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Determination of mechanical properties of a MEMS directional sound sensor using a nanoindenter

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ABSTRACT

We use a nanoindenter to measure the stiffness of mechanical components of a microelectromechanical directional sound sensor. The results validate analytical and numerical linear elastic models, identify the physical structures associated with each resonant frequency, and provide an estimate of the maximum sound pressure the sensor can tolerate. Because the sensor has bending and twisting components that act as springs in series, the overall compliance is the sum of several terms, each of which varies with the location of the loading force along the sensor's surface. By fitting a curve to a plot of the measured overall stiffness vs. location of the loading force, we quantify the separate compliance terms and thereby estimate the resonant frequencies of the corresponding vibrational modes. The frequencies estimated by this method for the two modes are in reasonably good agreement with the measured resonant frequencies. Finally, we establish a minimum failure strength of the sensor, from which we estimate that it can tolerate a sound pressure level greater than about 162 dB without damage.

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1. Introduction

We demonstrate the use of a nanoindenter to determine the spring constants of a set of coupled springs incorporated into a microelectromechanical system (MEMS). Nanoindenters are commonly used on micro-scale cantilever beams to investigate the elasticity and hardness of the beam material as originally described by [1]. Nanoindenters have also been used to mechanically actuate MEMS components, either to investigate behavior of electrical contacts [2–4], to investigate failure modes of microstructures [5], or to assess mechanical stability [6]. A nanoindenter transducer has even been incorporated into a hand-built apparatus to measure the stiffness of single cantilevers [7]. Here we use a nanoindenter to analyze a more complex MEMS structure whose stiffness varies across its surface due to simultaneous bending and twisting motions of several coupled components.

The MEMS structure in question is a directional sound sensor inspired by the hearing organ of the parasitoid fly *Ormia ochracea*, which uses hearing to find crickets as a food source for its larvae [8]. Despite the handicap of being much smaller than the wavelength of the cricket's chirp, the fly is able to locate its prey by homing in on the sound. It accomplishes this through mechanically coupled eardrums.

The eardrums can be modeled as two rigid bars connected by a flexible bridge. In this configuration the bars can vibrate in two normal modes in response to incident sound: a "bending" mode, in which the bars vibrate in phase, and a "rocking" mode, in which the bars vibrate exactly out of phase. When the eardrums are excited by the sound field, the amplitude of the bending mode depends on the sum of the forces acting on the two eardrums, while the rocking mode depends on the difference between the forces. As a result, the phase difference between the two eardrums depends on the direction of sound incidence [8].

The MEMS directional sound sensor mimics the eardrum of the fly. The sensor (see Fig. 1) is constructed from the single-crystal (1 0 0) silicon device layer of a silicon-on-insulator (SOI) wafer, using a standardized commercial micromachining process [9]. The lateral and longitudinal axes of the sensor are oriented along ⟨11 0⟩ crystal directions. The silicon layer is 9.5 μm thick as measured with a profiler.

Structurally, the sensor comprises two relatively stiff wings (rectangular plates) connected by a flexible bridge which acts as a spring. This bridge is connected to the substrate by two thin legs which, by twisting, enable the bridge as a whole to rock back and forth in a see–saw motion. In this way the sensor is able to respond to sound pressure on the wings by oscillating in rocking and bending modes analogous to the two vibrational modes of the fly's ear, as illustrated in Fig. 2. Electronic readout of the wings' motion is

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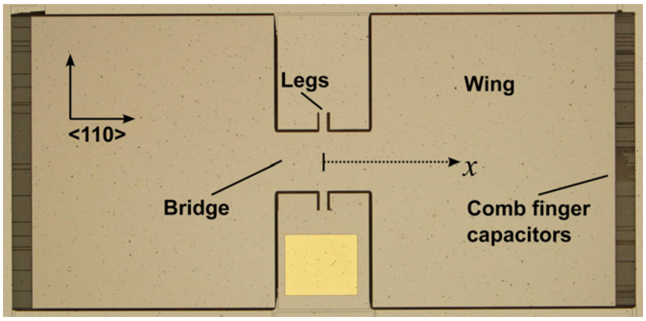

Fig. 1. A photograph of the MEMS sensor. The two wings are coupled by the bridge, which is connected to the substrate by the legs. The legs act as torsion springs and each end of the bridge acts as a flexible cantilever beam. Comb finger capacitors enable electronic readout of the wingtip displacement from equilibrium. The sensor is 2.5 mm from wingtip to wingtip.

enabled by interdigitated capacitive comb fingers on the wingtips [10]. The comb finger capacitors are 100 μm long by 2 μm wide, separated by a gap of 2 μm from the opposing interlaced fingers, and range along the width of the wing tip.

Since the vibrational response of the sensor depends on the stiffness of the bridge and legs, it is useful to measure the stiffness directly. Spring constants can be determined by measuring resonant frequencies with sound excitation, but for a device with multiple resonance modes, it may be difficult to associate each frequency with the corresponding structures. The advantage of the nanoindenter technique is that it enables precise, direct measurement of stiffness anywhere on the sensor. By comparing the measured stiffness with simple models, it is possible to identify the source of each resonant frequency. The nanoindenter can also be used to explore the maximum loads the sensor can withstand, when it may not be practical to generate such high loads using sound pressure or other means.

In the following, we develop analytical and numerical linear elastic models of the MEMS sensor's stiffness vs. location of an applied loading force, use those models to predict the resonant frequencies, and check their validity by comparing with nanoindenter measurements. We also use a nanoindenter test to estimate the maximum sound pressure the sensor can tolerate.

2. Theory

The MEMS sensor can be modeled as a collection of springs acting in series. To simplify the analysis, only points along the extended centerline of the bridge (defined as the x-axis) are modeled. The overall stiffness $k(x)$ is the individual spring constants $k_i(x)$ added in series:

$$\frac{1}{k(x)} = \sum_i \frac{1}{k_i(x)}. \tag{1}$$

The three springs of the sensor model represent bending of the bridge, twisting of the legs, and vertical flexing of the legs and bridge. The vertical flexing does not affect the sensor's operation, but it is important for the nanoindenter study.

To estimate the bending stiffness, the bridge is modeled as a cantilever beam of rectangular cross section, fixed at the legs and free at the point where the load is applied (Fig. 3). For a cantilever of width w and thickness $t < w$, acted on by a transverse load F at a distance x from the fixed end, the deflection d is [11]

$$d(x) = \frac{4Fx^3}{Ewt^3}, \tag{2}$$

where E is the Young's modulus of the material. Strictly speaking, this model is only valid up to the end of the bridge. For a cubic material such as silicon, E may be taken as a scalar if all stresses are in the same crystal direction, as they are in the simple beam bending model. Because both of the MEMS sensor axes are oriented along $\langle 11\,0\rangle$ directions, the scalar Young's modulus is $E_x = E_y = 169$ GPa [12]. The bending stiffness of the cantilever $k_b = F/d$ is then

$$k_b(x) = \frac{Ew_b t^3}{4x^3} \tag{3}$$

where w_b is the width of the bridge.

To model the rocking stiffness, the bridge is treated as a rigid beam mounted on a pair of torsion springs (the legs) with rectangular cross section (Fig. 4). The angular deflection of a pair of torsion springs acting in parallel is [11]

$$\phi = \frac{1}{2}\frac{\tau l}{GJ}$$

where τ is the torque applied, l is the length of each spring, G is the shear modulus of the material, and J is the torsion constant, a function of the cross-sectional dimensions of each spring with dimensions of length raised to the fourth power [11].

The torsional stiffness for the rocking mode is

$$\kappa_r = \frac{\tau}{\phi} = \frac{2GJ}{l}. \tag{4}$$

The torsional stiffness is necessary to estimate the resonant frequency. However, the nanoindenter measures linear stiffness, which depends on the position of the force. If a transverse load F is applied to the bridge at a distance x from the spring, the torque about the rotation axis is $\tau = Fx$. For a small twisting angle ϕ, the displacement of the cantilever at x is

$$d(x) = \phi x = \frac{Flx^2}{2GJ}.$$

Then the linear rocking stiffness $k_r = F/d$ is

$$k_r(x) = \frac{2GJ}{lx^2}. \tag{5}$$

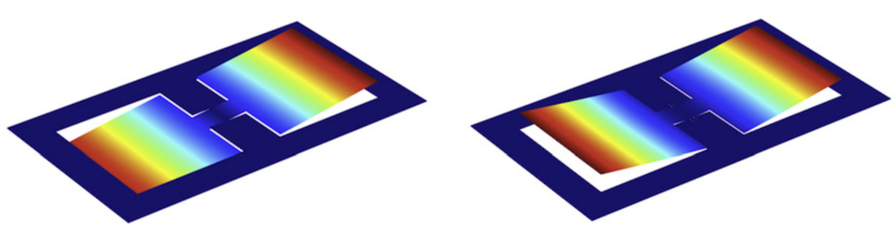

Fig. 2. The vibrational modes of the MEMS sensor, obtained from a COMSOL finite element model. Displacement is greatly exaggerated for clarity; actual displacement of the wingtips is typically much less than one percent of the length of the sensor. Capacitive comb fingers are not shown here.