Damage Reconstruction in Complex Composite Structures using Lamb Waves

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Abstract. The current maintenance and inspection strategy for aircraft structures is based on strictly scheduled inspection intervals considering the age and usage of the aircraft. This implies that the structures must be designed in a damage tolerant way, allowing a safe operation with undiscovered damages until the next major inspection. In addition, new aircraft are designed with even longer inspection intervals to reduce downtime and maintenance costs. For fiber-reinforced composite structures this approach is contradictory to the idea of reducing the weight of the aircraft. Especially blunt low-velocity impacts may cause large damages like delaminations that are likely to be missed during visual in-service inspection. It is therefore desirable to have an integrated structural health monitoring (SHM) system that will monitor the structure for damages and allow early damage detection between inspection intervals. This does not only pave the way to a more demand-driven maintenance, but may contribute to further exploiting the light-weight potential of composite materials. In contrast to other monitoring methods the use of Lamb waves allows determining the location of a damage. This has been shown many times for simple structures like plates or pipelines. However, these methods are often not applicable to complex structures that feature curvatures, anisotropic material properties and changing material properties throughout the structure. Therefore a damage reconstruction method is proposed, that is similar to methods known from conventional ultrasonic inspection, but takes into account the complex material properties and their influence on the wave propagation. The base for this approach is a time-of-flight calculation that can be applied to structures with many local changes in material properties and allows each material to be anisotropic. This is combined with a pulse compression to increase the temporal resolution of the signal and therefore the spatial resolution of the reconstruction. The proposed method can be applied to integrated monitoring systems with a limited number of fixed transducers, high-resolution scans of the wave field obtained with air-coupled ultrasound systems or laser-vibrometers and can also be adapted for acoustic emission monitoring.

1. Introduction

Modern aerospace structures feature an increased use of composite materials, mainly carbon fiber reinforced plastics (CFRP). They consist of carbon fibers, which carry the loads applied to the structure and a matrix, which defines the shape of the part, holds the fibers in place and distributes loads between the fibers. Compared to metals these materials have a higher specific strength and stiffness and can be tailored specifically to the expected loads. This makes CFRP an ideal material for lightweight structures.

Due to the inhomogeneous internal structure of composite materials and their manufacturing from single ply layers they also show much different damage behaviour than metals. This is especially true for low-velocity, blunt impact damages. These can lead to extended delaminations inside the material. Fig. 1 shows a 3D visualization of an ultrasound D-scan of such a delamination, which is barely visible from the outside.

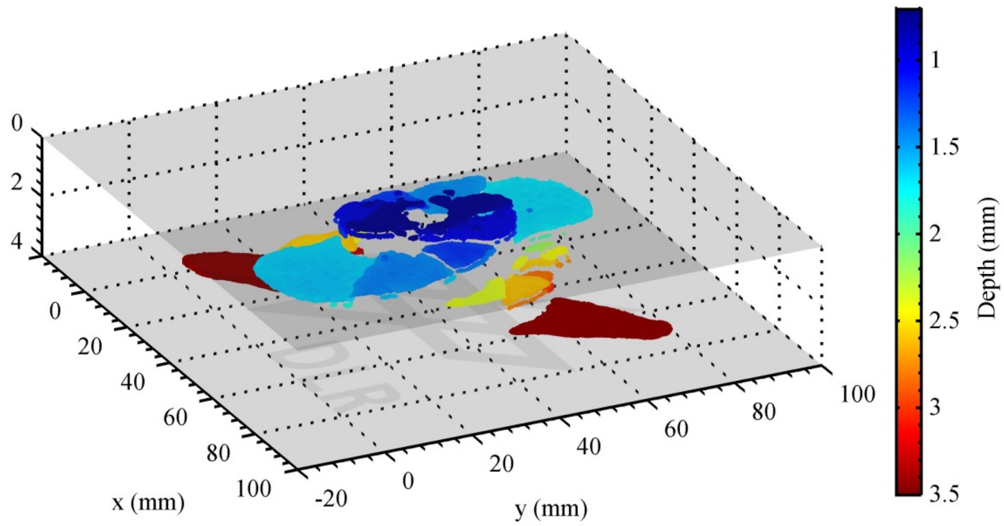


Fig. 1: 3D visualization of an ultrasound D-scan (depth image) of a delamination in a 4mm thick CFRP plate

In contrast to metal structures, where a remaining dent would indicate such an impact, the outer plies of a CFRP structure may remain undamaged or show only minor deformation. Therefore, such impact damages are very likely to be missed during in-service visual inspection and are only expected to be discovered during the next scheduled in-depth inspection [1]. The requirement for the damaged structure to be used without limitation until the next scheduled inspection together with the desire of the airlines to have longer inspection intervals for increased aircraft availability lead to large safety factors for the structural design and hence are contradictory to the goal of building lightweight structures.

An early, if possible instant, damage recognition using an integrated structural health monitoring (SHM) system can help to overcome many problems associated with otherwise unrecognized damages. Damage could be detected immediately, allowing an on-site inspection before an aircraft takes off and exposes passengers and pilots to the risk of a failing structure. Knowing the state of the structure at any time can also allow a transition from strictly scheduled inspection intervals to more demand-driven and economical maintenance plans. In addition to adding the ability to monitor a structure, in the long term SHM might also replace conventional inspection for parts of the aircraft, which are very difficult to inspect due to poor accessibility.

Different methods can be used for monitoring a structure. They can range from single sensor measurements for changes in eigenfrequency [2] over comparative vacuum measurements to large sensor networks for distributed strain measurements and ultrasonic monitoring using guided waves [3].

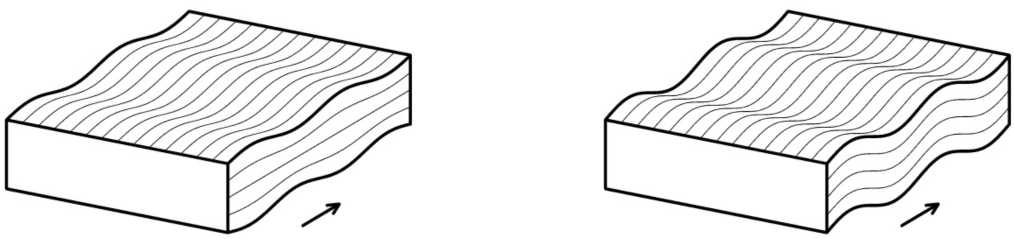
This paper focusses on structural health monitoring using Lamb waves. In contrast to many other techniques, this method allows detecting damages not only at a sensor location, but between sensors and therefore is suitable for locating damages. Because it is an active method it can be applied at any time and does not depend on detecting single events, like acoustic emission monitoring. The methods used for locating damages with an active monitoring, may also be adapted for improving damage localization using acoustic emission monitoring.

In order to locate damages in complex composite structures a combination of signal processing, time-of-flight calculation and damage reconstruction is proposed. This approach can overcome many drawbacks of currently used methods, which are often not applicable to complex structures and should help to bring structural health monitoring technology closer to an actual industrial application.

2. Structural health monitoring using Lamb waves

A permanently integrated SHM system should be able to monitor a large structure with a small number of sensors. This can be achieved by exciting Lamb waves and evaluate their propagation through the structure [4].

Lamb waves are acoustic waves, which propagated in thin-walled structures, where the thickness of the structure is smaller than the wavelength. Lamb waves excited at a given frequency usually occur in different wave modes. The symmetric wave mode (S-mode) can be thought of as a pressure wave with a periodic pressure gradient parallel to the surface. The particle displacement is oriented mainly in-plane and symmetric with respect to the centre plane. The antisymmetric wave mode (A-mode) is similar to a flexural wave with a parallel movement of the upper and lower surface and mainly out-of-plane displacement components. A schematic drawing of the displacement caused by these wave modes is shown in Fig. 2. The arrow indicates the propagation direction.



S-Mode A-Mode

Fig. 2: Schematic surface displacement of S- and A-modes

Other wave modes and higher order modes can exist, but are usually not relevant for monitoring large composite structures due to their high attenuation or interactions material inhomogeneity [5]. Therefore only the fundamental S- and A-mode are considered here. When applied to aerospace structures, the thickness of the structure is often just 1-2 mm. Depending on the homogeneity of the material and the required propagation distance the excitation frequency may be in a range of a 10 kHz up to a few 100 kHz.

As Lamb waves propagate through a structure they can show different forms of interaction with discontinuities. Waves can be attenuated, refracted, reflected and converted from one wave mode into another wave mode. For detecting damages especially the reflection and conversion are strong indicators. Fig. 3 shows a snapshot of the wave propagation obtained using laser vibrometry. The colours correspond to the out-of-plane displacement velocity of the surface. Both S- and A-Mode can be clearly identified by their wavelength. This figure also shows the reflection of the S-Mode at the edges of the plate and a conversion into the A-Mode at the vertical discontinuity in the middle of the plate.

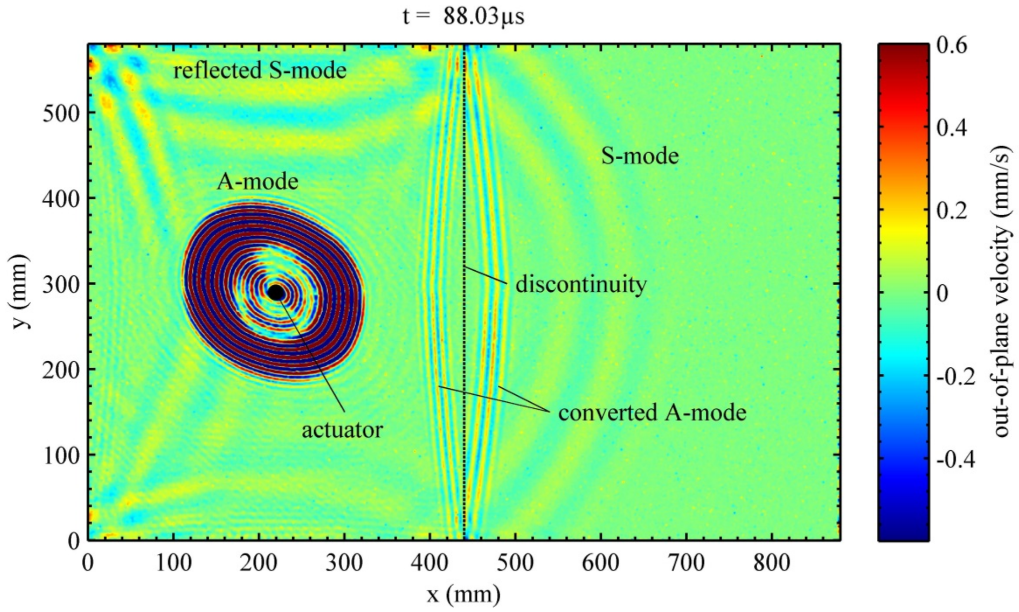
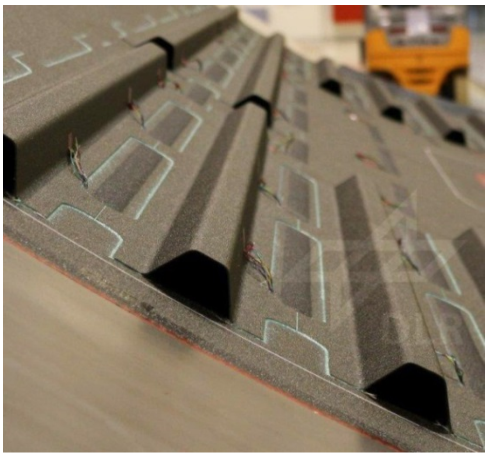


Fig. 3: Interaction of Lamb waves in a CFRP plate with a discontinuity

The actuation of Lamb waves is usually achieved using permanently applied piezoelectric actuators. They consist of a piezoelectric ceramic element and an epoxy encapsulation, which provides a mechanical preloading to protect the brittle ceramic element from fracture and also contains the electrical contacts [6]. For a more efficient integration several single sensor elements can be grouped into one multi-sensor array and applied to the structure in one step. The current state of the art regarding sensor integration has recently been demonstrated by DLR in the EU Project SARISTU, where a door-surrounding structure has been successfully equipped with a network of 584 sensors [3]. Fig. 4 shows both single-element DuraAct® sensors and integrated and grouped sensors.

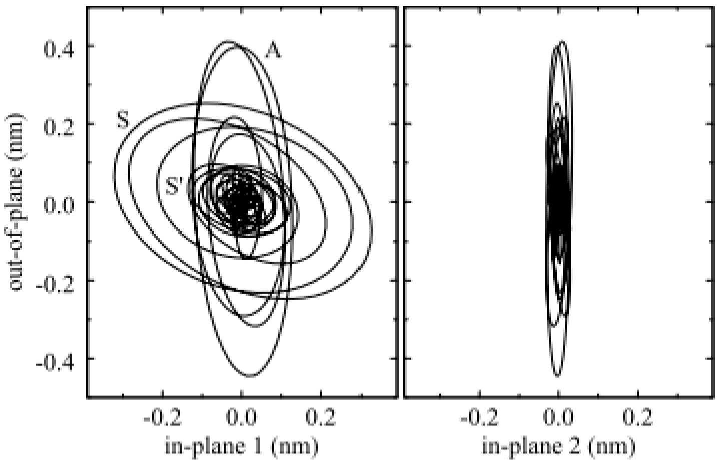
a) Single DuraAct® sensor element



b) Sensors integrated in the SARISTU door-surrounding structure

Fig. 4: DuraAct® piezo-composite sensors as single elements and as grouped elements integrated in a door-surrounding structure.

Besides using integrated sensors for detecting Lamb waves they can also be recorded using laser vibrometry. These devices can punctually measure the displacement of a surface caused by a passing wave. With this technique Lamb wave fields can be recorded at very high spatial resolution, which is also beneficial for understanding the wave propagation and the origin of signals recorded at integrated sensors. By combining vibrometry measurements from different directions at one point the three-dimensional displacement of a point can be determined [7].



S = S-Mode S’ = S-Mode reflected from plate edge A = A-Mode

Fig. 5: 3D trajectory of the surface displacement caused by Lamb waves and obtained using 3D laser vibrometry

Based on the signals acquired for different transducer combinations different methods can be applied for identifying and locating damages. In most cases a baseline signal is subtracted from the measured signal. This baseline presents the reference for an undamaged structure. If all other influences like temperature, humidity or loading conditions are compensated or included in the baseline, the remaining difference in the signal is expected to be caused by damage. However, providing a correct baseline is very challenging, because all possible influences, which affect the wave propagation and sensor properties, must be taken into account. Current approaches try to generate baseline signals based on measured operational conditions and simulation [8].

The methods used for determining the location of damages can be roughly divided into two groups:

In simple structures the focus of the applied signal processing algorithms is to determine the time-of-flight when a signal change appears at a sensor. Based on this information possible damage locations can be determined around sensor pairs. Using triangulations techniques and multiple sensor/actuator combinations a single, punctual damage location is determined [9]. While this works very well for small damages and simple structures, the adaptation to complex structures is very difficult. One challenge is the structure itself with the corresponding material properties. These are often directional and vary throughout the structure. In addition to that the geometric complexity, e.g. multiple curvatures must also be considered. Another weak point of triangulation methods is that, when applied to composite structures, small damages might be detected, but large damages may be overseen, because they cause signal changes originating at different locations and may therefore be falsely discarded as artefacts.

Due to these difficulties, the common approach for complex structures is to use a very dense transducer network and evaluate the transmission paths between them [10]. The assumption is that whenever there is a significant signal change, its cause – the damage – must be within a certain area near the corresponding sensor pairs. The actual structure with its properties is largely discarded in this approach and only the sensors and their relative position to each other is considered for further evaluation. With this approach the area that can be monitored is usually limited to an area within the sensor network. While neglecting the structure and the way the waves actually propagate this approach is often considered good enough to locate the damage within a sufficiently small area in which conventional non-destructive testing is performed subsequently.

The approach presented here is aimed at maintaining and considering the structure and the wave propagation within it. This allows damage localization without predefined probabilities derived from an abstract representation of the sensor network and without the complexity and limitations of triangulation-like methods.

3. Signal processing

In order to obtain clear results from any damage localization algorithm the input signals must be pre-processed correctly. The main aim of the signal processing is removing any noise and additional acausal contents, which is not addressed here, separating signal contents (e.g. Lamb wave modes) and preparing the signals in a way that improves the accuracy of the damage localization.

The separation of wave modes can be done in various ways. Mode-selective sensors can be used to emphasize signal components from different wave modes, e.g. based on their wavelength. However, these sensors are usually quite large and may be directional.

For the evaluation of measurements obtained from 3D laser vibrometry the S- and A-modes can be separated based on the ration of their in-plane and out-of-plane displacement. For the structures and frequencies regarded here, the in-plane displacement of the S-mode is smaller than its out-of-plane component and vice versa for the A-mode (see Fig. 5).

A key requirement for precise damage localization is a high temporal resolution of the input signals, since this resolution is directly linked to the spatial resolution via the propagation velocity of the waves. Due to the dispersive nature of Lamb waves the excited wave packages cannot be arbitrarily short. A short wave package would show a significant deformation as it propagates and would only contain a small amount of energy within the desired frequency range, resulting in poor signal quality. A good compromise between wave package length and a small bandwidth can be obtained by using a sine-windowed excitation signal.

A further increase of the temporal resolution can be obtained by applying pulse compression algorithms to the input signal. These algorithms identify wave packages by comparing them to a set of analytic wave packages. Based on the parameters of these wave packages a suitable pulse representation can be generated. The length of the pulses is a compromise between achievable spatial resolution and robustness of the damage localization. An example for the pulse compression of a measured signal is shown in Fig. 6.

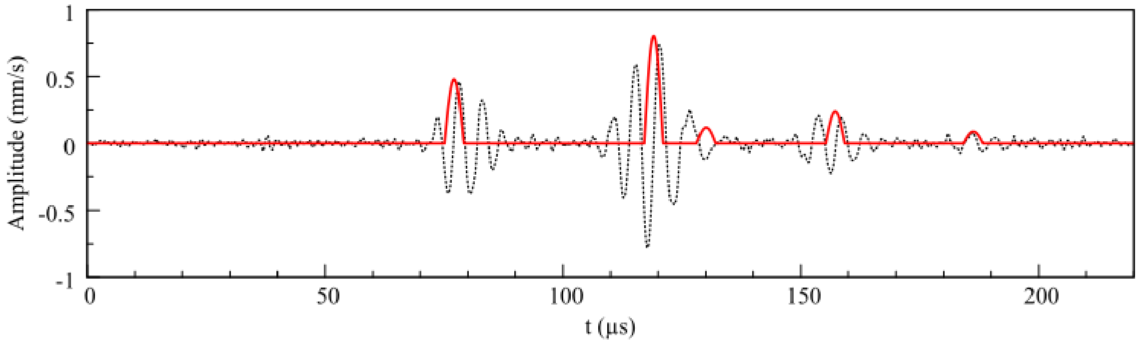


Fig. 6: Pulse compression of a measured signal

The position of the pulse with respect to the original wave package depends on how the propagation of the wave package is described. Often this is done based on the group velocity of the excited centre frequency. While this is often a good approach it yields a certain risk for error when using short wave packages. The group velocity itself is frequency-dependent. Due to the fact that short wave packages automatically contain a large frequency bandwidth this dependency cannot be neglected. Due to shape variations of the wave packages caused by dispersion using an amplitude threshold for determining the beginning of a wave package is not a reliable option either. It is therefore proposed here to place the pulse at the location of maximum amplitude of the hull of the original wave package and use the propagation velocity of this maximum to describe the propagation of the wave package.

4. Damage localization

As described before, most methods for locating damages, which are currently used for simple structures, are not applicable to complex structures. The solution proposed here is to apply a reconstruction algorithm similar to SAFT (Synthetic Aperture Focussing Technique) well known from conventional ultrasound inspection. This approach has already been shown for phased-array-like sensor configurations [11, 12] but yields much more potential for distributed sensor networks. Instead of determining a damage location from sensor signals this approach determines a probability for the presence of damage at a given location. Based on pre-determined interaction phenomena the algorithm calculates the time-of-flight at which the effect of damages is expected to appear in measured sensor signals. For the conversion of a symmetric wave mode into an antisymmetric wave mode this time-of-flight would be the propagation time of the S-mode from the actuator to the supposed damage plus the time of the converted A-mode from there to the sensor. The sensor signals at the respective times are summed at the supposed damage location. If no damage is present at a given location, the reconstruction value obtained this way will not be significantly different from the surrounding area. However, if damage is present and the signals are extracted correctly, a much higher value will be determined due to the constructive interference of the extracted amplitudes.

This approach is not limited to a specific sensor technology. It can be applied to integrated sensor networks as well as to data acquired using e.g. laser vibrometry. As a general rule of thumb it can be expected that the reconstruction will show a better contrast between damaged and undamaged areas the more combinations of sensors and actuators are available and the more the transducers are spread across the entire structure.

Fig. 7 shows the reconstruction of a plate with a magnet located at {900 mm, 500 mm} serving as an artificial damage. The measurement is obtained using laser vibrometry and a measurement grid with a spacing of 10 mm. Baseline data for undisturbed wave propagation is subtracted from the acquired signals.

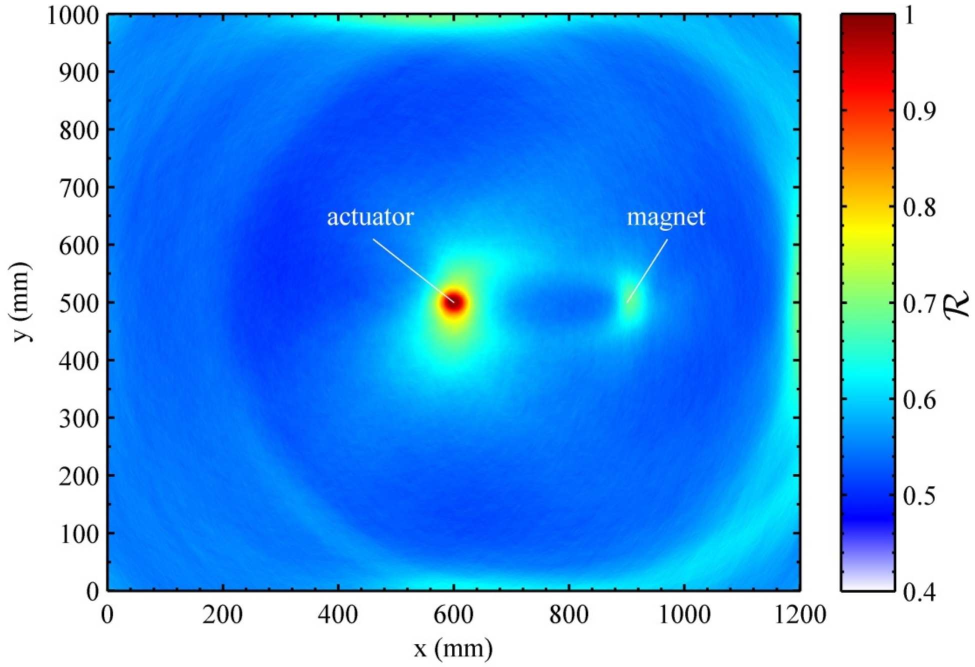


Fig. 7: Reconstruction of a magnet located on a plate using vibrometry data

This example shows that damage localization is even possible with a single actuator. The contrast of the reconstruction will be increased significantly when multiple actuators are used.

In order to apply this reconstruction to complex structures one has to consider both the directional and the spatial variation of the velocities at which the Lamb waves propagate. This can be achieved by discretizing a structure similarly to FEM models. In this case each cell can feature unique propagation characteristics. Starting from one node the time-of-flight is calculated to its neighbours, which are not only located at the element corners, but also along the edges. Fig. 8 shows an abstract example for calculating the time-of-flight from an actuator in a curved panel. The panel contains a section with increased stiffness, causing the propagation velocity c (3000 m/s) to be twice as high in this area. The time-of-flight map shows a clear distortion due to this local increase.

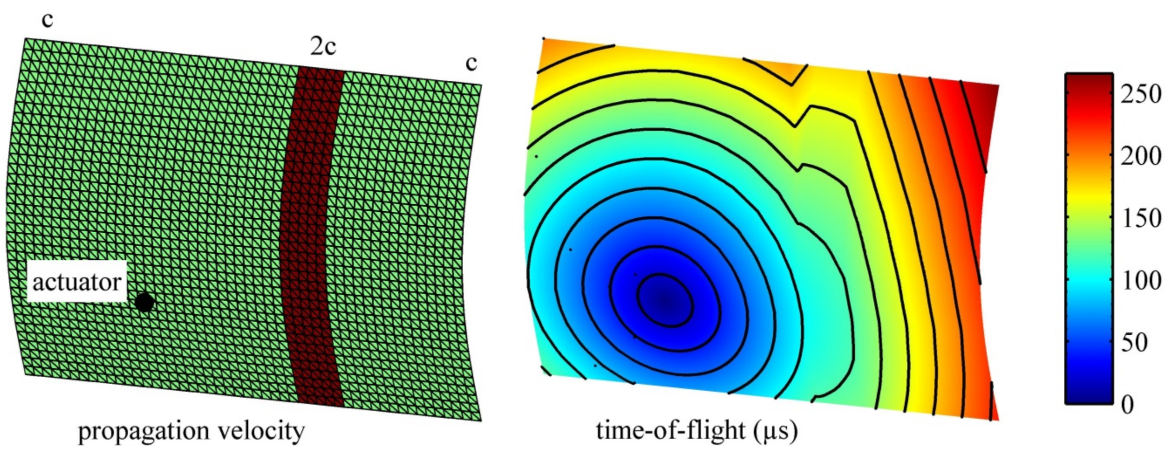


Fig. 8: Time-of-flight calculation for a curved panel with locally increase stiffness

5. Conclusion

This paper shows methods to be used for performing damage localization using Lamb waves in complex composite structures. The presented methods are very flexible and can be applied to a large variety of structures. Although this procedure is still part of ongoing research and many more questions are yet to be answered, it is expected that a proper application of the described methods can improve the accuracy of damage localization and bring structural health monitoring closer to an actual industrial application.

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