A Toolbox concept to configure a SHM solution on ageing aircraft structures based on acoustic and thermal methods

Ramanan Sridaran Venkat, Christian Boller
Chair of Nondestructive Testing, Saarland University, Germany
*corresponding author, E-mail: ramanan.sridaran@uni-saarland.de

Abstract

One of the challenging issues in aerospace industries is to configure a SHM solution for ageing aircraft structures. This is because of the lack of information regarding the current state of material properties and the higher likelihood of damage to occur. Principally, when classical NDT actuators/sensors are embedded onto/into structures to perform real-time monitoring of tolerable damages, a SHM-solution is obtained. However, in reality this is not that much easy to be realised since most of the NDT techniques are off-line methods meaning they are human based and not implicitly ready for automation. Classical ultrasonic NDT methods like phased array ultrasonics have undergone technological innovations in terms of data acquisition and data representation through the development of Sampling Phased Array (SPA) and Reverse Phase Matching (RPM) methods. These methods have advantages in determining in-situ material properties and result in a comparatively higher probability of damage detection. Unlike the classical ultrasonic methods, where transducers can be virtually moved to any location on a structure, guided waves (GW) based actuation and sensing in SHM is fixed to a ‘static’ actuator/sensor network. In order to detect damages considered to be tolerable efficiently the optimal positions of actuators/sensors need to be identified in advance. To identify those optimal positions numerical simulation is indispensable, allowing something to be generated called differential imaging, that identifies where damage related sensor signals are to be recorded best.

Introduction

There have been many research activities in the field of ultrasonic NDT, either in terms of damage or material characterisation using phased array transducers and methods such as Sampling Phased Array (SPA) or Full Matrix Capture (FMC) and an extended version of SPA, Reverse Phase Matching (RPM) methods. The primary aspect of any phased array ultrasonic transducer is beam steering, beam scanning and beam focussing which can be achieved by means of phasing/driving of individual piezoelectric elements at varying times during excitation and reception of ultrasonic beam. Such an aspect would allow one to focus an ultrasonic beam on a specific location at the target where a defect is placed. SPA uses phased array transducers and has two main advantages compared conventional the phased array principle: 1. In-situ material properties of anisotropic materials can be measured using the Reverse Phase Matching (RPM) algorithm and 2. Characterization of damages using the real-time Synthetic Aperture Focusing Technique (SAFT) method [13, 17], a well-known data processing method in ultrasonic NDT to reconstruct the data obtained from the SPA method. Thus, SPA enhances the signal to noise ratio. These methods have been used for metals as well as for composites in the past and most of this work has been performed in the context of bulk waves. Research in guided wave analysis has been widely triggered by their advantage of monitoring large planar structures using low-cost surface mountable piezoelectric patches. Unlike bulk waves, which can travel only on certain bulk volume of an inspection material, guided waves travel along a thin plate at larger areas and thus, provides a possibility to monitor a large structure from a single location.
The concept of non-linear analysis is echoed from the vibration-based SHM on the assumption that structures contain defects which can influence their physical characteristics such as eigenfrequencies, damping and mode shapes etc., such that any change in the stiffness coefficients due to the presence of damages can result in changes within the eigenfrequencies. Different methods applied consider non-linear acoustic analysis used when it comes to anisotropic materials such as composites [8] to detect early damage (i.e. fiber breakage, micro delamination). In the context of enhancing the sensitivity of nonlinear effects, Solodov [7, 8] has also developed a method named local defect resonance (LDR) that provides an efficient pumping of energy from the wave directly to the defect and causing effective generation of the higher harmonics. However, in the past, these methods (non-linear analysis, bulk waves, guided waves and LDR) have been applied individually for specific composite applications and none of them were applied as a combination. It is therefore important to highlight that when these methods are combined by taking the advantage of one over the other, a research platform, specifically in view of SHM, could be set. Earlier, an effort was made to explore the SAFT algorithm to a guided wave SHM by Sicard et al [12] for isotropic structures. In an attempt, the work presented here will try to provide an ‘umbrella’ under which at least a majority of such methods can be integrated. This could bring numerous advantages in terms of a holistic monitoring of structures together where the case of ageing composite structures will be specifically addressed here. This paper intends to make some contributions in establishing an acoustics and thermal based toolbox allowing SHM systems to be designed and developed by inheriting knowledge available or developed in classical NDT. For the first time, an effort has been made in this paper to bridge a gap between NDT methods and SHM.

**SPA with RPM to characterize the ageing material with unknown elastic constants**

In this section, material and damage characterization using SPA-RPM is described followed by the application examples.

### 2.1. Working principle of SPA and RPM

A state-of-the-art phased array system requires several shots at different angles to cover an entire cross section. In SPA the same can be achieved with a single insonification (single shot). The returning ultrasonic echo signals from a single shot by one transducer element are captured by every one of the transducer elements as shown in Fig. 1. The signals received are later used to reconstruct one or more arbitrary angles and/or focus depths. The reconstruction of the data is greatly enhanced through the application of the SAFT algorithm, which eliminates noise and enhances sensitivity. One shot or one inspection cycle in SPA means one of the elements in the phased array acts as a sender and all the other elements including the sender act as receivers. The A-scan information of this particular shot in terms of sender-receiver combination is stored as an information matrix as shown in Fig. 1 on the right side. This is called a 1xN shot. In a similar fashion, when all the remaining elements repeat the above process this constitutes a N x N shot where N is the number of elements in the phased array transducer. The information matrix thus obtained after N x N shots has all the A-scan information of each sender to receiver combination and will be used to reconstruct the image. Travel time computation is the important step in the reconstruction process in which the travel time between a point in the inspection volume and the transducer element is computed. The elementary wave phase information, which is accessible with SPA through the information matrix, can be adjusted as per the anisotropic property of the material. The travel time associated with this anisotropic medium basically derived from the stiffness matrix is calculated with the help of the ray tracing method. This technique is called “Reverse Phase Matching” (RPM)[13, 14].

![Figure 1: Principle of SPA](image)

The hardware in the SPA method gives the user the possibility to access all the individual A-scans that are acquired during the inspection. For example, a working sequence of a 16-element phased array transducer in the SPA method will result in 256 A-scans (16 x 16). The phase information of these A-scans can be adjusted in such a way that the anisotropy of the CFRP material is considered for SAFT image reconstruction.

### 2.2. Application examples

The geometry of the CFRP material shown in Fig.2 has Ø 1 mm flat bottom hole located at 3 mm from the bottom of the test sample’s surface. Due to symmetrical properties, the number of elastic constants is reduced to 21 independent elastic constants for the anisotropic medium, but it is even reduced to five independent elastic constants for the case of a transversely isotropic medium. Once the data is acquired using SPA, the reconstruction of images with different sets of elastic constants are obtained and a numerical search algorithm is used to identify the correct set of elastic constants from the collection of reconstructed images. The numerical search algorithm works by iterative means. The iteration begins with an initial set of elastic constants to
obtain the reconstruction of the image. Once all the images are stored as shown in Fig. 3, a search algorithm is used to identify the images where the reflectors (flat bottom hole in this case) are placed correctly. The elastic constants belonging to that reconstructed image are used for further analysis. Details regarding the implementation of such an algorithm can be referred to as Gradient Elastic Constants Descent Method (GECDM) [18] and also in [17].

Figure 2: CFRP test sample with the flat bottom hole

Figure 3: Numerical search algorithm for determining elastic constants

3. **Nonlinear acoustics and Local Defect Resonance (LDR) for identifying incipient damages**

Another option in characterizing materials and structures regarding their damage condition is to take the advantage of their vibrational behaviour. Vibrations based health monitoring methods are interesting topics and have been discussed for many decades. An overview of the various vibrational-based methods for structural health monitoring is well described in [17]. In this section, nonlinear vibrational and LDR approaches are explained.

3.1. **Nonlinear acoustics**

When early identification of damages is one of the important requirements in structural integrity assessment then nonlinear vibrational methods are the means to identify and characterize those early stage damages. When elastic waves with large amplitudes are incident to the imperfect interfaces of a damage such as due to contact and friction it is called contact acoustic nonlinearity (CAN). As a result, the most interesting and common nonlinear feature being generated is higher harmonics in the structural response. Other nonlinear features include sub-harmonics, waveform distortions, shift in the natural frequency, coherence functions and signal modulation etc.. Many non-classical non-linearity cases have been reported in various references [7, 17]. The acoustic vibro-modulation method has been used to demonstrate the non-linear behavior of the opening and closing action of cracks as shown in Fig. 4 as an example for CAN. This method is otherwise known as nonlinear wave modulation spectroscopy (NWMS) because it uses both low frequency and high frequency excitation to study the non-linear feature due to the presence of the opening/closing actions of cracks. In this method, a low frequency vibration is applied to the material, which can generate tension and compression forces in the material that eventually causes the cracks to open in the tension phase and close in the compression phase. In parallel a high frequency excitation, which is in the ultrasonic range is applied to the material. During the tension or dilatation phase the high frequency signal is decoupled as shown in Fig. 5 due to the opening of the crack.

Figure 4: Schematic picture of breathing crack

Figure 5: Principle of CAN

This phenomenon also reduces the amplitude of the signal but during compression, where the crack is closed, it does not interrupt with the high frequency signals. Representation of the time domain signals to frequency domain indicates that two new frequency components exist due to the opening action of the crack under vibration. The two other frequency components correspond to the input frequencies.

3.2. **Principle of LDR**

According to Solodov et al [7, 8], each defect has its own resonance frequency. When that resonance frequency for a
defect is matched with the excited ultrasonic waves, one can noticeably see the higher harmonics and frequency mixing of modes. LDR is based on the fact that a defect leads to a local decrease in stiffness for a certain mass of the material in this area, which has a particular characteristic frequency of the defect. LDR can be introduced as a natural frequency $f_0$ of the defect with an effective rigidity $K_{eff}$ and mass $M_{eff}$. $f_0$ is written as given below [7, 8]:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{K_{eff}}{M_{eff}}} \quad (1)$$

$$K_{eff} = \frac{192\pi D}{a^2} \quad (2)$$

Potential and vibrational energies of the defect are used for the evaluation of $K_{eff}$ and $M_{eff}$. For a circular flat bottom hole of radius ‘a’ and thickness ‘h’, the effective rigidity and mass rigidity are calculated as follows:

$$M_{eff} = 1.8m$$

where, $D = \frac{Eh^3}{12(1-v^2)}$ is the bending stiffness and $m$ is the mass of the plate at the bottom of the defect. By substituting the values of $K_{eff}$ and $M_{eff}$ in $f_0$ we get the LDR frequency of the circular flat bottom hole as below [7]:

$$f_0 = \frac{1.6h}{a^2} \sqrt{\frac{E}{12\rho(1-v^2)}} \quad (3)$$

In a similar manner, LDR for a notch type defect can be given as follows [7, 8] where, $\rho$ is mass density, $v$ is Poisson’s ratio and $E$ is Young’s modulus respectively.

$$f_0 = \frac{2\pi}{w^2} \sqrt{\frac{D}{3\rho h}} \quad (4)$$

The expressions for $f_0$ obtained above for flat bottom holes and notch type defects are applicable to laminar defects in rolled sheet metals and delaminations in composites but due to the presence of higher order modes, an analytical evaluation using the theory of plate vibrations may not be possible further. The other reason as mentioned in [7, 8] is the boundary conditions around the defect edges that cannot be derived for practical applications. In this case, the numerical solution of LDR for various damage configurations is sought by the application of COMSOL Multiphysics.

### 3.3. Application examples

The geometry and material properties are shown in Fig. 6 for a CFRP specimen subjected to three-point bending. The vibrational frequency is in the ultrasonic range (20 kHz). The description of the experimental setup, the role of numerical model and damage index measures can be referred to in [16, 17].

![Figure 6: CFRP test sample used for three-point bending](image)

The numerical model has been established using COMSOL Multiphysics to replicate the opening/closing action of the breathing delamination in the composite plate as shown in Fig. 7. This is achieved by means of defining the contact-pairs boundary condition on the crack interfaces.

![Figure 7: Numerical simulation results illustrating opening and closing of cracks](image)

Results obtained for various growing delamination sizes are shown in Fig. 8. The first frequency component in the FFT spectrum is the eigen frequency of the composite plate followed by the higher harmonics due to the opening and closing action of the crack interfaces subjected to three-point bending loads.

![Figure 8: Results of higher harmonics for various sizes of the delamination obtained from numerical simulation](image)
The experimental and numerical results are compared as shown in Fig. 9 where there is a shift in the second and higher harmonics due to the fact that there is certainly a higher number of incumbent damages/inhomogeneities that exist in the reality [16, 17].

![Figure 9: Comparison of experimental and numerical simulation results](image)

Fig. 10 shows the LDR vibration pattern of the first and higher order modes of a circular flat bottom hole in a Poly (methyl methacrylate) PMMA material.

![Figure 10: LDR of circular flat bottom hole of radius 1 cm and depth 2 mm in a PMMA plate (a) Fundamental LDR at 10.4 kHz, (b) Higher order LDR at 23.25 kHz](image)

Solodov et al. verified their numerical model of LDR for various defect configurations using Scanning Laser Doppler Vibrometry (SLDV). For this purpose, wide band frequency (400 Hz- 100 kHz) excitation was applied through conventional piezoelectric disc transducers. The out-of-plane velocity components were measured by SLDV and the results are shown in Fig. 11. The first peak of 8 kHz is one of the natural frequencies of the whole specimen. The main peak at 11 kHz is the fundamental LDR which is followed by the higher order LDR at 23.25 kHz. The images obtained by SLDV are found to be similar to Fig. 10. In the frequency spectrum shown in Fig. 11, LDR provides a selective excitation of a defect that results in high vibration amplitude. Rahammer [10] used LDR in combination with thermography to record higher dissipation of heat at the defect subjected to LDR.

![Figure 11: SLDV imaging of LDR of circular flat bottom hole of radius 1 cm](image)

**Guided waves for monitoring ageing structures**

When a wave propagates in an infinite medium where boundaries have no influence on the wave propagation the wave is called a bulk wave. In contrast, when it propagates in a finite medium, which has a boundary for its existence, it is called a guided wave, which again can be differentiated between Lamb waves and surface (Rayleigh and Love) waves in general. Thin plates, rods, tubes and multi-layered structures are waveguides. When ultrasonic waves travel in waveguides at some angle and frequency, they are reflected back and forth inside the waveguides. This causes mode conversion, whereby the longitudinal and shear waves are reflected and transmitted at interfaces leading into both constructive and destructive interferences being superimposed together to form guided waves [9]. For a particular angle and frequency chosen, the interference phenomena can be totally constructive, destructive, or intermediate in nature. There are certainly more than one constructive interference point for a set of incidence angles and frequencies for a guided wave problem. The constructive interference points can be plotted to produce wave velocity dispersion curves of frequencies versus phase velocities [9, 20]. For a particular angle and frequency chosen, the interference phenomena can be totally constructive, destructive, or intermediate in nature. There is certainly more than one constructive interference point for a set of incidence angles and frequencies for a guided wave problem. The constructive interference points can be plotted to produce wave velocity dispersion curves of frequencies versus phase velocities.

**4.1. Identification of optimal sensor position for GW sensors using differential imaging**

The damage tolerant design principle enhances a structure to be designed lightweight. The key factor for guided wave based SHM is to find the key locations where a damage information can be extracted. Various studies have been undertaken by different institutions [4, 6, 11, 21] in the context of sensor optimisation for guided wave-based monitoring. Most of the work has been focused on random sensor placement. However, in [11] scanning LDV
measurements have been used on a test component to find the optimum sensor layout for an artificial damage. Concentrated sensors and distributed sensor arrays have been used for the investigation. LDV, by its advantage of non-contact measurement, could record the out-of-plane and in-plane displacements for a given set of scanning points defined by the user which could otherwise have been achieved by a PZT mounted on the surface of the specimen [20].

When the excitation voltage is applied on a piezoelectric transducer attached to a structure, the strain obtained in the structure such as an aluminium plate is used for simulating the wave propagation problem in COMSOL Multiphysics. The relationship between the stress ($\sigma_{ij}$) and the displacement by ($u_i$) is obtained through the equation of motion (Eq. 5):

$$\sigma_{ij} + \rho f_i = \rho u_i \tag{5}$$

where, $\rho$ and $f_i$ are the density of the medium and the applied force respectively. For the known elastic constants and by means of Hooke’s law $\sigma_{ij} = C_{ijkl} \varepsilon_{kl}$, the following constitutive relation is established between stress, strain and the displacements, which is implemented in the COMSOL structural mechanics module. Strains are defined from the deformations by (Eq. 6):

$$\varepsilon_{ij} = \frac{1}{2} (u_{ij} + u_{ji}) \tag{6}$$

With respect to displacement in z-direction, the strain can be written as $\varepsilon_{zz} = \frac{\partial u}{\partial z}$ and one can write the differential displacements in the form of Eq. 7:

$$\frac{\partial z}{\partial z} \Delta u = \left[ \frac{\partial z}{\partial z} u_{\text{damaged}} - \frac{\partial z}{\partial z} u_{\text{undamaged}} \right] \tag{7}$$

where $\sigma$ and $\varepsilon$ are the Cauchy stress and strain tensors and $u$ is the displacement. In guided wave analysis, the signals at the present state of the structure are often compared with the signals that were stored during stress condition. This process is often done only after placing the sensors for monitoring, which are supposed to be at an optimum location for measuring the damage. However, in order to find the optimum position of the sensors, differential imaging is an interesting option to be applied, which is very similar to differential signals [20]. In this method, the wave propagation at particular time intervals for the given damage is subtracted from the wave propagation of the pristine condition using Eq. 7. The multi-physics FEM model for GW is established as shown in Fig. 12.

4.2. Application examples

The geometry of the stiffened panel is shown in Fig. 13 and its material properties are given in Table 1.

![Figure 12: Multiphysics approach for guided waves](image)

![Figure 13: Stiffened panel](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th>Dimensions</th>
<th>Crack geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin- Aluminium</td>
<td>Young's modulus: 70 GPa</td>
<td>1300 x 1200 mm</td>
<td>Crack length: 51 mm</td>
</tr>
<tr>
<td></td>
<td>Density: 2700 kg/m$^3$</td>
<td>Thickness: 2 mm</td>
<td>Crack height: 1 mm</td>
</tr>
<tr>
<td>Stringer- Aluminium</td>
<td>Same as above</td>
<td>Ø 5 mm - S1 holes</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Material properties of the panel

The wave propagation at various time intervals for damaged cases is shown in Figs. 14 (a) to 14 (d) for the stiffened panel respectively. The resultant wave propagation shown in Figs. 15 (a) to 15(d) show the differential image results for the stiffened panel, where the points of maximum and minimum residual displacements are visible for the given crack condition as the wave propagates over time. The differential FEM model is built by implementing a parametric sweep for an undamaged and a damaged condition using COMSOL Multiphysics. Based on the results of differential imaging, the maximum residual displacement points have been selected as shown in the differential images. Application of differential imaging to repaired patches is described in [3]. In a similar manner hotspots for transducer placement have been used in [19]. An alternative approach to differential imaging called “damage indices mapping” has been described in [15].
A correlation output versus crack sizes as shown in Fig. 16 is drawn for different sensor positions during the experimental validation of the differential imaging. The sensor S1 as illustrated in Fig. 14 showed the maximum correlation output. More applications of differential imaging and experimental verifications can be referred to in [5, 15] for sensor optimization.

**Figure 14:** GW propagation in a stiffened panel at various time intervals a) 60 μs, b) 75 μs, c) 90 μs and d) 110 μs

**Figure 15:** Differential images at various time intervals a) 60 μs, b) 75 μs, c) 90 μs and d) 110 μs

A correlation output versus crack sizes as shown in Fig. 16 is drawn for different sensor positions during the experimental validation of the differential imaging. The sensor S1 as illustrated in Fig. 14 showed the maximum correlation output. More applications of differential imaging and experimental verifications can be referred to in [5, 15] for sensor optimization.

**Approach towards a structural ageing problem through a SHM toolbox**

5.1. Configuration of the toolbox

Polymer based composite materials are increasingly used today. Some of the structures made from these materials have already achieved the end of their operational life and as such have become subject of recycling. However, since the operational life of structures can vary significantly there are situations that can be anticipated in the future that structures with very long-life cycles can become subject of a structural reassessment. Such issues are currently becoming increasingly relevant in the context of civil infrastructure with materials such as steel and reinforced concrete. However, similar situations may be anticipated with polymer-based composites in the future and it would therefore be good to already have some relevant solutions available. A solution on how this could be solved is therefore given by means of integrating NDT methods and combining those with SHM methods in terms of a toolbox concept. The role of SHM in life cycle management of a structure is shown in Fig. 17.

**Figure 16:** Correlation output obtained from experimental data

**Figure 17:** Role of SHM in life cycle management

The different elements of this process chain represent essential elements in the design process, which are first subject to a numerical simulation to provide flexibility with regard to the approach. The results of such an approach are then finally validated through experimentation, which requires hardware tools as well. With all of this numerical simulation and experimentation data are generated, which need to be processed in an adequate way. When simply associating SHM with NDT, sensing is easily limited to damage detection only. However, when sensing is considered on a broader scope such as also sensing loads in general or strains in damage critical areas then SHM
achieves a scope, which can easily encompass the complete design process being shown in Fig. 18. Establishing an SHM toolbox in that regard therefore may result in a multilevel approach for which the highest level can obtain a form as shown in Fig. 19.

![SHM Toolbox Diagram]

**Figure 19: Structure of SHM toolbox**

It is beyond the scope of this paper to fill all the elements shown in Fig. 19. However, what is demonstrated here is how the element ‘NDT’ can be gradually filled and what complexity stands behind making the toolbox to some degree complete in the end. Many of the techniques used in NDT can be considered for SHM. Those being of interest include acoustic emission, eddy current, electromagnetics, microwave/radar, optics including visual, thermography, ultrasonics, and vibrations in terms of modal analysis. Only a limited number of those are intensively followed up within the context of SHM so far, which may have different reasons. However, due to the inheritance of SHM into NDT no completeness of a potential of a SHM toolbox can be claimed here but rather the principle on how to structure such a toolbox such that it can be continuously filled with the respective tools in accordance to their availability and structural assessment needs.

Fig. 20 is a trial to summarise how the NDT related information and technology available in acoustics and thermal methods can be made available to design and develop a thermo-acoustics based SHM system. Since SHM can be part of an NDT solution where the sampling of information is limited due to its transducers being fixed to defined locations, this fixation requires an optimisation process to be gone through prior to hardware realisation of the SHM system under consideration. This optimisation process, which is achieved in classical NDT through continuous sampling until the volume to be inspected has been fully covered, can only be solved through simulation and possibly intelligent signal processing. As a consequence, simulation is considered as the first sub-module in such a toolbox followed by hardware, with data handling including signal processing serving as a linking sub-module between the simulation and hardware sub-modules. Within the simulation sub-module, specifically when considering the complete process chain shown in Fig. 20, various design and simulation tools are to be considered to carry out digital modelling, including a CAD based component’s geometry, stress/strain analysis, fatigue analysis and NDT/SHM simulations. NDT/SHM being in the focus here mainly includes piezoelectric driven acoustic wave generation transducers either resulting in bulk or more often even in guided waves. In addition to this, thermographic methods are suggested as well for monitoring heat dissipation from the tolerable damages with the aid of LDR. Further considerations do also include the acoustic wave being generated by electromechanical transducers, lasers or through air coupling. Another acoustic technique to be mentioned here is acoustic emission, which is the passive monitoring option when compared to the active acousto-ultrasonic part. The hardware sub-module involves the transducers, wiring and various electronic components allowing signals to be generated, amplified, multiplexed, recorded, processed and displayed. Once the data is generated from the hardware, they need to be processed along the data handling sub-module to obtain useful information about the condition of the structure. This includes mainly signal and image processing modules to handle the data obtained from the hardware components on the one hand and to compare them with data having been obtained through simulation on the other. What is not considered in the approach in this paper are the economic factors such as the analysis of the life cycle cost of the structure considered.

Once such a toolbox is sufficiently filled with the respective tools, assessments and designs of SHM systems can be considered where the case of an SHM system for ageing composite structures is an example being very much of interest to be analysed and demonstrating how to fill and validate the toolbox. This may build the basis for a concept encompassing NDT, simulation and a SHM system, possibly with a residual life management concept to be established in the end.

![Thermo-acoustic based SHM toolbox Diagram]

**Figure 20: Thermo-acoustic based SHM toolbox**
5.2. Implementation of the toolbox for ageing problem

A relevant example considered here is a composite structure of which the material properties including the stacking sequence are unknown and which has been designed safe life. Starting from this condition an approach is now proposed where the logic of developing the SHM system can be summarised as a workflow for implementation as shown in Fig. 21.

![Workflow in SHM toolbox](image)

**Figure 21: Workflow in SHM toolbox**

5.2.1. Elastic constant determination using RPM

In this step, RPM algorithm along with numerical search algorithm as mentioned in the section 2 is applied. In case of no reflectors being available as a reference, geometrical features of the test material can be considered as reflectors to determine the elastic constants and also backwall reflection methods as proposed in [17].

5.2.2. Damage characterization using SPA

Once the elastic constants are determined, SPA-RPM can be carried out to screen and quantify the whole structural component with regard to damages present in other locations. This step gives a possibility to explore the current damage conditions of the test component.

5.2.3. Numerical simulations to determine the frequencies sensitive to damages through non-linear acoustics and LDR

In this step, nonlinear analysis as mentioned in section 3 is carried out with the help of numerical simulations to identify the incipient damages and inhomogeneities. Furthermore, LDR is also applied to identify the frequencies sensitive to those damages. LDR analysis along with an infrared camera can be effective in this step to monitor the temperature changes when the structure is subjected to vibrational frequencies which are sensitive to the damages.

5.2.4. Guided wave simulation to identify optimal sensor pattern through differential imaging

Once the elastic constants, damages and frequencies are identified from the previous steps respectively, an optimal sensor location is determined using differential imaging mentioned in Section 4. Therefore, piezoelectric patches (actuators and sensors) are to be placed on the structural component recommended by the differential imaging. Data handling plays a major role in this step to identify the signal features representing the damage. Various data handling methods mentioned in Fig. 20 are applied for this purpose. An example of data handling for a guided wave-based model has been explained in [1].

5.2.5. Validation of the simulation models through experiments

Numerical simulations are essential to build a monitoring concept, which has to be validated through experimentation preferably at every step mentioned above using the hardware modules shown in Fig. 20. Establishing numerical simulation models for guided wave propagation and nonlinear acoustics in a composite structure is a crucial step in the simulation part mentioned in Fig. 20. The guidelines to develop an efficient model for such cases have been explained in [2]. Homogenization of the layers could be an option to reduce the degrees of freedom in FEM problems and to ensure the model is computationally efficient. Modelling of delaminations being a subsequent step to be handled is also explained in [2].

**Conclusion and future work**

By means of SPA-RPM approaches, the elastic constants of an anisotropic material can be determined with the help of known reflector locations. However, the stacking sequences and layer orientations have not been specifically considered in this study but have rather been replaced by homogenized elastic constants to determine the respective wave velocities in an anisotropic medium for reasons of computation efficiency. By considering the incumbent damages due to non-linearities, the modes and frequency components sensitive to these damages can be identified using numerical simulation of vibrational loads. Composite laminates subjected to three-point bending have been taken as a demonstration case to explore the acoustics induced nonlinear behavior and its detection. The LDR concept along with infrared thermography is an option suggested at this stage which gives a possibility to look for a dissipated heat as a result of higher harmonics locally coming from the damage. While the tolerable damage of the structure is known, guided waves and differential imaging methods can be potentially good for identifying the actuator/sensor locations using simulations.

In the end, this all can define an SHM system that can be applied to an ageing anisotropic structure such as made of composites for which a defined damage pattern can be tolerated. Considering the methods and simulations discussed here when integrated as a system allows a fairly holistic assessment procedure to be realized in the sense of SHM in the context of dealing with ageing composite structures.
References


