1. Final Report: IMPROVED PERFORMANCE OF MEMS BASED FILTERS

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2. Overview/Objective

As the demand for wireless communications technology continues to increase, so too does the demand for effective and efficient filters, as these devices, which pass signals with frequency components inside a specific bandwidth while attenuating those outside of it, are often integral components of such technology. While much research has been done on the design and performance of conventional electrical band-pass filters (e.g., Taylor and Huang, 1997), and their mechanical analogs (e.g., Johnson et al., 1971), the aforementioned demand for increased performance has led to a search for other alternatives. One that has shown early promise is to create microelectromechanical systems (MEMS) filters (e.g., Nguyen, 1999). These micro-scale components are more desirable than their more conventional counterparts primarily due to their size, low power consumption, and ease of integration with electrical systems. Equally important is the fact that MEMS filters have been shown to exhibit large quality (Q) factors (as high as 80,000, as reported in Wang and Nguyen, 1997), which provide good filter performance. In addition, MEMS oscillators are highly tunable, that is, one can design them such that they have desired linear and nonlinear dynamic characteristics (Adams et al., 1998, Zhang et al., 2003a). More relevant to the present work is the fact that parametric resonance is inherent in certain types of MEMS, a feature with excellent potential for filtering applications (Turner et al., 1998).

Our approach to developing switches and filters is unique among MEMS research, since we use parametric resonance, as opposed to the usual linear resonance, for frequency selection. The response outside of the parametric resonance zone is essentially zero, leading to very sharp roll-off characteristics and ideal stopband rejection. However, the parametric resonance has some undesirable features from the standpoint of filter performance, most notably: the bandwidth depends on the amplitude of the input; there is a nonlinear input/output relationship, which includes hysteresis; and multiple parametric resonances, some undesirable, may exist in a given system. Our work was focused on the design of MEMS oscillators that overcome these deficiencies, and of logic systems using these oscillators to construct a band-pass filter with nearly ideal stopband rejection. In addition, in order to enable systematic design of MEMS with desired response features, we have undertaken a systematic approach to characterizing the nonlinear dynamic response of parametrically-excited MEMS. This allows for a quite complete description of their response, which is very useful in the design of devices that exploit parametric resonance, including sensors, filters, and switches.

Our approach has combined experiments and analysis, with experiments guiding the device modeling and characterization work, and analysis guiding the design of filter devices. Descriptions of our achievements follow.

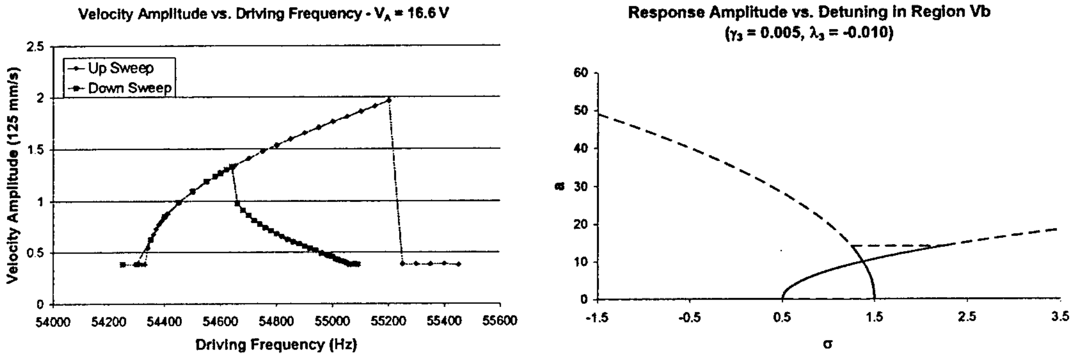
3. Accomplishments

a. Device Characterization

During the course of research on parametrically excited MEMS, the lead PI has observed a number of anomalous behaviors in devices, for example, situations in which devices appeared to have "mixed" nonlinear linear behavior, that is, their frequency responses did not fit the classical hardening or softening classifications. This was problematic for the design of filters and sensors that utilize parametric resonance.

An example of such anomalous behavior is shown in Figure 1, which exhibits two nontrivial response branches, one of which follows the usual hardening behavior, and the other follows softening behavior. This type of "mixed" nonlinear behavior cannot be described by the most commonly employed nonlinear oscillator models. For this device a relatively imple, single degree of freedom model was developed, based on the physics of the system, paying special attention to the manner in which the electrostatic forces provide the parametric excitation. Specifically, the parametric excitation acts through the electrostatic forces, which are nonlinear, and this leads to parametric excitation acting on both the linear and nonlinear terms. This feature significantly enriches the response (when compared to textbook problems on parametric excitation), and allows the model to capture the experimentally observed behaviors.

To this end, we applied a novel scaling scheme to the forces acting on the system and applied perturbation methods to the governing equation. The results completely describe the full range of device behavior over a range of input parameters. Furthermore, the predictions are expressed in terms of system design parameters, such as mechanical stiffness, mass, and electrostatic comb drive geometry. This creates a powerful design tool, since it allows one to select device parameters to achieve specified features in the response before fabrication.



(a) (b)

Figure 1. (a) Experimental frequency response of a parametrically excited MEMS device, showing "mixed" nonlinear behavior. (b) Predicted response from the analytical model.

A complete bifurcation analysis of the model was carried out and compared with systematic experimentation of a representative device. The device has the same essential dynamics as the one shown in Figure 2 (schematically) and Figure 3 (SEM of actual device, including a blowup to show details of the comb drives). The results of the study are summarized in Figure 3, which shows a two-parameter bifurcation diagram of AC voltage amplitude versus AC voltage frequency. The usual subharmonic instabilities are marked as AT, and the secondary instabilities are marked as SN, for saddle-node. These diagrams delineate the operating voltages for various response features, including hardening, mixed, and softening nonlinear behavior. One of the more important results of this investigation is the discovery that devices cannot be characterized by a single effective nonlinearity, but that each nontrivial response branch has a distinct effective nonlinearity. It is the dependence of this nonlinearity on the amplitude of the AC voltage that accounts for the observed range of responses.

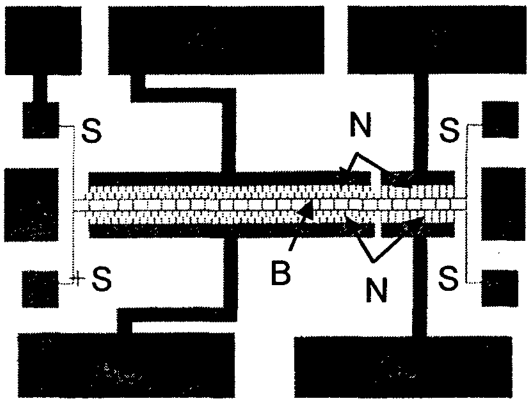


Figure 2. CAD Design of a representative MEM oscillator.

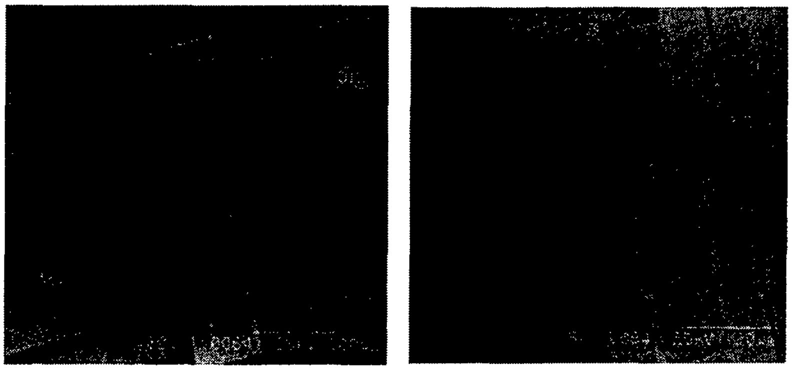

(a) (b)

Figure 3. (a) Parametrically excited MEM oscillator. The backbone "B" is the main oscillator mass, the springs "S" provide attachment to ground as well as the mechanical restoring force, and the non-interdigitated combs "N" are used for parametric excitation. "AC" and "DC" indicate voltage sources. (b) Enlarged view of the non-interdigitated combs.

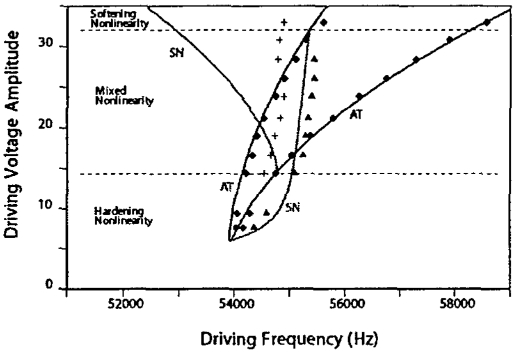


Figure 4. AC voltage amplitude versus AC voltage frequency bifurcation diagram. Bifurcation curves for the parametric instability are marked with AT, and saddle-node bifurcations of the non-trivial response branches are marked with SN. Note that the bifurcation curves were numerically produced and that the data points were obtained via experiment.

Various aspects of these results have been presented in a number of conference talks and conference papers [??], and the entire results are collected into a lengthy paper submitted for archival publication [??]. The results provide a complete picture of the possible responses of these devices, and this knowledge will be very useful for the design of filters, switches, and sensors. We now describe such an application, to single frequency filtering based on parametric excitation.

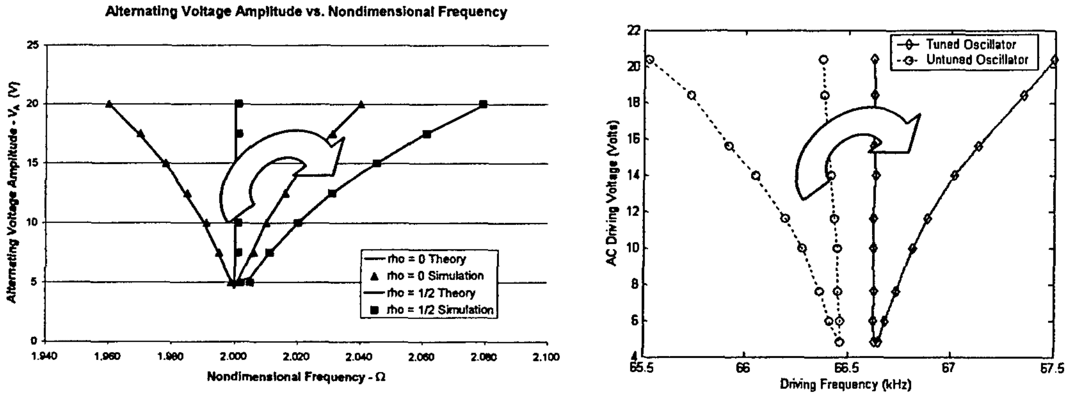
b. Filter Systems

With the above-described device characterization in hand, we were able to systematically develop filter systems based on parametric excitation. The filters of interest here are devices that take an input dominated by a single harmonic and pass the signal only if its dominant harmonic frequency meets certain specifications. Specifically, we can achieve high-pass filtering, low-pass filtering, or band-pass filtering.

The work began with a class of proposed theoretical designs based on the predicted response of the nonlinear MEMS oscillator model, as described above. These designs employed a unique arrangement of comb drives. In particular, the devices use two independent drives, one for the usual AC voltage input, and the other for "on the fly" device frequency tuning using a DC bias voltage. These devices can be tuned for low-pass or high-pass filtering, and a combination of these with some logic leads to a band-pass filter. The general filter system model was analyzed using perturbation methods and the results were used to select the desired linear and nonlinear tuning characteristics. Simulations of the model verified its effectiveness. Based on these results, various device layouts were designed that provided the desired features for both low- and high-pass tuning (for example, the layout shown in Figure 2). These were successfully fabricated (for example, see Figure 3) and experimentally tested, yielding the desired results. Highlights of these developments are described below. It should also be noted that this work naturally complements related research by K. Turner on sensors that makes use of similar tuning capabilities (Zhang et al., 2002 and Turner et al., 2003).

The key component to the filter designs are tunable MEMS oscillators driven by parametric excitation. Typically, the parametric resonance zone is shaped essentially like a "V" in the voltage amplitude vs. frequency parameter space, where the trivial (zero amplitude) response is stable outside of this "wedge of instability" (representing the stop-band for the filter), and unstable inside the wedge, where the system will respond in a nearly-pure harmonic manner (representing the pass band for the filter). Using a specially-tuned DC bias in the second set of comb drives, the natural frequency of the oscillator can be made to depend on the amplitude of the input voltage in such a manner that the "V" is rotated, either clockwise or counter-clockwise. In this manner either of the two stability limits (the legs of the "V") can be made vertical, that is, independent of frequency. Figure 5a shows theory and simulation results for the stability boundaries of such a tuned oscillator (designated by $\rho = 1/2$), along with those of the system wherein the DC bias is turned off (designated by $\rho = 0$). Note that the left boundary is vertical for this tuned oscillator, leading to a system wherein the response is zero below the (nondimensional) frequency threshold, independent of the input voltage. By designing this oscillator to have a cubic hardening restoring force, one can insure that the response is zero below this threshold, so that it acts as a high-pass switch. However, it should be noted that the response may be nonzero above the upper stability threshold, due to the hysteretic nature of the response (as observed in Figure 1 for a system with mixed nonlinear behavior). Figure 5b shows an experimental realization of this tuning strategy, for a device similar to that shown in Figures 2 and 3. The "V" has been successfully rotated in the manner desired.

A similar oscillator, tuned so that its upper stability limit is vertical and designed with a softening cubic nonlinearity, likewise serves as a low-pass switch, since its response is known to be zero above the stability threshold and nonzero below it. These two oscillators can be employed in a logic system, such as the one shown in Figure 6, wherein the high-pass and low-pass switches (designated by -H- and –L-) have their base frequencies slightly shifted so that they overlap in order to form a frequency passband. In this system the output of the AND gate is used as an enabling signal to an element P which completely rejects the signal outside of the passband. Simulations show that this system acts as an ideal band-pass filter that passes only noise outside of the passband. More details about the switches and the filter system can be found in Rhoads et al., 2005a and Shaw et al., 2004.



(a) (b)

Figure 5: (a) Analytically predicted stability boundaries in input voltage-frequency space for the tuned ($\rho = 1/2$ for a high-pass switch) and nominally tuned ($\rho = 0$) cases (from Shaw et al., 2004). Solid curves are from theory, data points are from simulations of the MEMS model. (b) Experimentally tuned and untuned parametric high pass filter (vacuum level = 7 mTorr). The wedge has rotated due to tuning, so that the response to an external signal is activated at voltage level that is independent of frequency.

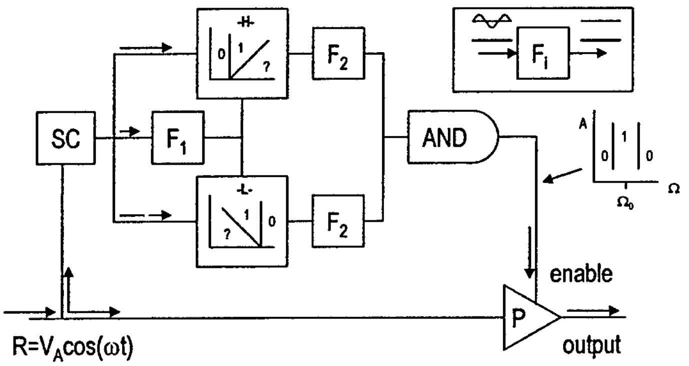


Figure 6. The logic system employing the filter switches to provide a band-pass filter (from Rhoads et al., 2005a). Blocks labeled F are essentially AC to DC converters, and block P passes the input signal only when the enabling input is active. Note that the amplitude is fed into the switches and is used to achieve the type of tuning shown in Figure 1.

c. Extensions and Future Directions

The first obvious extension of this work is to make devices of simpler geometry, smaller, more efficient, and with higher operating frequency ranges,. This can be accomplished using microbeams with special arrangements of parallel-plate types of capacitive drives. Again, the idea is to use independent drives for tuning and input. We have carried out the modeling and analysis for such model systems based on cantilever and fixed-fixed microbeams (Rhoads et al., 2005), and fabrication and testing are being planned.

Another extension is the use of individual and coupled oscillator systems for sensing using parametric excitation. The lead PI has extensive experience in this area, and the tuning strategies developed in this project will be very useful for a variety of such devices. In addition, one can envision designs of filter systems based on systems of coupled oscillators; however, the introduction of combination resonances may hinder progress along such lines.

Finally, this work on filters has led the second PI into investigations of nonlinear digital filters, wherein one is not constrained by the physics of MEMS resonators. Since these filters are merely digital implementations of oscillator equations, one has complete freedom in the selection of tuning, nonlinearity, etc., in order to achieve desired response features. This line of work has significant potential for improving certain specialized techniques in digital signal processing.

d. References Acknowledging This Grant

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Rhoads, J., Shaw, S., Turner, K., Baskaran, R., 2005a, "Tunable Microelectromechanical Filters that Exploit Parametric Resonance," *ASME Journal of Vibration and Acoustics* **127(5)**, 423-430.

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4. Personnel

a. Faculty: PI: Dr. Kimberly Turner
Co-PI: Dr. Steven Shaw
b. Postdocs: none
c. Graduate Students: Jeffrey Rhoads, Ph.D. candidate, Michigan State University; Barry De Martini, Ph.D. candidate, UCSB; Rajashree Baskaran, Ph.D., UCSB (2003)

5. Publications Resulting from this Grant:

Baskaran, Rajashree. "Parametric resonance and amplification in single and coupled Micro Electro Mechanical Systems," Dissertation, UC Santa Barbara September 2003.

DeMartini, B., Moehlis, J., Turner, K., Rhoads, J., Shaw, S., and Zhang, W., 2005, "Modeling of Parametrically Excited Microelectromechanical Oscillator Dynamics with Application to Filtering," to appear in *Proceedings of IEEE Sensors 2005: The 4th IEEE Conference on Sensors*, Irvine California, October, 2005.

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Zhang W., Baskaran R., and Turner, K. L., 2003a, "Tuning the Dynamic Behavior of Parametric Resonance in a Micro Mechanical Oscillator," *Applied Physics Letters* **82**, 130.

6. Interactions:

a. Presentations Given

Zhang, W., R. Baskaran, R., and Turner, K. L., 2003b, "Changing the behavior of Parametric Resonance in MEMS oscillators by tuning the effective cubic stiffness," in *Proceedings of MEMS 2003*, Kyoto, Japan, January 2003.

Shaw, S., Rhoads, J., Turner, K., and Baskaran, R., 2004, "Parametrically Excited MEMS-based Filters," *Proceedings of the IUTAM Symposium on Chaotic Dynamics and Control of Systems and Processes in Mechanics*, Rome, Italy, June, 2003.

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7. New Discoveries

One patent disclosure filed at Michigan State University and UC Santa Barbara.

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14. ABSTRACT

As the demand for wireless communications technology continues to increase, so too does the demand for effective and efficient filters, as these devices, which pass signals with freuency components inside a specific bandwidth while attenuating those outside of it, are often integral components of such technology. Micro-scale components are more desirable than their more conventional counterparts primarily due to their size, low power consumption, and ease of integration with electrical systems.

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