DETECTION OF PLASTIC ZONE AT CRACK TIP BY NON-COLLINEAR MIXING METHOD

Hai-yang LI[1], Zhi-wu AN[1*], Guo-xuan LIAN[1], Xiao-min WANG[1]

[1] State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences Beijing 100190

[*] Corresponding author, E-mail: jizhang@nbu.edu.cn; Tel.: 86-135-81839865.

The non-collinear mixing method for detection of plastic zone at crack tip is studied in this paper. When stress loaded on crack in solid is more than critical stress, which is related to length of crack, the crack will happen to expend fast leading to material fracture. However, critical stress of crack is affected by plastic zone existence at crack tip, so detection of plastic zone at crack tip is significant. By non-collinear mixing method, a nonlinearity parameter is utilized to evaluate plastic zone at crack tip. This paper demonstrates feasibility of non-collinear mixing method for measuring range of plastic zone at crack tip.

Keywords: Non-collinear mixing method; Nonlinearity parameter; Plastic zone

1. INTRODUCTION

The existence and propagation of cracks in solid materials are fatal for mechanical performances. According to prior researches, critical stress is related length of crack and range of plastic zone at crack tip. When stress loaded on crack is more than critical stress, crack will happen to expand fast leading to material fracture. So detection of plastic zone at crack tip is helpful to obtain crack propagation rate.

Jones and Kobett[1] has shown that interaction of two waves in an isotropic solid, under resonance condition, leads to a new wave with sum or difference frequency generated, the amplitude of which is dependent on third order elastic constants of material. And the third order elastic constants are changed when fatigue appears in solid material. Croxford[2] and LIU Siming[3] experimentally observed two transverse waves interaction by non-collinear mixing method, and applied nonlinearity parameter to assess plasticity and fatigue damage. Tang[4] utilized collinear mixing method to obtain spatial distribution of material nonlinearity and locate the plastic damage in the material.

Starting from basic theories of nonlinear acoustics and elastic-plastic mechanics, we will supply a method to measure ultrasonic nonlinearity parameter β to evaluate mechanisms of nonlinear effects at crack tip. From experimental results, it is found that non-collinear mixing method can realize evaluation of material nonlinearity. And by changing location of mixing zone, it is possible to obtain spatial distribution of plastic strain at crack tip, which reveals a metrical method of ultrasonic nondestructive to evaluate the propagation rate of cracks.

2. THEORETICAL ANALYSIS

Two transverse waves, which satisfy resonance condition, interact in solid material, and then a longitudinal signal with sum frequency is generated. The resonance condition and the scattered signal[4] are given by

$$[(\omega_1+\omega_2)/C_l]\hat{r}_s-\mathbf{k}_1-\mathbf{k}_2=0, \quad (1)$$

$$u(r,t)=\frac{(I^+\cdot\hat{r}_s)}{4\pi C_l^2\rho_0 r}\frac{\hat{r}_s}{r}V\sin(\omega_1+\omega_2)(t-\frac{r}{C_l}), \quad (2)$$

where $\hat{r}$ is a unit vector along the distance vector r, $\mathbf{k}_1,\mathbf{k}_2$ are wave vectors, and $|\mathbf{k}_1|=k_1$, $\hat{r}_s$ is a vector in interaction volume satisfying Eq. (1), I^+ is shown by

$$\begin{aligned}I^+ &= -\frac{1}{2}(\mu+\frac{1}{4}A)\{(A_0\cdot B_0)(k_2^2\mathbf{k}_1+k_1^2\mathbf{k}_2)\\&+(\mathbf{B}_0\cdot\mathbf{k}_1)(k_2^2+2\mathbf{k}_1\cdot\mathbf{k}_2)\mathbf{A}_0\\&+(\mathbf{A}_0\cdot\mathbf{k}_2)(k_1^2+2\mathbf{k}_1\cdot\mathbf{k}_2)\mathbf{B}_0\}\\&-\frac{1}{2}(K+\frac{1}{3}\mu+\frac{1}{4}A+B)(\mathbf{A}_0\cdot\mathbf{B}_0)(\mathbf{k}_1\cdot\mathbf{k}_2)(\mathbf{k}_2+\mathbf{k}_1)\\&-\frac{1}{2}(\frac{1}{4}A+B)(\mathbf{A}_0\cdot\mathbf{k}_2)(\mathbf{B}_0\cdot\mathbf{k}_1)(\mathbf{k}_1+\mathbf{k}_2)\end{aligned}, \quad (3)$$

where r_0 is material density, μ is shear modulus, κ is compression modulus, A , B and C are third order elastic constants.

It is seen that amplitude of scattered wave is dependent on third order elastic constants and amplitudes of two incident waves. A nonlinearity parameter is defined by

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$$\beta = \frac{A_3}{A_1 A_2}, \quad (4)$$

where A_3 is amplitude of mixing frequency signal, A_1 and A_2 are amplitudes of transverse waves, respectively. Due to being normalized by product of two incident waves' amplitudes, nonlinearity parameter β is only related to material mechanics. So by β, a relationship between the material nonlinear properties and material mechanical status is built.

3. EXPERIMENTAL PROCEDURE

Fig.1 shows a schematic of proposed non-collinear mixing method ultrasonic measurement system. Two longitudinal signals of 15 cycles at 2.2*MHz* are generated by a function generator (Ritec RAM-5000 SNAP). In order to ensure two signals interact, number of signals' cycles is not too small. The angle of polystyrene wedges is 40° so that longitudinal wave generated by input transducers transform into transverse waves. On the basis of non-collinear mixing method, a new generated signal will be received by a longitudinal transducer at the other side of the aluminum block. Due to receival amplifier and oscilloscope, the receival signal should be magnified and eliminated any other possible harmonics generated by experimental system. Both voltage and current signals of receival ultrasonic waves are recorded and averaged 256 times with oscilloscope, and then transferred into a computer for extract mixing signal's amplitude. The accurate time of two acoustic signals arriving at interaction zone and a new generated wave arriving at receiver transducer must be computed. Longitudinal and transverse wave velocity in the aluminum block and polystyrene wedges are shown in Table1.

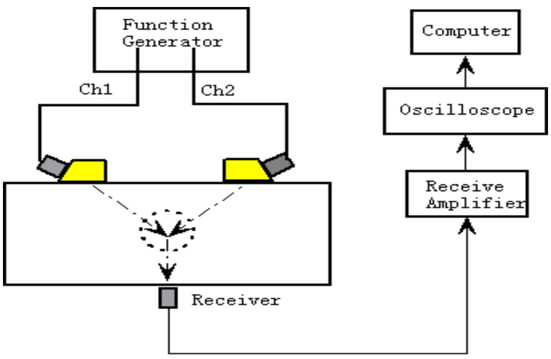
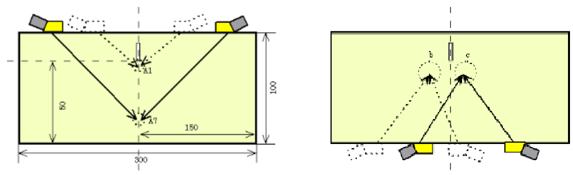


Figure 1. Experiment setup

Experimental measurements are performed on LY12 aluminum alloy specimen. The specimen is a block with a width 2*mm* and length 15*mm* defect, and position is shown in Fig.2. By altering the separation of two input transducers or moving two input transducers simultaneously with the same separation, the position of interaction zone will change. To obtain nonlinearity parameters around crack tip, three serials of detected points are chosen to be measured. In Fig.2(1), a serial of detected points is along longitudinal direction. In Fig.2(2), two serials of detected points are symmetrical in transverse direction at crack tip. The dotted line stands for initial position.

Table 1. The acoustic velocity

Category	*LY12(m/s)*	*Polystyrene(m/s)*
Longitudinal wave velocity	6383	2320
Transverse wave velocity	3141	1150



(1)The longitudinal direction (2)The transverse direction

Figure 2. Defect position

In longitudinal direction, we choose eight points at crack tip. The position of points are shown in Table 2. The distance means the detected points far from up surface of specimen. And then, material nonlinearity at eight points on a line is measured. In transverse direction, two serials of detected points are also measured in a line, whose positions are shown in Table 3 and 4. The distance means the detected points far from the left side of specimen. In addition, the material inherent nonlinearity must be detected as a reference. The nonlinearity parameters at detected points should be divided by the material inherent nonlinearity to acquire the relative nonlinearity parameter which denotes the relative variation of material nonlinearity. In this paper, the relative nonlinearity parameter is utilized to estimate to range of plastic zone at the crack tip.

Table 2. The detected points in longitudinal direction

Points	*A1*	*A2*	*A3*	*A4*
Distance(mm)	50.92	52.05	53.75	54.88
Points	*A5*	*A6*	*A7*	*A8*
Distance(mm)	56.88	57.71	59.41	62.24

Table 3. The detected points in transverse direction

Points	*b1*	*b2*	*b3*	*b4*	*b5*
Distance(mm)	135	138	141	144	147

Table 4. The detected points in transverse direction

Points	*c1*	*c2*	*c3*	*c4*	*c5*
Distance(mm)	153	156	159	162	165

4. EXPERIMENTAL RESULT ANALYSIS

On the specimen, we choose a perfect zone to investigate the nonlinear mixing phenomenon. The contrast between two received signals on the specimen is shown in Fig.3. One is the mixing signal when the two input transducers are excited simultaneously, and the other one is that only one input transducer is excited.

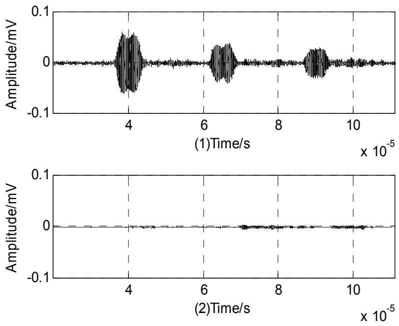


Figure 3. Nonlinear mixing phenomenon

At the computed time 38.2μs, the mixing wave expected is shown in Fig.3(1). And the first and second reflection of the mixing signal between the sample surfaces are also received, but the amplitudes is smaller than the mixing signal's due to the material attenuation. In Fig.3.(2), at the expected time, no signal but noise and nonlinearities in the measurement system is obtained. It can be seen that non-collinear mixing method has potential to assess the material mechanical performance.

Throughout all stages of experimentation, in longitudinal and transverse direction the relative nonlinearity parameter is obtained. Fig.4(1) shows the relative nonlinearity distribution in longitude direction, and Fig.4(2) shows that relative nonlinearity distribution in transverse direction.

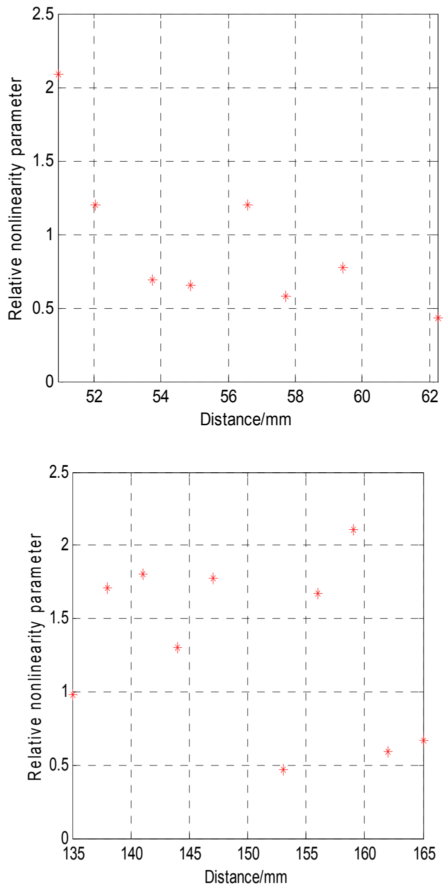


Figure 4. Spatial distribution of material nonlinearity

By changing two waves interaction region, the spatial distribution of material nonlinearity at crack tip is measured. So relative variation of material nonlinearity is obtained. From Fig4(1), it is seen that when distance is less than 52mm, data are more than one, otherwise data are less than one. From Fig4(2), during the distance between 144mm and 156mm, the relative nonlinearity is almost more than one, or less than one. This illustrates that plastic deformation range in less than 52mm in longitudinal direction, between 144mm and 156mm in transverse direction. Based on position of defect in Fig.2, the plastic zone can be assessed. So a conclusion is made that the plastic zone at crack tip, which is about less than 3mm in longitudinal direction and less than 8mm in transverse direction, can be measured by non-collinear mixing method.

5. CONCLUSION

This paper reports on experimental investigation of the measurement of material nonlinearity at crack tip by the non-collinear mixing method. The experimental results demonstrate that non-collinear mixing method can realize measurement of material nonlinearity at crack tip. As a result, spatial distribution of plastic zone at crack tip is obtained, which affects the propagation rate of crack. This paper reveals potential application of ultrasonic nondestructive to evaluate mechanical properties.

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