NONLINEAR ELASTIC WAVES
FOR EVALUATION OF COMPOSITE MATERIAL DETERIORATION

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1. Introduction

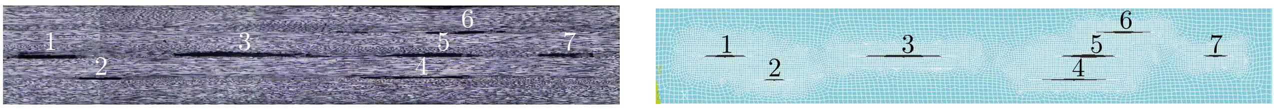
In composite structures cyclic loading leads to micro-structural damage even at an early lifetime stage and thus gives rise to the development of microscopic cracks in the matrix material and fiber/matrix interface debonding. In order to detect this micro-structural damage accurately new methods are currently under investigation. Guided waves, e.g. generated by piezoelectric devices, allow for the reliable detection of damage like delaminations [1]. However, the size of micro-structural damage is too small to cause noticeable effects in the wave propagation pattern like mode conversion.

However, methods based on nonlinear elastic waves are promising for the development of appropriate tools which enable the detection of micro-structural damage. These methods make use of the fact that a damaged structure behaves in a nonlinear way. So, a monofrequent structural excitation causes not only a wave at the respective frequency but also higher harmonics. However, their amplitudes are very small so that a cumulative effect has to be used which ensures growing amplitudes with increasing propagating distance and thus an accurate amplitude determination. To get a better insight into the physics behind this inspection method numerical simulations are essential beside experimental investigations.

This study deals with numerical investigations of a two-dimensional model of a plate in a plane strain state. The nonlinear structural behavior is included in two different ways. First, the micro-structural damage is modeled geometrically by breathing cracks of which the surfaces get into contact when a wave is running through. Subsequently, a novel nonlinear hyperelastic material model is applied which substitutes Murnaghan's five constant nonlinear elastic theory [2] and which accounts for the transverse isotropy. The computations show that both models lead to comparable results.

2. Nonlinear models and quantification of nonlinearity

The first model is based on a damaged plate structure. A single crack is investigated as well as a section with multiple cracks which is presented in Fig. 1(a). This microscopic picture shows 7 microcracks and is the basis for the respective finite element model in Fig. 1(b). Linear elastic transversely isotropic material behavior is assumed.



(a) Microscopic picture of the damaged specimen (b) Finite element model of the damaged specimen

Figure 1. Part of the specimen with 7 microcracks; length $15\,\mathrm{mm}$, thickness $2.3\,\mathrm{mm}$

The second model is built from a non-damaged plate structure with a nonlinear hyperelastic material model based on a strain energy function taking into account the fiber orientation as well as the compressibility of the material, see [3].

The extent of nonlinearity in the course of elastic wave propagation is defined by the relative acoustical nonlinearity parameter $\beta' = A_{hh}/A_{pri}^2$ and thus by the amplitudes of the higher harmonic wave and the square of the primary wave.

3. Analysis and results

First of all it should be noted, that the cumulative effect is only observed, if the conditions of a power flux are fulfilled and the phase velocity of the primary excited wave mode at ω and the higher harmonic wave mode at $n\omega$ coincide, see [4]. If the group velocities match also both wave modes do not separate and thus the higher harmonic wave does not extend over the covered propagation distance.

Investigations on a waveguide with a single crack show the generation of higher harmonic waves. The results show, that the relative acoustical nonlinearity parameter β' is sensitive to the crack length but not to the crack width. Further computations on a waveguide with multiple cracks, see Fig. 1(b), show, that the longest crack has the main impact on β' and that this parameter becomes not significantly larger due to further cracks.

Wave propagation in a non-damaged waveguide with a nonlinear hyperelastic material model also gives rise to higher harmonic waves. The bulk modulus K in the nonlinear term of the material model influences the amplitude of the second harmonic wave but does not affect its overall behavior along the propagation distance.

The computational results are in good agreement with experiments, in which the relative acoustical nonlinearity parameter β' was also determined. Additionally, the material deterioration was captured by careful determination of Young's modulus. The results indicate clearly a strong correlation between an increasing nonlinear acoustical parameter β' and a decreasing Young's modulus for the analyzed specimens.

4. Conclusions

In this study it is shown that a nonlinear hyperelastic material model allows to simulate the cumulative effect of higher harmonic guided waves. Regarding the wave propagation, the nonlinear material model leads to comparable effects than micro-structural cracks. It may be concluded, that micro-mechanically damaged material can be modeled by a nonlinear material model with appropriately adapted material parameters in case of wave propagation analysis. Furthermore, the relative acoustical nonlinearity parameter β' is appropriate for the evaluation of material degradation in composite structures.

5. References

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