MASS TUNING IN WEAKLY COUPLED LOW-Q PIEZOELECTRIC MEMS RESONATOR ARRAYS FOR PARTICULATE SENSING

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ABSTRACT

This paper reports the achievement of a mass balanced condition in a low-Q weakly coupled MEMS resonator array for ultrafine aerosol particulate sensing. The mass balancing technique enables the lifetime extension of such real-time particulate sensors without employing any wet or dry-cleaning techniques to remove particles from the resonators. This mass balancing is demonstrated for both the flexural and bulk modes of the same coupled resonator array occurring at ~54kHz and ~2.53MHz, respectively. This system also demonstrates for a degree of passive environment immunity to temperature effects by using an amplitude ratio output metric. The Q factor of the coupled MEMS resonator system do not degrade substantially with increased particulate loading.

KEYWORDS

mass tuning, mass balancing, sensor lifetime, weak coupling, piezoelectric MEMS, common-mode rejection, cleaning particles, Q factor.

INTRODUCTION

MEMS resonator arrays continue to be of interest due to their range of applications including narrow bandwidth filters and precision sensors [1,2]. Consistent efforts are underway to realize fully integrated, low-power, portable, inexpensive, real-time chip scale sensors by utilizing these resonator arrays as core transduction elements.

In recent years, FBAR and free-standing MEMS structures [3,4] have been configured to sense particulates with the natural frequency variations providing a highly sensitive readout of adsorbed mass. These devices have demonstrated sensitivity to ultra-fine particles (diameter <100nm) and could be used in conjunction with techniques based on light scattering that are limited in their ability to measure particulate concentrations for this size range. Nevertheless, these devices tend to have limited lifetimes as the small active surface area of the resonator becomes saturated in a few minutes depending on loaded particle concentration. Consequently, various cleaning techniques have been pursued over the past decade to address surface regeneration for automated real-time chip scale particulate sensors [5, 6, 7].

In this context, Merzsch et al. combined wet cleaning methods with ultrasonication and dry-cleaning approaches such as nitrogen purging for MEMS cantilever sensors and demonstrated a high regeneration efficiency. On the other hand, Mehdizadeh et al. have used CO_2 snow jet as a dry-cleaning approach and demonstrated 99.9% regeneration efficiency for their particulate sensors. However, these methods require the MEMS chip to be extracted from the instrument and cleaned in a laboratory environment, limiting real-time continuous measurements.

In conjunction, weakly coupled MEMS resonator arrays have been realized as mass sensors [8,9] based on eigen state variations or resonator amplitude ratios with higher parametric sensitivities demonstrated in comparison to resonant-frequency shift-based sensors. Recent work in [10] has demonstrated the sensitivity of such a system to ultra-fine particulates.

In this paper, we have presented a new approach to extend the sensor lifetime by employing mass tuning in such a low-Q weakly coupled MEMS resonator system without using any of the wet or dry-cleaning techniques. By using this specific coupled MEMS resonator, we have demonstrated their potential for common-mode rejection to temperature and their ability to sustain the low-Quality factor observed in the system, with increased particulate mass loading.

AEROSOL IMPACTOR SETUP

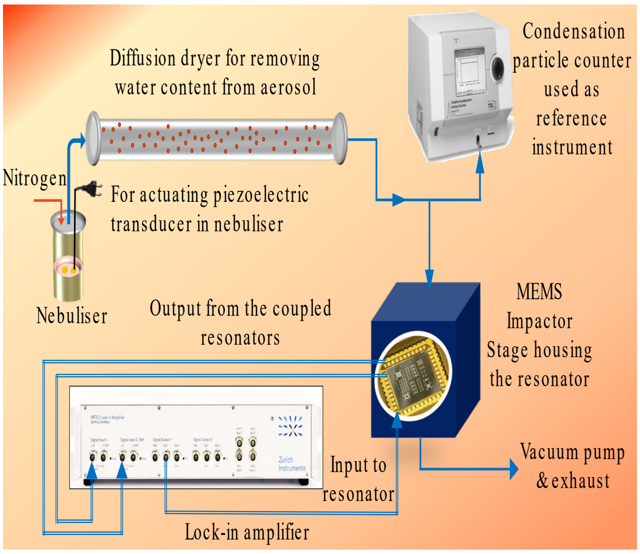

Figure 1: Experimental setup including particle generator, MEMS impactor stage and associated instrumentation.

An experimental setup is built in order to test the MEMS chip. This setup consists of the packaged MEMS mounted in an impactor arrangement and subjected to a continuous flow of ultra-fine particulates (model Polystyrene Latex (PSL) particles of diameter ~100nm) through a nebulizer arrangement, as shown in Fig. 1. A constant flow rate at 0.6 LPM through the inlet nozzle is controlled by a vacuum pump connected at the exhaust. Polystyrene particles of diameter ~100nm are mixed with filtered water from the clean room environment and filled in the nebulizer. This then produces a mist of ultra-fine PSL particles sprayed from the nebulizer when a piezoelectric transducer embedded within the nebulizer is activated. These ultra-fine particles are then passed through a diffusion dryer filled with silica gel to remove the water content from the particles. This ensures that any water content is removed prior to the particles depositing on the resonators. A lock-in amplifier (HF2LI) is employed for

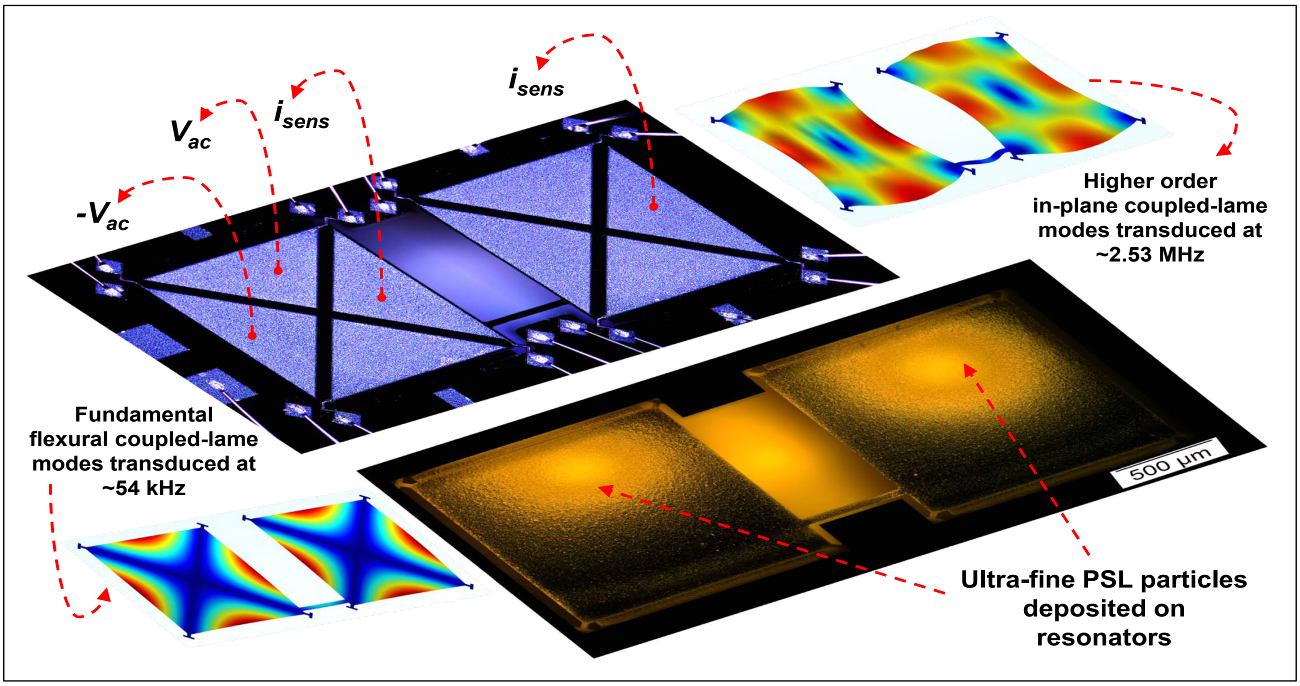

Figure 2: Microscopic image of MEMS resonator array illustrating the differential excitation and sensing of flexural and in-plane coupled-lamè modes with dark-field microscopic image of ultra-fine particles deposited on resonators.

monitoring the signals from the coupled resonator array during the particulate loading experiments. Furthermore, a condensation particle counter (CPC) is used as a reference instrument for monitoring the particulate concentration in parallel with measurements from the MEMS chip.

MEMS RESONATOR ARRAYS

Weakly coupled resonators

This coupled resonator operates on the principle of vibration mode localization. In a symmetric coupled system, the mode shapes are also symmetric and the amplitudes of motional current transduced from the individual resonators are same. If a small mass perturbation is then applied to one of the resonators, the symmetry is broken, and vibration energy localization follows.

Design, fabrication and transduction

The coupled MEMS resonators are designed and fabricated in an AlN-on-SOI MEMS process. Two square plate resonators are weakly coupled by using a quarter wavelength mechanical beam connected near the nodal point of the desired transduced mode, as shown in Fig. 2. The piezoelectric AlN film enables the transduction of the motional currents from individual resonators in the array. The four triangular electrodes patterned on top of the resonators allow for the differential excitation and sensing of the desired coupled-Lamè modes (vibrating in-phase and out-of-phase) in the resonator array as shown in Fig. 2. It should also be noted that the frequency of the sensed coupled-Lamè modes is inversely proportional to the side length of the resonators. The coupled-Lamè modes are differentially excited and sensed at frequencies ~54kHz and ~2.53MHz which indicates the flexural and in-plane motion of the coupled-Lamè modes, respectively in the same coupled resonator. The Q of this coupled resonator vibrating at its flexural and in-plane Lamè modes is strongly dependent on its supports, and the highest Q's could be obtained by using thinnest & fewest supports [2].

Mass tuning in the coupled resonators

The mass tuning in the coupled resonator array is demonstrated by depositing ultra-fine particles of diameter ~100nm on first resonator for 5 minutes and then on the second resonator for the next 5 minutes, respectively. The nozzle arrangement in the aerosol impactor setup allows for precise deposition on specific location on the resonators. The deposition of particles is done by flipping the resonators such that the particles get deposited at desired locations on the silicon plate anchored at the four corners. This deposition is preferentially conducted near the anti-nodal points of the transduced Lamè modes.

RESULTS AND DISCUSSION

Fundamental flexural mode transduced at ~54kHz

The frequency response of the coupled resonators with a resonant peak centered at 54kHz is obtained from the individual resonators in the array by using the Zurich instruments lock-in amplifier. This response centered at ~54kHz corresponds to the in-phase vibration of the coupled flexural Lamè mode in the array as shown in Fig. 3(a). Initially, the amplitude ratio for this system was equal to ~1 indicating the symmetrical displacements/motional current transduced from the resonators. The open-loop frequency response is then monitored around this 54kHz peak by loading one of the resonators in the array with particles for about 5 minutes at 1-minute time intervals. With an increase in particle accumulation on the surface for about 5 minutes, the amplitude of resonator-1 loaded with particles increases whereas the amplitude of unloaded resonator-2 decreases as shown in Fig. 3(b). The amplitude ratio output varies from ~1 to ~2 during this experiment

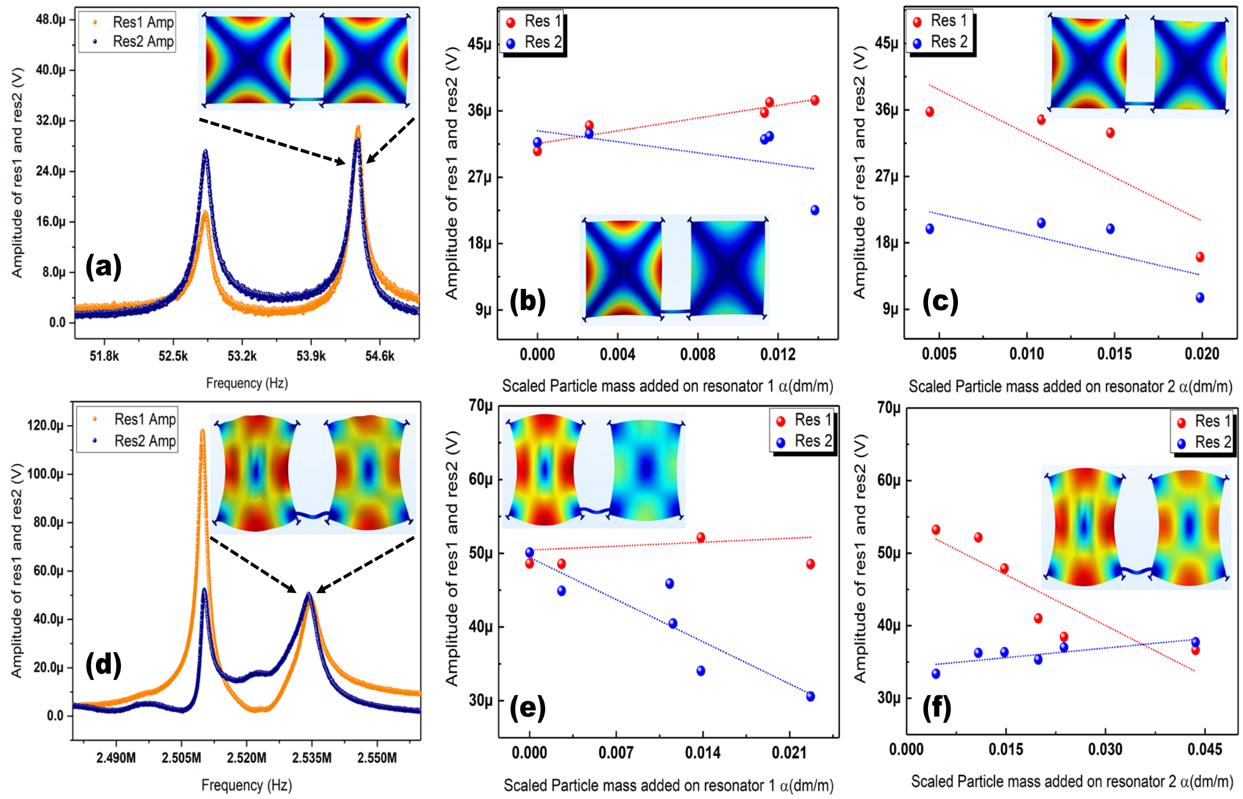

Figure 3: Frequency response of unloaded coupled resonators at flexural and in-plane coupled-lamè modes (a) and (d); when PSL particles are deposited on 1st resonator for 5 minutes at 1-min time intervals (b) and (e); when particles are loaded on 2nd resonator for further 5 minutes at 1-min time intervals (c) and (f). The COMSOL simulated images at the inset (b), (c), (e) and (f) indicate amplitude variation in coupled resonators with increased particle addition.

indicating the increasing asymmetry due to mass loading. The same experiment is then continued by loading the 2nd resonator with particles for about 5 minutes. This time, the amplitude ratio changed its value from ~2 to about ~1.6, indicating the motional current values return towards the initial state as shown in Fig. 3(c). This experiment clearly demonstrates that at a frequency of 54kHz, mass balancing condition can be achieved by tuning the mass of both the resonators in the array.

Higher order in-plane mode transduced at 2.53MHz

Similar to the fundamental flexural mode at 54kHz, the frequency response of the coupled resonators with a resonant peak centered at 2.53MHz is obtained from the individual resonators in the array by using the Zurich Instruments HF2LI lock-in amplifier. This peak at 2.53MHz corresponds to the in-phase vibration of the coupled in-plane Lamè modes in the array as shown in Fig. 3(d). Initially, the amplitude ratio of the individual resonators at this mode was equal to ~1 indicating the symmetrical displacements/motional current transduced from the resonators. The open-loop frequency response is then monitored around this 2.53MHz peak simultaneously with that of the 54kHz peak by following the same experimental procedure as explained in the previous section. The amplitude ratio varies from ~1 to ~1.58 and back to ~1 as shown in Fig. 3(e) and 3(f) when particles are loaded on both resonators. This shows that the amplitude ratio returns to the initial state when mass balancing is achieved for this mode.

Common mode rejection and mass estimation

At the higher order in-plane mode observed at 2.53MHz, the potential of the system to demonstrate passive immunity to temperature variations is studied. During this experiment, the amplitude ratio output of the coupled resonators is observed by placing the resonators in an RF probe station containing a temperature and pressure-controlled chamber. The temperature in the chamber is then increased in steps of 10K from 300K to 400K and the amplitude ratio output is noted at every 10K increment in temperature. The output response is plotted in Fig. 4(a). It can be seen that the amplitude ratio output is nearly insensitive to variations in temperature demonstrating the common mode rejection capability of the coupled resonators. In addition, the mass resolution of this coupled resonator system is approximated to be about ~95pg assuming negligible particle loss, while considering the amplitude ratio stability and the minimum detectable amplitude ratio shift as noted in [10].

Q factor of the coupled MEMS resonator array

During particulate loading, the Q factor of the array varies for both the fundamental mode at 54kHz and the higher order mode at 2.53MHz. The Q of the fundamental flexural coupled Lamè mode is approximately 600 and that for the higher order in-plane coupled Lamè mode is 530 before particulate deposition. Though the Q factor varies during particulate deposition, the value does not substantially degrade throughout the experiment. Fig. 4(b)plots the Q factor over the course of the experiment.

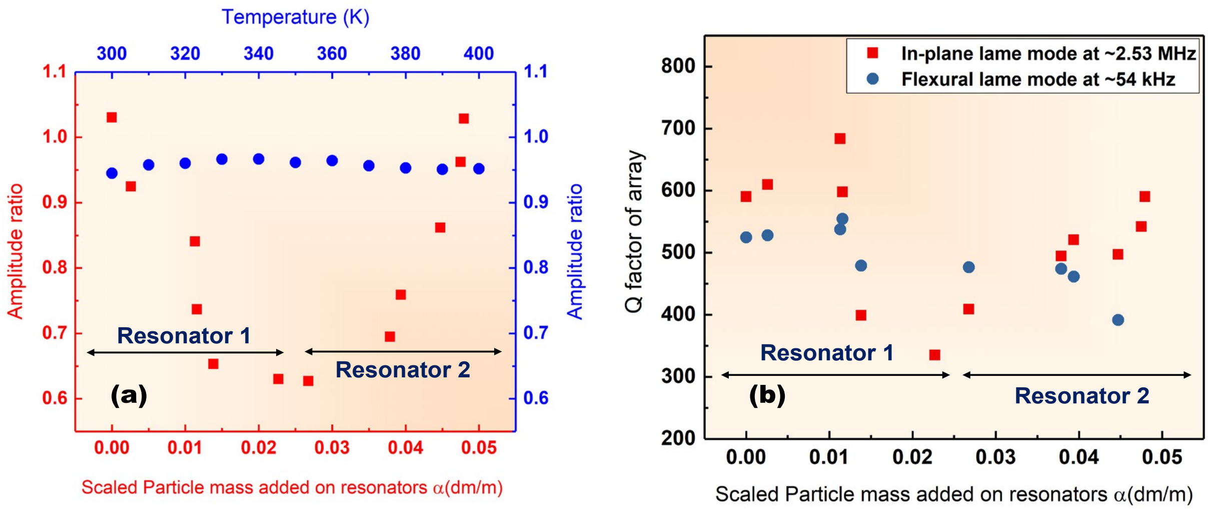

Figure 4: Experimental measurements during mass tuning indicating (a) sensitivity of coupled resonators to particulates and their common mode rejection, (b) Q factor of the array over the entire 10 minutes of particle deposition

The variation in Q factor can be described by surface losses due to the addition of the particulates and variations in acoustic energy radiated from the resonators, including anchor loss. It should be noted that mass balancing can impact anchor loss as the system moves from a dynamically balanced state to an unbalanced state and then back to the balanced condition.

CONCLUSION

This paper demonstrates the potential for recovering an initial balanced configuration in a system of weakly-coupled MEMS resonators in the context of particulate sensing. By periodically switching the resonators on which particulate deposition is conducted, mass balancing can be achieved, thereby enabling recovery of an initial response and utilizing the process of particulate loading as the mass tuning mechanism for state recovery. It should be noted that this approach is unique to the system of weakly-coupled MEMS resonators employed in mode-localized particulate sensing. Implementing a rotating array of these weakly-coupled resonators in conjunction with other cleaning techniques would enable an increase in sensor lifetimes when deploying these resonators as real-time chip scale particulate sensors.

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