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Development of Self-compensated Technique for Evaluation of Surface-breaking Crack by Using Laser Based Ultrasound

Sang-Woo Choi*†, Joon-Hyun Lee** and Younho Cho**

Abstract It is required to evaluate nondestructively depth of surface-breaking cracks in structures. In this paper, the self-compensated technique by laser-based ultrasound is used to measure the depth of surface-breaking defect. Optical generation of ultrasound produces a well defined pulse with reliable frequency content. It is broad banded and suitable for measurement of attenuation and scattering over a wide frequency range. The self-calibrated signal transmission data of surface wave shows good sensitivity as a practical tool for assessment of surface-breaking defect depth. It is suggested that the relationship between the signal transmission and crack depth can be used to predict the surface-breaking crack depths in structures.

Keywords: laser based ultrasound, surface-breaking cracks, self-compensated techniques, nondestructive evaluation, signal transmission

1. Introduction

It is well known that the fracture of structures originates from micro cracks. The micro cracks can grow up by the load in service, and finally cause the fracture. For the purpose of safety and maintenance, the detection and the evaluation of the defects should be conducted nondestructively. Generally, the ultrasound is used for nondestructive evaluation of the crack propagation and the size of surface-breaking cracks (Wu, Fang and Liu, 1995). Since conventional contact techniques required a secure coupling condition between material and transducer under a room temperature, non-contact method has been used with potentiality of application in the high temperature environment. One of the promising non-contact methods is the use of a laser-generated ultrasound, which is the ultrasonic waves generated by the illumination of a pulse laser on the materials (Scruby, Dewhurst, Hutchins and Palmer, 1980). The frequency and directivity of the laser-generated ultrasound can be controlled by varying the variation of the specifications of the illumination of the pulse laser. In this study, a self-compensated technique (Achebach, Komsky, Lee, Angel, 1992; Park and Cho, 2000) and an one-sided technique (Lee, Song, Popovics and Achenbach, 1997; Lee and Park, 1999) using laser based ultrasound were combined to evaluate the surface-breaking cracks in the materials. The self-compensated technique compensates for the uncertainties of coupling condition of the test set-up. In addition, the self-compensated technique is used to measure natural crack size appropriately. The one-sided technique is used to measure the creeping wave and the Rayleigh wave at the same time, with two receivers

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Received: April 26, 2005. Accepted: May 31, 2005 * Research Institute of Mechanical Technology, Pusan National University, Pusan 609-735, Korea, ** School of Mechanical Engineering, Pusan National University, Pusan 609-735, Korea, † Corresponding author: woochoi@pusan.ac.kr

placed on one side to evaluate semi-infinite media nondestructively, such as the concrete pavement and other concrete structures. The one-sided technique can also provide us with a reliable way to measure the velocities of the elastic waves when it is impossible to apply the pulse-echo or the through-transmission methods because of high attenuation of the ultrasonic waves in the materials. With the conventional one-sided technique, elastic waves are generated by dropping a steel ball from a certain position onto the surface of specimen. A DC powered solenoid with a spring-loaded steel shaft was also used for the improvement of impact consistency. Time domain signals captured from each receiver usually contains high level incoherent noise which obscures the signal of the creeping wave. In order to reduce this noise level, signal-averaging scheme was applied by using numerous signals obtained from repeated impact tests. However, it took too much time to select received signal manually for data manipulation, due to some problems, such as the electric noise of solenoid switching. In this study, the one-sided technique was improved by using a pulse laser as the impact source. Capturing the elastic waves was automated by using the Q-switch trigger of the pulse laser in order to reduce the time of signal processing. The intensity of impact, which is the source of the elastic wave generation, can be controlled by adjusting the energy of pulse laser. In addition, the laser-generated ultrasound has high intensity on the surface and the effect of bulk waves reflected from bottom were not so much as ball drop testing and solenoid striking. In this paper, a combination of the one-sided, self-compensated and the laser-generated ultrasonic techniques are proposed for developing depth evaluating technique. The signal transmission along the surface was obtained to evaluate the size of the surface-breaking crack by the one-sided self-compensated technique with the laser based ultrasound.

2. Principle of One-sided Self-compensated Technique

2.1. Laser-based Ultrasonic and One-sided Techniques

The one-sided technique is useful to measure elastic properties and to evaluate damage when there is only one accessible surface. In addition, when the conventional ultrasonic testing is not available, the one-sided technique makes it possible to measure the velocity of elastic waves in thick materials, because of the high attenuation in wave propagation. The one-sided technique was firstly applied to measure the longitudinal wave velocities in concrete by Long et al (Long, Kurtz and Sandenaw, 1945). In the mid 1950s, Whitehurst (Whitehurst, 1954) used a hammer to generate transient elastic waves, which propagate on the surface of concrete. Signals of these transient elastic waves were obtained by two accelerometers on the surface. The arrival time for each accelerometer was acquired by measuring the time of the first disturbance signal. In the most of previous studies, elastic properties were calculated based on an assumed Poisson's ratio value for the concrete. The surface wave velocity between two receiving sensors was obtained from the cross-correlation data compiled by Wu et al. (Wu, Fang, Liu and Kuo, 1995). The obtained velocity data agrees with the surface wave velocity measured using the through-transmission method in ultrasonic testing, when receiving sensors were located farther than 15cm from the source of impact. Qixian et al. (Qixian and Bungey, 1996) proposed measuring method of the longitudinal wave and the Rayleigh wave velocities simultaneously by generating elastic waves with an ultrasonic wave transducer. Popovics et al. (Popovics, Lee, Song and Achenbach, 1998) measured the longitudinal wave velocity and the Rayleigh wave velocity simultaneously using the one-sided technique. In that technique, the striker, driven by a DC powered solenoid, was used for generating elastic waves with controlling condition of striking for impact, however the generated elastic waves were not consistent. The principle of the one-sided technique is described in Figure 1. Transient elastic waves are generated from the impact source by dropping a steel ball, striker driven by DC powered solenoid or pulse laser beam illumination. There are various modes of elastic waves generated in the material and its surface, such as longitudinal wave, shear wave, creeping wave, and Rayleigh wave. The creeping wave is the longitudinal mode wave on the surface and the Rayleigh wave is the shear vertical mode wave on the surface. The creeping wave and Rayleigh wave are simultaneously obtained by two PZT on the surface. The velocities of these waves are calculated from the distance between the two sensors and time delay of each wave arrival.

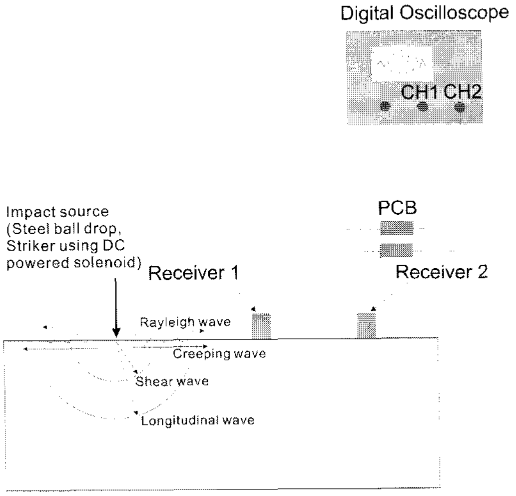


Fig. 1 Schematic diagram of the generation and reception of the transient wave using one-sided technique.

2.2. Self-compensated Technique

Two receivers are placed along a line on the surface of the specimen as shown in Figure 2. A shock excitation of thermal expansion is applied at location A by a pulse illumination of a Nd:YAG pulse laser. The elastic waves induced by the thermal expansion through the solid will be observed by the receiver, R1 at location B and the receiver, R2 at location D, subsequently. In frequency domain, the signal, V_{AB} detected by the receiver, R1 at location B can be represented as a simple product of terms, where S_A the generating response term, R_B the receiving response function, and d_{AB} the signal transmission function, respectively.

$$V_{AB} = S_A d_{AB} R_B \tag{1}$$

As the waves propagate between the two receivers, R1 and R2, some of the energy will be dissipated and as a result, the wave amplitude will attenuate. Therefore, d_{AB} includes the material attenuation effect. In the same way, the elastic wave signal from the impact source at location A, detected by the receiver R2 at location D is given by

$$V_{AD} = S_A d_{AB} d_{BC} T_{cr} d_{CD} R_D \tag{2}$$

Here $T_{cr}(f)$ is the transmission coefficient of surface waves impinged onto a surface-breaking crack as a function of frequency. The additional elastic wave signals, V_{ED} and V_{EB}, can be similarly obtained from the other side where V_{ED} and V_{EB} denote the signals of the impact source at location E, detected by the receivers R2, R1 at location D and B, respectively.

$$V_{ED} = S_E d_{ED} R_D \tag{3}$$

$$V_{EB} = S_E d_{ED} d_{DC} T_{cr} d_{CB} R_B \tag{4}$$

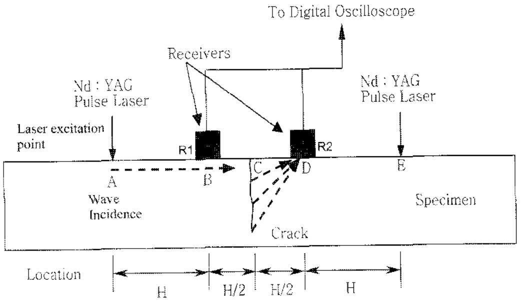


Fig. 2 One-sided, self-compensated surface wave transmission measurement set-up

If each of two receivers R1 and R2 locates at the same distance from the location of the surface-breaking crack, C, the signal transmission functions d_{BC} and d_{CD} become identical to d_{DC} and d_{CB}, respectively. Consequently, the expression for the signal transmission between the location B and D, d_{BD}^{cr}, can be obtained as following.

$$\left|d_{BD}^{cr}(f)\right| = \left|d_{BC}T_{cr}d_{CD}\right| = \left|\sqrt{\frac{V_{AD}V_{EB}}{V_{AB}V_{ED}}}\right| \qquad (5)$$

The transmission response, d_{BD}^{cr}, is a function of frequency and can be determined as the amplitude ratio of the signals from each of two receivers R1 and R2 for the two different source location, A and E. Thus, when transmission response becomes 1, this indicates that there is no attenuation of the elastic waves between location B and D whereas zero transmission response means no transmission of the elastic waves. In addition to that, surface waves are reflected and scattered by the presence of the surface-breaking crack. Therefore, the value of the transmission response, d_{BD}^{cr}, becomes smaller as the depth of the surface-breaking crack increase.

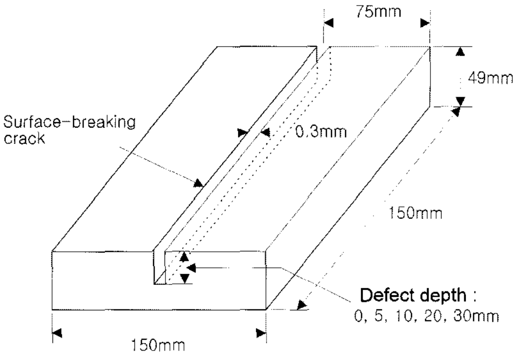


Fig. 3 Dimension of specimen

3. Specimen and Experimental Set-up

The dimension of a thick steel plate (SM400) used in this study, is presented in Figure 3. EDM notches with different depths were machined as artificial surface-breaking defects, as shown in Figure 3. The depths of these surface-breaking defects were 0 mm (no defect), 5 mm, 10 mm, 20 mm, and 30 mm respectively.

Two accelerometers are used as receivers, which are mounted at location B and C respectively and capture the surface elastic waves on the specimen. The nominal resonant frequency is 80 kHz, and the diameter is 5.6 mm. A wax is used as coupling medium between the receivers and the surface of the specimen. The surface-breaking defect is placed at the center between the two receivers, at the same distance from each receiver, as shown in Figure 4. 100 waveforms were captured and averaged to reduce noise in the digital oscilloscope (LeCroy 9310A) synchronized with Q-switch trigger of the Nd:YAG pulse laser. FFT of the averaged waveform was performed in PC for data manipulation.

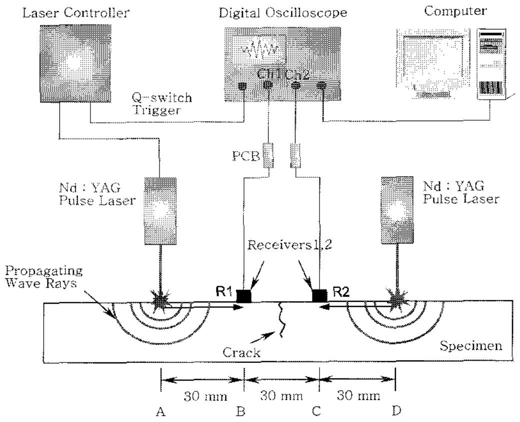


Fig. 4 Schematic diagram of experimental setup

4. Surface Wave Signal Transmission Measurement

The elastic waves generated by the single shot illumination of the pulse laser propagate in all directions through the specimen. Some wave components propagate along the surface of the specimen while others propagate into the specimen and reflect from free boundaries. Figure 5 shows a typical time domain signal generated by the pulse laser at the location A and obtained from the receiver, R1 mounted on the surface. The signals are sampled over 50 μsec time period. As seen in Figure 5, Q-switch trigger signal appears prior to the captured elastic wave signal. The creeping wave and the Rayleigh wave arrived at 5 μsec, and 10 μsec, respectively.

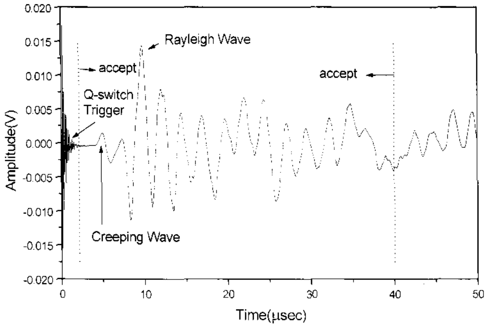
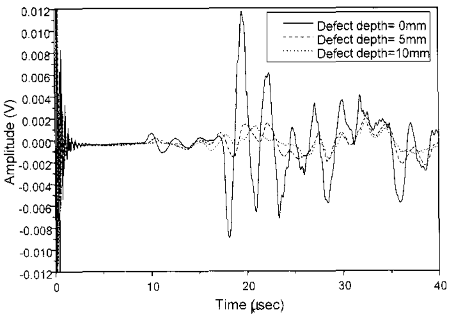


Fig. 5 Typical experimental waveform detected by R1 (Signal excited at the location A, V_{AB} in time domain)

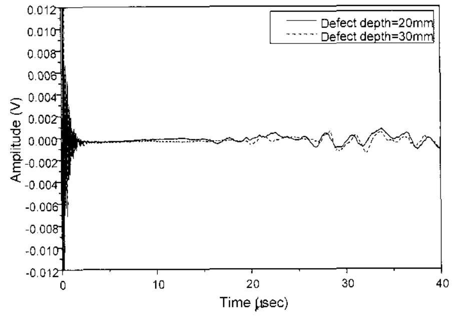
The time domain signal from 4 μsec to 40 μsec, excluding components of the Q-switch triggering noises, was selected to determine the signal transmission through FFT and the Eqs (1)-(5). There could be the longitudinal wave signal and the shear wave signal reflected from bottom. These waves had two times of propagating path and 30 degree angle in this thick specimen. In this selected time range, the shear wave could not be included and the longitudinal wave could be ignored since the longitudinal wave has little intensity at about 30 degree in directivity of laser-generated ultrasonic waves. The amplitude of the creeping wave is negligible compared to one of the Rayleigh wave. Thus, the Rayleigh wave is dominant in the captured signal. Therefore, as intended the experimental data of signal transmission, d_{BD}^{cr} will be mainly influenced by the component of Rayleigh wave.

5. Evaluation of Defect Size With Surface Wave Signal Transmission

The self-compensated surface wave transmission technique by laser-generated ultrasound was applied to evaluate the surface-breaking defect. The waveforms of the surface waves excited at the location A were monitored at the location C as shown in Figure 4. Figure 6 represents the comparison of signals with respect to the variation of defect depth. The amplitudes of the surface wave become lower as the defect depth increases. This is because the surface wave is scattered more by deeper defects, resulting in more attenuation.



(a) Defect depth = 0 mm, 5 mm, 10 mm



(b) Defect depth = 20 mm, 30 mm

Fig. 6 The comparison of signals with respect to the variation of defect depth

V_{AB} is a signal of the surface waves in frequency domain which was generated at the location A and captured at the location B. V_{AC} is a signal of the surface waves in frequency domain which propagates from the location A to the location C. Similarly, V_{DC} and V_{DB} are the signals of surface waves in frequency domain from the location D to the location C and from the location D to the location B, respectively. $V_{AB}V_{DC}$ which is factor of mainly Rayleigh wave not affected from the defect. However, there could be the creeping wave reflected from the defect. This creeping wave component could be negligible since the amplitude of creeping was little and the creeping wave was weakened by enveloping with window function in FFT procedure because of the creeping wave's arrival at the end of time range. $V_{AC}V_{DB}$ which is factor affected from the defect in the transmission are shown in Figure 7. The amplitude of signal should be reduced by the increasing the length of propagation path. However, the amplitude of higher frequency than 170 kHz did not obey this trend of the amplitude, because of scattering through propagation, etc. In this study, the components of frequency domain signals less than 170 kHz were accepted for the signal transmission values.

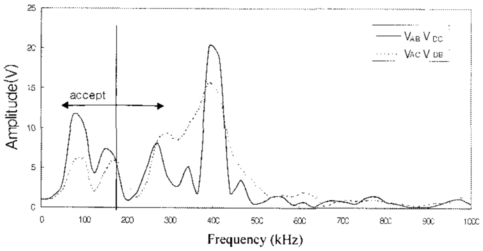


Fig. 7 Frequency response by self-compensated technique (defect depth: 0 mm)

The signal transmission as a function of frequency is plotted with respect to the variation of the defect depth, in Figure 8. The values of the signal transmission are less than 1.0, even in the case that defect depth is zero. This is due to the scattering of the elastic waves and dissipation of the energy in propagation between the two receivers. In addition, this shows that the frequency range less than 170 kHz is acceptable in case of defect sizes such as 5, 10, 20 and 30 mm. The behavior of the signal transmission for a higher frequency than 40 kHz shows that increase of the depth of the surface-breaking defect leads to reduction of the surface wave transmission across the defect. Therefore, the signal transmission obtained by the self-compensated technique could be capable of estimating the defect depth. The signal transmission was not proportional to the depth of defect but it was varied by frequency. When the frequency was about 100 kHz, the signal transmission has decreased proportionally by increase depth of defect. However, the signal transmission at 170 kHz has an inverse proportion due to the increase of defect depth. Since the surface wave has most energy in shallow region of a few wavelengths from surface, the signal transmission value due to the increase of defect depth was decreased rapidly by the increase of the frequency.

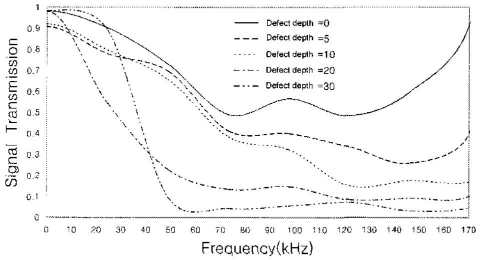


Fig. 8 Signal transmission as a function of frequency

6. Conclusion

The laser generated elastic wave with a good experimental reliability was employed to enhance the inconsistency of conventional ball-drop test. The reasonable signal transmission data were obtained by combining the self-compensated technique and the one-sided technique based on the use of a pulse laser for the elastic wave generation. The trend of the signal transmission shows a good correlation with variation of the surface-breaking defect depth. Thus, the self-compensated technique by the pulse laser was a promising tool to estimate the size of the surface-breaking defect when only one surface is accessible.

Acknowledgement

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