Application Note *VIB-M-03*

FIELD OF APPLICATION

- **A** Aerospace
- **B** Audio & Acoustics
- **C** Automotive
- **D** Data Storage
- **G** General Vibrometry
- **M Microstructures & systems**
- **P** Production Testing
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- **U** Ultrasonics

Sensing Picogram Masses: Laser Vibrometry Leads to Breakthroughs in MEMS Dynamic Analysis

Laser-Doppler Vibrometry (LDV) measurements have been instrumental in the development of resonant microelectromechanical systems (MEMS). In this article, the benefits of LDV for MEMS analysis and measurement are discussed for the specific case of a resonant Mass/ Chemical Sensor.

Introduction

Only 10 years ago, quantification of three-dimensional motion in MEMS required placing the device in a scanning electron microscope, operating it, and videotaping the resultant motion. Video analysis could be done to quantify the motion, though substantial error remained in the measurement. On-chip measurement circuitry was also used, but this, too, had some problems, including not being able to diagnose motions or instabilities which were not anticipated by the designer.

Due to these difficulties, it was not easy to get experimental verification of nonlinear behavior in MEMS devices, behavior which was often present, and detracting from the optimal operation of the device, be it a micro STM or micro AFM, switches, filters, resonators, accelerometer, or other resonant MEMS.

With the integration of an optical microscope and the Polytec LDV (collaboration between MacDonald group, Cornell, and Polytec), the microscope-based vibrometer was born.

This new instrument enabled single-point, out-of-plane measurements from a 1-micron diameter laser spot precisely located on the MEMS device. In-plane measurements could also be made with the same laser beam by integrating a 45 degree mirror into the device [20] (see Figure 3; editor's note: or by using Polytec's planar motion analyzer). Measurements that had been tedious and error-filled became accurate and simple. The microscope-based LDV significantly increased the understanding and the ability to model nonlinear behavior in MEMS devices, resulting in many new applications based on this behavior. Mass sensors are one such application which is being developed using LDV as a measurement technique. In this project, we use a different approach to improve sensitivity.

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Mass Sensor Background

As the technology of miniaturization develops rapidly, building ultra-small micro/nano scale oscillators is achievable. In micro/nano chemical sensors, one commonly employed method involves tracking mass change on a surface-activated cantilever. The concept of tracking resonant frequency or phase shifts of micro/nano-oscillators in the simple harmonic resonance mode to measure mass change has become a well-established technology for chemical and biological sensing [1 – 8].

Since the fundamental resonant frequency of simple harmonic resonance depends on the mass and stiffness of the oscillator, mass change can cause the resonance frequency to shift and thus can be tracked. High mass sensitivity can be achieved by using an oscillator with extremely small mass and high resonant frequency.

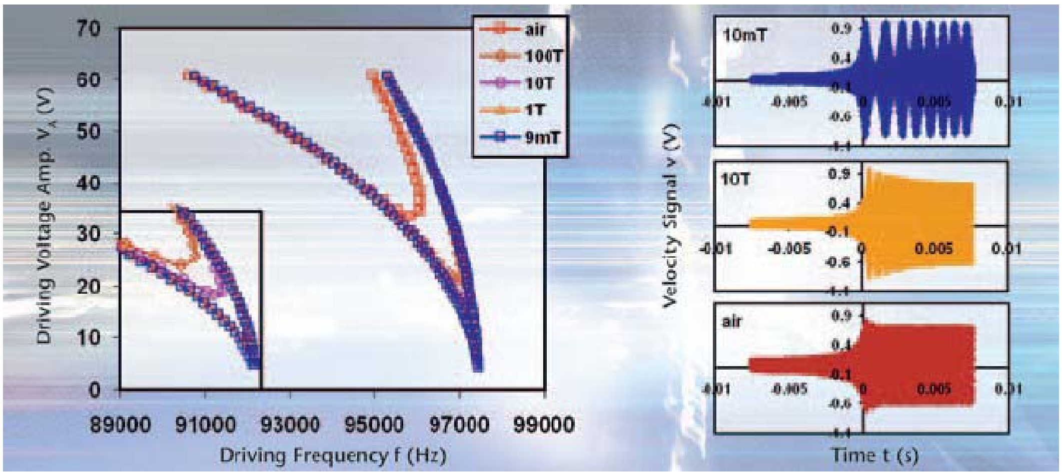

Figure 1: Damping Response. Left graph, instability regions of the sensor at different pressures. Right graph, sensor response inside the 'tongues' at different pressures (in Torr)

In a micro-cantilever array, information on cantilever resonant frequency shifts can be used for recognition of a variety of chemical substances, including water, primary alcohols, and alkanes [3]. By creating even higher-frequency nanoscale oscillators with a resonance frequency in MHz or GHz range, the ability to detect femtograms (10^{-15} g) or even attograms (10^{-18} g) of mass change may be achievable [5, 7 – 11].

Theoretically, any mass change in the sensing oscillator can cause a certain amount of frequency shift. However, the performance of frequency shift detection is governed by many factors, including readout circuitry, noise, quality factor of the oscillator, and others. Quality factor (Q), which denotes the sharpness of frequency response curve of simple harmonic resonance, is one of the important factors that limit the sensitivity of simple harmonic resonance (SHR) based mass sensors. Micro/nano-oscillators with high Q can detect small mass changes because of the ability to resolve small frequency shifts.

Currently, silicon oscillators can achieve $Q \sim 10^4 - 10^5$ at high vacuum and low temperature. However, for detection of chemicals in air, the Q factors are significantly lower, due to higher damping conditions. For this type of sensing, we utilize another approach to improve sensitivity, while retaining the other benefits of micro-scale devices.

Parametric Resonance

We have previously reported the conceptual basis of mass sensing using the parametric resonance phenomenon [13, 14]. In this mass sensing process, mass change is monitored by measuring frequency shift at the stability boundary of the first order parametric resonance 'tongue' [13, 14]. The frequency transition at this boundary is very sharp [15], thereby making small frequency changes easily detectable and the frequency shift resolution high [14, 16]. The sharpness of the boundary does not depend on the quality factor [17, 18].

Figure 1a shows the stability boundary, and how these boundaries respond to damping. Figure 1b shows that the device response amplitude (the quantity which must be sensed) does not depend on damping.

Therefore, very small mass change can be detected in high-pressure environments, such as in air or even in water, where traditional resonant sensors fail. Of course this does not come for free, as there is more power required to create the oscillation in highly damped environments.

Testing Technique

Experiments are carried out using the approved MEMS characterization suite [20]. By combining an optical microscope with long working distance (> 20 mm) objectives and a fiber optic laser vibrometer, the instrumentation suite shown in Figure 2 is used to measure the motion of MEMS. Using a 50x final lens, the minimum spot size is ~1 µm and can be focused on a movable feature of most MEMS structures.

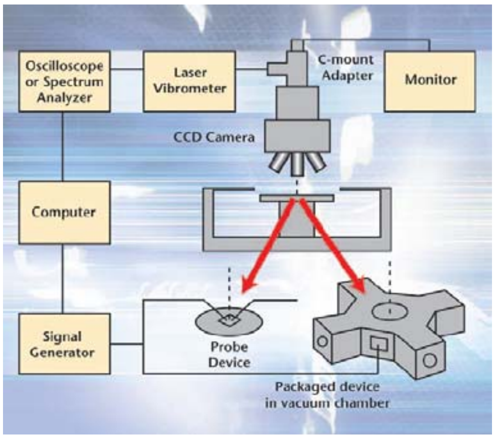

Figure 2: A schematic of the test setup used to perform the real-time dynamic analysis of MEMS

Minor modifications allow the integration of a small vacuum chamber with a topside view port, which can control the pressure from atmosphere to 1.0 mTorr. The vibrometer instrumentation used here is capable of resolving velocities to 0.1 µm/s and displacements to 4 nm while operating with bandwidths up to 2.5 MHz. Other configurations would allow for even higher bandwidth and resolution. 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 (Figure 3).

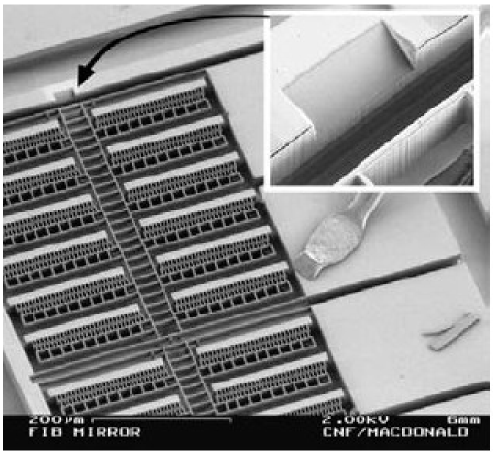

Figure 3: A MEM oscillator showing the 45-degree mirror

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.

Mass Sensing Results

This mass sensor is comprised of a single crystal silicon micro-oscillator (Figure 4), in which the backbone is supported by four folded beams to provide recovery force for the oscillation and driven by a set of non-interdigitated comb-fingers using fringing-field electrostatic force [19].

Parametric resonance can be activated at certain frequencies because the non-interdigitated comb-fingers change the effective stiffness of the oscillator periodically in case an AC voltage signal is applied to actuate the oscillator [14]. Mass change can be determined by measuring the frequency change at the boundary of parametric resonance. This preliminary device has sensitivity at the picogram (10^{-12} g) level when operating in air.

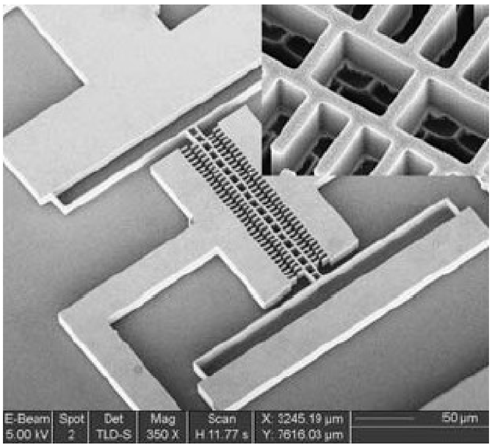

Figure 4: A SEM picture of the prototype mass sensor. It has a backbone and four springs with folded beams

The ultimate sensitivity of this conceptual mass sensor is studied by testing water vapor content change in the test environment. Less than 1 pg of mass change in the oscillator has been detected in air. This sensing capability agrees very well with noise analysis results considering Brownian motion effects. Figure 5 shows the sensor response to water vapor adsorption tests.

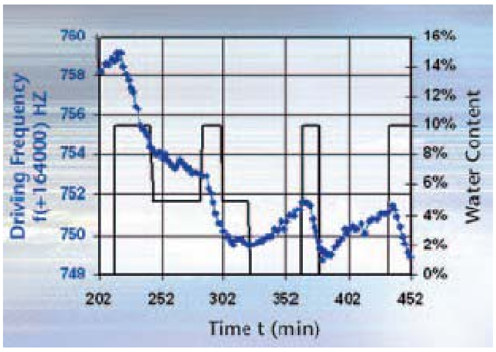

Figure 5: Frequency shifts at the right side of the first parametric resonance area as adjusting water content in the testing chamber. Resolvable mass change is less than 10-12 g

Conclusion

Figure 6 compares a number of resonant mass sensors. By utilizing parametric resonance, vacuum level sensitivity can be achieved in air. In conclusion, this example points out just one of many applications which have significantly improved development thanks to the measurements achievable with LDV.

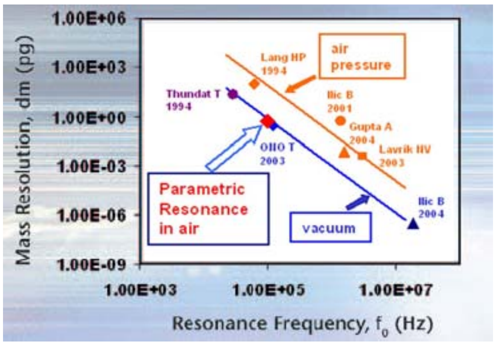

Figure 6: Comparison of Technology. Note that our sensor, although an air-sensor, is operating at the sensitivity of the sensors operating under vacuum

The Author

Kimberly L. Turner, Ph. D.

Associate Professor, Mechanical & Environmental Engineering

Director, Mechanics of Microsystems Laboratory

University of California,
Santa Barbara, CA 93106

turner@engineering.ucsb.edu

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If you have specific requirements or need help for your custom solution, please contact Polytec's application engineers.

Polytec GmbH
Polytec-Platz 1-7
76337 Waldbronn
Germany
Tel. + 49 (0) 7243 604-0
Fax + 49 (0) 7243 69944
info@polytec.de

Polytec-PI, S.A. (France)
32 rue Délizy
93694 Pantin
Tel. + 33 (0) 1 48 10 39 34
Fax + 33 (0) 1 48 10 09 66
info@polytec-pi.fr

Lambda Photometrics Ltd. (Great Britain)
Lambda House, Batford Mill
Harpenden, Herts AL5 5BZ
Tel. + 44 (0) 1582 764334
Fax + 44 (0) 1582 712084
info@lambdaphoto.co.uk

Polytec KK (Japan)
Hakusan High Tech Park
1-18-2 Hakusan, Midori-ku
Yokohama-shi, 226-0006
Kanagawa-ken
Tel. +81 (0) 45 938-4960
Fax +81 (0) 45 938-4961
info@polytec.co.jp

Polytec, Inc. (USA)
North American Headquarters
1342 Bell Avenue, Suite 3-A
Tustin, CA 92780
Tel. +1 714 850 1835
Fax +1 714 850 1831
info@polytec.com

Midwest Office
3915 Research Park Dr., #A12
Ann Arbor, MI 48108
Tel. +1 734 662 4900
Fax +1 734 662 4451

East Coast Office
25 South Street, Suite A
Hopkinton, MA 01748
Tel. +1 508 544 1224
Fax +1 508 544 1225