Backscattered Transverse Wave Imaging of Cracked-Faces with Linear and Nonlinear Ultrasonics

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A new backscattered-wave imaging of a cracked-face itself is proposed. Different from the conventional TOFD and phased array techniques, the wave scattered on a rugged fatigue-cracked face and/or intergranular stress-corrosion-cracking, SCC, face is captured in this technique. By focusing ultrasonic beams at every peak on those faces with a point-focused transducer and a scanner and by mapping the scattered-wave amplitudes on the scanned plane, we make an image of the cracked face itself. For tight cracked faces of nm opening, the second and higher harmonic amplitudes, generated by clapping and/or rubbing such a face with finite amplitude burst waves, are mapped in the similar way. By comparing the linear and nonlinear images of cracked faces, we can classify the extent of the crack opening. Some images of fatigue cracked faces are shown. [doi:10.2320/matertrans.I-MRA2007847]

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1. Introduction

Increase in aged civil structures is one of common problems in advanced nations. Those are nuclear power plants, fossil power stations, oil refineries, chemical plants, highway bridges and pillars and so on. For safe operation and service of these structures, nondestructive detection of various damages and flaws, and the evaluation of severity of those damages are key factors.

In particular, the recent introduction of a damage tolerant system for fundamental structural components of in-service nuclear power plants in Japan, is forced to precise nondestructive sizing of fatigue cracks and SCC, stress corrosion cracking. Among various nondestructive testing methods, only ultrasonic method is applicable for in-service evaluation of crack sizing of pressurized structural components.

The precise sizing of intergranular SCC depth of welded steel pipes in plants is sometimes difficult by conventional crack sizing technique, crack-tip echo method with an angle-beam transducer. This problem has been solved to a certain extent by combining TOFD and phased array, PA, flaw imaging techniques. These methods do visualize the top and bottom crack tips with diffracted or reflected waves, however, they can’t image the cracked face itself. Moreover, the tight cracked-faces having gaps of some nm show very low reflectivity due to partial transmission of incident ultrasonic wave.2,3 Each grain facet of intergranular SCC, has different orientation, therefore, the orientation of the reflected or scattered beams at each grain facet does not always coincide with that of the incident wave, even with a phased array transducer. This also results in no or weak received signal, which would lead to underestimation of the crack depth.

To solve this problem, several schemes have been proposed. For example, Saka et al. proposed a technique to make tight cracks open by local cooling or heating. However, it takes some minutes to open the crack. Buck, Nagy, and Solodov showed the tight cracks were detected by nonlinear ultrasonics, namely higher harmonic. However, no quantitative evaluation of crack size has reported with higher harmonics. Kawashima et al. showed the crack depth dependence on the second harmonic amplitude of the leaky Rayleigh wave. Yamanaka et al. showed that sub-harmonic amplitude is very sensitive to crack opening. These paper deals with detection of tight cracks, but no paper shows images of cracked face itself.

In other industrial fields, ultrasonic imaging is widely used. For example, scanning C-scan acoustic microscopes are commonly used for the imaging of delamination of IC packages and breaking of lead wires. In this imaging, longitudinal wave is used in normal incidence. The similar systems are used for delamination detection of CFRP structures. In these testing, the delamination plane is mostly perpendicular to the incident wave direction.

On the contrary, the fatigue cracks and SCC’s in pipes and vessels nucleate at the inner surface subjected to the highest tensile stress, and grow towards the outer surface mostly along the heat affected zone, HAZ, in welds. Such a SCC is not perpendicular to the incident ultrasonic beam, therefore, the test scheme used for delamination detection is not applied for such defects.

The conventional ultrasonic imaging techniques, such as TOFD and PA, utilize reflected and diffracted waves at the crack-face or crack-tip. No imaging technique with scattered wave is utilized for minute defects far smaller than the wavelength, except for damage detection of GFRP.10

Fatigue cracked faces have striations of several microns in pitch, and an intergranular SCC has rugged facets of grain diameter size. The ultrasonic wavelength used in nondestructive evaluation is generally far greater than these sizes, however, we would be able to capture the scattered wave with a focused transducer in water immersion. In addition, we can capture higher harmonics excited at the tight cracks of extremely narrow gaps of nm.
In the previous paper, we have demonstrated the second harmonic images of minute disbonds in bonded interfaces, spall damage under high speed plate impacts, and local fiber/matrix debonding.

In the present paper, we demonstrate scattered wave images of cracked faces itself and the applicability of the higher harmonic imaging for tight cracked-faces.

2. Imaging with Backscattered Transverse Wave

In the present paper, we propose an imaging technique of cracked faces with backscattered transverse wave, as shown in Fig. 1. For the imaging of cracked-face itself, we use a focused transducer in water immersion. When the ultrasonic beam is focused on the every peak on a rugged cracked face, some waves scattered there are received by the same transducer. Of course, the amplitude of scattered wave is far lower than that of the reflected at the crack or diffracted at the crack tip. To receive the weak backscattered wave, we utilize the mode-converted transverse wave. As shown in Fig. 2, the main beam of high energy is reflected away at the water/solid interface. The mode-converted transverse wave excited at the interface is refracted into the solid and a backscattered wave is captured if any defect lies in the ultrasonic beam path. We also capture the wave scattered at the water/solid interface, therefore, we can evaluate the depth of the defect with the time difference between two waves.

This scheme is valid only if the incident beam, the crack face’s normal and the main beam of the backscattering wave lie in a plane. For a plane fatigue crack, this is easily accomplished by adjusting incident wave direction. However, the cracked-facets of intergranular SCC have different orientations with respect to the incident beam, therefore, the configuration mentioned above is not always satisfied.

3. Higher Harmonic Imaging of Cracked Faces

The idea of contact acoustic nonlinearity, CAN, has been proposed by Solodov and applied for nondestructive material evaluation. The key concept is briefly summarized here.

In the measurement of acoustic nonlinearity, higher harmonics in this paper, tone-burst waves of a fixed frequency are transmitted for the material tested, then the higher harmonics excited at the cracked face are captured through a pertinent band-pass or high-pass filter. The higher harmonic amplitudes are generally less than one percent of the fundamental wave amplitude, therefore, the latter must be attenuated by 40–50 dB.

Different from the classic acoustic nonlinearity for nonlinear elastic continuum, CAN is excited by clapping and/or rubbing cracked faces of which opening is less than the incident wave amplitude. The simplified CAN model of clapping is shown in Fig. 3. When the incident amplitude of tone-burst wave is greater than the crack opening, the cracked faces contact under the compressive stress. Thus, only compressive stress is transmitted across the cracked faces, but no tensile stress is transmitted. This strong nonlinearity results in the waveform distortion, namely harmonic generation. In addition to clapping, rubbing of crack faces also generates higher harmonics of odd ordinal numbers.
4. Numerical Simulation of Backscattered Transverse Wave from Cracked Face

A finite element model of wave propagation scattered at a rugged cracked face is shown in Fig. 4(a). A subsurface crack of 10 mm in height is assumed in an aluminum block. Incident wave is 4 MHz short stress pulse of 2 cycles. The subsurface vertical crack is modeled by square voids arranged like a rack shown in the inset. The side length of the void is 40 or 100 µm, which is about 5% or 13% of the mode-converted transverse wavelength. The calculation was performed for a model (b) where the transverse wave was transmitted and received on the top surface.

The results of simulation for the model of voids size of 100 µm are shown in Fig. 5, where the Rayleigh wave is excluded for avoiding the complexity of received waveforms. In the figure, the waveforms of the crack tip diffraction and scattered waves at the cracked face are drawn by shifting time scale to show the level of received wave amplitudes. For the simulation of crack tip diffraction, the crack tip is located at the focal point in Fig. 4(a).

The scattered wave amplitude is about 10% of the crack tip diffraction, however, we can identify the signals. No scattered wave is observed for the smooth cracked face. The frequency of crack tip diffraction wave is 4 MHz, however, that of the scattered wave is about 9 MHz. The latter results from the void geometry, i.e., the pitch of voids is 200 µm and the difference in the ultrasonic beam path length for adjacent corners of the voids is about 140 µm in refraction angle of 45 degree.

5. Backscattered Imaging of Artificial Defects and Cracked-Faces

The key concept of scattered wave imaging with transverse wave of the refraction angle of 45 deg is illustrated in Fig. 6 for a back-surface breaking crack. When the back surface, BS, is a flat plane, we can catch the scattered wave along the direct beam paths, such as 1-T-1, 2-M-2, 3-C-3, and that reflected at BS, such as 4-M'-M'-4, 5-T'-T'-5. By scanning the transducer in the horizontal direction, we obtain the image shown by the thick black bar for the direct scattered wave, and the image shown by thick gray one for
that reflected on the BS. When the crack is vertical, the lengths of the black and gray bars coincide with the crack height. When the crack is inclined left, the image length of direct scattering is longer than that of the reflected at BS and vice versa. For an internal crack, the images of direct scattering and reflected on BS are separated as shown in Fig. 6(b). The change in the beam path length is proportional to that of time-of-flight, TOF.

The validity of the scattered wave imaging was confirmed for artificial defects shown in Fig. 7. These defects of 0.3 mm in gap width were formed by EDM in a SUS 316 plate of 15 mm in thickness. A 10 MHz flat transducer of φ3 and a focused transducer of 10 MHz, φ9.5 and focal length 75 mm were used. Incident angle was 19 deg., therefore the refraction angle is nearly 45 deg. The scattered wave images are shown in the middle and right in the figure. With a flat transducer, we can’t distinguish the respective shape, but we can image those shapes with a focused transducer.

The scattered wave image of a fatigue crack face is shown in Fig. 8 for a 7075 aluminum alloy plate of 10 mm in thickness shown in the right figure. A through-thickness crack was introduced by fatigue test with a mean stress of 30 MPa and a range of stress intensity factor of 26 MPa. A 30 MHz transducer of a focal length 25 mm was used. The refraction angle of transverse wave is 45 deg.

We notice bright region in $2 < X < 14$ mm, which denotes the cracked-face. In the waveform, the signals in 19~20 µs denote the scattered wave at the front surface, and the signals of large amplitude in 20~27 µs correspond to the scattered waves at the cracked-face. The arrival time of the scattered signal from cracked-face is delayed for large X, which means longer propagation distance. This proves the image is constructed by the scattered wave at the cracked-face.

In the conventional angle beam technique with a flat transducer, the echoes from the crack tip and corner shown in Fig. 9 are usually observed for a sample of flat back surface, where the beam path lengths 1-T-T’-5, 2-M-M’-4 and 3-C-3 are the same, therefore, their time-of-flight are theoretically the same. Thus we have, in time domain, the stationary signal shown in the middle of the bottom, when the transducer is scanned in the horizontal direction in a certain range. Therefore, we have similar images shown in the middle of Fig. 7. However, those are the reflection images of cracks.

When the ultrasonic beam transmitted from the point 5 or point 1 reaches to the point T, we have the crack tip signal shown in the bottom left or the skipped tip signal in the bottom right.

Another measurement configuration uses mode-converted waves, as shown in Fig. 10. In this figure, the incident longitudinal wave is partially reflected as transverse wave at the cracked-face, and the transverse wave is reflected again on BS. Finally the wave is received by the same transducer. However, this measurement scheme is difficult to realize, because this scheme hold only at a special incident angle.

6. Higher Harmonic Imaging of Tight Cracked-Faces

When cracked faces are in contact under residual or external stress, the detection of such cracks is difficult due to...
partial transmission of the incident wave across the cracked-faces. We will be able to image the cracked faces by combining the higher harmonics technique described in section 3 with the backscattered wave imaging. For higher harmonics imaging, we have used a tone-burst wave pulser, RITEC RAM-5000, to excite large amplitude wave and a band-pass or high-pass filter to extract higher harmonics, as shown in Fig. 11. We also used RITEC SP-801 broadband pulser for linear imaging. The signals scattered at defects and cracked-faces were amplified by a RITEC BR-640 amplifier, then the amplitudes were mapped with SONIX Flex-scan software. The sample shown in Fig. 8 again used for the higher harmonic imaging.

The incident wave direction is shown in the top left inset of Fig. 12. In this harmonic imaging, a burst wave of 7.5 MHz and 5 cycles were transmitted to the sample, then higher harmonics were captured with a high-pass filter of 14 MHz, by which the fundamental 7.5 MHz component was attenuated by 40 dB. Figure 13 shows schematically the relation among the crack faces, B-scan and C-scan images. The beam paths for the crack tip and the root of V notch are 1-T-1 and 2-C-2, respectively. The C-scan images of the cracked face and V notch edge are shown by the black and gray line, respectively. The corresponding B scan images are expressed by the line Tb-Cb, and Cb-Eb.

In Fig. 12, the left and right figures show the linear and higher harmonic images of the cracked faces. The contrast of the linear C- and B-scan images of the V notch is high, but that of the cracked-face is low. This comes from that the received wave amplitude from the cracked-face is far smaller than that the scattered wave at the surface. The contrast of the linear image of the cracked face is improved due to the beam convergence if a high pass filter of 14 MHz is used.

On the contrary, as shown in the right figure, B- and C-scan harmonic images of the cracked-face have high contrast. Namely, the higher harmonic amplitude from the cracked face is higher than the surface scattering. From the comparison of higher harmonic images and linear ones, we conclude the higher harmonic measurement is useful to detect and image tight crack faces.

7. Concluding Remarks

The new technique of backscattered wave imaging of cracked face itself is proposed and the validity is confirmed for artificial defects and fatigue cracks. By focusing ultrasonic beams at every peak on cracked-faces with a point-focused transducer and a scanner and by mapping the scattered wave amplitudes on the scanned plane, we make images of the cracked face itself. This imaging is also applicable to intergranular SCC.

The combination of the scattered wave technique with higher harmonic imaging using large amplitude tone-burst wave makes possible to clear imaging of tight cracked faces.
The higher harmonic amplitude depends on the average crack opening and compressive stress acting on the cracked face, therefore, we should know the relation the between compressive stress and the higher harmonic amplitude and establish calibration technique for the relation in future.

REFERENCES