Proceedings of the American Control Conference
Arlington, VA June 25-27, 2001

DESIGN AND ANALYSIS OF A DYNAMIC MEM CHEMICAL SENSOR

Kimberly L. Turner and Wenhua Zhang

Department of Mechanical & Environmental Engineering, University of California, Santa Barbara, CA 93106. Email: turner@engineering.ucsb.edu, Phone: 805-893-5106, Fax: 805-893-8651

1. ABSTRACT

One possible definition of MicroElectroMechanical Systems (MEMS) encompasses any electro-mechanical structure or device which has feature sizes on the order of $1\mathrm{x}10^{-6}$ m. In this size regime certain effects become important which were not important at more macroscopic scales. These effects include damping and electrostatic actuation methods. In addition, fabrication methods and design of microsystems has progressed to the point where simple structures can be fabricated which isolate certain features or aspects of the structure. Not only can these dynamic effects be utilized in transduction systems, but they can be used to visualize and study systems which cannot readily be duplicated in a macroscopic system. In this paper, an example of microelectromechanical system is presented which utilizes novel dynamics for sensing. Such devices can also be used to investigate the experimental behavior of mathematical systems previously not accessible. The example presented here is a mass/chemical sensor based on parametric resonance.

2. INTRODUCTION

In the recent past, dynamic sensors have been utilized in MEMS for many applications, and in many cases, have proved to be significant improvements over their static or quasi-static counterparts. Nonlinear and quasi-linear effects which are not observed or utilized on the macroscopic scale can be extremely important and impact greatly on existing technology at smaller scales. In MEMS (smallest feature ~1μm), these effects can be used to improve on existing mechanical filter technology and sensing techniques, among others. The theoretical development of a novel ultra-sensitive mass sensor using parametric resonance phenomenon is presented. The devices discussed can be used for chemical, biological agents and other types of sensing, and testing is underway. The sensing element is based on parametric resonance technology to achieve high sensitivity. This work extends prior work done by the authors on parametric resonance phenomena [1,2], as well as chemical sensor work performed by various groups [3,4].

2.1 BACKGROUND

High-discrimination, accurate sensors have been a goal in recent years that has led to the use of MEMS for sensing. Current MEMS sensors for chemical detection use changes in electrical properties (resistance, voltage, and capacitance) or resonant frequency shifts (change in mass, or polymer properties) to detect the presence of chemicals[3]. Changes in chemical concentrations in the environment can be related to these properties in many ways. When chemicals species react with a sensitive layer there are three possible results: heat produced, a change in electrical properties within that film, and/or a change in mass. First, considering heat changes, endothermic and exothermic reactions can be detected through resistance changes when the sensitive layer is on a bimorph with a piezoresistor. These reactions also can be detected through frequency shifts when heat changes affect the resonator such as with quartz[4]. Changes in the resistance, voltage, or capacitance in the sensitive layer is directly measured to detect changes caused by reacting chemical species. Finally, changes in mass are detected by the shifting of the resonant frequency in the resonator. Damping can reduce the accuracy of resonant frequency measurement, thus depending on the damping present, the method can vary in sensitivity. These methods give concentration detection in the range of 10^{-3} to 10^{-5} ppm[3]. Using parametric resonance as a mechanism for detecting the presence of chemicals is a previously uninvestigated idea, and one which has potential to improve the sensitivity of resonant chemical sensors.

3. THEORY OF PARAMETRIC RESONANCE

Parametric resonance, more specifically the Mathieu and Hill equations, have been studied for many years (Mathieu 1850), however, due to air-damping effects, have not been utilized in macroscopic engineering systems to a broad extent. However, in MEMS, damping effects can be minimized both by design of the MEM structure, as well as the environment the structure is operated in. One example of this is an electrostatically-driven torsional MEMS oscillator [5] The oscillator is shown in Figure 1. When driven with a sinusoidally-varying voltage, the single degree of freedom equation of motion is modeled. Using a simple 1-D mechanical model, the equation of motion for such a system is the Mathieu Equation.

$$\frac{d^2\theta}{d\tau^2}+(\beta+2\delta\cos 2\tau)\theta=0 \qquad (1)$$

0-7803-6495-3/01/$10.00 © 2001 AACC

where (for the torsional system) $\beta = 4(k + \gamma A_{DC}) / \omega^2 I$ and $\delta = 4\gamma A_{AC} / \omega^2 I$, and $2\tau = \omega t$ (k=torsional stiffness, I=mass moment of inertia, *Adc* is the DC voltage signal applied, *Aac* is the ac voltage applied, and ω is the driving frequency).

Equation 1 possesses unique stability properties. In contrast to a second-order directly-forced system, there are multiple unstable regions, which are mapped out as a function of β and δ in Figure 3.

4. EXPERIMENTAL VERIFICATION OF THEORY

The device modeled above (shown in Figure 1) was experimentally tested. The test procedure is discussed in section 4.2. The transition between stable and unstable is extremely sharp. Therefore, by sweeping the frequency, the response will transition from stable (small) to an unstable, or resonant (large amplitude) oscillation. This is illustrated in Figure 4. The frequency change necessary to move from small amplitude to large has been experimentally measured to be <0.001 Hz. when operated at a pressure of 5mPa. Figure 5 is the result of a frequency sweep near the edge of the n=1 transition region. A frequency shift of 0.001 Hz moves from a stable state to an unstable (or limit cycle, due to nonlinearity not included in the model here) one. This is in contrast to a conventional resonant cantilever, which possesses a Lorentzian-type of response near resonance. This sharp transition leads to unique possibilities as a sensor, with greater resolution than a single cantilever type of sensor. Using precise experimental techniques for accurately measuring the real-time response of micro-scale devices, the transition between stable, and unstable behavior was characterized. The damping effects were also previously characterized [6]. Using the results from this study, a design for the chemical sensor was conceived.

4.2 EXPERIMENTAL TEST PROCEDURE

Experiments are carried out using the MEMS characterization suite [7]. By combining an optical microscope with long working distance (>20mm) objectives and a fiber optic laser vibrometer, the instrumentation suite shown in Figure 6 is used to measure the motion of MEMS. Using a 50x final lens, the minimum spot size is ~1 μm and can be focussed on a movable feature of most MEMS structures. Minor modifications allow the integration of a small vacuum chamber with a topside viewport, which can control the pressure from atmosphere to 1.0 mTorr The vibrometer instrumentation is capable of resolving velocities to 0.1 μm/s and displacements to 4 nm while operating with bandwidths up to 2.5 MHz. The real-time velocity and position information are viewed using an oscilloscope and a spectrum analyzer. These instruments are controlled using a LabView interface on a PC.

Laser vibrometry is typically limited to measuring motions perpendicular to the incident beam (out-of-plane), however, with one additional fabrication step, measurements can be made on MEMS devices which move in-plane. We have used a focused ion beam system to mill an integrated, 45 degree, micro-mirror adjacent to a MEMS device. Mirrors could also be made using other techniques, such as KOH etching, and used with microscope tilt to compensate for the incident angle difference. The mirror reflects the incident laser light into the plane of the wafer where it strikes the MEMS structure parallel to the direction of motion. Normal reflection from the MEMS structure and the micro mirror sends the interfering signal back along the incoming laser path. By integrating mirrors along the primary in-plane motion directions, and by also measuring the out-of-plane motion, three-dimensional motion characterization can be achieved.

5. CHEMICAL SENSOR DESIGN

We have designed a mass/chemical sensor, which utilizes the unique properties of parametric resonance. Because of the sharp transition (0.001Hz, shown experimentally in Figure 4) from stability to instability which depends on the device parameters, it provides an extremely way to detect things such as small changes in mass of a device.

5.1 DEVICE DESIGN

The device to be used as a mass sensor here is a novel in-plane fringing-field comb drive resonator [8](see Figure 7). The in-plane resonator is sensitive to minute changes in mass, whereas the torsional resonator shown and described in the previous section, was sensitive to changes in the mass moment of inertia. Thus, the torsional device is sensitive to the location on the structure where mass was added or taken away. In this design (in-plane), the total change in mass (for mass change that is small with respect to the device size) will affect the location of the transition curve, rather than the location on the device where the absorption of mass occurs. Thus for early experiments, this is a design of choice. When voltage is applied to the moving comb fingers, the device will move laterally. The device exhibits an $n=1$ parametric resonance.

5.2 SENSITIVITY

The equation of motion can be written in Mathieu-Hill form similar to Equation 1 above, and the transition curves can be determined in the same fashion. The transition describing the transition curves for *n=1* is, to a first approximation:

$$m = \frac{4k}{\omega^2} + \frac{4\xi V_{DC}}{\omega^2} \pm \frac{2\xi V_{AC}}{\omega^2} \qquad (2)$$

where k is the stiffness of the system, m is the mass, ξ is the linear stiffness coefficient of the fringing-field comb-drive, ω is the frequency of signal, and V is the applied signal magnitude. When the system is subject to a change in mass, the parametric frequency shifts. A small change in mass, *dm*, shifts the parametric frequency $d\omega$ The equation, which relates a change in mass to a resolvable shift in frequency, is:

$$dm = \left|(4k + 4\xi V_{DC} \pm V_{AC})\frac{1}{\omega^3}\right| d\omega \qquad (3)$$

Using MEMS bulk Silicon fabrication technology, there is a lot of flexibility in the device design. For the highest sensitivity, the device should be as small as possible. Devices with resonant frequencies from 100Hz-1MHz are possible with single mask, bulk Silicon fabrication processes [9]. And since the transition from stable region to unstable region is selective to $\delta\omega$=0.001Hz (Figure 4), very small changes in mass can be resolved. Because the transition is extremely sharp, there is a very high degree of discrimination for small mass change.

5.3 SENSOR EXPERIMENTAL DESIGN

To test the device, experiments have been designed to detect humidity. The surface of the devices is coated with the native oxide of silicon (naturally occurring when the device is exposed to air), which will absorb water molecules on the surface of the device and therefore change the mass of the device. The mass change can therefore be detected by the shift of the n=1 transition curve.

6. FUTURE WORK

The device has been fabricated at Cornell University. Experiments are in progress to verify ultimate sensitivity in such device. Theoretically, sensors of this design are able to detect such small mass changes as 1e-15--1e-16 g, which is ~two orders of magnitude more sensitive than the ordinary cantilever mass sensor [3, 4]. The ultimate resolution of the device depends on the parameters of the resonator, as well as calibration methods, signal to noise ratio, and detection scheme, all of which are being investigated. Control algorithms to accurately operate the device, and determine the location of the transition between stable and unstable are in development as well.

7. CONCLUSION

A novel sensor using parametric resonance has been developed and fabricated. Tests are underway to determine its ultimate performance. Parametric resonance shows promise as a useful technique to improve resolution in resonant chemical sensing.

8. ACKNOWLEDGEMENT

The author would like to acknowledge Rajashree Baskaran for contributions to this work. This work is supported by NSF CAREER award #0093994.

9. REFERENCES

[1] K. L. Turner, et. al., "Five Parametric Resonances in a MicroElectroMechanical System," *Nature*, 396, 149-153 (1998).

[2] K. L. Turner and N. C. MacDonald, "Understanding Parametric Resonance Effects in common MEM actuators," *presented at Hilton Head 2000, Solid-State Sensors and Actuator Workshop, Hilton Head, SC* 2-6June2000.

[3] Thundat, T., Oden, P. I., and Warmack, R. J., "Microcantilever sensors," *Microscale Thermophysical Engineering* 1 (1997) 185-199.

[4] J. R. Vig. Chemical sensor based on quartz microresonators. *J. Microelectromechanical Systems*, 5(2) 138-140, (1996).

[5] Miller, S. A., K. L. Turner, and N. C. MacDonald, "Micromechanical Scanning Probe Instruments for Array Architectures," Review of Scientific Instruments, **68**, 4155-4162 (1997).

[6] Turner, K.L., "Application and Analysis of Parametric Resonance in MicroElectroMechanical Systems," Ph.D. Thesis, Cornell University, 1999.

[7] Turner, K. L., Hartwell, P. G., Webb, R. W., and MacDonald, N. C. (1999b) Three dimensional MEMS motion characterization using Laser Vibrometry, *proceedings of Transducers '99, the 10th international conference on Solid-State sensors and actuators*, 1144-1147.

[8] S. G. Adams. Design of electrostatic actuators to tune the effective stiffness of Micro-electro-mechanical Systems, Dissertation, Cornell University (1996).

[9] K. A. Shaw, Z.L. Zhang, and N.C. MacDonald, "SCREAM-I, A single-mask, single-crystal silicon, reactive ion etching process for microelectromechanical structures," *Sensors and Actuators A* **40** 63-70 (1994).

10. FIGURES

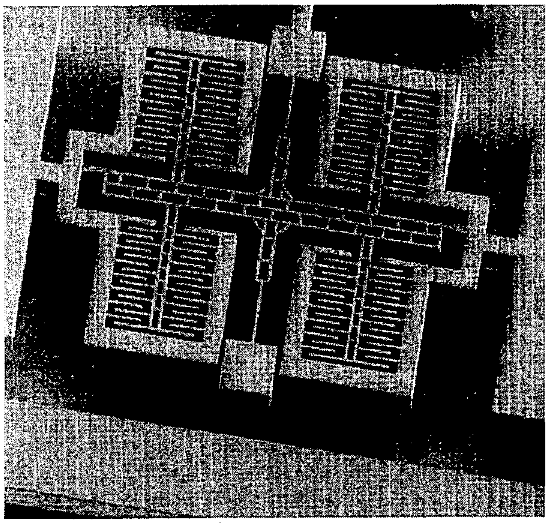

Figure 1. A Single-crystal Silicon torsional resonator. The device is actuated (and sensed) using interdigitated levitation capacitive drives. The device was fabricated using the SCREAM-1 process. []

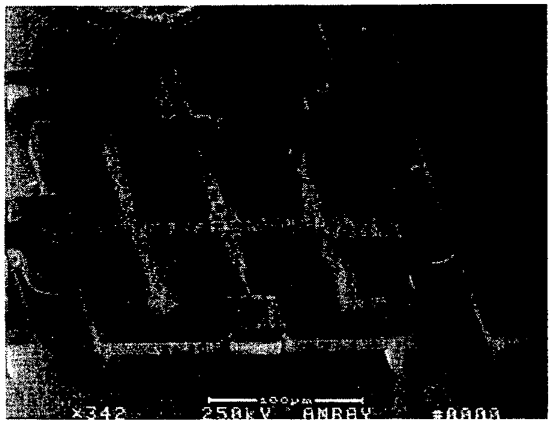

Figure 2. This scanning electron micrograph (SEM) shows a torsional oscillator in motion. The ends of the cantilever are moving ~16µm. The device resonates at approximately 69kHz.

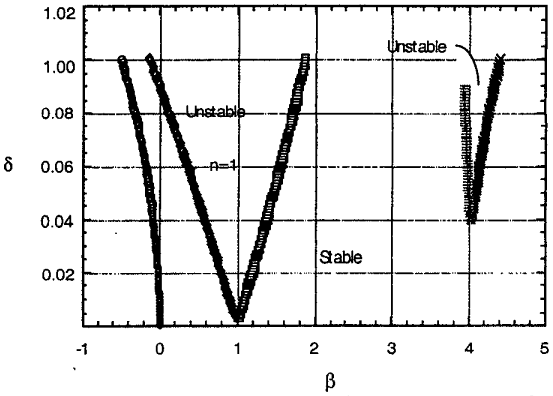

Figure 3. Theoretically determined parameter space for n=0,1,and 2 instability regions. The area inside the 'tongues' is unstable (large amplitude response), where the area outside of the 'tongue' is stable (small amplitude response)

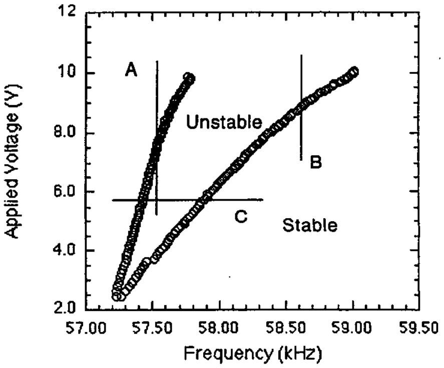

Figure 4. Experimentally determined n=1 transition curve, plotted in Frequency-Applied Voltage space. Moving from top to bottom along Line A (increasing the voltage holding frequency constant) will cause a transition from unstable (large motion) to stable; Moving from Left to Right along Line C (increasing the frequency holding the voltage constant) will cause a transition from stable to unstable and then back to stable again; and moving from bottom to top along line B (an increase in Voltage holding the frequency constant) will cause the opposite transition of line A (stable to unstable).

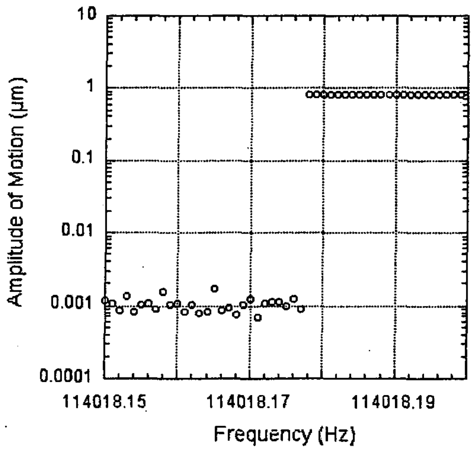

Figure 5. Experimentally measured transition between stable and unstable for the n=1 transition region. A change in driving frequency of 0.001 Hz will transition the response from stable (small amplitude, <5nm) to unstable (actually a limit cycle due to nonlinearity, large amplitude response). This measurement was performed on a device similar to that shown in Figures 1 and 2.

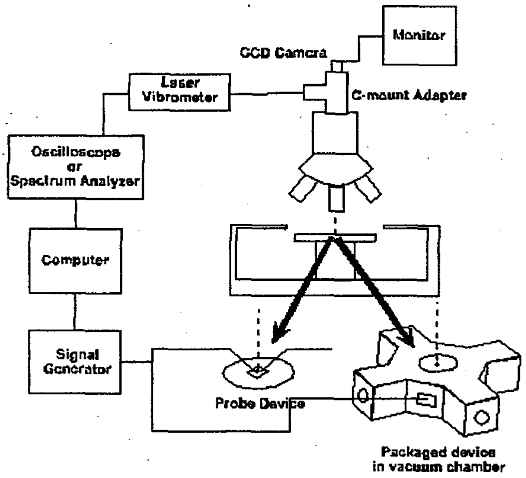

Figure 6. A schematic of the test setup used to perform the real-time dynamic analysis of MEMS.

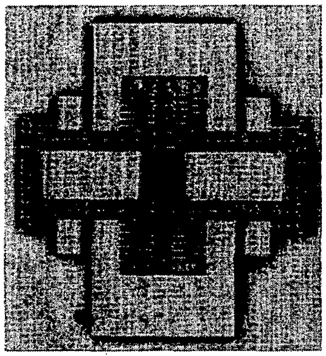

Figure 7. The microfabricated in-plane mass sensor device. The device is actuated using in-plane fringing-field actuators. The actuators will cause the device to move in the vertical direction in the figure (from top to bottom). The area which will be treated to absorb molecules is the backbone, ladder-type structure in the center. The structure is fabricated from Single-crystal Silicon, and is suspended from 'springs' on either side of the backbone.