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Numerical study of resonant frequencies in multi-material microstructures excited by ultrasonic vibrations

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Abstract

Surface structuring has become an important tool to adjust for instance optical, tribological or adhesive properties of surfaces. It is well known that materials, especially thermosets and elastomers, can change their mechanical properties compared to the bulk behaviour at certain length scales. Several concepts of microstructures exist, differing in shape, size, combination of materials and manufacturing approach for example. Taking into account the potential fields of application, it is of importance to develop non-destructive testing (NDT) and quality control concepts for e.g. reliability and safety considerations. However, conventional characterization techniques, such as nanoindentation are limited in their ability to evaluate superimposed properties resulting from a complex physical and mechanical assembly. Ultrasound is a well-known method to measure elastic constants. Furthermore the resonance frequencies induced by ultrasonic excitation and the velocity and attenuation of ultrasonic waves depend on the combination of geometrical dimensions as well as material properties. This allows correlating mechanical properties of microstructures with characteristics of ultrasonic waves. In this work, we focus on multi-material structures with a cylindrical shape known to modulate surface interaction. To define the ultrasonic requirements of an adequate NDT-system to assess the elastic properties of structures in the micrometer range, we theoretically studied the dependency of the material properties and different geometry concepts on the resonant frequencies. A systematic study of parameters including different wave types and frequencies based on numerical simulations will enable the effective design of experiments to validate the theoretical approach and open up a field of possible applications for ultrasonic characterisation of microstructures.

1. Introduction

The request for improvement today is as high as never before in all technological fields. On the one hand, costs, energy efficiency and environmental sustainability represent hard conditions and on the other hand fast innovation cycles and excessive consumption apply pressure to develop materials which combine technological, mechanical and chemical improvements. A lot of material scientists worldwide do research for example on optimized properties for adhesive surfaces[1–6] and their upscaling to industrial relevant dimensions.[7–9] But the more expenses and/or safety considerations are involved with such innovations, the more methods for quality assurance are needed just before market launch. Thus classical development in the field of non-destructive testing (ndt) does not provide the quick-response needed for these requirements. We assume that the extension of the ndt-measurement itself with a priori data, for example mechanical, material or geometry data, can result in fast solutions for quality assurance on a cost level of today's standard ndt-equipment.

In this study, we present a numerical approach to predict the variation in eigenfrequencies of complex microscopic multi-material structures. The design process of composite-microstructures results in optimized material combinations.[10–16] But even if the used materials in different microstructures are quantitatively the same in properties and ratio, the geometrical conditions can show broad variations, depending on the application the design is meant for. Therefore we choose an already often used pillar-shaped microstructure with three variants of geometrical composition, a flat-layer-composition [10], a curved-layer-composition [10] and a core-shell type [17], all build up on a backing layer of defined thickness.

We use the fact that a pillar of defined geometry provides eigenmodes depending on material properties and dimensions. With the analytical solutions for single-material pillars we created reference results. The numerical experiments are executed under the assumption that the ratio of material composition as well as the assembly of the materials in the pillar result in a significant change in the vibration behaviour of the microstructures. These changes are investigated for transversal excitation and the results are compared in the time domain as well as in the frequency domain. With this method changes in the vibration amplitudes and the changes in eigenmodes can be investigated.

The data obtained in this study allows to define requirements for inspection systems which are able to recognize small changes in the properties of microstructures produced on large scales.

2. Methods

Numerical simulations were performed using Comsol Multiphysics 5.0 together with Matlab and Simulink to test a large parameter space. The study was restricted to four multi-material microstructure variations as shown in Figure 1: reference single material cylindrical pillars, composite microstructure with flat and curved interface based on Fischer et al.[10] and core-shell microstructure based on Bae et al.[17]. Two-dimensional models were constructed in Comsol and parametrized as shown in Figure 1 to enable a systematic variation of material (E_1/E_2) and geometrical parameters (h_{tip}/h_{stem}) while containing the overall shape of the microstructures ($d_{pillar} =$

$d_{shell} = 60\ \mu m, h_{pillar} = 3 * d_{pillar}; h_{back} = 2 * h_{pillar})$. The materials were assigned ideally elastic material properties with variable Young's modulus, E_1 and E_2, Poisson's ratio of $\nu = 0.49$ and density of $\rho = 970\ \text{kg/m}^3$.

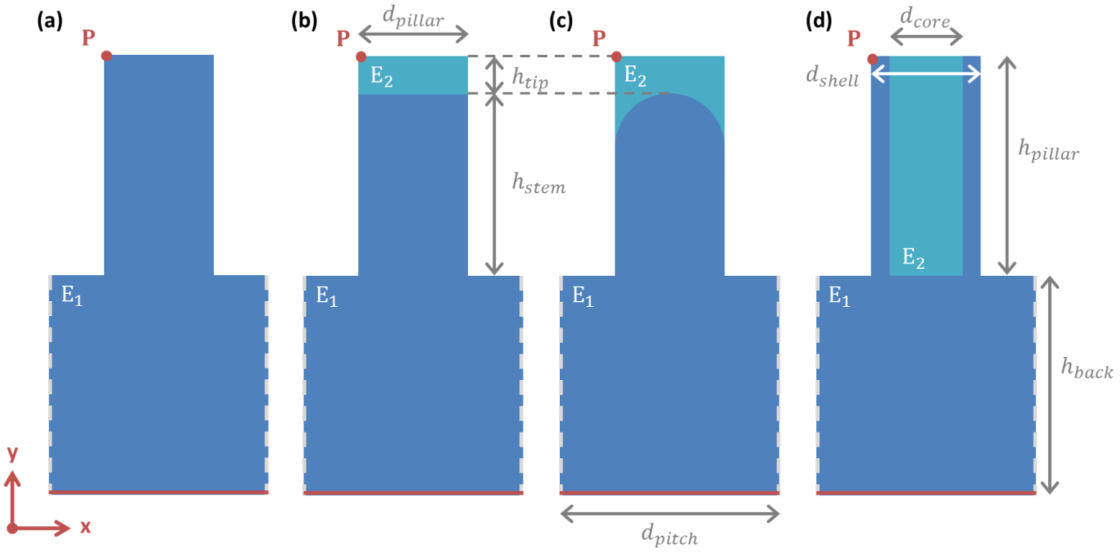

Figure 1: Three multi-material structures and reference structure. (a) Reference microstructure, composite microstructure with (b) flat and (c) curved interface based on Fischer et al.[10] **and (d) core-shell microstructure based on Bae et al.**[17]

A prescribed movement was applied below the backing layer as a function of time, t , and frequency, f, and a constant amplitude of A= 0.1 µm. Our study was restricted to two different excitations, transversal waves, with displacements of:

$$u_x = A \cdot \sin(t \cdot f \cdot 2\pi)\,;\ u_y = 0\,,$$

or longitudinal waves, with displacements of:

$$u_x = 0;\ u_y = A \cdot \sin(t \cdot f \cdot 2\pi)\,,$$

associated with a frequency sweep. This paper focusses on transversal excitation and results from simulations with longitudinal excitation are not shown. In each simulation, 50 excitation cycles were simulated with 20 time points in each cycle.

3. Results

In the following paragraphs, reference simulations will be presented, analysing the displacement at top of the pillars in the time and frequency space. Thereafter, simulations of multi-material composite structures with varying geometrical and material parameters will be described.

3.1 Study of single-material reference pillars: Displacement on top of pillar

First, simulations were performed on pristine reference pillars to analyze the displacement induced by a shear wave at the bottom of the backing layer. Results are exemplarily shown for an excitation frequency of 51 kHz and pillars with elastic modulus of 1, 10 100 and 1000 MPa in Figure 2. The oscillation of point P on top of the pillar is delayed compared to the subscribed excitation due to the computation and the delay time decreased with increasing elastic modulus. In fact, at E=1000 MPa, the excitation wave and displacement on top of pillar show higher harmonics of the excitation frequency. At lower elastic modulus phase shifts are obvious and also frequency shifts occur.

For smaller elastic modulus, displacement on top of pillars additionally varies from excitation in terms of amplitude and also shape, as not only one frequency appears, but several seem to overlap. This could result from resonances induced and overlapping of influence from backing layer and pillar structure. This is a valuable result as it can be used to distinguish different pillar properties.

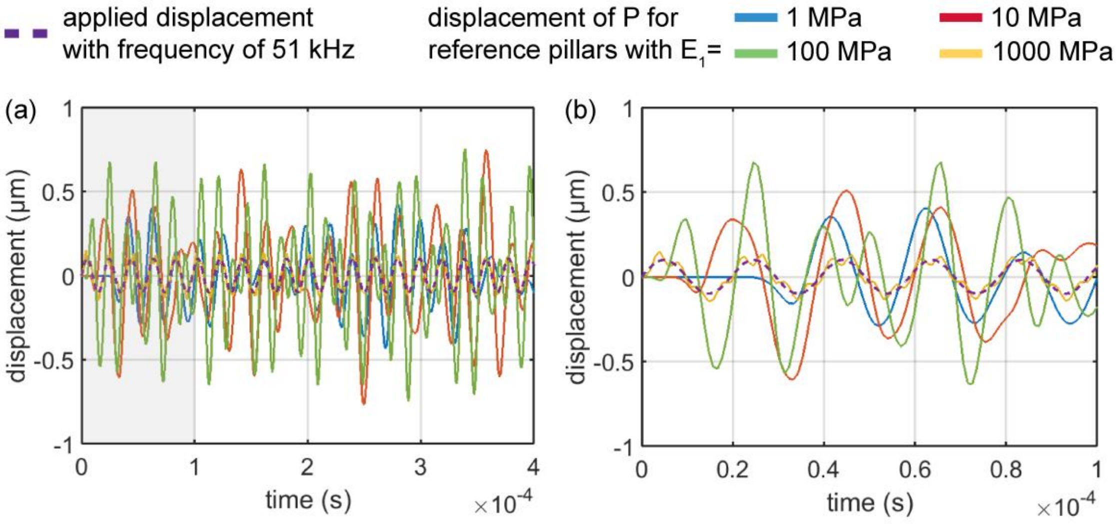

Figure 2: Displacement at the top of reference pillar induced by 51 kHz shear wave.

3.2 Study of single-material reference pillars: Fourier Analysis of the displacement of pillar top

To study the observed complex waves in more detail, it is possible to further analyze the signal of the displacement of point P on pillar top by Fourier transformation to understand the contributions of waves with different frequencies to the resulting vibration. This is exemplarily shown for four different excitation frequencies (1kHz, 101 kHz, 251 kHz, 851 kHz) and three different elastic moduli (1, 10 MPa, 1000 MPa) in Figure 3. As expected, different excitation frequencies cause different frequency-answers of the material depending on the elastic properties. The previous shown behavior in the time domain can be analyzed by their fractions of additional frequencies occurring under constant excitation. In a first step these results allow to qualitatively compare the structures and the influence of changes in the proportions of elastic constants and volume fractions.

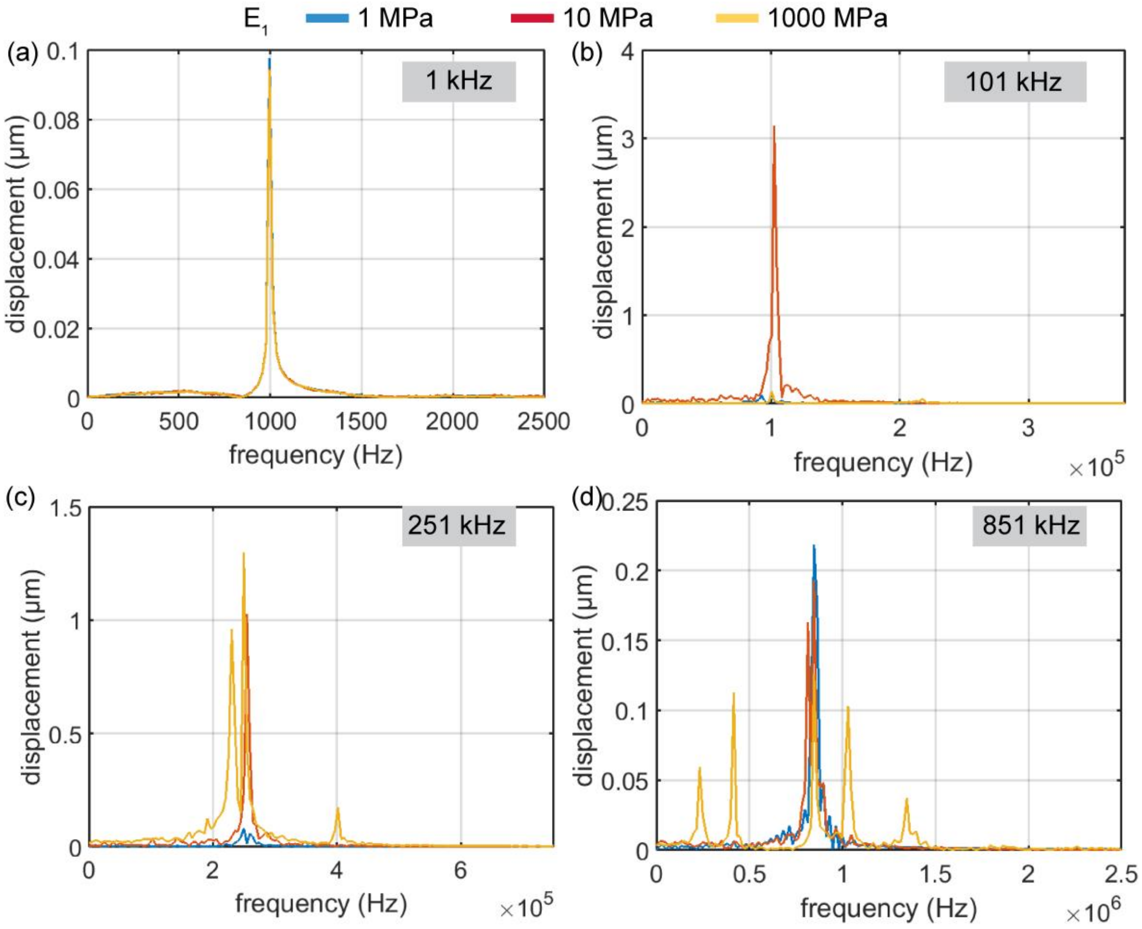

Figure 3: Fourier transformation of the displacements of point P for different combinations of frequency and elastic modulus. (a) 1kHz, (b) 101 kHz, (c) 251 kHz and (d) 851 kHz.

3.3 Comparison of max. displacement at top of pillar for different pillar geometries

To reduce the complexity of the analysis when introducing different multi-material pillar geometries, we first concentrated on the maximum displacement of the point P, knowing that this is a strong simplification compared to the Fourier analysis. In the following, the maximum amplitude of the point P is shown over an excitation frequency range of 1kHz to 900kHz for two different soft material thicknesses, 20% and 80%, of structures with an elastic modulus ratio of 100 as well as the respective reference structures with 1 MPa and 100 MPa.

The composite structures with a layer design show vibration amplitudes very similar to the stiffer reference material with higher values than the refernce. But the amplitudes change depending on the ratio of tip thickness to pillar height. Here it is to mention that with a curved interface the amplitude is higher at low ratio whereas for flat interfaces the higher ration leads to more tip amplitude. Possible explanations could be found in the Fourier-spectrum of the samples.

The results for the similar material combinations as core-shell structures show mostly low amplitudes comparable to the soft reference. There seem to be characteristic frequencies and at these frequencies there is no significant difference visible caused by the different height ratios.

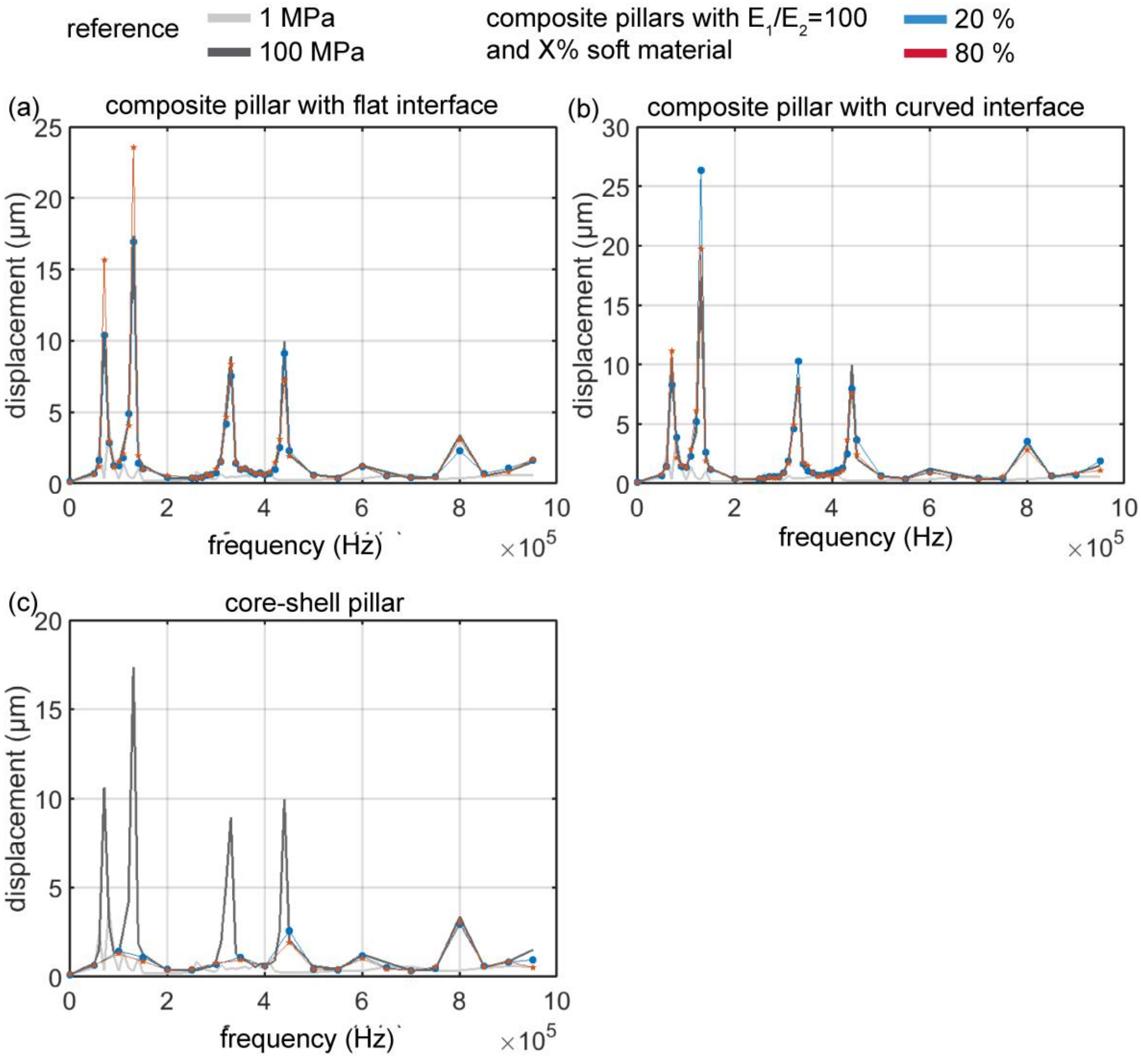

Figure 4: Comparison of maximum displacement at top of pillar for different pillar geometries: (a) composite pillar with flat interface, (b) composite pillar with curved interface and (c) core-shell pillar.

4. Discussion

The vibrations show that changing the microstructure properties strongly affects the vibration behaviour, but also results in very complex data output. Fourier transformation is a good mean to generate quantitative output and provide another comparison between different geometries. In general, the large number of variables make quantitative interpretation difficult because the changes in time and in the frequency domain are not yet connected theoretically.

But it can be observed that for microstructures from layer-type the transversal excitation of the backinglayer seems to have more influence on the results than for core-shell structures. In any case different materials compositions lead to different amplitudes in the frequency domain and can be an indicator for geometrical quality of the structures.

In the future, more accurate material models will be necessary to include damping and more accurately capture the microstructure behaviour. In addition to numerical simulations, an experimental setup to measure the microstructure vibrations will be very important in order to verify the numerical models and determine whether this might be a good method to characterize non-destructively multi-material microstructures and facilitate their manufacturing and quality control on large scale in the future.

5. Conclusions

In this study, we showed a preliminary numerical experiment evaluating vibrations of microstructures with a wide property parameter space. The aim was to find ways to non-destructively assess the properties of multi-material microstructures as otherwise physical insufficient or destructive testing would be necessary, which gives only very local information and is very time consuming.

The results give a clear hint of what type the ndt-methods have to be. With one type of measurement which provides integral results over a certain area as well as overall influencing parameters, the knowledge and processing of boundary conditions and existing a-priori-information has to increase significantly. For these types of problems a detailed physical description of all influencing parameters is almost impossible. But with intelligent data pre- and postprocessing algorithms assisted by very detailed parameter-variation-studies, calculated in real-time or provided through databases, we can approach development of non-destructive testing systems keeping pace with material and technological innovation.

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