8th European Workshop On Structural Health Monitoring (EWSHM 2016), 5-8 July 2016, Spain, Bilbao
www.ndt.net/app.EWSHM2016

Ultrasonic Guided Wave Simulation Performance Evaluation for QNDE-SHM Processes

Nitin BALAJEE RAVI [1], Ramanan SRIDARAN VENKAT [2], Nibir CHAKRABORTY[1], Debiprosad ROY MAHAPATRA[1] , Christian BOLLER [2]
nitinb@aero.iisc.ernet.in, ramanan.sridaran@uni-saarland.de,
nibir.chakraborty@aero.iisc.ernet.in,
droymahapatra@aero.iisc.ernet.in, c.boller@mx-uni-saarland.de

[1] Department of Aerospace Engineering, Indian Institute of Science, Bengaluru 560012, India
[2] Non-Destructive Testing and Quality Assurance (LZfPQ), University of Saarland, Campus Dudweiler, 66125 Saarbrücken, Germany.

Keywords: Bulk waves, guided waves, structural health monitoring, ultrasonic transducer, PWAS, scattering, crack, rivet hole.

Abstract

In this paper, we show the effect of different computational parameters used in ultrasonic NDE process simulation and what important roles these parameters play in improving the efficiency and reliability of a system optimization. We present two simulation examples, one involving inspection of bulk geometries using ultrasonic probes and other involving guided Lamb waves in a stiffened aircraft structure. The computational scheme shown was developed as part of INDEUS project. The examples shown here simulate typical inspection process involving complex structures and illustrate how assumptions regarding different parameters used in the models considering constraints on computational resources affect the output in situations requiring rapid simulation instead of traditional computational models being used currently.

1 INTRODUCTION

Numerical simulations in ultrasonic NDE have been applied for bulk waves and guided waves for many decades. Various complex models for different kinds of materials and damages have been developed and simulated in literature. Various different specialized simulation tools such as CIVA, COMSOL and several others, besides finite element software exist and help in visualizing how the ultrasonic waves interact with various different structural features within a component. This helps to identify the optimal parameter settings suitable for performing the inspection on the component without the operator having to test and decide the settings through several trials. This in turn helps in reducing the inspection time. Thus, Quantitative NDE and SHM, as it is emerging today, require simulation to optimize inspection/monitoring effectiveness and hardware design. While simulation can accelerate optimizing the inspection process, certain challenges such as computational resources, computation time, and parameter accuracy pose constraints in use of such methods.

Inspection reliability is one of the key parameters for any NDE inspection method. Statistical methods are currently being employed to generate the Probability of Detection (PoD) curves though experiments on sample coupons, which can be time consuming and costly. Simulation can aid in offsetting difficulties such as where the uncertainties, measurement errors, effects of geometry, structural and material properties, flaw properties could be modeled. However, such statistical data generation through simulation requires rapid simulation outcome, which could be limited by constraints such as simulation speed and computational resources. Increasing complexity becomes inevitable in quantitative NDE-SHM involving complex geometry and various details of damages/flaws that typically occur. To model such details, the existing commercial tools are either limited or they require very intensive computation resources. Modelling the geometries in 3D also increases the complexities further. Simplified modeling schemes are useful in these simulations along with algorithm based optimization strategies.

We demonstrate here ultrasonic NDE process simulation in two case studies using quantitative techniques and sensitivity analysis. In the first case study, we consider inspection of thick geometries with ultrasonic probe, which involves B-scan and variable extent of scattering from complex flaws such as drilled hole with cracks and other features of defects in it. In the second case study, we consider a segment of a metallic stiffened panel having an array of rivet holes, which are inspected/monitored by ultrasonic probes and alternatively by bonded piezoelectric transducers. In this NDE method, the ultrasonic guided waves of Lamb waves scatter due to rivet hole with crack and other defects. Simulation results based on computational schemes developed in the INDEUS project are discussed. We show how simulations can enable probabilistic estimates of various quantities of interest in NDE-SHM and how computational parameters play important roles in improving efficiency and reliability of the optimization process through simulation.

2 BULK WAVE SIMULATION

A flat bottom hole of 5mm diameter on a 20mm thick Aluminum block is considered for bulk wave propagation simulation as shown in Fig 1. The depth of the hole is 10mm. A B-Scan simulation was performed with the probe position varied along the x-direction. A 4MHz central frequency with amplitude-modulated signal was used as an excitation signal and the simulation was performed in non-contact mode with water as coupling medium.

To perform a B-Scan, the probe was simulated to move along the scan direction at fixed steps. At every step, the beam was projected on the component using a ray-based approach. The geometry of the crack was modeled such that the crack was discretized into finite number of line segments. The ultrasonic wave generated by the transducer is assumed to be incident on the surface of the sample where there is energy spread as it propagates through the material. Beam spread is a measure of the whole angle from side to side of the main lobe of the sound beam in the far field. The beam divergence, which is divergence of the beam with respect to the central axis of the transducer probe, is dependent on radius of the transducer and the frequency of excitation and is determined by Eqn. (1).

$$\sin\left(\frac{\theta}{2}\right) = \frac{0.514V}{2aF} \qquad (1)$$

Where V is the velocity of sound in material, a is the radius of the transducer and F is the frequency of transducer in Hz. As the wave continues to propagate from one medium to another, refraction occurs due to change in material densities. The refraction angle of the incident wave, which is a component of the incident wave field, can be determined using Snell's Law. It is therefore easier to model the interaction of the wave field with other geometric features in the component using ray-based simulations. The reconstruction of wave-packet is then performed at the transducer since the inspection process is performed in the pulse-echo mode.

To accurately capture the crack and its growth using B-Scan, the step size and geometry discretization needs to be optimally chosen. We define a step size as the number of steps along the scan direction that is required to accurately image the damage. The crack is likely to be missed if the chosen step size is greater than the crack size. Similarly, if the crack growth is not modelled accurately, it is also likely that the effect of crack cannot be captured in the scans. The parameters can therefore be chosen with the help of simulation based QNDE where the multiple scans can be analyzed to determine the best possible parameter settings.

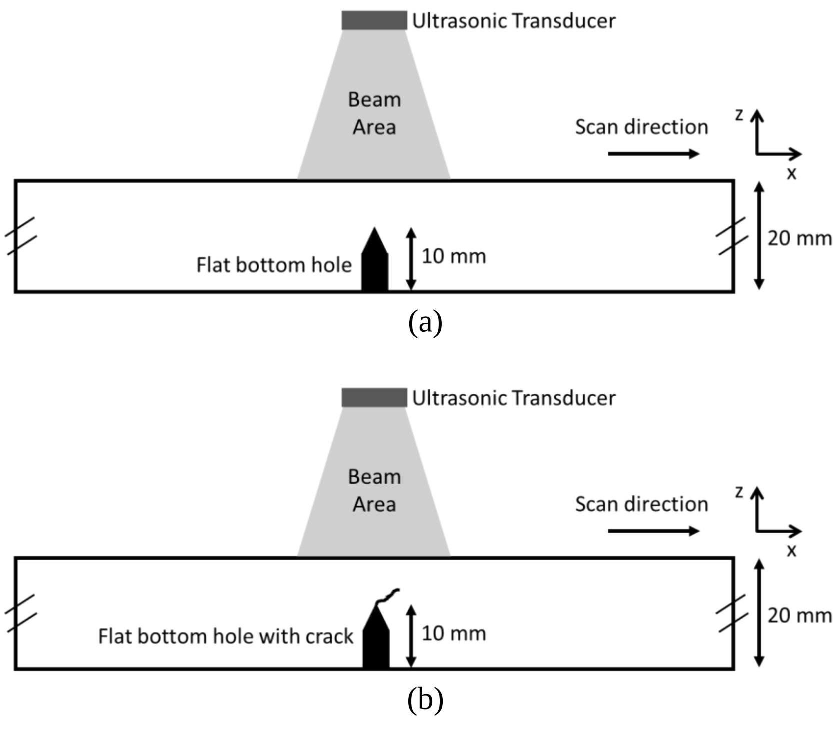
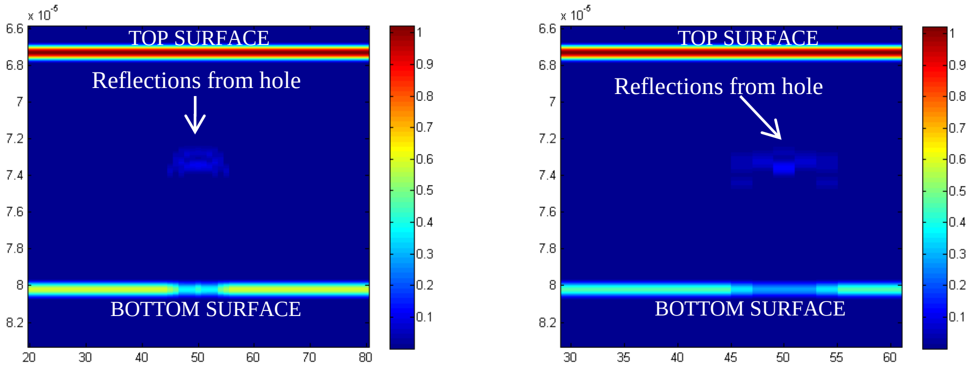


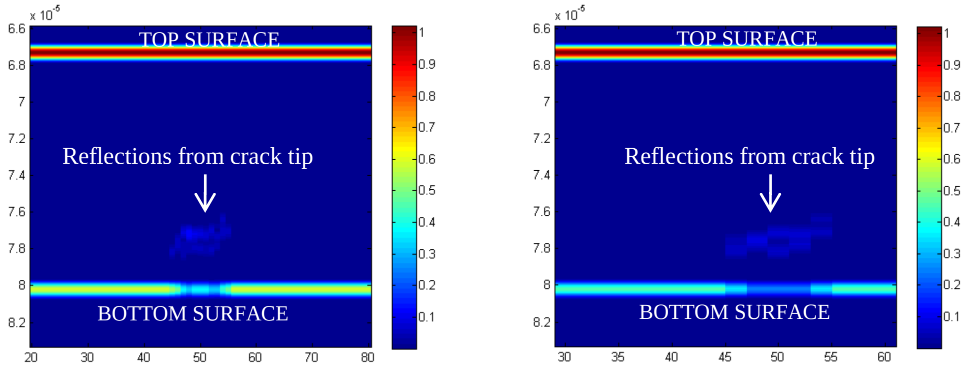
Fig 1(a) Aluminum block containing a flat bottom hole of 5mm diameter (b) with crack at the tip of the hole

In this simulation, we used a probe of 10mm diameter at 4MHz frequency. Therefore the beam divergence was measured to be 4.5^{o}. A crack of 2mm was introduced at the tip of the hole in the component geometry. A ray-based simulation of bulk wave propagation within the component was performed where complex wave-field was modeled based on the interactions with geometric features within the component. Fig 2 & Fig 3 are the B-Scan images of bottom drilled holes with and without crack, reconstructed through simulation.



(a) (b)

Fig 2 Bulk wave simulation for Bottom drilled hole (a) with slower step size, (b) with larger step size



(b) (b)

Fig 3 Bulk wave simulation for hole with crack (a) with slower step size, (b) with larger step size

For accurate reconstruction, the step size along the scan direction should be in the order of the smallest damage size to be imaged. It can be seen from Fig 2(b) & Fig 3(b) that as the step size is larger than the crack size of 2mm, the damage image is highly discretized, thereby leading to inaccurate imaging of damage. A traditional NDE methodology usually involves interfacing with robotic setups fitted with encoders. However, the speed at which the imaging is to be performed is determined based on the encoder resolution and pulse repetition frequency. Thus a trial and error based methods are employed by NDE inspectors to determine the optimum speed to perform the inspection. But given the geometry of the component under inspection and using rapid simulation methods as described above, an ideal speed to perform the inspection can be determined which could be used by the inspector for actual inspection.

3 GUIDED ULTRASONIC WAVE SIMULATION

A 2mm thick Aluminium panel with a stiffener attached by a rivet line is considered for simulation of guided waves. The panel is assumed to have rivet lines with rivet pitch of 30mm is considered, and it assumed that a fatigue crack of 50mm is emanating from one of the rivet holes. To study the effect of the crack and holes on the guided wave generated on the panel, two piezo-electric sensors, one acting as an actuator and other as sensor operating in pitch catch mode, were placed between two stiffeners equidistant with respect to the crack. The schematic of section of the test panel with sensor locations is shown in Fig 4. The simulation was performed on the panel with crack sizes of 10mm to 50 mm with objective to study the effect of increasing crack size on the signal shape.

To model propagation of lamb wave within the component, a spectral finite-element based modelling scheme was developed to analytically evaluate the displacement fields at any given point in the component. Since energy is equally transmitted emitted by transducer in all directions, we consider only the component of the energy that was transmitted in a particular direction and its interactions with other structural features using appropriate numerical scattering models. The wave when incident on any structural feature, it is reflected along a particular direction based on Snell's law of reflection and refraction [1, 2, 3]. Propagation of rays in three dimensional medium using propagation of sound wave in air has been discussed in literature [4]. Different ray tracing methods in various media have also been reported in [1].

To study the effects of holes and the crack at various sensor locations, we consider fraction of wave that is incident on the crack surface. When the actuator is excited, the wave propagates in cylindrical manner. So it is assumed that the energy is distributed equally in all the directions. To capture the interaction of the wave with various boundary features in the component, it is important that the wavelength of the signal launched at the actuator match the dimensions of the features to be captured. Such a condition was also imposed during simulation.

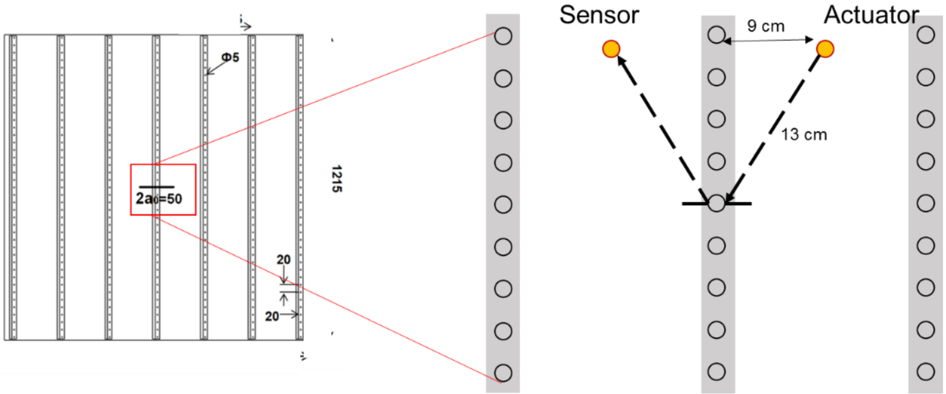
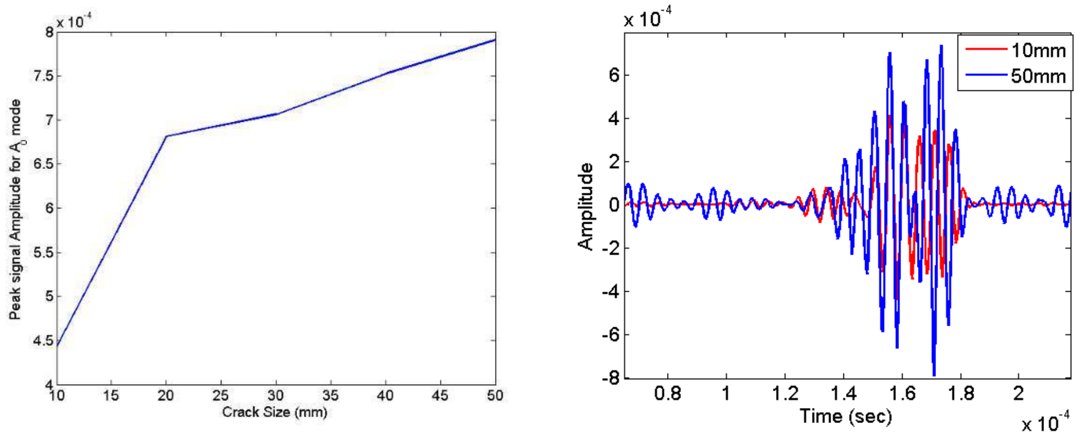


Fig 4 Stiffened panel showing the location of sensors with respect to the crack.

The guided wave simulation was performed on a 2mm thick Aluminum plate. Appropriate transfer function was used to convert the actuator signal into displacement field and scattering models for reflections [5] from cracks and rivets was included in the simulation. A receiver transfer function was used to convert the displacement field into voltage signal at the sensor.

The simulation is used to analyze and determine the wave packet that is incident on the sensor. It was observed that, sensor will receive the packet that is reflected off the crack edge. As the crack length increases, it was observed that the sensor receives the packet with a phase shift introduced due to varying path length and increased amplitude due to larger surface area of reflection along the crack edge. This is evident in Fig 5.



(a) **(b)**

Fig 5 (a) Increase in signal amplitude with increase in crack size, (b) Increase in signal amplitude and phase shift with increase in crack size

When the sensor locations are not fixed for a given geometry, the above simulation process can aid in studying the effect of variation of structural features on the sensor signals. This could then help in deriving damage detection algorithms suitable for a given component and which could then be deployed and tested on real time. To drive such rapid process, accurate analytical models, which require very little computational resources, are preferred. The models can also be fine-tuned by varying the model parameters and running it through the simulation almost on a real-time basis.

4 CONCLUSIONS

Bulk wave and guided wave simulations were performed on different components with object to study the effect of a physical parameter on the inspection process. A bulk wave simulation was performed on material with bottom drilled hole with crack from the hole tip. The simulation as used to determine the optimum step size along the scan direction to accurately image the crack from the hole tip. For guided wave simulation, a stiffened panel was considered. The simulation was used to determine the effect of increasing crack size on the signal at a given sensor location. We then show why such simulations are required to quickly identify the parameters that might affect the given inspection process and structural constraints.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support by the Indo-German Science & Technology Center (IGSTC) for this work.

REFERENCES

[1] Sridaran Venkat et al., "Optimized Actuator/Sensor Combinations for Structural Health Monitoring: Simulation and Experimental Validation," in International Workshop on Structural Health Monitoring , Stanford, USA, September 2015.

[2] Nitin B Ravi et al., "Modeling ultrasonic NDE and guided-wave-based structural health monitoring," in Proc. SPIE 9437, Structural Health Monitoring and Inspection of Advanced Materials, Aerospace, and Civil Infrastructure , San Diego, CA, USA, 2015.

[3] Sridaran Venkat et al., "Establishing a Simulation Platform for Acoustics based SHM System Configuration," in 7th International Symposium on NDT in Aerospace, Brehem, Germany, 2015.

[4] A. Kulowski, "Algorithmic Representation of the Ray Tracing Technique," Applied Acoustics, vol. 18, pp. 449-469, 1985.

[5] Ajay Raghavan et al., "Review of Guided-wave Structural Health Monitoring," The Shock and Vibration Digest , vol. 39, no. 2, pp. 91-116, 2007.

[6] M. A. Chang Z, "Scattering of Lamb waves from a rivet hole with edge cracks," Mechanics of materials, vol. 31, no. 3, pp. 197-204, 1999.