APPLICATION OF FIBER-OPTIC DOPPLER SENSOR TO ROCK STRUCTURES

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Abstract: Fiber Optic Doppler (FOD) sensor that can measure AE (Acoustic Emission) has been invented and developed. FOD sensor is made by looping an optical fiber and it is attached on an object or embedded. It measures a displacement rate (strain speed) as the frequency changes of laser light due to the Doppler Effect. FOD sensor has the following advantages; (1) small diameter and small weight, (2) long-distance transmission, (3) immunity from the electro-magnetic noise, (4) usability under high temperature, (5) wide frequency coverage to ultrasonic, (6) durability and anti-corrosive. In order to examine applicability of FOD sensor to monitoring of rock structures, the authors compared the sensitivity and the frequency response of FOD sensor to those of the conventional PZT sensor in laboratory experiments. The results indicated that FOD sensor has strong possibility to be used for real rock structures.

1. INTRODUCTION

During and after excavation/construction of underground hydro-power stations, tunnels, dams or rock slopes, rock engineers are monitoring displacement and strain for safety and intelligent construction management. The authors group have been engaged with such monitoring, using Acoustic Emission (AE) technology which is detecting rock fracture, as well as displacement and strain measurement. In view of Japanese future project, such as the "High Level Nuclear Waste" into the depth of more than 500m, the sensor must have longer-term reliability. The sensor must be explosion-proof to monitor rock stability of the huge underground storage of LPG (liquefied petroleum gas), governed by the regulation.

Meanwhile, the fiber optic sensing technology in strain or temperature has been developed world-wide. Recently, the innovative fiber optical sensor is invented and developed to detect very fast elastic wave inside a solid [1) 2)]. Fiber optic is made of silica, and it provides superior durability and corrosion resistance in comparison with electric cable. The sensor component without using electricity causes few troubles like insulating failure, and it has longer-term durability than electrical sensors. In addition, as the fiber optic sensor does not need electricity to be activated, it is essentially explosion-proof. Therefore, the fiber optic sensor will be utilized in environments where the electrical PZT sensor could hardly be used.

Hereafter, this sensor is designated "Fiber Optical Doppler (FOD) sensor". FOD sensor can detect the fine AE as the conventional PZT sensor does. However, these two sensors' measuring principles are completely different. The PZT sensor is a velocity sensor that the ceramic motion corresponding to vibration is converted to the electric voltage. On the other hand, FOD sensor is a velocity sensor that the Doppler effect causes the laser frequency modulation, corresponding to fiber optic's elongating and shortening motion, i.e. change in length of fiber optic in time domain. FOD sensor has the following characteristics:

(1)Small-size and light-weight with O.D.20-30mm
(2)Long distance transmittable due to little attenuation of laser signals through the fiber optic
(3)Free from electromagnetic noise
(4)Heat resistance to approx. 600 degrees centigrade
(5)Wide frequency coverage with a few Hz -1MHz
(6)Durability and corrosion resistance

The authors carried out the experiment by rock specimen, and made comparison of sensitivity and frequency response between FOD sensor and PZT sensor in view of utilization at the future underground construction projects. The result was promising and here are reports:

2. PRINCIPLE

2.1 Summary of principle

A sensing region of the fiber optic is attached on a measured object as shown in Fig.1. When the object vibrates with some elastic motion on surface, the attached fiber optic elongates and shortens simultaneously. If the light wave of frequency f_o is emitted into a corresponding fiber optic region, change in length of fiber optic causes a laser frequency modulation, because the number of light waves in that region is constant in a moment. In other words, the frequency modulates by f_d because the light velocity is constant. This is called "Laser

Doppler effect" that the frequency of light wave transmitted from other part is given "f_o - f_d". The frequency modulation f_d is proportional to the velocity of fiber optical length, i.e., the displacement rate of attached region.

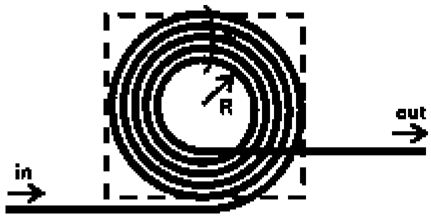

Figure 1. Sensing elements of FOD

2.2 Doppler effect in fiber optic

Frequency modulation by Doppler effect is described as formula (1). f_d as modulated frequency, λ as light wavelength, and *dL/dt* as displacement rate. The negative (-) indicates that the frequency modulation is opposite to displacement rate in terms of phase analysis (+),(-).

$$f_d = -\frac{1}{\lambda}\frac{dL}{dt} \tag{1}$$

As shown in the formula above, the frequency modulation f_d and the displacement rate *dL/dt* are proportional. The frequency modulation f_d is detected using the heterodyne interferometry and is converted into the voltage *V* with the frequency/voltage converter. The relation between the converted voltage *V* and the displacement rate *dL/dt* is indicated in formula (2) including the proportional constant *K*.

$$V = kf_d = -\frac{k}{\lambda}\frac{dL}{dt} = K\frac{dL}{dt} \tag{2}$$

$$\text{where, } K = -\frac{k}{\lambda}$$

2.3 Method of detecting frequency modulation

Fig. 2 shows the Laser Doppler Interferometry system (LAZOC Inc.). The laser with frequency f_o is emitted and divided into the sensing optical path and detecting optical path. Where measured object has a certain displacement at sensing region dynamically, the length of optical path changes accordingly. Then the proportional frequency modulation f_d occurs to the laser light, which is "$f_o - f_d$". At detecting optical path, frequency f_M (80 MHz) is added by AOM (Acousto Optical Modulator) to create the frequency "$f_o + f_M$". The difference in frequency given as "$f_M + f_d$" is converted into the voltage.

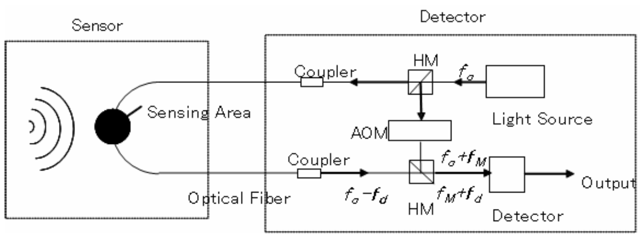

Figure 2. Laser Doppler Interferometer

3. FUNDAMENTAL TEST

3.1 Experimental method

3.1.1 Sensitivity test

In this test, the rectangular wave (pulse wave) was added by PZT sensor with the pulse generator through a rock of granite of 75 mm (H) x 25 mm (W) x 25 mm (L) as the transmitting media. Both FOD sensor and PZT sensor were compared in maximum amplitudes of waveforms. As shown in Fig. 3, pulsing PZT was glued to a side of a specimen with instantaneous adhesive. And in the same way, FOD sensor and PZT sensor for receiving were glued to the opposite side. PZT sensors both for transmitting and receiving had 150 kHz resonance. FOD sensor was the 30-coiled, which is approx. 0.9 meter gauge long. The input voltage was 15 V as the maximum. The received waveform was not amplified at both sensors and was recorded into the digital oscilloscope hard disk with 100 kHz high-pass filter.

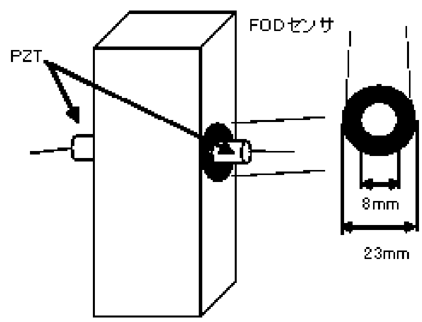

Figure 3. Experimental Set-up

3.1.2 Frequency response test

In this test, the range of frequency was between 50 kHz – 200 kHz in accordance with authors [1), 2)] worksite experience. There are several methods, which are relative calibration method, sound pressure method, and contact method. Contact method was chosen due to simplicity.

Contact method is that the sensing surfaces of two sensors are attached to each other and that the sine-wave with the same amplitude is input with change in frequency. The amplitude (sensitivity) for each frequency was recorded. Both PZT sensors for pulsing and receiving were broadband type with frequency 100 kHz – 1 MHz. FOD sensor was 30-coiled.

PZT sensor was greased by silicon paste to each other, while FOD sensor was attached to pulsing PZT via an aluminum plate of 40 mm x 40 mm, 0.5 mm thick, in order for FOD sensor to have a wider contact with very narrow pulse point of PZT.

3.2 Result

3.2.1 Sensitivity test

Fig. 4 shows the sensitivity test results; (a) input pulse, (b) received FOD waveform, (c) received PZT waveform. From the data (b) and (c), it was known that the maximum amplitude of both sensors is ±0.05V and they have almost the same sensitivity. Also the duration of waveform was almost equal.

Fig. 5 shows the FFT (Fast Fourier Transform) analysis of received waveform by both sensors. According to the results of FOD sensor shown in figure (a), spectrum peak was clearly displayed at 140 kHz, 190 kHz and 280 kHz. Looking into figure (b), PZT sensor had shown the similar frequency characteristics. The reason of distinct 150 kHz was estimated due to PZT resonance.

Next, Fig. 6 shows the S/N (signal to noise) ratio. This figure is an enlarged section of primary wave, so that the background noise (N) can be compared with signal level (s) clearly. For simplicity, here was defined S/N ratio as an amplitude value against background noise. It was found that the S/N ratio of FOD sensor was approx. 10, while that of PZT sensor was approx. 80. FOD showed less S/N ratio due to shorter fiber optic gauge length (0.9 meter at this experiment).

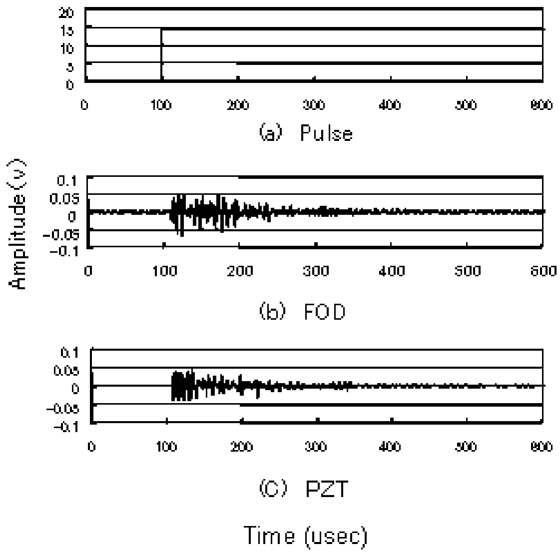

Figure 4 Sensitivity test result

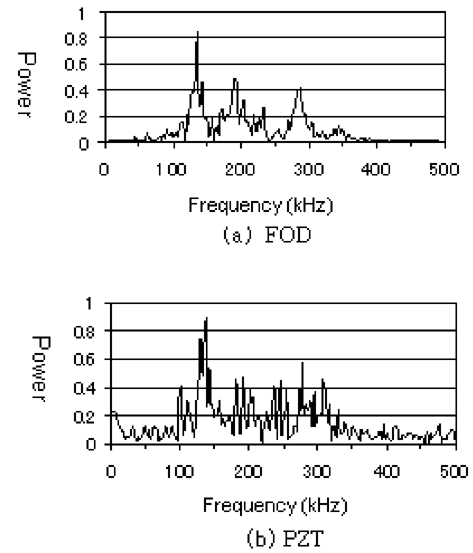

Figure 5 FFT analysis

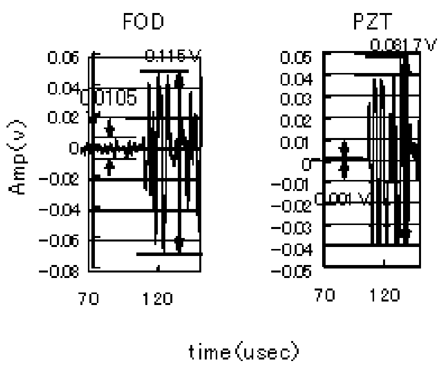

Figure 6 Signal to Noise ratio

3.2.2 Frequency response test

Fig. 7 shows the test results. This figure displays the relation between pulse frequency and amplitude of both sensors in the range of 50 kHz – 200 kHz, and the solid line and perforated line show FOD sensor and PZT sensor respectively. Accordingly, FOD sensor at frequency range higher than 70 kHz has a similar frequency response. From the above, it is concluded that the frequency characteristics of FOD sensor in 70 kHz – 200 kHz are almost equal to those of the broadband PZT sensor.

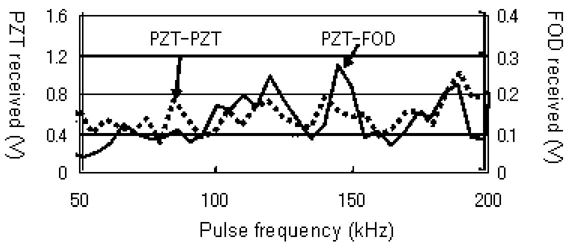

Figure 7 Frequency response

4. UNIAXIAL COMPRESSION TEST

The test to compare FOD sensor with PZT sensor in the previous section enabled to make clear, to some degree, the characteristics of FOD sensor in the high frequency range. Thus, we proceeded to actual AE measurement generated by rock destruction at the uniaxial compression test of the granite.

4.1 Experimental method

A rock of granite of 75 mm (H) x 25 mm (W) x 25 mm (L) was used as a specimen. The hydraulic servo type fatigue testing machine with maximum capacity 100 kN was used. Loading was controlled at constant distortion speed of 0.5 mm/min. Fig. 8 shows the measuring systems, having PZT block flow and FOD block flow. The measuring system for PZT sensor consists of the preamplifier, signal conditioner, AE waveform recorder and analyzer. FOD system consists of the light source, photo detector and frequency/voltage converter (FV converter). Both systems are connected to AE logging unit and analyzer. Three broadband PZT sensors (100 kHz – 1 MHz) were used in consideration of analyzing the frequency of waveform and were glued to the upper part, middle part and lower part of side face of a specimen. One FOD sensor was glued, next to the PZT type sensor, to the center of side face of a specimen. AE data was compared between PZT sensor and FOD sensor that were at the center of side face.

The amplifying value of PZT sensor was 80 dB (preamplifier 40 dB, plus main amplifier 40 dB). FOD sensor was amplified by only 20 dB. The threshold was set a little higher than the noise level. It automatically transmitted only the waveforms, which exceeded the threshold, into the AE logging unit for both FOD sensor and PZT sensor. At the same time of waveform recording, the time, ring-down counting, and maximum amplitude were also recorded. Sampling interval of waveform, recording duration and pre-trigger duration were 0.2 micro sec, 2,048 words and 512 words, respectively. After measurement, the frequency analysis (Fast Fourier Transform) and AE parameters were analyzed.

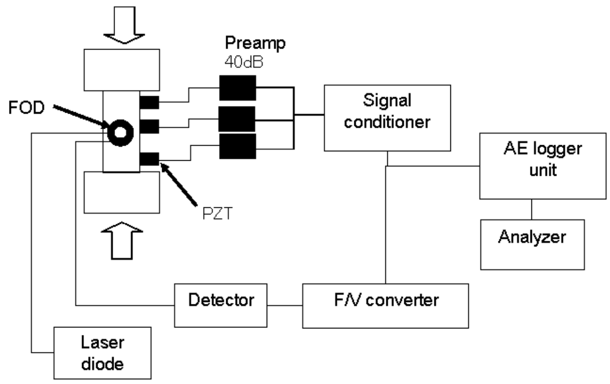

Figure 8 Measuring set-up

4.2 Result

Fig. 9 shows the AE event (counts/sec) and its frequency (kHz) caused by destruction of a specimen of granite. (a) and (b) are FOD data and PZT data respectively. The frequency analysis was calculated from the measured waveform and the center gravity was determined from the spectrum form with frequency in horizontal axis and spectrum power in vertical axis. Small circle in Fig. 9 shows the averaged AE frequency over 10 waveforms along with the elapsed time. First, FOD sensor in Fig. 9 (a) indicates that the specimen was broken at approx. 130 MPa after 1,300 seconds from the beginning of loading. The generation of AE started rapidly at 96% (125 MPa) of destruction load and the maximum AE events was 200 counts/sec for 1,300 seconds. The frequency of AE was in the range of 200 kHz to 500 kHz. Large circle is the frequency averaged over 50 waveforms from 10 small circled frequency data. The frequency becomes lower as it is nearing toward the destruction of a specimen.

Meanwhile, PZT sensor in Fig. 9 (b) indicates AE event in the same tendency as FOD sensor, but the maximum AE events was recorded 130 counts/sec. The main frequency range was 200 kHz to 500 kHz as well as FOD sensor. The frequency, which is averaged over 100 waveforms that 10 events enclosed with a small circle, 2 times of FOD sensor, are calculated on the average in order, displays the tendency to lower as it is nearing along toward the destruction.

As above, the AE characteristics measured by both sensors indicate almost the same tendency, so that it is concluded that FOD sensor has the same mechanical performance as PZT sensor in such an AE measurement.

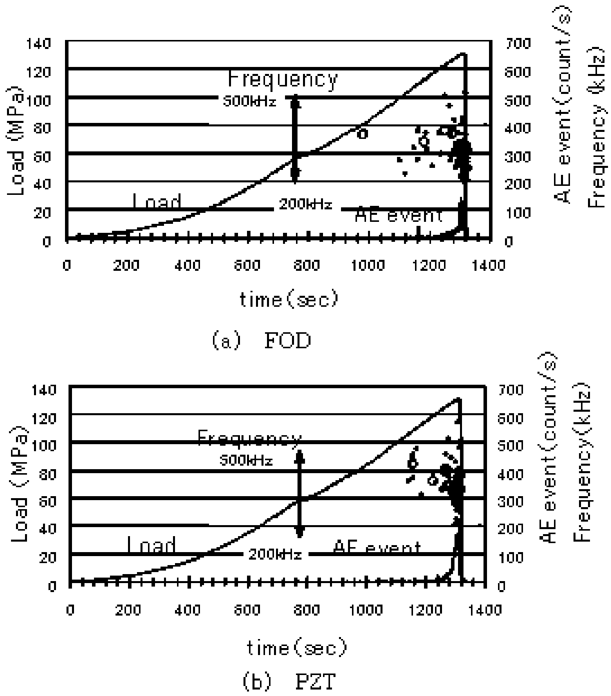

Figure 9 Compression test data

5. CONCLUSIONS

In order to investigate the application of FOD sensor to the rock engineering, comparison test was carried out against the conventional PZT-AE sensor. From the experiment, we confirm that FOD sensor has the same performance as PZT-AE sensor in terms of sensitivity and frequency response. We shall plan to apply this innovative sensor to the filed application where PZT sensor cannot be used and where explosion-proof, deep and remote, long-term durable requirement is observed.

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