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Simple method for quality factor estimation in resonating MEMS structures

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Abstract. The quality factor of a packaged MEMS resonating structure depends on both the packaging pressure and the structure's proximity to the walls. This type of mechanical constraints, which causes energy dissipation from the structure to the surrounding air, are applicable for oscillating energy harvesters and should be considered in the design process. However, the modelling of energy losses or the measurements of their direct influence inside a packaged chip is not trivial. In this paper, a simple experimental method to quantify the energy loss in an oscillating MEMS structures due to the surrounding air is described together with preliminary results. The main advantage of the method is the ability to characterize the damping contributions under different vacuum and packaging conditions without requiring any packaging of the harvester chip or fabrication of multiple devices with different cavity depths.

1. Introduction

Usually microelectromechanical system (MEMS) resonating structures need to be packaged for protection from external influences, as well as for reliability since it prevents the fabricated structures from excessive displacements. However, the package introduces additional parasitic damping mechanisms and thus energy losses, such as viscous drag losses (packaging pressure) and squeeze film damping (proximity to the walls). These effects must be considered in the design process when resonating structures are manufactured [1,2]. Usually, for the experimental characterization of these damping effects, extra processing steps are needed that can be of high complexity (hermetic packaging, various cavity depth, electrical connections, etc.) [1], be time consuming, and require optically transparent packaging for characterization of the mechanical behavior in addition to the electrical properties.

In this paper, a simple experimental method to quantify the energy loss of oscillating MEMS structures due to the surrounding air, without requiring any packaging or complex microtechnology fabrication is described together with preliminary results.

2. Experimental characterization

This section describes the experimental techniques that allows characterization of the Q-factor and thereby the energy loss of oscillating MEMS structures due to packaging.

2.1. Measurement setup

A laser Doppler vibrometer (LDV) measures the velocity of a moving object by measuring the frequency shift in the reflected light via interferometry leading to very accurate velocity measurements. The LDV used has a special objective that allows measurements of MEMS structures.

The motion is excited by a shaker which is driven by the LDV (Polytec Inc.) internal signal generator and an amplifier. The fact that the shaker excitation is phase locked to the detection implies that phase sensitive measurements can be carried out, showing how different parts of the structure moves relative to each other.

As the damping is typically dominated by viscous effects [2], it is essential to control the pressure during measurements as this allows the necessary sealing pressure for the MEMS component to be determined. This has been achieved by placing both the small-size shaker (The Modal Shop, Inc.) and the sample in a vacuum chamber (Figure 1). The air is evacuated using two pumps; a mechanical pump for pressures down to about 10 mbar, and a turbo pump for pressures down to about 10^{-5} mbar. Such low pressures are not possible to obtain in a sealed device but this allows the damping to reach the intrinsic damping regime and indicates the level of the internal damping mechanisms in the device.

For measurements of the squeeze film damping effect on the Q-factor, a distance structure is manufactured by fine mechanics (Figure 2). This squeeze-film structure can be easily attached to the sample holder to obtain a selected gap size to the oscillating structure.

2.2. MEMS sample

The measured MEMS structures are silicon cantilevers and meanders, as shown in Figure 3, with proof mass to decrease the resonance frequency as we target low-frequency energy harvesting. The MEMS structures are manufactured on SOI wafers with a 400 µm thick handle and a 15 µm thick device layer. On the device layer, a 2 µm SiO_2 is grown and a bottom electrode is deposited, on top of which the sol-gel PZT is spun. The PZT and the bottom electrode are patterned by wet and dry etch, respectively. The top electrode is sputtered TiW/Au layers and patterned by wet etch. The proof mass is released by DRIE Si etch. The chips have dimensions of about 6mm x 4mm.

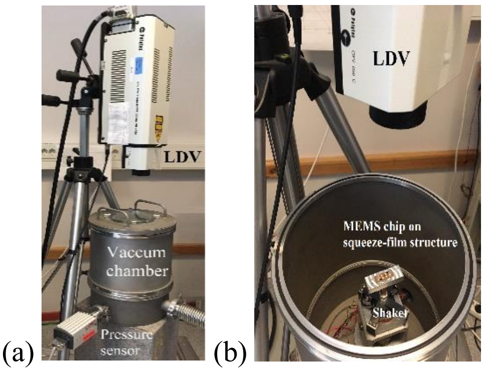


Figure 1. (a) Image of the experimental setup to estimate the energy losses showing the LDV with a special objective that allows measurements of MEMS structures. Below the LDV, the vacuum chamber is seen. The measurement is made through the glass window. (b) View of the small-size shaker inside the vacuum chamber with a MEMS chip on the sample

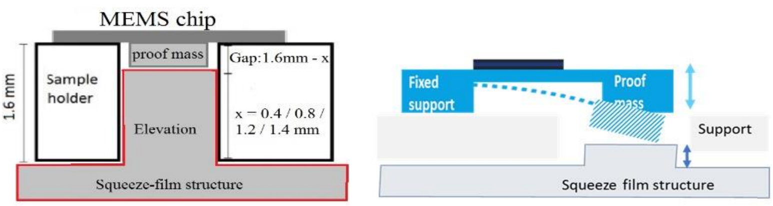
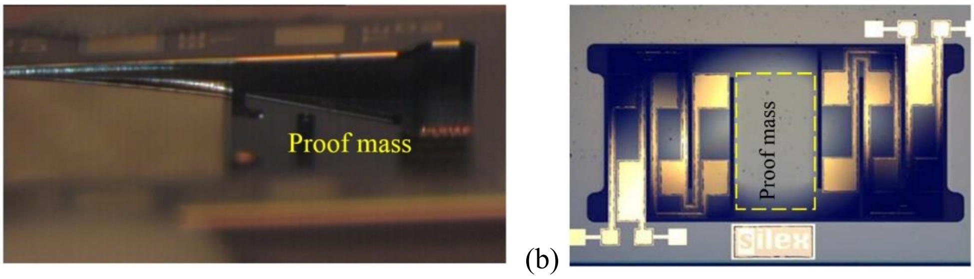


Figure 2. Sketch of the elevation module placed under sample for squeeze film damping experiments.



(a) (b)

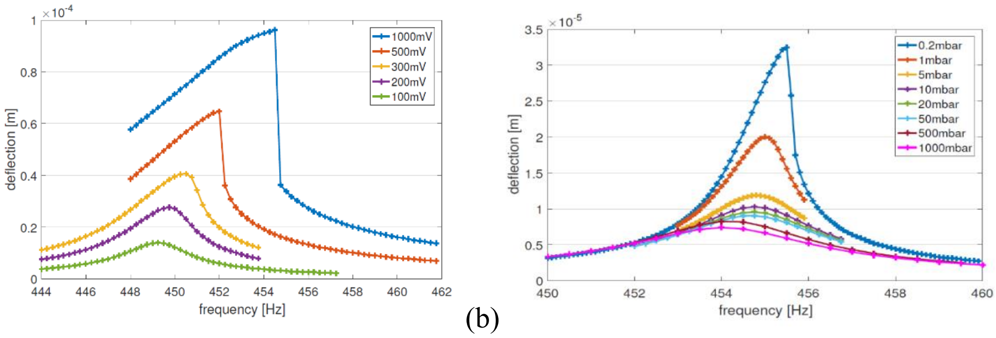
Figure 3. Image of MEMS (a) cantilever and (b) meander structure with proof mass.

3. Results and Discussions

Tests were done to define the optimal values (e.g. excitation amplitudes) for the LDV, mechanical shaker and vacuum chamber (Figure 4). Using these settings, testing of the measurement setup shows the expected behavior of the Q-factor, as shown in Figure 5.

The novelty of our measurement system is the possibility to have a multi-probe measurement setup by combining in one system the LDV, shaker, vacuum and squeeze-film structure. Thus, it is possible to simultaneously measure the Q-factor and the influence of damping in an easy way. The Q-factor for MEMS meanders and cantilevers as a function of pressure with and without wall is shown in Figure 6. Three different regimes can be observed in accordance with theoretical results [2,3]. At low pressure, the Q-factor saturates on the intrinsic damping level, then drops rapidly in the molecular regime and changes more slowly in the viscous regime above 1 mbar.

Q-factors as a function of gap distance for cantilever and meander samples at 1000 mbar are shown in Figure 7. It can be seen that squeeze film damping has little or no significance with a gap larger than 400 μm for the meander structure. The experimental results indicate that the proposed method can quantify both drag and squeeze film damping losses in resonating MEMS structures without packaging.



(a) (b)

Figure 4. Spectra for the first resonance peak measured with the single frequency sine sweep method of MEMS cantilever as function of frequency and (a) excitation amplitudes in air, (b) pressure in the vacuum chamber with the excitation amplitude of 100mV.

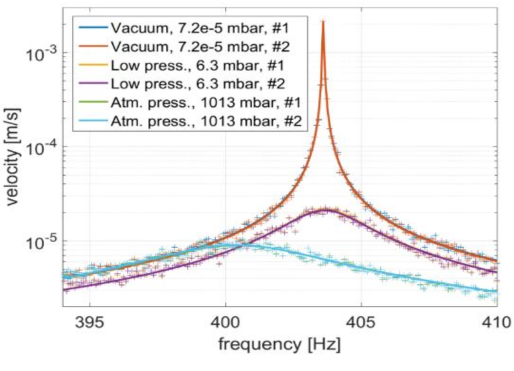
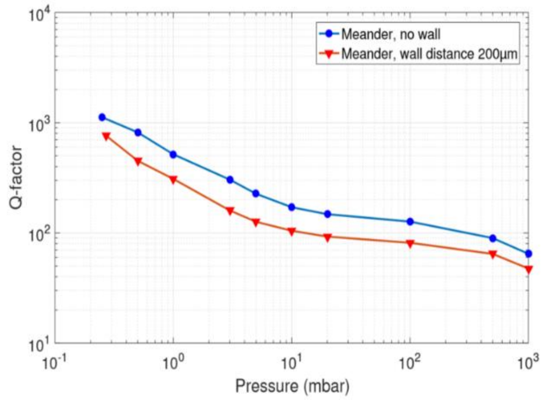
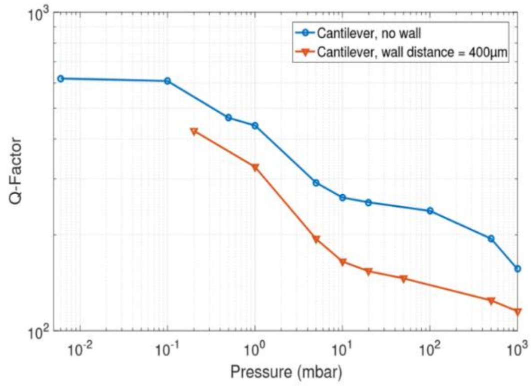


Figure 5. Measurement data (crosses) and fitted curves (solid lines) for the meander structure at three different pressures



(a)



(b)

Figure 6. Q-factor for (a) meander and (b) cantilever as a function of pressure with and without wall.

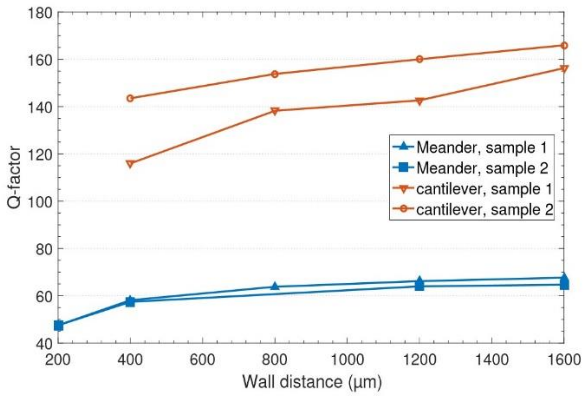


Figure 7. Q-factor as a function of the wall distance for cantilever and meander samples at 1000 mbar.

4. Conclusions

A simple experimental method to quantify the energy loss of oscillating MEMS structures due to the surrounding air is described. The combination of LDV measurements with the shaker, the squeeze-film structure and the placement of the sample in a vacuum chamber gives the possibility to study mechanical characteristics (e.g., resonance frequencies and the corresponding modes), piezo-mechanical coupling (by monitoring the output voltage with selected loads) and the damping mechanisms under varying pressure and excitation conditions. Thus, measurements with this combination setup can serve as a benchmark on the accuracy of numerical simulations, but also gives complementary information about the sample behavior that is difficult to obtain numerically.

Acknowledgements
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