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Proceeding Paper

Micro Oscillator as Integrable Sensor for Structure-Borne Ultrasound †

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Abstract: Motivated by their functional conformity due to the small size and acoustic properties of the materials used, micro-cantilever based MEMS oscillators are investigated as structure-integrable ultrasonic transducers for their use in SHM of fiber-metal laminates. In contrast to conventional acceleration sensors, the presented oscillators are operated *quasi-free*, at frequencies above the first harmonic mode. Proof for this unconventional microsensor concept, which has not been demonstrated before, is provided by the dynamic sensor response characteristic on a test rig with structure-borne ultrasound. The sensor's response is discussed with regard to its usability for SHM.

Keywords: Structural Health Monitoring (SHM); Fiber Metal Laminates (FML); MEMS oscillator; ultrasound transducer; forced quasi-free oscillation; structure-integration; acoustic impedance matching; functional compliance

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1. Introduction

For Structural Health Monitoring (SHM) of composite materials such as Carbon Fiber Reinforced Plastic (CFRP), the propagation of Guided Ultrasonic Waves (GUW) can be monitored using a network of surface mounted piezoelectric transducers recording the local displacements as function of time [1]. Any defects, as cracks or delaminations in the monitored structure result in a local change of the acoustic impedance, which causes reflections and mode-conversion of the acoustic signal, finally resulting in a change of the acoustic footprint in the sensor recordings. From this digital footprint, damages can be localized, quantified and classified.

Modern aircraft use Fiber Metal Laminates (FML), e.g., GLARE (Glass Laminate Aluminum Reinforced Epoxy) as construction material, as they combine the favorable ductile properties of metals with the high tensile strength of composite materials [2]. A further benefit of FML is that material degradation occurs as a steady process, so that the material's condition can be monitored and quantified until service is required.

Elastic waves in plates propagate in form of GUW. They are characterized by velocity dispersion, which describes the dependence of the phase velocity from the signal frequency, and the material's elasticity and density. Lamb waves occur in symmetric modes and antisymmetric modes of increasing order.

In contrast to homogenous materials such as metals or CFRP, the high difference in acoustic impedance between the layers of FML, e.g., glass fiber and aluminum layers for

GLARE, is expected to have an impact on the wave propagation [2]. For further investigations, the wave propagation within the FML's inner layers needs to be monitored and investigated for damage detection.

Therefore, SHM of FML requires embedded sensors, which should minimally interfere with the propagating waves. The typical ceramic piezoelectric transducers are inappropriate because their typical dimensions are large and since the material is poorly adapted to the acoustic impedance of the surrounding material. Suitable sensors should therefore be made of materials with better-matched acoustic impedance. Sensors, which are smaller than the wavelength of the propagating ultrasound waves should even less interfere [3].

2. Micro Oscillator Concept

The acoustic impedance for GUW is calculated as follows: $\boldsymbol{Z_f = \rho \cdot c_g}$ with the density $\boldsymbol{\rho}$ and the group velocity $\boldsymbol{c_g}$. Investigations for a frequency-thickness product of 48 kHz mm show that the acoustic impedance of typical MEMS materials such as silicon ($\boldsymbol{Z_f = 20.2 \cdot 10^6\, kg \cdot m^{-2} \cdot s^{-1}}$) or borosilicate glass ($\boldsymbol{Z_f = 11.8 \cdot 10^6\, kg \cdot m^{-2} \cdot s^{-1}}$) is much better adapted to glass fiber laminate ($\boldsymbol{Z_f = 10.1 \cdot 10^6\, kg \cdot m^{-2} \cdot s^{-1}}$) than typical piezo ceramics, e.g., PZT ($\boldsymbol{Z_f = 35.8 \cdot 10^6\, kg \cdot m^{-2} \cdot s^{-1}}$). Further, the shape and size of MEMS devices can be adapted. A micromechanical oscillator consists of a spring-loaded mass that, when subjected to a force by an external acceleration, displaces relative to its frame. The displacement can be transduced (typically by capacitive or piezoresistive schemes) into an electrical sensor signal [5]. Considering the dynamics of a spring-loaded mass, a second-order model must be used to calculate the complex amplitude. The real part of this complex quantity is given in Figure 1, where a weakly damped system is assumed as an example. As long as the excitation frequency is well below the resonance frequency, a *quasi-static* response with a signal amplitude proportional to the acceleration amplitude is obtained. A forced *quasi-free* oscillation is obtained if the excitation frequency is far above the resonance of the spring-mass system, as it is known for a seismograph. In this regime, the sensor signal only weakly depends on the acceleration amplitude, making it unsuitable for acceleration sensing applications. If however instead of acceleration the displacement of the sensor frame is considered, a strong and practically frequency-independent relation is obtained. For this reason, structure-borne ultrasound can be picked up as a *quasi-free* oscillation of a micro-cantilever or of other MEMS accelerometers.

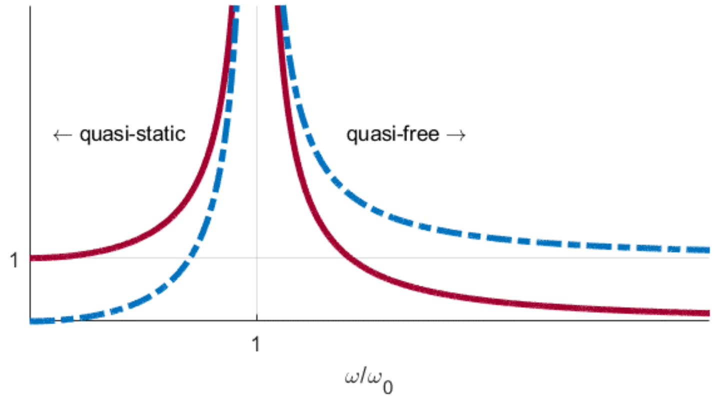

Figure 1. Signal amplitude of a generic mass-spring oscillator, divided by constant external acceleration amplitude (red) compared to signal amplitude divided by constant external displacement amplitude. Amplitude ratios are given in arbitrary units.

3. Materials and Methods

3.1. Sensor Manufacturing

For the proof of the *quasi-free* oscillation concept for structure borne ultrasound recording, a recently developed structure-integrable pressure sensor [6] was modified to form a micro cantilever oscillator. The unsupported silicon membrane of the pressure sensor is released from three sides, using femtosecond laser micro machining. This yields a single crystalline micro-cantilever with piezoresistive read-out with a well-defined spring constant, which is presented in Figure 2. The signal for cantilever displacement is read out through a quarter-bridge circuit, which consist of piezoresistive paths defined by local boron doping. Four pads on the sensor's bottom side provide the terminals of the circuitry allowing flip-chip bonding to a PCB substrate by soldering.

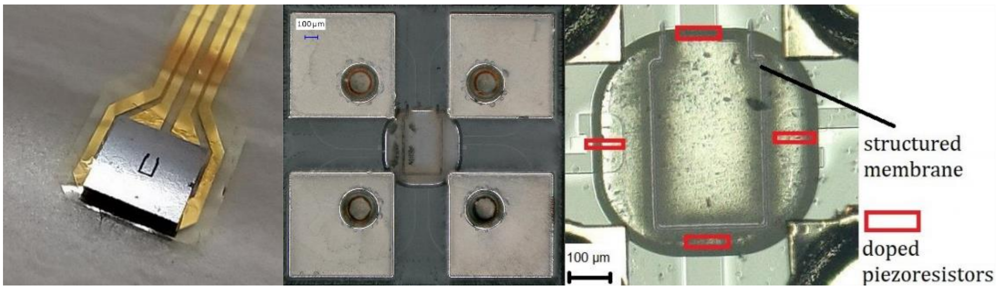

Figure 2. Photography of the micro-cantilever sensor mounted onto polyimide substrate (**left**). Microscopic bottom-view of the sensor, showing the position of the micro cantilever in relation to the glass-cavity (**middle**) and the marked positions of the piezoresistors (**right**).

3.2. Test Setup

To generate an environment for ultrasonic excitation and recording, a test bed as illustrated in Figure 3 is used. For ultrasound excitation, a piezoelectric transducer is soldered onto a FR4 PCB substrate, which is adhesively bonded to a metal plate as a socket. The micro cantilever chip is flip-chip bonded (soldered) onto a thin polyimide PCB for signal transport. This PCB is then bonded to the piezoelectric ultrasound source driven by a signal generator using a thin layer of superglue. The sensor's Wheatstone circuit is evaluated using a high-frequency bridge amplifier (DEWETRON, DAQP-BRIDGE-B) without filtering and the amplification set to *10x*. The amplifier's output is recorded using one channel of a digital oscilloscope, while the excitation signal is simultaneously recorded on the second channel.

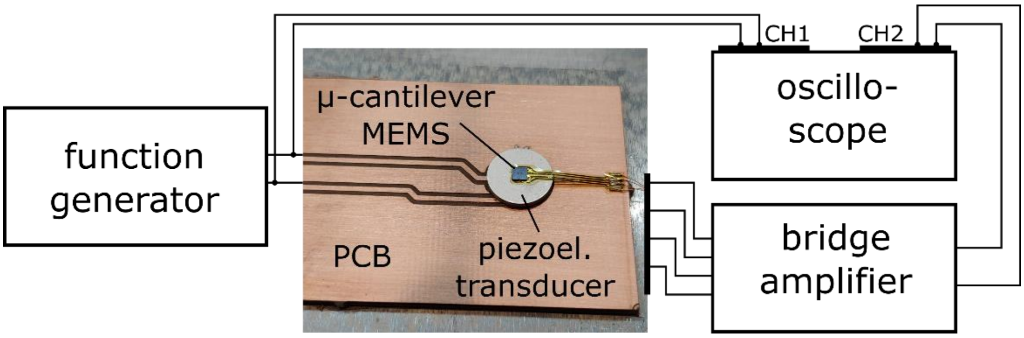

Figure 3. Test setup with piezoelectric excitement and MEMS µ-cantilever sensor.

4. Results

Bursts of eight sine waves with an amplitude of 10 V_{pp} and different frequencies are used for the out-of-plane excitation.

First, the frequency is set to 42 kHz, the first bending mode resonance frequency of the micro cantilever. The transfer behavior is presented in Figure 4. In resonance, more energy is transferred into the oscillatory system than is dissipated by damping. The stored energy accumulates and the cantilever's deflection amplitude increases with each excitation cycle. In resonance, the structure-borne ultrasound waveform cannot be reconstructed easily.

Next, a frequency is chosen, which lies between the first (≈42 kHz) and second (≈280 kHz) bending mode resonance frequency of the micro cantilever. Figure 5 shows the time response of the cantilever to a burst of 100 kHz. The obtained signal waveform is, after a short transient, proportional to that of the ultrasound.

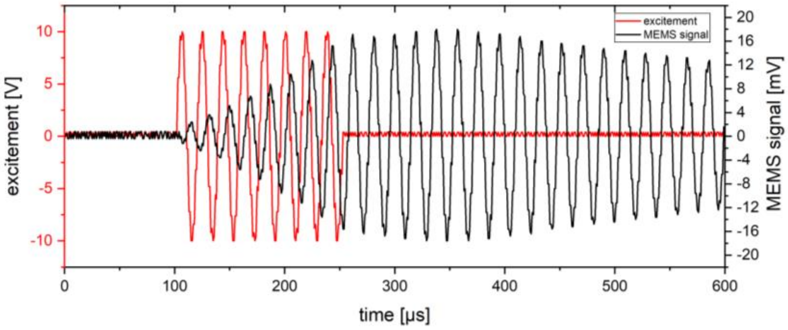

Figure 4. Transient response of the µ-cantilever sensor (black), excited with a resonance-near 42 kHz eight-period sine burst (red).

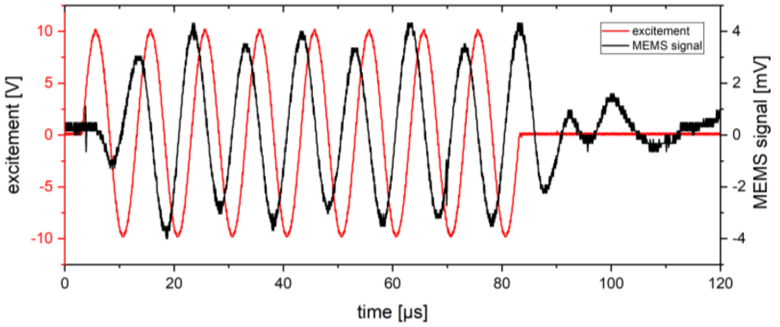

Figure 5. Transient signal response of the µ-cantilever sensor (black), excited with a 100 kHz eight-period sine burst (red).

At frequencies below the first bending mode (resonance) frequency, the local periodic displacement is not sufficient to be extracted from the sensor signal.

5. Discussion and Outlook

The presented experiment could already prove the concept of structure-borne ultrasound recording using a MEMS oscillator in quasi-free excitation. The obtained sensor signal is almost proportional to the waveform of structure borne ultrasound excitation. However, the sensor signal contains small non-linear contributions, which probably are a result of the cantilever-harmonic modes, which are weakly excited by the signal's bandwidth.

In further investigations, the presented quasi-free sensor concept will be investigated in depth. Tailored sensors will improve the sensitivity and adjust the sensor's inherent dynamics. An anodically bonded sensor lid will allow for material integration and would additionally provide a possibility for damping adaption by adjustment of the enclosed atmosphere. Moreover, an ultrasonic test setup will be designed to allow experiments with mode selective excitation of the sensors.

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