NONLINEAR INTERNAL RESONANCE FOR GAS SENSING

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ABSTRACT

We present a new method to identify gases based on the nonlinear phenomenon of internal (auto-parametric) resonance of resonant microbeams. The concept is demonstrated based on a MEMS device, which is designed to experience a 2:1 internal resonance between its first and second vibration modes. The basic idea relies on the fact that gas mixtures have different coefficients of viscosity (damping), and hence can lead to the activation or suppression of internal resonance. We propose to use the activation of internal resonance as a possible condition to identify gas types and concentrations. The concept is demonstrated for variety of gases.

KEYWORDS

Internal (auto-parametric) resonance, gas sensing, nonlinear dynamics, damping and energy dissipation

INTRODUCTION

Nano/micro-electromechanical systems (NEMS/MEMS) have been driving technological advances in the last few decades. To improve the performance of MEMS and NEMS, there has been active research recently to exploit their nonlinear dynamic behaviors, which have been proven to yield more improved performance compared to the operation in the linear dynamic regime. Nonlinear operations can lead to larger actuation displacement, bigger quality factors, wider bandwidths, enhanced efficiency, and for sensors higher sensitivity and larger Signal-to-Noise Ratio (SNR) [1].

Saturation is an intriguing nonlinear phenomenon that has been explored for a long period, and it was first cited in the problem of the capsizing of ships [2]. This phenomenon refers to the transfer of energy from the directly excited vibration mode to another in-directly excited mode through the nonlinear coupling, where the response of the directly excited mode saturates when reaching a certain excitation threshold, while the response of the other unexcited modes keeps increasing. This phenomenon requires the two involved modes to have a frequency ratio of 2:1, to allow for internal resonance, and the presence of quadratic nonlinearity. The internal resonance between two modes allows different modes of vibration to transfer and exchange energy. One aspect of this, for instance, is when a lower-order mode of higher amplitude response transfers energy to a higher-order mode of lower amplitude, which boosts its response. Consequently, the higher-order mode does not show any significant response to the excitation, until the conditions are met for internal resonance and the exchange of energy.

Portal frames (of U-shape) have attracted the interest of researchers because of their complex and rich dynamics that allow different ways to exploit nonlinear phenomena [3,4]. For example, it was shown that a portal frame structure with a 2:1 internal resonance is very sensitive to pressure variations (and hence damping conditions) [4]. In a portal frame, the saturation phenomenon is achievable through geometric nonlinearities and can be easily accessed due to the high frequency-tunability of the structure.

Damping in MEMS is caused primarily by the viscosity of gases. Damping impacts the amplitude of the signal and can inhibit the nonlinear behavior. This behavior was already demonstrated in [4]. However, MEMS devices can be used to measure viscosity. For instance, Dias et. al [5] used a parallel-plate actuator for gas sensing using the pull-in time as an indirect measurement of viscosity. Etchart et. al [6] varied the width of clamped-clamped beams to measure the quality factor and indirectly measure density and viscosity.

This work aims to demonstrate the exploitation of internal resonance for gas-sensing applications. We investigate the activation of the internal resonance of a portal frame (U-shaped microresonator) subjected to electrostatic force at atmospheric pressure and while changing the surrounding gases.

THE DEVICE

The device in Fig. 1 is fabricated using an in-house conventional surface micromachining process using an SOI wafer. The substrate has an electrical sheet resistance of 500 ohm-cm, and the device layer has a resistivity of 0.1 ~ 0.2 ohm-cm. The process starts with the sputtering of 50 µm Cr and 200 Au µm layers on an SOI wafer. The wafer is patterned using the 1st mask layer for fabricating device pads. Afterward, the wafer is spun-coated with the 4 µm thick photoresist ECI 3027 and is patterned with the second mask layer. The 25 µm device layer is anisotropically etched using deep reactive Ion etching (DRIE). At last, the photoresist is removed, and the micro resonator is released using HF vapor etching.

The portal frame structure is composed of two main structures: two columns with their ends attached to a supported beam. The fabricated device is shown Fig. 1. Fig. 1a depicts a schematic showing the actuation pads and the main parameters of the structure with the points of interest for dynamics x and y, while Fig. 1b shows the fabricated device and the main areas of interest 1 (x-direction) and 2 (y-direction). In Fig. 1a, L_1 is the length of each column and L_2 is the length of the supported beam. The columns and beam widths are expressed respectively as h_1 and h_2. In addition, the microstructure is subjected to an electrostatic force, by a DC actuation voltage V_{dc2} and an AC harmonic voltage V_{ac2}, which actuate the 2nd mode (y-direction), through two electrodes, while V_{dc1} and V_{ac1} actuate the 1st mode (x-direction). One electrode is placed on top of the supported beam (Electrode B) and the other is placed on the column (Electrode A). The distances between the supported beam and columns from their electrodes are given by d and g, respectively. Using a finite-element model, the first two vibration modes can be obtained, as shown in Fig. 1c, which shows the first mode dominated by horizontal motion in the x direction (sway) and the second mode dominated by motion of its middle beam in the y direction (bending). These two distinct modes will be involved in the exchange of energy via internal resonance as discussed next.

INTERNAL RESONANCE

We used the electrostatic tunning to bring the two resonance modes to a ratio of 2:1. This and the fact that the structure has inherent quadratic nonlinearity from its geometry makes the activation of internal resonance possible under the proper damping conditions. Fig. 2 shows an example for the activated internal resonance, where it shows the activation of mode one (sway, in black) while actuating mode two (bending, in magenta), which gets suppressed.

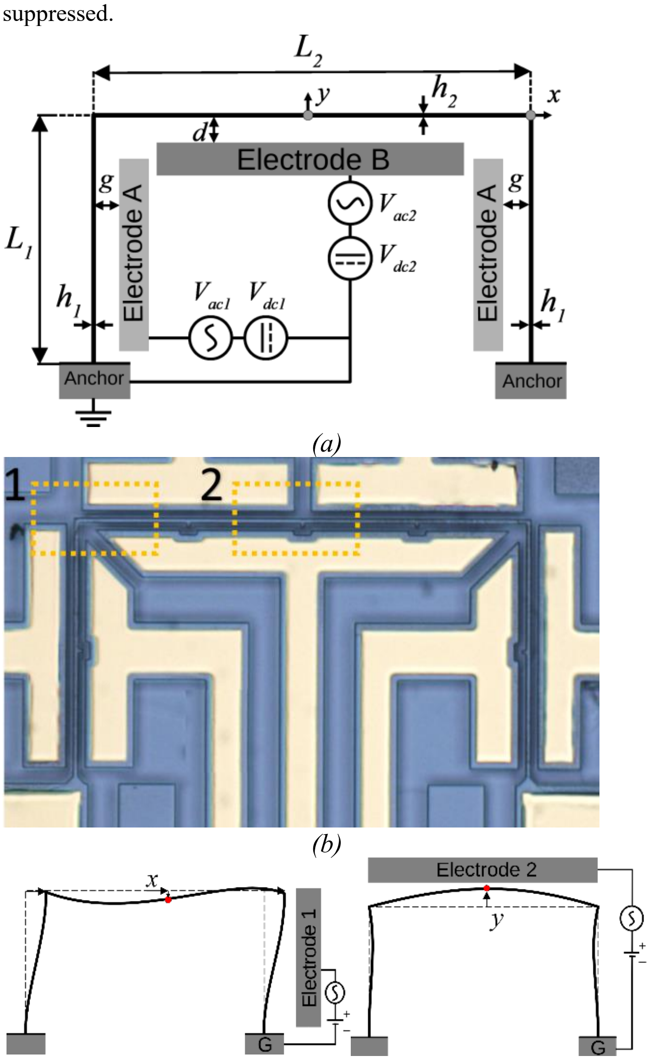

Figure 1: (a) Schematic of the micro portal frame with the actuation electrodes. (b): An optical image. (c) The two vibration modes involved in the internal resonance (left 1st sway mode, right 2nd bending mode).

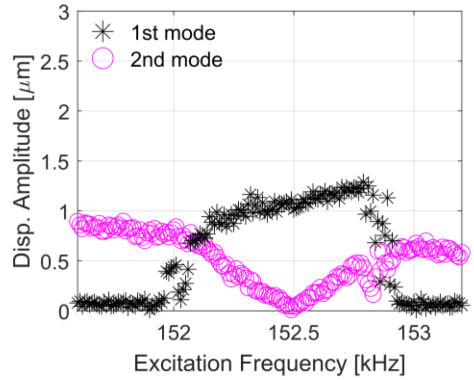

Figure 2: An example of the measured frequency-response curves in the case of a 2:1 internal resonance between the two modes.

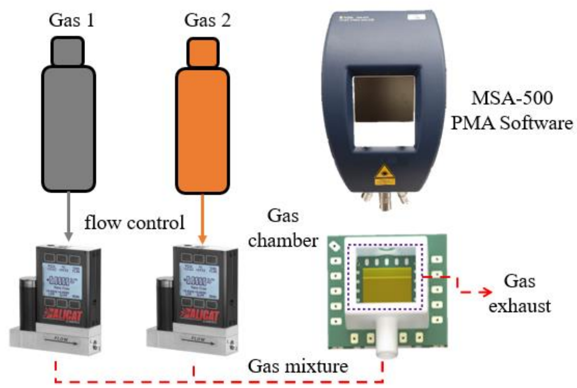

Figure 3: The gas testing setup showing an optical instrument MSA-500 to measure the dynamic amplitudes.

Table 1: Molar fraction (Dilution with N_2) and calculated viscosity coefficients of the used gases.

Name	μ* (μP)	CH_4	CO_2
Gas 1	169	0.8	0
Gas 2	168	0	0.8
Gas 3	162	0	0.2
Gas 4	161	0	0.4
Gas 5	156	0.3	0
Gas 6	154	0	0.6

Name	μ* (μP)	He	Ar	CO_2
Gas 7	186	0.5	0	0
Gas 8	199	0	0.5	0
Gas 9	213	0	0.8	0
Gas 10	161	0	0	0.5
Gas 11	152	0	0	0.8

Table 2: Viscosity coefficients of mono gases for activating internal resonance.

Name	μ (μP)	Name	μ (μP)
He	196	**CO_2**	147
N_2	176	**CH_4**	11
Ar	223		

GAS SENSING

Fig. 3 shows the experimental setup for gas sensing and measurements. The in-plane resonance frequencies are measured through the stroboscopic video microscopy of the Micro System Analyzer (MSA-500) from Polytec, using a ring-down measurement. The camera's targets are set on the end of a column, square 1, and in the mid-span of the supported beam, the square 2, as illustrated in Fig. 1a, to measure the response of the 1st (*x*-direction) and 2nd (*y*-direction) modes, respectively. For the experimental measurements, two devices from the same wafer with similar dimensions were used, chosen with minor variations in fabrication. The electrical resistance between anchors was measured 4.3 kΩ, and the resonance frequencies of the 1st and 2nd modes of both structures were initially measured approximately, respectively, 66.11kHz and 144.03kHz. The portal frame resonator is actuated with DC and AC electrostatic voltages under gas exposure, through the parallel electrode B.

In the following, the activation of internal resonance is investigated when the device is exposed to different gases concentrations, perturbing its surrounding environment inside the chamber. Therefore, as an initial point, the electrostatic actuation was chosen at V_{atm} = 5V and V_{dc2} = 110V, where there is no activation of the phenomenon, but maintain the main condition of the internal resonance, which is the 2:1 frequency ratio. In this case, the force magnitude is maintained constant, and the gas exposure induces the change of the environment viscosity inside the chamber; thus, changing the damping conditions according to the properties of the gases' mixtures. The flow was limited to 50cc/min, and the gas chamber has 4.93 cm^3 (design volume). The selection of gases and mixtures are shown in Table 1 (gas mixtures) and Table 2 (pure mono gasses) with the viscosity coefficients given in μPoise.

Figs. 4a and b show the frequency responses of the 1st and 2nd modes when the structure is under gas exposure according to the gases shown in Table 1 at V_{gas} = 5V (V_{atm} = 5V under gas exposure) excited around the 2nd mode. Note that, when the gases Gas 1 and Gas 2 are flushed inside the chamber, the behavior of the structure does not show any large amplitudes or resonances. However, when Gas 3 is flushed, internal resonance is activated. From Table 1, we observe that the activation of internal resonance occurs when there is a reduction of the viscosity inside the chamber. In other words, damping is reduced. Similar behavior is observed for Gases 4,5, and 6.

Next, we experimentally study the sensitivity of the activation of internal resonance by varying the viscosity of the medium inside the chamber versus the V_{gas}, as presented in Fig. 5. All the gases from Tables 1 and 2 were selected to estimate the range and the viscosity sensitivity. In this study, we set an operation point at a fixed frequency of 130kHz, which is in the middle of the range of the frequency response curves where the internal resonance is activated as shown in Fig. 4b.

As shown in Fig. 5, the activation of the internal resonance can change depending directly on the viscosity and amplitude of excitation. For gases with lower viscosity, damping is lower, and the critical amplitude of excitation to activate the nonlinear phenomenon is smaller, for instance when only N_2 or He is flushed into the chamber. However, other denser gases such as CO_2 suppress the activation of internal resonance at the same excitation amplitude because damping increases. Therefore, increasing the magnitude of excitation is needed to reactivate the phenomenon.

To obtain an analytical relationship, the dashed line is obtained by ordinary least squares regression, to represent the activation of the internal resonance threshold regarding the change in the viscosity atmosphere. This curve presents a linear trend with a sensitivity of 21.73 V/μP. From the obtained results, we can highlight that the phenomenon is achievable at any gas change according to the relation between damping and excitation amplitude.

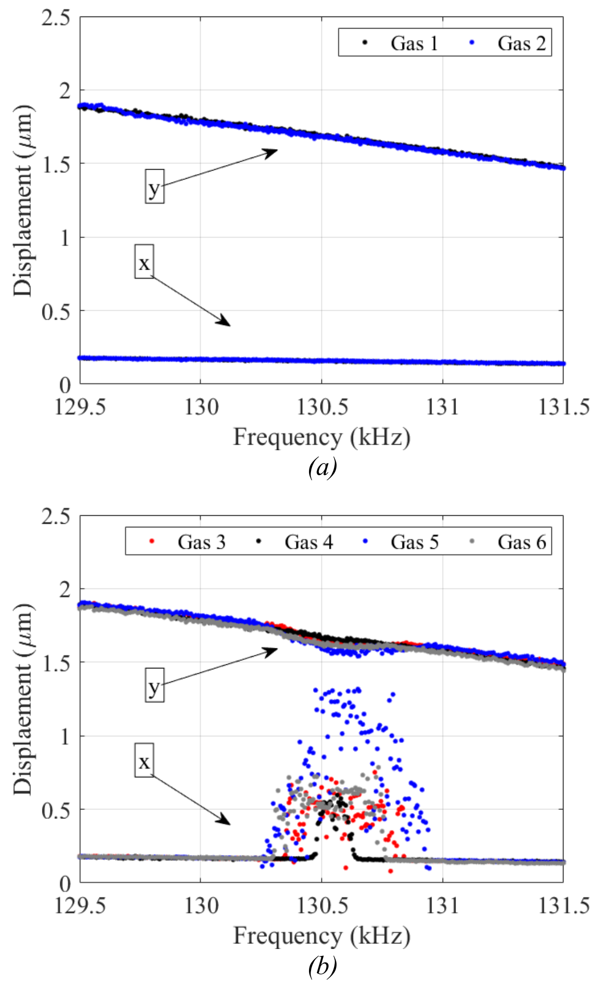

Figure 4: Frequency response curves of the 1st (x) and 2nd (y) modes showing when exposed to various gases from Table 1. (a) Gases that do not activate internal resonance. (b) Gases that activate internal resonance.

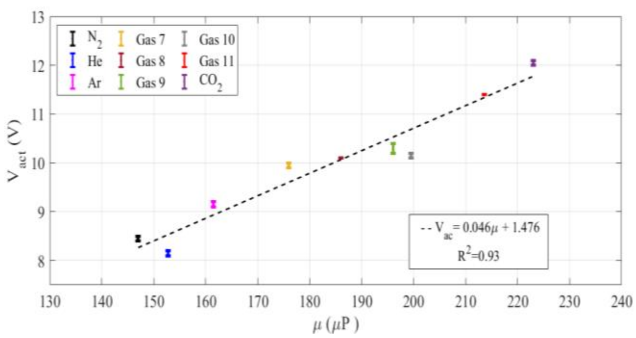

Figure 5: The thresholds to activate internal resonance for gases of different viscosities. Below the line no internal resonance is activated. The line can be used for calibration to identify various types of gases.

CONCLUSION

In this paper, we presented gas sensing based on the 2:1 internal resonance of a micro portal frame resonator. The work was based on the variation of viscosity of different gases accounting for the AC excitation as the critical amplitude threshold for the activation of the internal resonance. Experimental results were shown that demonstrate the concept.

First, we determined an operation point where the gas sensing was applied depending on the viscosity of air at atmospheric pressure, and the excitation amplitude through the AC voltage. For that, the 2:1 frequency ratio between the 1st and 2nd modes of vibration was established by setting the DC load. Frequency responses were obtained to determine the frequency range where internal resonance is activated. Then, the activation of the internal resonance was investigated for different gases of various viscosity features.

We successfully demonstrated that the internal resonance in the portal frame structure can be used to sense different gases of various viscosity coefficients based on the actuation force. It is also observed that the presented sensing method allows the portal frame to be used to sense small variations in gas concentration or physical perturbations in the environment. In addition, the micro resonator device has the feature that, when the internal resonance is activated, the maximum displacements of both vibration modes are orthogonal to each other, which makes them independent for driving and sensing. Thus, the portal frame accounting for 2:1 internal resonance is a promising device that can be used as a reliable and powerful gas sensor.

ACKNOWLEDGEMENTS

This publication is based upon work supported by King Abdullah University of Science and Technology (KAUST).

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