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NUMERICAL SIMULATION OF ULTRASONIC WAVE INTERACTION WITH A CLOSED CRACK OF DIFFERENT ORIENTATIONS UNDER VARIOUS PRESTRESSES

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ABSTRACT

Contact acoustic nonlinearity (CAN) is well-known source in nonlinear ultrasonic, resulting from the interaction of a finite-amplitude wave with contact-type defects, including imperfectly bonded interfaces, closed fatigue cracks, and composite delaminations. Practical nonlinear ultrasonic wave propagation involves complex boundary conditions and need to be studied delicately. A numerical study was performed to investigate the interactions between elastic waves and a closed crack of different orientations under various prestresses. Validated FE models of both clapping and slipping mechanisms using proper boundary conditions were extended to investigate the nonlinear interaction between an arbitrary elastic wave and a general contact interface. The transmission, second harmonic and third harmonic coefficient as a function of static prestress and orientation angle are obtained. This work leads to possibilities in NDE applications to quantitatively evaluate the size and orientation of closed cracks.

Keywords: Contact Acoustic Nonlinearity, Closed Crack, Static Pressure, Crack Orientation

NOMENCLATURE

E	Young's modulus
ρ	density
ν	Poisson's ratio
u	displacement
ε	harmonic efficiency
k	wave number
p	pressure
ω	angular frequency
λ	wavelength
Δx	mesh size

1. INTRODUCTION

Ultrasonic methods based on linear elastic wave scattering are efficient for detecting defects on the scale of the wavelength and characterizing material elasticity, but are less sensitive to tight contact-type defects, such as closed cracks, glued bondings, and partially delaminated material interfaces. When an ultrasonic wave with high amplitude is incident on a contact-type defect, higher harmonics appear in the frequency spectrum of both transmitted and reflected waves. This effect, called contact acoustic nonlinearity (CAN) [1], exhibits much greater harmonic generation than classical material nonlinearities and is of increasing interest for characterization of closed cracks or imperfectly bonded interfaces.

In order to yield a basic insight into elastic waves propagating through contact interface, a simplified nonlinear contact stiffness model is incorporated into a 1D framework by Richardson [2], and higher harmonic generation were derived in terms of mechanical properties, incident wave, and the static pressure. Realistic features of finite and nonlinear interface stiffness were not accounted for by Biwa [3], who took the contact interface asperity configuration into consideration. On the other hand, the slipping model account for the shear wave interaction with contact interface was developed by O'Neil [4], following the classic framework of Richardson. It predicted that the reflected and transmitted waves are "clipped" versions of the incident pulse at the positive and negative values equal in magnitude to the critical yield stress. Both longitudinal and shear wave propagation through a rough surface were investigated by Pecorari [5] using an interface contact model based on Hertz theory, again for time harmonic incidence.

However, internal cracks are not always normal to the incident waves, which are always excited with a pulsed or tone-burst signal. Harmonic generation for the contact interfaces at various load and oblique incidence were analyzed with a theoretical model by Nam [6]. The nonlinear behavior of clapping occurring at a delamination in a composite plate was studied by Delrue [7]. The delaminated interface was simulated using a spring model and showed that sub- and higher-harmonics were generated. More recently, the interaction between in-plane

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elastic waves and a crack of different orientations was studied by Meziane [8]. Higher harmonics was a function of the angle of incidence and the excitation level. However, few numerical studies consider both the clapping mechanism and slipping mechanism to build the gap between theoretical models and numerical results.

Here we used the commercial FEM software ABAQUS for our analysis, which has been validated in our previous work [9, 10]. In the present work, both the clapping and slipping mechanisms of CAN will be introduced along with the extended model based on the verified model in part 2. The numerical results including transmission coefficient and higher harmonics generation for different orientated cracks will be illustrated in part 3. Part 4 will give the conclusion remarks.

2. MATERIALS AND METHODS

2.1 CAN Mechanisms

The relative motion of the contact interfaces is the source of the CAN, which could make the waveform distorted. Two kinds of mechanisms have been named to explain for these phenomena. The clapping mechanism is dominant for the harmonic generation from the interaction of the longitudinal wave and the closed crack; while the slipping mechanism for the shear wave. When an incident longitudinal wave is incident normally to the defect, the tensile part makes the interface open, while the compressive part makes it close to propagate through. This kind of mechanism is referred as "clapping" or "kissing" mode. The analytical result of higher harmonic generation can be obtained from Richardson' result for the hard contact [2]. For a sine wave incident on a normal interface, the harmonic efficiencies are expressed as:

$$\varepsilon_k = \frac{1}{\pi}\left|\int_{u_1}^{u_2} \exp(-iku)\phi(u)\,du\right| \qquad (1)$$

where $\phi(u) = \cos u - \cos u_1 + \sin u_1 (u - u_1)$, $u_1 = \pi + \sin^{-1}\eta$, and $\eta = p_0 / p_i$; k is the order of the higher harmonic.

Considering a shear wave incident normally on a flat frictional interface, only odd harmonics are generated for time harmonic incident wave motion. Physically the friction leads to nonlinearity due to switching between the sticking and sliding states of the interfacial contact [4]. When the incident wave is in the same direction with the defect, it can propagate well when the amplitude level low enough so that the contact interface is sticking. However, when the amplitude increases to make the interface move tangentially, the wave will be distorted in a symmetrical way. The corresponding high harmonic efficiency for sine wave is:

$$\varepsilon_k = \frac{\omega}{2\pi}\left|\int_{t}^{t+\frac{2\pi}{\omega}} \exp(-ik\omega t)\Delta(t)\,dt\right| \qquad (2)$$

where $\Delta(t) = 1/2\left(u(+0,t) - u(-0,t)\right)$, $\xi = \mu p_0 / p_i$.

2.2 FE Model for Closed Cracks with Different Orientations

In order to verify the FEM model, classic analytical result should be used for verification at first. The nonlinear interaction between longitudinal wave and infinite planar contact interface has been verified in our previous work and the good agreement has reached [9, 10]. Numerical studies were performed using the commercial software ABAQUS to treat the interaction between an elastic wave and a closed crack. An isotropic and homogeneous aluminum is considered; its mechanical properties are those of aluminum. The Young's modulus is E = 68 GPa; Poisson's coefficient is ν = 0.36; and density is ρ = 2700 kg/m3.

With the verification of the clapping and slipping mechanisms, it is possible to extend the FE models for the complex nonlinear crack-wave interaction modeling. Our focus here is the influence of the crack orientation on the harmonic generation. The present study considers the nonlinear interaction of an ultrasonic wave with a closed crack of finite extent. The defect length is fixed at 3mm. The fracture mechanics aspects (SIF, crack propagation) are not of concern here. Therefore, the simplest way to deal with the stress singularities is to refine the mesh, in order to ensure the convergence of the model and maintain its accuracy. Therefore, the global mesh size is chosen as Δx=0.04mm ($N=\lambda/\Delta x$=30) and the mesh size around the crack tips is Δx=0.02 mm. The geometry model is designed as Figure 1 to guarantee the same meshing scheme for different orientations. ② is receiver and ① are set as infinite element boundaries to suppress the reflection. The angle step of 5 degree is chosen to get the higher harmonic as a function of orientation.

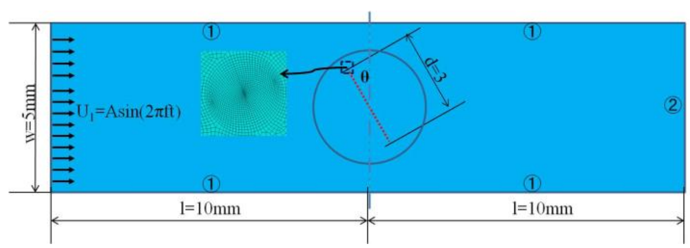

FIGURE 1: FEM MODEL FOR CRACKS WITH DIFFERENT ORIENTATIONS

3. RESULTS AND DISCUSSION

In order to investigate the angular effect of the contact defect, different orientated defects have been studied. Very high frictions at the defect tangential direction are applied to exclude the slipping mechanism, resulting from the state change between sticking and slipping. At first, a static pressure $p_0 = 1\,\text{MPa}$, which is corresponding to $\eta = 0.18$, has been taken into consideration. The first three harmonic evolution as a function of the crack angle has been illustrated. The fundamental harmonic increases until it reaches the amplitude the same as no static pressure. The second and third harmonics show a monotonic decrease as the angle of crack orientation increases. Again, the amplitude of the second harmonic is an order of magnitude above that of the third harmonic. as the pre-stress is a dominated parameter in CAN, different static pressures are also desired to investigate the harmonic evolution with the crack orientations. Figure 2 shows transmisson coefficient, the second and third harmonics generation as a function of crack orientation and static pressure.

When the low static pressures are applied, the transmission coefficient increases until it reaches the amplitude of the incident wave. The second and third harmonics show a monotonic decrease as the angle of incidence increases. Again, the amplitude of the second harmonic is an order of magnitude above that of the third harmonic. When the higher pre-stresses are applied, the transmission coefficient decreases and there is a small peak around $p_0 = 2p_i$. Moreover, one peak occurs in second harmonic and two peaks occur in third harmonic generation. When the defect is parallel to the incident wave, the static pressure will not make any difference to the harmonic generation. The transmission coefficient is about 0.5, which is due to the generation of interface wave.

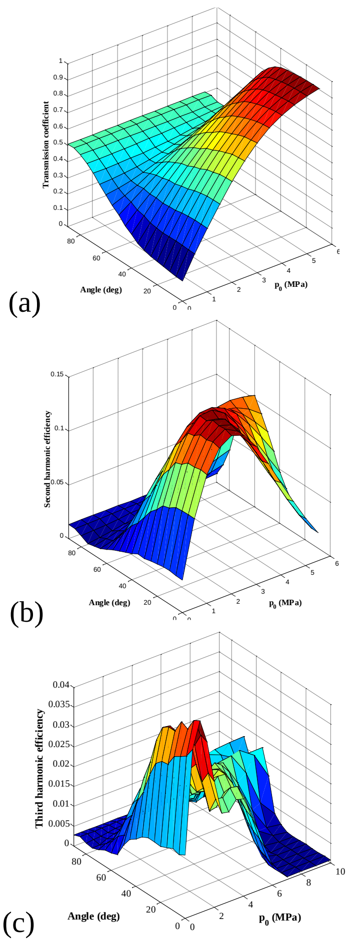

FIGURE 2: INFLUENCE OF CRACK ORENTIAON AND PRESTRESS: (a) TRANSMISSION COEFFICIENT, (b) SECOND HARMONIC, AND (c) THIRD HARMONIC EFFICIENCY.

4. CONCLUSION

In this study, FE models are built to simulate the higher harmonic generation from contact acoustic nonlinearity (CAN), including the clapping and slipping mechanisms. With verification of the clapping and slipping mechanisms, a finite element model was built to study interactions between elastic waves and a closed crack with different orientation under various prestress. The main conclusions of this work are as follows:

1) With low static pressures, the transmission coefficient increases until it reaches the amplitude of the incident wave. The second and third harmonics show a monotonic decrease as the angle of incidence increases.

2) When the higher pre-stresses are applied, the transmission coefficient decreases and there is a small peak around p_0=2*p_i. Moreover, one peak occurs in second harmonic and two peaks occur in third harmonic generation.

3) Clapping mechanism is the dominant nonlinear effect on longitudinal wave interaction with different orientated closed cracks. When clapping occurs, it dominates the nonlinear behavior of the system.

This work leads to possibilities in NDE applications to quantitative evaluation of the orientations of closed cracks.

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