

MECHANICAL DOMAIN NON-DEGENERATE PARAMETRIC RESONANCE IN TORSIONAL MODE MICRO ELECTRO MECHANICAL OSCILLATOR.

Rajashree Baskaran and Kimberly Turner

Department of Mechanical Engineering, University of California, Santa Barbara, CA 93105

Ph: 805 8937849 Fax: 805 893 8651 Email: raji@enr.ucsb.edu

ABSTRACT

We present experimental results of operation of a single oscillator with time varying stiffness as an auto-parametric resonator in both degenerate and non-degenerate mode. The stiffness corresponding to the first two natural modes of this oscillator is designed to be time dependant and under such a condition the "sum type" parametric resonance is observed. This two mode non-degenerate version of parametric resonance offers some advantages over the degenerate version. The driving frequency and the response frequency are totally decoupled (they are related by integer or fractional harmonics in the case of degenerate amplification). The drive frequency, which is the sum of the first two natural mode frequencies, can be designed to be as far away as needed from the first natural frequency at which the signal gets amplified.

INTRODUCTION

Resonant mode operation of micro electro mechanical oscillators has many applications which include sensing, on-chip filters/switches/mixers in the radio frequencies[1], scanning probe microscopy[2, 3] and small force detection[4]. When operated in the linear regime as simple harmonic oscillators there is a tradeoff between the selectivity (Quality factor) and the bandwidth of operation. Also, the selectivity (Quality factor) is primarily controlled by viscous damping which depends on the ambient working conditions. This makes vacuum packaging, an expensive and relatively new technology, a requirement for the micro oscillator operation. Operation in parametric resonance mode offers advantages such as very high selectivity and independence of selectivity and ambient conditions (damping)[5]. Parametric resonance can be excited in many MEMS configurations if there is a displacement dependent force generation.

In this paper, we present experimental results of operation of a single oscillator with time varying stiffness (due to electrostatic actuation) as an auto-parametric resonator in both degenerate and

non-degenerate modes. While there is previous work regarding degenerate parametric resonance and amplification in single micro electro mechanical oscillators[5-7] and non-degenerate amplification using non-linear mechanical stiffness [8, 9] or in coupled two oscillator systems[10, 11], this study presents parametric coupling between *two distinct mechanical modes* in a *single* electrostatic MEM oscillator. The stiffness corresponding to the first two natural modes of this oscillator can be time dependant and under such a condition the "sum type" parametric resonance is observed. This two mode non-degenerate version of parametric amplification offers some advantages over the degenerate version. The driving frequency and the response frequency are totally decoupled (they are related by integer or fractional harmonics in the case of degenerate amplification). The drive frequency, which is the sum of the first two natural mode frequencies, can be designed to be as far away as needed from the first natural frequency at which the signal gets amplified. This can reduce parasitic coupling between drive and sense.

DEVICE DESCRIPTION

The non-degenerate mode-coupled parametric resonator is an electrostatically driven MEM oscillator fabricated with the bulk micromachining process SCREAM [12]. A SEM of the device is shown in Figure 1. The device has three external bonding pads between which there is electrical isolation. This would allow electrostatic actuation and capacitive detection. In this study, we use electrostatic actuation and optical (laser vibrometry) detection[13] of the out of plane motion. However capacitive detection and comparison with laser vibrometry of similar comb finger architecture has been demonstrated previously, and shown to be a sufficient transduction mechanism for these frequency and amplitude ranges [14]. The first two modes of oscillation for this design are both out of plane vibration and are shown in Figure 2. Experimental results of the mode shapes mapped with the device operating in air using POLYTEC

MSV 300 Micro Scanning Vibrometer is shown in Figure 2.

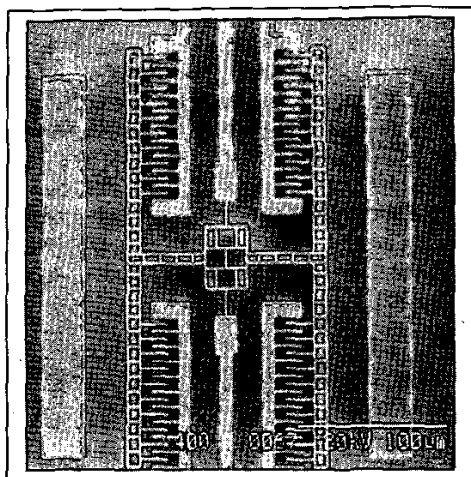


Figure 1: Scanning Electron micrograph of the oscillator under study. All features including the torsion beam and the comb fingers are $\sim 1 \mu\text{m}$ wide. The oscillator spans $\sim 150 \mu\text{m} \times 200 \mu\text{m}$ and is $\sim 25 \mu\text{m}$ deep.

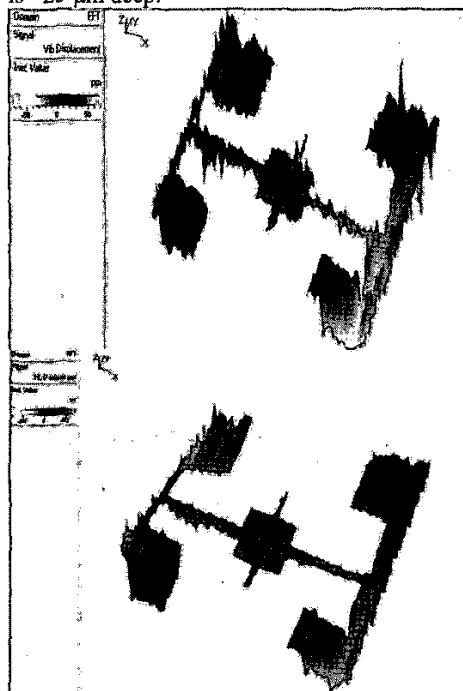


Figure 2: The first and second natural modes of the oscillator mapped using a scanning micro vibrometer (Polytec MSV 300). An actuation

voltage of 20Vpk-pk is used and the device is in air.

EXPERIMENTAL RESULTS

A multi-dimensional MEMS motion characterization suite is used to measure the out of plane movement of the device [13]. The schematic setup is shown in Figure 3. The device is placed in a vacuum chamber, where the pressure range is 5mTorr to atmosphere. The Laser Doppler Vibrometer with built in controllers and sensor heads (Polytec, OFV-3001, and OFV-511) uses a 633-nm wavelength, 205-mm cavity length Helium-Neon laser. The principle of measurement is optical interferometry. It is a heterodyne interferometer, meaning the velocity magnitude as well as the direction is determined by use of an additional Bragg cell [14]. A voltage source (HP3245A) was used for input voltage signal generation and the displacement and velocity outputs from the Vibrometer were recorded and analyzed with a HP Spectrum Analyzer (HP89470A) and Tektronics Oscilloscope (TDS 420 A). The velocity measurements presented in this paper are obtained from the above described set up with measurements taken at one corner of the device

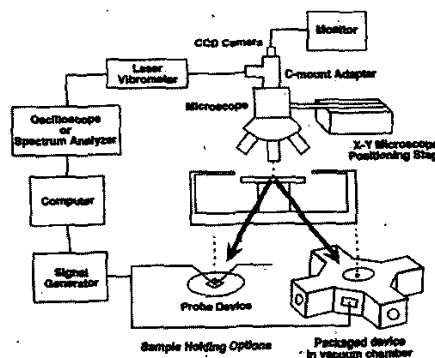
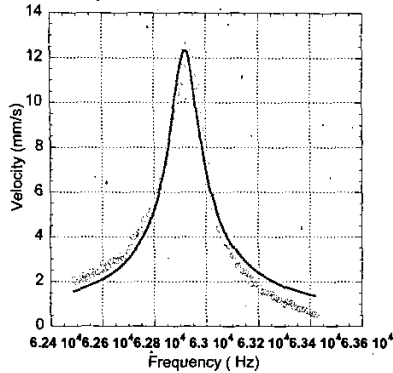


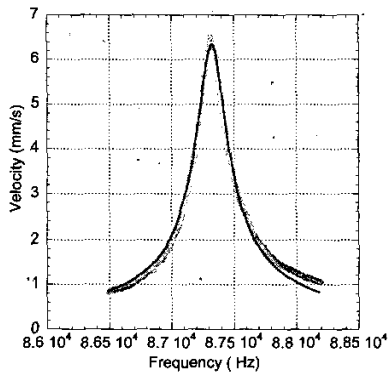
Figure 3: Schematic of characterization suite used to test the MEMS oscillator. For the results presented in this paper, we used a vacuum chamber with a pressure of $\sim 5\text{mTorr}$.

The electrostatic force generated with the out-of-plane electrostatic comb finger configuration is known to be proportional to square of the applied voltage. Hence, in order to have a single-frequency sinusoidal forcing function with a known DC offset, we use square-rooted sinusoidal voltage signals as our input signal.

The frequency response characteristics when driven with 5 Volts RMS square-rooted sinusoidal input signals near the first two natural frequencies are shown in Figures 4a and 4b. The small RMS value of the input would ensure that no parametric resonance or non-linearity effects are induced [5]. The natural frequencies can be extracted assuming each mode of the oscillator a forced under-damped SHO. These numbers are only used as a guideline for the testing range of the parametric amplification drive frequencies.



$m_1^2 m_0 \sqrt{(m_2^2 m_2 - m_0^2 m_0)^2 (m_2^2 m_2 - m_0^2 m_0) + 4^2 m_3^2 m_3^2 m_0^2 m_0}$		
	Value	Error
m1	1372.3	27.951
m2	62919	1.7148
m3	55.578	1.8194
Chisq	25.077	NA
R ²	0.97325	NA



$m_1^2 m_0 \sqrt{(m_2^2 m_2 - m_0^2 m_0)^2 (m_2^2 m_2 - m_0^2 m_0) + 4^2 m_3^2 m_3^2 m_0^2 m_0}$		
	Value	Error
m1	1438.5	6.6958
m2	67323	0.79023
m3	113.56	0.86038
Chisq	5.4643	NA
R ²	0.99322	NA

Figures 4a and 4b: The frequency response characteristics of the device when driven with a small amplitude voltage signal around the first two modes of the oscillator respectively. The

data fits well with the response of a single degree of freedom Simple Harmonic Oscillator for each of the modes separately and the fitted parameters are used as a guideline for the locations of the parametric mode resonance regions.

When driven with a square-rooted sinusoidal signal with large amplitude range [20-70Volts RMS] at ~twice the natural frequencies and near the sum of the two natural frequencies, the device is excited at the natural frequencies. Figure 5 shows an experimental map of the areas of parametric excitation. The “tongues” on the extreme correspond to the two degenerate resonance cases. When driven with an amplitude and frequency corresponding to any point inside these “tongues” (A and C), the oscillator has a single frequency response at half the drive frequency. For “tongue” B, the response of the oscillator has two frequency components, such that their sum corresponds to the drive frequency.

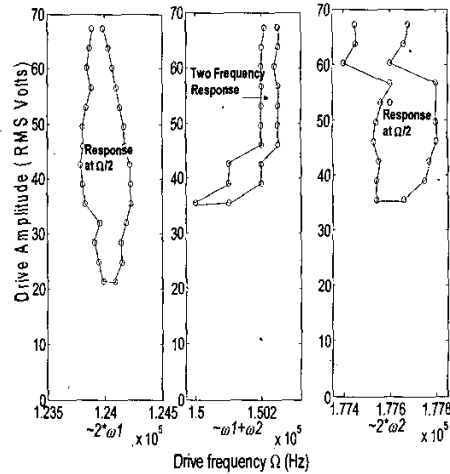


Figure 5: Experimental mapping of the regions or “tongues” of parametric resonance. When the drive frequency is near twice the natural frequencies, the device has a sub-harmonic response at half the drive frequency. When the drive frequency is near the sum of the first two natural frequencies, the device is excited simultaneously in both the modes and the response has two frequency components such that their sum is equal to the drive frequency.

The non-degenerate parametric resonance is possible due to displacement dependent force generation in either modes of oscillation and due to the interaction between the modes. These conditions are not restricted by device geometry

or material system and are satisfied in many common MEMS resonator configurations including simple cantilevers. We have observed similar dynamics in polysilicon cantilever beams.

CONCLUSION

We have demonstrated non-degenerate parametric resonance in a torsional MEM oscillator with two interacting mechanical modes of oscillation. The parametric nature arises from time varying stiffness in the system which is in turn caused by displacement dependant electrostatic force generation in both modes of oscillation. The concept of two-mode parametric self-resonance in the mechanical domain could be used in various resonant operation micro and nano scale applications such as mass sensing, communication components like filters and switches.

Acknowledgements:

The authors would like to thank Eric Lawrence of Polytec PI, Inc. 1342 Bell Ave S-3A Tustin, CA 92780-6440 for mapping the mode shapes using Polytec MSV 300. The work was supported by NSF -CAREER 0093994 and Air Force contract FA9620-02-1-0069.

References:

- [1] C. T. C. Nguyen, "Micromechanical filters for miniaturized low-power communications," presented at Smart Electronics and MEMS Newport Beach, CA, USA, 1999.
- [2] W. M. Dougherty, K. J. Bruland, J. L. Garbini, and J. A. Sidles, "Detection of AC magnetic signals by parametric mode coupling in a mechanical oscillator," *Measurement Science & Technology*, vol. 7, pp. 1733-9, 1996.
- [3] B. W. Chui, T. W. Kenny, H. J. Mamin, B. D. Terris, and D. Rugar, "A novel dual-axial AFM cantilever with independent piezoresistive sensors for simultaneous detection of lateral and vertical forces," presented at The 1997 ASME International Mechanical Engineering Congress and Exposition Proceedings of Symposium on Micro-mechanical Systems, Dallas, TX, USA, 1997.
- [4] T. Kenny, "Nanometer-scale force sensing with MEMS devices," *IEEE Sensors Journal*, vol. 1, pp. 148-57, 2001.
- [5] W. Zhang, R. Baskaran, and K. L. Turner, "Effect of cubic nonlinearity on auto-parametrically amplified resonant MEMS mass sensor," *Sensors and Actuators A (Physical)*, vol. In Press, 2002.
- [6] A. Dana, F. Ho, and Y. Yamamoto, "Mechanical parametric amplification in piezoresistive gallium arsenide microcantilevers," *Applied Physics Letters*, vol. 72, pp. 1152-4, 1998.
- [7] D. Rugar and P. Grutter, "Mechanical parametric amplification and thermomechanical noise squeezing," *Physical Review Letters*, vol. 67, pp. 699-702, 1991.
- [8] M. B. Wolfson and N. C. MacDonald, "On a MEMS-based parametrically amplified atomic force sensor," presented at TRANSDUCERS '01. EUROSENSORS XV, 11th International Conference on Solid-State Sensors and Actuators. Digest of Technical Papers, Munich, Germany 10-14 June 2001, 2001.
- [9] J. P. Raskin, A. R. Brown, B. Khuri-Yakub, and G. M. Rebeiz, "A novel parametric-effect MEMS amplifier," *Journal of Microelectromechanical Systems*, vol. 9, pp. 528-37, 2000.
- [10] R. Baskaran and K. L. Turner, "Electrostatic interactions in coupled micro electro mechanical systems," presented at SPIE's Micro/MEMS, Adelaide, Australia, 2001.
- [11] A. Olkhovets, D. W. Carr, J. M. Parpia, and H. G. Craighead, "Non-degenerate nanomechanical parametric amplifier," presented at Technical Digest. MEMS 2001. 14th IEEE International Conference on Micro Electro Mechanical Systems, Interlaken, Switzerland, 2001.
- [12] N. C. MacDonald, "SCREAM microelectromechanical systems," *Microelectronic Engineering*, vol. 32, pp. 49-73, 1996.
- [13] K. L. Turner, "Multi-dimensional MEMS motion characterization using laser vibrometry," presented at Transducers'99 The 10th International conference on solid-state Sensors and Actuators, Digest of Technical Papers,, Sendai, Japan, 1999.
- [14] Polytec, "Vibrometer User's Manual," 1999.