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Mode-selective noncontact excitation of microcantilevers and microcantilever arrays in air using the ultrasound radiation force

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We demonstrate the use of focused ultrasound waves to excite eigenmodes of microfabricated structures such as atomic force microscopy microcantilevers and coupled microcantilever arrays, among the smallest objects that have been excited in air using ultrasound radiation force. The method is based on the radiation force produced by a double-sideband suppressed carrier ultrasound waveform, centered at 500 kHz. The difference frequency between the sidebands, ranging from 10 to 200 kHz, excited resonances of these structures. Frequency response curves and deflection shapes were consistent with conventional base excitation, demonstrating the feasibility of noncontact excitation for a variety of microscale devices. © *2010 American Institute of Physics*.
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Resonant mass sensors, such as micro- and nanocantilevers, microbeams, and similar microfabricated structures, have great promise as a method for detection of biological or chemical agents[1] such as mercury vapor,[2] trinitrotoluene (TNT),[3] plastic explosives,[4] single cells,[5] and virus particles.[6] As target molecules bind to the microcantilever, the change in mass results in a change in resonance frequency. Recently there has been a significant increase in work related to coupled microcantilever systems for highly sensitive mass detection with intrinsic common mode rejection, since it has been shown that changes in eigenmodes of such coupled arrays are extremely and exclusively sensitive to disorder arising from the differential added mass of the analyte.[7–9] Resonant microcantilevers also play a key role in the field of dynamic atomic force microscopy (AFM) for high resolution imaging and force sensing on surfaces.

The direct and artifact-free excitation of resonances of these microfabricated structures remains a challenging problem. Because of the small dimensions, in most cases the microcantilever chip is fixtured onto a piezoelectric or similar mechanical shaker. In this mechanical base excitation method, oscillation of the base causes vibration of the microcantilever. A number of problems may result from mechanical base excitation. Reliable fixturing of a microfabricated structure to a mechanical shaker may be inconvenient or time consuming and may risk damaging a part. Another problem with this technique is that resonances of the shaker as well as the support fixture may cause spurious resonances to be detected that are unrelated to the resonance frequencies of the microcantilever itself. Another important disadvantage is that for coupled microcantilever arrays, this method is not able to excite effectively all the eigenstates. For instance in a coupled two cantilever system studied in the current experiment, while the symmetric state is effectively excited by base motion, the antisymmetric state is not as well excited.[7] For these reasons there is a need for excitation mechanisms that are noncontact and are able to excite effectively the higher eigenmodes of the structures.

It has been demonstrated for a variety of systems that ultrasound radiation force excitation is an alternative to mechanical base excitation.[10–14] However many mass sensors and AFM systems operate in air under ambient conditions, and ultrasound has not yet been demonstrated as a viable alternative for excitation of microcantilevers and microcantilever arrays in such settings. The current study demonstrates the capability of using ultrasound radiation force in air to excite the fundamental and higher order eigenmodes of an object as small as an AFM microcantilever or microcantilever arrays with resonance frequencies in excess of 200 kHz.

Previous papers have described in detail the mechanism for ultrasound radiation force excitation.[10,15–17] In the current experiment, a single ultrasound transducer emits waveform consisting of a pair of sine waves with frequencies of $f_a = f_C - \Delta f/2$ and $f_b = f_C + \Delta f/2$ that were symmetric about a central frequency f_C. Since the acoustical radiation force goes as the square of this velocity potential, the result is a sinusoidal radiation force that contains both the sum and difference of the two frequencies. The component of interest for the current experiment is the difference frequency $\Delta f = (f_b - f_a)$. In the current experiment, the difference frequency Δf was varied, and the response of the microcantilever and microcantilever array was measured at each frequency using the laser Doppler vibrometer system shown in Fig. 1(a). If the radiation force at frequency Δf corresponded to one of the microcantilever resonance frequencies, it would induce a larger amplitude vibration.

To produce the ultrasound, an Ultran NCG500-D25-P76 transducer was used. This transducer has a central frequency of 500 kHz, a bandwidth of 250 kHz, and was driven with a power of about 10 W. The focus diameter of this transducer was 3 mm, so the entire microcantilever structure, as well as its base, was roughly uniformly ensonified. The transducer

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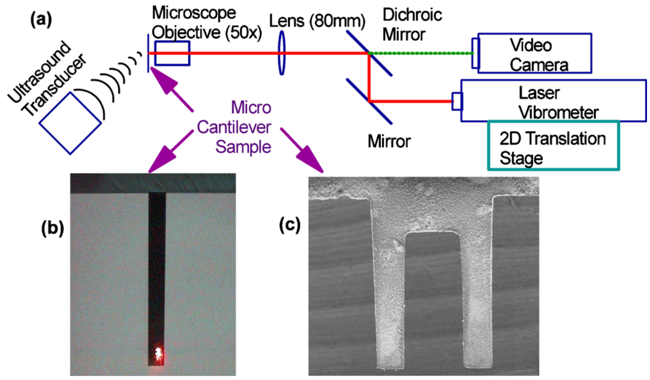

FIG. 1. (Color online) (a) Apparatus used for ultrasound radiation force excitation of microcantilever. The two-dimensional translation stage, mirrors, and lenses allowed the laser vibrometer measurement point to be focused onto the microcantilever sample. (b) Image taken using video camera of apparatus (a) showing the vibrometer measurement spot focused near lower right corner of the Mikromasch 350 μm AFM cantilever used for Fig. 2. (c) Scanning electron microscope image of the coupled pair of 500 μm gold microcantilevers used for Fig. 3.

was oriented at 45° relative to the surface to minimize standing waves due to reflections. The stepped-frequency sinusoidal modulation signal at frequency $f_m = \Delta f/2$ used for excitation was generated with a 1 Msample/s National Instruments NI-USB-6251 data acquisition unit. This modulation waveform was directed into a 20 MHz Hewlett Packard 33120A function generator in amplitude modulation (AM) mode. This function generator produced a dual-sideband, suppressed carrier waveform with a pair of frequencies symmetric about $f_C = 500$ kHz.

During ultrasound radiation force experiments, cantilever vibration was determined using a Polytec OFV-3001 laser Doppler vibrometer with OFV-502 measurement head with a 1 MHz bandwidth. The measurement head was mounted on a two-dimensional translation stage. By using the optical components in Fig. 1(a), the vibrometer measurement point was focused to a spot with a diameter of roughly 10 μm. The analog output of the laser Doppler vibrometer was sampled at 1 MHz with the NI-USB-6251. A Fast Fourier Transform (FFT) was performed in National Instruments LABVIEW on the data set; for each modulation frequency f_m, the amplitude and phase at the difference frequency $\Delta f = 2f_m$ were extracted from the FFT data set. Operational deflection shapes were determined by animating the amplitude and phase measured at many points on the surface.

One sample studied, shown in Fig. 1(b), was a $350 \times 35 \times 1$ μm^3 tipless Mikromasch CSC12-E silicon AFM cantilever.[18] Figure 2 shows the frequency response of the lowest three resonances of the AFM microcantilever obtained with ultrasound radiation force excitation (●). The fundamental 11.2 kHz resonance frequency is within the nominal range for this microcantilever.[18] The second and third bending frequencies were 72.4 and 204 kHz; these are in qualitative agreement with elementary Euler–Bernoulli beam theory that would predict 6.267 and 17.55 times the fundamental for a clamped-free homogeneous beam of uniform cross section.[19] Because of the 250 kHz bandwidth of the Ultran transducer used, the highest resonance of this cantilever that could be excited was 204 kHz. For comparison with a conventional mechanical base excitation technique, the microcantilever was separately characterized using a

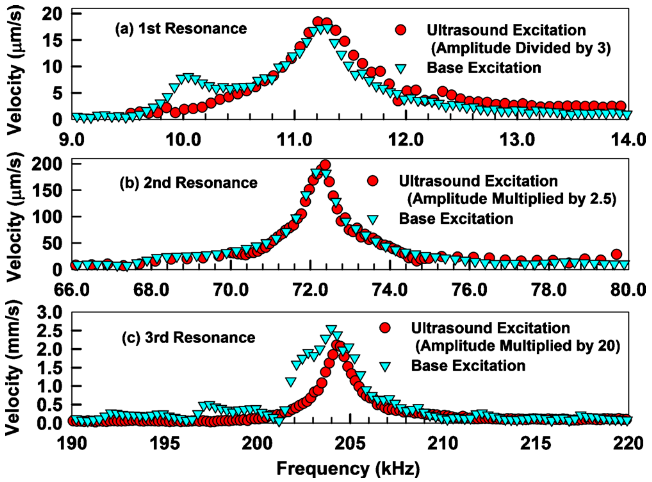

FIG. 2. (Color online) Graphs showing strong agreement between the frequency response of lowest three transverse resonances of a microcantilever excited using conventional base excitation (▼) and ultrasound radiation force (●). The resonances for ultrasound radiation force have been scaled to match the peak amplitude of the base excitation spectra.

Polytec MSA-400 scanning laser Doppler vibrometer system with a 1.5 MHz bandwidth and integrated piezoshaker base; the microcantilever was affixed to the shaker which was excited with a swept sine wave from 0 to 1000 kHz, and the MSA-400 vibrometer measured the resulting vibration (▼). The amplitudes of the data sets have been scaled so the peaks of both techniques roughly overlap. As had been demonstrated with previous studies using macroscopic cantilevers,[12] the resonance frequencies and Q-values obtained using the noncontact ultrasound radiation force were nearly the same as those obtained with mechanical base excitation. The deflection shapes measured using both excitation methods were consistent with the lowest three transverse modes of a simple clamped-free cantilever.

The other sample studied, shown in Fig. 1(c), was a coupled pair of $500 \times 100 \times 10$ μm^3 gold cantilevers separated by 250 μm. This structure was used in earlier studies to detect added masses via disorder induced mode localization.[7] Figure 3 shows the frequency response obtained for the gold microcantilever pair excited using ultrasound radiation force (●); resonance frequencies and deflection shapes were consistent with a finite-element model.[20] The lowest resonance was also characterized using a Nanotec Electronica scanning-probe microscopy system; these results are shown in Fig. 3(a) (■). Figure 3 demonstrates that ultrasound radiation force could excite both the symmetric/antisymmetric pairs of eigenstates. The ability of ultrasound to excite both pairs of the eigenstates is remarkable, since mechanical base excitation does not effectively excite the antisymmetric states of such coupled microcantilevers.

The current study demonstrates the feasibility of performing noncontact excitation using the ultrasound radiation force for objects as small as a 350 μm microcantilever; this is the smallest object that has been excited to date using ultrasound radiation force. One of the key findings of this study is that the resonance frequency and Q-values measured using ultrasound excitation is nearly identical to those measured completely independently using different measuring devices and excitation techniques; when combined with previous studies, this supports the capability of using ultrasound excitation as a noncontact alternative to conventional me-

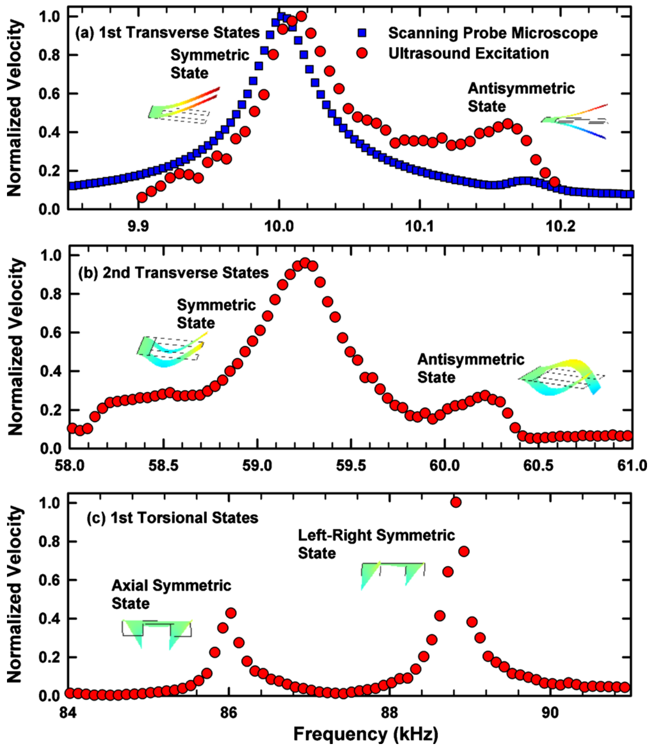

FIG. 3. (Color online) Normalized velocity response of lowest three pairs of eigenstates of gold microcantilever pair using ultrasound radiation force (●). In (a), the results obtained using ultrasound radiation force and laser Doppler vibrometer are compared to results obtained using a scanning-probe microscope (■).

chanical base excitation for microcantilever samples. Prior to the current experiment, the highest resonance frequency that had been excited in air using the ultrasound radiation force technique was 86 kHz.[20] Therefore, the excitation of a 204 kHz resonance of the microcantilever in the current study is a substantial extension of the method.

An important question is whether the microcantilevers are being excited directly by the ultrasound radiation force versus the ultrasound radiation force causing vibration of the base, which induces vibration of the microcantilevers. Extracting the relative importance of these two effects is of critical importance for some applications of ultrasound radiation force excitation. Investigations are currently underway to isolate and optimize each of these effects for a number of different excitation parameters including the dimensions of the microfabricated structure and base, ultrasound beam location and geometry, rigidity and nature of fixture used to support the sample, central carrier frequency, and other parameters. In conclusion, it has been shown that the ultrasound radiation force is a promising alternative to conventional mechanical base excitation for microcantilevers.

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