Development of efficient hybrid finite element modelling for simulation of ultrasonic Non-Destructive Evaluation

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Abstract
The measurement and numerical modelling of ultrasonic wave scattering is essential for detecting complex defects in safety critical components for engineering structures across a range of industries. Fast and accurate numerical modelling to simulate candidate set ups for Non-Destructive Evaluation (NDE) is attractive as it both improves confidence in the inspection results and reduces the cost of experimental qualification. As the scope of applications broaden and the modelling complexities increase, simulations become more computationally intensive. However, such demand can be reduced by using different kinds of modelling for different features and combining them in a hybrid method. For example, analytical methods are efficient for modelling propagation through the volume of the material, whereas the Finite Element (FE) method is a better solution for modelling discrete complex details such as the local scattering from an irregularly shaped real defect. The authors have developed this concept into a generic hybrid method, in which separate small local domains containing the distinct features, for example, the source, defect and receiver can be modelled by separate, appropriately chosen, local models (e.g. FE), while the propagation through the volume between them is modelled analytically.

Despite the computational gains achieved by using the hybrid method, the FE model of the region around the defect can still be very demanding of computer resources, especially for simulations in 3D. The authors have been investigating approaches to improve the efficiency of the FE modelling for ultrasonic NDE, for example: more efficient sound-absorbing elements around the FE domain, regular mesh generation and GPU-driven FE calculations. The wave propagation simulations from the hybrid method, with additional development to incorporate the results of these investigations, show similar accuracy but require less computational power than previously. Furthermore, the hybrid model has been developed, within the SIMPOSIUM project, to link with the CIVA software for NDE. The CIVA simulation software manages the overall model and the wave propagation in the component, while the hybrid model brings in FE simulation for the defect. In this case the FE simulation can be done using a commercially available package that has the quality approval and familiarity needed for industrial users. This paper will present the development of the hybrid method and demonstrate its application.

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Keywords: Ultrasonic Testing (UT), Hybrid modelling, Finite Element (FE) simulation, SIMPOSIUM project

1. Introduction

Ultrasonic inspection (UT) is the most frequently used NDE method for safety-critical components in the power generation industry. It has several advantages such as a deep penetration capacity and a relatively economic system cost. In such inspections, ultrasonic waves generated by a transducer propagate into the target structure and a receiver detects the waves reflected from any defects.

The qualification of inspections is done conventionally using experimental validation programmes, but this is extremely expensive. Hence, modelling of such ultrasonic inspection becomes increasingly important in the NDE community. There are many methods for UT simulation, and each has its own advantages and disadvantages. For example, analytical methods can simulate ultrasonic wave behaviour exactly in ideal conditions and simple geometries, but when these conditions are not fulfilled, it is difficult to estimate the behaviour.

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Thus, semi-analytical solutions such as those used in the CIVA software package [3] assume relaxed conditions to estimate an approximation to the reflection from a rather complicated geometry, but still have difficulty modelling reflections from very complex geometries. On the other hand, numerical simulations such as the Finite Element (FE) method are known to be good at simulating complex geometry, but the computational burden increases as the complexities increase.

In order to make best use of the relative advantages from such different techniques, a lot of effort is devoted to linking the different simulation tools. This idea was expanded by researchers at Imperial College (IC) to a more general formalism, called the generic hybrid method in which an independent hybrid interface connects two different modelling schemes. As part of the SIMPOSIM project, the hybrid method has been applied to link the CIVA and FE methods. In this paper, the improvement to the FE part of the link will be presented. The background to the model will be given in the next section then the three main new developments to the FE model will be explained, simulation results will be described for the CIVA-FE link in 2D and for a 3D hybrid method simulation of a realistic rough crack, this is all then followed by some concluding remarks.

2. A generic hybrid method

2.1 Background

The FE method has been widely-used when the model geometry is not regular. However, with a rough geometry fine meshes are required for the FE model, which increases both computational time and memory requirements, particularly with 3D problems. Thus most wave propagation simulations have been conducted in 2D space. For efficient modelling, a hybrid method has been introduced for ultrasonic NDE by researchers at Imperial College [1] and recently extended to 3D application [2].

In the hybrid method, the UT inspection process is divided into several steps with calculations carried out on smaller domains and a hybrid interface to connect the domains, as shown in Fig. 1. In the interface, Green’s functions link the physically separated domains, and the calculations of this link are configured in the frequency domain. For a practical simulation in
the time domain, the Fast Fourier Transform (FFT) and inverse FFT (IFFT) are used to transform between the time and frequency domain signal formats.

2.2 CIVA-FE method link

The hybrid interface is used for linking the CIVA and FE methods for UT simulations as part of the SIMPOSIUM project. CIVA is a semi-analytical simulation tool for the NDE community [3], which is known to simulate wave propagation from transducers well, and reflections from defects are predicted using semi-analytic methods such as Kirchhoff or GTD theory. Thus, reflections from a smooth crack are estimated well but reflections from an irregularly-shaped crack are less accurate. On the other hand, the FE method is known to be good at modelling reflection from complex geometries, but requires a lot of computational labour for long wave propagation paths. Therefore, within the framework of the hybrid method, using CIVA for the source domain and the FE method for the defect domain with a rough crack can compensate for the relative weakness of each method in UT modelling.

As discussed in the introduction, the hybrid interface links two such domains and for this example, with CIVA simulating the domain including the transducer and FE modelling the domain including the defect, the link can be seen in Fig. 2.

![Figure 2. CIVA-FE hybrid concept](image)

3. Development in FE simulation

As mentioned in the previous section, a rough defect can be well simulated using FE, but it often requires significant computational labour, particularly for three-dimensional (3D) problems. In this paper three methods, developed at Imperial College, are used to increase the efficiency of FE simulation: an improved method for the absorbing region, a regular mesh generator for the region, and GPU-driven FE computation.

An infinite domain is difficult to simulate using the FE method. One of the most widely-used methods when using commercial FE code is to surround the finite region of interest by Absorbing Layers with Increasing Damping (ALID). In order to properly absorb wave energy propagating towards the outside of the FE domain, the thickness of the absorbing region normal to the propagating direction is typically required to be three times the longest wavelength [4]. This artificial region often occupies more area or volume than the region of interest and the minimisation of this has attracted much attention by researchers. Recently, researchers at Imperial College have developed an improved method called the Stiffness Reduction Method (SRM), in which stiffness decreases with distance into the absorbing
region whilst damping in the region still increases as in ALID. Using this method, the thickness of the absorbing region can be reduced to a third of that with standard ALID [5].

Secondly, a regular mesh is created and used for the absorbing region. In simulating wave propagation using the FE method, mesh quality is one of the key factors deciding the accuracy of the simulation result. In general, a FE domain is ideally modelled when the size of all the elements are identical to a certain number called the CFL number [6] so that a regularly-meshed domain is the most efficient FE design. However, it is difficult to generate a regular mesh when the FE method is used to simulate complex geometry, which is normal in a realistic simulation. Thus it is normal to use a free-mesh algorithm, and as a result the size of the elements of the mesh generated will be different. This algorithm sometimes generates meshes which are locally too coarse and/or too dense, particularly when the region to be meshed is 3D and is large. In addition, the computation time to generate meshes with the algorithm exponentially increases as the domain size to be meshed increases. Although the size of the absorbing region can be made smaller by using SRM rather than ALID, it still normally occupies a significant area, which can lead to a size problem. A regular mesh generator is developed for the absorbing region in three dimensions (3D), which helps to reduce the size.

Thirdly, a Graphic Processing Unit (GPU) is used for the FE simulation. A significant computational efficiency in solving linear algebraic problems has been achieved in recent years by using the GPUs that were initially developed for processing graphical images, and this idea is now widely-used in the science and engineering community. A GPU-driven FE code called Pogo [7] has been developed at Imperial College and is used for explicit 3D FE computation in this paper.

4. Simulations

4.1 CIVA-FE link

Reflection from a Side Drilled Hole (SDH) of 2 mm diameter, a widely-used reference case in UT inspection, is modelled using the CIVA-FE link. The model simulates a steel specimen (density 8700 kg/m3, shear and longitudinal wave speed 3230 and 5900 m/s) which is immersed in a water tank (density 1000 kg/m3, longitudinal wave speed 1483 m/s). The UT source is a 2 MHz single crystal transducer and a SDH is located 20 mm from the Source Monitoring Box (SMB) as can be seen in Fig. 3. In this example, the transducer within the SMB is simulated using CIVA, and ABAQUS [8] is used for modelling the defect domain in the Defect Monitoring Box (DMB).

![Figure 3. An example for CIVA-FE link](image-url)
Within the CIVA simulation, an incident wave from a 2MHz single crystal transducer is generated and the wave field on the Source Monitoring Box (SMB) is monitored. The hybrid interface estimates values for the stresses on a line (shown in Fig. 4(a)) which is used for excitation to the FE model. Then, based on values of the signal monitored on the DMB, the reflected signal on the SMB is predicted. Fig. 4 shows the hybrid process and also a full FE simulation. Fig. 5 shows the reflection result at a point on the SMB: the hybrid and full FE results show excellent agreement.

Figure 4. UT simulation using (a) hybrid model and (b) a full FE model

Figure 5. Reflected wave at the middle node on line L of the SMB (a) in the x and (b) in the y direction

4.2 Hybrid method with the novel developments

As mentioned in Section 3, within the hybrid method three methods are introduced to increase efficiency of FE modelling for 3D UT simulations. Reflection from a rough crack is simulated as a realisticand challenging example. A plane wave of 5-cycle toneburst with 4 MHz centre frequency is excited in a steel medium (Young’s modulus 200 GPa, Poisson ratio 0.3 and density 8000 kg/m$^3$) propagating towards a rough crack sized $3\text{mm} \times 3\text{mm}$ and the reflection is monitored 5 mm from the crack centre, as shown in Fig. 6. Since this example is to demonstrate the efficiency of this FE modelling, only the backward part of the hybrid process from DMB to a monitoring point is conducted and hence CIVA is not considered in this section.
In order to simulate reflection from a rough crack in 3D, an FE model including a rough crack is generated as in Fig. 7 and can be described as follows. First, a crack geometry was artificially created using an Auto-Regression (AR) method [9] based on the statistics of a real rough surface sample measured by SIMPOSIUM industrial partner AMEC using an Alicona optical microscope. The size of the crack is approximately $3 \times 3 \times 1 \, \text{mm}^3$, which is implanted into a hexagonal domain of $4 \times 4 \times 2 \, \text{mm}^3$ size, and then the crack is subtracted from the domain. This is the region of interest and is meshed with a nominal element size of 0.05 mm (approximately 1/30 input wavelength). In the meshing process, the six outer surfaces of the domain are first regularly divided into $0.05 \times 0.05 \, \text{mm}^2$ square intervals, based on which the inner volume is then freely meshed using a free mesh algorithm in ABAQUS CAE [8]. Surrounding the region of interest, additional regular elements for the absorbing region are generated based on the regular grids on the surfaces. The thickness of this region with SRM is 2 mm, approximately 1.3 wavelengths, so that the size of the total domain becomes $8 \times 8 \times 6 \, \text{mm}^3$.

Figure 7. Defect FE domain for 3D hybrid method: (a) A crack shape, (b) a main domain, and (c) a defect FE domain including the main domain and the absorbing region with SRM generated by a 3D mesh generator.

The geometry shown in Fig. 7 was generated by the procedure mentioned above using the regular mesh generator discussed in the previous section. The free mesh algorithm in ABAQUS CAE was also tried for comparison, but it failed to generate a satisfactory mesh. Using SRM, the number of nodes in this domain is 3 million, which would be 11 million if ALID were to be used. As for the running time of the simulation, a significant time reduction was achieved by the methods proposed in this paper. For the example above, Pogo took 8 minutes with Nvidia’s GeForce GTX Titan Black graphics card [10] on an Intel core i7.
machine with 8 GB memory, whereas ABAQUS Explicit took 10 hours with an Intel Xeon machine running the simulation on 8 threads in parallel with 256 GB memory.

5. Conclusion

A generic hybrid method has been developed to link two regions for UT simulation and is applied to link the CIVA simulation package with the FE method using separately-run FE codes under the SIMPOSIUM project. The link was shown to be successful in estimating UT reflection from a SDH in 2D. Although the hybrid method helps to reduce the computational burden in UT simulations, FE modelling for the defect side can still be difficult, particularly in 3D problems. In order to increase efficiency in 3D FE modelling, the absorbing region with SRM, a regular mesh generator, and Pogo, a GPU-driven FE code, have been developed by the researchers at Imperial College and are adopted for an example in this paper. A regular mesh generator helped to create the mesh efficiently, the SRM reduced the number of nodes to less than a third of the number using the previous alternative, ALID, and Pogo computed the simulation within 1/70 of the running time of the non-GPU FE method for this example.

References