NONDESTRUCTIVE EVALUATION OF CLOSED CRACKS USING AN ULTRASONIC TRANSIT TIMING METHOD

J. Takatsubo[1], H. Tsuda[1], B. Wang[1]

[1]National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan

Abstract: In this study, we investigated a method for the non-destructive detection of cracks based on an ultrasonic transit timing method. This method is considered to be an effective means for crack monitoring over an extensive coverage area. Aluminum specimens were prepared with a range of crack sizes and subjected to a tone burst wave to investigate the relationship between crack depth and the transit time difference of the surface wave. A good correlation was obtained between these two variables. The dependence of transit delay time on frequency was also examined over the frequency range from 500kHz to 5 MHz. The results showed that greater transit time differences occurred in the lower frequency range less than 1MHz. With these frequencies, ultrasonic waves can travel over a long distance with little attenuation and are better suited for crack monitoring over an extensive area. The technique was applied to real-time monitoring of fatigue crack growth in stainless steel specimens and found to be useful for crack detection.

Introduction: Cracks in machineries and other structures do not usually lead to direct destruction, but affect the safety until the cracks grow to a certain size. With the exception of unavoidable disasters such as earthquakes, many damaging and destructive accidents are caused either by overlooking large cracks, or by a failure to detect the growth of known cracks. The allowable size of a crack depends on the material and the shape of the crack. With respect to nuclear facilities, allowable crack sizes range from several mm to several scores of mms [1], [2]. Periodic inspection with nondestructive techniques such as ultrasonic inspection is a useful method for detecting the presence of cracks. However, periodic inspections are not usually carried out on a daily basis and therefore potentially serious cracks may remain undetected. Furthermore, it is often difficult to predict when and where a crack will occur, and the area of monitoring may be very large. Clearly, there is a need for monitoring systems that can regularly and reliably detect cracks in mechanical structures. Such systems could also potentially provide economic benefits by reducing maintenance costs and increasing the life of the structure.

Many studies have reported the use of ultrasonic waves for crack detection. Cook proposed a method for detecting small fatigue cracks using an amplitude change of Rayleigh waves [3]. Himawan used maximum

[1] ADDRESS CORRESPONDENCE TO: Structural Health Monitoring Research Group, Research Institute of Instrumentation Frontier, AIST,1-1-1, Umezono, Tsukuba Central 2, Ibaraki-ken, 305-8568, JAPAN

Abstract Number: 246

Name: Junji TAKATSUBO,
Phone: +81-29-861-3067, Fax: +81-29-861-3126, E-mail: takatsubo.j@aist.go.jp

amplitude of reflection echo due to cracks to evaluate them quantitatively [4]. Salam proposed an ultrasonic shear wave method for sensitive detection and sizing of small closed cracks [5]. Kawashima have investigated a nonlinear ultrasonic method to detect closed cracks with leaky surface wave [6]. Although these methods are useful for detecting and sizing cracks using portable equipment, they are not suitable for monitoring over large areas because they require several sensors or water dipping or scanning in order to detect flaws.

Two important considerations for the development of novel crack monitoring techniques are reliable detection and accurate measurement of cracks. However, crack monitoring systems capable of performing both of these functions are very expensive, and therefore it is considered more practical to divide these functions into A) primary monitoring, which seeks to detect cracks, and B) secondary monitoring, which attempts to accurately measure crack dimensions. It is desirable that primary monitoring can be carried out using remote automatic measurement system, can be applied over an extensive surface area, and is low cost and simple to operate. The major requirement for secondary monitoring is that it can be carried out quickly and with high accuracy of measurement. Secondary monitoring involves the measurement of known cracks with portable equipment.

Our study was carried out with the goal of developing a primary monitoring system. An ultrasonic transit timing method was used for detecting cracks over an extensive area. For open cracks (such as slits), the surface wave is known to diffract around the crack, causing an echo at the crack tip. This echo can be measured with sufficient sensitivity that the crack can be detected based on the change in the transit time of the wave. However, for closed cracks, the ultrasonic wave passes directly through the crack due to contact at the crack interface. The resulting ultrasonic wave is therefore very weak [7]. Visualization of ultrasonic propagation around cracks [8] revealed that the transit time of the ultrasonic wave increases slightly when the wave transits the closed-crack interface. This time difference is dependant on the frequency of the incident wave and is more pronounced in the low-frequency region of less than 1 MHz. Ultrasonic waves in the wavelength range of several hundred kHz are routinely used for crack inspection of concrete and are considered suitable for monitoring extensive areas because they can travel long distances with little attenuation. In this paper, we report a method for the nondestructive evaluation of fatigue cracks that makes use of the transmission time difference.

Propagation Behavior of Ultrasonic Waves around a Crack: Using a laser-based ultrasonic visualizing system [8], we observed the propagation behavior of ultrasonic waves around both slit and fatigue cracks. The propagation characteristics of the two crack types were then compared. The samples used for the ultrasonic visualization are shown in Fig. 1. Compact Tension (CT) specimens with fatigue cracks were used to investigate closed cracks. After generating fatigue cracks in the specimens by applying a load of 15 kN at a frequency of 10 Hz, we cut the specimens as shown in Fig. 1. To investigate open cracks, the specimens were treated with electric discharge machining. This resulted in a slit crack of a width 0.3 mm. The material used to produce both specimens was aluminum alloy. An angle beam transducer with a frequency of 5 MHz (90º) was

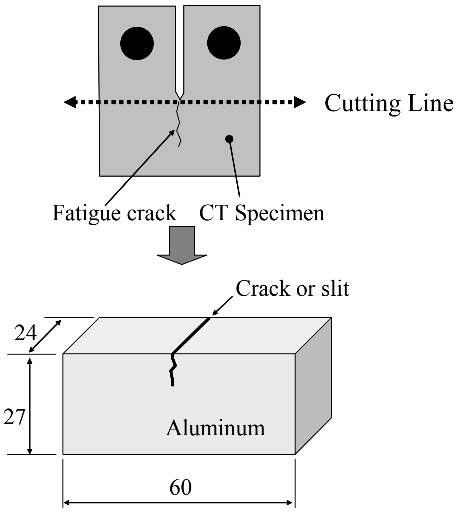

Fig.1 Preparation of cracked specimen

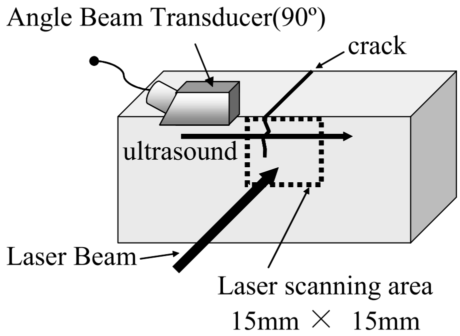

Fig.2 Scanning area of laser beam, and mounting position of an angle beam transducer for visualizing ultrasonic waves.

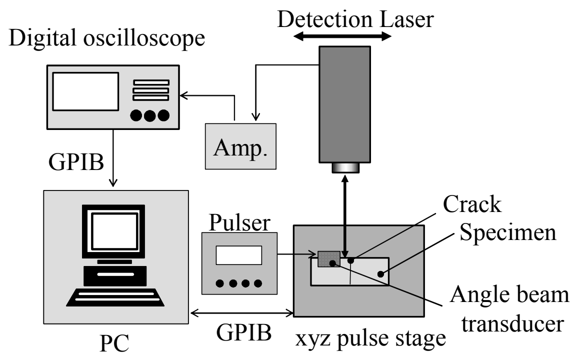

Fig.3 Heterodyne optical system for visualization of ultrasonic waves

attached as shown in Fig. 2. Short-pulse ultrasonic waves were generated by the transmission of spike waves from the pulse generator. A heterodyne optical system (Fig. 3) was used to measure the waveform displacement of the ultrasonic wave propagating through a 15×15 mm area of the specimen. The measurement pitch was set at 0.15 mm. The displacement waveform data was stored on a computer using a digital oscilloscope. After completion of each measurement, displacement data acquired at an arbitrary time at all measurement points were intensity-modulated and displayed synchronously on a PC screen. The propagation behavior of the ultrasonic waves could be visualized using this method. The visualized images obtained using this technique are shown in Fig. 4. The slit (fatigue crack) depth was 6.0 (5.2 mm) for these images. As Fig. 4 clearly indicates, although ultrasonic waves for slit crack propagate by diffracting the tip of the slit, the waves for fatigue crack were found to pass through the interface. Few ultrasonic waves were found to detour the tip of the fatigue crack. The technique, measuring the diffracted waves across the tip of the crack was therefore considered to be of little use for the detection of closed cracks.

Further studies investigating the propagation behavior of ultrasonic waves across fatigue cracks showed that the slight delay of transit time appeared when ultrasounds across the crack interface. To explain this observation, there may be some areas where the crack interfaces are in contact, and other areas where they are

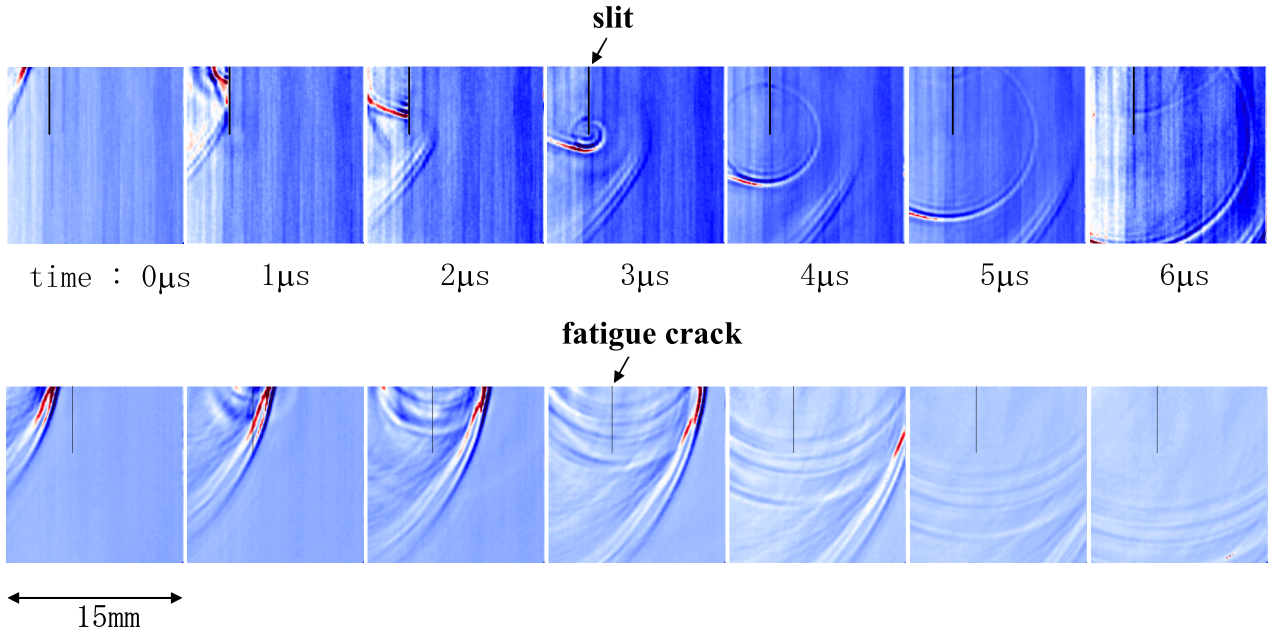

Fig.4 Propagation images of ultrasounds measured around a slit (or fatigue crack). The depth of the slit (or the fatigue crack) is 6mm (or 5.2mm).

not in contact. Ultrasonic waves can only travel across areas where the interfaces are in contact. This might explain the delay in transit time observed in our experiments. The relationship between the delay in transit time and crack depth is discussed in the following section.

Transit Time Delay of Ultrasonic Waves Passing through a Crack: Differences in the ultrasonic waveform propagation characteristics of slit cracked, fatigue cracked and undamaged specimens were investigated. As shown in Fig. 5, transmission and reception angle beam transducers (90º) were positioned on either side of the

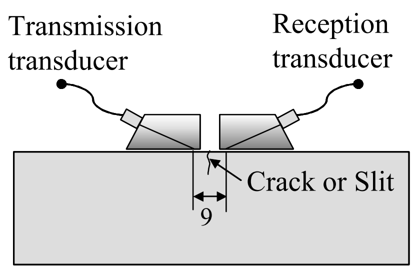

Fig.5 Transducer position for the measurement of burst waves passing through a fatigue crack.

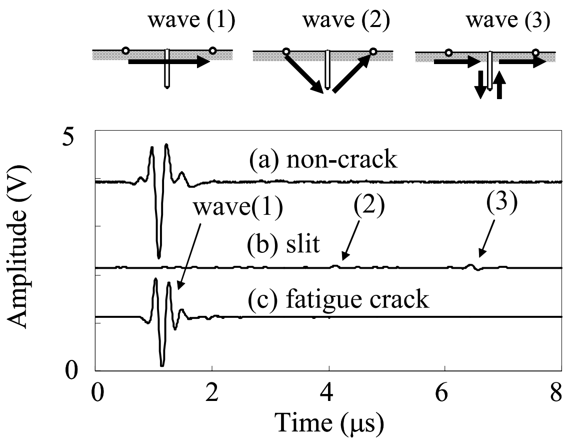

Fig. 6 Ultrasonic waveforms passing through (a) undamaged, (b) slit cracked, and (c) fatigue cracked specimens.

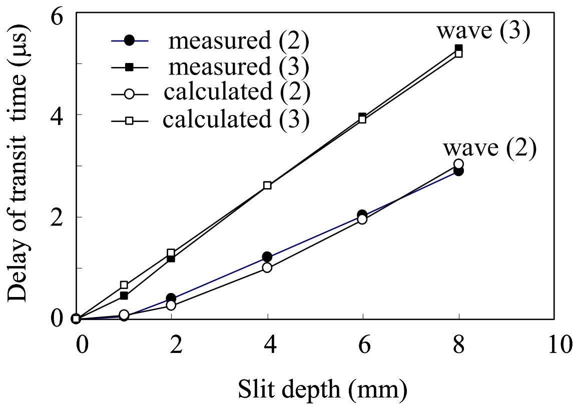

Fig.7 Relationship between slit depth and delay time of ultrasound passing through slits.

crack, at 9 mm intervals. Short-pulse ultrasonic waves were generated by transmitting a spike wave with amplitude of 250 V from the pulse generator. Figure 6 illustrates examples of the propagated waveforms. The slit (crack) depth was 8.0 mm (7.0 mm). For the fatigue-cracked specimen, most of the waves transited the interface (wave (1)) and therefore, we could not find a distinct change in the waveform. For the slit crack, the waves were so significantly affected that transit waves were not observed at all, and only the waves that diffracted around the tip of the crack (waves (2) and (3)) could be detected. The sound velocity of the ultrasonic waves was found to be 3080 m/s, which was equal to the sound velocity of the surface wave. Based on a theoretical calculation of ultrasonic propagation time, it is likely that wave (2) propagated along the shortest route that passed through the tip of the slit, and wave (3) propagated along the slit interface. The relationship between the transit time delay of the waves and crack depth was plotted on a graph and compared with the calculated values. Figure 7 presents the results of this comparison. The measured and calculated values were found to agree well for specimens with open cracks (such as a slits), indicating that crack depth can be estimated from the transit time of the waves that are diffracted around the tip of the crack. For specimens containing closed cracks however, waves (2) and (3) were only observed in a few cases, and therefore information regarding the crack must be obtained from the transit wave at the crack interface.

Figure 6 exhibits a slight delay in the transit time of ultrasonic waves that passed through a fatigue-cracked specimen compared to the undamaged specimen. The delay in transit time was found to depend on the oscillation frequency of the ultrasonic wave, as well as the crack depth. The influence of the frequency and crack depth on the transit time delay is discussed in the following section.

Influence of Frequency and Crack Depth on the Transit Time through the Fatigue Crack: To investigate the relationship between transit time and frequency, a 10-cycle tone burst wave was transmitted from the angle beam transducer, and the transit time delay of the ultrasonic waves passing through the crack was measured at several different wavelengths. The amplitude of the burst wave transmitted to the transducer was 50 V. To investigate the influence of crack depth, aluminum-alloy specimens with crack depths of 1.1, 1.5, 3.2, 5.2, and 7.0 mm were prepared as shown in Fig. 1. Figure 8 illustrates an example of the waveform resulting from a 2-MHz burst wave that transited through a fatigue crack with a depth of 7 mm. Similar measurements, carried out on an undamaged specimen, are included for comparison. The amplitude of the wave was much lower in

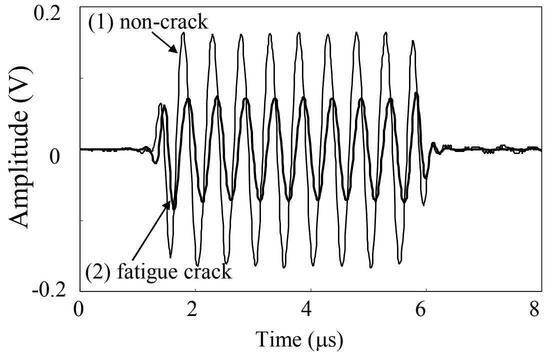

Fig. 8 10-cycle burst waves (2MHz) passing through (1) undamaged and (2) fatigue cracked specimens.

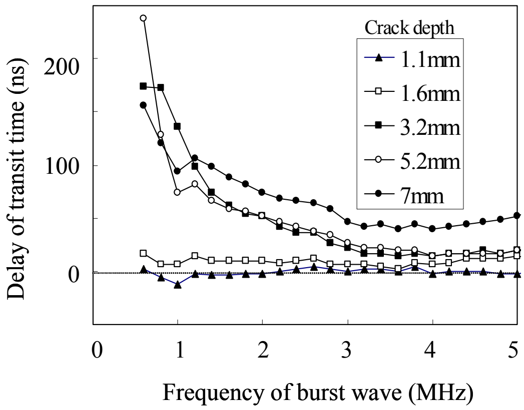

Fig. 9 Effect of burst wave frequency and crack depth on ultrasonic transit times.

the cracked specimen, leading to a delay in transit time. Figure 9 depicts the delay in transit time caused by a crack plotted against the frequency of the burst wave. The transit time recorded for the undamaged sample was used as a reference. A cross-correlation method was used to measure the delay in transit time. Only small delays in transit time were observed in the specimens with crack depths of 1.1 and 1.6 mm. However, significant delays in transit time (10 to 200 ns), were observed in specimens with crack depths exceeding 3 mm. Furthermore, it was found that the lower the frequency, the greater the delay in transit time. For example, the transit time was found to differ 10-fold between 5 MHz and 1MHz.

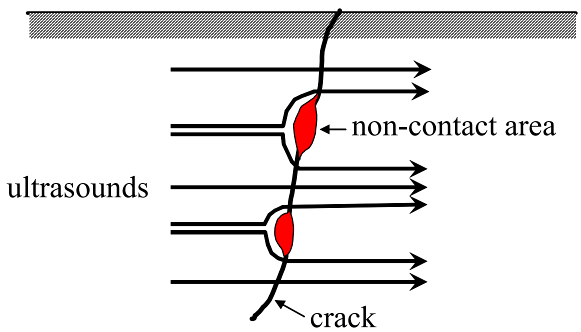

Fig.10 Propagation model of ultrasounds passing through crack interface.

The greater transit times observed at lower frequencies can be explained as follows. Figure 10 demonstrates that when ultrasonic waves arrive at the air layer at the crack interface (non-contact area of the interface), they propagate by detouring the region because they seldom travel in gas. Though ultrasonic waves detour with little attenuation in the low-frequency range, the attenuation is much greater in the high-frequency range. As a result, the ratio of the detour wave to the wave transiting the crack interface is greater for low-frequency as compared with high-frequency waves. Therefore, we can speculate that the transit time is greater for low-frequency waves containing detoured components. Ultrasonic waves in the several hundred kHz range are known to travel long distances. The technique used in this study is therefore likely to be useful for

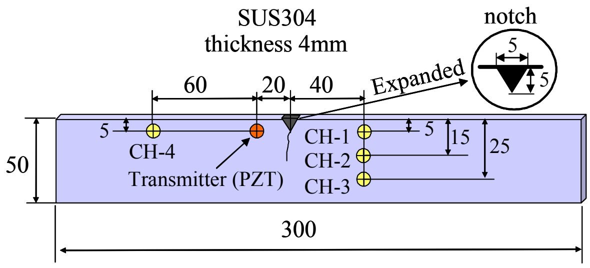

Fig.11 Sensor position for detecting fatigue crack.

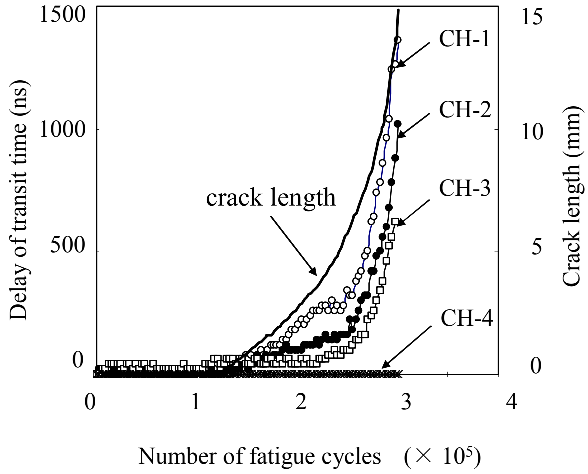

Fig.12 fatigue crack length and delay time of ultrasound at each channel.

crack monitoring over an extensive area. In future research, we plan to evaluate closed cracks in a more quantitative manner. To achieve this, it is necessary to study the relationship between the degree to which the crack is closed, and the ultrasonic wave frequency.

Monitoring Fatigue Crack Growth: To investigate the application of this technique to monitoring crack growth, we conducted a fatigue test on a flat specimen made of stainless steel (SUS304). Variation in the transit time of the burst waves was monitored in real-time relative to crack growth. A PZT sensor with a diameter of 5 mm and thickness of 0.2 mm was used as the transmission transducer. The reception sensor consisted of four AE transducers with outer diameters of 4 mm. Although a wide-band type angle beam transducer was used in the previous section, for this part of the work, a resonant type PZT sensor was used. This type of sensors is considered to be more sensitive for receiving ultrasonic waves. A tone burst wave of the frequency 400 kHz was used. Figure 11 depicts the shape of the specimen and the sensor mounting positions. A triangular notch with a depth of 5 mm was inserted into the center of the specimen and the delay in the transit time of the ultrasonic wave was monitored in relation to the growth of the fatigue crack that developed at the tip of the notch. The delay in transit time was measured by monitoring the transit time in each channel at the start of the experiment. Crack length was measured at the tip of the notch. The fatigue test was carried out by applying a load of 50 kN at a frequency of 2 Hz. This was continued until the crack reached a length of 15 mm. Ultrasonic signals detected in each of the channels were stored on a personal computer at 5 min intervals. The ultrasonic waves were oscillated in the interval of 10 Hz. The detected waveforms were stored in the digital oscilloscope after obtaining an average for 10 waves.

Figure 12 illustrates the relationships between the delay in transit time of ultrasonic waves detected in each of the channels and the crack length. The delay in transit time remained at zero in channel 4 because the ultrasonic signals arrived directly, without passing through the crack. Detectable delays in transit time were observed at crack lengths of 1 to 2 mm on channels 1 to 3. For a crack length of 15 mm, transit delay times ranging from 600 to 1500 ns were observed. The result showed that ultrasonic transit timing method is effective for detecting and monitoring fatigue cracks.

Conclusions: In living organisms, pain caused by an injury is detected by a neural network. In an attempt to develop a system that can feel “pain” when a crack occurs in a non-living structure, we investigated a nondestructive technique making use of ultrasonic signals to detect fatigue cracks. To achieve this, we measured the transit delay time of ultrasonic waves crossing a closed crack interface. Using tone burst surface waves, we found a strong correlation between crack depth and transit time difference. By investigating the delay in transit time in the frequency range from 0.5 to 5 MHz, we found that greater transit time delays occurred at the lower frequency range. Ultrasonic signals with frequencies of less than 1 MHz exhibit little attenuation and can travel over long distances. The results therefore show that the ultrasonic transit timing method described here is an effective method for crack monitoring over an extensive area. This technique was used for the real-time monitoring of fatigue crack growth in stainless steel specimens and was found to be a simple and reliable method for crack detection.

References:

1. K. Kashima, Proc. of Symp. of Maintenance Technology, Vol.2, p.23 (2003), (in Japanese)
2. S. Konosu, Proc. of Symp. of Maintenance Technology, Vol.2, p.27 (2003), (in Japanese)
3. D.A. Cook and Y.H. Berthelot, NDT & E Int., Vol.34, p.483 (2001)
4. R. Himawan, Y. Arai and E. Tsuchida, JSME Int. J., Vol.45, No.4, p.603(2002)
5. M. A. S. Akanda and M. Saka, JSME Int. J., Vol.45, No.2, p.252 (2002)
6. K. Kawashima, R. Omoto, T. Ito, H. Fujita and T. Shima, Ultrasonics, Vol.40, p.611 (2002)
7. M.Saka, Trans. IEE Jpn.、Vol.119-A, No.3, p.241 (1999)
8. J. Takatsubo and M. Imade, Trans. Visualization Soc. Jpn., Vol.22, No.3, p.23 (2002), (in Japanese)