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MEMS Vibrometer: Micro Modal Analysis

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Summary:

Automated structural health monitoring of modern fiber metal laminates requires the integration of ultrasound sensors into the inner layers of the laminate to be monitored. One requirement for structure-integrated sensors is therefore that they have a minimal effect on ultrasound propagation. MEMS are suitable as ultrasonic transducers due to their size in the sub-wavelength range of ultrasound and due to their typical materials. MEMS-based acceleration sensors are the most commonly manufactured MEMS sensors and are used for structural monitoring in the construction industry, among other applications. In principle, inertial sensors integrated into lightweight structures are also suitable for measuring local acceleration due to ultrasonic waves passing through them. In practice, however, there are no MEMS acceleration sensors for the ultrasonic frequency range. The reason for this is that the bandwidth of inertial acceleration sensors is inversely proportional to their sensitivity to the acceleration acting on them. The resonance frequency of the internal spring-mass system is decisive for the bandwidth. Its signal is only proportional to acceleration in the quasi-static frequency range ($\omega \ll \omega 0$). Inertial seismometers do not differ in their basic physical design from inertial acceleration sensors. In the quasi-free frequency range ($\omega \gg \omega 0$), they show an output signal proportional to the displacement of the sensor. The modal analysis of the oscillator system is fundamental to model the transfer behavior correctly. The results of the micro modal analysis are presented in this paper. Based on these, the dynamic behavior of the sensor is derived and discussed with reference to its application.

Keywords: MEMS vibrometer, inertial sensor, structural health monitoring, guided ultrasonic waves,

Background and Motivation

For structural health monitoring (SHM) of lightweight structures, guided ultrasonic waves (GUW) and their reflections on impedance discontinuities are used to identify defects, such as cracks and delaminations [1]. Traditionally, surface applied piezoelectric transducers serve as pickups for propagating GUW [2]. For novel fiber metal laminates, especially the observation of the materials inner layers is crucial as it is topic to current research. Mainly the large size and their ceramic body of piezoelectric transducers impede their integrability into FML. Therefore, an alternative sensor concept is needed.

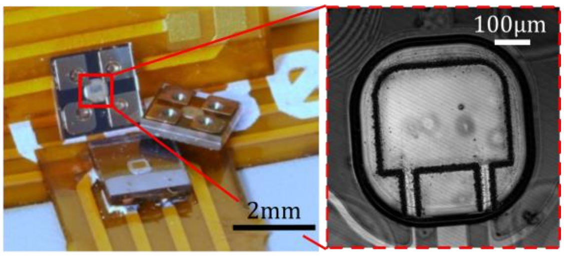

Fig. 1. 3 MEMS vibrometers partly soldered onto polyimide PCB. The microscope image exposes the silicon core resonator.

Motivated by their superior integrability due to small size and acoustically adapted materials, such as glass, novel inertial MEMS (micro electro mechanical system) vibrometers were recently utilized to measure GUW at the inner layers of fiber metal laminates (FML) [3].

Working Principle of the MEMS Vibrometer

The MEMS vibrometer is unique in terms of its transfer behavior. While near all inertial sensors operate as accelerometers or gyroscopes in their quasi-static frequency regime, the MEMS vibrometer operates at frequencies above its core resonator's first eigenfrequency, making the sensor directly sensitive to displacement. Its working principle is similar to that of a seismometer. Due to its continuous nature, however, the oscillator has infinite eigenfrequencies with associated eigenmodes. In order to transduce displacement resulting from narrow band ultrasonic bursts (such as GUW) into an electrical signal, the resonator must have a high mechanical impedance for vibrations in the spectrum of the GUW. The causal chain is presented in the course of this paper.

FEM based Modal Analysis

For dynamic characterization of the resonator, simulations have been carried out by finite element method (FEM). Using ANSYS software, the eigenmodes of the resonator and the associated eigenfrequencies can be identified. Based on the results, the transfer behavior of the MEMS vibrometer can be modeled and evaluated.

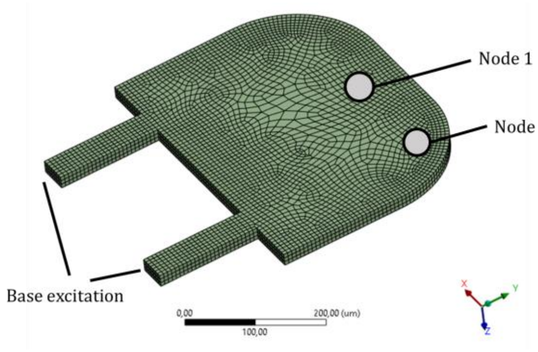

Fig. 2. Resonator model with mesh for FEM analysis

Results and Interpretation

Figure 3 illustrates the results of the local displacement response for Node 1 and Node 2 when excited by a linear frequency sweep. From low to high frequencies, the plot shows the first bending mode at 60 kHz, the first torsional mode (magnification) at 220 kHz and the second bending mode at 556 kHz. In the 100±30 kHz band, which represents the center frequency of GUW typically used for SHM (cf. Figure 5, “Input”) the gain has a negative slope but is relatively consistent. Note, that the amplitude of the first torsional mode is small due to perfectly in-phase excitement in out-of-plane direction, which in theory cannot excite the torsional mode.

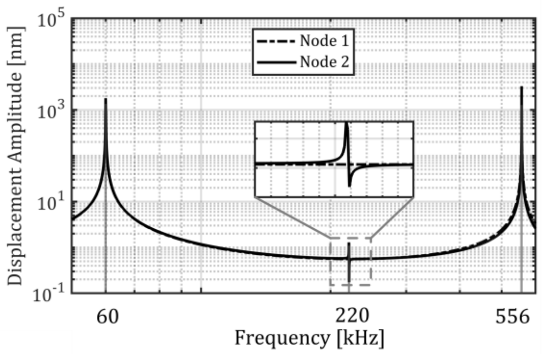

Fig. 3. Local vibration analysis results for Node 1 and Node 2 (cf. Figure 2) exposing the first three eigenmodes of the resonator.

From the phase and amplitude information for every node, the eigenmodes of the resonator can be visualized for a better understanding. Figure 4 presents the resulting mode shapes.

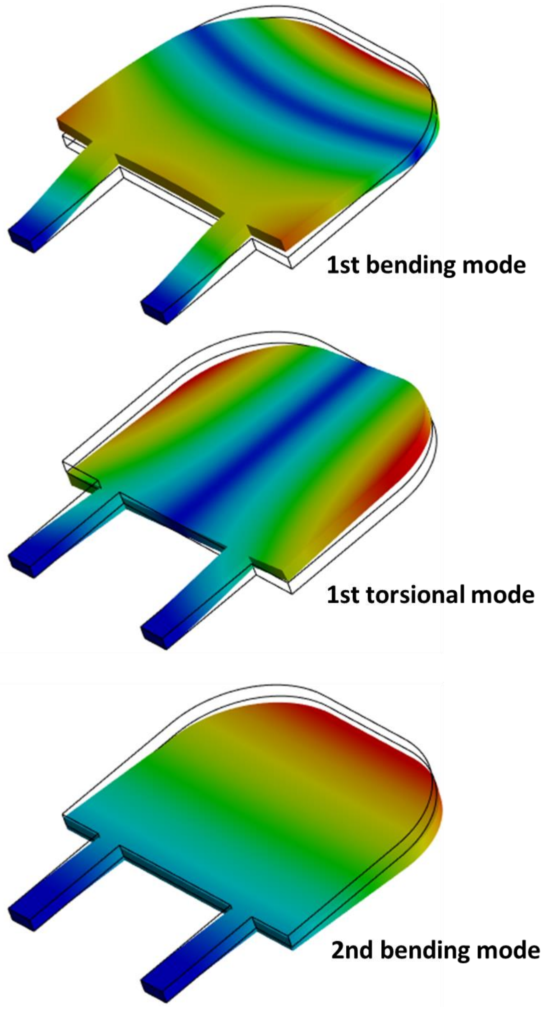

Fig. 4. Mode shapes of the resonator for the first three eigenmodes.

When exposed to transient excitation, resembling the displacement profile of a passing GUW, the transfer function of the MEMS vibrometer can be derived. The stress at the resonators cantilever edge qualitatively represents the output of the piezoresistive sensor. With some distortion, this output follows the stimulus, generally confirming the functionality of the MEMS vibrometer. The distortion stems from the not perfectly homogenous gain in the bandwidth of the GUW. Lower frequency components are amplified stronger than higher frequency components. This becomes especially visible in the frequency plot, virtually shifting the spectrum to lower frequencies.

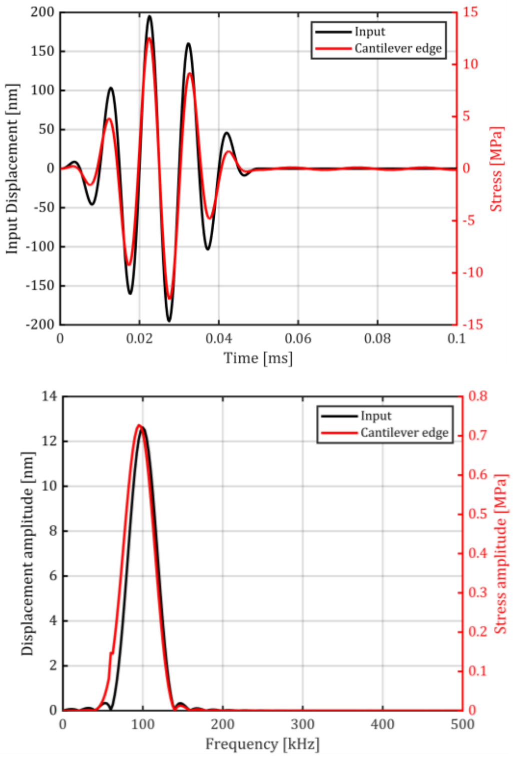

Fig. 5. Transfer behavior of the resonator exposed to GUW-like transient excitation in time and frequency representation.

References

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