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Scattering of a Rayleigh wave by a surface-breaking crack with faces in partial contact

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Abstract

In this work, the scattering of a Rayleigh wave by a surface-breaking crack with faces in partial contact is investigated. The elastic properties of the crack faces in contact are modeled within the framework of the quasi-static approximation (QSA). Two different contact distributions are considered. The first distribution is uniform over the whole extent of the crack faces. In the second one, the contacts occur only in the proximity of the crack mouth. The gradient of the crack opening displacement (COD) caused by the incident wave is obtained by solving a system of uncoupled integral equations. An integration of the COD gradients over the crack depth yields the components of the COD. The reflection and the transmission coefficients, as well as the energy of the incident Rayleigh wave, which is carried away by the mode-converted bulk waves can be calculated by employing the COD components in conjunction with reciprocity theory. Contrary to the expectations based on the behavior of the reflection coefficient of a bulk wave at normal incidence on an imperfect interface of infinite extent, the reflection coefficient of a Rayleigh wave scattered by a partially closed surface-breaking crack is predicted to increase initially with the load applied to the crack faces. Experimental evidence supporting such a surprising behavior is also presented.

Keywords: Rayleigh wave; Quasi-static approximation; Crack opening displacement; Surface-breaking crack

1. Introduction

The interaction of ultrasonic waves with imperfect interfaces and, in particular, with surfaces in partial contact and of infinite extent, has been the subject of numerous investigations [1–9]. A few theoretical approaches accounting for the experimental observations to various degrees of accuracy have also been developed to describe such a scattering phenomenon [4,10,11]. Among these models, the quasi-static approximation (QSA) [10] has been shown to provide a suitable framework within which the problem of interest can be addressed when the typical dimension of the interfacial imperfections and their average spacing are smaller than the wavelength of the interrogating wave.

According to the QSA, the elastic behavior of an imperfect interface, and that of two surfaces in partial contact in particular, can be modeled by a distribution of elastic springs with stiffness constant K. Although the link between the latter and the micromechanical properties of two contacting surfaces has not yet been completely understood, several important features of the wave scattering by such a system have been well-established [10]. At normal incidence, for example, the reflection (transmission) coefficient is a function that monotonically increases (decreases) with the

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wave frequency. Furthermore, both the reflection and transmission coefficients are equal to 0.5 when the frequency of the interrogating wave coincides with the characteristic frequency of the interface, f_K. The latter is proportional to the ratio between the interfacial stiffness, K, and the material acoustic impedance, Z, that is $f_K = K/\pi Z$. Thus, at frequencies lower than f_K, the interface appears increasingly closed as the frequency of the incident wave decreases, while the opposite is true at frequencies higher than f_K.

Cracks in real components are often subjected to externally applied or residual stress fields that may cause partial closure along their whole extent or only within a limited area of their surface. Whether uniform or localized, the partial closure of a crack may strongly affect the scattering properties of such a defect.

Achenbach and Norris [12] investigated the loss of specular reflection caused by the nonlinear interaction between the faces of a crack embedded in the bulk of a sample. They obtained the displacement discontinuities at the crack faces by assuming the elastic behavior of a finite crack to be sufficiently well-approximated by that of an unbounded plane flaw. The interfacial properties of the defect considered in this work accounted for the different behavior of the interface under compression and tension, and for the dependence of the interface shear displacement on the normal stress. This approach led to a system of nonlinear differential equations for the displacement discontinuities. The reflected and transmitted fields were evaluated by means of appropriate integral representations including the displacement discontinuities. Both normal and oblique incidence of longitudinal and shear waves were considered in this work.

More recently, Boström and Wickham [13] and Boström [14] have examined the scattering of bulk ultrasonic waves by a crack with faces in partial contact. In both references, the authors modeled the contacting surfaces by means of a very thin layer with effective elastic constants. The latter were used to evaluate the normal, K_N, and tangential, K_T, interfacial constants that appear in the spring boundary conditions enforced under the QSA. In the first work [13], the values of K_T and K_N were estimated to be equal to each other, while in [14], Boström used a value of the ratio between the transverse and the normal spring constants of the order of 3. Boström calculated the back-scattered signal from a penny shaped crack with the above-mentioned spring constants by utilizing the transfer matrix approach in combination with Auld's electromechanical reciprocity theory [15]. In that work, both SV and longitudinal finite probes at normal and oblique incidence were considered.

Hirose [16] used a time-domain boundary integral equation to investigate the two-dimensional scattering of longitudinal and shear waves by a crack with contacting surfaces. Hirose considered boundary conditions on the crack faces which, while subjecting the crack either to a tensile or compressive static stress, allowed for the crack faces to be either initially apart from each other or in partial contact. The shear displacement at the contacts was governed by a friction law. The integral equation was solved numerically, and the time domain signal was analyzed in the frequency domain to show the generation of higher harmonics occurring during the scattering process.

Finally, Buck et al. [17] used the diffraction of bulk wave occurring at the crack tip to investigate the shielding effect of contacting asperities in that region. They utilized the QSA [10] to model the elastic response of the region containing the contacting asperities. Central to the model was the assumption that the typical dimensions of the contacts are much smaller than the wavelength of the interrogating ultrasonic wave, and that the density of the contacts is sufficiently large. The displacement discontinuity predicted by the QSA for the case of an infinite imperfect interface was used to calculate the crack tip scattering coefficient. The latter was obtained by means of the electromechanical reciprocity theory by Auld [15]. In that work, the values of the interfacial stiffness constants were allowed to vary with the distance from the crack tip. Only waves at normal incident were considered. The correct behavior of the crack opening displacement (COD) at the crack tip was not included in the model.

In the investigations mentioned above, the crack was surrounded by an infinite medium [12–14,16], or, wherever a traction-free surface was present [17], the effects of the latter on the wave scattering were considered to be negligible. In this work, the scattering of a Rayleigh wave incident on an one-dimensional, surface-breaking crack with faces in partial contact is examined within the framework of the QSA. To this end, the rigorous approach developed by Achenbach et al. [18] and Mendelsohn et al. [19] for an open surface-breaking crack is utilized. Thus, the effect of the stress-released surface and the correct behavior of the COD at the crack tip are included in the model. The elastic properties of the contacting crack faces are modeled according to the QSA, and in agreement with the experimental evidence, a value of about 0.5 is assumed for the ratio K_T/K_N. Nonlinear phenomena due to the dependence of