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Short communication

Damage localization in composite structures with smoothly varying thickness based on the fundamental antisymmetric adiabatic wave mode

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ABSTRACT

This work is based on the experimental observation that the phase and group velocity of the fundamental antisymmetric wave mode in a composite structure with linearly varying thickness changes as it propagates along the nonuniform waveguide (Moll et al., 2015). This adiabatic wave motion leads to systematic damage localization errors of conventional algorithms because a constant wave velocity is assumed in the reconstruction process. This paper presents a generalized beamforming approach for composite structures with nonuniform cross section that eliminates this systematic error. Damage localization results will be presented and discussed in comparison to existing techniques.

1. Introduction

Modern technical structures in the aviation industry show a high degree of carbon fiber and fiberglass composites. In order to optimize material efficiency and to obtain an optimized weight the structural thickness changes locally according to the particular load case [2]. Structural health monitoring (SHM) of those components by means of guided waves is challenging, because the phase and group velocity changes not only with the product of frequency f and thickness d, but also with the direction of wave propagation θ.

When guided waves propagate in a waveguide with slowly varying cross section then they are called adiabatic wave modes, because they adapt to the slowly varying thickness of the structure [3,4]. Recently, it was found experimentally that the wave velocity of the antisymmetric wave mode changes in a glass-fiber reinforced structure with smoothly varying cross section [1]. Similar results for the second shear horizontal wave mode SH_2 can be found in [5]. These results are further supported by De Marchi et al. [6] who predicted the guided wave mode in irregular waveguides when the overall dispersive behavior is known.

In the literature, a variety of damage localization techniques for complex structures can be found. A first example is given by a damage localization algorithm for planar anisotropic structures in [7]. More recently, Haynes and Todd [8] presented a damage localization technique for complex structures that incorporates statistical modeling and sensor fusion. In addition, Harley and Moura [9] demonstrated a data driven matched field technique in which the wave propagation features are estimated from the sensor signals. An imaging technique based on multi-path in complex structures is proposed in [10]. Reflections from structural boundaries have been exploited for damage localization in order to reduce the number of transducer elements in [11]. The importance of including the dispersive properties of the ultrasonic waves in acoustic source localization techniques has been discussed, and an alternative technique that does not require the knowledge of the plate properties has been introduced in [12,13]. More details on recent developments in guided wave-based SHM systems are described in [14].

In contrast to existing damage localization techniques, this short communication presents a generalized beamforming formulation that takes the nonuniform nature of adiabatic wave motion into account. The theoretical background is proposed in Section 2, followed by the description of the simulation setup in Section 3 and a discussion of damage localization results in Section 4. Finally, conclusions are drawn at the end.

2. Theoretical background

Lets assume that each point of the structure can be described not only by its coordinates (x, y), but also with a velocity model $c(f, S(x, y, d, \theta))$ which is a function of frequency f and cross-section $S(x, y, d, \theta)$, cf. [6]. The latter term is a function of the

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coordinates (x, y), the local thickness of the structure d and, for anisotropic materials, a function of the direction of wave propagation θ. This leads in a composite structure with varying thickness to the case that the velocity model at one point is different to the velocity model at another point. The simple case of a homogeneous plate with constant thickness is included in this formulation as a special case.

Consequently, the time delay from the actuator i to the voxel P and from this voxel to the receiver j can be computed as

$$\tau_{iP} = \frac{\|\vec{x}_i - \vec{x}_P\|}{c(f, S(x,y,d,\theta))}, \quad \tau_{Pj} = \frac{\|\vec{x}_j - \vec{x}_P\|}{c(f, S(x,y,d,\theta))}. \tag{1}$$

The total time delay is $\tau_{ij}(x,y) = \tau_{iP} + \tau_{Pj}$. Unlike conventional beamforming techniques this method operates in the time rather than the distance domain, cf. [15]. Assuming a sensor network of N_A transducers that act in turn as emitters, the energy at the focal point (x, y) can be expressed as

$$I(x,y) = \int_0^{T_{win}} \left[\sum_{i=1}^{N_A-1} \sum_{j=i+1}^{N_A} y_{ij}(t - \tau_{ij}(x,y)) \right]^2 dt, \tag{2}$$

where the employed time window leads to a greater robustness against jitter and measurement noise [16], and is typically in the order of 10 µs. In this equation $y_{ij}(t)$ denotes the differential sensor signal, i.e. the sensor signal measured in the healthy state of the structure minus the sensor signal of the damaged structure.

3. Description of the setup

In this paper, a glass fiber reinforced structure of 1 m by 1 m is considered in which the thickness changes in twelve discrete steps from 0.695 mm to 4.132 mm. Each segment has an equidistant length of approximately 83 mm. The phase and group velocity are based on those values that have been used in a previous experimental study to predict the antisymmetric wave motion in a similar structure [1]. Fig. 1 shows the corresponding phase and group velocity wave curve at 50 kHz for different thicknesses. Besides the anisotropic properties of the wave field the phase and group velocity changes strongly with the thickness of the structure. These wave curves have been calculated by means of the well-known global matrix method for anisotropic multi-layered waveguides exploiting third order plate theory [17,18]. The material properties are listed in Table 1.

The simulation framework proposed elsewhere [19] uses Fourier domain techniques to propagate the ultrasound wave in the irregular waveguide by including the dispersion maps in the phase term. The scatterer is approximated as a point-target with idealized scattering properties. Here, nine piezoelectric transducers are placed randomly on the structure. Each transducer acts in turn as emitter and sends a toneburst signal with five cycles at a carrier frequency of 50 kHz. In total, this leads to $N_A(N_A - 1)/2 = 36$ receiver signals. The point-like damage in this example is located at (0.25 m, 0.36 m). It has been assumed that dispersion does not have a significant influence on the sensor signals as demonstrated in [1].

Table 1
Material properties of the GFRP material.

ρ (kg/m^3)	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23}	ν_{12}	ν_{13}	ν_{23}
1700	30.7	15.2	10.0	4	3.1	2.75	0.3	0.3	0.3

Each voxel of the discretized structure is defined by its coordinates and a velocity model that corresponds to the thickness of the structure. The implementation of the method uses a database of velocity models where each voxel has an identification number pointing to the respective velocity model. In order to determine the time delay associated with Eq. (1) the coordinates, and also the velocities, from the actuator to the voxel and from the voxel to the sensor must be interpolated by a straight line and the individual contributions added in an incremental way. In this work, a total number of 40 segments per each line is used that minimizes the errors in the incremental time delay calculation.

4. Results

Fig. 2 shows the localization result for the actual velocity model and the average velocity, respectively. It can be observed that the scatterer can be precisely located when the actual wave curve in the generalized beamforming algorithm is considered. As soon as the average velocity is used the localization accuracy degrades although the average velocity is the best guess that can be made for the conventional delay-and-sum beamforming technique. In this example the localization error for the latter case is about 84 mm.

For an in-depth analysis the individual contribution of the transducer pair P5–P7 is considered in Fig. 3. On the top left it can be observed that the image contribution crosses as expected the position of the scatterer. When the average velocity is assumed then the deviation from the actual sensor location is already significant as shown on the top right of Fig. 3. Taking the maximum as well as the minimum velocity leads also to a significant deviation from the actual position of the target. This underlines the importance to consider the actual adiabatic wave motion for an accurate solution of the damage localization problem in a structure with nonuniform cross section.

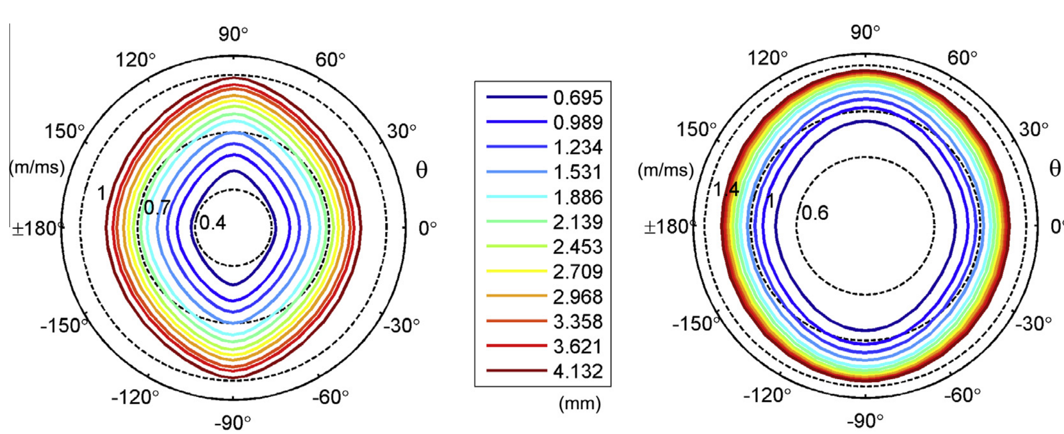

Fig. 1. Phase and group velocity wave curve of the A_0-mode at f_c = 50 kHz for different plate thickness; (left) phase velocity and (right) group velocity.