communication, IoT utilization, and unmanned automatic measurement are increasing.

Table 1. The influential factors the blasting vibration

Influence factors of blasting vibrations	·Geological conditions (the type of rock) · Height of bench · Number of free faces · The angle of the free plane towards the structure · Minimum burden and spacing · Sub-drilling · Stemming and length of stemming · Number of holes and lows in one line · The energy of the explosives · Formation and type of detonator and ignition · Amount of charge per delay · Number of Decks · Distance to structure	 *Image source: D.W Kang, Applied blasting engineering, book, 1997

Variables	Category	Impact			Remarks
		Serious	Normal	Weak	
Adjustable factor	·Amount of charge per delay	○			
	·Delays	○			
	·Character of explosives		○		
	·Minimum burden and spacing		○		
	·Stemming			○	
	·Drilling direction		○		
	·Direction of detonating			○	
	·Amount of charges in a round			○	
Non-adjustable factor	·Distance to target structure	○			
	·Terrain condition		○		
	·Thickness and shape of topsoil		○		
	·Condition of rock		○		
	·Condition of air			○	

Table 2. The allowable vibration limits by country

USA [1]

Type of construction	**Peak Particle Velocity (cm/sec)**
Ancient and historic monuments	0.75
Housing in poor repair	1.2
Good residential, commercial, and industrial structures	2.5
Welded gas mains, ground sewers, engineered structures	5.0

Safe Level (cm/sec) / **Type of structures**	**Frequency < 40 Hz**	**Frequency > 40 Hz**
Modern homes-drywall	0.75	2.0
Older homes-plaster on wood	0.50	2.0

Russia(Soviet union) [2]

Type of structure	**Velocity (cm/sec)**	
	Long blasting period (repeatable)	**Short blasting period (one-shot)**
Hospital	0.8	3.0
Kindergarten and residential building	1.5	3.0
Factory, public station, small residential building	3.0	3.0
Office, industrial factory, waterway(tunnel), high reinforced concrete pipe, elevated construction	6.0	12.0
Steel frame concrete structure, mine shaft(over 10 years)	12.0	24.0
Mine shaft(within 3 years)	24.0	48.0

(*continued*)

Table 2. (*continued*)

Portugal [3]

Ground condition / Type of structure	Vibration limit (cm/sec)		
	Mixture of non-cohesive soil and gravel	Low cohesive soil, high cohesive sand	Cohesive soil, rock
	P<1000m/s	P=1000~2000m/sec	P>2000m/sec
Ruins, hospital, skyscraper	0.25	0.5	1.0
Very usual structures	0.5	1.0	2.0
Reinforced concrete, seismic design	1.5	3.0	6.0

Germany [4]

Type of structure	Vibration Velocity, Vi, in (mm/sec)			
	Foundation			Plane of floor of uppermost full story
	Frequency			
	< 10Hz	10~50Hz	50~100Hz	Frequency mixture
Business, industrial building and similar	20	20 ~ 40	40 ~ 50	40
Residential and similar	5	5 ~ 15	15 ~ 20	15
Vibration-prone structure (ruins and major structure)	3	3 ~ 8	8 ~ 10	8

Swiss [5]

Category	Type of structure	Blasting vibration	
		Frequency (Hz)	Particle velocity (mm/sec)
1	Steel Structure and Reinforced Concrete Structure	10~60	30
	Factory building, retaining wall structure, Bridge, an iron tower, Open channel An underground tunnel and underground cavity treated with concrete lining, or without lining.	60~90	30~40
2	Building with foundation wall and constructed from concrete slab or stone walls.	10~60	18
	masonry retaining wall Loose stratum tubularis Stone lining treated in underground tunnels and underground cavities	60~90	18~25
3	A building with a wooden ceiling along with a stone wall	10~60	12
		60~90	12~25
4	Structures of historical value and other vibration-sensitive structures	10~60	8
		60~90	8~12

(*continued*)

Table 2. (*continued*)

Particle velocity (mm/sec)	500.0	Great damage occurs to the building.
	100.0	Great damage occurs to the building.
	5.0	Light damage occurs to the building.
	2.0	Extremely light damage occurs to the building. (Man feels like a building is about to collapse)
	1.0	The human body feels strongly, but there is no damage to the building.
	0.5	In general, many people feel vibrations.
	0.1	A very sensitive person feels a vibration.
	0.05	Can't feel it in the human body.

Human response	**Velocity (cm/sec)**
Can feel	0.2 ~0.5
Strongly feel	0.5 ~0.95
Feels uncomfortable	0.95 ~2.0
Get pain	2.0 ~3.25
Can not endure	3.25 ~5.0

South Korea [6], [7]

Classification		**Limit of PPV (cm/sec)**
Category	**In detail**	
sensitive structure	ruins, high technology	0.3

(*continued*)

Table 2. (*continued*)

masonry structure(bricks, stone) a structure with wooden walls and ceilings	an old house, low floor house	1.0
masonry structure of subbase and concrete slab	low floor slab house, townhouse	2.0
Small to medium-sized buildings with reinforced concrete frames and slabs	medium and low–rise apartment small to medium-sized shopping mall factory	3.0
Large building with reinforced concrete or steel frame and slab	seismic design structure high-rise apartment, huge structure	5.0

Type of structure	Frequency band	
	over 30 Hz	under 30 Hz
Ruins or very old structure	0.2	0.2
Damaged building, cracked structure	0.5	0.4
Cracked but not damaged	1.0	0.8
Industrial structure with non cement wall	1.0 ~ 4.0	0.8 ~ 2.0

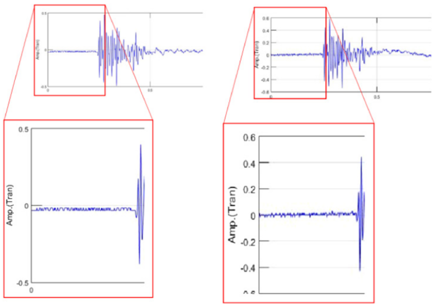
2 Development of New Type Blasting Vibration Monitor

This case studied the unmanned automatic measurement of MEMS-based precision tri-axial accelerometers to replace the existing analog geophone. MEMS-based acceleration sensors perform superbly in measuring vibration of high frequency and sinusoidal waves, such as motor vibration, the vibration of belt conveyors, the friction of rotating bearings, etc., but blasting vibration is completely different from those; it is subject to one-time measurement, changing location each time of measurement, coupling with various ground conditions. Thus, it is essential to calibrate the direction of gravitational acceleration for each measurement. To overcome these limitations, the new type monitor induces more accurate three-axis vibration components to be measured by the offset correction of the differences in the fine angle of the measuring sensor during each vibration measurement. Figure 1 shows the program for zero off-settings embedded in the new type monitors, while in Fig. 2, data collected in the case of manual zero settings is compared with those automatically set by the embedded program [9, 10].

In addition, all data is automatically transferred to the server through a mesh network in the 2.4G band in line with IoT, as illustrated in Fig. 3, while simplifying the procedures for installing, measuring, withdrawing, and backing up data by personnel manually.

```
void GetReference(void)
{
    int16_t xAccel, yAccel, zAccel;
    int32_t xData, yData, zData;

    for(int i=0; i<100; i++)
    {
        xAccel = GetAccel(0);
        yAccel = GetAccel(1);
        zAccel = GetAccel(2);

        xData += xAccel;
        yData += yAccel;
        zData += zAccel;

        HAL_Delay(10);
    }

    xRef = xData / 100;
    yRef = yData / 100;
    zRef = zData / 100;

    DEBUG_Printfln("Accel Ref:%d %d %d", xRef, yRef, zRef);
}
```

Fig. 1. Re-arm with zero offset command in embedded board



(a) Incorrect zero match (b) Corrected zero match

Fig. 2. Zero offset corrected by offset command

Fig. 3. Description of the wireless mesh networking for vibration monitor

For the comparative test of this study, the BM series of Canada "I" company, which is known as a worldwide standard model, was selected as the target of comparison, and the three-axis acceleration sensor of Hong Kong "G" company were tested simultaneously and the cross-correlation was analyzed.

3 In-Situ Test for the Comparative Study

For comparative experiments at the actual site, a site separated by 20–41 m from the rock blasting location was selected as the site for vibration monitoring; the monitoring location was within a building construction site in the urban district of Busan, Korea.

The blasting operation was a typical urban blasting, with the maximum amount of charge per delay being limited to 0.1–0.4 kg/delay. Figures 4 and 5 show the location of the study site and its aerial view, while Figs. 6 and 7 are the scenes for blast hole cleaning and charging. And Figs. 8 and 9 include all the sensors compared in this study.

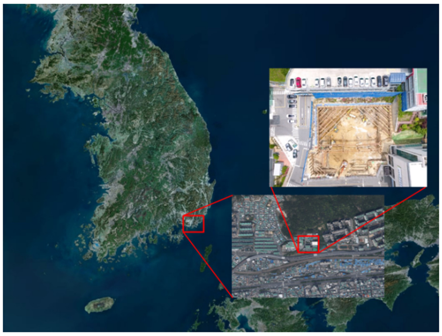


Fig. 4. Geological location of the field test

Fig. 5. Aerial view of the in-situ test site

Fig. 6. Cleaning up the blast hole

Fig. 7. Charging

Fig. 8. Whole view of the monitor layout

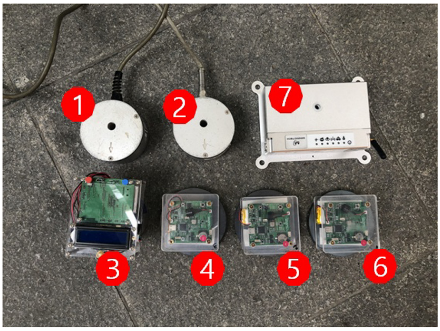


Fig. 9. Monitors for comparative test

The blasting vibration monitors used in this comparison test are pictured in Fig. 9. as follows.

1) Analog type –Instantel(Canada) BlastMate series 2
2) Analog type –Instantel(Canada) BlastMate series 3
3) Analog type –Oyo(Japan) 3-axis geophone

4) Digital(MEMS) type –New type monitor(Korea) _ z axis auto offset
5) Digital(MEMS) type –New type monitor(Korea) - z axis auto offset
6) Digital(MEMS) type –New type monitor(Korea) - z axis auto offset
7) Digital(MEMS) type –Wireless GSS(HongKong) 3GV

Each measuring sensor is fully bonded to the ground with epoxy adhesive for the same coupling with the ground and secured firmly. A total of over 100 vibration-monitoring experiments were performed at the site, but only from the 31 cases, data were found to be complete for comparisons among the five monitors. For all sensors, the trigger vibration level and sampling rate were set to 0.03 Kine (cm/sec) and 1024 per second, respectively.

4 Test Results

All of the vibration seismic data were saved in the serial text files and plotted. Matlab (R2015) data analysis tools were applied for signal alignment, analysis of correlation and cross-correlation, Fourier transformation and power spectral density estimation. Since the distance from the blasting site was very close, all seismic signals showed mainly vertical components. Therefore, in this study, only the vertical components that are the basis for PVS(Peak Vector Sum) were compared.

4.1 Peak Particle Velocity(Vertical) Comparisons

Figures 10 and 11 show that all the measurements from the analog-type sensors are very similar, and those from the MEMS-based sensors also show similar characteristics. As illustrated in Fig. 12, the determination coefficient, R^2, is 0.97 between the peak particle velocity measurements by the analog and MEMS type units, and this indicated the new type monitoring system could be applied comparably and reliably with the internationally-renowned analog-type blasting vibration monitors.

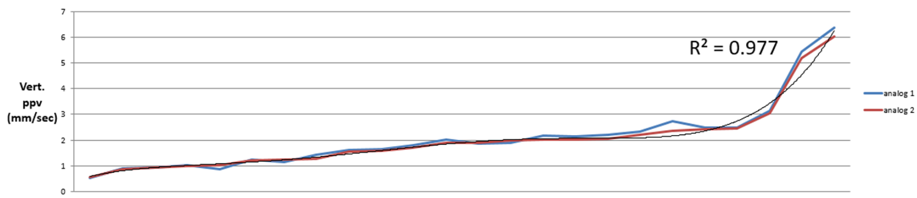


Fig. 10. Similarity between analog monitors

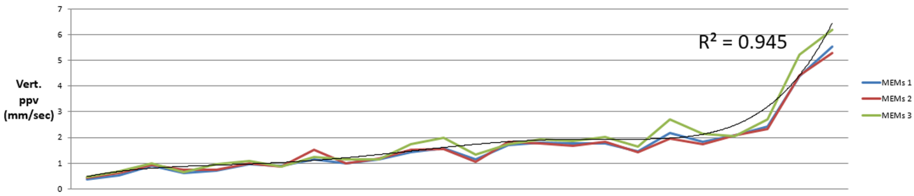


Fig. 11. Similarity between MEMS(digital) monitors

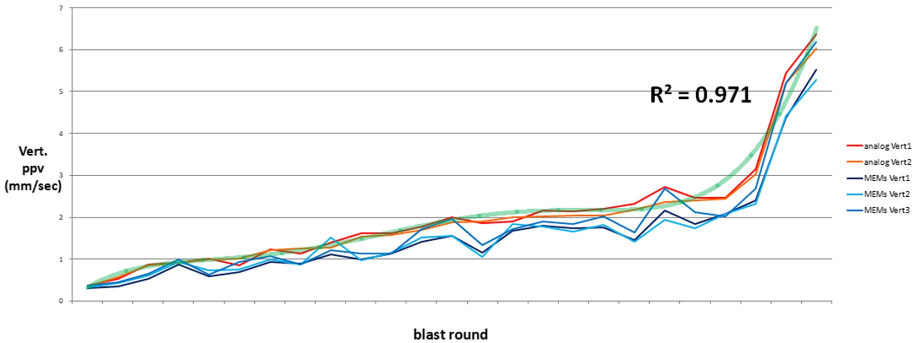


Fig. 12. Peak Particle Velocity(vertical) comparison between Analog type and MEMS type units

4.2 Correlation Analysis of the Full Waveform

The initial vibration wave measurements with different trigger time obtained by different sensors were realigned. Then the correlation analysis was carried out to check the similarity of the full waveforms. The correlation analysis was performed by Matlab. Figure 13 illustrates the vibration waveforms collected from the analog-type sensors with short post-trigger time, while Fig. 14 from MEMS-based sensors with relatively long post-trigger time. Figure 15 shows the seismic forms aligned with respect to the trigger time. Also, cross-correlation analysis was done for the aligned data, and the results plotted in Fig. 16 shows a very high similarity between the waveforms from the different sensors. The correlation analysis results plotted in Fig. 17 shows the correlation between the well-known analog-type sensor and the new type of MEMS-based sensors ranges from 0.80 to 0.87; the average is 0.84.

4.3 Domain Frequency Comparisons

In addition, the analysis of domain frequency was conducted using Matlab's FFT(Fast Fourier Transformation) function to analyze the spectrum and find the domain area of each vibration signal wave, and the results were as follows.

In Figs. 18 and 19, the Fourier-transformed data are plotted for the analog-type and MEMS-based sensors, respectively. As shown in Fig. 20, each domain frequency is very similar. If the noises can be filtered effectively, their similarity is expected to be close to the correlation coefficient of 1.0.

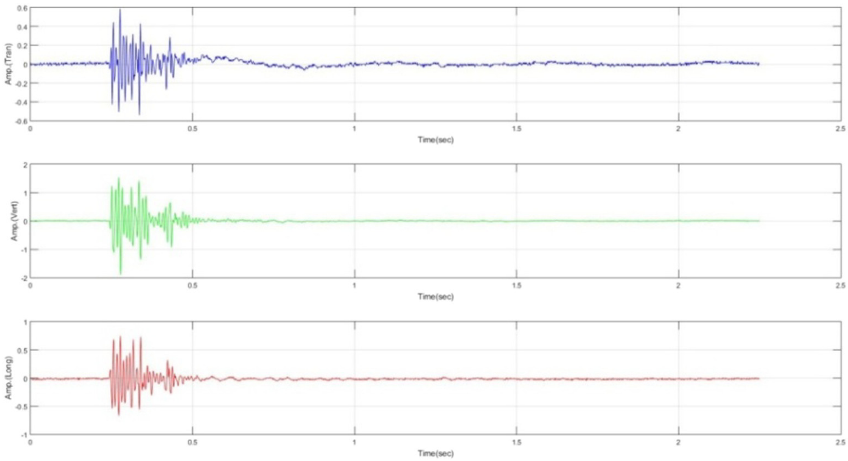


Fig. 13. Examples of seismic graph from analog-type sensors with short post-trigger time

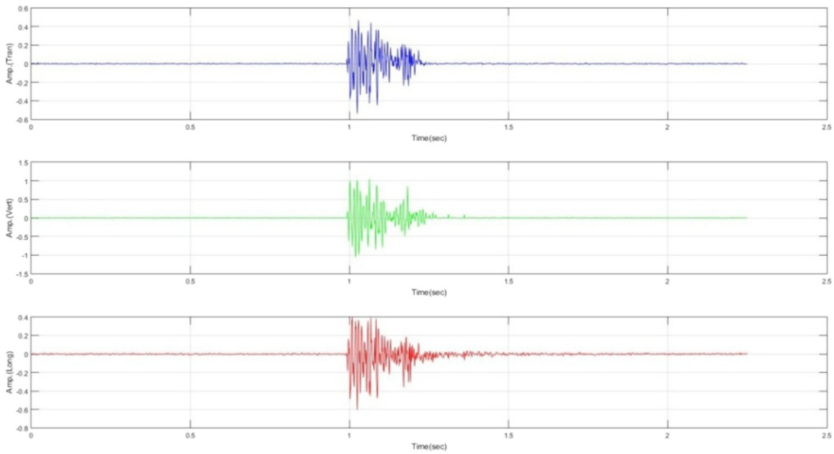


Fig. 14. Examples of seismic graph from MEMS-based sensors with long post-trigger time

4.4 Results of the Wireless Data Transferring

In this study, to overcome some of the inefficiencies of the blasting vibration monitors, which relies on manpower, wireless data transferring devices are assembled to the new-type MEMS-based sensor. This sensor is designed to be used as a portable device like internationally-renowned analog units or as a wireless device and includes several wireless communication modules that can be selected freely with user's demands. The wireless mesh network can be built with multiple sensors, and LoRA, WiFi, LTE, or even Bluetooth can be selected to cover long and also short-range data communication. In the new devices tested in this study, 2.4 G mesh networks and gateways were used, and LTE was adopted.

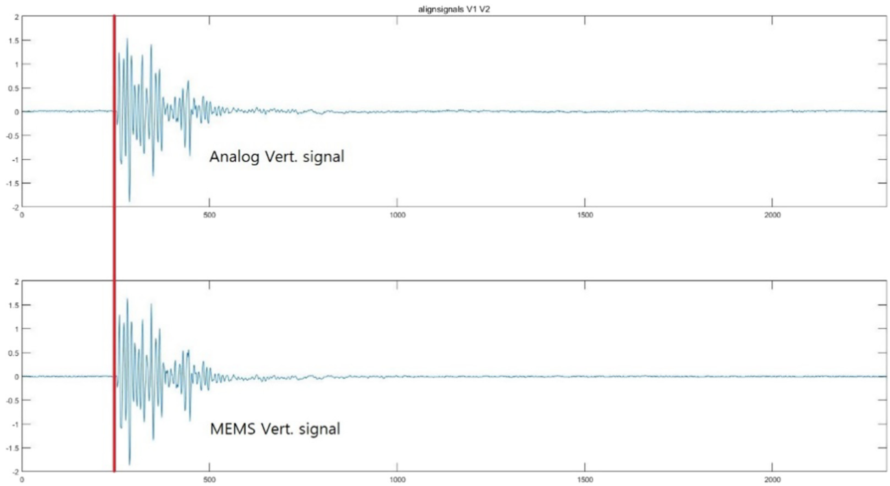


Fig. 15. Examples of the graphs aligned for the first trigger(arrival) time

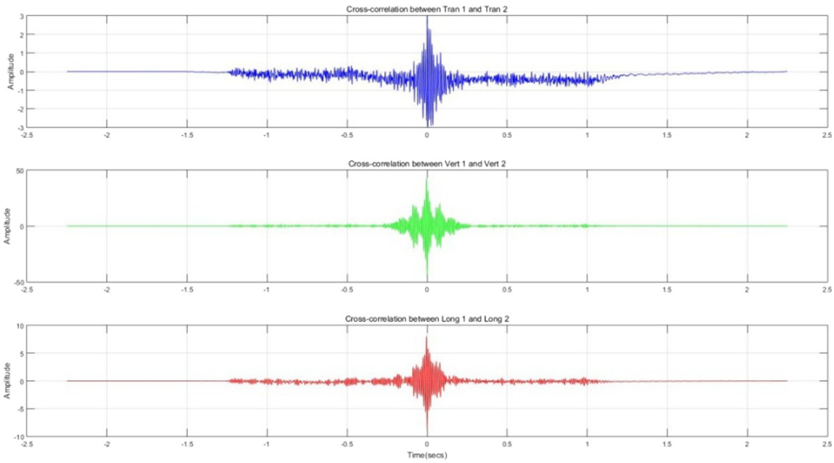


Fig. 16. Three sets of the aligned vibration measurements analyzed by the cross-correlation analysis

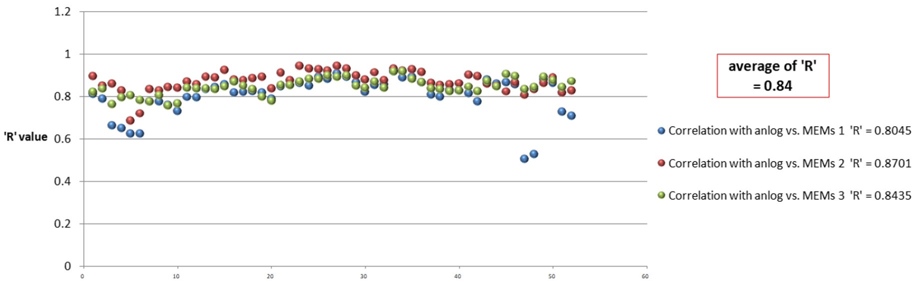


Fig. 17. Correlation analysis results between analog-type and MEMS-type sensors

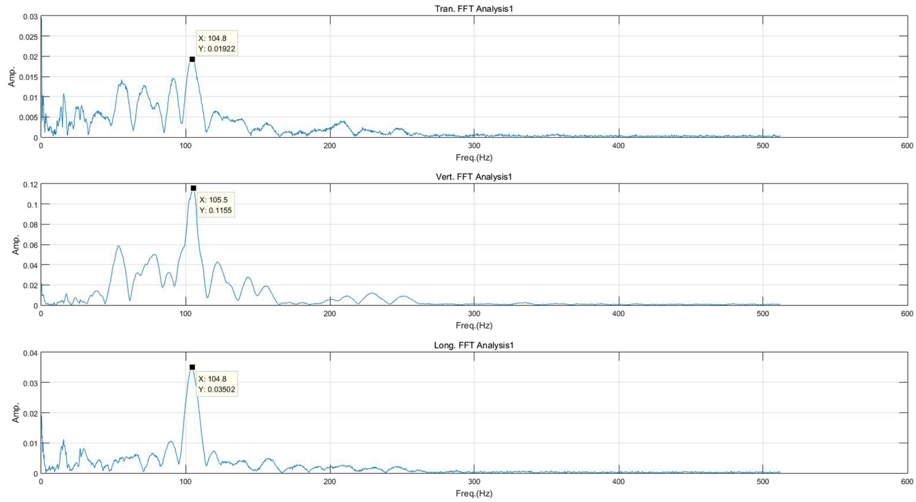


Fig. 18. Examples of FFT results for the data from the analog-type sensors

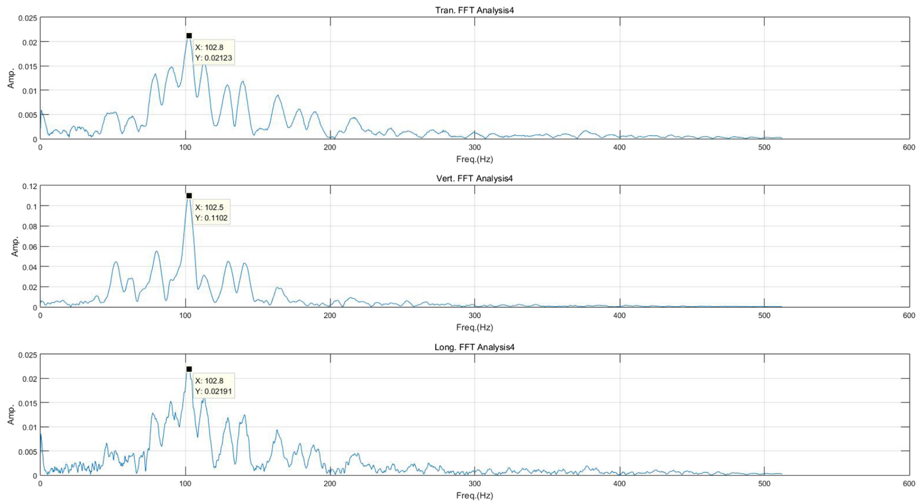


Fig. 19. Examples of FFT results for the data from the MEMS-based sensors

As shown in Fig. 21, all of the full seismic waveforms can be reliably transferred to the FTP server within several seconds to 3 min after event recording. This indicates that most of the laborious operations with conventional devices can be replaced with the new wireless MEMS-based units.

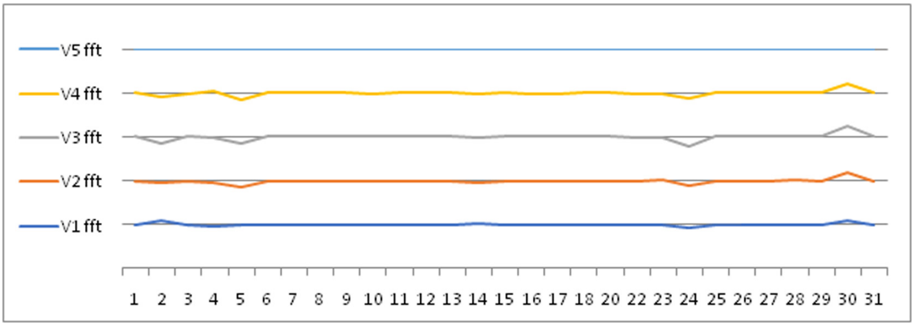


Fig. 20. Domain frequency comparison results

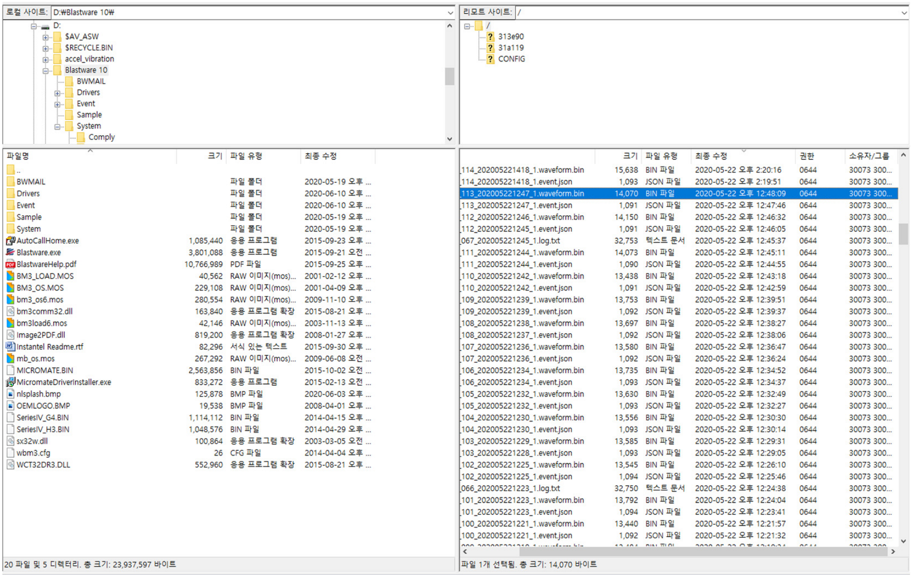


Fig. 21. List of real-time event reports transferred to the FTP server

5 Conclusions

In this study, a wireless blast vibration monitoring system based on MEMS was developed to solve the limitations with the conventional analog-type monitoring system, which is expensive analog equipment and also dependent on manpower. To evaluate the accuracy and efficiency of the developed sensors, the new-type devices were tested along with internationally-renowned conventional blasting vibration monitors at a construction site. And the comparisons can be summarized as follows:

1. The PPV(Peak Particle Velocity) value obtained by the MEMS-based tri-axial accelerometer showed very high similarity to the analog instrument. When only the vertical PPV values, the major component of PVS(Peak Vector Sum) in this

study, were taken into consideration, the comparison results show the coefficient of determination value is 0.971.
2. For a more accurate comparative analysis, the full waveforms recorded by the analog-type sensors were compared with those obtained by MEMS. The results from two analog and three MEMS devices were cross-compared, and show a very high average correlation coefficient of 0.84 for all waveforms.
3. The domain frequency of all waveforms was derived from the frequency analysis, one of the main evaluation items of the seismic analysis, and also the cross-correlation analysis was performed. The results showed that the domain frequencies in all axial directions were consistent.
4. To solve the limitations with the conventional analog-type monitoring system, one of the most important functions considered in developing the new blasting vibration monitoring system was the wireless data transmission. The new device enables communication with the server through an integrated gateway using the 2.4 G mesh network module and the LTE module, confirming that all data can be transmitted within a maximum of three minutes after the blasting event recorded on each device.

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References

1. Siskind, D.E., Stagg, M.S., Kopp, J.W., Dowding, C.H.: Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting, United States Bureau of Mines Report of Investigations 8507 (USBM RI 8507), pp. 72 (1980)
2. Russian Regulation SanPin 2.1.2.2645-10
3. Esteve, J.M.: Control of Vibrations Caused by Blasting, Porutugal
4. German Standard from DIN 4150
5. Studer, J., Susstrunk, A.: Swiss standard for vibrational damage to buildings. In: Proceedings, X. International Conference on ISSMFE, Stockholm, vol. 3, pp. 307–312 (1981)
6. Allowance of blasting vibration according to structural damage criteria, Korea society of tunnel (1999)
7. Allowance of blasting vibration with frequency band, Seoul Metro (2005)
8. Looney, M.: MEMS vibration monitoring: from acceleration to velocity. Analog Dialogue, 51-06 (2017)
9. Datasheet of ADXL 355, Analog Devices Co. Ltd.
10. Datasheet of LPT5901-IPM, Analog Devices Co. Ltd.