A MODE-LOCALIZED MEMS ACCELEROMETER WITH 7µg BIAS STABILITY

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ABSTRACT

This paper reports on the experimental characterization of the resolution, sensitivity and common mode rejection metrics for a mode-localized MEMS accelerometer. A bias stability of 7µg is achieved for closed-loop amplitude ratio measurements at an integration time of 30s representing a significant advancement in the development of high-stability accelerometers employing this transduction principle.

INTRODUCTION

Mode localized MEMS devices have been the topic of recent research due to their intrinsic common mode rejection capabilities [1] and improved parametric sensitivities (2-3 orders of magnitude) [2] relative to traditional frequency shift sensing devices. For these reasons, they have been researched for application to gravimetric sensing [3], and force and inertial sensors [4][5].

The first published implementation of a mode-localized accelerometer [5] was in an open loop readout configuration. An open loop resolution of 0.619mg was reported in this work with the readout configuration and electronics limiting measurement accuracy. A low-noise closed-loop readout configuration is essential for the characterization of these devices as accelerometers, and represents a key step towards practical implementation.

Recent work on mode localized resonators proposes the use of a simple direct feedback topology as a self-sustaining loop [6] as part of the front-end readout interface. The work proposed biasing the mode-localized resonators in a highly asymmetric condition (large amplitude ratios), reducing the system to a pseudo single resonator system. The motional current of the resonator with the higher amplitude of vibration was used to close the loop while the amplitude of vibration of the second resonator was read out in an open loop configuration. Using this configuration, a resolution of 85ppb was achieved with respect to input-referred stiffness perturbations [7].

Although there are advantages to operating at high amplitude ratio regimes such as greater sensitivity and linearity of the output metrics with tilt [8], recent work suggests that the noise due to drive power variations are lower in the symmetric condition [9]. Thus, to improve the resolution of the device, the oscillator design as suggested in [6] is modified for operation in the symmetric condition.

In this work, we report on results from the implementation of a closed-loop oscillator configuration adapted for a mechanically coupled mode-localized accelerometer system. A bias stability of 7µg is achieved which is approximately 2 orders of magnitude better than the state of the art in mode-localized accelerometers. We also discuss the common mode rejection capabilities which have been attributed as the primary reason for improved stabilities at long integration times.

DEVICE

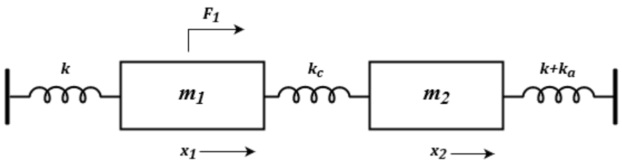

Figure 1: Spring-mass representation of a 2DOF mode localized accelerometer.

A spring mass representation of the mode-localized accelerometer device is shown in Figure 1. Two identically designed resonators are coupled using a mechanical coupling beam (k_c). Perturbations (k_a) in the form of an acceleration force are applied on one of the resonators, thus, changing the stiffness of that resonator with respect to the other resonator. The force is applied axially to ensure greater linearity with respect to tilt. The ratio of the two amplitudes is the output metric in this system and its sensitivity to input acceleration can be modelled as:

$$S_{AR} = \left| \frac{k_a}{4k_c} \right| \tag{1}$$

The device (shown in Figure 2) under test is a wafer-level vacuum packaged silicon MEMS accelerometer consisting of a 2-DOF mechanically coupled clamped-clamped (C-C) resonator readout. One of the resonators is connected to a proof mass through a micro-lever configuration that amplifies the inertial axial force applied on the resonator system due to change in gravitational acceleration. The device parameters are shown in Table 1.

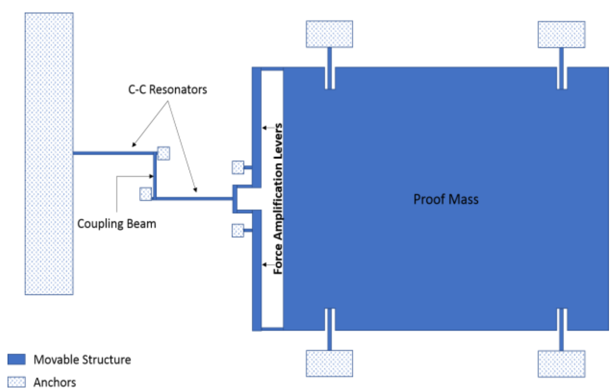

Figure 2: Schematic of the mode-localized accelerometer.

Table 1: Device Parameters.

Device Parameter	Dimension
Resonator beam length	700µm
Resonator beam width	7µm
Coupling beam length	400µm
Coupling beam width	4µm
Proof Mass length	9000µm
Proof Mass width	5500µm
Device layer thickness	40µm

SIMULATION

The resonator system was simulated in the Finite Element Modelling (FEM) simulator COMSOL® to study the sensitivity to applied acceleration in the form of tilt. The results of the simulation are shown in Figure 3.

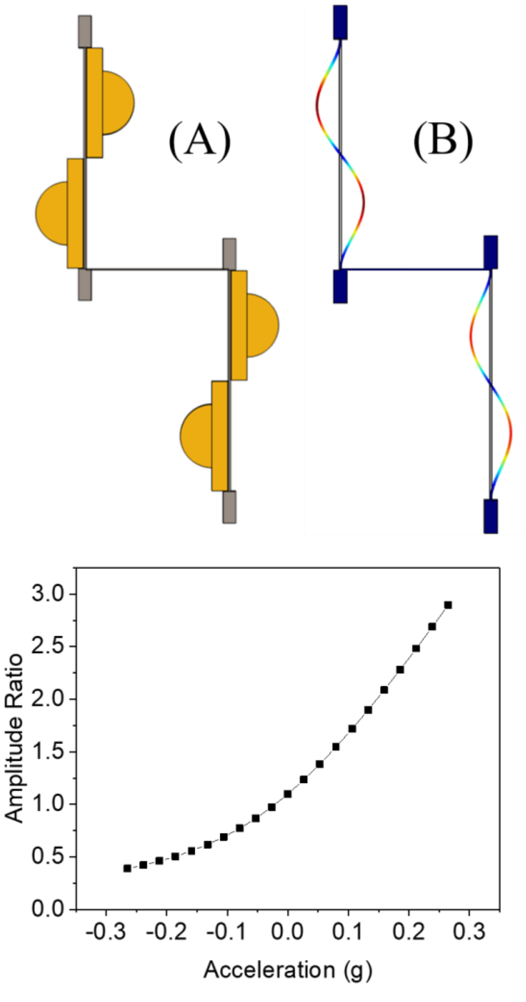

Figure 3: Simulated sensitivity of amplitude ratio to acceleration for the anti-phase mode with the electrode drive configuration (A) and mode shape as simulated in COMSOL® (B).

The drive and sense electrode configuration and the excited mode shape are shown in Figure 3(A) and (B). The sensitivity of the amplitude ratio to an axial force due to acceleration is shown in the same figure. The electrode configuration facilitates drive and sense in the second flexural mode of vibration. The second flexural mode has higher motional resistance and higher mechanical stiffness as compared to the first mode. This also allows for a larger nonlinear threshold which in turn allow for higher drive amplitudes and output amplitudes. Since the system is dominated by electronic noise, it is desirable to have higher output amplitudes to increase the signal to noise ratio (SNR).

EXPERIMENTAL SETUP

Closed-loop oscillation is achieved by employing a transimpedance amplifier (TIA) based oscillator circuit comprising a soft limiter for amplitude gain control and a phase shifter to tune the loop phase in accordance with the Barkhausen criteria.

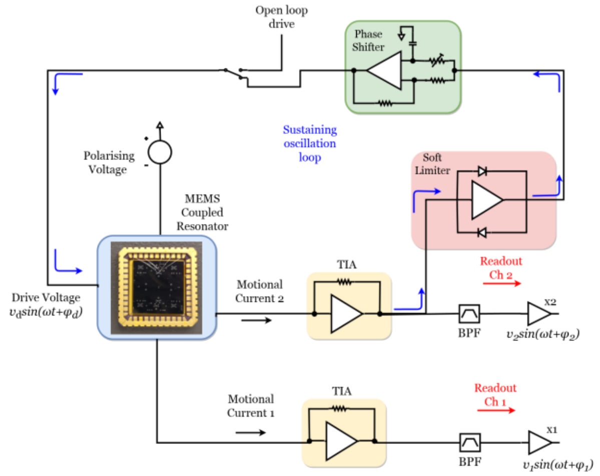

Figure 4: Schematic of the experimental setup with packaged chip (inset).

The oscillator works on a master-slave drive system whereby only the motional current of resonator 2 (slave resonator) is used as input to the oscillator circuit, while the motional current of resonator 1 (master resonator) is read out separately in an open loop configuration. This is an adaptation of the closed loop oscillator system employed in [6] where the operating region was limited to high amplitude ratios. In this modified configuration, the self-sustaining loop can be operated near the symmetric operating condition. This is made possible by the reduced sensitivity to parametric variations on the amplitude of vibration of the non-driven resonator. This ensures that the sense amplitude that is used to close the loop remains constant over the operating region. The experimental setup is shown in Figure 4.

The amplitudes of vibration were measured using two Zurich Instruments MFLI lock in amplifiers. All the measurements are carried out for the second vibration mode (shown in Figure 2(B)). The resonant frequency is approximately at 350 kHz and the quality factor of the device was measured to be 50000.

RESULTS

Sensitivity

To test the sensitivity of the device to input acceleration, a tilt test was performed on the system. The sensor was fixed to a tilt table and the tilt angle was changed from -30º to +45º with respect to the horizontal static position, thereby varying the component of the gravitational force acting along the sensitive axis. The corresponding variation in amplitude ratio was measured and is plotted in Figure 5. The values agree reasonably well with the simulation of the device in COMSOL® (shown in Figure 3). The slope of this curve provides the sensitivity of the amplitude ratio to gravitational acceleration, and is found to be 1.007/g in the linear operating region.

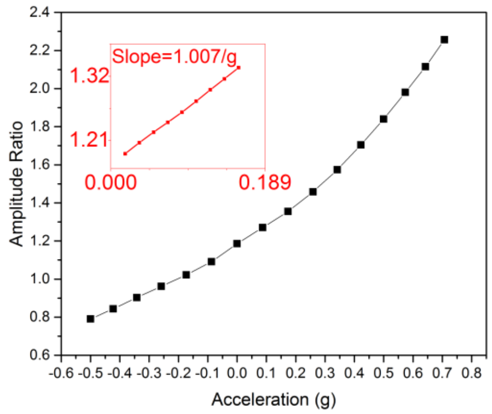

Figure 5: Measured amplitude ratio sensitivity to change in gravitational acceleration using a tilt test with the linear operating region shown near the horizontal position (inset).

Bias Stability

To calculate the bias stability, the amplitude data of both the resonators is collected for a representative period of 1500s. The modified Allan variance of the amplitude ratio is calculated and is divided by the sensitivity to determine the input-referred stability which is plotted in Figure 6. A bias stability of $7\mu g$ is achieved at an integration time of 30s. A 1 Hz measurement bandwidth in the lock-in amplifier causes rapid fluctuations at timescales larger than the filter bandwidth value to be attenuated as represented in the Allan variance plots below an integration time of 3s.

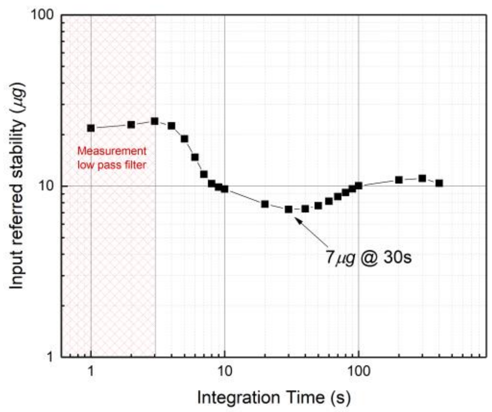

Figure 6: Modified Allan variance plot of the amplitude ratio measurements showing the bias stability of the accelerometer.

Common mode rejection

The common mode rejection properties for amplitude ratio measurements can be seen for integration times above 100s where the Allan variance plot tends to flatten out. Figure 7 further compares the Allan variance plots of the individual amplitudes of vibration with that of the amplitude ratio. The Allan variance of the individual resonator amplitudes increases with the integration times suggesting their dependence on environmental factors. The ratio of the two amplitudes rejects these environmental factors that would otherwise result in measurement drift, enabling stable long duration measurements.

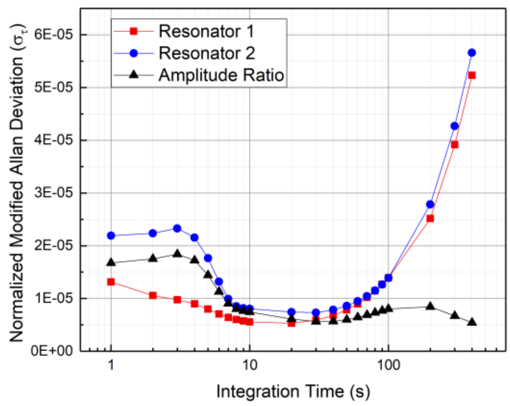

Figure 7: Modified Allan variance plot comparing the normalized stability of the individual resonator amplitude and the ratio of the two amplitudes.

A further comparison can be made between amplitude ratio and the conventional frequency shift method of sensing. Figure 8 compares the input referred stability of these two output metrics on the same device and it is clear that due to the common mode rejection capabilities and the high sensitivity, the amplitude ratio shows a better stability with exceptional drift cancellation abilities. This illustrates the potential of amplitude ratio sensing over conventional frequency shift sensing methods.

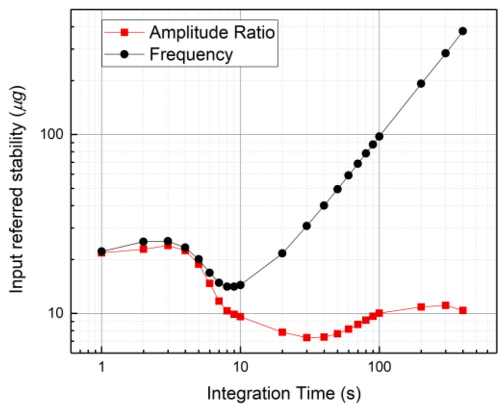

Figure 8: Modified Allan variance plot comparing the input referred stability of the amplitude ratio and the frequency of the resonator system.

DISCUSSION

The bias stability achieved in this work is unprecedented in the field of mode-localized accelerometers. However, there are several areas where further optimization can be carried out to improve the resolution and long-term stability. A crucial component of mode-localized devices is the coupler since the sensitivity of the device is inversely proportional to the coupling strength. So far there have been two methods of coupling shown – mechanical [5] (for e.g. using a coupling beam) and electrostatic coupling [1] (for e.g. using a voltage difference across a parallel plate capacitor located between the two resonators). Electrostatic coupling is tunable and allows for low coupling stiffness, potentially enabling significant further gains in sensitivity and hence, resolution. However, the coupler is nonlinear and requires low-noise highly stable tunable voltage references to bias the electrodes.

A mechanical coupling beam is used in this design representing the limiting factor for the sensitivity of the device. Furthermore, the mechanical coupling limits the common mode rejection capabilities of the device. The effect of variations in the temperature and pressure on the individual resonators is cancelled in mode-localized sensors, however, the coupling beam is not immune to the variations in the temperature and pressure variations. Since the coupling stiffness impacts the amplitude ratio as well as its sensitivity to acceleration, any variations in the coupling stiffness impacts the sensor response as well. The use of an electrostatic coupling will reduce temperature dependence of the coupler and allow for optimization in the coupling stiffness (and in turn sensitivity) of the device. Thus, it is a more suitable choice for high resolution at long integration times.

CONCLUSION AND FUTURE WORK

This work reports on a mode-localized accelerometer design with a bias stability of $7\mu g$ and excellent stability over long integration times, representing a significant advance in this area. The system is characterized in a closed-loop configuration, adapted from previous work using a direct feedback oscillator topology for mode-localized sensors. The common mode rejection capabilities of the device are demonstrated with a significant intrinsic rejection in amplitude ratio measurements when compared to the uncompensated individual amplitudes as well as the conventional resonant frequency shift sensing method. It may be noted that the mechanical coupling appears to be one of the limiting factors in the measured stability at long integration times.

Future work in this area is addressing the understanding of the various drift mechanisms that affect mode-localized inertial sensors limiting the long-term stability of the device. These devices offer great potential to compete with traditional frequency shift sensing especially at long integration times, but further work needs to be conducted on optimizing the operating point, and on the oscillator topology and readout electronics.

ACKNOWLEDGEMENTS

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REFERENCES

[1] P. Thiruvenkatanathan, J. Yan, and A. A. Seshia, "Differential amplification of structural perturbations in weakly coupled MEMS resonators," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 57, no. 3, pp. 690–697, Mar. 2010.

[2] P. Thiruvenkatanathan, J. Yan, J. Woodhouse, and A. A. Seshia, "Enhancing Parametric Sensitivity in Electrically Coupled MEMS Resonators," *J. Microelectromechanical Syst.*, vol. 18, no. 5, pp. 1077–1086, Oct. 2009.

[3] M. Spletzer, A. Raman, A. Q. Wu, X. Xu, and R. Reifenberger, "Ultrasensitive mass sensing using mode localization in coupled microcantilevers," *Appl. Phys. Lett.*, vol. 88, no. 25, p. 254102, Jun. 2006.

[4] C. Zhao, G. S. Wood, J. Xie, H. Chang, S. H. Pu, and M. Kraft, "A force sensor based on three weakly coupled resonators with ultrahigh sensitivity," *Sens. Actuators Phys.*, vol. 232, pp. 151–162, Aug. 2015.

[5] H. Zhang, B. Li, W. Yuan, M. Kraft, and H. Chang, "An Acceleration Sensing Method Based on the Mode Localization of Weakly Coupled Resonators," *J. Microelectromechanical Syst.*, vol. 25, no. 2, pp. 286–296, Apr. 2016.

[6] C. Zhao, M. Pandit, B. Sun, G. Sobreviela, X. Zou, and A. Seshia, "A Closed-Loop Readout Configuration for Mode-Localized Resonant MEMS Sensors," *J. Microelectromechanical Syst.*, vol. 26, no. 3, pp. 501–503, Jun. 2017.

[7] M. Pandit, C. Zhao, G. Sobreviela, A. Mustafazade, and A. A. Seshia, "Closed-loop tracking of amplitude and frequency in a mode-localized resonant MEMS sensor," in *2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFC)*, 2017, pp. 510–513.

[8] C. Zhao, G. Wood, J. Xie, H. Chang, S. H. Pu and M. Kraft. "A comparative study of output metrics for an MEMS resonant sensor consisting of three weakly coupled resonators". *J. Microelectromechanical Syst.*, vol. *25, no.* 4, pp.626-636, June 2016.

[9] M. Pandit, C. Zhao, G. Sobreviela, A. Mustafazade, and A. A. Seshia, "Reduction of Amplitude Ratio Dependence on Drive Level in Mode Localized Resonant MEMS Sensors," in *2017 IEEE Sensors, Glasgow, UK, 2017*.

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