REDUCED LINEARITY ERROR DESIGNS FOR CAPACITIVE MICROMACHINED SENSORS

Christoph Menzel

Ford Microelectronics, Inc.
Colorado Springs, Colorado 80921-3698

ABSTRACT

This paper describes a general design solution which breaks the link between sensitivity (percent deflection) and DC linearity error for a torsional spring, capacitive, micromachined accelerometer. Modeling and device data for a specific sensor configuration show the effectiveness of the design change. The reduced linearity error is achieved by designing in non-linearity that counter balances the device's inherent non-linearity. As the solution involves changing only the relative size of stationary metal electrodes, it has little or no impact on other device functions such as DC and AC response and general device robustness.

INTRODUCTION

The design solution presented herein has found applicability on the transducer of accelerometers used within automotive airbag systems. While automotive linearity requirements are not particularly stringent (~1% of full scale), the high volume production and 6σ goals of automotive manufacturing are in themselves forces for tight tolerances. The transducer is an iteration of a centrally tethered, two beam, capacitive device introduced by Silicon Designs[1]. The heavy/light mass ratio is approximately 3:1. Differential capacitors are formed by independent, stationary metal electrodes underneath the heavy and light sides of the single crystal silicon structure.

The interface electrical circuit outputs a delta-sigma pulse stream [2,3] proportional to $\Gamma = (C_h - C_l) / (C_h + C_l)$ where C_h and C_l are the heavy and light side capacitance values respectively. Switching voltage levels applied to the stationary electrodes transfer charge on-to(off-of) the heavy(light) sides of the element. The charge flow is analyzed by a first order "charge mode" delta-sigma modulator[2]. The output frequency is proportional to the total amount of charge transferred, which in turn is dependent, through the capacitance, on the deflection of the plate caused by acceleration. The voltage transitions are set using EEPROM and hence, by setting the magnitude of the transitions, the product can be fully calibrated for zero-g output and gain.

The sensor system is an open loop system. Maximum deflections and electrical gain parameters are designed to function in the 10% deflection range at 50g full scale. In addition, the system architecture requires that the transducer provide mechanical filtering in the 400 Hz range.

SOURCES OF NON-LINEARITY

The sources of non-linearity in a differential torsional capacitive system can be listed. The primary contributors are:

- Large deflections i.e. deviations from Hooke's law resulting only from the size of the deflection.
- The non-linear nature of $\partial C_{ap} / \partial g_{ap}$ within a system where $\partial g_{ap} / \partial a_{ccel}$ is linear.
- Common Mode Signals.
- "Extra," systematic forces e.g. sensing voltage forces.

Of this list, the first item will not be considered. The effect of these sources on Γ are investigated below. Other potential sensor outputs are ∂C , and $C_h - C_l$. These outputs are significantly more non-linear than gamma [2] and will not be investigated here.

NON-LINEAR NATURE OF $\partial C_{ap} / \partial g_{ap}$

In general the resultant change in capacitance is not linear for linear changes in gap. As such, using either ∂C , or $C_h - C_l$ yields rather non-linear outputs. By contrast, using Γ yields a remarkably linear sensor. In terms of differential and common mode gap displacements, D_{dm} and D_{cm} respectively, the first few terms of a series expansion for Γ gives:

$$\Gamma = \frac{\left(-\frac{D_{dm}}{d_o} + 2 \cdot \frac{D_{cm} \cdot D_{dm}}{d_o^2} - 3 \cdot \frac{D_{cm}^2 \cdot D_{dm} + D_{dm}^3}{d_o^3} \dots\right)}{\left(1 - \frac{D_{cm}}{d_o} + \frac{D_{cm}^2 + D_{dm}^2}{d_o^2} - \frac{D_{cm}^3 + 3 \cdot D_{cm} \cdot D_{dm}^2}{d_o^3} \dots\right)} \quad (1)$$

Here a linear system has been analyzed instead of the torsional system in order to simplify the calculation. The increased linearity of Γ arises from the fact that both the numerator and the denominator have non-linear terms with respect to differential displacement. The two effects tend to cancel each other out.

If no other sources of non-linearity existed, going to a Γ based design would neutralize the inherent non-linearity of $\partial C_{ap} / \partial g_{ap}$ sufficiently for virtually every application.

COMMON MODE SIGNALS

Γ is, however, susceptible to common mode signals. Here common mode signal refers to any displacement that causes same direction changes in both the heavy and the light side capacitors. Examples are beam sag or plate curling. From equation 1 it is clear that common mode deflections effect the denominator significantly more than the numerator. Consequently, Γ is effected. If the common mode deflection decreases the gap, then the output is depressed. If the gap is increased, then the output is inflated.

"EXTRA", SYSTEMATIC FORCES

By definition, a voltage must be applied across the capacitor to get capacitive transduction. Hence a force is applied across the plates. Unless the sensing voltage is scaled to compensate for the deflection caused by acceleration, this systematic force will increase at increased deflection. Furthermore, the rate of increase of this force also increases. Theta will no longer be linear with respect to accelerations. Figure 1 shows modeling results of the incremental effect of sensing voltage on a Γ based system.

DESIGN SOLUTION

One approach to designing a reduced linearity error device is to minimize the contribution of each of the sources. With this

approach, the design is pushed towards an insensitive device to reduce the sensing voltage contribution to non-linear. Furthermore, the device needs thick beams to reduce the common mode to differential mode deflection ratio. This approach can cause conflicts with AC response and signal to noise ratio specifications. In addition, it places constraints on device size and processing.

Figure 1. Effect of Sensing Voltage on Device Non-Linearity.

A less restrictive, more system oriented approach involves making the heavy side capacitor larger than the light side capacitor. This change makes D_{cm} non-zero even if no common mode displacement occurs. Now, as the element deflects, the denominator gets bigger and works with the common mode deflection to offset the non-linearity caused by the sensing voltage.

In practice, making the heavy side stationary metal plate a different area than the light side stationary metal achieves any arbitrary mismatch ratio. No change in the element structure is required. So AC response, robustness and fabrication processes are not changed. Furthermore, the DC response of the device is not reduced and signal to noise ratio need not be compromised.

MODELING RESULTS

Modeling confirmed that the design change would, in fact, reduce the linearity error. In addition, is showed approximately what level of mismatch was needed given the design's inherent common mode deflections and that no other device outputs were significantly effected. Modeling was done using a Ford Microelectronics Inc. proprietary computer model that converts geometry into a mass/spring system, performs the device calibration process and then "tests" the device at various accelerations. All calculations included sensing voltage effects.

Results are shown in Figure 2. The only device parameters that changed in any significant manor were the linearity error and the calibration value that controls zero-g output. The change in linearity error is reasonably linear with respect to mismatch ratio over the range tested.

EXPERIMENTAL RESULTS

Devices were fabricated using the standard process at 4 levels of mismatch ratio: 1, 1.175, 1.253 and 1.343. Results are shown in Figure 3. The improvements in maximum linearity error are evident and consistent with the modeling and conceptual results.

Regression analysis gives the result:

$$\text{Max. } L\text{-error} = -.599 * (\text{Mismatch ratio}) + 1.0354 \quad (2)$$

with $\text{adj}R\text{square} = .84$. Equation 2 is not a general equation.

Clearly, the intercept term contains information about the device deflection sensitivity and common mode deflection

CONCLUSIONS

In a Γ based system linearity error, deflection sensitivity and sensing voltage relationships can be favorably altered by changing the relative sizes of the stationary metal electrodes. This decoupling gives greater design freedom in setting other device functional parameters. The design advantage is based on an approach that seeks to optimize total device function as opposed to an approach that seeks to optimize components of the total device

Figure 2. Linearity Error for various designs of mismatch ratio ranging from 1.75 to .745

Figure 3. Experimental results of four different levels of mismatch ratio. Maximum linearity error over the zero to 35 g range is used as a measure of the device linearity error.

REFERENCES

1. John Cole, "A New Sense Element Technology for Accelerometer Subsystems", *Transducers '91*, June 24-27, 1991, pp. 93-96.
2. Christopher J. Kemp, Leland "Chip" Spangler, "An Accelerometer Interface Circuit", *IEEE Custom Integrated Circuits Conference Digest 1995*, pp. 345-348.
3. Leland "Chip" Spangler, Christopher J. Kemp, "ISAAC-- Integrated Silicon Automotive Accelerometer", (Unpublished-to be published in *Sensors and Actuators 1996*)