ESTABLISHING A SIMULATION PLATFORM FOR ACOUSTICS BASED SHM SYSTEM CONFIGURATION

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Abstract. Lamb wave based SHM has the advantage of waves propagating over comparatively larger distances which are widely considered for aeronautical applications as an active SHM system. Numerical simulations of Lamb waves have been used by the SHM community to understand the physical features of wave to structure interactions and to study the occurrence of multiple Lamb wave modes. Simulating the performance of Lamb wave based SHM systems with state-of-the-art FEM can become increasingly time consuming when it comes to damage detection in real and larger aeronautical structures. The paper describes how this process can be enhanced considering a specially designed approach based on ray tracing combined with spectral finite element methods. Application of the approach will be demonstrated along a riveted stiffened aluminum panel under fatigue loading.

1. Introduction

There has been an increasing trend to use active acoustic-based SHM approaches such as Lamb waves for continuously monitoring the ageing or repair of large aircraft of both metallic and composite structures. The objective of such systems is to reliably monitor the growth of damages present in those structures (diagnosis) and predict their remaining life (prognosis). The conventional maintenance routine involves non-destructive testing methods such as based on eddy current and ultrasonic techniques etc. to be used in scheduled intervals to determine a damage being within the range of damage tolerance allowables. This often needs the whole aircraft components to be dis- and reassembled for the inspection process. This increases the time and cost of the inspection in addition to the limited information on structural integrity of the component obtained. An active structural health monitoring (SHM) involves integrated actuators and sensors usually based on PWAS (Piezoelectric Wafer Active Sensors) attached onto the structure to continuously monitor the integrity of the structure considered [3]. The advantage of elastic wave propagation to quantitatively characterize a damage that is more than half the size of its wave length has attracted different research communities to develop monitoring strategies using Lamb waves for detection of smaller fatigue cracks which are of growing nature. When such waves propagate between the same constant geometric boundaries of a structure they are called guided waves.

Numerical simulation of guided waves brings thorough understanding of governing mechanisms of the wave propagation when it interacts with structural features and has been used as a major tool in scientific research. One of the main concerns with dispersive waves is the occurrence of multiple modes of waves, which can seriously affect the detectability of damages. Although extraction of desired modes using signal processing methods does exist [14], numerical analysis can typically aid the interpretation of those damages being observed through waves which have been mode converted as a consequence of the presence of damage. There are numerous methods listed for carrying out guided wave simulations of which some are briefly discussed in the next section. However, all of those have limitations when the structure either becomes too large or defects become too small to be detected. The damage tolerant design (DTD) approach helps us to operate a structure safely in the presence of damage until the damage reaches a maximum threshold without affecting the structural integrity. One of the prime requirements of the guided wave SHM approach is to deploy actuators/sensors for determining the known damage size. For a given appropriate loading condition, the probable location of the damage can be obtained from a load (stress/strain) distribution simulation analysis. An assumed initial crack length further defines the onset of crack propagation and combined with classical fracture mechanics calculations and a load sequence determined or made available allows the interval to be determined, within which inspection of the damage considered can be 'tolerated'. Based on the two inputs of location and size of the tolerable damage, the number of actuators/sensors required to be placed on the structure for reliably detecting the respective damage can now be determined. Various schemes have been widely used to detect the damage from the guided wave signals obtained.

A pragmatic approach for damage detection in that regard is to use a signal differential method for the separation of damage related echoes. The application of this method for an aircraft panel is described in [16]. This method involves recording of the signal of a pristine (undamaged) condition based on a set of given actuator and sensor positions and subsequently subtracting from those signals the signals that are taken while the structure is in operation and hence becomes subject to the damage to be monitored. The resulting signal clearly shows at least at specific locations on the structure if any damage on the structure exists or not. Based on this simulation one even obtains the locations where this differential signal becomes most sensitive for a given actuator combination. This is then also an indicator where sensors should then be placed best in case the differential signal becomes the basis of damage monitoring. It is essential to note that the differential signals method is one dimensional that gives only the differences in arrival times resulting from the difference in structural condition which in the case here is the damage while any other information resulting from the geometry (i.e. boundaries) including mode conversions is cancelled due to similarity. An extension within the differential signals method is to use differential images [13] as a method in which wave propagation at each time step is recorded for undamaged conditions and is subtracted from the damaged ones to give a resultant set of 2D/3D images. This method gives additional information of the x, y, z coordinate-points where maximum differential displacements could occur. Both differential signals and differential images can therefore operate on a baseline-free information of the structure in the end.

In contrast to the above methods, *Park et al* [5] uses a time-reversal concept as an alternative approach. However, the idea of this paper is not to highlight the different detection schemes in guided wave SHM but to demonstrate how the numerical simulation along with differential imaging can help to optimize the sensor locations for monitoring a growing crack in a large structure such as an aircraft panel. The current paper therefore focuses on the development of a full-scale simulation platform as a part of the Indo-German joint project called *IN-DEUS*. This platform will allow geometric modelling to be performed combined with fatigue damage analysis and guided wave simulation through different computational numerical methods being widely used in the context of SHM.

An important requirement with respect to many applications and which regards SHM specifically is that either the simulation is close to real time in speed or an optimisation procedure is found that allows the optimum actuator/sensor pattern to be determined for the specific structure. Since the latter is still more a vision than a reality at present the former stays as a requirement that has to be met. A stiffened aircraft panel with a crack propagating within the damage tolerance range has been taken as an example to demonstrate the simulation capabilities which will be described in more detail below.

2. Development of hybrid method for guided wave simulation using Ray Tracing- Spectral Finite Element Method (RT-SFEM)

2.1 State of the art simulation tools

Guided wave simulations in SHM are often used to predict the possible wave fields, proving an insight into mechanisms that drive the wave interactions with structural features. Interesting contributions have been recently made by researchers especially in the development of theoretical Lamb wave models in SHM applications for both isotropic and anisotropic structures [2, 6, 14, 15, 16]. Driven by the advancements in the computational methods and electronics, there exists analytical and exact models for performing the numerical simulation but their solutions are limited to either simple shaped structures or artificial damages. There are different numerical tools available for modelling the Lamb wave based SHM system such as finite element method (FEM), finite difference method (FDM), elastic finite integration technique (EFIT) and spectral FEM (SFEM) to just name a few. The application of FEM and FDM to structural health monitoring of plates by *Xu et al.* can be referred to in the [6]. SFEM for SHM has been studied by *Ostachowicz et al.* [17]. Two dimensional ultrasonic modelling has been extensively studied by *Schmerr et al.* using Gaussian beams [8, 9] and three dimensional modelling of bulk waves using EFIT was studied and validated by *Chinta et al.* [12]. Except for SFEM, the above numerical methods are time consuming and in some cases cannot be applied to higher order frequencies where the detection of smaller defects is of more importance. In such cases, analytical and numerical methods can be combined together to form hybrid methods. The advantages of hybrid methods include faster computation time and the ability to model the Lamb wave interactions to smaller damages. A well-known ultrasonic module in an NDE simulation tool exists in EXTENDE's *Civa 2015*, which uses an add-on hybrid method called ATHENA 2D to combine both a semi-analytically formulated raytracing and FEM models for simulating the complex problems in ultrasonic NDE [4, 10].

2.2 Ray tracing integrated spectral finite element methods (RT-SFEM)

Complex wave scatterers like defects and other structural features are difficult to model. The Spectral Finite Element Method is a powerful tool to model such defects and features. The ray tracing technique can be combined with spectral finite element techniques to reduce computation cost and time. This can be achieved by modelling complex defects and structural features using a finite element mesh and letting them interact with the wave using the wave field that is carried by rays. The approach is to integrate the ray tracing technique into FEM where the wave launched from the transducer is transported as rays to the various scatterers and defects being modelled through the finite element mesh of solid elements. Ray tracing

assumes that the energy emitted from a source is divided into discrete elements called rays whose propagation and interaction with features such as edges and damages inside the material is governed by Snell's law of reflection and refraction. Propagation of rays in three dimensional media using propagation of sound waves in air has been discussed in the literature [7]. Different ray tracing methods in various media have also been studied [11].
By classical methods, a set of rays can be represented by an equation of a line originating from a point, which is given by

$$x = x_s + \alpha d \tag{1}$$

where x is a coordinate on a ray originating from x_s whose direction vector is given by d and α is the distance between original and the new point. Consider ray $\vec{r}_{inc}$, to be incident on a surface at an angle θ with a surface normal N as shown in Fig.1 .

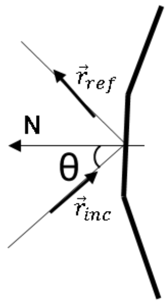


Fig. 1. Determination of reflected ray component along the surface of hole approximated as line segments

The reflected ray component $\vec{r}_{ref}$ is given by the following equation

$$\vec{r}_{ref} = \vec{r}_{inc} - (\vec{r}_{inc}.N)N \tag{2}$$

Since the guided wave is modelled in an isotropic medium, only the reflected component of the wave is considered. The magnitude of wave field displacement at ray origin along with the direction is estimated at the beginning. The field is revaluated when the ray interacts with boundary features, thereby incorporating the scattering properties of the boundary. The spherical losses due to ray propagation in the medium are also incorporated. The interaction of the ray with the boundary is studied by discretizing the edges of the boundary into finite line segments (Fig.1). The discretisation of the line segments is introduced by the meshing software during meshing of the geometry. The accuracy of the scattering effects therefore depends on the size of the line segments. To study the effects of holes and the crack at various sensor locations, only a finite set of rays has to be launched at the actuator. When the actuator is excited, the wave propagates in a cylindrical manner. Hence it is assumed that the energy is distributed equally in all the directions. Therefore only a fraction of energy is considered along the ray path. An additional condition is that only the rays, which will reach the sensor after interaction with the boundary was imposed during simulation. This was done to identify the rays that will be incident on the sensor after reflection from the holes and the crack. For the signal to interact with various boundary features on the sample, it is important that the wavelength of the signal launched at the actuator matches the dimensions of the features to be captured. Such a condition was also imposed during simulation.

3. Stress and fatigue analysis of aircraft structure panel

The test component shown in Fig. 2 is a riveted panel of 1224 mm x 1215 mm x 2 mm in size with seven 'L' shaped stiffeners of 25.4 mm x 38.1mm x 2 mm dimension being attached. A rivet diameter of 5 mm has been considered for this case. The stiffeners are provided to support the skin and to prevent the skin from bending in the z direction. One end of the panel has been constrained to 6 degrees of freedom (DOF) and on the other end a 21 kN in-plane pressure has been applied. The stress analysis was carried out for a healthy panel as well as for panels with various crack lengths. The cracks were introduced at a rivet location in the centre of the panel including the centre of the stiffener. The stress contour is shown in the Fig. 3 for various crack lengths. It can be observed from the contours that for the undamaged panel the maximum stress arises around the rivet hole and these are the areas prone for crack initiation.

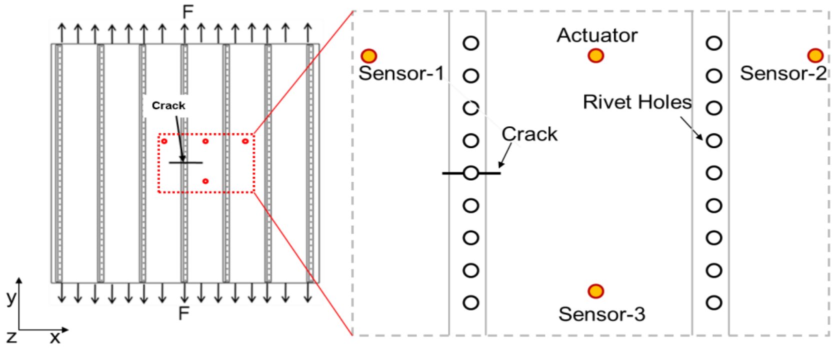


Fig. 2 Stiffened Panel with crack showing loading conditions and sensors mounted for rapid inspection

Table 3

Part	Material	Young's modulus	Poisson's ratio
Skin	ENAW-2017A	72.4 GPa	0.33
Stringer	2001T79511	71.7 GPa	0.33

As crack length increases, stress at the crack tip increases too. There are other probable locations where crack can initiate and grow. Generally the stress or strain response of a structure or component to loads applied is the starting point for any type of fatigue analysis, which is usually presented as a load spectrum in general and possibly even in a stress or strain time history when it comes to local analyses. When the load history is irregular with time, then rainflow cycle counting is used to decompose the irregular time history into stress blocks of equivalent loading before a fatigue life estimation is performed on the basis of S-N curves. A probability of damage can be determined by performing a fatigue analysis even for a cracked structure as seen in Fig.3. The initial crack length was set here to 50 mm and stress and fatigue analysis was carried out for different crack lengths up to 340 mm, which has been the damage tolerant criterion set.

4. Experimental investigation

The Lamb wave actuation signal was simulated at 310 KHz for the 2mm thick aluminium plate referenced above. An appropriate transfer function was used to convert the actuator signal into a displacement field and appropriate scattering models were applied to cope with the reflections resulting from the cracks, rivets and holes to model the signal around the crack location. A receiver transfer function was used to convert the displacement field into a voltage signal at the sensor location considered. All the signals were unit normalized for comparison. To validate the simulated signal, signals were measured with sensors at the locations considered in the simulation using data acquisition systems. Fig. 4 shows a comparison between the signals generated through a ray tracing model and actual signals measured by sensor-2 (Fig. 2) considering data acquisition for a healthy and a damaged sample. The differences observed in the present simulation are attributed to the approximation that scattering is only due to the rivet hole, whereas in the experimental case a large amount of scattering may be also due to the stiffener edges. Further detailed insight regarding this aspect is subject to investigations currently ongoing.

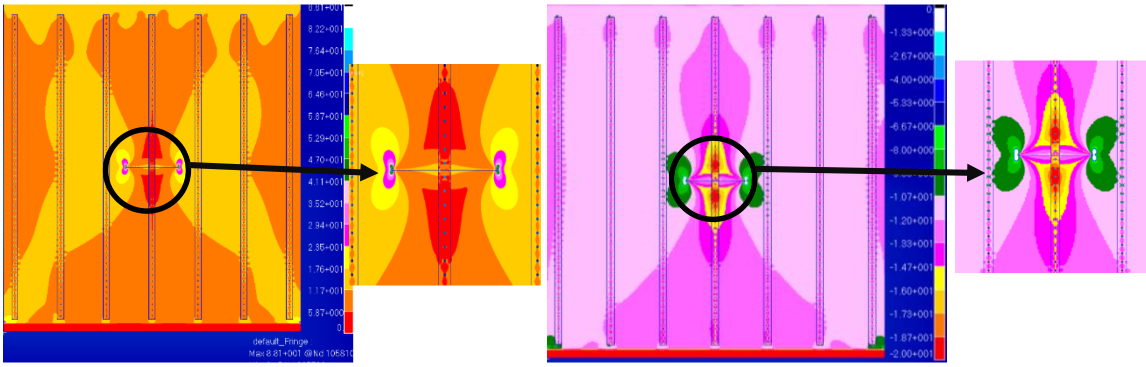
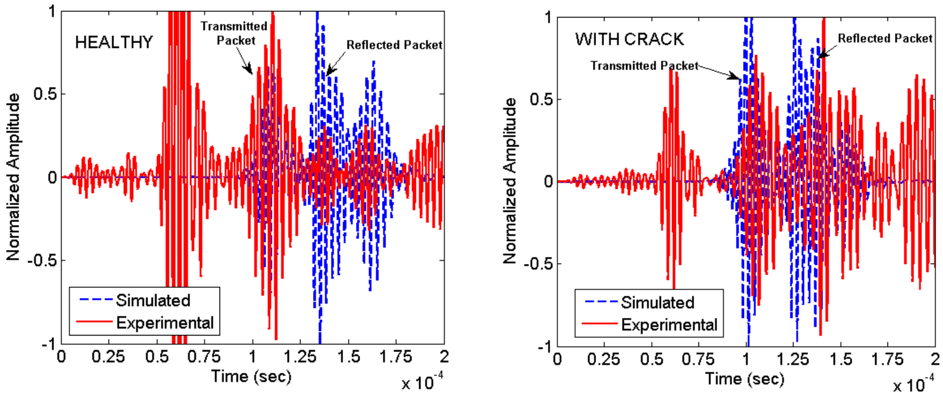


Fig. 3. Stress distribution (left) and probability of damage analysis results (right) for 200mm crack length



(a) (b)

Fig. 4. Comparison between signal generated through RTSFEM model and experimental signal measured at Sensor-2 on (a) sample with no crack, (b) sample with 50mm crack

5. Sensor optimization using finite element COMSOL simulation

The finite element method based COMSOL tool has been used to also simulate the guided wave propagation in the panel structure introduced above (Fig. 2). The objective of this simulation is to record the wave propagation at regular intervals for the undamaged and damaged condition of the panel. Fine triangular solid mesh elements of 2 mm in size have been used. The Courant Friedrichs Lewy (CFL) criteria had to be satisfied in order to get the stability while solving the partial differential equations (PDE) and as a result a minimum time step of 1µs has been applied. The maximum element size has been taken as λ/12 mm. Following the structural mechanics module options a boundary load has been applied on the actuators for the generation of the A_o *(asymmetrical)* mode. To study the placement of potential actuators and sensors a 3D laser Doppler vibrometer (LDV) was also used to monitor the wave propagation in the damaged sample. It can be seen that a signal packet gets reflected due to the crack (Fig. 5e, 5g) and by placing a sensor at that locations of the signals reflected from the crack a decent signal will be captured. The effect of the crack is evident in both the snapshots from the LDV as well as from the FEM simulation. Fig. 5g and Fig. 5h show similarities in capturing signals in both regions being reflected and shadowed by the crack respectively. In addition to this, the differential image in Fig. 5d shows that there are multiple locations where the maximum resultant displacement could happen when the wave propagates in the medium, which are considered as locations sensitive to the damage and as such locations where sensors should be placed optimally.

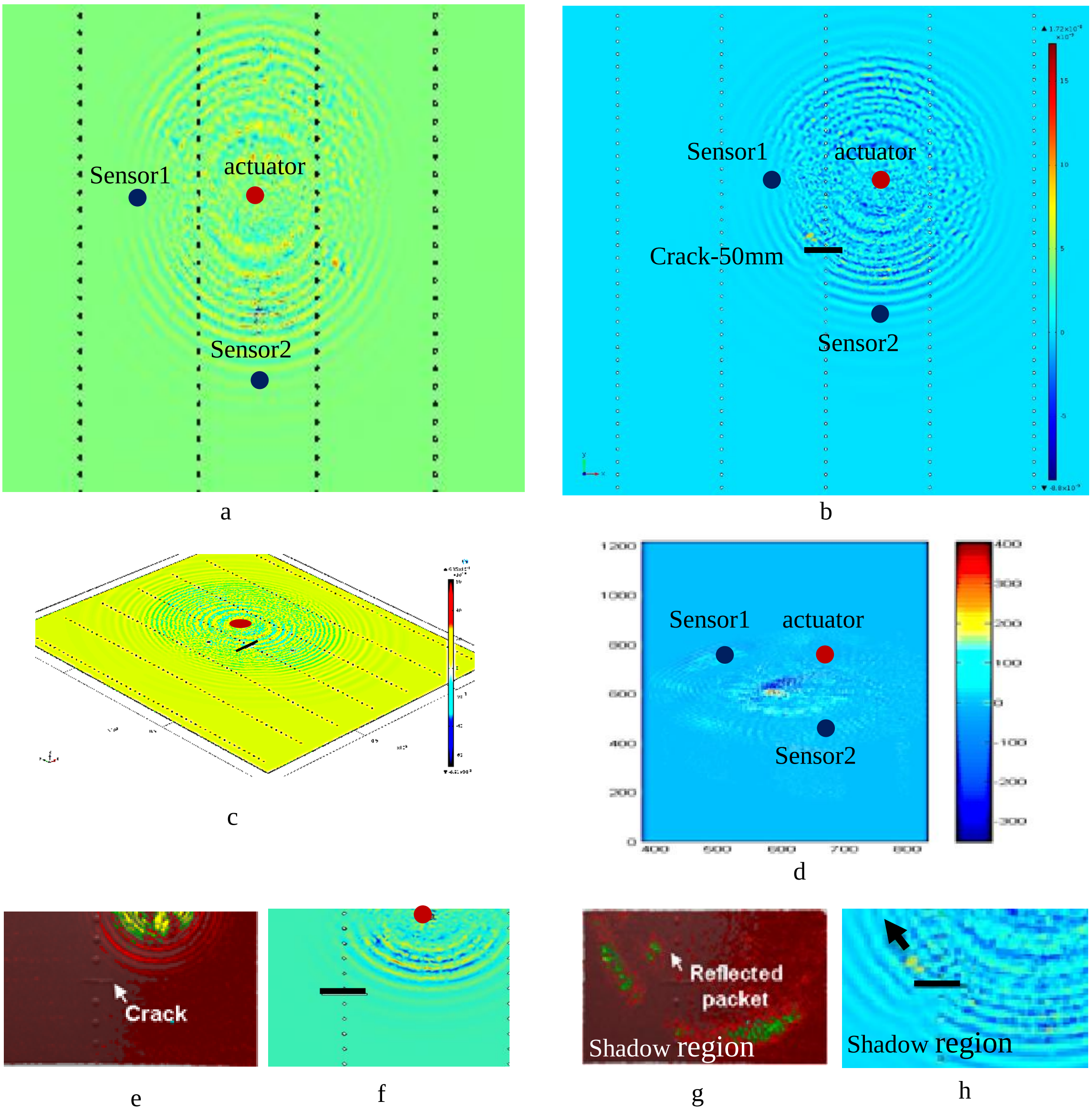


Fig. 5 Wave propagation for without and with crack at 50 µs (a and b), 3D wave propagation (c) , differential image (d), LDV image from experiment (e) snapshot of the simulation (f), reflected waves (g) and shadow region (h) from LDV and simulation

6. Conclusion

Deployment of real-time guided and even acoustic wave SHM systems demands for fast and efficient numerical simulation tools such that an optimum actuator/sensor pattern can be determined to reliably detect damage of a tolerable size. The solution to the problem of near to real time simulation in SHM processes for large and even complex structures can be generally seen in the use of hybrid models. The variety of simulation approaches and tools developed should be made available to a broader community on a simulation platform in the light of validation. This would allow the complete structural integrity assessment process chain to be demonstrated in hopefully near to real time to determine an optimum and reliable acoustics based SHM system.

Guided wave simulation combined with RT-SFEM can be performed as a time efficient method to visualize signals for various sensor locations. Verification and validation of the simulations can be done on the real structure using a LDV. Generating images or better image sequences determined from FEM or better hybrid model simulations resulting from the difference in signals between the undamaged and damaged condition will allow locations where the difference in signals are maximum to be determined being the locations where sensors would be placed best. Approaches of that latter kind need to be further developed such that SHM simulation and hence the realisation of reliable SHM systems will have a true future.

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