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A Simulation Platform for Structural Health Monitoring

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Abstract

The CIVA platform is a well-known multi technique simulation and analysis software in NDT. Developed by CEA LIST, but also resulting from the contribution of numerous industrial and academic partners within Europe, the software keeps evolving to offer its users the best performances in terms of numerical efficiency, imaging, and reliability demonstration. CIVA can simulate UT, GWT, ET, RT, CT, and now Thermography in NDT. CIVA has also recently expanded its modelling tools to Structural Health Monitoring based on guided ultrasonic waves.

Based on a combination of spectral Finite Elements methods and a parametric macro-mesh technique, CIVA SHM can address many industrial SHM configurations (metallic or composite materials, planar, cylindrical, or curved geometries) with very competitive performance.

SHM by guided waves needs to rely on more quantitative performance demonstration and optimization studies to significantly increase its industrial deployment. This is why an efficient and dedicated simulation tool looks particularly useful since computational and hardware costs are very often prohibitive for large simulation campaigns with most traditional Finite Elements software packages.

After a brief description of the numerical techniques involved in this tool, some validation and application examples are presented in this paper.

Keywords: Simulation, Modelling, SHM, Guided Waves, Imaging, Performance demonstration, Optimization, MAPOD.

1. Introduction

Among Structural Health Monitoring methods, guided wave SHM is a technique relying on the permanent integration of a transducers' network aiming at detecting potential damages affecting the structural integrity of the monitored structure. To be part of a competitive predictive maintenance strategy, the choice of relevant GW-SHM sensors, their number, and their location in the specimen is of paramount importance to optimize critical flaws detection while limiting their number and thus the whole cost. Since building monitored and flawed prototypes is even more costly than simple mock-ups, simulation can play a key role as a virtual prototyping tool before physical implementation.

To increase the industrial deployment of GW-SHM systems, a solid performance demonstration stage is also required. Indeed, due to the fully automated measurement process, the large number of influential parameters involved, the numerous sources of false alarms and the potential failures of the embedded sensors themselves, reliability studies must be conducted. Experimental campaigns become rapidly prohibitive if you want to take all uncertainties into account. This is why simulation can help since it can provide a large amount of data and information regarding some of the most influential parameters, which will greatly reduce the need for costly mock-ups, limiting their number to a relevant sampling.

By nature, GW-SHM provides complex signals (several dispersive modes, several sensor paths, influence of component features and edges, etc.) and simulation can also be useful to help the interpretation of these results and develop relevant signal or image processing strategies. Simulation should help to improve our mastering of the SHM technique as well as generating large data sets to train deep learning algorithms in the context of an on-going Machine Learning approach of SHM analysis.

2. Modelling techniques and tools for SHM

CIVA is a software platform dedicated to NDE and SHM, widely used worldwide for the simulation and analysis of several NDE methods (Ultrasounds, Guided Waves, Radiography, Eddy Current and now Thermography). SHM by guided waves has recently joined this platform. Finding the best compromise between computation performance, easiness of use and versatility for the targeted application has always been the three pillars of the CIVA strategy.

Contrary to some other applications based on long range ultrasonic guided waves such as pipe NDE inspections where 2D-like models are suitable for a lot of configurations, modelling SHM applications requires to fully consider the three-dimensional nature of the wave propagation. However, traditional 3D Finite Elements approaches often fail to simulate realistic configurations due to prohibitive computational costs in an industrial context, that is why the choice has been made to rely on the Spectral Finite Elements technique (SEM) in CIVA SHM. The SEM technique implemented in CIVA relies on high-order elements coupled with an optimized meshing strategy thanks to a structured macro-mesh parameterized with respect to the geometry of the SHM configuration. For readers interested in the numerical techniques, more detailed information is provided in [2]. It has shown very competitive performances with accurate predictions obtained with a gain of a factor higher than 100 in terms of computation time compared to generic FEM packages and a negligible RAM footprint [3] which allows to use CIVA SHM on a traditional hardware or launch several simulations in parallel on a cluster.

An industrial tool for SHM also requires convenient user interfaces and relevant analysis environments. In terms of user interface, CIVA SHM benefits from the same NDE-oriented environment than the other modules of the CIVA platform. The mesh being fully parametrized, it is automatically managed without need for advanced FEM skills from the user. Due to the numerous sensors involved and the automatic monitoring process, SHM intrinsically generates a large amount of data, and it is challenging to be able to treat them efficiently. From the data collection, a data analysis stage is then required to provide meaningful metrics so that the decision-making process can follow. Imaging is one way to improve defects detection and identification by providing a clear signature for a given indication and CIVA SHM includes such imaging reconstruction techniques. Parametric studies, metamodels and scripting approaches are also compatible with CIVA SHM to help conducting efficient, massive, and customized sensitivity studies and analyses.

CIVA is developed by CEA and distributed worldwide by EXTENDE [1]. CIVA SHM can currently simulates metallic or composite panels, potentially multi layered, and with an Omega stiffener. An irregular curvature can be applied to the initial planar profiles so that components such as leading edges or bended parts can be modelled. Metallic cylinders can also be addressed. While CIVA lets you easily define typical piezo electric circular patch sensors assuming a radial uniform loading, user can also simulate other profiles such as a normal loading or a custom one. Sensors can be regularly or arbitrary positioned on the monitored structure. Provided results include the raw signals obtained on all receivers as well as wave field snapshots or local stress measurements but also, as mentioned above, defect signature reconstruction images through a Delay And Sum (DAS) algorithm [6], analogous to the Total Focusing Method in ultrasound imaging.

Many evolutions are in process for implementation in future releases, for instance new specimen geometries such as multi-layered and composite tubes or elbows, but also the accounting of attenuation during wave propagation, new sensor types such as Fiber Bragg Grating as well as additional imaging algorithms and the capacity to load experimental data.

3. Validation

As for any simulation software, it is important to rely on experimental validation references to verify the relevance and accuracy of the models and use it with confidence in an industrial project. Several validation studies have been conducted around CIVA SHM for isotropic metallic plates, cylinders, or for composite panels [3], [4]. Some of these validation cases are compared to experimental data provided by the « Open Guided Waves » initiative, detailed in [5].

Let’s focus on one of these latter cases which deals with the instrumentation of a composite panel made with 16 carbon-epoxy plies for a 2mm total thickness. This type of structure exhibits anisotropic properties with respect to the ultrasonic guided waves propagation.

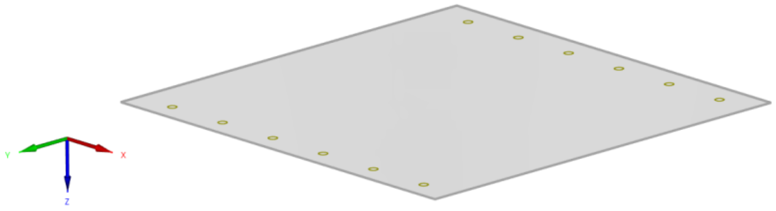

Figure 1: Monitored composite panel proposed in the Open Guided Wave validation benchmark.

The dispersion curves calculated by CIVA SHM are presented below in Figure 2. A0 mode data appears in red (group velocity of 1280m/s and wavelength of 19mm at 40kHz in direction 0°) while S0 is in blue (group velocity of 3400m/s and wavelength of 85mm at 40kHz in direction 0°). This composite material being anisotropic, a polar representation of group velocities versus the angle of the wave path is also provided.

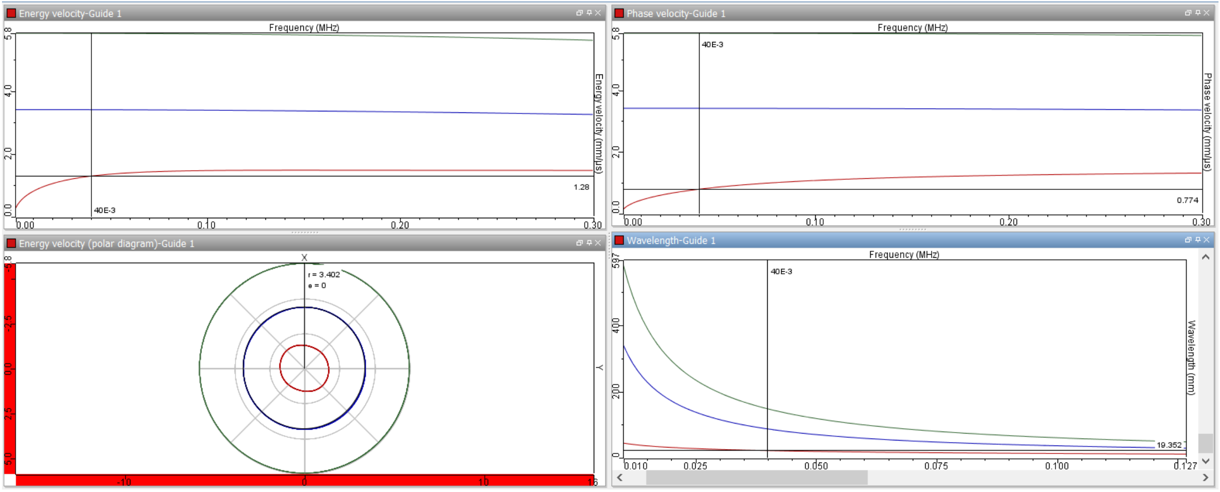

Figure 2: Dispersion curves calculated for A0 (red), S0 (blue) and S1 (green) modes (on the left: group velocity with a polar view at the bottom and a frequency domain view for the selected angle at the top; on the right: wavelengths at the bottom and phase velocity at the top).

12 piezo-electric patches of 10mm diameter are located as shown in Figure 1. Several excitation frequencies are considered, all sensors are successively excited as transmitters (with a radial load) while the 11 others are receivers (also called round-robin). In Figure 3 below, measurements and simulations are compared for the whole set of receivers when sensors #1, then #3, and then #8 (illustrated with a red point on the specimen schematic) are used in transmission with a 40kHz 5 cycles burst excitation. On the left, a B-Scan is shown where each column represents the signal received by one sensor (Simulated B-Scan is below the corresponding experimental B-Scan). On the right, each A-Scan signal is shown (simulation in red, experiment in blue). Experimental and simulated data are normalized with respect to the measured/simulated amplitude maximum on all the receivers channels (excluding the Pulse-Echo channel).

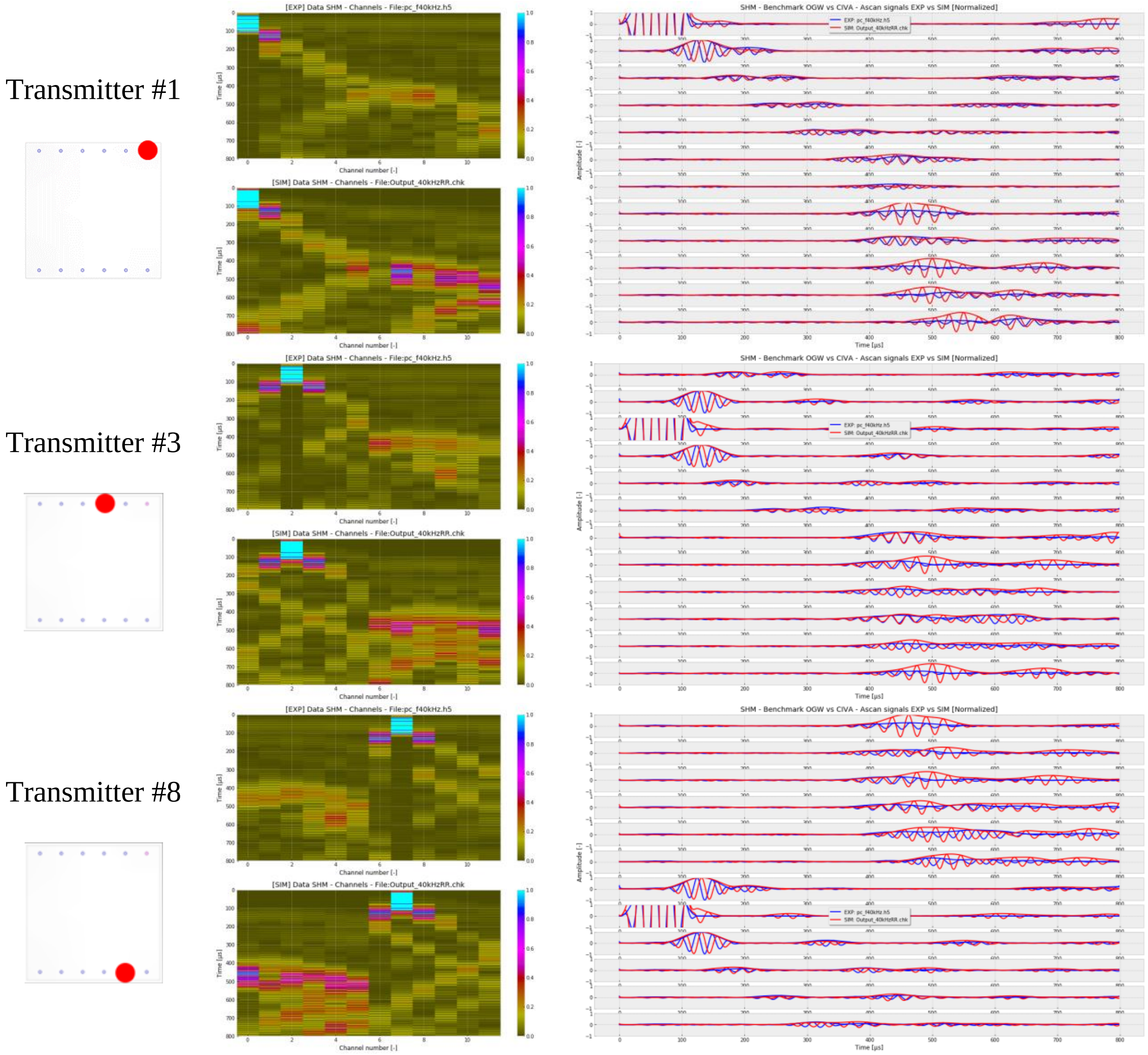

Figure 3: Results obtained for 3 successive transmitters: On the left, B-Scans for all receivers (experiment at the top, simulation at the bottom); On the right, detailed A-Scans (simulation in red, experiment in blue).

The comparison shows a good agreement between the calculated signals and the measurements: the different modes are well predicted (first the fastest S0 mode, then A0 one), the time of flights, the signals shapes as well as the different signals components due to the reflections on the edges appear very representative of the measurements. Modelling is never an exact copy of a measurement, due to both the model approximations and the experimental uncertainties. For the case under study, the main uncertainties are linked to the reflections on the specimen edges (assumed to be perfect in the simulation model), especially because the sensors are close to the plate edges. It can be also mentioned that the wave attenuation is currently neglected in the simulation model. Despite this, the agreement between simulation and experiment looks very satisfying to validate the use of CIVA SHM on this application case to predict the transmitted modes and the interactions with the specimen and potential defects. More details on these validation cases are given in [4].

4. Imaging applications for defect detection and identification

Defects detection is based on the processing of the signals received by the sensors' network which usually relies on the comparison between the defective state and a reference « baseline » state. While this process can be directly performed on the time domain raw signals with subtraction and signal processing techniques, imaging tomographic reconstruction techniques also exist to provide a more comprehensive information to detect and localize an anomaly. Of course, guided wave imaging will be efficient only if the generated modes are suited to the defect to inspect (in terms of wavelength mainly). Moreover, the imaging technique can also produce artefacts due to the algorithm itself or due to parasitic signals (for instance those due to the reflection on specimen edges or features).

The composite panel and sensors network (radial excitation) previously described are studied below in Figure 4. Each image displayed below results from DAS processing of signals predicted without any flaw and with a through-hole of 20mm diameter located in at the specimen center. Here three configurations are considered with similar sensors/flaw relative positions but with three different plate dimensions: 500mm*500mm (validation case), 700mm*700mm and 1000mm*1000mm.

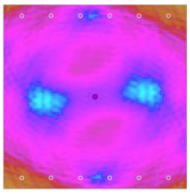

Figure 4a: Hole Ø20mm
Plate 500mm*500mm.

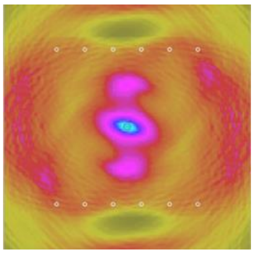

Figure 4b: Hole Ø20mm
Plate 700mm*700mm.

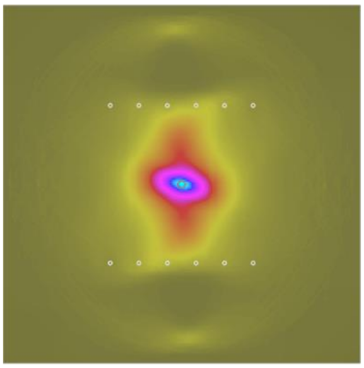

Figure 4c: Hole Ø20mm
Plate 1000mm*1000mm.

This reconstruction is based on A0 mode velocity. The consequence of the component size and thus the sensors to edges distance appears clearly: the bigger the distance, the better the defect is located through the imaging and with a higher signal to noise ratio. Whenever it is possible (and depending on the location of the expected defects), it appears then relevant to avoid positioning the sensors too close (with respect to the wavelength) to the specimen edges unless the used imaging algorithm can deal with wave reflections at these edges.

The instrumentation design includes the choice of sensors number and their location on the component. The probability of detection will be reduced if not enough sensors are used, while too many sensors will lead to unacceptable costs and burden for the monitoring industrial deployment. Simulation enables beforehand a study of the performance of potential implementation strategies, quickly and at low cost, without having to instrument real mock-ups, so that only promising solutions can be further tested with real prototypes. For instance, let’s compare in Figure 5 the images obtained with 12, 8, 6 or 4 sensors (18mm diameter) when placing them along a circle around the hole in the composite panel. You can observe that the image « quality » remains relevant for 6 sensors and above while it deteriorates significantly for 4 sensors for such layout.

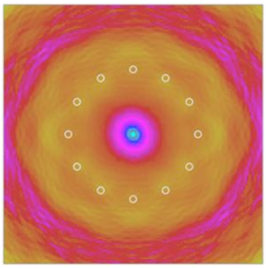
Figure 5a: 12 sensors.

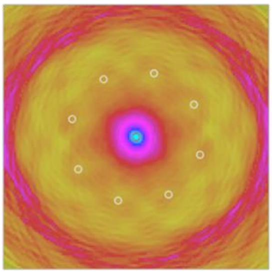
Figure 5b: 8 sensors.

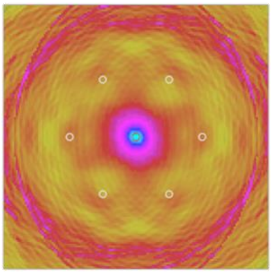
Figure 5c: 6 sensors.

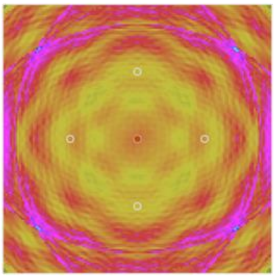
Figure 5d: 4 sensors.

Then, you can observe below in Figure 6 the images obtained with 4 networks of 12 similar sensors but with different layouts: aligned, along one circle, or along staggered circles. You can see that the quality of the defect spot improves (less artefacts so fewer false alarms) when you try to reduce the symmetry of the transducers’ arrangement with respect to the component and the targeted flaws.

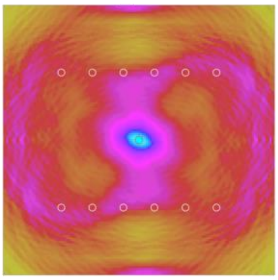
Figure 6a: Linear layout.

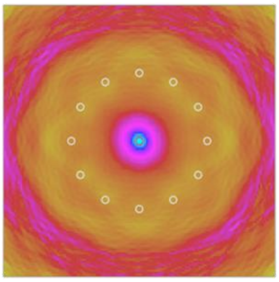
Figure 6b: Circle layout.

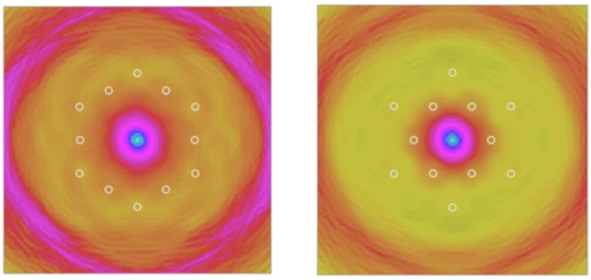
Figure 6c and 6d: 2 staggered circles layout.

Obviously, the monitoring design also includes the choice of the sensors themselves (technology, size, excitation). It is especially fundamental to generate preferentially modes with a wavelength adapted to the defect that you want to detect and maybe characterize. The next simulations focus on the detection of a delamination which is a typical defect in composite multi-layered structures. Such delamination can for instance occur after an impact on the structure during the service life. First, an elliptical delamination of 96mm*48mm and propagated over 6 successive inter-plies has been studied as illustrated below in Figure 7.

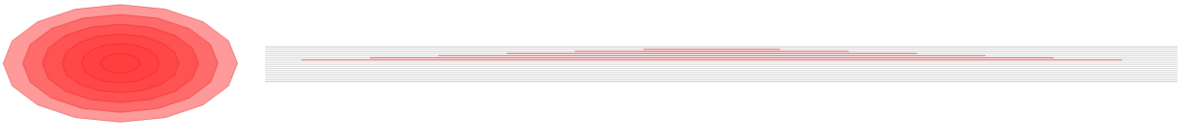

Figure 7: Elliptical delamination defined in CIVA SHM.

You can observe below in Figure 8 (the red ellipses represent the true defect size and position) the signatures obtained with this defect type for 2 excitation frequencies (40kHz and 100kHz, respective A0 mode wavelengths of 19mm and 10mm) and 3 sensor diameters (18mm, 10mm, 5mm). At 40kHz, the obtained image gives a clear spot at the defect location but quite badly resolved versus the defect size and shape, independently of the used sensor diameter. With a higher frequency (100kHz), you achieve to obtain an indication closer to the real defect dimensions. And this is further improved for smaller sensors (10 and 5mm diameters) as they preferentially excite the A0 mode at these frequencies, reducing the artefacts from other modes.

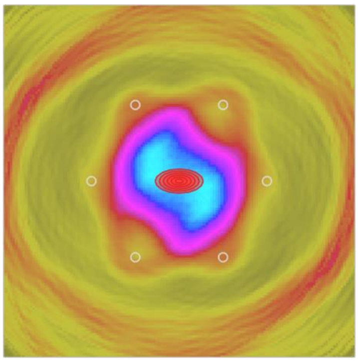

Figure 8a: Frequency 40kHz + Ø18mm.

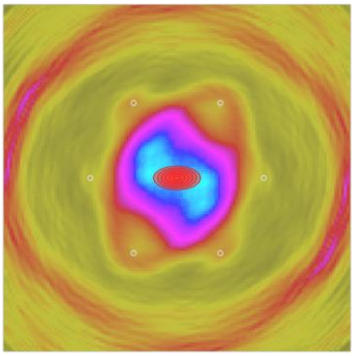

Figure 8b: Frequency 40kHz + Ø10mm.

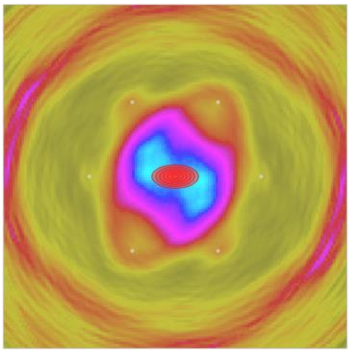

Figure 8c: Frequency 40kHz + Ø5mm.

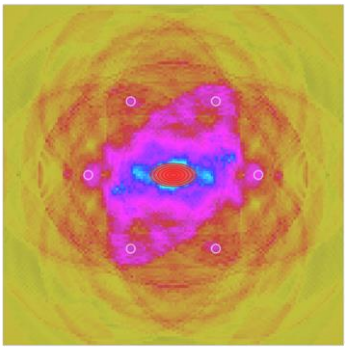

Figure 8d: Frequency 100kHz + Ø18mm.

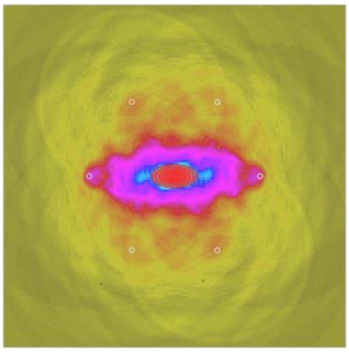

Figure 8e: Frequency 100kHz + Ø10mm.

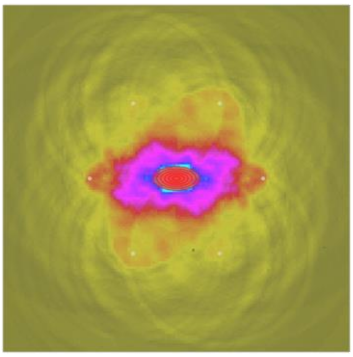

Figure 8f: Frequency 100kHz + Ø5mm.

These simulations prove that a good compromise for this inspection configuration is based on 6 sensors of 10mm diameter and operating at 100kHz to detect and characterize this delamination. Of course, the performances will also strongly depend on the size of the targeted flaw. Below are illustrated the reconstructions obtained with the previous optimal monitoring set up for different elliptical delamination dimensions: 96mm x 48mm, 48mm x 24mm, and 24mm x 12mm.

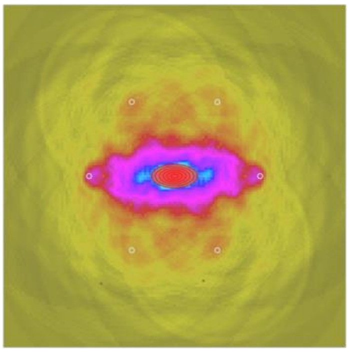
Figure 9a: Delamination 96mm x 48mm.

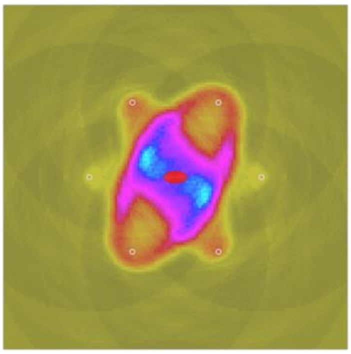
Figure 9b: Delamination: 48mm x 24mm.

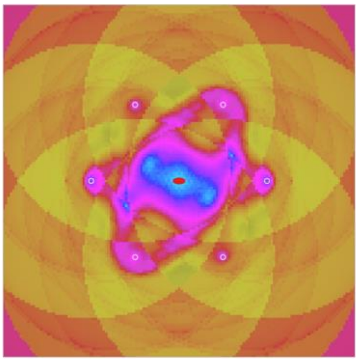
Figure 9c: Delamination 24mm x 12mm.

These simulations show that this setup could remain suitable for smaller delaminations detection (an indication is visible) but the characterization capabilities are noticeably affected as the spot is far less resolved when the defect gets smaller.

The simulation easily provides a better understanding, illustration and justification of performances and limits of a monitoring device for a given targeted defect, from which it is possible to work on optimizations. Here, these images have been obtained assuming the sensors array to be centered around the defect, which is a strong hypothesis. A good knowledge of the materials and the maximum stress zones for a given structure can allow to anticipate preferential areas for defect initiation but it is hard to predict them with a very high accuracy. Once your simulation model has been correctly initiated, it is very easy to modify the defect location and repeat several simulations to study the impact of the flaw position on its detection and characterization with a given SHM setup. It would be much more complex and costly to build as many instrumented mock-ups as possible defect positions with a purely experimental approach.

5. Conclusions

The modelling approach of CIVA SHM as well as its capabilities have been introduced in this paper. After presenting some experimental validation cases, several application examples of CIVA SHM in the context of a damage monitoring in a composite plate have been illustrated. Various parameters have been studied (sensors to specimen edges distance, number and location of sensors, transducer size and frequency, different defect type and dimensions). Simulation represents a powerful tool to help the development and the qualification of monitoring devices. While it does not eliminate the need for experimental trials, prototypes, and mock-ups, it can help reducing the number of needed trials.

More than a competition, a complementarity between simulation and experiment is pointed out: experiments can precisely show the behaviour of real monitoring devices and see the impact of environmental parameters change (structural noise, temperature, aging process, etc.), while simulation can quickly, massively and at low-cost test different monitoring scenarios and predict many damages situations. It would be very costly to design an instrumented mock-up for any defect or sensor set-up cases which would prevent to conduct optimization and performance demonstration studies. Simulation variation studies can help to build large enough data sets when you must describe these performances in a statistical way and work on process qualification.

CIVA SHM provides to the SHM community a dedicated tool which offers very optimized computation times compatible with an intensive usage in an industrial context.

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