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Highly sensitive mass detection and identification using vibration localization in coupled microcantilever arrays

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We study the use of vibration localization in large arrays of mechanically coupled, nearly identical microcantilevers for ultrasensitive mass detection and identification. We demonstrate that eigenmode changes in such an array can be two to three orders of magnitude greater than relative changes in resonance frequencies when an analyte mass is added. Moreover, the changes in eigenmodes are unique to the cantilever to which mass is added, thereby providing a characteristic "fingerprint" that identifies the particular cantilever where mass has been added. This opens the door to ultrasensitive detection *and* identification of multiple analytes with a single coupled array. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2899634]

Microcantilever sensors have been extensively used to detect a variety of biological and chemical analytes over the past decade.[1–4] Most of these sensors use changes in resonance frequencies or static bending of the microcantilever to detect the adsorption of an analyte of interest. In contrast, the concept of using vibration localization[5–10] in an array of nearly identical coupled oscillators has also been proposed as a sensing mechanism in recent years in two or three coupled microbeams under ambient conditions.[11–13] Besides its high sensitivity to added mass, an eigenmode-shift based sensor possesses intrinsic common mode rejection[12] that renders it less susceptible to false-positive readings than resonance-frequency based sensors; environmental factors or nonspecific bindings that influence all cantilevers uniformly will not affect the eigenmodes of the system, while changes in resonance frequencies will still occur. In an effort to improve the *sensitivity* and *selectivity* of vibration localization based microcantilever arrays, in this article, we examine an array of fifteen weakly coupled microcantilevers in a low pressure environment.

In order to estimate the sensitivity to added mass of the eigenmodes of the coupled array, we begin with the eigenvalue problem of a perfect array of identical spring-mass oscillators (cantilevers), with each oscillator connected to its neighbor by a coupling spring

$$\underset{\sim}{M}^{-1}\underset{\sim}{K}u = \omega^2 u, \tag{1}$$

where u is a normalized eigenmode ($|u_i|=1$) of the system representing the tip amplitudes of each cantilever of the array at the corresponding eigenfrequency, ω is an eigenfrequency of the system, and $\underset{\sim}{M}$ and $\underset{\sim}{K}$ are the mass and stiffness matrices of the system, respectively, given by

$$\underset{\sim}{M} = \begin{bmatrix} M_1 & 0 & \cdots & 0 \\ 0 & M_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & M_{15}+\Delta M \end{bmatrix}, \tag{2}$$

$$\underset{\sim}{K} = \begin{bmatrix} K_1+K_C & -K_C & \cdots & 0 \\ -K_C & K_2+2K_C & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & -K_C & K_{15}+K_C \end{bmatrix}$$

where M_i and K_i represent the mass and stiffness, respectively, of each cantilever, K_C represents the coupling stiffness between cantilevers, and ΔM represents the added mass of the target analyte that binds to one cantilever.[14] Solving Eq. (1) when $\Delta M=0$ and $M_i=M$, $K_i=K$ yields 15 eigenmodes of the initially perfectly ordered system. The first mode consists of all cantilevers moving in phase with identical amplitude, while higher modes of the array are characterized by increasing spatial modulation with decreasing wavelength. The actual values of M, K, and K_C can be estimated from experimental data.[14] However, manufacturing errors will inevitably cause differences in the cantilevers. The effects of these differences were studied by allowing the length, width, and thickness of each cantilever to vary randomly up to $\pm 1\%$ from nominal values. When mass is added to the system ($\Delta M \neq 0$), the magnitude of the relative shift in the i^{th} eigenmode u_i and the relative shift in the i^{th} resonance frequency after mass is added to a cantilever can then be written as

$$|\Delta u_i| = |u_i - u_{i,0}|, \quad \Delta\omega_i = \frac{\omega_i - \omega_{i,0}}{\omega_{i,0}}. \tag{3}$$

$u_{i,0}$, $\omega_{i,0}$ and u_i, ω_i represent the i^{th} eigenmode vector and its eigenfrequency before and after mass is added, respectively, so that $0 \leq |\Delta u_i| \leq 2$. One thousand calculations were performed with the random variations in cantilever dimensions, and the sensitivity of the eigenmodes of the array to added mass on one cantilever was calculated for each case. Based

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on these simulations for realistic initial disorder in the array, we find that *for any given added mass location, an eigenmode always exists whose relative shift is at least two orders of magnitude higher than its relative frequency shift*. In addition, because adding mass to one cantilever changes only one row of the matrix $\underset{\sim}{M}$, *the resulting pattern of eigenmode shifts will be unique to the added mass location*, allowing the exact location of an added mass to be determined by examining the matrix of eigenmode shifts Δu_i.

The *sensitivity* of the eigenmodes to added mass can be defined as the magnitude of the relative change in the eigenmodes $|\Delta u_i|$ divided by the amount of added mass.[15] Using this definition, the theoretical sensitivity of the eigenmodes to added mass is expected to be two to three orders of magnitude greater than that of the resonance frequencies. However, in a practical implementation of an eigenmode-shift sensor, the *minimum detectable mass*, which can be defined as the minimum resolvable eigenmode shift divided by the sensitivity, may not be very different from a frequency shift sensor. This is because frequency shifts can be usually resolved with greater precision than amplitude changes. However, with very precise measurements of the amplitude shifts the minimum detectable mass using eigenmode shifts could surpass that due to frequency shift methods. This possibility together with the intrinsic common mode rejection property make eigenmode shift based sensors particularly attractive.

The arrays being tested consist of fifteen coupled polysilicon beams which are 200 μm long, 20 μm wide, and 2.25 μm thick. A small base overhang between the microcantilevers and support compliance provides the mechanical coupling between the beams. The chip was mounted on a piezoelectric shaker, which in turn excited the chip with vertical oscillations. A laser Doppler vibrometer in a microscope measured the velocities at one point on the base of the array and 35 points on each of the 15 cantilevers on the array. The measurements were conducted under 7 mTorr air pressure to ensure high Q factors and to minimize hydrodynamic interactions between cantilevers.[16]

The measurements reveal the presence of many closely spaced resonance frequencies, indicating that the cantilevers are weakly coupled. Figure 1(a) shows the frequency response function (FRF) between the reference velocity at the base of the array and the response velocity at the end of one cantilever. Figure 1(b) shows the portion of the FRF highlighted in Fig. 1(a), with inset images of selected operating deflection shapes. In a high-Q environment with nonoverlapping peaks, these are in fact the eigenmodes of the array.

First, the eigenmodes of the initial array are fully characterized. Figure 1(c) provides a convenient way to display all the modes of the array in a single plot. Each row in Fig. 1(c) corresponds to one normalized mode u_i of the array, while each column corresponds to a given cantilever over many different modes. The color shading in each cell (i,j) is determined by the amplitude of the tip of the i^{th} cantilever in the j^{th} eigenmode. The fact that the measured eigenmodes, shown in Fig. 1(d), and predicted eigenmodes for the perfectly ordered system appear slightly different confirms the presence of initial disorder in the system.

Next, a 5 μm diameter borosilicate microsphere with a nominal mass of 150 pg (Ref. 17) was added to one cantilever in the array, as shown in Fig. 2(a), and eigenmode and resonance frequency measurements were then repeated. The microsphere was then removed from the cantilever, and a final set of measurements were then taken. Modes 4, 5, and 14 were affected significantly by the process of adding and removing mass, while modes 6–13 were affected very little. This is because in the process of adding or removing the mass using a tungsten probe, it is possible to irreversibly damage the specific microcantilever. Therefore, subsequent results will focus on modes 6–13 when discussing the effects of added mass on the array.

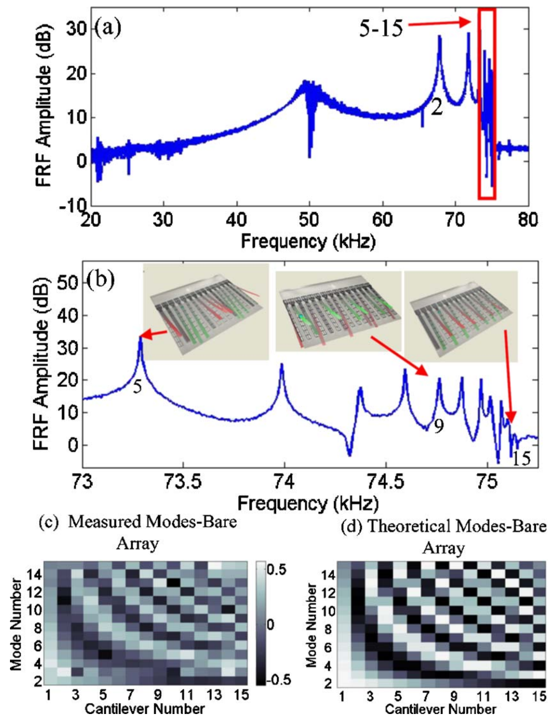

FIG. 1. (Color online) (a) Frequency response function between the velocity of the free end of one cantilever and the reference velocity measurement made at the base of the array with no mass added. The effective Q factor of the second mode is ~2500 in this case. (b) Zoomed view of the highlighted portion of the FRF shown in (a). The measured eigenmodes are shown in the inset images for selected modes. (c) Plot of measured eigenmodes 2–15 of the fifteen cantilever array with no added mass (the first mode of the array was obscured by the resonance of the piezoelectric shaker). Rows correspond to individual modes u_i of the array, while columns correspond to an individual cantilever over all measured modes. The shading of each cell is determined by the amplitude of a particular cantilever in a particular mode. Negative amplitudes correspond to out-of-phase oscillations. (d) Plot of all calculated eigenmodes for an ideal array of fifteen identical cantilevers.

The localization of individual modes was observed after the addition of a microsphere to cantilever 14. Figure 2(b) shows the significant differences in the sixth mode of the array before and after the addition of the microsphere, respectively, while the resonance frequency of the mode changes only very slightly.

The experimentally measured eigenmode shifts compare well with the theoretical predictions described earlier. Figure 2(c) plots the relative shift in eigenmodes $|\Delta u_i|$ for the modes of interest due to the addition of a single microsphere on cantilever 14. Most of the experimentally measured relative eigenmode shifts fall within the theoretically predicted envelope, indicating that the theoretical model with initial imperfections included correctly predicts the eigenmode shifts due to an added mass. All of the measured modes in Fig. 2(c) undergo large relative changes on the order of 10%–100% due to the added mass; in contrast, the highest relative frequency shifts, plotted in Fig. 2(d), are on the order of 0.1% in this case, indicating that the relative eigenmode shifts are

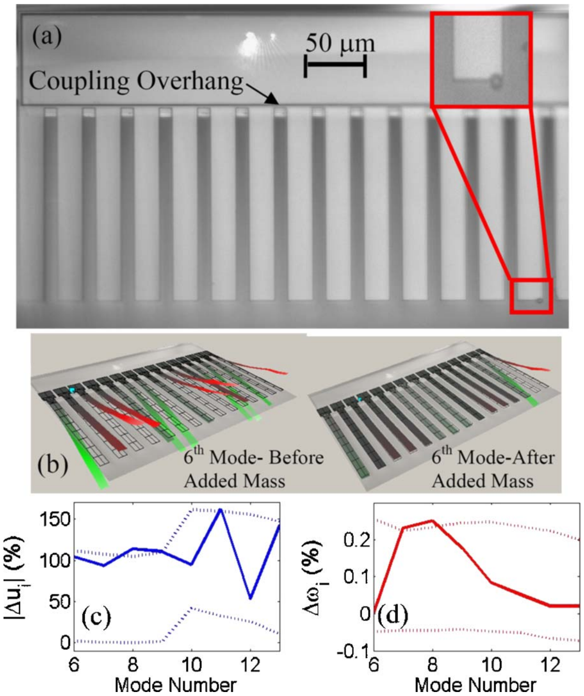

FIG. 2. (Color online) (a) Photograph of the array of fifteen coupled cantilevers with a 5 μm diameter borosilicate microsphere attached to cantilever 14 (inset). The coupling between cantilevers is labeled. (b) Representation of the measured sixth mode of the array before (left) and after (right) the addition of a 5 μm microsphere to cantilever 14. In this case, the vibrations have localized in cantilevers 14 and 15 after the sphere is added. (c) Plot of the magnitude of the relative eigenmode shift $|\Delta u_i|$, as defined in Eq. (3), vs mode number for selected modes. The upper and lower dotted lines represent the average predicted relative eigenmode shift plus and minus the standard deviation in the eigenmode shift, respectively. The solid blue line represents the experimentally measured relative eigenmode shift values when a mass is added to cantilever 14. (d) Plot of the relative frequency shift $\Delta\omega_i$ of each mode due to the addition of a mass to cantilever 14. The upper and lower dotted lines represent the average predicted relative frequency shift plus and minus the standard deviation in the frequency shift, respectively. The solid line represents the experimentally measured relative frequency shift values when a mass is added to cantilever 14. The relative eigenmode shifts plotted in (c) incorporate data from the frequency response functions of all cantilevers, while the relative shifts in resonance frequencies in (d) are the same for all cantilevers in the array.

two to three orders of magnitude greater than the relative frequency shifts. *This represents one to two orders of magnitude improvement in sensitivity over previous attempts at the use of mode localization for mass sensing.*[12]

The effects of adding mass to different cantilevers in the array were also examined by adding and removing a 2 μm diameter borosilicate microsphere with a nominal mass of 10 pg (Ref. 17) from two different cantilevers in the array. Figures 3(a) and 3(b) plot the changes in the eigenmodes after a 10 pg mass is added to cantilevers 10 and 14. Since each pattern of shifts is unique, *it becomes possible to examine an experimentally measured pattern of eigenmode shifts and determine to which cantilever a target analyte particle has adhered*. The quantitative mass of the target particle can in principle be determined by extending the theory developed in previous work[12] to an array of 15 cantilevers.

In conclusion, we have demonstrated that eigenmode changes in a large array of fifteen coupled cantilevers can be as much as three orders of magnitude greater than relative frequency shifts. These changes represent an order of magnitude improvement in mass sensitivity of localization based

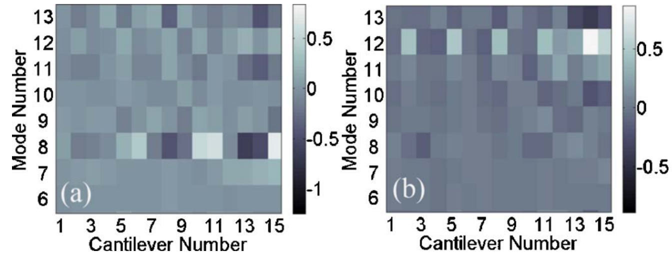

FIG. 3. (Color online) (a) Plot of the change in each eigenmode Δu_i before and after the addition of a 10 pg microsphere to cantilever 10. In this case, mode 8 undergoes the greatest change. (b) Plot of Δu_i before and after the addition of a 10 pg microsphere to cantilever 14. The greatest change is observed in mode 12 in this case.

sensing over previous works involving two coupled cantilevers. We have also shown that adding mass to different cantilevers in the array leads to a unique pattern of eigenmode shifts. These findings open the door to the ultrasensitive simultaneous detection of multiple analytes using a single coupled array.

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