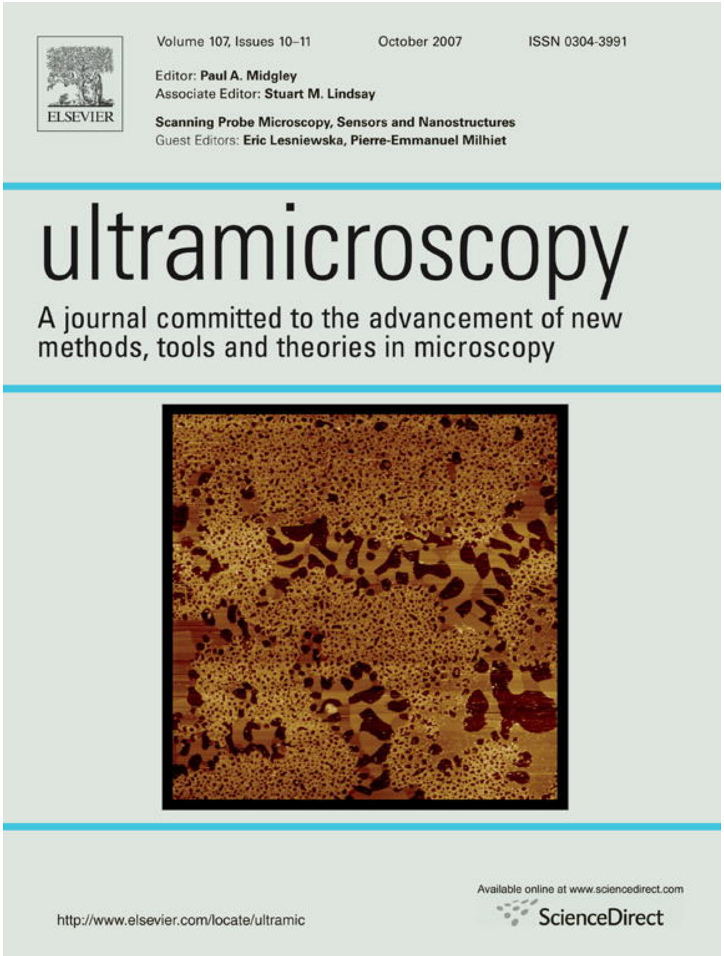
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# An experimental investigation of analog delay generation for dynamic control of microsensors and atomic force microscopy

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**Abstract**

We present an implementation of pure-time-delay generation in analog signals located in the kilo-Hertz frequency band. The controlled constant delays that are produced engage in a feedback system to investigate the dynamic response of microcantilevers. Delayed systems offer a vast richness of eigenvalues resulting in the possibility of excitations at frequencies other than that of the fundamental mode. Different cantilever actuation and delay generation approaches are investigated and compared, and detailed experimental observation of the dynamic response of the system is presented. Based on our results, an acoustic excitation is devised that may be used as an efficient sensor.


*Keywords:* Atomic force microscopy; Delayed oscillations; Dynamic control; Feedback

## 1. Introduction

The operating principle of microcantilever sensors relies on the transduction of chemical or physical processes into a mechanical response, namely the bending of the cantilevers and the change of their resonance frequencies. Main applications of the chemical sensors include the detection of vapors [1], gases [2], explosives [3], and other chemicals [4–6]. As biosensors, coated cantilevers can be utilized to trace the unspecific adsorption of proteins, antigen–antibody interaction, blood glucose levels, DNA hybridization, etc. In their work, Moulin et al. showed that microcantilever-based surface stress measurements provide a sensitive tool to probe the adsorption of proteins on solid surfaces, particularly over a long period of time. Two proteins, immunoglobulin G (IgG) and albumin (BSA), were studied. The change of surface stress upon adsorption of IgG is found to be compressive, whereas that of BSA is tensile [7]. In another experiment, Kooser et al. used coated piezoresistive cantilevers to study the interaction of anti-bovine serum albumin (a-BSA) with bovine serum albumin (BSA). Large and consistent deflection of the BSA-coated cantilever was observed while exposed to the analyte of a-BSA solution. The cantilever deflection was measured as a resistance change in the piezoresistive channel within the cantilever [8]. Similarly, Pei et al. reported a technique for micromechanical detection of biologically relevant glucose oxidase (GOx) onto a microcantilever surface [9]. The enzyme-functionalized microcantilever undergoes bending due to a change in surface stress induced by the reaction between glucose in solution and the GOx immobilized on the cantilever surface. The specific transduction, via surface stress changes, of DNA hybridization and receptor–ligand binding into a direct nanomechanical response of microfabricated cantilevers was reported by Fritz et al., where the cantilevers, in an array, were functionalized with a selection of biomolecules. The differential deflection of the cantilevers was found to provide a true molecular recognition signal despite large nonspecific responses of individual cantilevers [10]. In all such processes, the ability to control and adapt the response of the sensor is of great importance for reliable detection.

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In parallel to the above development of new applications, various methods have been attempted to control the dynamics of cantilever vibrations in an effort to improve the sensitivity of the cantilever. Recently, active feedback has attracted increasing attention since it can be used to increase the quality factor of the cantilever system, which indicates a decreasing minimum detectable frequency change and therefore a better resolution [11–15]. Mehta et al. reported a positive feedback technique by which the Brownian motion amplitude and the $Q$ factor of a cantilever in air and water could be amplified by three and two orders of magnitude, respectively [14]. In a similar experiment, Muralidharan et al. examined the conditions under which the small amplitude of thermal vibrations of cantilevers typically used for atomic force microscopy and sensor applications can be enhanced through a feedback mechanism [15]. In a mathematical model, it was then shown that for certain values of two parameters, a time delay $\tau$ and a gain factor $G$, such amplification is feasible [16,17]. In these studies, "Brownian noise" or "thermal vibration" of microcantilever sensors was amplified and controlled through a delayed-feedback system, where the delay was acquired through a phase shifter. However, in the reported experimental investigations thus far, the authors presented only the effect of certain particular delays to their feedback system. Additionally, the fundamental resonant mode was exclusively used in these studies, whereas the higher frequency modes with the potential of reaching higher sensitivity and better resolution were not utilized. Recently, Passian et al. reported an experimental and theoretical investigation regarding the higher modes of microcantilevers and their applications for highly sensitive surface displacement detection [25]. We present in this article an optimized experimental design, which enables a more complete study of the effects of constant delays to the feedback system. Furthermore, as an application of the delayed dynamics, an acoustic transducer was used as an external actuator of the cantilever. The detection of acoustic waves with microcantilevers may open new venues to acoustic source/event localization. The experimental setup and procedures are described in Section 2, while Section 3 contains the experimental results and discussions. The final Section 4 concludes the presented results.

## 2. Experiments

### 2.1. Electronic delay implementation

The schematic of the experimental setup is shown in Fig. 1a. A commercial AFM head (Nano3, Veeco) as the cantilever actuator and a Veeco as well as a home-made readout system were used. The cantilever was mounted on a piezoactuator, which when driven by an AC signal with a frequency equal to the resonance frequency of the cantilever effectively excites the corresponding mode. Commercial rectangular cantilevers (NSC12, Makromasch) were used in all experiments. The signal from the

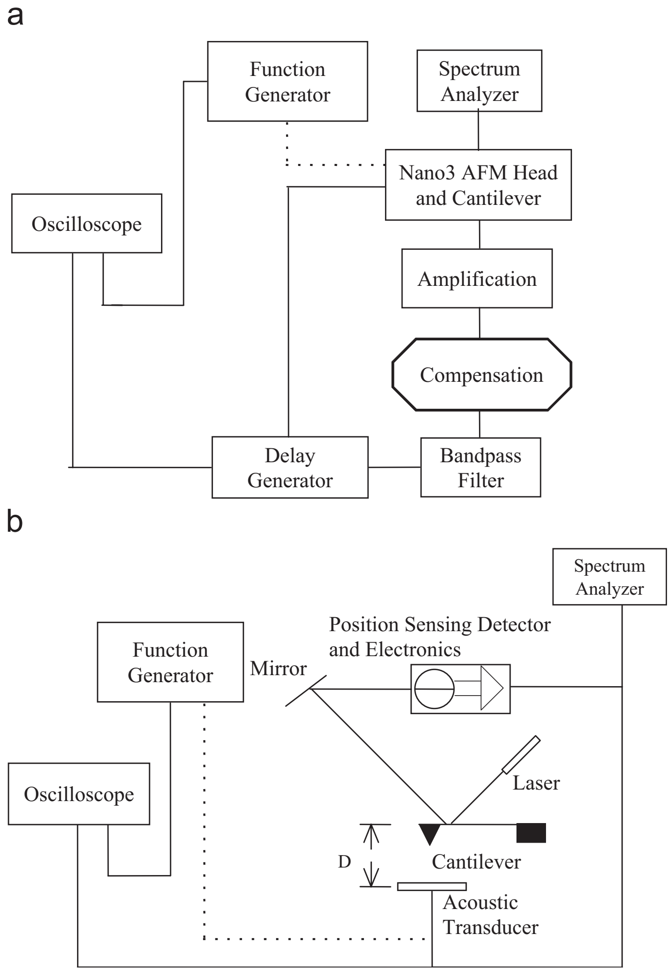


Fig. 1. Schematic of the experimental setup. In setup (a), delay modules are used to generate system delay and an internal piezoelectric actuator is used as the cantilever oscillator. In setup (b), the delay modules and the piezoactuator are replaced by an acoustic transducer.

AFM head was then amplified by a two-stage amplification system. The preamplifier, with its built-in band-pass filter, preset the frequency window of interest.

A consistent generation of delays was accomplished by cascading several delay modules (L-C delay lines, Engineered Components Company), which systematically provided a pure time delay within a range of 50 ns–20 μs. The delay modules consist of passive delay lines, which serve the special purpose of low-pass filtering designed to delay (phase shift) the input signal by a specified increment of time. These are composed of a network of parallel-coupled inductors and shunt capacitors with values dictated by the line impedance [18]. The output is tabbed such that the module's total delay is equally divided between the tabs. A 20-tab module with a total delay of $\tau_{tot} = 1\,\mu s$ yields therefore delay increments of $\Delta\tau = (50 \pm \delta)\,ns = \frac{1}{20}\,\mu s$, where $\delta$ is the relative error (smaller for larger $\tau_{tot}$). In contrast to a phase shifter used in previous studies, here the delay from the delay modules does not vary with signal frequencies. To assure linearity, this was tested over a wide frequency range including the frequencies of interest. There is a maximum attenuation of 1 dB for each of these delay modules. We therefore invoked compensation electronics to maintain constant amplitude and to balance the loss caused by the delay modules for various delays.

For each measurement, in order to determine the overall delay of the feedback system, an appropriate signal from a function generator (in most cases a sine wave of adequate amplitude and with a frequency equal to that of the cantilever) was routed to oscillate the piezoactuator and drive the cantilever. The same signal from the function generator was then compared to the final output signal from the cantilever system using a digital oscilloscope programmed for delay and phase measurements. The desired constant delay and gain were acquired in this step by adjusting the delay generator and the compensation electronics. The function generator was then disconnected and the output signal of the cantilever system was utilized to drive the cantilever, as shown in Fig. 1a. This then completed the pure-time-delay generation and the feedback loop. We assume that in the case of feedback loop the system delay remains the same as measured when an external function generator is used. The step size of delay change is 0.5 μs (or about 10° of phase change). In each step, the function generator was used to find out the system delay and then disconnected to test the feedback loop. This procedure was repeated until a full cycle of phase shift had been studied.

A spectrum analyzer (R760, Stanford Research Systems) was used to monitor the cantilever frequency. The resonant frequency $F$, full width at the half maximum (FWHM), and the quality factor $Q = F/\mathrm{FWHM}$ were simultaneously recorded.

### 2.2. Acoustic coupling and delay generation

A further experiment that examines the potential of analog delay generation is displayed in Fig. 1b. Here an acoustic transducer (CEB-27D44, CUI Inc.) is used as the cantilever actuator. The distance $d$ between the acoustic transducer and the cantilever could be adjusted precisely. A small variation in $d$ translates into a shift in the acoustic propagation time and is thus detected as a shift in the delay. No delay modules were required in this experiment, as the relative system delay was determined by the experiment itself. The position of the cantilever was controlled to move toward the acoustic transducer in a step size of 50 μm with a total travel of the cantilever in this experiment being 18 mm. The same parameters as above, that is, $F$, FWHM, and $Q$, were recorded for each step.

### 2.3. Effects of ambient media

In order to study the effect of different working media on the feedback system, the experiment was repeated in different gases, including ambient air, helium, and oxygen, as well as in vacuum. In the case of vacuum, the pressure in the chamber was pumped down to 0.01 torr. While experimenting with other gases, the pressure was maintained close to that of the ambient atmosphere. Apart from the experiments, where the pressure remained constant, the cantilever was also experimented under different pressures. Both the frequency and the bending undergo variations as a function of the pressure. Although the origin of such variations is still under investigation, the acquired data are in accordance with the reported results, where similar variations in the frequency and bending as a function of pressure and temperature were examined in various pressure regimes from the continuum to free molecular [19–23].

## 3. Results and discussion

Fig. 2 shows the variations of resonant frequency $F$, FWHM, and $Q$ of a cantilever with varied delays in a feedback system. For a known frequency, the time delay can be converted to phase shift. All three parameters show periodical variations with varied delays/phase shifts. This is in agreement with the reported theoretical simulations [17]. The resonant frequency of the cantilever fluctuated between 58,946 and 59,437 Hz when different delays were applied to the system. The original frequency was 59,167 Hz, and the FWHM and $Q$ factor varied from 528 to 2932 and 20 to 112, respectively. When one considers that the original $Q$ factor for this cantilever was 33, it is easy to see the impact of the delayed feedback. A higher $Q$ factor means better resolution in frequency measurement, while a decreased $Q$ factor, on the other hand, represents less noise. Both situations are applicable and required for relative projects.

With any fixed delay, the cantilever characteristics also varied with different system gains. These results are shown in Fig. 3. Fig. 3a shows the resonant frequency varied with the delay while different gains from $\frac{1}{3}$ to 2 were applied to

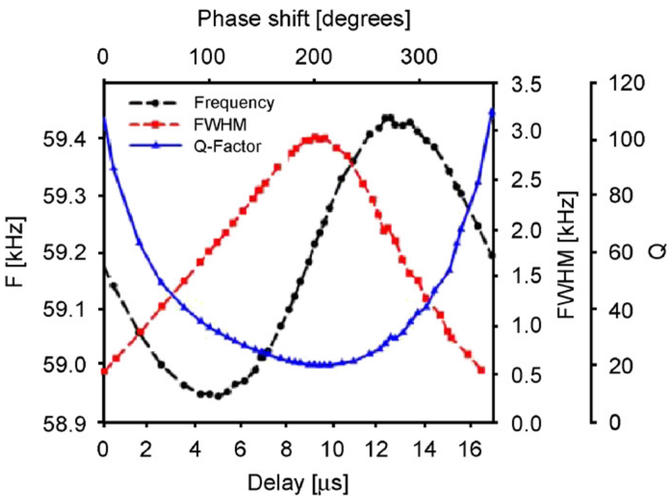


Fig. 2. The shift of resonant frequency, FWHM, and $Q$ factor as a result of varied delay. Here the system delay is also represented in the form of phase shift.

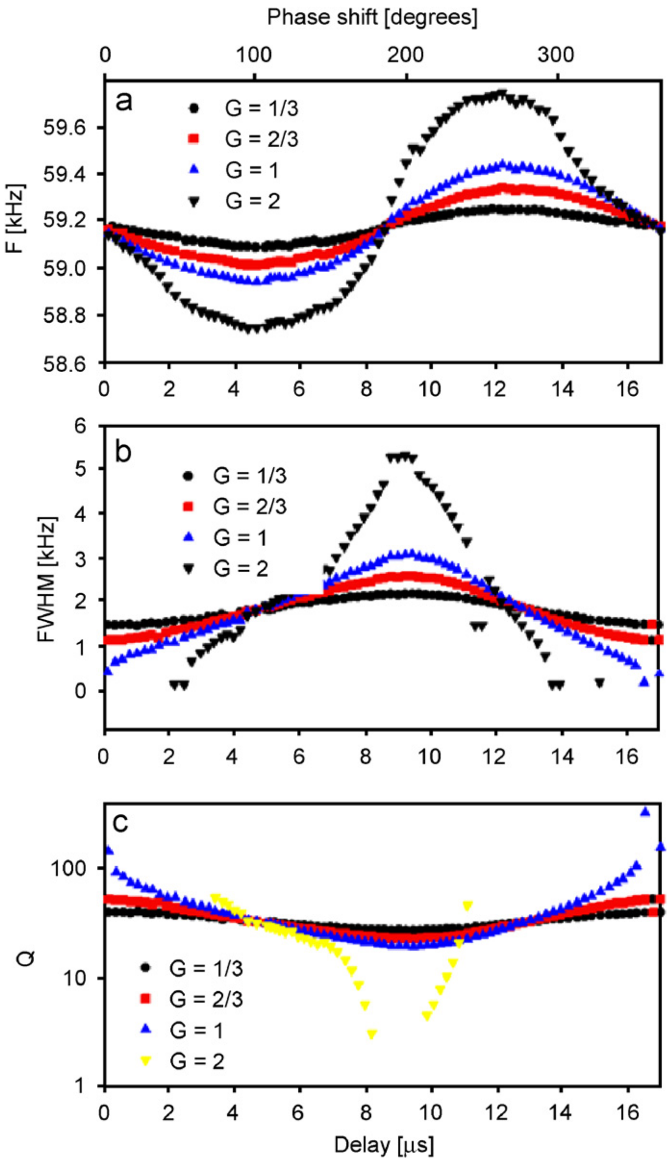


Fig. 3. The variation of resonant frequency, FWHM, and $Q$ factor with varied delay while different gains were applied. (a) Resonant frequency, (b) FWHM, and (c) $Q$ factor.

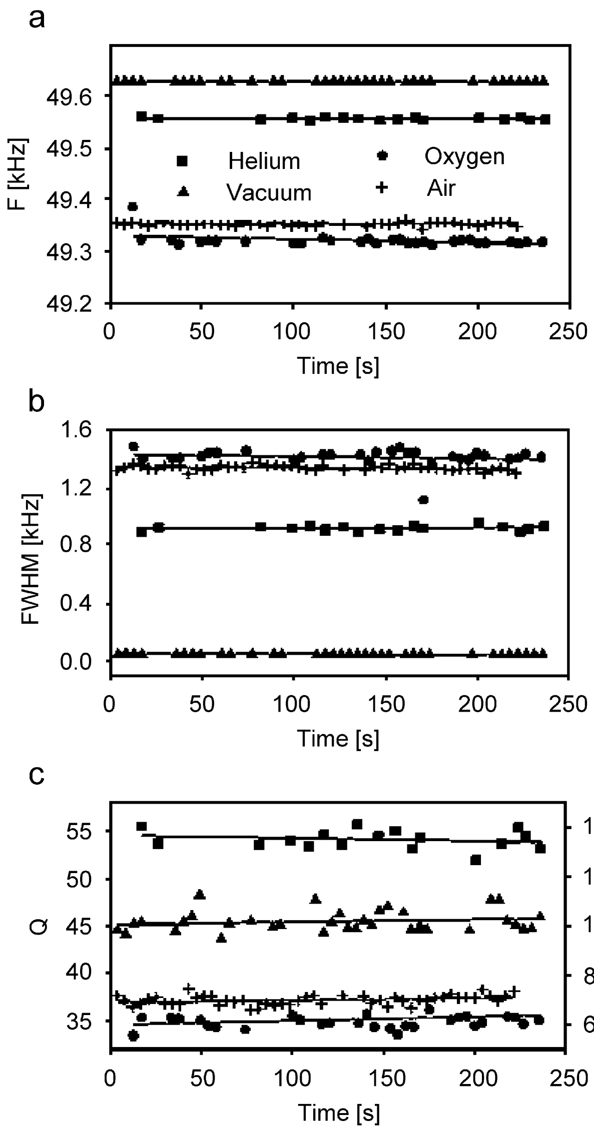


Fig. 4. The room temperature environmental effect on the noise parameters, frequency $F$, FWHM, and quality factor $Q$ detected at the fundamental frequency of the microcantilever. In (a) the fundamental frequency, in (b) FWHM, and in (c) the quality factor are monitored in four distinct environments, air, oxygen, helium, and vacuum. The solid curves are linear fits.

the feedback system. Fig. 3b and c shows the variation of FWHM and $Q$ factor with varied delays while different gains were applied. For all the parameters, an increased gain was accompanied by a larger amount of change. For example, while the gain was increased from 1 to 2, the total maximum variation of resonant frequency increased from approximately 500 to 1000 Hz. Otherwise, under the same experimental conditions, the variation in FWHM and $Q$ factor changed even more obviously.

Fig. 4 displays a measurement of the effect of the working media on $F$, FWHM, and $Q$. No driving signal or feedback was deployed in this experiment and the parameters were measured from the naturally occurring thermomechanical noise. As one can see, the cantilever noise response clearly differentiated ambient media. A frequency shift of around 300 Hz was observed in vacuum compared to that in oxygen, as seen in Fig. 4a. Furthermore, for the same case, a 29-fold increase of the quality factor is readily seen from Fig. 4b. Fig. 4c shows the variation of FWHM for different gases.

Fig. 5 shows the change of the resonant frequency and bending of the cantilever with varying air pressure. The cantilever underwent more bending when the air pressure increased, while its resonant frequency decremented with higher pressure. The cantilever also changed its behavior in a very low vacuum, due largely to the attribution of thermal transpiration effect, as discussed previously [19–23].

The effect of feedback for the cantilever's frequency spectrum is illustrated in Fig. 6. These data were collected

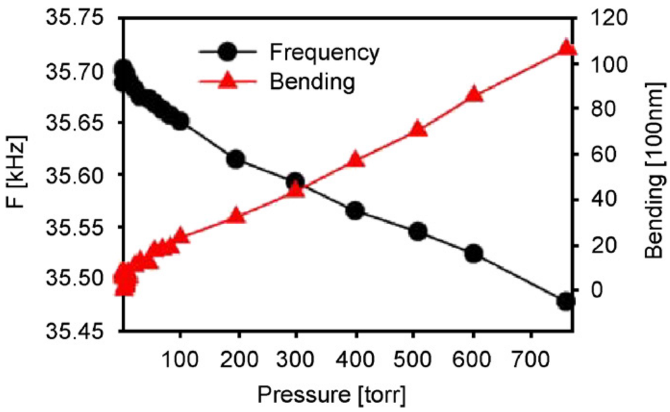


Fig. 5. The change of the resonance frequency and bending of a microcantilever with varying air pressure.

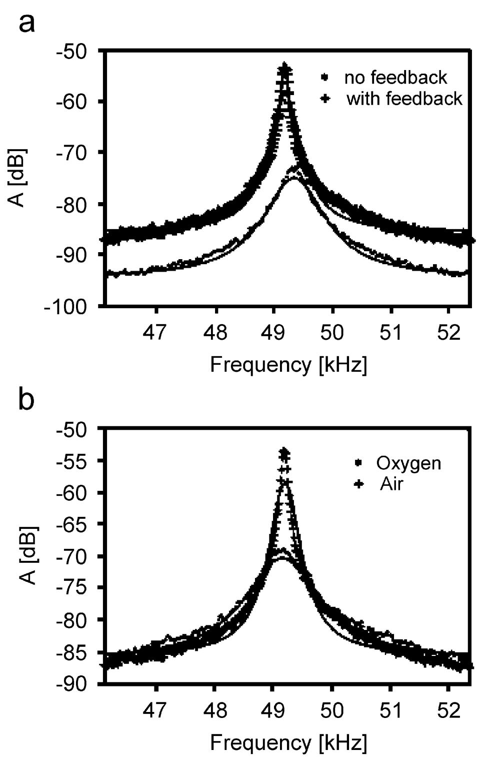


Fig. 6. The effect of feedback for different working media. (a) In air and (b) in air and oxygen.

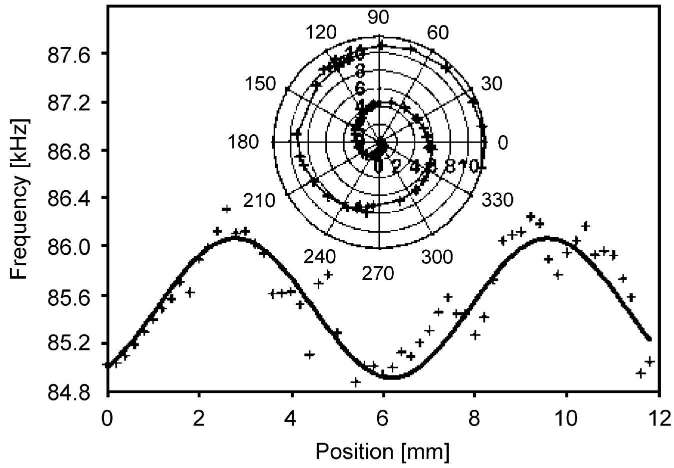


Fig. 7. Frequency response and phase shift of the second resonance peaks (85 kHz) for a delayed-feedback system. The lower part shows the frequency shift while the cantilever is traveling toward the acoustic transducer. The solid curve is the sinusoidal fit. The upper part shows the corresponding phase shift of the cantilever during its travel.

by using the setup described in Fig. 1b. With feedback, the resonant frequency shifted 170 Hz and the $Q$ factor increased from 37 to 70, as shown in Fig. 6a. Additionally, different working media resulted in obvious changes in the cantilever's frequency spectrum with feedback. In a separate experiment, ambient air and oxygen were tested, respectively, while the system delay remained unchanged. As shown in Fig. 6b, compared to oxygen, the resonant frequency of the cantilever appeared as 49.2 Hz higher in air, and the corresponding $Q$ factor increased from 34.8 to 70.2.

It is possible to achieve varying system delays by changing the distance between the cantilever and the acoustic transducer. In a feedback scheme, the traveling time of the acoustic wave decremented as the transducer approached the cantilever. Thus the delay between the driving signal and the cantilever oscillation varied. In ambient atmosphere, the speed of sound is around 340 m/s. For each movement of the cantilever in a step size of 50 μm, this corresponds to a delay of 0.147 μs. For the three different resonant frequencies, namely 13, 85, and 241 kHz, this delay represents to 0.69°, 4.49°, and 12.75°, respectively, in terms of phase shift. Here, the cantilever traveled a total distance of 11.8 mm to the transducer.

The lower part of Fig. 7 shows the frequency shift of the second resonant peak. From the solid curve (sinusoidal fit), the experiment showed that the resonant frequency shifted periodically with distance and it experienced two cycles of shift during the travel of the cantilever. This is consistent with the phase shift shown in the upper part of Fig. 7. This polar plot shows two 0-phase crossings, which represent two periodical cycles during the cantilever travel. The frequency and phase shift information of the other two resonant peaks were discussed in Ref. [18].

For the sake of completeness, we also examined the relationship between the cantilever delay and its resonance frequency. This delay is the main part of the system delay. Different frequency modes of 6 different cantilevers were measured (for example, $C_{13}$ represents the third mode of the first cantilever, and so on). These experiments clearly show that the exhibited delay is a function of its corresponding resonance frequency. As shown in Fig. 8, the response time decremented with increasing resonant frequency. The solid line represents an inverse fit function.

With the delayed-feedback mechanism, the resonant frequency of cantilever can be measured extremely precisely. For a cantilever with resonant frequency of 60 kHz, our measuring error is around 0.05 Hz, which shows two orders higher than the sensitivity while no feedback mechanism is applied.

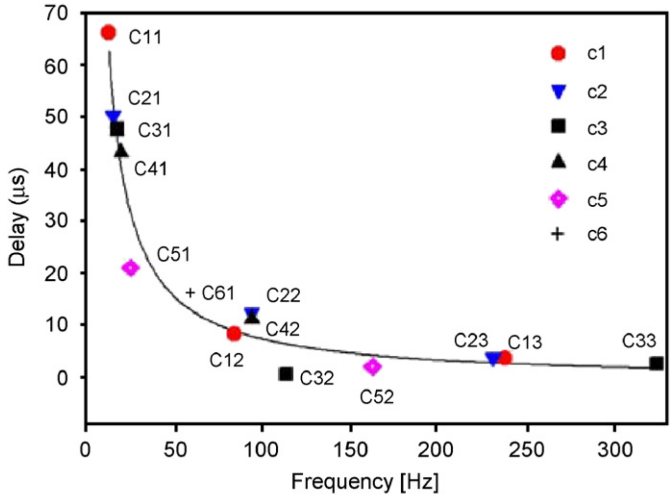


Fig. 8. The response time required by the cantilever for different resonant frequencies. The solid line is the inverse first order fit curve.

As mentioned in the Introduction previous work by others had attempted to improve the sensitivity of the cantilever system through a self-supported feedback mechanism. However, in their studies, a phase shifter, instead of pure-time-delay generator, was adopted. The results presented here demonstrate that pure-time-delay generation performs more efficiently. Also, the phase shifter responds poorly in the low-frequency range and lacks linearity, especially when the signal is very weak. Another key factor is that we noticed that a constant feedback system has to be maintained during the entire experiment, implying the gain of the amplifiers and the delay combination has to be adjusted accordingly. Therefore, a complete picture of the impact of the system delay (or phase shift) to the frequency, quality factor, as well as the sensitivity of the cantilever system was acquired successfully through careful examination of all the parameters.

## 4. Conclusions

A comprehensive experimental investigation of a pure time delayed-feedback microcantilever system was presented. The established results for the effects of constant delays to a feedback cantilever system, acquired over wide ranges of the system gain and delay, provide important information for sensing applications of the kind, where frequency tuning and control play a dominant role. The frequency shifts of the higher frequency modes, as well as the fundamental mode of the sensor, were measured so as to provide the optimum working parameters. Furthermore, from the responses of the system to the internal piezoelectric bimorph, as well as an external acoustic actuator, it was established that the usage of the latter efficiently and conveniently provides an auxiliary sensory channel. Such a sensor, based on the technique implemented in the experiment, may be applied to various fields such as remote microscale surface movement measurement, gas composition detection, and acoustic wave detection. The dynamic aspects of the presented delayed-feedback system may naturally be utilized in atomic force microscopy. In such a case, the extension of the presented results is fairly straightforward.

Finally, the effect of different working media and the corresponding pressure dependence of the behavior of the cantilever were also studied. These investigations shed light onto the development of new sensors, and furthermore stimulate discussions towards a study of probing acoustic fields remotely using micrometer sized sensors. Using similar experimental results as presented, it may also be interesting to investigate the case where fluctuation and dissipation of the oscillator may be studied under delayed feedback. Such experiments may present unique opportunities in obtaining stochastic information such as those formulated by the fluctuation dissipation theorem [24].

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