ULTRASONIC SMALL INCIDENCE METHOD AS A TOOL FOR SENSITIVE EVALUATION OF TIGHTLY CLOSED SMALLER FRONT/REAR-WALL CRACKS

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Abstract

The paper reviews the potential of the ultrasonic small incidence method of testing, which enables us to characterize smaller tight cracks quantitatively under load-free conditions. Recently, an important characteristic of the method of being capable of evaluating the cracks from both the accessible and inaccessible sides of material structures with almost similar level of sensitivity, has been identified. Experimental verification is performed through the evaluation of smaller open as well as tightly closed rear and front-wall cracks in stainless steel samples. Tight closure of the crack is verified by comparing the measured results with those of identical open crack.

1. Introduction

Sensitive nondestructive evaluation (NDE) of small cracks in actual structures is an important practical issue. Most of the cracks encountered in actual structures, for example, stress corrosion cracking, fatigue cracks, experience crack closing effect. This closure [1] poses significant problems to their reliable characterization under load-free conditions, as most of the usual techniques of evaluation are found to be affected by it. And this problem becomes more serious in the case of smaller cracks, as, in many cases, they are left simply undetected because of the combined effect of their small size and tight closure. A number of authors have reported that opening the cracks by loading is necessary for evaluating the closed cracks. However, the loading is not practical, because in-service the inspection is carried out when structural components are not in operation.

There is a long history of using ultrasonic techniques to evaluate the size of cracks. The potential of using the ultrasonic wave in evaluating the closed cracks has already been recognized and verified by fundamental experiments [2-7]. For the evaluation of closed cracks, a number of testing techniques were reported using both the ultrasonic shear and longitudinal waves, however, few of them [8-9] are found to be successful to evaluate the crack size under a load-free condition. For the purpose of quantitative testing, sensitive detection of the crack is a prerequisite. Increasing requirements for improved defect assessment have established the need for a sensitive testing method for small closed cracks under load-free conditions. In an attempt to enhance the sensitivity of the ultrasonic testing technique, recently the ultrasonic small incidence method of testing [10-11] has been developed, in which the use of an oblique longitudinal wave with a small angle of incidence upon the object surface is emphasized. Recent researches and discoveries in using the new ultrasonic method of testing have generated much renewed interest in the field of NDE of small cracks [12-15].

In many practical cases, it is found that the access is restricted, that is, both the front and rear-wall sides of the test component are not accessible to the investigator, rather either of them is usually appeared as the measuring surface. Although the ultrasonic testing is generally recognized as being the preferred method for the non-destructive evaluation of cracks, especially when the access is limited, however, none of the standard techniques is found to be reliable and equally effective for the sensitive detection as well as evaluation of the closed cracks from both the accessible and inaccessible sides of the test object under a load-free condition.

The present research is an attempt to overcome the lack of flexibility of the testing techniques, in which the potential of the ultrasonic small-incidence method has been investigated for the evaluation of the cracks from both the front and rear-wall sides of test objects. It has been identified that the method is capable of evaluating small cracks from both the front and rear-wall sides of material structures with

Table 1: Conditions used for introducing the closed fatigue crack

Sample	t (mm)	K_{Imax} (MPa.m$^{1/2}$)	Crack-plane orientation	Stress ratio, K_r	Frequency (Hz)	Crack depth, a (mm)	Crack length, b (mm)
SS-3	30	22	L-S	0.1	1.0	4.78	22.1

almost similar level of sensitivity. The distinguishing features of the typical small incidence response curve of a closed crack, as observed for the case of front and rear-wall cracks, are discussed in comparison with those of identical open cracks. The capability of the small incidence method is verified through the evaluation of open as well as tightly closed small fatigue cracks in stainless steel samples, having different depths, lengths and also with different wall thickness, under load-free conditions. The results of the present small incidence method are compared with those obtained by the standard method of testing in an attempt to realize the superiority of the present approach in dealing with smaller tight cracks. Finally, in order to verify the tight closure of the crack tested, measured results of the closed crack are also compared with that of an identical open crack.

2. Experimental details

Both the open and tightly closed fatigue cracks are considered for the present study. The open cracks are modeled by extremely narrow EDM slits (width = 0.1 mm) and were extracted from the original samples of austenitic stainless steel (SUS304). Two open cracked specimens, namely, SS-1 and SS-2, having the associated crack depths of a = 0.5 and 4.0 mm, respectively, are considered for the experimental measurement. The specimens were prepared as plates having the dimensions of 230 mm (l) × 35 mm (w) × 15 mm (t). The fatigue-cracked specimen (SS-3) was prepared as plate from the same material of SUS304. Figure 1 shows the geometry of a specimen containing a fatigue crack. A semi-elliptical fatigue crack was introduced at the tip of a semi-elliptical EDM starter notch, and was grown by cyclically loading the plate in four-point bending (tension-to-tension) on the dynamic testing machine. The conditions used for introducing the fatigue crack are listed in Table 1. The stress ratio in fatigue, K_r (= K_{Imin}/K_{Imax}) was maintained during the crack growth. To take tighter closure into account, all the samples were extracted in the L-S orientation of the crack plane. After the fatigue crack initiated, the plate was machined and polished to remove the initial notch, thereby obtaining the final dimension of the specimen (SS-3) as 230 mm (l) × 60 mm (w) × 30 mm (t).

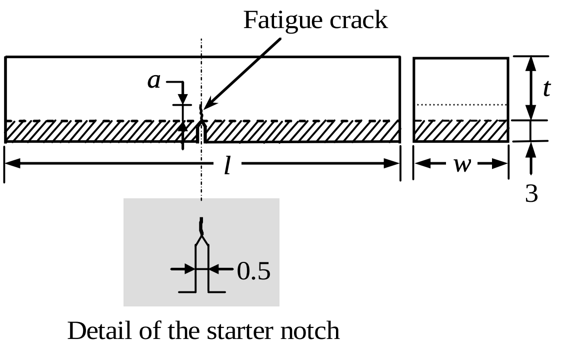

Figure 1 : *Geometry of specimen containing a fatigue crack (dimensions in mm)*

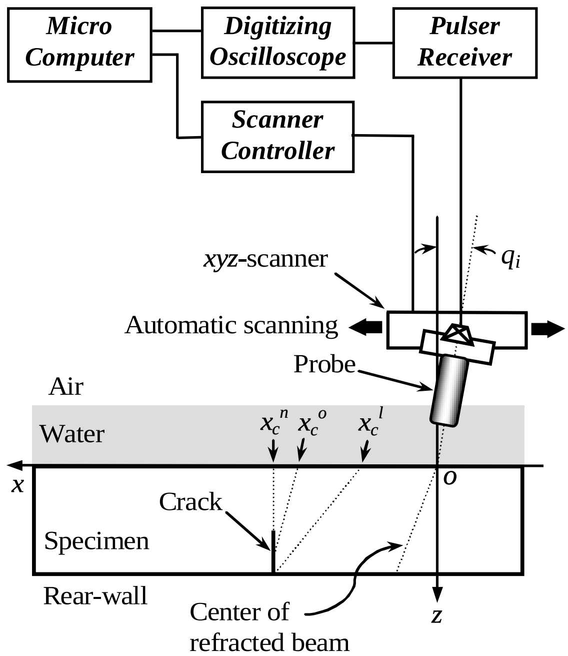

Figure 2 : *Schematic of the ultrasonic testing configuration*

Linear scanning was performed automatically by an *xyz*-scanner using a water immersion technique. A schematic of the testing configuration is shown in Fig. 2, where a crack is situated at the rear-wall. The cracks inspected were situated vertically at the centre of the specimen front/rear-wall. All the measurements were performed at room temperature under no load condition using commercial ultrasonic instrumentation. A single flat pulse-echo probe of radius, r_t = 3.2 mm, transmitting a normally incident longitudinal wave of nominal frequency 5MHz was used. The vertical distance between the transducer surface and the specimen back-wall was kept fixed as 45 mm for ensuring far field measurement. The probe was scanned over the top surface along the centerline of the specimen width, which coincides with the *x*-axis (see Fig. 2). A Cartesian coordinate system (*x*, *y*, *z*) is chosen in such a fashion that the origin *O* is located at the centre of incident beam on the top surface of the specimen. The apparent crack location as indicated by the entry point of the beam on the top surface is assumed to be rather dependent upon the nature of wave propagation. As shown in Fig. 2, the crack situates at x = x_c^n for the normal incidence method, and for the small and large (q_i = 10°) incidence methods, x = x_c^o and x = x_c^l, respectively.

The amplitude of the first back-wall echo, $|\bar{s}|^{ex}$, was measured for the specimens at several positions of the probe along x-axis, and the corresponding difference in amplitude from that of a crack-free condition is expressed in a normalized form by the quantity, Ds^{ex}, as follows:

$$\Delta s^{ex} = [|\bar{s}|^{ex} - |\bar{s}_0|^{ex}] / |\bar{s}_0|_n^{ex} \qquad (1)$$

where, $|\bar{s}_0|^{ex}$ is the amplitude of the reference back-wall echo obtained under the same beam incidence as that used for $|\bar{s}|^{ex}$, and $|\bar{s}_0|_n^{ex}$, the corresponding reference value obtained under the normally incident beam.

3. Response of ultrasonic small incidence method

In contrast with the usual techniques, a novel angle-beam testing approach, namely, the small incidence method has been developed [10-11]. The method provides the way to deal with sensitivity to the smaller cracks, especially the closed ones. The small (optimum) angle of testing has been defined as the angle of incidence given to the normally impinging longitudinal wave beam upon the specimen surface, by which the smaller cracks can be tested with higher sensitivity. It has been verified experimentally by using both open and tightly closed cracks at the rear wall that the detection sensitivity can be enhanced significantly when the beam is directed with a small angle of incidence, $q_i \cong 2^o$, the response curve of which is characterized by the nearly anti-symmetric variation in amplitude of the back-wall echo signal around the position of the crack.

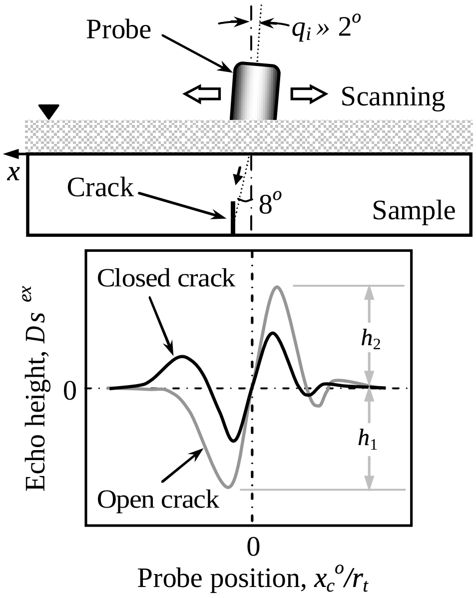

Figure 3 : *Typical ultrasonic small incidence responses of small rear-wall crack*

Figure 3 illustrates the typical response curves of an identical open and closed crack obtained by the present small incidence method of testing, in relation to the position of the probe with respect to the rear-wall crack. As appears from the illustration, crack closure affects the response of small incidence method, as the corresponding response curve of a closed crack differs substantially from that of an identical open crack both in terms of shape and echo height. Typical anti-symmetric variation of the echo height is observed around the position of a rear-wall crack, which is due to the similar contribution of the crack tip and corner on the response ($h_1 \cong h_2$). From the variation of the first back-wall echo height around the position of a front-wall crack it is observed that the contribution of the crack tip is more significant than that of the crack corner on the response, as the echo height representing the attenuation phenomenon, h_1 is always greater than the representative echo height of the rise in amplitude phenomenon (h_2), which makes the response curve different from that of a rear-wall crack. However, likewise the case of a rear-wall crack, the response of a front-wall closed crack differs from that of an identical open crack in terms of both the echo height and shape as illustrated in Figure 3. For a tightly closed front-wall crack, the small incidence response curve assumes nearly a V-shaped relation with respect to the probe position.

4. Evaluation of open cracks

In this section, the measured results of two open cracks having known depths are presented. Both the cracks are evaluated as a rear-wall and front-wall crack using the present small incidence method of testing. Figure 4 shows the measured results of a small crack in Sample SS-1, which has a depth of a = 0.5 mm. The results show that the present small incidence method is capable of evaluating such a small crack sensitively, and the associated sensitivity of the crack is found to be almost same for both the rear and front-wall crack. The measured results of a relatively large crack, a = 4.0 mm, in sample SS-2, obtained by the present method is shown in Fig. 5. Figures 4 and 5 show that very well defined small incidence response curves are obtained for both the cracks in SS-1 and SS-2 at both of their positions on the front and rear-wall. It has been observed that, for larger cracks, detection sensitivity of a rear wall crack becomes slightly larger than that of an identical front-wall crack. However, for the small cracks up to the depth of a = 6.0 mm, the evaluation sensitivity obtained by the present small incidence method is found to be much higher for both the cases of rear and front-wall cracks, when compared with the corresponding results of the standard normal and large incidence methods of testing.

5. Evaluation of closed fatigue crack

A semi-elliptical closed fatigue crack having the dimensions of a = 4.78 mm and b = 22.1 mm (Sample SS-3) is considered for its evaluation by the present and usual method of testing under a load-free condition. After performing the tests, the sample was broken by cyclic fatigue loading to observe the actual dimensions of the crack on the fractured surfaces. The crack was evaluated by the present small incidence method from the surface it is situated as well as from its opposite side, the results of which are shown in Fig. 6. Both the results of the rear and front-wall crack show that the response curves agree well with the typical characteristics of the small incidence responses of closed cracks, as illustrated in Fig. 3; nearly anti-

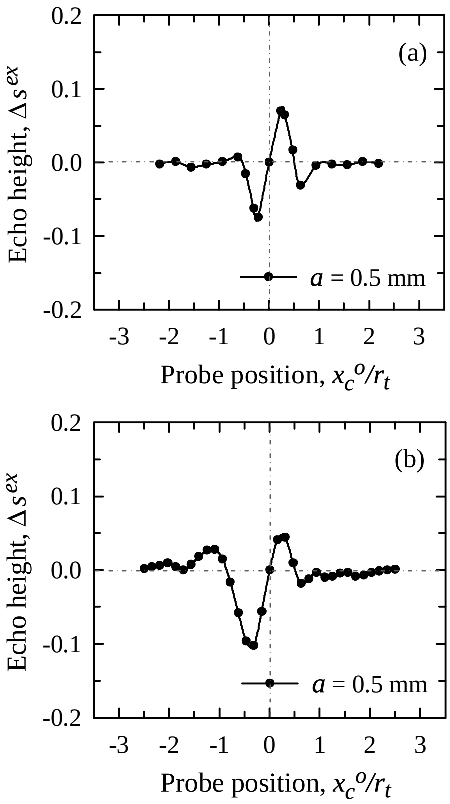

Figure 4 : *Ultrasonic small incidence responses of the open crack in Sample SS-1; (a) rear-wall, (b) front-wall crack*

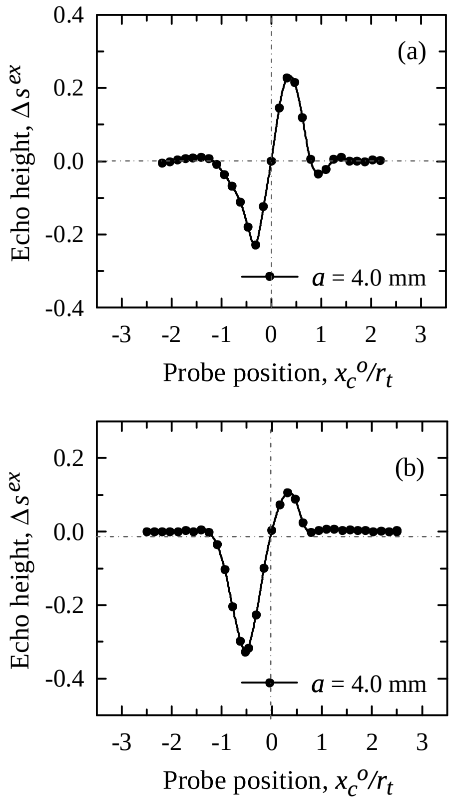

Figure 5 : *Ultrasonic small incidence responses of the open crack in Sample SS-2; (a) rear-wall, (b) front-wall crack*

symmetric variation of the echo height is observed around the rear-wall crack, whereas almost a symmetric V-shaped response curve is encountered when the crack is situated on the measuring surface. The evaluation sensitivity of the closed crack obtained by the present method is found to be nearly similar for the cases of its evaluation from the measuring surface and the opposite side. The change in echo height in the case of a closed crack takes always a smaller value than that of an identical open crack, which is mainly due to the transmission of the wave through the contacting surfaces. A quantitative analysis of the change in echo height for the case of the rear-wall crack in SS-3 shows that the decrease in echo height from that of an identical open crack is around 57%; this large shortening of the echo height is only because of crack closure.

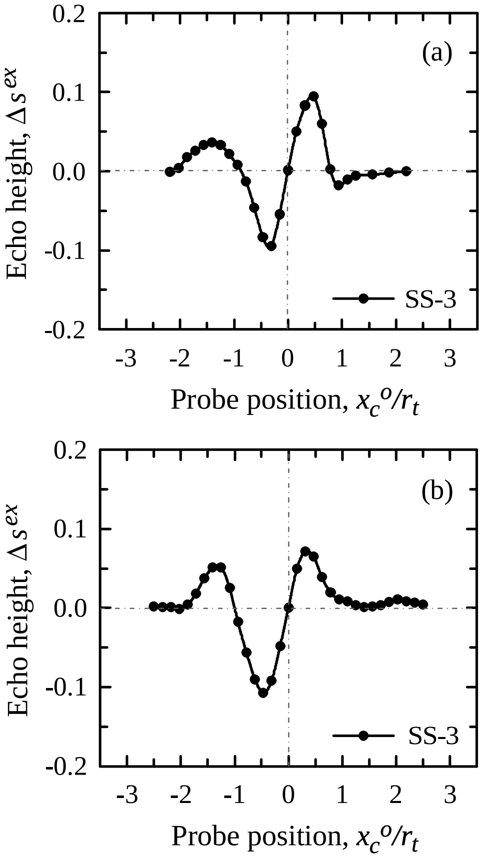

Figure 6 : *Ultrasonic small incidence responses of the closed crack in Sample SS-3; (a) rear-wall, (b) front-wall crack*

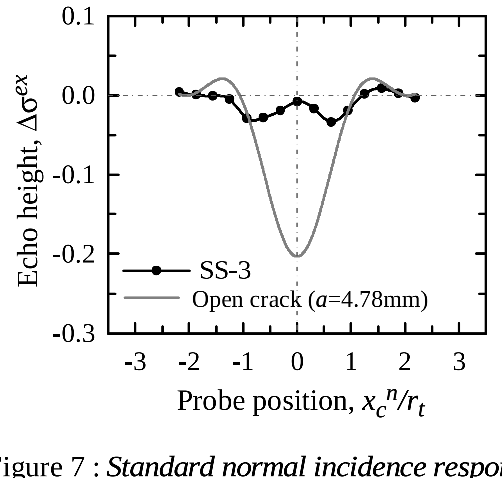

Figure 7 : *Standard normal incidence response*

In an attempt to compare the sensitivity of the present small incidence method with standard method of testing, the crack was also evaluated by the standard normal incidence method, and the corresponding results of the rear-wall crack are presented in Fig. 7. In addition to the response of the crack in SS-3, the normal incidence response of an identical open crack is also included in Fig. 7. The normal incidence response of the open crack is predicted here by using the calibration equation derived in our previous research [13]. The comparative presentations of Fig. 7 clearly verify the existence of tight closure in specimen SS-3, as the measured response curve of the closed crack differs significantly from that of the open crack in terms of both the echo height and shape. A comparison of the maximum change in echo height shows that the shortening of the echo height due to the crack closure for the case of the normal incidence method is around 84%, which is only 57% for the present small incidence method of testing. For the present closed crack, the detection sensitivity of the small incidence method is found to be 5.4 times higher than that of the normal incidence method. The measured results as well as the comparison thus verify that the present ultrasonic small incidence method is capable of evaluating tightly closed smaller cracks sensitively from both the accessible and inaccessible sides of the test sample under load-free conditions.

6. Conclusions

The evaluation of smaller cracks has been investigated from both the front and rear-wall sides of test samples using ultrasonic small incidence method of testing under no load condition. Results of the present study show that the evaluation sensitivity can be enhanced significantly for both the cases of front and rear-wall tight cracks by using the present method. The present ultrasonic small incidence method of testing is thus verified to be a powerful tool for NDE of smaller cracks from both the accessible and inaccessible sides of structural components.

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7. References

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