UGC APPROVED JOURNAL - 47746
© INNOVATIVE RESEARCH THOUGHTS | Refereed | Peer Reviewed | Indexed
ISSN : 2454 – 308X | Volume : 04 , Issue : 04 | January – March 2018

Digital signal processing using MATLAB for damage identification using lamb waves

Aniket Kashinath Gonde

MSc Physics , department of physics , Fergusson College , Pune.

Abstract

The use of guided waves as a method for locating damage has become increasingly popular in recent years due to the fact that it is dependable and can be carried out in a relatively short amount of time, in addition to the fact that it has the advantage of being able to inspect large areas as well as find subtle structural issues. Additional positive aspects of this technology include the following: A dispersed field is produced whenever a travelling wave on a plate has an interaction with a fault in the plate. The geometry of the flaw will affect the form of the dispersed field that it creates. One is able to as a result describe the kind of plate damage that has occurred.as the magnitude of the damage by analysing the dispersed field. It is the first time that a Bayesian framework that is based on an interaction model for guided waves has been developed for the purpose of damage detection of an infinite plate. In order to extract the scattering characteristics for damage geometries that have circular symmetry, a semi-analytical technique based on the lowest order plate theories is utilised. This leads to an efficient inversion process. After that, ultrasonic tests are carried out on a huge plate made of aluminium that has a circular depression in it.

The purpose of this paper is to review Digital signal processing using MATLAB for damage identification using lamb waves

Keywords: Guided waves Damage identification Bayesian inference Structural health monitoring Digital twins

Introduction

Plate-like structures are used extensively in a broad variety of systems, such as wind turbines, aircrafts, and ships, amongst others. After the initial damage has been done, more damage will be caused by variables such as fatigue load, which may eventually result in a catastrophic breakdown of the whole system. As a result, the early identification of damage is very necessary for the safety vital components of a building. “The next thing to do is to define the damage by determining its characteristics such as the length and depth of a crack. This is an important phase in the repair process. Online detection and characterization, in the context of structural health monitoring (SHM), leads to a condition-based maintenance approach. This approach allows for the reliability of the structure to be quantified, and maintenance procedures are only carried out when they are absolutely necessary. This style of operation is efficient with regard to costs, but it calls for the use of trustworthy monitoring and inference strategies that are able to provide correct parameters of the harm.

The capacity of sensors and algorithms to discover and identify structural deterioration is essential to the success of the Structural Health Monitoring (SHM) system. In spite of the progress made in the creation of very advanced sensors, SHM systems have not yet gained universal acceptability among aircraft operators. Therefore, until SHM is able to satisfy the same degree of damage detectability as is established by the present NDI techniques, Non-Destructive Inspections (NDI) done at a certain number of flying hours will continue to be the method of choice. NDIs are carried out at a predetermined number of flight hours. These problems include the capacity of SHM makers to offer reliable damage detection algorithms, with the goals of minimising or eliminating false calls and ensuring the correct functioning of these sensors during the course of their useful lifespans. Additionally, certification authorities may require SHM system manufacturers to offer the same degree of Probability of Detection (PoD) as is required for the existing NDI approaches. This may be a requirement for the SHM system makers. There are currently no standards in place for developing a PoD curve for a particular SHM sensor setup, and any method would likely require a large experimental programme with multiple reference samples, both with and without damages, in an environment that is representative of the whole, which would be a very expensive endeavour. Implementing a reliable Model Assisted PoD (MAPoD) approach, in which one makes use of high quality digital models to cut down on the number of costly experimental evaluations, is one way that this cost may finally be reduced. Another alternative is to find another way to cut costs. The purpose of this study is to provide the framework for this project by investigating whether or not it is possible to numerically model the behaviour of guided Lamb waves on a typical aircraft structure that has a fatigue fracture.

Role of structural diagnostic in aircraft maintenance

The Maintenance Steering Group – Task 3 (MSG-3) logic has been a root methodology for modern aircraft maintenance. Among the important tasks in the MSG-3 process is the Special

© INNOVATIVE RESEARCH THOUGHTS | Refereed | Peer Reviewed | Indexed
ISSN : 2454 – 308X | Volume : 04 , Issue : 04 | January – March 2018

Detail Inspection (SDI), which has the purpose of detecting hardly visible aircraft structural damages by a human inspector and requires non-destructive testing. In the world of aircraft maintenance, the Maintenance Steering Group – Task 3 (MSG-3) logic has been a root methodology for modern aircraft maintenance (NDT). The time and money required to train an NDT inspector in a variety of inspection procedures up until they attain the level of expertise required for certification is a time-consuming and costly endeavour. Automated nondestructive testing (NDT) and structural health monitoring are the two mainstays of automated structural diagnostic inspection, which have been suggested in order to make the inspection process more effective (SHM). With most cases, robot-assisted non-destructive inspection (NDI) is what is meant by automated non-destructive testing (NDT). However, in SHM, the NDI instruments are built right into the structure. SHM and NDI each have their own advantages and disadvantages, but in both approaches, it is necessary to have a more complex processing for the data captured by the NDI instruments as the degree of complexity (not only the complexity of the aircraft structures on the geometrical level, but also on the material level) of the system increases. This is because the complexity of the system is proportional to the amount of information that can be extracted from the data. Because of this, we have a strong conviction that more advanced digital signal processing (DSP) approaches are required in order to be able to deal with the ever-increasing complexity that are being presented.

Complexity and higher performance requirements are two hallmarks of modern structures, especially those with military applications. These characteristics, in conjunction with economical and safety constraints, make it difficult to realise current design concepts in their entirety. In many cases, the selection of materials, the design, and the safety aspects all need to be coordinated in order to produce a building that is secure, lightweight, and has minimal initial and ongoing expenses. The initial stages of failure for critical components should be identified as quickly as possible, preferably at a low cost, so that adequate time can be allotted for the appropriate repair work to be completed within a budget that is manageable. This will ensure that the system continues to be safe and reliable. In addition, monitoring the evolution of damage allows for the estimation of the amount of remaining life and assists in the establishment of inspection and maintenance intervals. Throughout the years, a wide range of defect detection methods, including as optical, liquid penetrant, magnetic particles, ultrasonic,

© INNOVATIVE RESEARCH THOUGHTS | Refereed | Peer Reviewed | Indexed
ISSN : 2454 – 308X | Volume : 04 , Issue : 04 | January – March 2018

and eddy currents inspection techniques, have been developed. The bulk of these methods take a significant amount of time, may be rather costly, and need for further processing of the structure, such as the disassembly of certain components. In addition, in most cases, they are not utilised to determine the extent of damage in real time. Structural Health Monitoring refers to a group of non-destructive evaluation methods that are supported by the requirement for real-time, low-cost damage detection, as well as the limitations of traditional inspection techniques and the technological improvement in embedded actuators, sensors, reasoning algorithms, and life-prediction methodologies. These factors combine to lend support to the non-destructive evaluation methods (SHM). The term structural health monitoring, or SHM, refers to the process of continuously and independently monitoring a structure while it is in service using sensors that are either incorporated into the structure or connected to it.

Lamb waves, also known as guided elastic waves on a narrow plane, are one method that has been investigated for the purpose of developing fresh ways to non-destructive evaluation (NDE). Damage to a structure may be localised by analysing the collected signals from one sensor–actuator pair and calculating the time of flight (ToF), which is the amount of time that elapses between the wave that causes the damage and the wave that is reflected by the damage. Nevertheless, the interpretation and comprehension of Lamb wave signals is a notoriously difficult problem. When a piece of piezoelectric element is used as the actuator, in contrast to a Lamb wave that is excited by angle variable ultrasonic probes coupled with an angle-adjustable Perspex wedge, multiple Lamb modes, including symmetric (S0) and anti-symmetric (A0) modes, will be generated simultaneously. In particular, this is the case when compared to a Lamb wave that is excited by an angle variable ultrasonic probe". It is possible for the incipient wave to be swiftly reflected by the structural barrier if the wave's propagation velocity is extremely high. This may significantly obscure the damage-scattered components in the signals. This interference is an issue that should be taken very seriously in regard to smaller constructions. The exact estimation of ToF in Lamb wave signals, and the damage estimate that follows, thus becomes a challenge.

Review of literature

(Li et al. 2006) studied "A Correlation Filtering-based Matching Pursuit (CF-MP) for Damage Identification Using Lamb Waves" discovered that and Time of flight (ToF) plays an important role in locating structural damage, although the correct estimation of ToF in intricate Lamb wave signals may be fairly difficult to accomplish. An method to signal processing was devised, and it makes use of correlation filtering-based matching pursuit (CF-MP). The correlation among wave signals acquired from the same structure under various damage statuses was calibrated in this method. This functioned as an indication for the incidence of structural damage as well as its severity. It was possible to determine the ToF of a damage-scattered Lamb wave with a high degree of accuracy. After acquiring it, the method was used to Lamb wave signals obtained from delaminated carbon-fiber/epoxy (CF/EP) composite beams. As a result, the position and extent of the delamination were accurately predicted. The experimental validation showed that such a method is able to filter boundary-reflected signal components that are involved in a complex wave signal. This enables the wave-based damage diagnosis methodology to be used in a realistic setting for smaller buildings.

(De Fenza, Sorrentino, and Vitiello 2015) studied “Application of Artificial Neural Networks and Probability Ellipse methods for damage detection using Lamb waves discovered this and A presentation is made here on how Artificial Neural Networks and Probability Ellipse approaches may be used to the process of damage identification utilising Lamb waves. The data on wave propagation are utilised to identify the location of damage in metallic and composite plates, as well as the severity of that damage. The structural components are going to be instrumented with an array of actuators and sensors (PCB) that will be able to record and stimulate the dynamic response of the component. A dam-age index is presented as a determinant of structural damage. This index is generated using the wave propagation data collected in a reference state (baseline) and the data measured in the current state. The index is a relative measure that contrasts the two states of the structure when it is subjected to the same environmental circumstances. When there is a greater overall amount of damage, the damage index will have a greater impact. In addition, its computation may take place along a variety of routes connected with Artificial Neural Networks or Probability Ellipse approaches, which makes it possible to determine the location and nature of the damage. In the course of the testing, two panels comprised of an aluminium and fabric composite material were used. For the investigation of damage in aluminium panels, one damage entity was simulated as a through-thickness hole with a diameter equal to 6 millimetres, whereas for the investigation of damage in composite materials, three damage entities (through-thickness holes with sizes equal to 2.5 millimetres, 4.5 millimetres, and 9 millimetres) were considered. In order to acquire the necessary training for the implementation of the ANN approach, a finite elements analysis was carried out on the aluminium panel while taking into consideration the many ways in which it may be damaged. Simulations have been run in order to define the route that Lamb waves take as they travel through a composite plate, with the damage entities' diameters ranging from 2.5 mm up to 9 mm. This was done by altering the damage entities' hole sizes. The damage index for each damage magnitude will be compared, taking into account both simulations and experiments. There is discussion of the possible uses of these technologies in the development of health monitoring systems for use in structures that are defects-critical as well as structures made of composite materials.

(Pant et al. 2017) studied Damage Detection Methodology for Structural Health Monitoring (SHM) Applications based on Multi-frequency Anti-symmetric Guided Waves Shashank established that that Structural Health Monitoring (SHM) depends on the capability of sensors and algorithms to find and detect structural problems in buildings. In spite of the progress made in the creation of very advanced sensors, SHM systems have not yet gained universal acceptability among aircraft operators. Therefore, until SHM is able to satisfy the same degree of damage detectability as is established by the present NDI techniques, Non-Destructive Inspections (NDI) done at a certain number of flying hours will continue to be the method of choice. NDIs are carried out at a predetermined number of flight hours. These problems include the capacity of SHM makers to offer reliable damage detection algorithms, with the goals of minimising or eliminating false calls and ensuring the correct functioning of these sensors during the course of their useful lifespans. Additionally, certification authorities may require SHM system manufacturers to offer the same degree of Probability of Detection (PoD) as is required for the existing NDI approaches. This may be a requirement for the SHM system makers. There are currently no standardised methods for developing a PoD curve for a particular SHM sensor setup, and any method would likely require a large experimental programme with multiple reference samples with and without damages, in a representative environment, which would translate into a very costly effort. In addition, there are no standardised methods for developing a PoD curve for a specific SHM sensor setup. Implementing a reliable Model Assisted PoD (MAPoD) approach, in which one makes use of high quality digital models to cut down on the number of costly experimental evaluations, is one way that this cost may finally be reduced. Another alternative is to find another way to cut costs. The purpose of this study is to provide the framework for this project by investigating whether or not it is possible to numerically model the behaviour of guided Lamb waves on a typical aircraft structure that has a fatigue fracture.

(He et al. 2017) studied Damage identification in welded structures using symmetric excitation of Lamb waves discovered that and Damage monitoring systems based on Lamb wave health monitoring technology have gained a substantial amount of interest for the purposes of scientific study and industrial applications. In order to identify a crack identification signal, this paper obtains two distinct kinds of single-mode Lamb waves by employing symmetric and anti-symmetric approaches, respectively. The ABAQUS/EXPLICIT module, which is a dynamic solver, was used to carry out a numerical simulation of a welded steel plate model. The simulation was carried out on a computer. Simulations are run that recreate both the mechanism of propagation and the impact that the Lamb waves have as they pass through whole and damaged models. The location of the crack damage is determined based on the propagation characteristics, and with the assistance of the ellipse localization method with MATLAB, the amplitude addition method is used to simulate the location of the crack damage, and then the location of the crack damage is determined. The findings indicate that the results of the simulation are in excellent agreement with the fracture damage that really occurred. Additionally, the received signals are compared to one another and examined from the point of view of energy. Comparisons are also made between two distinct kinds of single-mode Lamb wave monitoring systems. From an experimental point of view, this study demonstrates that a symmetric excitation may simplify the received waves and detect fracture damage in plates in welded steel structures. In addition to this, the work shows that this can be accomplished.

(Hameed et al. 2017) studied Lamb-Wave-Based Multistage Damage Detection Method Using an Active PZT Sensor Network for Large Structures” discovered this and This study presents a multistage damage detection approach that makes use of piezoelectric lead zirconate titanate (PZT) transducers to excite and sense Lamb wave signals. The method is a part of the introduction of this work. In order to correctly analyse the intricate wave signals that were brought on by the damage, a continuous wavelet transformation (CWT) that is based on the Gabor wavelet is used. Damage to a network of transducers can be detected in one detection cell based on the signals scattered by the damage, and then it can be quantitatively estimated by three detection stages using the outer tangent circle and least-squares methods. This can be done after the damage has been detected in one detection cell based on the signals scattered by the damage. Exciting a transducer in the centre of the detection cell to identify the damaged subcell is the first step in a single-stage damage detection technique. This step is carried out by the detection cell. After that, in the second and third phases of detection, the corner transducers are thrilled to increase the damage detection, particularly the size estimate. The approach does not call for any kind of baseline signal, and it merely makes use of the same configuration of transducers and the same kind of data processing methodology across all of the phases. The findings obtained from earlier rounds of detection are taken into account to help increase the accuracy of succeeding phases of damage detection. The capability of the approach to properly measure the damage location and magnitude was validated by a combination of numerical simulation and experimental assessment. Within the context of this Lambda-wave-based multistage damage detection approach, it was discovered that the size of the detection cell is a significant factor in determining the reliability of the findings.

(Rai and Mitra 2017) studied “A hybrid physics-assisted machine-learning-based damage detection using Lamb wave” discovered this and In this study, a hybrid physics-aided multi-layer feed forward neural network (MLFFNN) model is presented with the goal of enhancing damage detection in the presence of Lamb wave responses. The complicated reactions of a thin aluminium plate obtained by finite-element (FE) simulations are used to construct a damage parameter database (abbreviated as DPD) in this section. Over the 1.6 mm thick aluminium plate with notch-like defect, a double pulse-echo transducer design has been built. This configuration creates just A0 mode in the plate structure and records damage-specific S0 mode. Sixty-six different FE simulations are run, and each one represents a different damage scenario in terms of the location of the damage and the frequency of the Lamb wave. To compensate for the interference caused by the surroundings, artificial noise has been introduced. In order to reduce the amount of noise in the signal, an orthogonal matching pursuit was carried out. After that, the DPD for all 66 FE simulations is constructed by extracting the damage-specific characteristics from the sparse S0 signal. An MLFFNN that is being trained is being supervised by a robust Levenberg–Marquardt algorithm. The fully built DPD is being used to train the MLFFNN. A series of preliminary experiments was carried out with a greater damage-depth to plate-thickness ratio with a notch depth of 1.0 millimetre, and the fully trained MLFFNN achieves an accuracy rate of 99.94 percent when predicting the site of the damage. The suggested method is capable of reaching a high degree of generality, including handling situations in which there are overlapping echoes and replies that are congested as a result of many reflections for the damage scenarios that have been provided.

(Sfoungaris and Triantafyllou 2017) studied “Wave-based numerical methods for damage identification in components and structures” discovered that both components and structures

© INNOVATIVE RESEARCH THOUGHTS | Refereed | Peer Reviewed | Indexed
ISSN : 2454 – 308X | Volume : 04 , Issue : 04 | January – March 2018

incur damage while in use, which reduces their load-bearing capability and makes them more prone to catastrophic collapse. More composite materials are being included into the design of many different structures, particularly those that are used in the aircraft industry, as a direct result of the requirement for greater fuel economy and lower pollutant emissions. Composite materials are particularly prone to catastrophic failure as a result of operation-induced and unintentional damage types, both of which have a detrimental influence on the material strength. In order to maintain the structural integrity of a building and guarantee its safety, it is essential to discover and identify any damage as soon as possible. Continuous and reliable monitoring of the state of the components is even more crucial in lightweight constructions since there is less loadbearing redundancy in these types of buildings. Model-based monitoring and damage detection solutions have become more appealing as a result of recent developments in sensor technology and signal processing, as well as the increased availability of computing power. However, computational models for wave simulation are not yet at a point where they can be used in a conventional setting. In order to describe some types of damage, such as cracks, in a way that is both accurate and economical, numerical models of solids need to be made more complicated. When many solutions for unknown and sought-after damage parameters are needed, the computational cost for inverse methods might even become prohibitive. This is because of the complexity of the problem. In the field of wave analysis, this study presents a mesh-independent modelling of damage via the use of XFEM. The behaviour of damage is studied using the technique that was devised, and the findings are validated using existing explicit Finite Element models. To further study the viability of using wave scattering as a technique of damage diagnosis, a signal processing approach using wavelet transform has also been built. This was done with an eye over the various wave actuation and measurement methods that are now accessible. The approach that was suggested is capable of accomplishing considerable model reduction while calculating wave scattering. In addition, it is possible to identify fractures, given that numerous wavemodes can be monitored and recognised.

(Wu et al. 2017) studied "Guided waves-based damage identification in plates through an inverse Bayesian process" discovered this and Because of its reliability and speed of execution, as well as the benefit of being able to check broad areas and discover subtle structural problems, the use of guided waves to identify damage has been a prominent approach in recent years. Other advantages of this technology include: When a travelling wave on a plate interacts with a defect, a scattered field is generated. The shape of the scattered field is determined by the geometry of the defect. One is thus able to define the kind of plate damage as well as the magnitude of the damage by analysing the dispersed field. It is the first time that a Bayesian framework that is based on an interaction model for guided waves has been developed for the purpose of damage detection of an infinite plate. In order to extract the scattering characteristics for damage geometries that have circular symmetry, a semi-analytical technique based on the lowest order plate theories is utilised. This leads to an efficient inversion process. After that, ultrasonic tests are carried out on a huge plate made of aluminium that has a circular depression in it. The purpose of these experiments is to create wave reflection and transmission coefficients. The suggested method's usefulness and efficiency are evaluated with the assistance of various signal processing methods. In order to validate the damage detection strategy, a comprehensive finite element model is deployed. In the end, the scattering coefficients are recreated, and they provide a reliable match to the findings of the experiment. In order to facilitate digital twin technology for structural health monitoring, the framework provides assistance. Plate-like structures are used extensively in a broad variety of systems, such as wind turbines, aircrafts, and ships, amongst others. After the initial damage has been done, more damage will be caused by variables such as fatigue load, which may eventually result in a catastrophic breakdown of the whole system. As a result, the early identification of damage is very necessary for the safety vital components of a building. The next thing to do is to define the damage by defining its parameters, such as the length and depth of a crack. This is an important phase in the repair process. Online detection and characterisation, in the context of structural health monitoring (SHM), leads to a condition-based maintenance strategy. This technique allows the structural dependability to be measured, and maintenance operations are only carried out when they are absolutely essential. This style of operation is efficient with regard to costs, but it calls for the use of trustworthy monitoring and inference strategies that are able to provide correct parameters of the harm.

(Ewald et al. 2017) studied “Perception modelling by invariant representation of deep learning for automated structural diagnostic in aircraft maintenance: A study case using Deep SHM” discovered this and The airline maintenance industry is not an exception to the rule that predictive maintenance, which is one of the core components of Industry 4.0, takes a proactive approach to maintaining machines and systems in good order to keep downtime to a minimum. Industry 4.0 also includes the concept of smart factories. In order to accomplish this objective, practises in Structural Health Monitoring (SHM) have been created in recent decades. These practises complement the non-destructive testing (NDT) methods that are already in place. Recently, one of the primary drivers in the development of predictive analytics in condition monitoring has been the rising computing capabilities, such as the employment of a graphics processing unit (GPU), in conjunction with sophisticated machine learning methods such as deep learning. DeepSHM is the name of the unique technique that we suggested utilising deep learning in our earlier work for guided wave-based structural health. For the purpose of this research, we used a convolutional neural network to analyse an ultrasonic signal obtained via guided Lamb wave SHM (CNN). Within the scope of the study, we took into account just a single central frequency excitation. This resulted in the determination of a single controlling wavelength, which in most cases is enough for the detection of a single damage size. In traditional signal processing, using a wider excitation frequency offers a nightmare for analysis and interpretation since it includes more complicated information and is thus harder to grasp. This is due to the fact that it contains more complex information. Deep learning is a solution that can be used to solve this issue; however, this solution introduces a new challenge. Although deep learning may provide predictions that are normally more accurate, it is designed specifically for the completion of just a select few categories of problems. While many have already introduced deep learning for diagnostics, the majority of these works only propose novel predictive techniques; the mathematical formalisation is missing, and we are not informed about why we should treat acoustic signals with deep learning. While many have already introduced deep learning for diagnostics, the majority of these works only propose novel predictive techniques. Therefore, there is a lack of a foundation for "explainable AI" in both SHM and NDT at the moment. Because we would want to broaden the scope of our past work, we will be using this opportunity to expand it. We propose a plausible theoretical perspective inspired from neuroscience for signal representation of deep learning framework to model machine perception in structural health monitoring (SHM). This is especially important given that SHM typically involves multiple sensory input from a variety of sensing locations. Rather than focusing on a novel technique, we have chosen to focus our attention on this plausible theoretical perspective.

Conclusion

Plate-like structures are used extensively in a broad variety of systems, such as wind turbines, aircrafts, and ships, amongst others. Detecting deterioration in a structure's safety-critical components as soon as possible is very essential. In spite of the progress made in the creation of very advanced sensors, SHM systems have not yet gained universal acceptability among aircraft operators. Non-Destructive Inspections (NDI), which are carried out after a certain number of flying hours, will continue to be the technique of choice until Self-Healing Measurements (SHM) are able to match the degree of damage detectability achieved by NDI. At the moment, there are no standards that can be used to construct a PoD curve for a particular SHM sensor configuration. To be able to deal with the ever-increasing complexity of today's complex and demanding structures, more advanced digital signal processing (DSP) approaches are required. It is important to identify the early stages of breakdown in crucial components as quickly as possible, ideally at a low cost, so that appropriate time may be allotted for repairs while yet remaining within a budget that is manageable. Lamb waves, also known as guided elastic waves on a narrow plane, are one method that has been investigated for the purpose of developing new non-destructive evaluation (NDE) strategies. The location of structural damage may be determined by using a method known as time of flight (ToF) in the signals that were collected by one sensor–actuator pair.

References

1. Ewald, Vincentius, Ramanan Sridaran Venkat, Aadhik Asokkumar, Rinze Benedictus, Christian Boller, and Roger M. Groves. 2017. "Perception Modelling by Invariant Representation of Deep Learning for Automated Structural Diagnostic in Aircraft Maintenance: A Study Case Using DeepSHM." *Mechanical Systems and Signal Processing* 165(May). doi: 10.1016/j.ymssp.2017.108153.
2. De Fenza, A., A. Sorrentino, and P. Vitiello. 2015. "Application of Artificial Neural Networks and Probability Ellipse Methods for Damage Detection Using Lamb Waves." *Composite Structures* 133(January 2017):390–403. doi: 10.1016/j.compstruct.2015.07.089.
3. Hameed, M. Saqib, Zheng Li, Jianlin Chen, and Jiahong Qi. 2017. "Lamb-Wave-Based Multistage Damage Detection Method Using an Active PZT Sensor Network for Large Structures." *Sensors (Switzerland)* 19(9). doi: 10.3390/s19092010.
4. He, Jian, Liang Yang, Xiaodan Sun, and Muping Hu. 2017. "Damage Identification in Welded Structures Using Symmetric Excitation of Lamb Waves." *Advances in Mechanical Engineering* 10(9):1–12. doi: 10.1177/1687814018794817.
5. Li, Fucai, Zhongqing Su, Lin Ye, and Guang Meng. 2006. "A Correlation Filtering-Based

Matching Pursuit (CF-MP) for Damage Identification Using Lamb Waves." *Smart Materials and Structures* 15(6):1585–94. doi: 10.1088/0964-1726/15/6/010.

6. Pant, Shashank, Marcias Martinez, Marko Yanishevsky, and David Backman. 2017. "Damage Detection Methodology for Structural Health Monitoring (SHM) Applications Based on Multi-Frequency Anti-Symmetric Guided Waves." *9th European Workshop on Structural Health Monitoring, EWSHM 2017*.
7. Rai, Akshay, and Mira Mitra. 2017. "A Hybrid Physics-Assisted Machine-Learning-Based Damage Detection Using Lamb Wave." *Sadhana - Academy Proceedings in Engineering Sciences* 46(2). doi: 10.1007/s12046-021-01582-8.
8. Sfoungaris, Konstantinos, and Savvas Triantafyllou. 2017. "Wave-Based Numerical Methods for Damage Identification in Components and Structures." (March).
9. Wu, W., M. K. Malik, S. Cantero-Chinchilla, T. Lawrie, W. J. Yan, G. Tanner, R. Remenyte-Prescott, and D. Chronopoulos. 2017. "Guided Waves-Based Damage Identification in Plates through an Inverse Bayesian Process." *Ultrasonics* 125(May). doi: 10.1016/j.ultras.2017.106773.