Designing closed-loop MEMS-based capacitive inertial sensors

By Ayman Ismail

MICROMACHINED INERTIAL SENSORS have become an integral part of many consumer products, such as handheld mobile terminals, cameras, and game controllers. In addition, micromachined inertial sensors are widely used in vibration monitoring in industry, automotive safety and stability control, and navigation. In general, micro-sensors can be piezoelectric, piezoresistive or capacitive. However, the high thermal stability and high sensitivity of capacitive sensing makes it more attractive for a wide range of applications.

A basic capacitive sensor interface circuit, with digital readout, is composed of a capacitance-to-voltage converter (C/V) followed by an analog-to-digital converter (A/D) and signal conditioning circuitry. Operating the sensor, in an open-loop configuration (no feedback signal) results in a relatively simple system that is, inherently stable. Nevertheless, open-loop operation causes the system to be very sensitive to MEMS parameters. Moreover, the overall system linearity is affected by the linearity of each block in the sensor system chain. Also, the C/V and the A/D may need to satisfy challenging dynamic range requirements. On the contrary, enclosing the MEMS sensor in a negative feedback closed-loop has many benefits, such as improved bandwidth, and lower sensitivity to process and temperature variation of the MEMS device. Also, the C/V needs to only process the error signals. Therefore, the C/V dynamic range and linearity specifications can be relaxed compared to the open-loop mode of operation. Proper design of the feedback loop to ensure system stability is required.

In capacitive sensors, the feedback signal is applied to the MEMS in the form of a voltage signal on its capacitive actuating electrodes. The voltage applied generates an electrostatic force that acts upon the MEMS proof mass. Therefore, the resulting system is called a force-feedback system. However, capacitances have a quadratic voltage to force relationship, which imposes a limitation to system linearity.

One way, to overcome the burden of the voltage-to-force (V/F) quadratic relation, is to apply an actuation signal in a differential form, such that the quadratic terms are cancelled. However, this technique requires positive and negative voltage levels, which increases the complexity of the sensor interface ASIC. More important, the mismatch in the two actuation capacitances needed for differential operation, leads to incomplete cancellation of the actuation quadratic terms, and therefore capacitance mismatch limits the achievable performance.

Another way to implement closed-loop, depends on using a two-level, bang-bang feedback signal. Since, only two points of the quadratic V/F relation are exercised, this approach is inherently linear and does not rely on MEMS capacitor matching or using negative voltage for cancelling non linearity. The use of two-level actuation implies transforming the information in the feedback signal amplitude into information in time. Therefore, Σ-Δ modulation arises as an effective technique to implement closed-loop digital readout sensors. In addition, the Σ-Δ based loop provides implicit analog-to-digital conversion, eliminating the need for a stand-alone A/D. Thus, Σ-Δ closed-loop architecture represents an optimum architecture for high performance digital readout sensors. It should be noted that the oversampling nature of Σ-Δ systems imposes an operating system at relatively high frequencies, and hence the system becomes more susceptible to coupling through the MEMS parasitic capacitances. Nonetheless, circuit techniques to cancel this coupling are possible and can be readily implemented in the interface ASIC of the sensor. The architecture selection of Σ-Δ closed-loop sensors is based on the deep knowledge developed for electrical Σ-Δ systems. However, system-level design and optimization of the Σ-Δ closed-loop sensors, which are of electro-mechanical nature, need a proper understanding of MEMS operation and modeling. The sensing part of a typical MEMS sensor behaves as a second-order lumped mass-damper-spring mechanical system, with a single resonant frequency, and hence, exhibits the following transfer function:

$$H_{mech} = \frac{x(s)}{F_{in}(s)} = \frac{1}{s^2+\frac{D}{m}s+\frac{k}{m}} = \frac{1}{s^2+\frac{\omega_0}{Q}s+\omega_0^2}$$

where Fin(s) is the input force (Coriolis force in the case of gyroscopes or force, due to input acceleration, in the case of accelerometers). x(s) is the displacement in the sensor proof mass, corresponding to the input force. m is the mass of the proof mass, D is the damping coefficient, and k is the spring constant (stiffness).

The principle of operation of a MEMS sensor depends on the fact that the input force (Fin) to the MEMS results in a certain displacement that alters the MEMS capacitance (Cout). This Cout can be measured by an electronic circuit that interfaces to the MEMS element. A MEMS sensor with actuation electrodes can be modeled as shown in figure 1. The model has a gain, Kx/c, representing output capacitance variation due to the MEMS proof mass displacement. Kx/c is given by:

$$K_{x/c} = 2\frac{C_d}{X_0}$$

where Cd is the MEMS detection capacitance, and X0 is the capacitance gap separation. The factor of two accounts for differential operation. The model, also, includes a factor, KV/F, which is the force generated due to fed-back voltage VACT:

$$K_{V/F} = \frac{1}{2}\frac{C_a}{X_0}V_{ACT}{}^2$$

where VACT is the actuation voltage and Ca is the MEMS actuation capacitance. One important phenomenon of capacitive MEMS sensors is snapping (pull-in), where the capacitor plates stick together in response to a large applied voltage, causing operation failure. The maximum static voltage allowed, before stick in, is given by:

$$V_p = \sqrt{\frac{8}{27}\frac{kX_0^2}{C_0}}$$

where C0 is the rest capacitance of the capacitor. The expression above for Vp is only helpful in showing Vp dependencies. However, it is not accurate for determining the exact value of Vp, in the case of dynamic voltage actuation, as in a Σ-Δ loop. In Σ-Δ based sensors, the MEMS serves as the loop filter, resulting in a 2nd order electro-mechanical Σ-Δ system.

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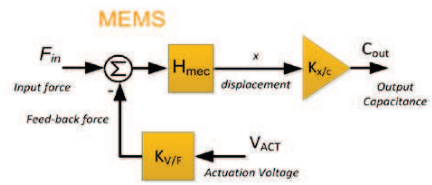

Fig. 1: Sensing part model of a MEMS inertial sensor.

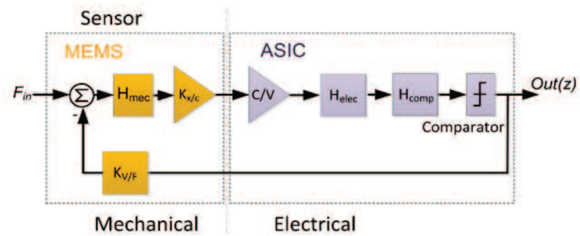

Fig. 2: Σ-Δ based closed-loop sensor.

Also, an electronic filter (Helec) can be introduced to the Σ-Δ loop to increase its order and suppress quantization noise further. The resulting Σ-Δ based sensor is demonstrated in figure 2, where a MEMS is interfaced to an Application Specific Integrated Circuit (ASIC) to form a complete sensor. The system incorporates an additional block Hcomp to compensate the loop and maintain its stability.

The system level design of the closed-loop sensor determines the optimum values for the MEMS and ASIC parameters such as stiffness (k), gap separation (X0), damping coefficient (D), actuation voltage (VACT), and ASIC noise. For stable operation of the ΣΔ-loop, the input signal to the sensor cannot exceed the feedback signal. Therefore the value of actuation voltage, VACT, defines the maximum allowable input signal for a given set of MEMS parameters. However, generating a large VACT, to allow a high input signal range, results in a power dissipation penalty, and sometimes requires adopting special technology for the ASIC that allows high-voltage operation. ASIC technology selection can affect sensor overall cost. More important, the maximum value allowed for VACT is limited by the MEMS snapping voltage, Vp.

The MEMS gap separation (X0) is a key parameter for achieving low noise operation. Reducing X0, leads to a higher Cd, and Kx/c. As a result, the MEMS forward gain (sensitivity) is increased. The high sensitivity reduces ASIC noise contribution to sensor input referred noise. On the other hand, the Brownian noise power of the MEMS is directly proportional to the damping coefficient (D). The total sensor noise is composed of the MEMS noise and the ASIC noise. The maximum tolerated ASIC noise can be estimated based on sensor target overall performance, MEMS sensitivity and damping coefficient. It should be noted that the minimum achievable X0 is limited by the MEMS technology. The effect of X0 value on the maximum input range depends on whether the actuation voltage (VACT) is limited by the snapping voltage of the MEMS or not. If VACT is limited by snapping then reducing X0 can cause a reduction in the maximum allowed input signal range. Otherwise, the actuation capacitance (Ca) and KV/F improvement with X0 reduction results in a higher feedback force, and consequently a higher input range.

The stiffness of the MEMS element (k) is a vital system design parameter, since it can be readily controlled in the MEMS element, compared to X0, whose minimum value is a MEMS technology limit. The maximum achievable dynamic range (VACT set to maximum allowed value before snapping), is independent on the value of k to the first order, assuming that ASIC noise is dominating sensor noise. That is because increasing k, not only reduces MEMS sensitivity and increases ASIC noise referred to the sensor input, but also allows increasing the feedback force with the same amount as this allows operation at a higher VACT. For the case that MEMS noise dominates sensor performance, then k should be increased to allow a larger dynamic range. While for the case that operation is not limited by snapping, it is beneficial to reduce the value of k so as to increase MEMS sensitivity and reduce ASIC noise contribution to the sensor noise. It should be noted that the value of k alters the resonance frequency of the MEMS element. In open-loop sensors the resonance frequency sets an upper bound on the sensor bandwidth, while for closed-loop systems that is not the case. Therefore, k can be set based on dynamic range and noise requirements.

The highlighted sensor performance dependencies on MEMS and ASIC parameters show that the system level design of closed-loop sensors exercises plenty of trade-offs, where ASIC noise budget, actuation voltage, power dissipation, and technology are highly dependent on MEMS parameters. Therefore, the co-design of ASIC and MEMS, based on the target overall sensor specifications, is the recommended way to reach an optimum sensor, in contrast to designing an ASIC for an already designed MEMS.