Comparison of parametric and linear mass detection in the presence of detection noise

2011 J. Micromech. Microeng. 21 025027

(http://iopscience.iop.org/0960-1317/21/2/025027)

IOP Publishing Journal of Micromechanics and Microengineering

J. Micromech. Microeng. **21** (2011) 025027 (5pp) doi:10.1088/0960-1317/21/2/025027

Comparison of parametric and linear mass detection in the presence of detection noise

Zi Yie, Mark A Zielke, Christopher B Burgner and Kimberly L Turner

Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA

E-mail: yie@engineering.ucsb.edu

Received 19 July 2010, in final form 10 December 2010
Published 27 January 2011
Online at stacks.iop.org/JMM/21/025027

Abstract
We experimentally investigate the performance of a nonlinear parametrically driven mass sensor in the presence of detection noise. Mass detection is achieved by measuring the amount of methanol vapor adsorption on the sensor. To demonstrate the advantage of parametric sensing in counteracting the influence of detection noise, we operate the sensor in both the parametric and harmonic resonance mode. Comparison of the results shows that in contrast to conventional linear harmonic sensing, the detection sensitivity does not deteriorate for the parametric case when a tenfold increase in detection noise is introduced. Furthermore, we demonstrate additional functionality of the parametric sensor by utilizing it as a threshold detector, whose performance remains the same despite the added detection noise. Taken together, these results suggest that for mass detection in the presence of detection noise, a parametrically operated sensor may offer better performance over one operated harmonically in the linear regime.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Mass sensors utilizing MEMS resonators have been widely researched due to their vast potential in biological and chemical sensing applications [1–4]. Normally, these sensors operate linearly in a simple harmonic resonance mode that employs resonant frequency tracking for detecting mass changes [5]. The ability to track the minimum shift in resonant frequency is determined by the noise. Various noise sources, both intrinsic and extrinsic, have been identified [6, 7]. Although intrinsic processes such as thermomechanical noise are often cited as the dominant noise source that affects ultimate sensitivity, the influence of extrinsic processes such as detection noise in the readout is also significant. This holds importance for a linearly operated sensor whose oscillation amplitude is limited, which in turn entails the use of low-noise optical and electronic detectors for measuring the output signal. However, for many practical applications, making use of sophisticated readout equipment may not always be possible. In such situations, the noise introduced by the measurement system can become the dominant noise source and be large enough to obscure the signal of interest. This implies that the presence of detection noise will not only prevent accurate sensing, but will set the limit of detection of the sensor.

Different theoretical and experimental studies have shown that by actively exploiting nonlinear behaviors, the sensitivity of a sensor for mass detection can be enhanced [8–10]. Operating a sensor in the nonlinear regime will usually induce large oscillation amplitudes and hence large output signals without simultaneously amplifying the noise. This is favorable in counteracting the influence of detection noise as large outputs can be measured more accurately and may improve the signal-to-noise ratio. Thus, operating the sensor in a region of nonlinear oscillations may represent a means to overcome the detection limit set in cases where detection noise is the main factor that determines sensitivity.

In this paper, we explore the nonlinear phenomenon of parametric resonance for mass sensing in the presence of detection noise. The concept of a parametric resonance based mass sensor was introduced in [11], where the method of operation involves bifurcation tracking, which detects frequency shifts at the onset of a parametric instability due to mass changes. This is observed at the stability boundary of the parametric resonance region, where a sharp transition from zero to large amplitude occurs. The abrupt jump to a large output signal is advantageous in terms of diminishing the influence of detection noise. Moreover, the large output can be measured easily and be applied to realize some additional sensor functionality such as threshold detection. To demonstrate these advantages, we compare mass sensing in the nonlinear parametric and linear harmonic resonance mode in the presence of detection noise. We show experimentally that compared to harmonic sensing, the detection sensitivity of a mass sensor operating parametrically remains essentially unaffected by the presence of a tenfold increase in detection noise. Mass detection is illustrated with chemical gas sensing, in which we compare real-time measurements of methanol vapor concentration in both sensing modes under normal conditions and conditions of increased detection noise level. In addition, we demonstrate that the parametrically operated sensor can also function as a threshold detector to indicate whether mass has been detected or not. The performance here is again shown to be the same even when detection noise is present.

2. Experimental details

2.1. Sensor and experimental setup

The sensor was fabricated using a silicon-on-insulator process [12] and comprised a fixed-fixed beam resonator measuring 986 μm long, 40 μm wide and 2.5 μm thick. The measured natural resonant frequency and quality factor in air are 32.24 kHz and 73, respectively. The resonator was base excited by an externally mounted shear-type piezo-actuator (P-121.01, Physik Instrumente), and the response was detected using a laser Doppler vibrometer through an optical microscope. All experiments were conducted under ambient pressure. Figure 1 shows a schematic of the experimental setup as well as a scanning electron microscope (SEM) image of the sensor.

For methanol vapor sensing, nitrogen was used as a carrier gas and methanol vapors were introduced through the use of a bubbler. Predetermined concentrations were obtained by mixing the vapors with pure nitrogen using mass flow controllers (MFC). Sensing involved taking measurements in pure nitrogen gas, followed by introducing methanol and measuring the resulting frequency shifts until the adsorption reached the steady state. Afterward, the methanol was turned off and pure nitrogen was reintroduced. This cycle was carried out twice in succession.

2.2. Sensor operation

The sensor can be operated in either the harmonic or degenerate parametric resonance mode depending on the driving voltage applied to the shear piezo. By applying a small driving voltage, enough out-of-plane motions can be created to drive the beam into harmonic resonance. Applying a larger driving voltage allows the shear piezo to generate strong in-plane motions that can excite intense resonant transverse vibrations in the beam and actuate parametric resonance. In harmonic resonance mode, the sensor behaves linearly. In order to determine the appropriate input, we need to apply the largest drive level that is consistent with producing a linear response. This ensures that for the given level of detection noise in our mass sensing experiment, we have maximized the signal-to-noise ratio for operation in the linear regime. Experimentally, it was found that a driving voltage of 1 V was best suited for producing a response that was still predominately linear. Operating at higher voltages would result in nonlinear behavior. Figure 2(*b*) shows a frequency sweep response of the beam when actuated with a 1 V sinusoidal driving signal around the natural resonant frequency. To track the resonant frequency for mass sensing, we employ a phase-locked loop in which a lock-in amplifier is used to detect the phase difference between the input and output signals, and the driving frequency is adjusted so as to always maintain the beam at resonance.

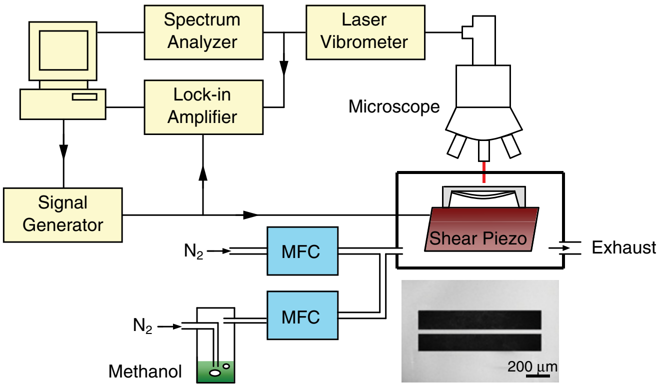

Figure 1. Schematic of the experimental setup and SEM image of the sensor. The resonator is made up of a silicon fixed-fixed beam with actuation from a shear-type piezo-actuator. Displacement of the beam is sensed by a laser Doppler vibrometer. Methanol vapors are created through the use of a bubbler and delivered to the chamber via mass flow controllers. All experiments were conducted under ambient pressure.

In parametric resonance mode, the sensor behavior is nonlinear. To determine the appropriate input, we must first establish the critical voltage needed to achieve parametric resonance. To do so, we map the resonance region of the first-order parametric resonance. Across the boundary of this region, a bifurcation occurs. This corresponds to an instability that results in an exponential growth of the beam displacement, and the response amplitude jumps from null outside the region to infinity inside. However, nonlinearities arising from both the fixed-fixed beam [13] and the actuator [14] limit the size of the amplitude. Figure 2(*a*) shows the experimental boundary curve for the region, which was obtained by setting the driving frequency to be close to twice the natural resonant frequency of the beam and then gradually increasing the driving voltage until a significant beam response was observed at half the driving frequency. From the plot, a critical voltage of 4.85 V is necessary to realize parametric resonance. We note that this plot is only relevant for characterizing the occurrence of parametric resonance, and the derived critical voltage does not pertain to the onset of nonlinearity when the sensor is operated in harmonic resonance mode. We set the driving

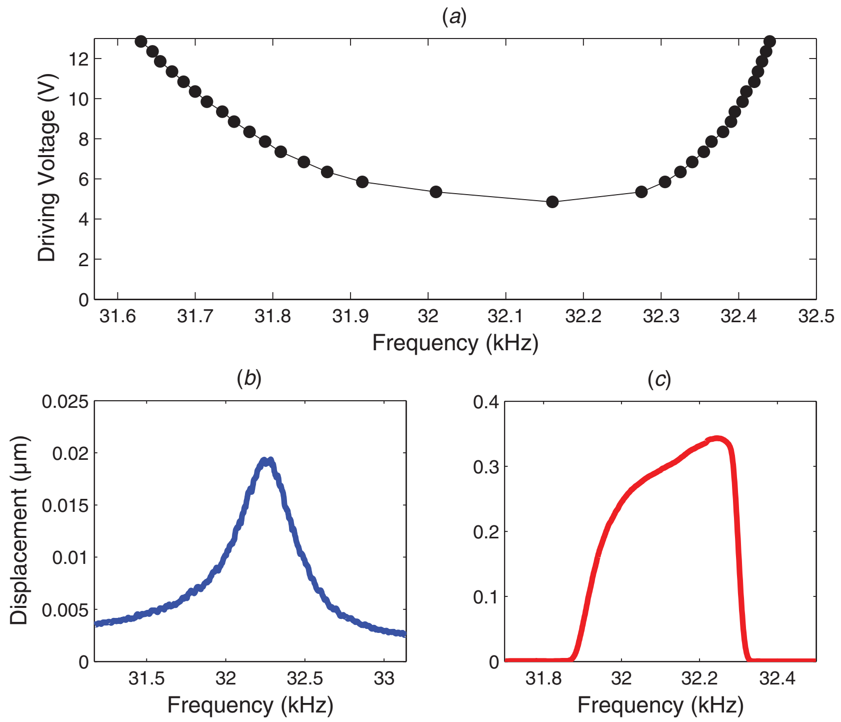

Figure 2. (*a*) Experimental mapping of the first-order parametric resonance region. (*b*) Frequency sweep response of the beam in harmonic resonance mode, when driven with a 1 V sinusoidal signal around the natural resonant frequency. (*c*) Frequency sweep response of the beam in parametric resonance mode, when sweeping down with a 10 V sinusoidal signal whose driving frequency is approximately twice the natural resonant frequency. The response occurs at half the driving frequency.

voltage to 10 V to operate the sensor in parametric resonance mode. Figure 2(*c*) shows a frequency response of the beam around the natural resonant frequency when sweeping down with a 10 V sinusoidal driving signal whose frequency is approximately twice the natural resonant frequency. This allows us to measure a significant amplitude change at the point of bifurcation, where the response jumps from zero to a large value, and reduces in amplitude thereafter until it reaches zero again. Generally speaking, having a higher driving input will result in a larger jump in the response amplitude. Therefore, to maximize the signal-to-noise ratio for operation in the region of parametric resonance, it is preferable to drive as hard as possible in order to recover the greatest output signal relative to the given detection noise floor. However, the 10 V driving input that we used provided a reasonably high output that was sufficient for the purpose of our mass sensing experiment. To track the bifurcation frequency for mass sensing, we sweep down in driving frequency and use a spectrum analyzer to monitor the point at which the abrupt change takes place.

When operated in parametric resonance mode, the sensor can also act as a threshold detector to provide additional functionality. The large amplitude response that occurs at the bifurcation point when we sweep down in driving frequency can be used simply as an indication of mass detection. This feature can be useful in threat detection scenarios, where the need to measure the quantity of mass is not as crucial as the need to execute an action upon its detection, such as in applications for detecting explosives or monitoring harmful substances in the environment. To realize the threshold detector, the sensor is parametrically driven at a fixed frequency throughout the mass detection process. By setting the driving frequency at a position just after the bifurcation point and hence inside the parametric resonance region, a large output response will result given zero initial conditions. This indicates a no-mass state. As mass is picked up, the bifurcation point will shift to the left. Eventually, the position of the driving frequency will come before the bifurcation event and thus lie outside of the parametric resonance region. Consequently, given the same zero initial conditions, the output will yield a zero response, which represents an added-mass state. Any subsequent shifts in the bifurcation point will cause the jump in output to occur either before or after the fixed driving frequency position. Accordingly, either a large or zero response will occur corresponding to an off- or on-state.

3. Results and discussion

To show the advantage of operating a mass sensor parametrically in the presence of detection noise, we performed two sets of experiments with methanol vapor sensing, both using a predetermined methanol concentration of 2900 ppm. The first set of experiments seen in figures 3(*a*)–(*c*) was carried out with full laser signal strength on the vibrometer. The ambient noise floor was characterized by a power spectral density analysis on the spectrum analyzer and averaged to be 6.2 μV Hz$^{-1/2}$ in the range of 25–40 kHz. In the second set of experiments, shown in figures 3(*d*)–(*f*), we added detection noise by reducing the laser signal strength to its minimum. The noise floor was characterized to be 60.4 μV Hz$^{-1/2}$ in the same range, which represents a tenfold increase. For each

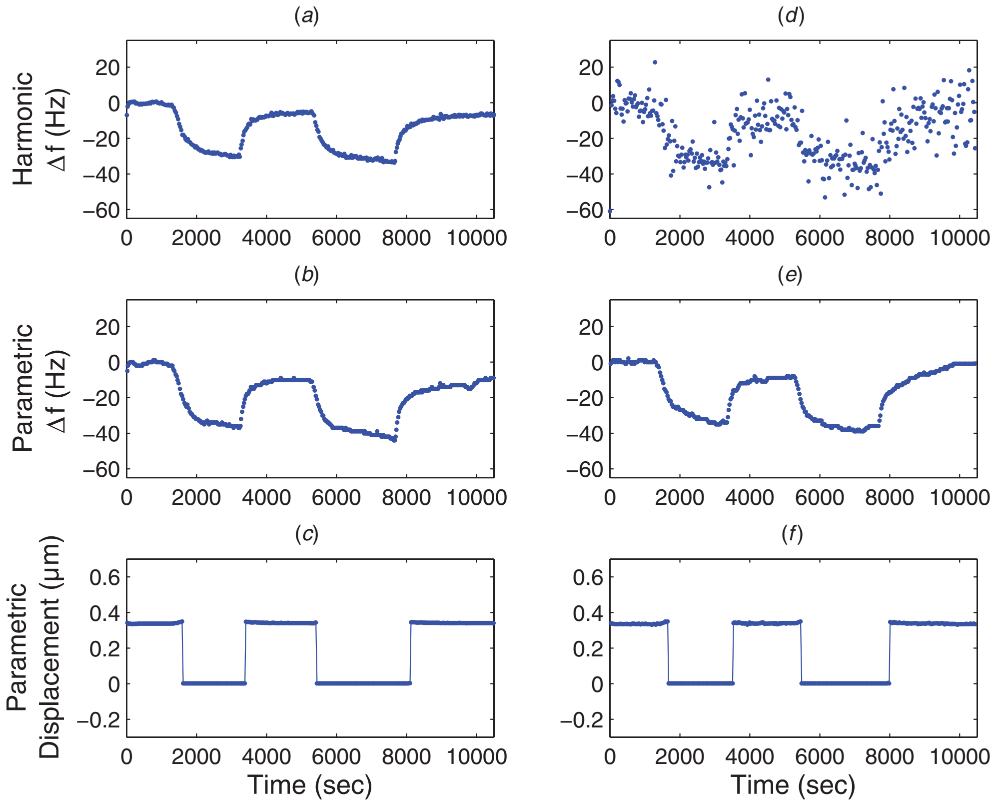

Figure 3. (*a*)–(*c*) Methanol vapor sensing with ambient noise (noise level: 6.2 μV Hz$^{-1/2}$). (*d*)–(*f*) Methanol vapor sensing in the presence of added detection noise (noise level: 60.4 μV Hz$^{-1/2}$). (*a*) Sensor performance in harmonic resonance mode without noise, where a concentration of 2900 ppm results in a discernable frequency shift (Δf) of 26 Hz. (*d*) Sensor performance in harmonic resonance mode with noise added, where the 26 Hz frequency shift is no longer distinguishable. (*b*) Sensor performance in parametric resonance mode without noise and a Δf of 30 Hz. (*e*) Sensor performance in parametric resonance mode with noise and a similar Δf of 29 Hz. (*c*) and (*f*) Sensor performance without and with noise, respectively, when employed as a threshold detector in parametric resonance mode, where a digital off-on response is observed.

set of experiments, we first operated the sensor in harmonic resonance mode and measured the shifts in resonant frequency. We then operated the sensor in parametric resonance mode and calculated the shifts in bifurcation frequency. Finally, we employed the parametrically operated sensor as a threshold detector to indicate whether mass has been detected or not. From figure 3, it is evident that a tenfold increase in detection noise impairs methanol sensing in harmonic resonance mode, but not in parametric resonance mode. Figures 3(*a*) and (*d*) illustrate sensing in harmonic resonance mode, where a downward frequency shift is seen with increasing exposure, signifying methanol adsorption and the detection of additional mass. A methanol concentration of 2900 ppm causes a frequency shift of 26 Hz as seen in figure 3(*a*), but the same shift cannot be discerned clearly with detection noise added in figure 3(*d*). From figure 3(*a*), the standard deviation of the fluctuation in frequency is calculated to be 0.7 Hz, which leads a minimum detectable concentration of 78 ppm. Figures 3(*b*) and (*e*) show sensing in parametric resonance mode, where the detection sensitivity is observed to be largely unaffected by the added detection noise. Without detection noise in figure 3(*b*), the same methanol concentration of 2900 ppm causes a frequency shift of 30 Hz, and the fluctuation in frequency is calculated to be 0.45 Hz, resulting in a minimum detectable concentration of 43.5 ppm. Similarly, with detection noise added in figure 3(*e*), a frequency shift of 29 Hz is seen with the fluctuation in frequency calculated to be 0.46 Hz, giving a minimum detectable concentration of 46 ppm. Finally, when the sensor is employed as a threshold detector, figures 3(*c*) and (*f*) demonstrate consistent sensor performance despite the increase in noise. The response resembles a digital signal with off–on behavior that could find application as an input to a switch, which could then be used to activate an alarm or a defensive system.

4. Conclusions

We have demonstrated that with a tenfold increase in the detection noise level, the detection sensitivity of a nonlinear parametrically driven mass sensor remains the same, while the sensitivity of the same sensor operated harmonically in the linear regime is degraded. The findings in our methanol vapor sensing experiments suggest that the large output resulting from operating the sensor in the region of parametric resonance could offer advantages in mass detection performance under conditions dominated by detection noise. As a further illustration, we have shown that the parametrically driven sensor can be used to provide additional functionality as a threshold detector, and the effect of detection noise on its performance is negligible as well. While this work makes use of a laser optical readout, measurements can also be obtained from a variety of other readout mechanisms such as capacitive or magnetic. Detection noise is often unavoidable, especially in many real applications. Although it can be minimized through sensitive readout equipment, the results in this work have shown that by making use of the parametric resonance phenomenon, it is possible to achieve reliable readout even when detection noise is present. This in turn implies that a sensor based on this principle would respond favorably with a less sensitive detection system, which is beneficial for developing sensors that are robust, low-cost and portable.

Acknowledgment

This work was supported by the National Science Foundation under grant CMMI-0800753.

References

[1] Thundat T, Wachter E A, Sharp S L and Warmack R J 1995 *Appl. Phys. Lett.* **66** 1695–7
[2] Ilic B, Czaplewski D, Craighead H G, Neuzil P, Campagnolo C and Batt C 2000 *Appl. Phys. Lett.* **77** 450–2
[3] Battiston F M, Ramseyer J-P, Lang H P, Baller M K, Gerber C, Gimzewski J K, Meyer E and Güntherodt H-J 2001 *Sensors Actuators* B **77** 122–31
[4] Su M, Li S and Dravid V P 2003 *Appl. Phys. Lett.* **82** 3562–4
[5] Albrecht T R, Grütter P, Horne D and Rugar D 1991 *J. Appl. Phys.* **69** 668–73
[6] Ekinci K L, Yang Y T and Roukes M L 2004 *J. Appl. Phys.* **95** 2682–9
[7] Robins W P 1982 *Phase Noise in Signal Sources* (London: Peter Pelegrinus Ltd)
[8] Buks E and Yurke B 2006 *Phys. Rev.* E **74** 046619–28
[9] Ramos D, Mertens J, Calleja M and Tamayo J 2008 *Appl. Phys. Lett.* **92** 173108
[10] Dai M D, Eom K and Kim C-W 2009 *Appl. Phys. Lett.* **95** 203104
[11] Zhang W H and Turner K L 2005 *Sensors Actuators* A **123** 23–30
[12] Zielke M A 2010 Nanostructured coatings for MEMS chemical sensors *PhD Dissertation* University of California, Santa Barbara, CA
[13] Zhang W H, Baskaran R and Turner K L 2002 *Sensors Actuators* A **102** 139–50
[14] Physik Instrumente (PI) 2009 Piezo Nano Positioning 2009, Karlsruhe