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Simulating the ultrasonic scattering from complex surface-breaking defects with a three-dimensional hybrid model

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ABSTRACT

Modelling is increasingly relied on for the design and qualification of ultrasonic inspections applied to safety-critical components. Numerical methods enable the simulation of the ultrasonic interaction with realistic defect morphologies; however, the computational requirements often limit their deployment. The hybrid simulation technique, which combines semi-analytical and numerical methods, realises the potential of high fidelity numerical modelling without the limiting computational factors. The inspection of thick section components for near-backwall surface-breaking defects results in large propagation distances, making them a key application of hybrid modelling. This work presents a methodology for efficiently simulating the ultrasonic inspection of complex surface-breaking defects using a hybrid model. The model is initially verified against full numerical simulation; further validation is presented by comparison to an experimental scan over an artificially machined surface-breaking notch. The potential of the new hybrid method is then demonstrated by carrying out a Monte Carlo analysis on the scattered field from surface-breaking defects with randomly rough surfaces and the results are compared to the Kirchhoff approximation.

1. Introduction

The ultrasonic inspection of safety-critical components in the nuclear sector commonly requires evidence-based qualification. Modelling is increasingly being relied upon to form the basis of inspection qualifications as it offers a more economical alternative to experimental data collection and enables the simulation of inspection scenarios that are infeasible through experiment. Historically, semi-analytical models have been used to estimate inspection performance in the UK nuclear sector [1,2]. Yet despite their computational efficiency, the broad physical assumptions that they use mean that the models are generally limited to predicting the scattering from simple defect geometries. In practice, defects often exhibit complex morphology, such as surface roughness [3], and commonly initiate at the surface of a component [4].

Numerical simulation using the Finite Element (FE) method is a popular approach to calculate the ultrasonic scattering from irregular shapes and complex structures [3,5]. Furthermore, recent developments in a Graphics Processing Unit (GPU) based solver have substantially reduced the limitation of computation time from this approach [6]. However, the spatial discretisation required to correctly conform to complex geometry combined with the size of components in the nuclear sector often leads to excessive and infeasible computational memory requirements.

Using a hybrid approach, it is possible to reduce the domain of the numerical model to a small region surrounding a complex defect or transduction system. The wave propagation between these points can be efficiently simulated using a semi-analytical model. The hybrid concept has been successfully developed for multiple applications within the field of NDT [7,8].

The technique developed by researchers at Imperial College [9,10] offers flexibility in the hybrid methodology, such that it can be adapted to suit specific requirements and applications. The method simulates an ultrasonic inspection by breaking it down into two separate domains, the source domain and defect domain, and couples them together using a semi-analytical hybrid interface, illustrated by Fig. 1; the interface is independent of the techniques used to simulate each domain. The work by Rajagopal et al. [9] and Choi et al. [10] provide validation of this hybrid technique in 2D and 3D respectively, where good agreement is found in comparison to full numerical simulation and experimental data.

Despite the great potential of this hybrid simulation method, very little attention has been given to utilising it for the scenario of simulating the ultrasonic inspection of surface-breaking defects. Whilst it is common

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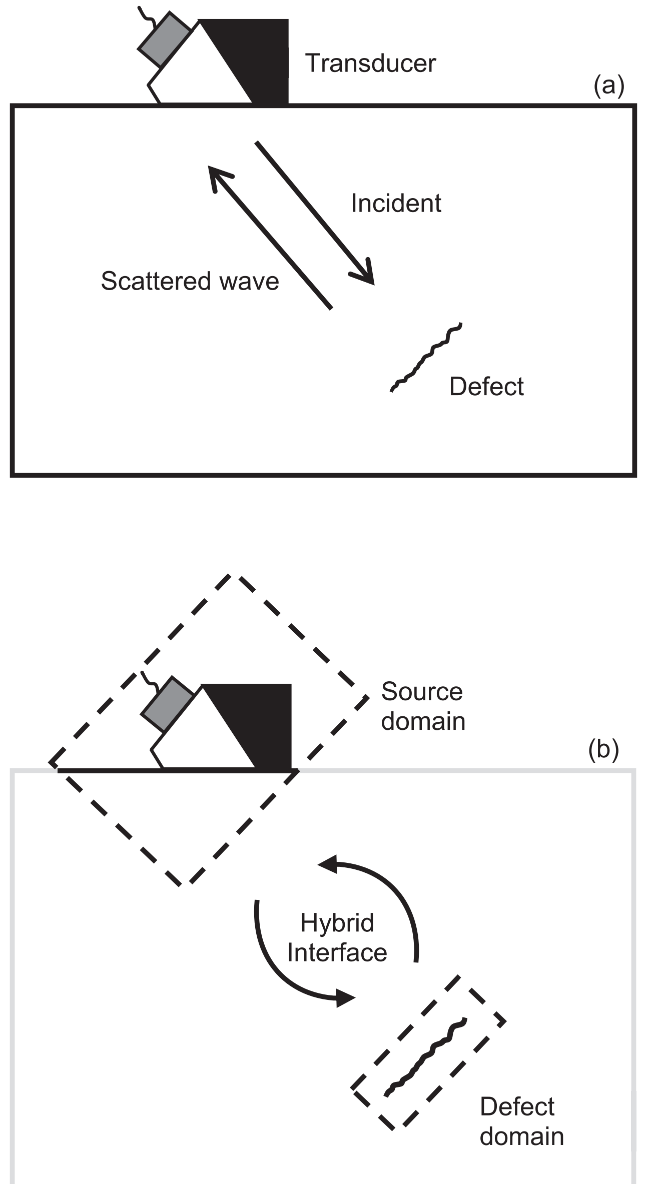

Fig. 1. An illustration of (a) a pulse echo ultrasonic inspection setup and (b) the hybrid methodology used to simulate the inspection.

for defects to initiate at the surface of a component, there is often restricted access to this surface. For example, the anticipated defect is likely to be on the inside of a pipe or vessel where the stress is most severe, yet the inspection is often restricted to the outer exposed surface. In such an inspection, the distance between the ultrasonic transducer and the defect is dependent on the wall thickness of the component and can be many orders of magnitudes larger than the ultrasonic wavelength. Hence, to simulate an inspection of this type in its entirety in three dimensions is often infeasible using a full numerical method and a hybrid approach is extremely desirable. Hybrid models proposed by other authors have also considered similar ultrasonic inspection scenarios, for example [7,11]; however, there are limited studies in the literature that demonstrate the validity of 3D hybrid techniques when simulating the inspection of components containing surface-breaking defects.

The work presented here provides a methodology to simulate the ultrasonic inspection of complex surface-breaking defects in three dimensions using the hybrid technique developed in Ref. [9]. In the next section, a discussion of common inspection techniques is given in the next section, followed by details of the methodology for simulating the ultrasonic inspection using the hybrid approach in section 3. Numerical verification and experimental validation are then given in section 4 and 5. This work is presented in the context of inspection qualification, yet the model could be used for a wide range of applications; as one example, section 6 presents a study into the ultrasonic attenuation due to surface roughness on surface-breaking defects.

2. Ultrasonic inspection of surface-breaking defects

To suitably extend the hybrid method for the simulation of a near-backwall surface-breaking defect inspection, consideration must first be given to the type of inspections commonly deployed within industry for the detection and characterisation of such defects.

Industry practice for the detection of surface-breaking defects is the angled shear wave pulse-echo (P-E) contact inspection [12], illustrated by Fig. 2. This method is effective because a strong reflection from the defect is achieved through the 'corner echo' mechanism, shown in Fig. 3, where the ultrasonic wave is reflected in a specular direction from both the crack face and the backwall.

Suitable incident wave mode and angles can be determined by considering the combined reflection coefficient of the corner echo mechanism for a perpendicular defect [13], which is plotted in Fig. 4 for a defect contained within stainless steel (Young's modulus 200 GPa, density 7800 kg m^{-3} and Poisson's ratio 0.3); the coefficient is calculated for the far-field reflection from two perpendicular semi-infinite stress--free boundaries that are joined to create a corner. It is clear from the figure that mode conversion strongly attenuates the longitudinal wave amplitude at oblique incidence. Yet for shear wave incidence, total reflection is achieved for incident angles between approximately 32° and 58°, providing the optimal angular range for detection via the corner echo. It is also common to operate within this angular range as it is past the first critical angle, such that only shear waves are generated within the component. Incident angles around 90° and 0° are impractical and

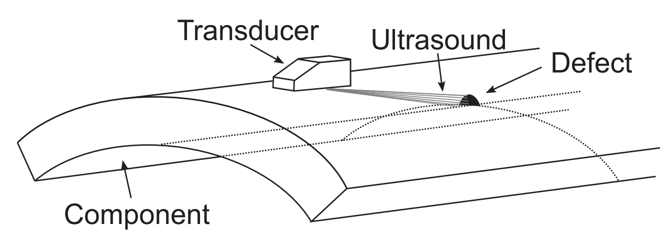

Fig. 2. A common arrangement of an angled beam pulse echo contact inspection: the wedge mounted transducer is located on the outer exposed surface of a pipe and a surface-breaking defect is present on the inside surface.

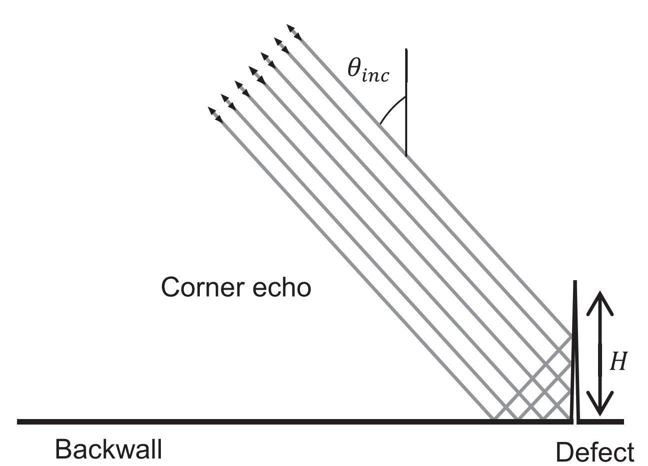

Fig. 3. Schematic of the "corner echo" scattering from a surface-breaking defect.