A Capacitive MEMS Accelerometer Readout with Concurrent Detection and Feedback Using Discrete Components

Yunus Terzioglu[1,2], Said Emre Alper[1], Kivanc Azgin[3], and Tayfun Akin[1,2]
[1]METU-MEMS Research and Application Center, Ankara, TURKEY
[2]Middle East Technical University, Department of Electrical and Electronics Eng., Ankara, TURKEY
[3]Middle East Technical University, Department of Mechanical Eng., Ankara, TURKEY

Abstract—**This paper presents an analog readout method for capacitive MEMS accelerometers in which the feedback actuation and capacitive detection are achieved simultaneously on the same electrode set. The presented circuit operates in closed-loop for improved linearity, and it is constructed in a hybrid platform package in which off-the-shelf discrete components are used together with the silicon-on-glass micro-accelerometer. The system is developed as a practical solution to reduce the complexity of the readout circuit and the accelerometer without degrading the overall system performance. Experimental results demonstrate 17.5 micro-g per square-root hertz velocity random walk, and 28 micro-g bias instability. Considering the estimated full scale range of 20 g, the dynamic range of the sensor is calculated to be close to 124 dB.**

Keywords—analog capacitive readout, discrete components, MEMS accelerometer, closed-loop feedback

I. Introduction

MEMS capacitive accelerometers find use in a wide spectrum of applications including commercial, military, and medical industries, due to their many advantageous aspects such as low-cost, small footprint, and low power consumption [1]. A critical component for MEMS capacitive accelerometers is the readout approach, and there exist various readout methods to be used, implemented with discrete components or a CMOS ASIC. Among these methods, the state-of-the-art closed-loop digital topologies taking advantage of ΣΔ modulators can offer great linearity and noise performances [2], but the trade-off shows itself with the circuit complexity and stability. In this method, a feedback signal is provided digitally to the proof mass of the accelerometer, causing residual motions on the proof mass of the sensor [3]. Besides, these systems may suffer from the quantization error, which can be further suppressed by using clocks at higher frequencies, at the expense of even higher circuit complexity. Such closed-loop systems also may require an extra pair of electrodes [4]-[5] for feedback, to be able to separate the detection and feedback signals, increasing the chip area. These problems can be solved by using an analog closed-loop system, where the detection and feedback can be achieved simultaneously using the same electrodes, thus increasing the effective sensitivity per unit chip area [6]. Also, in such systems, separating the feedback and detection cycles in time domain using switches and high frequency clock signals is not necessary. CMOS implementations of such systems offer low cost in high volumes, but the cost of such implementations is much higher for low volume applications and research platforms. A lower cost and a more versatile approach is to implement such readout circuits with off-the-shelf discrete components.

This study presents a low-cost accelerometer readout with a fully analog readout circuit and feedback structure, targeting a highly versatile research platform for development of high performance MEMS capacitive accelerometer systems. The developed analog readout circuit provides high performance with a simple circuit structure, as opposed to complex digital readout methods. The presented readout circuit is realized inside a hybrid platform package where off-the-shelf discrete components are used together with a silicon-on-glass micro-accelerometer. Considering the wide spectrum of ICs commercially available in the market, the most suitable discrete component for each building block of the readout circuit can be picked freely rather than being restrained by the performance parameters of a single CMOS fabrication technology. Eventually, the circuit flexibility is further increased, and the low-volume production cost is significantly decreased. Moreover, the constructed circuit can easily be modified to fit for sensing elements of different dynamic responses, or even the package can be sealed hermetically for testing the accelerometers under different atmospheric conditions, thus eliminating the application specific nature of an integrated readout circuit.

In Section II, The operation principles of the proposed closed-loop analog readout method are described. Section III presents the simulations and the MATLAB model utilized for the simulations. In Section IV, details about the production of the accelerometer and the test results are demonstrated.

II. Closed-Loop Analog Accelerometer with Concurrent Feedback and Detection

The proposed accelerometer readout is developed to be used with a micromachined, single-axis, lateral, varying-gap capacitive accelerometer. Figure 1 shows the conceptual mechanical structure and the equivalent electrical model of the acceleration sensing element, where the two complementary

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varying gap capacitors (C_A and C_B) are formed between the proof mass and the electrodes via intervened fingers. Since the sensing element is a varying-gap type micro-accelerometer, the two complementary capacitances have a non-linear relation with the displacement of the proof mass. This non-linearity is the main reason behind the need for a closed-loop system.

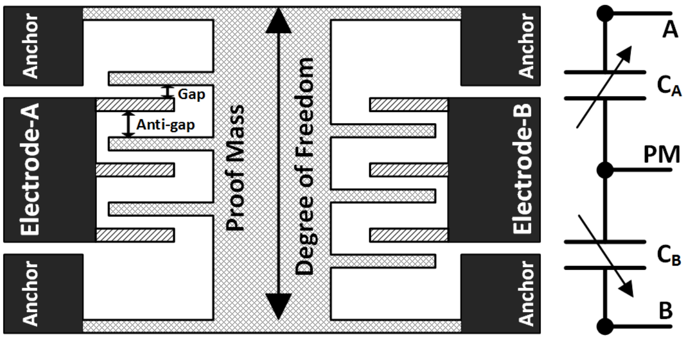

Fig. 1. The conceptual mechanical and the equivalent electrical structure of a lateral, differential, varying-gap type microaccelerometer. The dashed areas demonstrate the suspended parts of the structure, while the solid colored parts represent the anchors which are fixed to the chip substrate.

Figure 2 shows the simplified schematics of the proposed system. In the presented circuit, differential sinusoidal modulating signals V_{ac} and $-V_{ac}$ are applied to the electrodes, and the proof mass is virtually grounded by the pre-amplifier stage which is a transimpedance amplifier (TIA). In case of a capacitance mismatch between the two electrodes due to and external acceleration, an electrical current signal is generated, which is converted to voltage through the pre-amplifier stage. This voltage is then filtered by a passive RC high-pass filter, demodulated, and filtered by an active second order Butterworth low-pass filter to be input to the PI-controller. The output of the PI-controller (V_{FB}) is then superimposed onto the modulating signals by using two unity-gain-configured instrumentation amplifiers, and fed back to the sensor to keep the mass stationary, thus, resulting in a very high linearity performance for the accelerometer. In addition, by tuning the reference voltage V_{DC}, which is applied equally on both of the electrodes, the range and the noise performance system can be adjusted for different applications. Moreover, the analog voltage output from the accelerometer package can directly be used as a high performance acceleration reading without any post-processing.

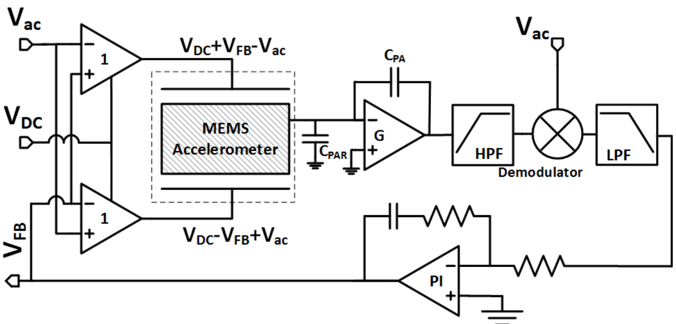

Fig. 2. The simplified circuit diagram for the proposed accelerometer.

The TIA pre-amplifier structure is insensitive to the parasitic capacitances, C_{PAR} in Figure 2. The second benefit of using a TIA is having a voltage gain independent from the frequency of the input signal. Considering differential AC signals are applied on the two electrodes of the sensing element, and a capacitance difference of ΔC exists between the two electrodes, the transfer function, H(s), from these AC signals to the pre-amplifier output can be calculated as:

$$H(s) \cong -\frac{\Delta C}{C_{PA}}$$

which, clearly, is frequency independent. Thus, the variations of the frequency of the modulating signal V_{ac} do not affect the overall loop gain. The frequency of this signal is selected to be sufficiently higher than the -3 dB frequency of the mechanical sensing element so that the effect of the residual motions on the readout performance is kept minimal.

The output of the pre-amplifier is later demodulated and filtered to be fed to the PI-controller. Note that the integral controller is utilized to eliminate the steady state error, and decouple the linearity performance from the off-set voltages and leakage currents of the active components. By using a PI-controller, the versatility of the readout circuit is also increased since the dynamic response of the loop can be directly altered by changing the controller parameters. As a result, the circuit can be utilized as a readout for a wide range of MEMS accelerometers with different dynamic properties.

The output voltage of the PI-controller, V_{FB}, is directly fed back onto the electrodes along with the constant reference voltage V_{DC}. These two voltages generate the balancing force on the proof mass. The value of the feedback voltage, V_{FB}, under the effect of an external acceleration, a_{ext}, can be calculated using the equation below.

$$V_{FB} \cong \left(\frac{m * d_{gap}^2}{2 * \varepsilon * A * V_{DC}}\right) * a_{ext}$$

where, m is the proof mass (kg), d_{gap} is the capacitive finger separation in gap region (m), A is the overlap area (m^2), and ε is the permittivity of air. Note that the effect of the anti-gap regions on the sensitivity is ignored for the sake of simplicity.

By using such a feedback mechanism, and reading out the voltage required to stabilize the mass rather than the mass displacement, a perfectly linear relation between the output voltage (V_{FB}) and the external acceleration is obtained. Indeed, V_{FB} is used as the scale factor of the proposed accelerometer. Moreover, the scale factor of the system can be tuned to a desired value by manipulating the reference voltage, V_{DC}, without a need to alter the mechanical design.

Also, the low-frequency signals V_{DC} and V_{FB}, which are used for force feedback, are electrically filtered on the electrode capacitances, thus they have no contribution to the current which is fed to the pre-amplifier. Whereas, the modulating signal, V_{ac}, is mechanically filtered by the sensing element, and has no contribution to the force feedback on the proof mass. Resultantly, the detection and the feedback can take place concurrently on the same electrodes, and the system can operate continuously, contrary to the digital sigma-delta readout architectures, which requires isolated time intervals for the detection and feedback.

III. SIMULATIONS

Figure 3 shows the SIMULINK model constructed for verifying the functionality of the presented circuit. The block titled as '*Accelerometer'* in Figure 3 models the sensing element with the following transfer function:

$$\frac{\Delta C(s)}{F(s)} = \frac{1}{ms^2 + bs + k} * \frac{dC}{dx}$$

where m, b and k represents the mechanical constants mass, damping coefficient and spring constant of the sensing element respectively. The coefficient dC/dx is the effective sensitivity of the sensing element, and ideally is a highly nonlinear function of the displacement, x. In the prepared SIMULINK model, this term is utilized as a fixed value by assuming the proof mass displacement is infinitesimally small due to continuous force-feedback. Note that the maximum proof mass displacement in the transient response to a 1 g step acceleration input is 54 nm, while the gap separation of sensing element is 3 μm.

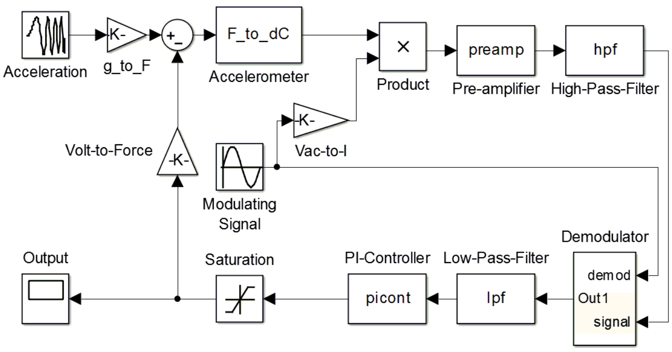

Fig. 3. The simulated model of the implemented accelerometer, constructed in MATLAB-Simulink environment.

In addition to the functionality verification, the SIMULINK model is used to simulate the operational bandwidth and the scale factor of the system using chirp and ramp signals, respectively, the results of which are compared with the test results in Section IV. Before the implementation phase of the system, another model in SPICE environment is also created. Instead of using transfer functions of the building blocks like in the MATLAB model, actual active component behavioral models provided by the IC manufacturer is utilized, and the overall electronic circuit functionality is verified.

IV. IMPLEMENTATION AND TEST RESULTS

Figure 4 shows the picture of the accelerometer system package. The proposed system is constructed in a single 0.1"-pitch, 0.6"-wide, 16-pin DIP hybrid platform package. The package includes the MEMS accelerometer, a number of passive components, and the discrete active components, all of which are integrated on a hybrid glass-substrate mounted inside the package. In Table 1, the list of active components used in the implementation of the circuit is given. The sensing element was fabricated at Middle East Technical University – MEMS Research and Application Center using the fabrication process described in [7].

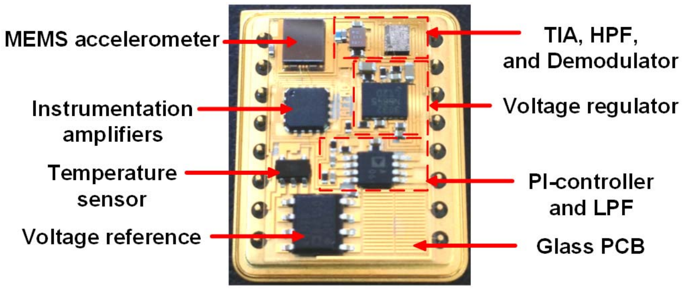

Fig. 4. The overview of the accelerometer system package.

TABLE I. LIST OF ACTIVE COMPONENTS

Component	Component Type	Usage
AD8222	Instrumentation amplifier	Electrode voltage generation
AD8606	Operational amplifier	Front-end electronics
AD630	Balanced modulator/demodulator	Demodulation
AD8629	Operational amplifier	PI-controller/low-pass filter
ADR4520	Voltage reference	Reference voltage (V_{DC}) generation
LT3032	Voltage regulator	IC supplies
TMP36	Temperature sensor	-

A centrifugal device is utilized for measuring the response of the accelerometer for the inputs ranging from -2.6 g to 4.1 g, being limited by the setup. The raw data is then processed and fit onto two lines for positive and negative acceleration inputs. The equations representing the lines are used to measure the scale factor and 0 g off-set voltages. Figure 5 shows the data measured from the centrifugal test and the fitted lines are presented along with the simulation results. This test yielded a scale factor of 202 mV/g, corresponding to an approximately ±10 g estimated full-scale range for a reference voltage, V_{DC}, of 2 volts. The scale factor is calculated as 166 mV/g using the SIMULINK model in consistence with the feedback voltage (V_{FB}) formula given in Section II. The reason for the scale factor difference between the simulation and the measurement results are within the tolerances of the capacitive gap enlargement during the fabrication process. This effect results in an increment in the gap separation, effectively reducing the sensitivity of the sensor.

Note that the acceleration can be input to the sensor only in one direction with the centrifugal test setup at a time. And to take measurements in the other direction, the accelerometer must be rotated by 180° around its principal axis resulting in a variation of the 0 g off-set value read from the accelerometer. For this reason, the measurements are presented in two different parts for positive and negative acceleration inputs, and two different lines are fit onto these data.

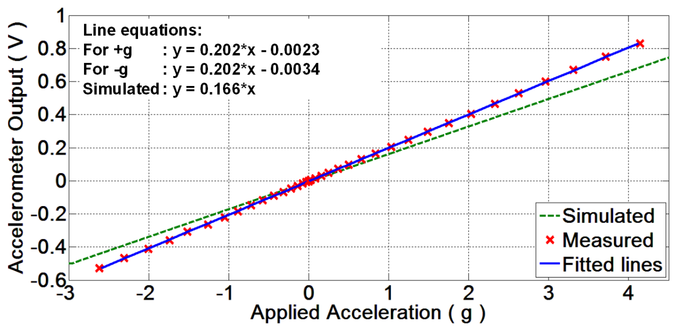

Fig. 5. Simulated accelerometer ramp response and the measurement results collected using a centrifugal test setup. Blue solid lines demonstrate the ideal line fitted onto the measurements.

Figure 6 shows the residuals left after taking the point-wise difference between the measured and fitted data. The linearity of the accelerometer is found as 0.15 % from this figure.

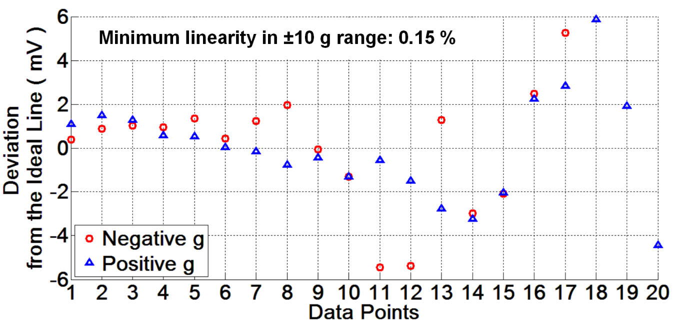

Fig. 6. The deviation of the measured centrifugal test data from the fitted ideal line.

In order to observe the operational bandwidth of the accelerometer, a chirp test is conducted using a shaker table. In this test, vibrations ranging from ~20 Hz to 200 Hz are applied on the accelerometer, and the results are compared with the simulated values. Eventually, the -3 dB point of the accelerometer was observed at ~70 Hz which are consistent with the simulation results. Figure 7 shows both the test and the simulation results for this test.

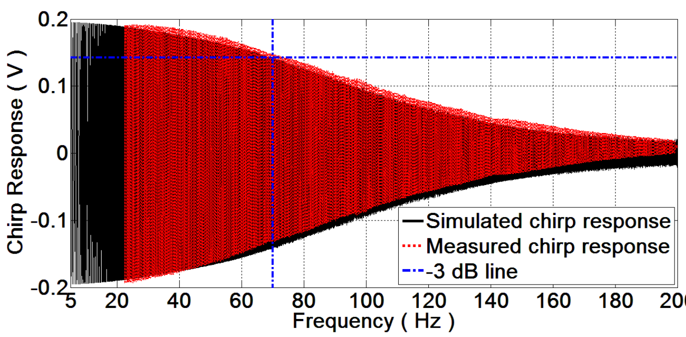

Fig. 7. The simulated and measured chirp test results.

Figure 8 shows the velocity random walk and the bias instability values of the implemented sensor system, which are 17.5 μg/√Hz and 28.6 μg, respectively, found by Allan variance analysis.

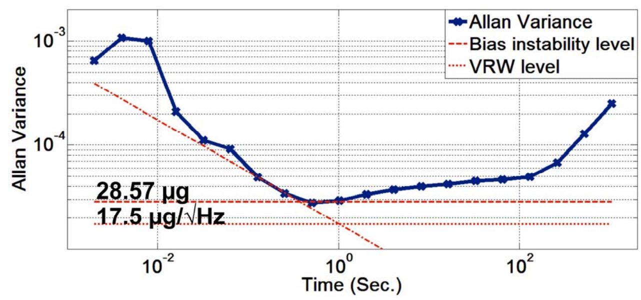

Fig. 8. The result of the Allan variance analysis conducted on the proposed system. The raw data utilized in this test is collected at room temperature while the sensor is kept at 0 g position.

V. CONCLUSION

In this paper, the operation principles of an analog readout method for capacitive MEMS accelerometers, which is realized using off-the-shelf discrete components, is introduced. In the presented system, a concurrent feedback actuation and acceleration detection method is demonstrated, and verified by the conducted tests. Moreover, this simultaneous operation is achieved using only a single set of differential electrodes by filtering the actuation signals electrically before the front-end electronics; and by filtering the detection signals mechanically preventing any significant residual motion on the proof mass.

By using a fully analog electronics loop, the requirement for high performance clocks, switches or complicated timing circuits have been eliminated. With the simple yet effective design of the system, high versatility is offered with the easily tunable parameters. Thus, the circuit parameters can easily be altered to fit the design for different sensors or applications.

Eventually, the presented closed-loop system proved worthy, offering a wide full scale range, high linearity, and low noise density. Moreover, the system is implemented using commercially available components resulting in an even higher versatility and lower cost for low-volume production.

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