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Detecting and classifying interfacial defects by inverse ultrasound scattering analysis

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HIGHLIGHTS

- We formulate an inverse problem to detect interfacial defects.
- We select the incident field that is most sensitive to interfacial flaws.
- We consider nonuniform interfacial imperfections.
- We solve the inverse scattering problem using an iterative scheme.
- The presented method performed well even for noisy input data.

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ABSTRACT

We formulate and solve a time-harmonic inverse scattering problem to estimate the interfacial stiffness distribution at an interface between two elastic solid half-spaces. We assume prior knowledge of the material properties of both solid half-spaces, as well as the ultrasound incident field. The interfacial stiffness distribution is then estimated from the reflected signal. We use the Quasi-Static-Approximation for the interface, where it is modelled by a set of tangential and normal springs, and allow the interfacial stiffness to depend upon the position along the interface. In addition, we use the Particle Swarm Optimization Technique to solve the formulated inverse problem. We validate our implementation and evaluate the presented method's performance for noisy input data and different measurement scenarios with the aid of numerical simulations. From the obtained numerical results, we may say that the proposed method is robust to the presence of noise and has the potential to detect and classify interfacial defects.

1. Introduction

In the present work, we address the problem of identifying and classifying interfacial flaws using ultrasound. More specifically, we formulate and solve a time-harmonic inverse scattering problem to estimate the effective interfacial stiffness distribution at an interface between two elastic solid half-spaces, as schematically represented in Fig. 1. We assume prior knowledge of the material properties of both half-spaces, as well as the incident wave field. The effective interfacial stiffness distribution is then estimated from the reflected scattered signal. We recognize that the present scenario is not fully realistic since the scattered field cannot be measured within the solid. However, the inverse problem tackled here presents its own

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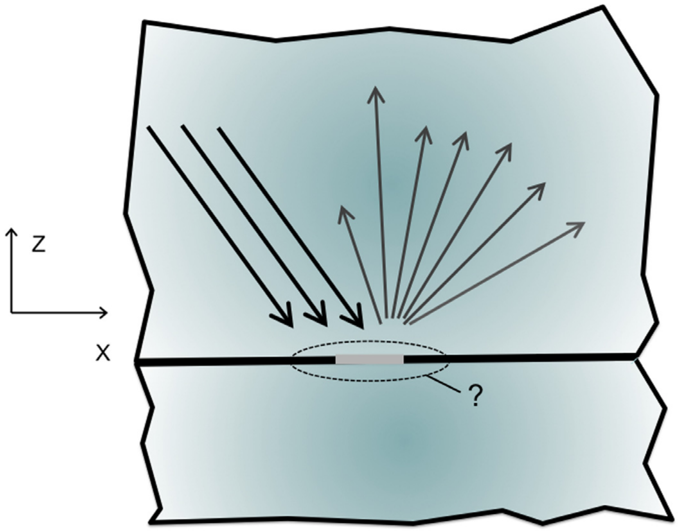

Fig. 1. We formulate and solve a time-harmonic inverse scattering problem to estimate the interfacial stiffness distribution at an interface between two solid half-spaces. The stiffness distribution is estimated from the measured reflected scattered signal.

specific challenges and complexity and, in that sense, we think it deserves to be investigated in isolation. In addition, we claim that all the conclusions we have drawn from the present work are fully extensible to more realistic scenarios, as for instance cases of multiple interfaces in multi-layered plates immersed in either acoustic fluid or vacuum. These will be considered in a further work.

We use the Quasi-Static-Approximation (QSA) for interfaces. This approximation was apparently first proposed by Baik and Thompson in [1] and consists in modeling the interface by equivalent continuous distributions of normal and transversal springs. It is valid when the inspecting wavelength to interface-thickness ratio is large and, in that sense, the interface itself is modeled as infinitesimally thick. Since its introduction, this approximation has been extensively used to model adhesive bonds and rough contact interfaces between solids (see, e.g., [2–9]). It was also used to model a fracture embedded in solid medium [10]. In the context of the QSA, the spring constants associated with the spring distributions represent the effective interfacial stiffness. Here, we allow the interfacial stiffness to depend upon the position along the interface. Therefore, we consider nonuniform spring distributions.

Related inverse problems were solved previously [11–15]. In [11], the authors used surface wave dispersion measurements to recover the bulk properties of an embedded adhesive layer. Further, in [12–14], the authors presented a method to recover not only the bulk properties of an embedded layer e.g., the adhesive layer, but also the adhesion interface stiffness. They considered the same interfacial stiffness along the whole interface. In practice, the methods introduced in [11–14] could provide the input background properties for the present inverse problem. In [16], the authors considered a time-harmonic inverse scattering problem to reconstruct the interfacial stiffness distribution in elastic laminated plates. They considered nonuniform interfaces, and have formulated the associated inverse problem as a direct problem, solving it accordingly. The presented method has revealed the potential of ultrasound, and in particular the scattering effect to reconstruct the interfacial stiffness distribution. Here, we solve the formulated inverse scattering problem using an iterative scheme. More specifically, we use the Particle Swarm Optimization algorithm that was developed by Kennedy and Eberhart as a population-based stochastic search for optimization [17]. We expect our iterative scheme to be robust to handle noisy input data.

In what follows, we present in Section 2 the mathematical formulation used for interfaces. Then, we formulate the considered inverse problem and the solution strategy in Section 3. In Section 4, we discuss the issue of the inspecting incident wave field selection. In Section 5, we present numerical simulations corresponding to ultrasound inspection of an adhesion interface between two solid substrates as illustration of the proposed method application. We evaluate the presented method's performance for noisy input data and different measurement scenarios. Next to it, we discuss the obtained results, the considered inverse problem, and the proposed solution strategy in Section 6, and conclude in Section 7.

2. Mathematical model for interfaces

We assume that wave fields are time harmonic and propagate in the x–z plane, as depicted schematically in Fig. 1. In addition, we assume that the thin interface between the two solid half-spaces is actually an interfacial layer with its own constitutive properties. By considering that layer as infinitesimally thick, we can replace it by a set of tangential and normal springs, as indicated in Fig. 2. The springs connect the constituent half-spaces, and enforce continuity of the traction and (approximately) displacement vectors. This approach is known as the Quasi Static Approximation (QSA) and gives us