Simulation of SHM System Solutions Based on Commercial Software Packages

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Abstract

Numerical simulations in ultrasonic NDE have been applied for bulk waves and guided waves for many decades. Those simulation tools use either analytical, semi-analytical or finite element methods to generate and detect the damages occur in the medium. The computation time and accuracy of those tools depend on the complexity of the problem. Hybrid methods combine analytical and numerical methods to solve complex problems in less computation time. One such method is ATHENA-2D from CIVA that combines analytical raytracing and finite element methods. However, when the structures to be monitored are large, those hybrid *simulation tools don't support* long-range ultrasonic waves. In this paper we present various scattering models implemented in the Indo-German joint project called IN-DEUS which uses spectral FEM combined with raytracing models. As a part of validation of our simulation tool, comparative study has been presented in this paper between IN-DEUS and CIVA for bulk waves and guided waves. Various validation cases presented in this paper show that there is huge potential for such tools in SHM applications.

1. Introduction

Numerical simulations are often used to predict the possible wave fields in both short and long-range ultrasonic NDE, providing an insight into mechanisms that drive the wave interactions with structural features[16]. The application of numerical simulations helps to choose optimal actuator/sensor locations for various damage configurations for a SHM system which involves guided ultrasonic waves and it even helps so as to design the transducer configurations for complex geometries and complex defects in a bulk wave ultrasonic testing. Driven by the advancements in the computational methods and electronics, there exists analytical and exact models for performing the simulation tasks but their solutions are limited to either a simple shaped structures or artificial damages. There are different numerical tools available for simulating both bulk waves and guided waves such as Finite element method (FEM), Finite difference method (FDM), Elastic Finite integration technique (EFIT) and spectral FEM

(SFEM) etc. The application of the FEM and FDM to structural health monitoring of plates by Xu et al can be referred in the [4, 16]. SFEM for SHM is studied by Ostochowicz et al [17]. Three dimensional modeling of bulk waves using EFIT was studied and validated by Chinta et al [11, 12]. Except SFEM, the above numerical methods are time consuming and in some cases, cannot be applicable to higher order frequencies where the detection of smaller defects is of enormous importance. In such cases, analytical and numerical methods could be combined together to form hybrid methods. The advantages of hybrid methods are faster computation time and ability to model either bulk or guided wave interactions to smaller damages. Brief literature review has been presented in the next chapter to highlight the various features of commercial and non-commercial simulation tools for bulk and guided ultrasonic NDE. In this paper, ray tracing method combined with spectral finite element approach has been developed and has been included in the ongoing research programme IN-DEUS which is sponsored by IGSTC (Indo-German Science and Technology Centre). The IN-DEUS platform is shown in fig.1 where the interface allows one to view the geometrical models built from commercial software packages and also gives possibilities to extract the stress and fatigue data into the platform. The numerical simulation interface allows one to input the transducer and flaw data for bulk wave analysis. The built-in raytracing module performs guided wave simulation for SHM sensor configurations and the experimental validation module is used to validate the simulation results. The objective of this paper is to demonstrate our methodologies for validating bulk and guided wave numerical models using commercially available tools such as CIVA, COMSOL Multiphysics etc., and to highlight their importance in the ongoing project.

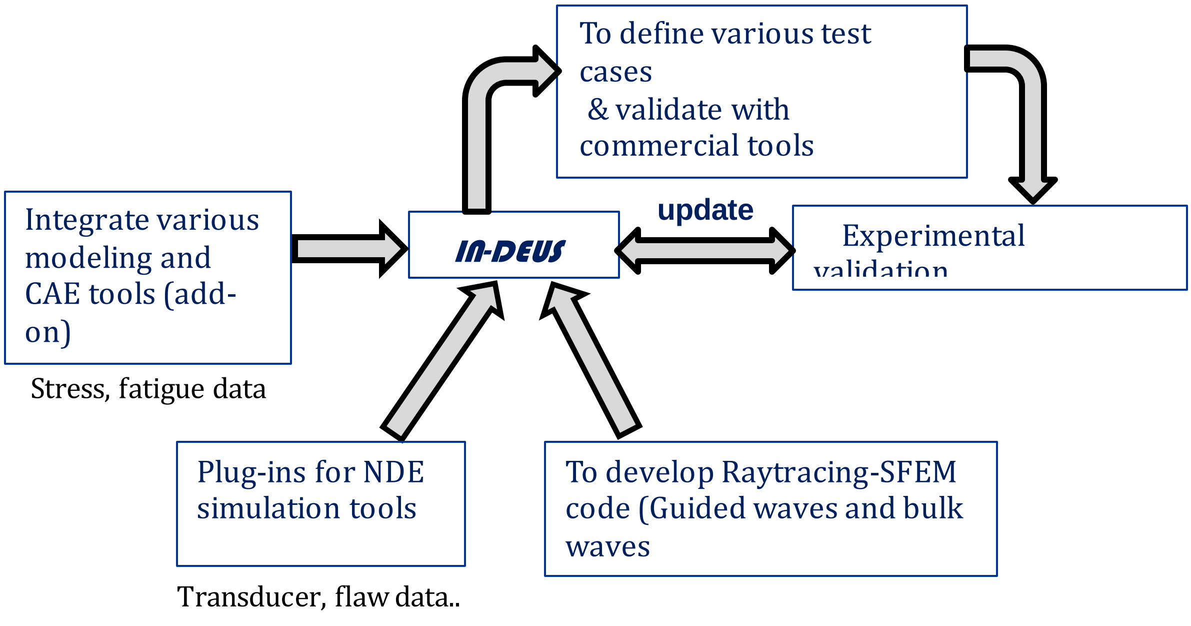

Fig.1 IN-DEUS platform

2. Literature review

Researchers used several hybrid methods to solve numerical problems in SHM. Well-known ultrasonic module in NDE simulation tool EXTENDE's CIVA 15 uses an add-on hybrid function called ATHENA- 2D which combines semi-analytically formulated raytracing and FEM models for simulating the complex defects in ultrasonic NDE [3, 8]. ATHENA-2D module is illustrated in the fig.2

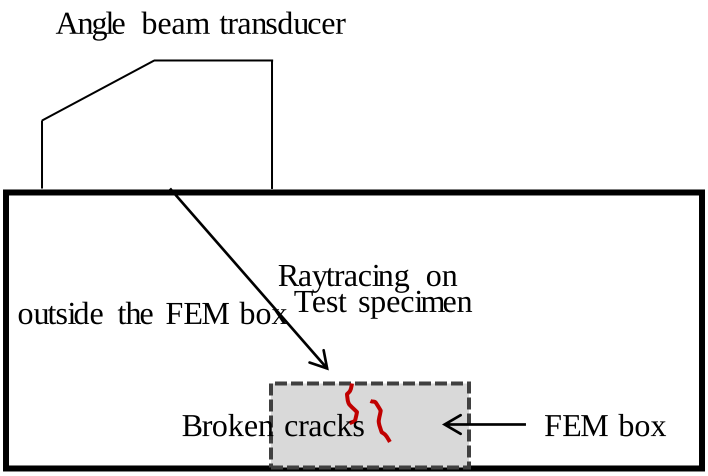

Fig.2 ATHENA 2D combines Raytracing outside and FEM inside the box.

There is a finite element rectangular box which is predefined before the calculation and the FEM calculations are made with in this box to simulate the interaction of ultrasonic beam to the defect. Outside the FEM box, the semi-analytic model (pencil model) is used to simulate the round trip propagation of ultrasounds from the transducer. Application of ATHENA-2D for surface breaking and irregular cracks were studied and validated in CIVA [3]. Although the ATHENA-2D could simulate complex situations in bulk wave ultrasonic NDE, its application is limited only to bulk waves, Lamb waves and Rayleigh waves cannot be modelled using ATHENA-2D, also this method is valid only to 2D problems, more realistic 3D model cannot be studied. In another approach Z. Chang et al [21] used hybrid method to investigate the scattering of Lamb waves from a rivet hole that contains edge cracks as shown in the following fig.3. In his paper [22], scattering of Lamb waves interacting with circular hole with or without edge cracks in a plate of infinite lateral extent was studied both numerically and experimentally in 3D. In this method conventional FEM is applied on the small mesh boundary and Lamb wave modal expansions in frequency domain are used external to the mesh boundaries. The condition of selecting the mesh boundary is the distance measured at least four times the plate thickness.

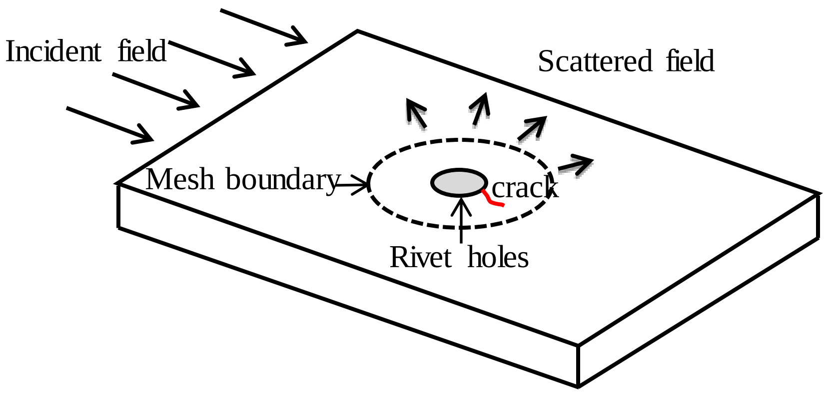

Fig.2 Finite element mesh on the rivet holes

In another modelling study, Srivatsava [22] used Global-Local method to simulate the ultrasonic guided waves interaction with structural defects. In his approach Semi-Analytical

Finite Element (SAFE) method was preferred in the global region than a pure analytical solution. The advantage of SAFE method is that it can handle complex geometries and multi-layered composites in an efficient manner. In his paper, he used SAFE method in global region and FEM analysis in the defect region for studying the defect interaction on an aluminium plate and aerospace composite joints and then validated his approach experimentally. In the more recent studies, Gresil and Giurgiutiu [9] used time-domain hybrid global-local concept for guided wave propagation using PWAS . In his paper, the time- domain analytical approach in the global region using analytical software called Waveform revealer (WFR) is developed by LAMSS [19] and Finite element mesh in the local region to describe the wave to defect interaction in the modelling. The approach is quite similar to Srivatsava [22] described above but Gresil et al used time domain signals in the global region using analytical solution rather a semi-analytical preferred by Srivatsava et al. The WFR software generates two time-domain signals S_0 and A_0 modes that go to the FEM module. This method is shown in the fig 4. The output from the FEM module serves as input to the WFR software again to generate the final waveform. Finite element method in the local region is achieved by means of ABAQUS Finite Element Analysis (FEA) software. Validation of this hybrid method with the experiment was carried out on Lamb wave interaction with notches and found similarity in experimental and simulation results. This approach compared to previous methods have many advantages however, time-domain hybrid model has to be run every time for each test frequency. In addition to this, it requires interface matching or more appropriate boundary conditions between the analytical and local FEM. The disadvantage of this method is that the analytical software (WFR) is not applicable to 2D or 3D problems as well as for anisotropic structures.

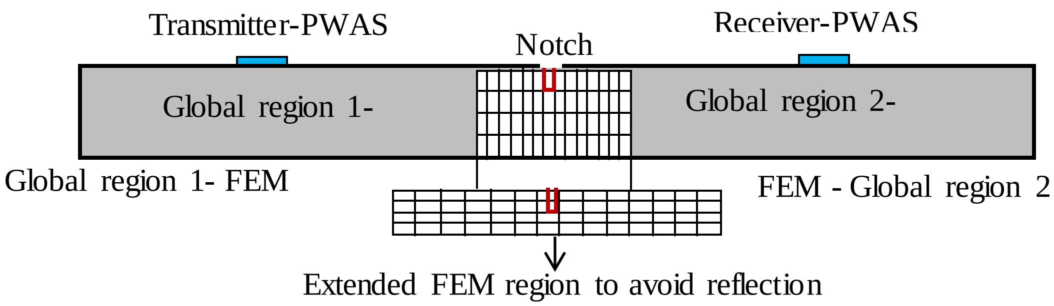

Fig. 4 Global-local FEM approach using PWAS patches

Y. Shen et al [18, 19, 20] has developed another hybrid method named Combined Analytical Finite element Approach (CAFA) for PWAS based Lamb wave simulation. In his approach, he computed Wave Damage Interaction Coefficients (WDIC) for coupling the analytical expression and the local FEM models. The purpose of WDIC is that it can describe the 3-D interaction between the incident wave and the damage for example, scattering and mode conversion can be accounted. In contrast to Gresil and Giurgiutiu model, he uses frequency domain based transfer function model in the global region and harmonic analysis of the local FEM model. One of the major features added to this approach is that the artificial non-reflecting boundary conditions to obtain WDIC and the entire analysis is carried out in 2D, the schematic representation of CAFA is shown in the fig.5. analytical ray tracing method for simulating bulk waves can be referred in the articles [5,15] . Schmerrr et al used multi-gaussian beam approach for modelling bulk waves and could be referred in the articles [6, 7]. Application of SFEM in SHM for various damage features is studied by Gopalakrishnan et al [13,14].

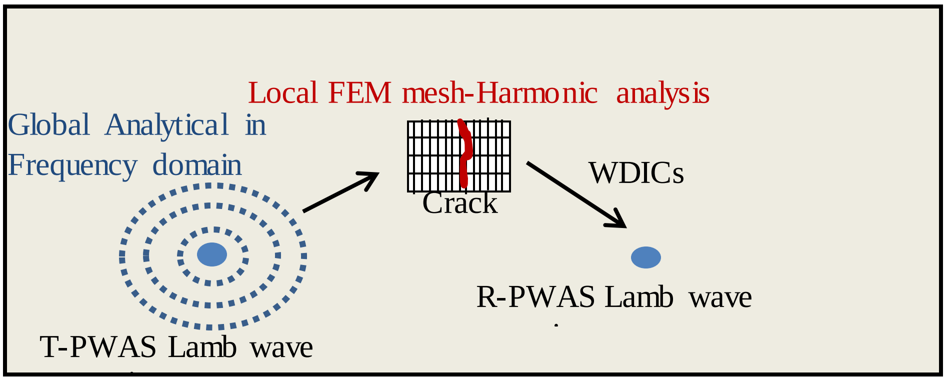

Fig 5 Schematic illustration of CAFA hybrid method

3. Test cases for bulk waves

Basic weld sample with artificial defects as shown in fig.6 has been taken as test case for validation purpose. In this case, L-angle inspection at 30°, 45° and 60° have been carried out using CIVA, COMSOL and Raytracing module in the IN-DEUS platform. The artificial defects such as lack of fusion at the side walls and porosities in the weld have been modelled. B-scan results have been obtained for different inspection angles using CIVA and Raytracing module as shown in fig. 7. CIVA has add-on module called ATHENA-2D that performs hybrid simulation for very complicated flaws such as branched cracks in the weld region. The FEM box of 30x30 mm has been defined for the finite element calculation in the region around the crack. The results of the ATHENA-2D are very similar to conventional CIVA results.

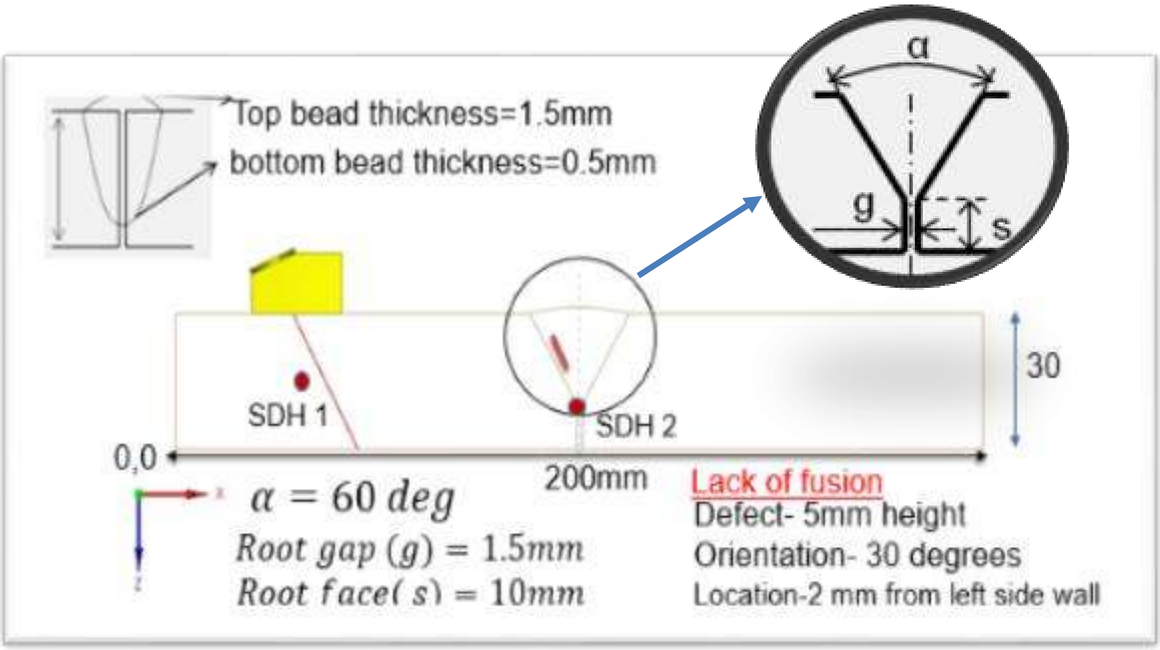

Fig.6 Weld geometry model for bulk wave validation .

Following assumptions have been made in the above model:

1. Only direct interaction of the incident wave field to the target is considered.
2. No interaction of front, back wall and side wall reflections are taken into account.
3. Mode conversion and attenuation are not considered.
4. Only longitudinal wave inspection is accounted.

5. Method of separation of variables (SOV) is chosen as scattering model for side drilled holes (circular flaws) and Kirchoff's and Geometrical Theory of Diffraction (GTOD) models have been chosen for lack of fusion kind of defect (rectangular defects).

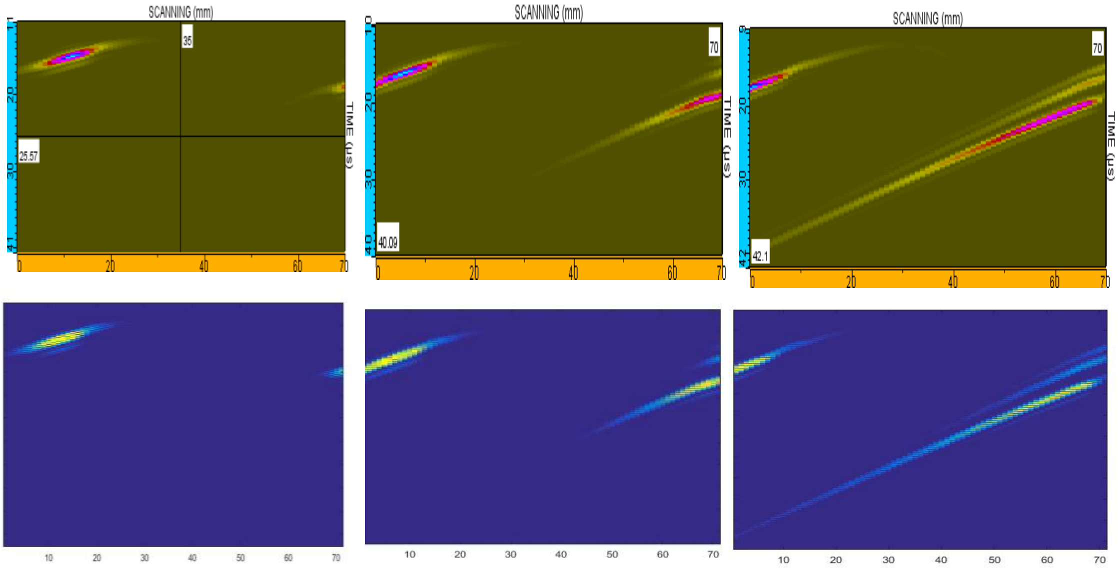

Fig 7. B-scan results for 30°, 45° and 60° angle of inspections using CIVA and raytracing tool

Verification of the travel time

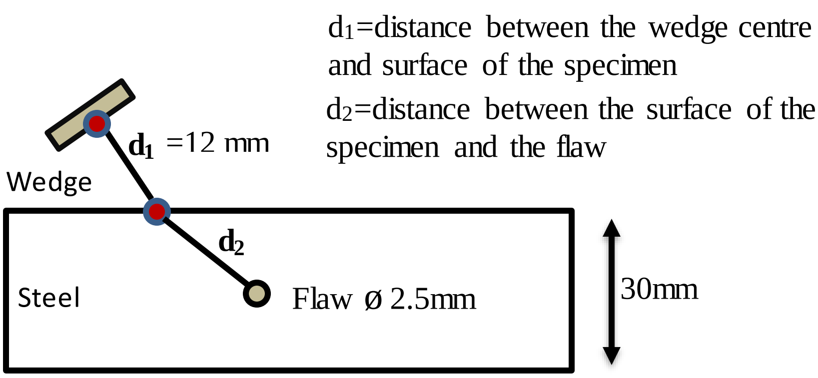

Fig 8. Travel time computation for angle beam inspection of 45°

Total travel time is the sum of the travel times in the wedge and the target in the specimen. $t = t_1 + t_2$ is the direct travel time and 2*t is the time received at the transducer as shown in fig.8

$$t_1 = \frac{12}{2680 \text{x} 1000} = 4.47 \mu s$$

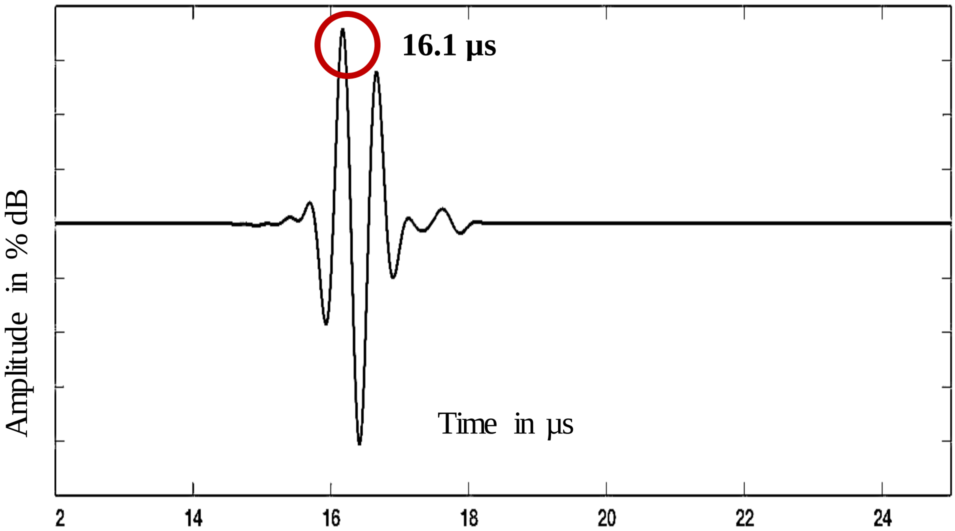

Fig 9. A scan at the target of angle beam inspection of 45°

$t_2 = \frac{15}{\cos(45) x 5900 x 1000} = 3.6\mu s$, therefore total travel time $t = 16.1\mu s$ which is relevant in the A-scan as shown in fig.9.

Bulk wave modelling using COMSOL Multiphysics

COMSOL Multiphysics is based on FEM, its advantages besides Multiphysics definition include potential interface links to various CAD/CAE and Matlab tools. The excitation function used here is the Hanning window sine function with five cycles tone burst with the frequency of 2 MHz at the surface of the wedge. The other important parameters in the FEM model are element type, its size and the critical time steps. Ghose et al. [1] mentioned in their paper the specific aspect of optimum element size and critical time step for the numerical simulation of the bulk waves. The maximum length of the element (Δx_{max}) is given in Eq. (1). In this model triangular mesh elements have been used,

$$\Delta x_{max} = \frac{\lambda_L}{R} \qquad \text{Eq. (1)}$$

where $\lambda_L$is the wavelength of the longitudinal ultrasonic wave and R is the ratio of wavelength to Δx_{max}. The value of R≥ 8 is recommended in this paper. The requirement for the critical time step ($\Delta t_{critical}$) is as shown in Eq. 2. where C_L is the longitudinal ultrasonic wave in the material to be analyzed both in the wedge and in the weld specimen. The circular flaw of Ø 2.5 mm is modeled on the weld region at the depth of 15mm from the surface. The properties of air are assigned at the flaw region. The wave propagation snapshot at 10 µs is shown in the fig.10 is for the angle of propagation of 45°, where one could clearly distinguish L and S waves. The one-way travel time taken for the L-wave to reach the target is 8.05 µs which can be seen in the figure as the wave hits the target and goes further away into the base material. Since the solution is similar for other targets, the time range up to 10µs is considered here for the demonstration purpose.

$$\Delta t_{critical} = \frac{\Delta x_{max}}{C_L} \qquad \text{Eq. (2)}$$

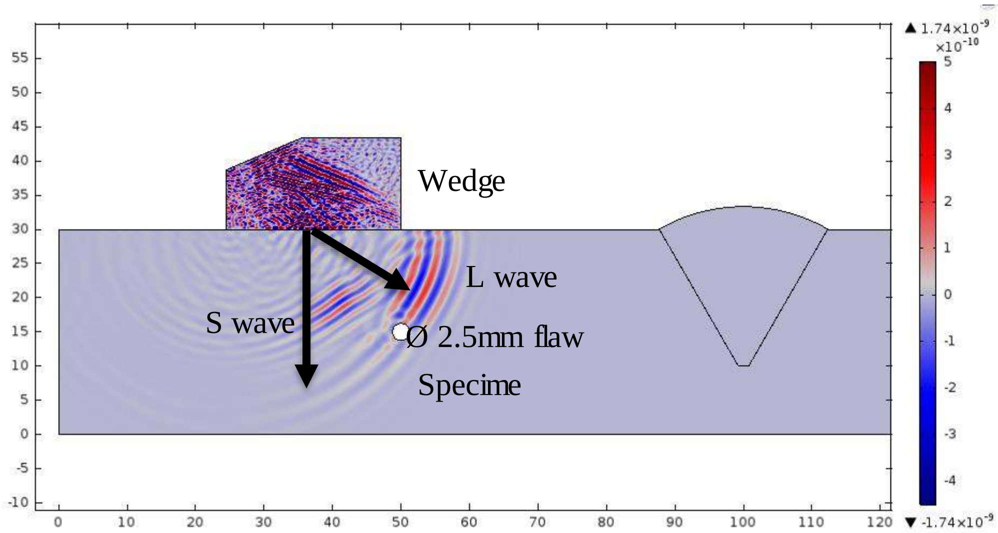

Fig 10. Bulk wave propagation using COMSOL-Multiphysics

Test cases for guided waves

Two different test cases have been considered, one for simple geometry and another one a more realistic aircraft panel which is shown in the fig.11. The case shown in fig.13 is used to obtain results using CIVA-GWT module which doesn't take into account the scattering of hole like defects. It uses Guided wave transducer unlike PWAS (Piezoelectric Wafer Acoustic Sensors) kind of transducers used in IN-DEUS platform and COMSOL for SHM applications. The initial crack of 51 mm length has been modelled. The panel shown in figure has skin connected to stringers by

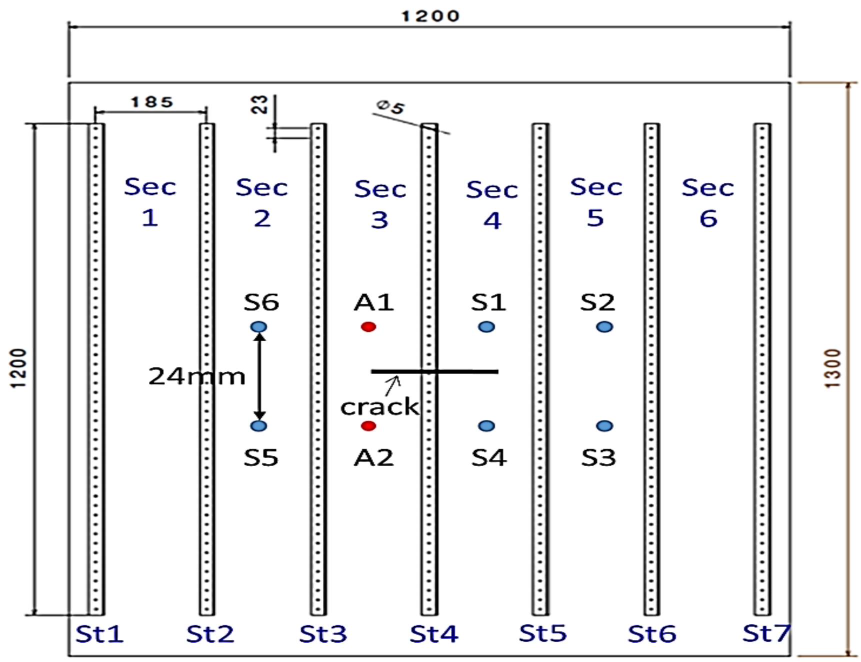

Fig.11 Aircraft fuselage panel

means of rivets. The wave propagation at time 150μs is shown in the fig.12. for a reduced version of the geometry considered in COMSOL as it requires enormous computation time when the degrees of freedom are increased due to the smallest mesh parameter. The fig.12(b)

shows the results from the raytracing module. The arrival time of the reflected wave front is about 150µs for the sensor S1 configuration as shown in fig.11. The wave fronts are just arriving at the sensor S1 in the COMSOL FEM simulation as shown in fig.12(a)
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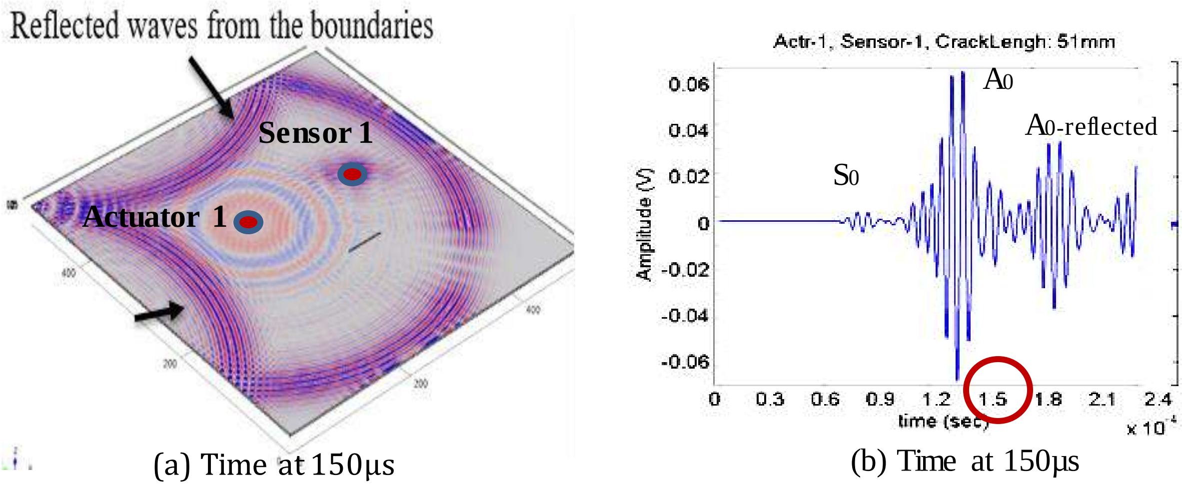

(a) Time at 150µs (b) Time at 150µs

Fig.12 Guided waves results from COMSOL simulation and raytracing module from IN-DEUS

Test cases for guided waves

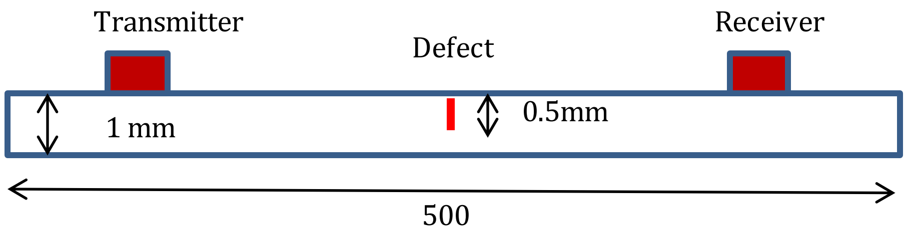

Fig. 13 Guided wave validation model of a rectangular plate

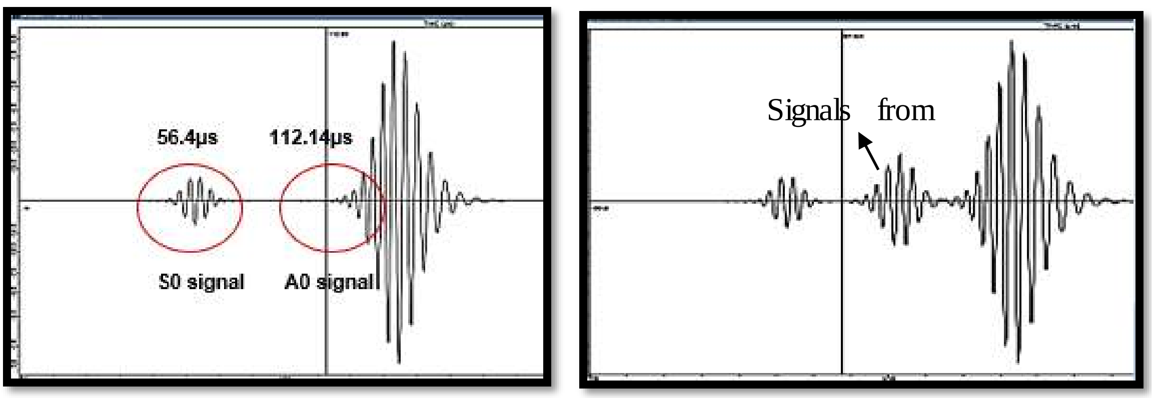

Fig. 14 Results of guided wave using CIVA-GWT module

4. Conclusion

Need for hybrid simulations in bulk waves and guided wave ultrasonic NDE is highlighted and brief literature review had been given on this topic. Raytracing combined with SFEM is being developed within IN-DEUS platform is one of such hybrid numerical methods.

Various simulation cases have been identified for bulk and guided wave simulations using CIVA, CIVA-GWT, COMSOL-Multiphysics and Raytracing-SFEM. Each method described in this paper has its own merits and demerits. The simulation tool CIVA performs fast and effective bulk wave simulations for simple as well as for a more complicated geometries and even for more complex materials. Its GWT module (2015 version) cannot take into account scattering from rivet holes for 3D geometry and it cannot also perform simulation using PWAS transducers that are used in SHM applications. On the other hand, COMSOL-Multiphysics perform both bulk and guided wave simulation using FEM. The advantage of looking at wave fronts for the entire time history allows one to understand the wave to flaw interactions in simpler way. This helps one to perform differential imaging i.e. subtracting wave fronts of damaged from undamaged condition to enhance the optimum actuator/sensor positions in SHM application [23-25]. It is well understood that the whole simulation process takes several hours which in turn dependent on the size of the geometry used. Raytracing-SFEM could perform more fast and efficient guided wave simulation for various types of scattering features. The Paper shown here demonstrates simple test cases for bulk waves and more realistic test cases for guided waves. The idea behind this paper is how one can efficiently integrate various simulation tools for validating Raytracing-SFEM within IN-DEUS platform and would one even go beyond by utilizing one or the others to perform more efficient SHM sensor system configurations.

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