Detection of a Surface-Breaking Crack Depth by Using the Surface Waves of Multiple Laser Beams

Seung-Kyu PARK [1], Yong-Moo CHEONG [1], Sung-Hoon BAIK [1], Hyung-Ki CHA [1], Sung-Hoon LEE [2] and Young-June KANG [2]

[1] *Korea Atomic Energy Research Institute, 1045 Daedeokdaero, Yuseong-gu, Daejeon 305-353, Republic of Korea*

Phone: +82-42-868-8225, E-mail: skpark4@kaeri.re.kr

[2] *School of Mechanical Engineering, Chonbuk National University, Duckjin-Dong 1 ga, Duckjin-Gu, Chonju, Chonbuk 561-576, Republic of Korea*

Abstract

A laser ultrasonic system is a non-contact inspection device with a long stand-off distance and it is applicable to hard-to-access locations such as in a nuclear power plant. In this paper, multiple surface waves generated by line-shaped multiple pulse laser beams are adopted to precisely detect a surface-breaking crack with its depth information. When a surface crack is positioned at the center of multiple pulse laser beams, acquired surface waves are composed of two parts, a reference part and a data part. The reference part is the front part of the acquired multiple surface waves and the data part is the rear part of the surface waves. Detail crack depth information can be extracted from the normalized multiple surface waves by using the reference part. The crack depth information is extracted by acquiring the difference between two peak frequencies of the reference and the data signal. Also, during a scanning test, we can elucidate a crack advent by observing the amplitude variation and frequency spectrum variation of the multiple surface waves when the crack is positioned in the range of the multiple pulse laser beams.

Keywords: Laser ultrasonic, Multiple surface waves, Crack depth, Surface-breaking crack, Reference part, Data part

1. Introduction

Nondestructive detection of small cracks is one of the key issues for industrial applications. Numerous ultrasonic detection techniques based on contacting or non-contacting techniques have been developed for crack detections. A surface wave has been widely used for the detection of small surface-breaking cracks by using conventional contacting transducers. These techniques, to detect crack depth information, have usually adopted crack reflection or transmission coefficients[1, 2].

A laser generated ultrasonic inspection, one of the several non-contacting detecting techniques, is a fully non-contact inspection method with large stand-off distances. This method remotely generates ultrasound by using a pulse laser beam and it remotely measures the generated ultrasound by using a laser interferometer. Laser generated ultrasonic technique has also adopted the reflection and transmission signals from a surface crack to detect a crack. Laser generated surface wave is usually used to detect small surface cracks by monitoring an amplitude variation of the reflected or transmitted signals[3, 4]. A scanning laser source which monitors drastically changing amplitude caused by interferences among transmitting and reflecting ultrasonic signals nearby a surface crack has also been used to detect a small surface crack[5]. In the near field, a surface-breaking crack can also be detected by observing the signal variation of the laser ultrasound[6].

Many data or averaged data is needed to detect and analyze a crack because the amplitude variation of a ultrasound signal is usually very high. From the acquired ultrasonic signal data, a normalization technique is needed to improve the measurement resolution of the crack depth information. Laser generated ultrasound provides a comparatively low signal-to-noise ratio when compared with the conventional PZT based contacting transducer. So, a line-shaped pulse laser beam is usually used to generate a laser ultrasonic surface wave with a high signal-to-noise ratio[7].

In this paper, we used a series of line-shaped multiple pulse laser beams to generate laser surface waves with an improved signal-to-noise ratio and to accurately detect a surface crack through a normalization of the acquired laser surface waves where the front part of the laser surface waves, that had not been passed through a crack, were used as a reference signal and the rear part of the signals, that had been passed through a crack, were used as a data signal. A crack advent can be detected by a real-time monitoring of a signal variation in the time domain and frequency domain when a crack is in the range of the multiple pulse laser beams during scanning inspections. The crack depth information can be extracted by acquiring the difference values between two peak frequencies in the reference signal and in the data signal. We have carried out detection experiments for a surface-breaking crack whose depth is from 100 ㎛ to 500 ㎛. As for the experimental results, we have confirmed that this method is effective.

2. Configuration of the laser generated ultrasonic inspection system

The block diagram of a fabricated laser ultrasonic system is shown in Fig. 1. This system is configured by using a pulse laser (Quantel-Brilliant), a CFPI (Confocal Fabry-Perot Interferometer, CFT-500, Buleigh) with a CW laser, a dynamic stabilizer and a computer. The multiple surface waves are generated whenever line-shaped multiple pulse laser beams are targeted onto the surface of an object through a grating and a focusing lens of L_o. Then, the CFPI measures the surface displacement caused by the multiple surface waves at the target position of a CW laser beam. The linear polarized CW laser beam is focused onto the surface of an object after passing it through a half wave plate (HWP), a polarized beam splitter (PBS), a quarter wave plate (QWP) and a focusing lens (L_1). And then the backscattered light enters the CFPI cavity after passing it through the L1, QWP and PBS. The ultrasonic signal will be detected after the laser beam is demodulated by the CFPI. The transmitted optical signal is converted to an electrical signal by a detector (APD : C3090E, PerkingElmer Inc.). The high-speed A/D converter (AL82G, ALI Inc.) is synchronized by a targeting pulse laser beam which is captured by a photo sensor of the trigger.

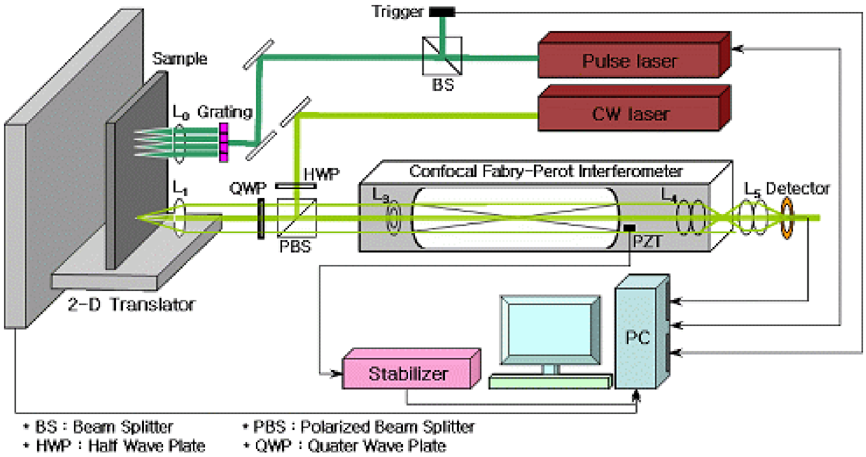


Fig. 1 The block diagram of the configured laser generated ultrasonic inspection system

The computer digitizes the analog signals to the digital signals by using a high speed A/D converter. By virtue of the dynamic stabilizer, the computer captures the ultrasound at the maximum gain time of the CFPI whose gain is varied periodically [10]. The optimum period of the pulse laser is 10 Hz and the full-width at the half-maximum (FWHM) of the pulse laser beam is about 10 ns. The computer processes the ultrasonic signal in a real time to extract the depth information of a surface-breaking crack.

3. Experiments to detect a surface-breaking crack

We artificially made a crack sample on polished stainless steel 304 for the experiments. The crack depths are no crack, 100μm, 200μm, 300μm, 400μm and 500μm for a sample. The crack widths are all 300μm. We used line-shaped multiple pulse laser beams of 6 lines each of whose step distance is 1mm and length is about 10 mm to generate ultrasound with a strong directivity. The energy of each line-shaped pulse laser beam is about 16 mJ. We used a stabilized CW laser beam to measure the laser ultrasound. The energy of the CW laser beam is about 380 mW. The experimental set-up to detect a surface-breaking crack is shown in Fig. 2.

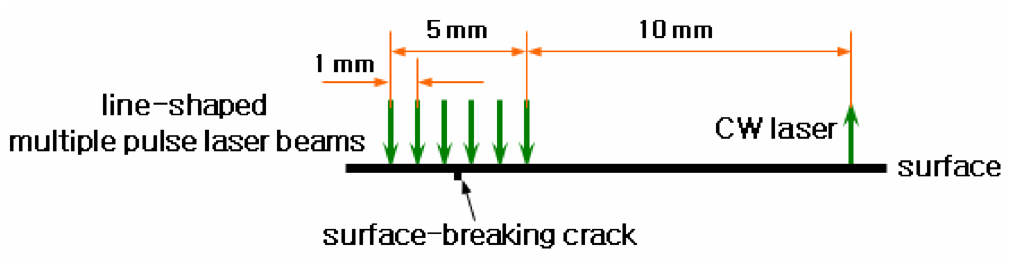
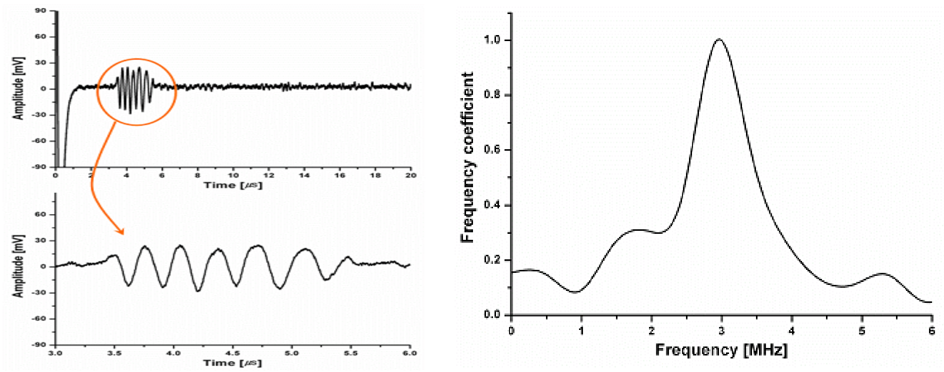


Fig. 2 Experimental set-up to detect a surface-breaking crack.

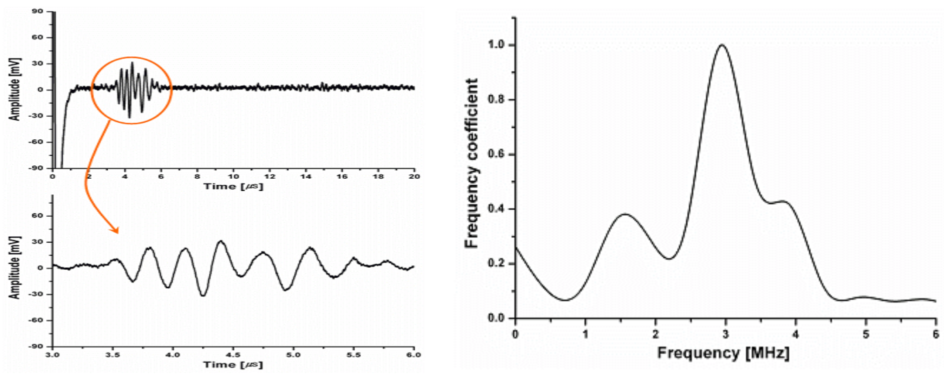
The acquired ultrasound by using the CFPI is the differential value for a surface movement. The distance between the 1st line-shaped pulse laser beam and the measuring laser beam is about 10 mm. The crack is detected when the crack is positioned in the middle of the line-shaped pulse laser beams of 6-lines.

The acquired laser surface waves and their normalized frequency spectrum for the no-crack sample are shown in Fig. 3. As shown in Fig. 3, there is a peak frequency for the 1st main ridge with a maximum peak because the surface waves have a similar pattern to the sinusoidal waves with one main frequency. The acquired surface waves and their normalized frequency spectrums for the crack depth of 100 μm are shown in Fig. 4 and the results for the crack depths of 200 μm, 300 μm, 400 μm and 500 μm are shown in Fig. 5, respectively. In each frequency spectrum, we can see a 2nd ridge whose peak frequency is lower than the peak frequency of the 1st main ridge. This 2nd ridge is produced from the laser surface waves that were passed through a surface-breaking crack. So, the high frequency components are decreased in the 2nd ridge.



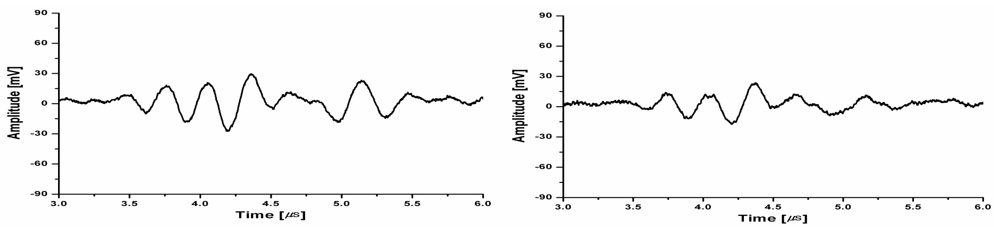
(a) Measured ultrasonic signal (b) Normalized frequency spectrum

Fig. 3 Laser surface waves for the no-crack sample.

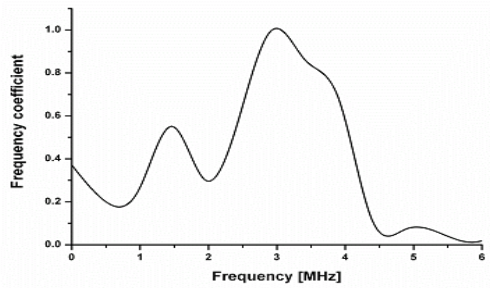


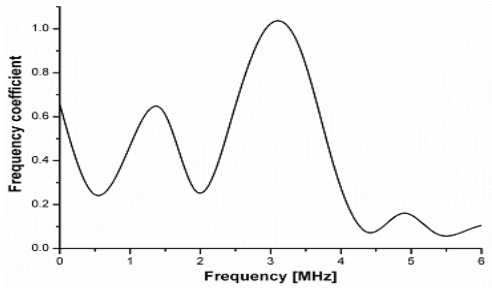
a) Measured ultrasonic signal (b) Normalized frequency spectrum

Fig. 4 Laser surface waves for the crack depth of 100 μm.

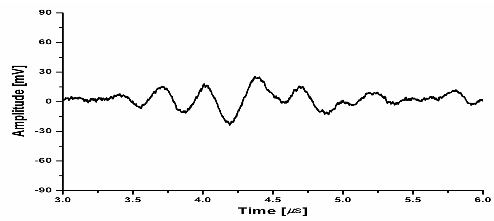


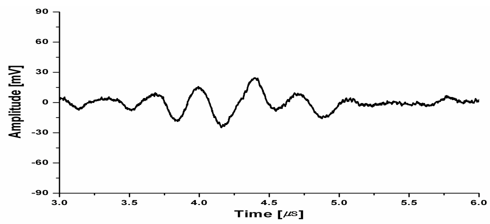
(a) Signal - crack depth of 200 μm (b) Signal - crack depth of 300 μm



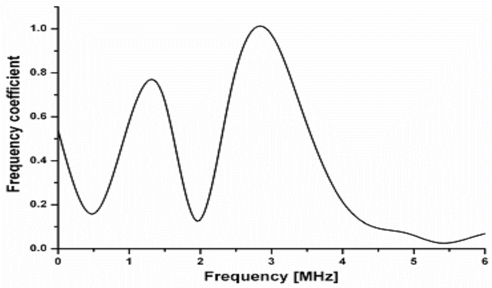


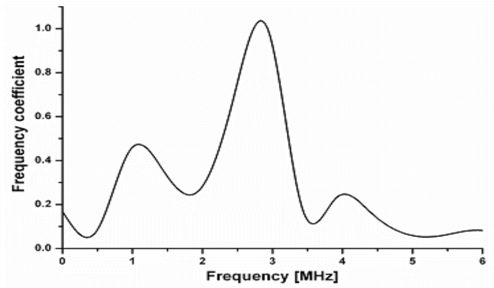
(c) Spectrum - crack depth of 200 μm (d) Spectrum - crack depth of 300 μm





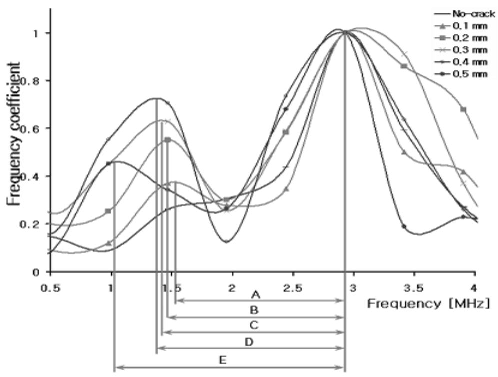
(e) Signal - crack depth of 400 μm (f) Signal - crack depth of 500 μm

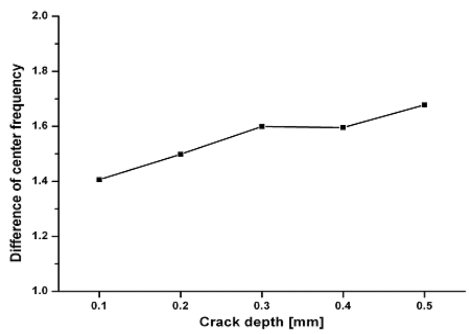




(g) Spectrum - crack depth of 400 μm (h) Spectrum - crack depth of 500 μm

Fig. 5 Laser surface waves on the crack depth from 200 μm to 500 μm.





(a) Normalized frequency spectrum (b) Difference frequency

Fig. 6 Normalized frequency spectrum and difference frequency according to crack depth.

We can elucidate a crack advent by observing the signal variation of the surface wave in the time domain or by observing the advent of the 2nd ridge in the frequency spectrum. The decreasing rate of the high frequency components in the 2nd ridge is increasing in proportion to the crack depth because the propagating skin depth of the surface wave is in inverse proportion to its frequency. So, we can calculate the crack depth information by extracting the difference between the peak frequency in the 1st ridge and the peak frequency in the 2nd ridge. The normalized frequency spectrum according to the crack depth from no-crack to 500 μm is shown in Fig. 6 (a). The extracted difference in the frequency spectrum, A, B, C, D and E of Fig. 9, according to the crack depths from 100 μm to 500 μm is shown in Fig. 6 (b).

The variation of the amplitude signal and its frequency spectrum components in a conventional ultrasonic signal is usually high. So, many data or averaged data is needed to analyze a crack. But in this experiment, by extracting a referenced difference value between two peak frequencies in the 1st ridge (a reference signal) and 2nd ridge (a data signal) in the frequency spectrum, we can acquire precise crack depth information.

4. Conclusion

We have carried out experiments for the detection of a surface-breaking crack by using line-shaped multiple pulse laser beams. We configured a laser generated ultrasonic inspection system by using a pulse laser with a slit providing multiple laser beams of 6 lines and a CFPI with a CW laser for the experiments.

A crack advent can be captured by observing the signal variation in the time domain or by monitoring the advent of the 2nd ridge in the frequency spectrum. The crack depth information can be extracted by calculating the relative difference value between the peak frequency of the 1st ridge and the peak frequency of the 2nd ridge in the frequency spectrum. The extracted difference values provided precise crack depth information when compared to the conventional ultrasonic signals because the value of the relative difference is robust for noises.

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