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LAMB WAVE PROPAGATION IN COMPLEX GEOMETRIES - MODEL REDUCTION WITH APPROXIMATED STIFFENERS

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ABSTRACT

Aviation companies show great interest in Structural Health Monitoring (SHM) systems. Although noticeable effort has been put into this research field, so far no system is ready for industrial use. One of the major issues is the processing of complex signals caused by complex aerospace structures. Numerical simulations can help to comprehend these signals, but are often unable to cope with the model detail required.

A ray tracing algorithm to approximate Lamb wave propagation is proposed, which enables a huge model reduction. The resulting minimal model mainly consists of the border lines of areas with different geometrical or material properties. Finite element simulations are used to determine the interaction behavior of these transition zones. A two stage concept is used to find paths from an actuator to a sensor and calculate time signals.

KEYWORDS : *Lamb waves, minimal model, ray tracing, anisotropic material*

INTRODUCTION

Lamb wave based structural health monitoring systems are in development for quite some time, but are still not ready for industrial application. There exist a lot of reasons for this, including for example the adaptation to aerospace requirements or missing standards. From a technological point of view, signal processing is one of the biggest challenges for SHM systems. To identify damage induced signal changes, reliable baseline signals are required. But varying environmental conditions, including temperature and external loads, change these signals. Different methods are known to cope with this fact. Measurements for a set of predefined conditions or learning systems are current research topics [1, 2]. As an alternative to expensive measurements, baseline signals can be calculated using numerical simulations. This offers a more flexible way to adapt to changing environmental conditions, but in order to get a good representation of real structures with a model, an exact knowledge of the actual structural properties combined with high repetition accuracy in manufacturing is required. Simulations are an important tool to analyze Lamb waves and get a better understanding of wave propagation. Nevertheless, modeling and simulation of complex structures still requires an unacceptable amount of resources. Different specialized algorithms have been proposed in the recent years. But while offering promising speed ups they often lack availability, flexibility or usability. Numerically calculated reference signals as part of a SHM system need to be obtained at real time. Suitable models need to be reduced to the minimal amount of necessary information. The resulting minimal model could not only be used to predict a baseline, but also for actuator sensor network design.

1. Ray tracing

Ray tracing is a technique that originates in optical physics, but is widely used in computer graphics and as a tool in different branches of research, nowadays. Rays traveling in homogeneous media can be calculated by finding the first intersection with any object inside the scene or model. Simulation time is limited by a set amount of bounces each ray performs or when the ray exits the model boundaries. This procedure with straight rays is often used to generate a 2D projection or illumination of a 3D scene [3]. For natural science problems with inhomogeneous media, ray propagation needs to be divided into small time steps. Examples include earthquake waves traveling through the earths interior or radio signals in the earths atmosphere [4, 5]. Ong and Chiu [6] selected a time step based ray algorithm to investigate methods to focus Lamb waves into hard to inspect regions of specimens. But relating to this classification, aerospace structures can be defined as segmented homogeneous medium. Considering this and the fact that the corresponding algorithms are computationally more efficient, the ray method with straight rays has been chosen. In the present work, a 2D model of the plate-like structure is used to represent aerospace parts with stiffeners. The curvature of structures like the fuselage does not need to be included into the model, because it's effect on Lamb wave propagation is neglectable [7]. The interaction behavior between Lamb waves and structural elements in plate-like components has been investigated in previous work [8]. Basically two of the observations made, led to the selection of ray tracing as approach for a minimal model. Firstly, interactions are concentrated at the edges of geometrical or material changes. Accordingly, reducing these areas in a model to their border lines is a valid simplification. Secondly, the interaction behavior itself can be summarized with the three effects of transmission, reflection and mode conversion. Most ray tracing algorithms use a huge amount of rays to get a detailed image of the scene. Contrary to this, the proposed algorithm will only calculate very few rays in detail, which define the relevant paths between actuator and sensor. Each ray represent a wave packet containing various information. With this approach, it is intended to get time signals at one or very few points in complex geometries with very small computational effort. Prior to this, the relevant paths have to be found. This preceding first stage requires a larger amount of rays, but properties associated with each ray are very limited. The relevant paths can be reused, once they have been identified for one geometry. Changing environmental conditions or excitation signals will alter the sensor signal but not the signal path.

2. Identification of relevant paths

To generate a time signal at a single sensor position, all relevant paths have to be found. In accordance with Fermat's principle, a relevant path for a wave packet is the path with the shortest travel time. The identification of these paths is influenced by three effects. First, reflections result in additional routes between actuator and sensor besides the direct connection. Second, refraction occurs at material transitions. While Snell's law can easily be applied for isotropic material to determine the angle of refraction, the presented model will be utilized to analyze anisotropic composite materials. A way to implement this effect is still under investigation. Last, anisotropic material properties result in directional velocity distributions. At first, this seems to imply that the shortest path could differ from the fastest path. But this is not the case, since the triangle inequality also holds true for homogeneous materials in an obstacle-free domain [9]. In theory, anisotropy could lead to the assumption that an indirect path is faster then a direct path where the calculated velocity is distinct lower compared to other angles. The indirect route does not necessarily consists of just two sections. A zigzag path with infinite sections along the direct path would also be faster then the direct path that is based on the theoretical speed distributions. The direct path is therefore always at least as fast as any indirect path. An immediate consequence is that all speed functions are convex (Figure 1). Despite concave distributions can be calculated for plates with strong anisotropic properties, diamond-shaped distributions are observed in experiments and simulations [10]. Shortest and fastest path are identical as long as they are only influenced by reflection and stay in an area of homogeneous material. As soon as refraction is included, group and phase velocities have to be taken into account to find the fastest path.

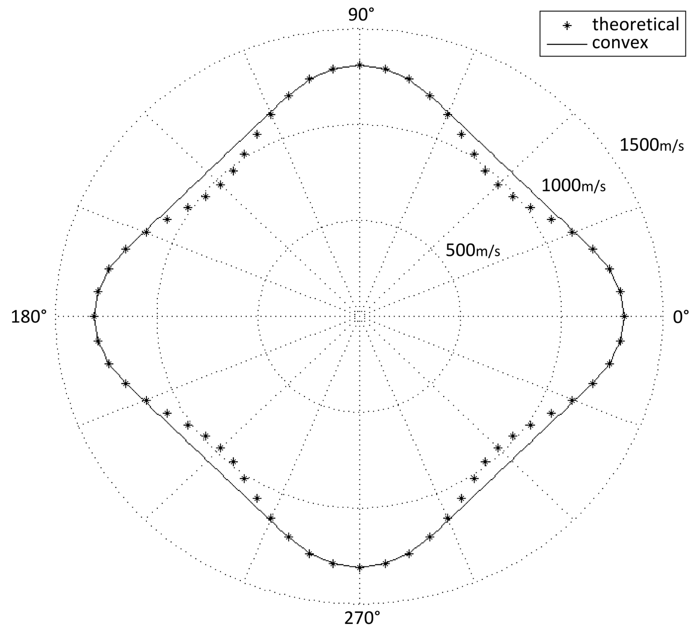


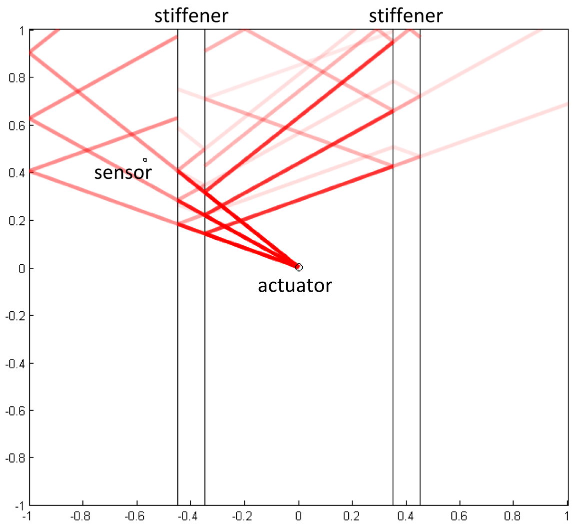
Figure 1 : Directional speed function in a composite plate: calculated based on material properties and corresponding convex envelope

To find all relevant paths, a number of rays is released in all directions from an actuator. A ray ends at the first edge of an obstacle in its way. There, a ray for transmission and one for reflection are released, if the corresponding border conditions permit this. At the outer edge of a plate, for example, only reflection occurs. At this stage, different wave modes are not distinguished, because all modes will take the same paths. For the same reason, no additional rays are released for mode conversion. With addition of refraction this could eventually change, given that the specific phases velocities of a wave mode determine the angle of refraction.

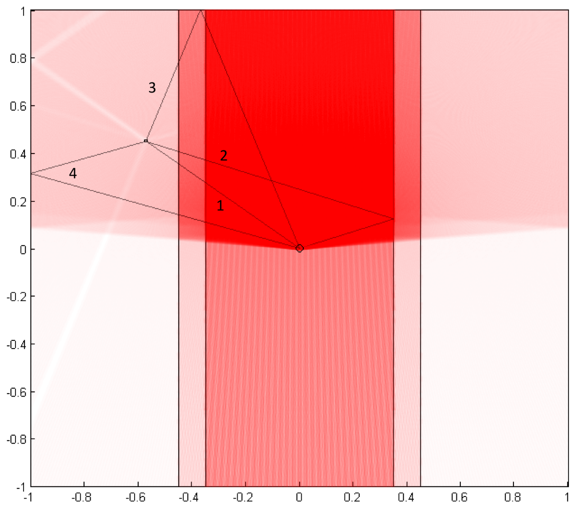
In Figure 2a a simple example for the ray tracing algorithm is given. An actuator located in the center of the plate emits three rays roughly in direction of the sensor. Colors indicate the amplitude loss as a result of interaction at the stiffeners border lines. No path to the sensor is found, since to few rays are launched. The fan of rays with an opening angle of 170° in Figure 2b finds four paths between actuator and sensor. Multiple nearly parallel paths are often found, but only the shortest ones are kept. On the one hand, the number of found paths is limited by the angle at which rays are launched. Frequently used piezoceramic discs will induce rays equally in all directions. Phased array techniques or interdigital transducers allow a directional excitation [7, 11, 12]. On the other hand, the presented algorithm computes a set number of interaction steps, which also restricts the amount of possible paths. Most types of interaction will reduce the amplitude of a wave packet significantly, thereby limiting the amount of required solution steps. In Figure 2 four steps were calculated.

3. TIME SIGNAL SYNTHESIS

The sensor signal is calculated by superimposing the signals of every relevant ray. Each ray in turn represents several wave packets, depending on the number and kind of interactions and Lamb wave modes included. In almost every published work related to Lamb wave based SHM, only the symmetric mode S_0 and the antisymmetric mode A_0 are considered, for various reasons. The presented algorithm is currently also limited to these two modes, but can easily be expended when necessary. The signal synthesis utilizes the plane wave solution of the wave equation. To get the individual sig-



(a) Three rays



(b) 170° fan of rays

Figure 2 : Ray tracing in a plate with two stiffeners

nals $g(t)$ at specific positions x, the solution for harmonic waves of n frequency steps have to be added up.

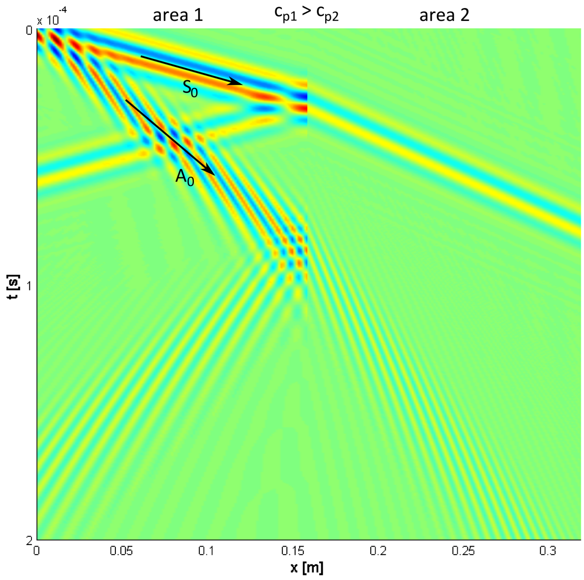
$$g(x,t) = \sum_{f_1}^{f_n} \left(A(f) \cdot \exp\left(i2\pi f \left(\frac{x}{c_p(f)} - t \right) \right) \right) \tag{1}$$

The amplitude A for every frequency f is defined by the spectrum of the excitation signal. The phase velocity c_p is not just a function of frequency but also of wave mode, propagation direction and material and is calculated in advance. For the sake of clarity, these dependencies are omitted here. An in-house program that is based on the stiffness matrix method is used to determine the dispersion curves for layered anisotropic plates [13]. Equation (1) is only valid for homogeneous areas and needs to be expanded to include changing phase velocities and interactions at the border of every area. Equation (2) includes all m interactions between actuator and sensor, where M_s are the frequency dependent interaction parameters and x_s the traveled distance from actuator to every border. $c_{p\ s}$ and $c_{p\ s+1}$ are the phase velocities corresponding to the incident and emergent rays.

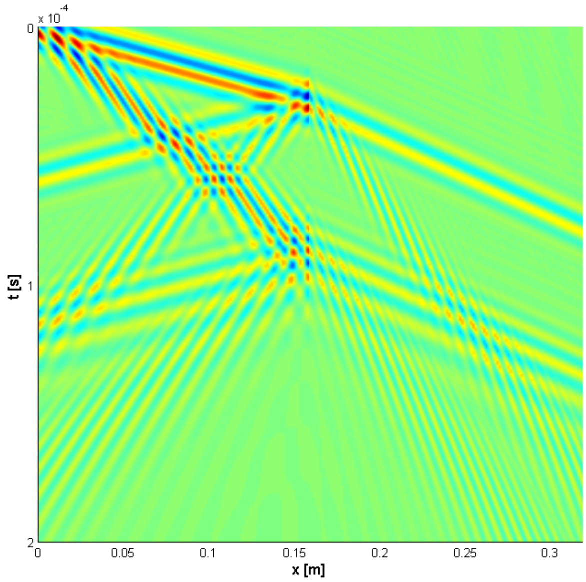
$$g(x,t) = \sum_{f_1}^{f_n} \left(A(f) \cdot \prod_{s=1}^{m} (M_s(f)) \cdot \exp\left(i2\pi f \left(\frac{x}{c_p(f)} - t + \sum_{s=1}^{m} \left(\frac{x_s}{c_{p\ s}(f)} - \frac{x_s}{c_{p\ s+1}(f)} \right) \right) \right) \right) \tag{2}$$

The real part of Equation (2) is used to determine the time signals at the sensor position for the individual rays. To visualize the effect of this equation, the signals for many points along a path that crosses two adjacent areas are plotted in Figure 3. At the boundary of these areas the A_0 and the S_0 wave packet are partly transmitted, reflected and converted. In Figure 3a only transmission and reflection are shown. Generally, only one effect is considered, since the relevant paths to the sensor are unbranched, but in this example both are displayed. Thus, the change in group velocity is visible for both modes as is the dispersion of the A_0 mode. This is not the case for the S_0 mode, because its phase velocity is nearly constant in the frequency range of the excitation signal. The third effect to be considered at boundaries is mode conversion. All three types of interaction are depicted in 3b.

Each path to the sensor covers multiple wave packages. Beside the primary A_0 and S_0 modes, every interaction can induce an additional packet as a result of mode conversion. In Figure 4 the time



(a) transmission and reflection



(b) mode conversion added

Figure 3 : B-scan of A_0 and S_0 mode traveling through two areas with different phase velocities

signals of the four paths marked in Figure 2b are plotted with individual colors. Only the the primary A_0 mode is considered here, for better comparability. Amplitudes are reduced through interactions, except at the outer plate borders, where all energy is reflected. Longer travel times result in more dispersed wave groups and slight amplitude decreases. The individual packets are hardly recognizable when all signals are superimposed (Figure 5). Similar problems arise during examination of measured sensor signals. The proposed algorithm provides an intelligent reference where the origin of every section of a signal is known. In consequence, changes to specific time ranges can be related to particular paths or geometric details and could be used to narrow down damage locations.

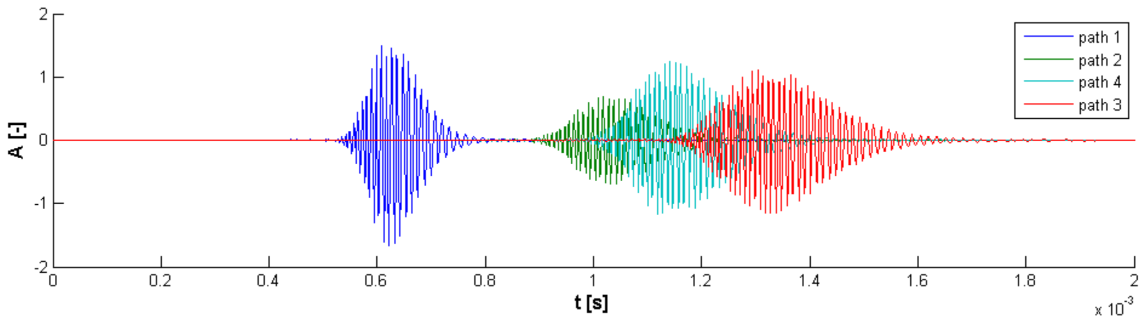


Figure 4 : Time signals of four different paths to the sensor for the primary A_0 mode

Conclusion

In this work, a technique to calculate time signals at discrete positions in a complex aerospace geometry is proposed. In a first step, the relevant paths for Lamb waves traveling from an actuator to the sensor are identified with a ray tracing algorithm. In the second step, the signals corresponding to these paths are computed by considering all interactions and materials along these paths. Transmission, reflection and mode conversion occur at borders of structural inhomogeneities, like stiffeners.

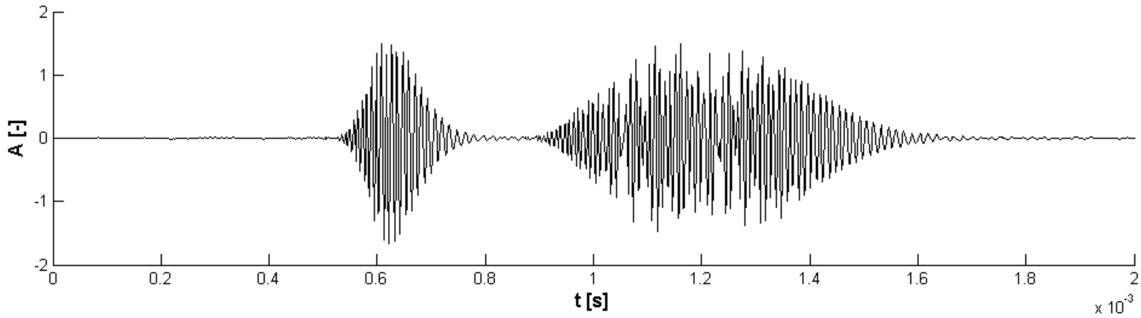


Figure 5 : Superimposed time signal at the sensor position for the primary A_0 mode

Parameters describing these interactions need to be determined with help of the FEM. Furthermore, only the phase velocity distributions for the anisotropic material are required as input for the time signals. At the sensor position, the individual signals of all paths are superimposed to get the sensor signal.

The proposed method is quite flexible and influences on both the paths and the time signal can be added with little effort. This includes different attenuation mechanisms, like scattering of wave energy on the plate geometry and material damping [14]. Another aspect that mostly influences the amplitude of the wave packet, is the focusing of Lamb waves in anisotropic materials. The fiber direction in composite plates does not only affect phase velocities but also directs wave energy [15]. Anisotropy could also have an impact on the relevant paths when refraction is considered. Contrary to isotropic materials, refraction mechanisms are not covered by Snell's law in this case. No work covering this topic for Lamb waves is known, for which reason detailed investigations are required before an implementation is possible. Furthermore, diffraction could be relevant at smaller inhomogeneities or corners. This problem can be solved, if each interaction point is considered as new wave source, but computation times of the ray tracing algorithm would increases massively. Another solution, yet to be found, is preferable to limit the computational costs. Finally, both transducers influence the signal, since they act as wavelength dependent filter and add directivity. The related frequency response and orientation dependent coefficients can be calculated as a function of geometry.

REFERENCES

[1] Y. Ying, J. Harley, J. Garrett, Jr., Y. Jin, I. Oppenheim, J. Shi, and L. Soibelman. Applications of Machine Learning in Pipeline Monitoring. In *Proc. Computing in Civil Engineering*, pages 242–249, 2011.

[2] N. Dervilis, M. Choi, I. Antoniadou, K.M. Farinholt, S. G. Taylor, R. J. Barthorpe, G. Park, C. R. Farrar, and K. Worden. Machine Learning Applications for a Wind Turbine Blade under Continuous Fatigue Loading. *Key Engineering Materials*, 588:166–174, 2011.

[3] A. S. Glassner. *An Introduction to Ray Tracing*. Morgan Kaufmann, 1989.

[4] J. L. Guiziou. 3D ray-tracing in anisotropic media. In *Stanford Exploration Project*, number 57, 1988.

[5] J. W. McKown and R. L. Hamilton Jr. Ray tracing as a design tool for radio networks. *Network, IEEE*, 5(6):27–30, 1991.

[6] W. K. Chiu W. H. Ong. Redirection of Lamb Waves for Structural Health Monitoring. *Smart Materials Research*, 2012.

[7] P. D. Wilcox. *Lamb wave inspection of large structures using permanently attached transducers*. PhD thesis, Imperial College London, 1998.

[8] C. Heinze. Reduction of Model Complexity in Aerospace Structures with the Help of Approximated Stiffeners. In *Proc. IWSHM*, pages 2496–2503, 2013.

[9] I. S. Dolinskaya and R. L. Smith. Fastest-Path Planning for Direction-Dependent Speed Functions. *Journal of Optimization Theory and Applications*, 158(2):480–497, 2013.

[10] C. Willberg, S. Koch, G. Mook, J. Pohl, and U. Gabbert. Continuous mode conversion of Lamb waves

in CFRP plates. *Smart Materials and Structures*, 21(7):075022, 2012.

[11] R. Hedl, J. Finda, and G. Parthasarathy. Optimization of PZT actuator/sensor array for monitoring of aircraft fuselage panel using ultrasonic Lamb waves. In *Proc. NDE for Safety / DEFEKTOSKOPIE*, 2010.

[12] D. Schmidt, M. Sinapius, and P. Wierach. Design of mode selective actuators for Lamb wave excitation in composite plates. *CEAS Aeronautical Journal*, 3, 2013.

[13] S. I. Rokhlin and L. Wang. Stable recursive algorithm for elastic wave propagation in layered anisotropic media: Stiffness matrix method. *The Journal of the Acoustical Society of America*, 112(3):822–834, 2002.

[14] D. Schmidt, H. Sadri, A. Szewieczek, M. Sinapius, P. Wierach, I. Siegert, and A. Wendemuth. Characterization of Lamb wave attenuation mechanisms. volume 8695, pages 869503–869503–8, 2013.

[15] B Chapuis, N. Terrien, and D. Royer. Modeling and experimental investigations of lamb waves focusing in anisotropic plates. *Journal of Physics: Conference Series*, 269(1):012020, 2011.