

Piezoelectrically Induced Resonance Frequency Tuning of Buckled-Diaphragm MEMS Ultrasonic Sensors for Multi-Frequency Measurement

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Summary:

The resonance frequency of a piezoelectric MEMS ultrasonic sensor with a buckled diaphragm was controlled by piezoelectrically induced stress for multi-frequency measurement. The sensitivity-enhancing buckled shape in the sensing region was maintained over the tuning-voltage range of 0 V to 10 V, despite changes in the overall buckling profile. Tuning voltages of 2 V and 9 V provided resonance frequencies of 90.6 kHz and 43.3 kHz, respectively, with vibration modes yielding adequate piezoelectric output. These results identified practical operating conditions for resonance control in this scheme.

Keywords: piezoelectric ultrasonic sensor, resonance frequency, vibration mode, resolution, buckling

Background, Motivation and Objective

Phased-array technology enables beam steering in ultrasonic measurement. In conventional phased arrays, angular resolution is improved by increasing the array aperture, while the element spacing must be smaller than half the wavelength to suppress grating lobes [1]. This generally requires a large number of sensor elements in a dense array. In contrast, it has been shown that multi-frequency measurement can improve angular resolution and suppress grating lobes in a sparse array [2], and that, if a single sensor element can operate at all required frequencies, the number of elements can be reduced. Figure 1 illustrates the grating-lobe elimination mechanism based on multi-frequency measurement. In the simplest design, multi-frequency measurement using a base frequency and half of that frequency reduces the required number of elements in a two-dimensional array to one quarter of that in the conventional arrangement. However, realizing such measurement requires sensors capable of stable multi-frequency operation.

Figure 2 shows the structure of the frequency-tunable piezoelectric MEMS ultrasonic sensor used in this study. The sensor has a circular diaphragm composed of a piezoelectric PZT capacitor and a silicon dioxide (SiO_2) film with strong compressive stress. This stress buckles the diaphragm into an upward-convex shape, which enhances the sensitivity [3]. The top electrode is divided into an inner electrode for ultrasonic sensing and an outer electrode for frequency tuning. By applying a voltage to the outer electrode, the resonance frequency can be tuned through piezoelectrically induced in-plane stress.

In a flat diaphragm, such stress mainly shifts the resonance frequency of the same vibration mode. In contrast, in a buckled diaphragm, the applied stress also changes the static buckling profile, which can in turn affect the vibration mode. Therefore, to realize stable multi-frequency operation in the present sensor, resonance control

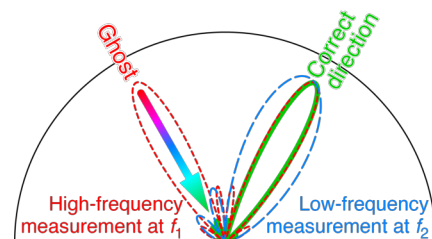


Fig. 1. Grating-lobe suppression in a sparse array by multi-frequency measurement. The grating lobe appearing in the high-frequency measurement at f_1 is suppressed by combining the f_1 and f_2 results so that a null of the f_2 response overlaps the f_1 grating lobe.

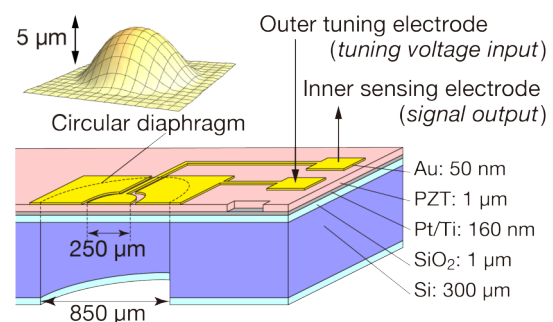


Fig. 2. Schematic illustration of the frequency-tunable MEMS ultrasonic sensor with a circular diaphragm. The diaphragm has an upward-convex buckling shape with buckling deflection up to 1.5% of the diameter.

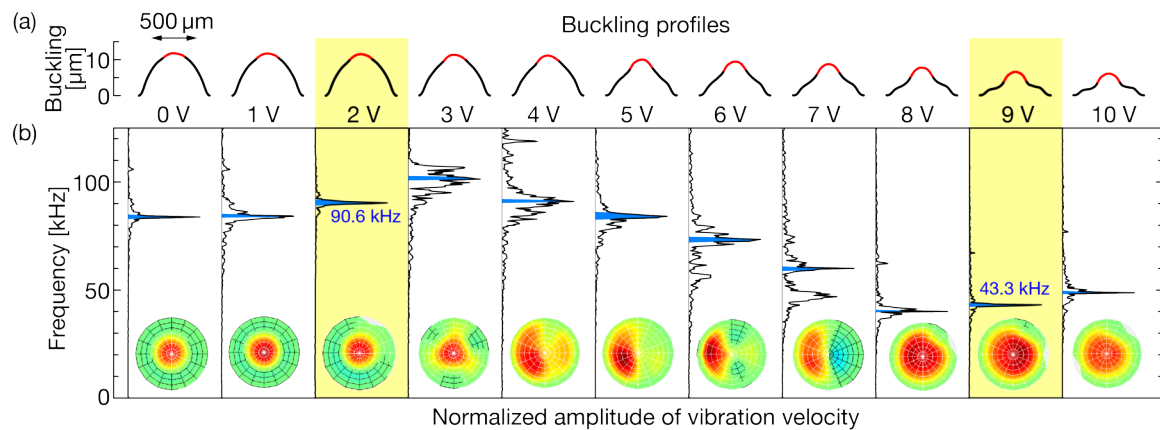


Fig. 3. Results of resonance control over the tuning-voltage range of 0 V to 10 V. (a) Buckling profiles of the diaphragm, showing that the diaphragm maintains the sensitivity-enhancing shape in the sensing electrode region (red part). (b) Vibration spectra and vibration modes corresponding to the dominant peaks indicated in blue in the respective spectra. Resonance frequencies of 90.6 kHz and 43.3 kHz were obtained at 2 V and 9 V, respectively, providing a frequency ratio greater than two, while maintaining single dominant peaks and axisymmetric modes.

must simultaneously provide suitable resonance frequencies, maintain the sensitivity-enhancing buckled shape in the sensing region, and preserve axisymmetric vibration modes within the sensing electrode region to avoid cancellation of piezoelectric output. The objective of this work is to identify tuning-voltage conditions that satisfy these three requirements.

Experiments

A diaphragm sensor with an initial buckling deflection of 12 μm was used in this study. The buckling deflection was controlled through the PZT stress during fabrication [4]. A dc tuning voltage in the range of 0 V to 10 V was applied to the outer electrode to generate piezoelectrically induced stress for resonance control. The static buckling profile of the diaphragm was measured using an optical profiler. Pulse ultrasound generated by electrical discharge was then applied to the sensor. The resulting vibration modes and resonance frequencies were evaluated using a two-channel scanning laser Doppler vibrometer [5].

Results and Discussion

Figure 3 summarizes the experimental results. As shown in Fig. 3(a), the sensing region under the inner electrode (red part) maintained the sensitivity-enhancing buckled shape over the entire voltage range. In contrast, the outer region of the diaphragm gradually deformed toward a flatter shape with increasing tuning voltage due to the piezoelectrically induced stress under the outer electrode. A marked change in the overall buckling profile started at 4 V, corresponding to the ferroelectric coercive field of the PZT film.

Figure 3(b) shows the vibration spectra of the diaphragm in response to an ultrasound pulse. The main resonance peak shifted to higher

frequencies with increasing tuning voltage in the ranges of 0 V to 2 V and 8 V to 10 V because of the in-plane tension generated by the piezoelectric stress. In contrast, the peak shifted to lower frequencies in the range of 3 V to 7 V owing to the decrease in the total buckling deflection. In this intermediate range, the dominant mode was non-axisymmetric, with many sub-peaks appearing around it.

Tuning voltages of 2 V and 9 V provided resonance frequencies of 90.6 kHz and 43.3 kHz, respectively, covering the 2:1 frequency ratio required for multi-frequency measurement. At these voltages, the vibration modes were axisymmetric within the sensing electrode region. Together with the maintained buckled shape in the sensing region, these results indicate that the voltages of 2 V and 9 V satisfy the three requirements for resonance control in the present sensor: appropriate frequency selection, preservation of the sensitivity-enhancing buckled shape, and suitable vibration modes for piezoelectric output. Thus, practical operating conditions were identified for multi-frequency measurement using the buckled-diaphragm frequency-tunable sensor.

References

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