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Ultrasonic Wave Propagation in Aerospace Structures: Highly Efficient Simulation with a Minimal Model

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Abstract:

Continuous monitoring of the state of a structure could provide a great benefit for many aspects of maintenance, repair and overhaul (MRO) of aircraft and can be an enabler for condition based maintenance. One approach to realize structural health monitoring (SHM) is based on actuator-sensor networks to excite and receive ultrasonic waves. Signal changes indicate damage, but can also be used to identify the location and type of a defect. Simulations of wave propagation could be beneficial to support development and design of SHM systems. However, currently no suitable tools exist due to the size and complexity of aerospace structures in combination with the required high frequencies. An innovative simulation technique is proposed to provide approximate solutions at selected points of the structure with drastically reduced computational cost compared to established numerical methods. In this paper an overview of the approach including necessary pre-processing steps is given. This is followed by a validation of the minimal model with the help of numerical and experimental result. In a first step, wave propagation and interaction inside an aluminum plate is analyzed. Results of the proposed method are compared to calculations with the finite element method (FEM) and measurements with a laser vibrometer. Signals of all three methods agree very well and only a few minor deviations point toward some shortcomings of the minimal model in its current state. But at the same time, the huge performance advantage of the minimal model becomes apparent, as calculation are about three orders of magnitude faster as the FEM. To validate the minimal model on a more complex structure, experimental measurements on a plate consisting of carbon fiber reinforced polymer (CFRP) are used. Good agreement of the results can be observed, but discrepancies are present. This is due to the fact that modelling of composites is more challenging as they induce different anisotropy effects.

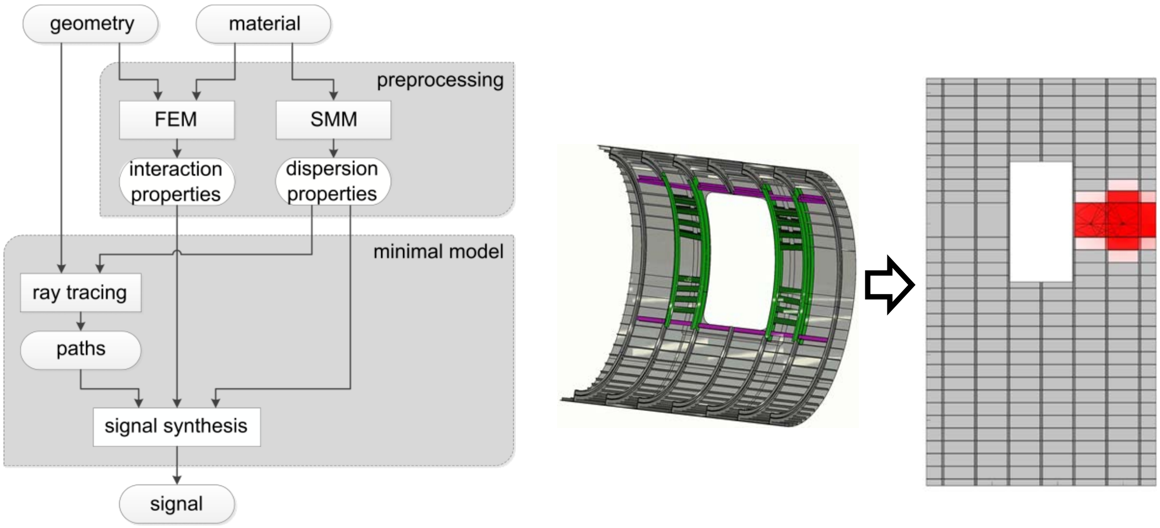
Keywords: composites, FEM, Lamb waves, model reduction, structural health monitoring (SHM)

Structural Health Monitoring

Currently, maintenance intervals in the aircraft industry are largely based on flight hours. A continuous monitoring of structures would allow a transition to condition based maintenance and reduce downtimes [1]. Different techniques to monitor aircraft structures are known, but Lamb wave based systems seem to be the most promising approach [2]. A sparse network of transducers to excite and receive ultrasonic waves is integrated into the structure. Signals change as waves interact with damage. The type and position of a defect can be determined by comparison with a reference of the intact structure. Environmental effects can also influence the wave propagation and need to be compensated for [3]. Structural health monitoring systems are not yet applied in aircraft, due to the complexity of the task and the requirements for the integration of new systems into aircraft. One obstacle for the development of such systems is the lack of tools to simulate wave propagation in larger structures. Established numerical methods are well suited to model specific effect in great detail, but miss the performance to cover larger areas. Among other things, this is caused by the small wavelengths and thus high frequencies required to detect damage, leading to an equally fine discretization in time and space. A large number of new simulation approaches have been proposed to solve this problem [4]. Nevertheless, simulation results for larger aircraft structures have not been published yet.

Minimal Model

Most specialized simulation techniques intend to increase performance without losing accuracy compared to established methods, like the FEM. However, high fidelity results are not required for every application. The proposed minimal model utilizes this to get approximate solutions with drastically reduced numerical effort. A flowchart of the minimal model and the necessary preprocessing steps are shown in Fig. 1(a). To minimize geometric complexity, the plate-like structure is approximated as a two-dimensional plane, as depicted in Fig. 1(b). This plane is composed of sections that represent homogeneous areas of different materials. Inhomogeneities, like stiffeners, are reduced to lines representing the positions of wave interaction. Preprocessing includes the calculation of phase velocities for each plate section with the stiffness matrix method (SMM) and interaction properties for all inhomogeneities [5]. These properties can be saved in a database and be reused for different structures that at least partly consist of identical materials and geometry. The 2D model uses ray tracing to find paths between an actuator and any position inside the structure. With the geometric information gained in this process a signal synthesis algorithm calculates wave packets for each path. The guided waves are approximated as plane waves that are affected by all crossed material, each inhomogeneity on the path and different attenuation effects [6]. The complete signal is generated by superimposing the individual wave packets. A more detailed description of the minimal model, parameters of models and experiments as well as first result are given in [7].

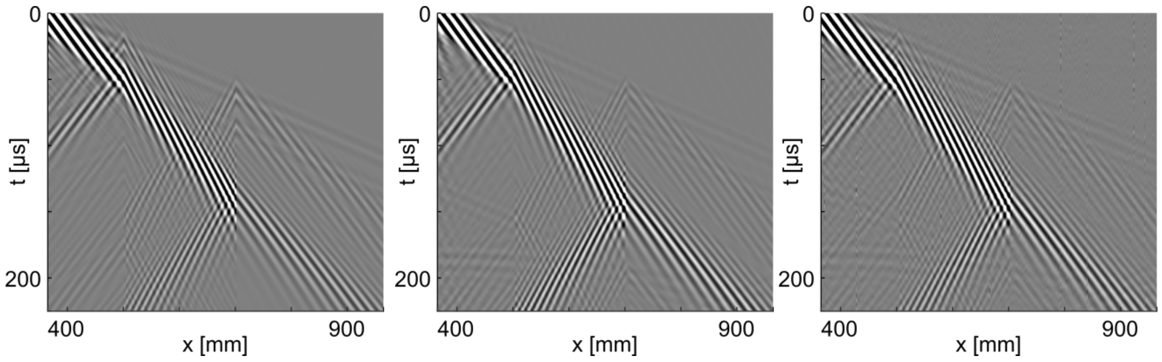


(a) flowchart (b) Transition to a 2D model

Fig. 1: Minimal model

Validation on an aluminum plate

The general functionality of the signal synthesis algorithm is checked by analyzing signals on an isotropic plate with geometrical simple inhomogeneities and comparing them to experimental and numerical results. The thickness of the aluminum plate is reduced from 4mm to 2mm in a 200mm long area starting at x=500mm. A laser vibrometer is used for non-contact measurement of the wave propagation [8]. Signals are obtained with all three methods along a straight line orthogonal to the inhomogeneities. These results are depicted in Fig. 2 as b-scans to visualize the change of the wave packets in time and space.



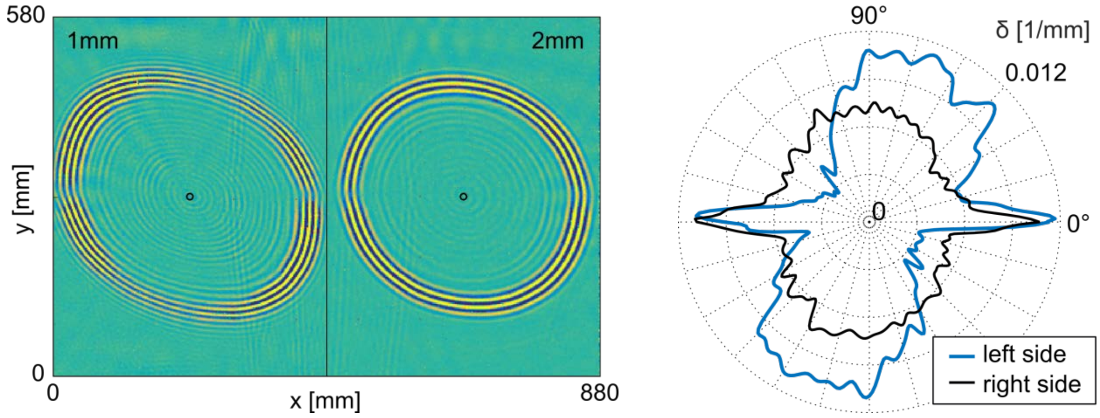
(a) Minimal model (b) FEM (c) Measurement

Fig. 2: B-scans of wave propagation in an aluminum plate

Very good agreement is apparent between all three variants. Minor discrepancies can be identified only at closer examination. While most interaction types are correctly predicted by the minimal model, amplitude and phase differ slightly in a few cases. This indicates that the calculation of interaction properties with the FEM should be replaced with a more reliable method. Currently there are no analytical approaches available to calculate the required properties for arbitrary inhomogeneities. It has however been announced that a suitable method is in development [9]. The results demonstrate the capability of the proposed method to simulate wave propagation with great efficiency, albeit the minor discrepancies.

Validation on a composite plate

Modelling of wave propagation on composites is much more challenging compared to metallic plates, as structural properties are mostly directional and additional effects occur. The most prominent properties that depend on the orientation of wave propagation are material damping and phase velocities. Both effects can be observed in the wave field of the analyzed quasi-isotropic CFRP plate in Fig. 3(a). The damping coefficients in Fig. 3(b) are extracted from such measurements and used for the minimal model. While work on the extension of the minimal model for anisotropic materials is still in progress, a first comparison of signals at different locations in Fig. 4 is promising. The time of flight is well predicted for individual wave packet and deviations a mostly related to the amplitude.

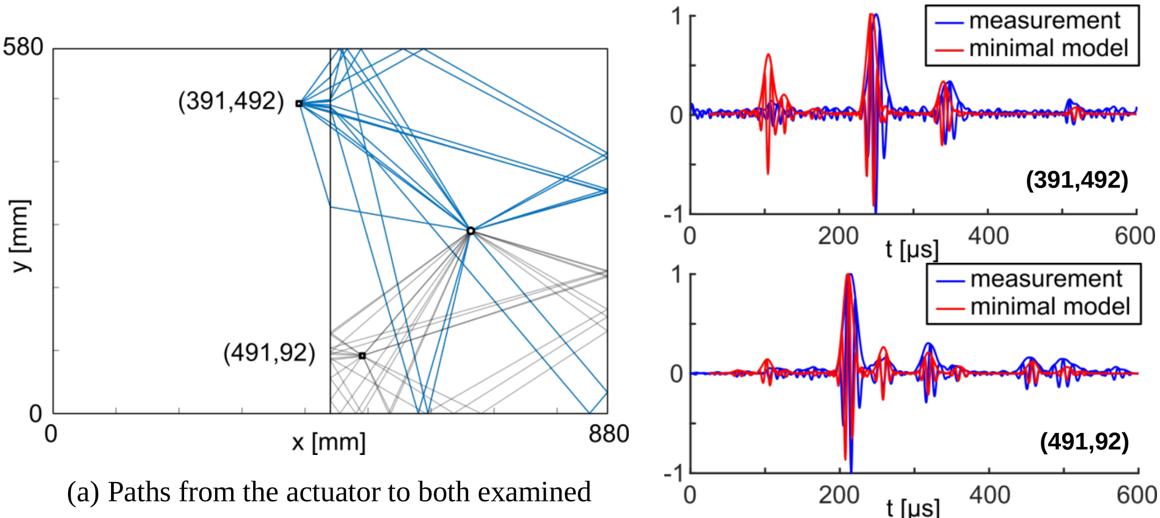


(a) Wave field (b) Damping coefficient

Fig. 3: Measured properties of the composite plate

Conclusion

A new analytical simulation approach to approximate wave propagation in large aerospace structures is proposed. This minimal model combines ray tracing and a signal synthesis algorithm to calculate signals at arbitrary positions. Results from the proposed method, FEM and measurements on an aluminum plate agree well, even though the analytical model requires three orders of magnitude less computation time compared to the FEM. On a composite plate measured and analytically calculated signals are compared at selected positions. While good agreement can be observed generally, deviations are visible. This will be tackled in the future development of the model. The efficiency of the minimal model could be utilized in optimization processes for sensor networks in SHM systems or the calculation of reference signals under varying environmental conditions.



(a) Paths from the actuator to both examined positions calculated with ray tracing

(c) Signals

Fig. 4: Signals after excitation with an actuator at the right side of the CFRP plate

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