A Fully Differential Lateral $\Sigma\Delta$ Accelerometer with Drift Cancellation Circuitry

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ABSTRACT

A monolithic, surface micromachined, force-balanced capacitive accelerometer is presented. The mechanical sense element provides a true differential capacitive output allowing differential circuitry to be used throughout the system. Even in this differential topology low frequency noise and offset in position sense electronics appear in the output, harming bias stability and dynamic range. An extended feedback topology is presented to eliminate these problems. The effectiveness of this method is confirmed with experimental measurements and simulation results.

INTRODUCTION

Sigma-Delta micromachined accelerometers provide digital output, high linearity, large dynamic range, and are significantly less sensitive to processing fluctuations than their open loop counterparts as reported in [1, 2]. The digital output provided by $\Sigma\Delta$ accelerometers lends itself to embedded applications such as head mounted displays for computer I/O devices, or digital control in the automobile market where digital signal processing of acceleration measurements are desired. CMOS is desirable for building digital circuits due to its scalability and low power consumption. Analog circuit design in CMOS, however, requires particular attention to low frequency flicker noise and offset. This paper addresses these analog circuit design issues and provides a system topology which solves the problem of drift and offset in $\Sigma\Delta$ accelerometers, extending the useful bandwidth of these sensors down to DC.

A block diagram of a surface micromachined $\Sigma\Delta$ accelerometer is shown in Figure 1. Above its resonant frequency the sense element acts as a mechanical double integrator, integrating acceleration twice in order to obtain position. Position is measured through electrical integration of charge resulting from a voltage pulse applied to a differential sense capacitor array [3]. The output of the position sense circuitry is amplified before entering a comparator which determines whether the proof-mass is above or below the zero position. Electrostatic feedback, controlled by the 1-bit position output, force balances the proof-mass. High resolution is achieved by averaging, or filtering, the 1-bit output. The filtered output represents the amount of force needed to balance the proof-mass at the zero position. This ability to trade bandwidth for accuracy is the basis by which $\Sigma\Delta$ data converters operate [4].

In this paper, a fully differential $\Sigma\Delta$ accelerometer is first described. Next, sources of low frequency noise and offset are discussed and their effect on sensor output analyzed. A method for cancelling low frequency noise and offset in the position sense circuitry is then presented. The effectiveness of this method is confirmed with measurement results from a fabricated device and computer simulations.

A FULLY DIFFERENTIAL $\Sigma\Delta$ ACCELEROMETER

A block diagram of a fully differential, surface micromachined $\Sigma\Delta$ accelerometer is shown in Figure 1. A schematic diagram of the differential sense capacitor array used for sensing position is shown in Figure 2. Sense capacitors are formed between stationary comb fingers and the proof-mass comb fingers, which act as a common node to the sense capacitors. Common centroid layout of the sense capacitors provides first order cancellation of off-axis translational and angular accelerations [3]. The $\Sigma\Delta$ loop is implemented as a sampled data system, allowing time multiplexing of different phases for sensing and feedback. Position is measured by applying a voltage pulse to the proof-mass and integrating the resulting charge difference [3, 5]. A fully differential charge integrator is used for position sensing, providing a differential output voltage directly proportional to proof-mass displacement. The output of the charge integrator is amplified by a preamp before entering a comparator. The comparator provides additional amplification of the small voltage difference from the preamp output and incorporates a regenerative latch to determine the sign of small voltage differences. A regenerative latch utilizes positive feedback to convert small voltage differences to digital output values providing the one-bit A/D conversion necessary for a $\Sigma\Delta$ converter.

The closed loop system is unstable without compensation, as described in [6]. Compensation of this system is accomplished in the feedback path via a 2-tap FIR lead filter, which provides 27 degrees of phase lead at one quarter the clock frequency ($f_s/4$). The 2-bit output of the compensator is converted to an analog voltage by an on chip D/A converter. This analog voltage provides electrostatic force feedback during the feedback phase of the cycle through a separate set of comb fingers.

All circuit components are integrated with the polysilicon proof-mass on the same die, except the external clock generator. Off chip clock generation allows comparison of system performance with and without the drift cancellation technique discussed in the section on noise and offset cancellation.

NOISE AND OFFSET

Noise and offset enter at the mechanical sense element as well as in the position sense interface. Through linear system analysis the transfer function between noise injected at the sensor (N_s^2 in Figure 1) and the output may be found to be unity, while noise injected in the position sense interface (referred to N_i^2 in Figure 1) is shaped by the inverse of the proof-mass transfer function. For a pure double integrator, corresponding to an unconstrained mass in a $\Sigma\Delta$ accelerometer, the transfer function between electrical noise at a frequency f injected in the position sense interface and the output is $(2\pi f)^2$. Noise power is attenuated by $(2\pi f)^4$, the square of the noise

Figure 1 $\Sigma\Delta$ force feedback loop. Mechanical (N_s^2) and Electrical (N_i^2) noise sources shown. Electrical noise sources referred to N_i^2 .

Figure 2 Schematic of fully differential, common centroid, sense capacitor array. Drive capacitors not shown for clarity.

transfer function. This relation shows noise and offset are greatly attenuated at low frequencies. This is also approximately the case in $\Sigma\Delta$ voltage A/D converters, where the integrator pole is set by opamp gain and can have a very low frequency. However, for surface micromachined sensors practical considerations such as warpage and shock survival set a lower bound of several kHz on the natural frequency of the sense element. This results in a noise shaping characteristic in which attenuation of sensor interface noise stops for frequencies below the proof-mass resonant frequency.

Brownian motion, due to the small mass of the sensor, results in a white acceleration noise in the sense element. At atmospheric pressure the Brownian noise for the sensor described in this paper is approximately $200 \mu\text{g}/\sqrt{\text{Hz}}$. This may be attenuated by running the accelerometer in a vacuum. Mismatch between sense capacitors provides a DC offset indistinguishable from an acceleration input. Typically this mismatch is a relatively small percentage of the sense capacitance due to good matching commonly achievable with modern photolithography.

Noise and offset in the sense electronics can be quite large however, especially in a CMOS technology. Flicker noise in the input transistors of CMOS amplifiers usually starts to dominate the electrical noise below several hundred kilohertz, with noise power increasing proportional to the inverse of frequency. For example, flicker noise from the input transistors of the preamp, when referred to the output, results in a measured output noise of approximately $2 \text{ mg}/\sqrt{\text{Hz}}$ at 1 Hz for this sensor. In addition input voltage offsets due to threshold voltage variations and transistor size mismatch, typically on the order of 15mV, generate an output signal of order 2 g, substantially reducing the dynamic range of the system. Changes in temperature affect this amplifier offset resulting in a temperature dependent offset at the sensor output.

Figure 3 $\Sigma\Delta$ force feedback loop with drift cancellation circuitry. Noise and offset from electronics are referred to the node labeled N_i^2 .

NOISE AND OFFSET CANCELLATION

The fundamental reason for poor rejection of low frequency noise and offset in the topology shown in Figure 1 is the high resonant frequency of the proof-mass. At frequencies below the sense element resonant frequency electrical interface noise appears in the output attenuated by a constant factor equal to:

$$\frac{N_{\text{Output}}^2}{N_i^2} = \left(\frac{C_i \omega_n^2}{\left(\frac{d}{dx} C_s \right) V_s} \right)^2, \quad \omega < \omega_n \quad (1)$$

where ω_n is the natural frequency of the sensor, C_i is the capacitance of the charge integrator, V_s is the sense pulse magnitude, and dC_s/dx is the differential change in sense capacitance for a proof-mass displacement. The sensitivity, dC_s/dx , as well as minimum achievable resonant frequency is set by the micromachining technology. Settling constraints in position sense electronics set the value of C_i for a given CMOS technology and sense capacitance. Increasing the sense pulse voltage improves performance only to a point dependent on technology and sampling rate. Further increases harm performance due to distortion imparted on the proof-mass during the sense part of the cycle [6].

Addition of a separate feedback loop to the system can drastically improve the noise transfer function between the sense electronics and the output. Figure 3 shows a diagram of the drift cancellation loop incorporated in the $\Sigma\Delta$ accelerometer. This inner loop is a purely electrical realization of a first order sigma-delta converter. As such the integrator pole of the noise shaping element may be made arbitrarily low. Thus the transfer function between sense position electronic noise and the output will decrease with decreasing frequency down to arbitrarily low frequencies for the inner feedback loop.

By adding one additional clock phase the integrator pole of the inner loop may be used to attenuate offset in the position sense interface. During phase 1 the sense capacitors are zeroed, the position sense electronics are allowed to settle and the comparator is clocked. At this point the comparator is unaffected by the position of the proof-mass, since no sense pulse has been applied. Any offset present in the sense electronics will cause the comparator output to change sign in the direction of the offset. The

Figure 4 Simulation of a 15mV preamp offset in a 1.9 kHz bandwidth with and without cancellation. Without cancellation the DC output is at 1.8g reducing the useful dynamic range of the sensor.

Figure 5 Simulation of $\Sigma\Delta$ accelerometer with low frequency colored noise. The top plot (a), without drift cancellation shows coupling of low frequency noise directly to the output. The inner feedback loop attenuates this noise as shown in the bottom plot (b).

comparator output is negatively fed back to the voltage integrator driving the output of the voltage integrator in the opposite direction of the offset. After many cycles the value needed to just cancel the sense interface offset is reached at the voltage integrator output. At this point the comparator output alternates sign every cycle. The voltage integrator gain is chosen so perturbations from this oscillation are below the quantization noise floor of the outer $\Sigma\Delta$ loop. Low frequency noise, which may be thought of as a slowly varying offset, is canceled in exactly the same manner as a stationary offset.

During the second, or sense phase, a voltage pulse is applied to the sense capacitors, the electronics are allowed to settle, and the comparator is clocked again. Note the voltage integrator, from the inner feedback loop, is still connected to the summing block at the preamp input. Its value is added to the input of the preamp during this phase, cancelling offset and low frequency noise from the sense circuitry. Since the sense pulse is not applied during phase 1, the voltage integrator in the inner loop does not respond to changes in sense element position. Thus the desired signal, from capacitance differences in the differential sense capacitor array, remains unattenuated. The corrected digital output is used for feedback during phase 3, which completes the cycle.

Figure 6 Die photo of fully differential surface micromachined accelerometer. The proof-mass is 400 μ m x 400 μ m and weighs 0.2 μ grams.

RESULTS OF SIMULATIONS

The system has been modeled and simulated in MATLAB. Figure 4 shows simulated rejection of a 15 mV preamp offset with zero input acceleration. Without cancellation the DC output is 1.8 g out of a full scale range of ± 3.5 g, reducing the useful dynamic range of the sensor. When cancellation is turned on the output of the sensor is brought to zero.

Figures 5a and 5b are power spectral density (PSD) plots of the complete sensor output spectrum with colored noise added at low frequency to simulate the effect of flicker noise in the position measurement interface. Because $\Sigma\Delta$ converters are oversampled, the sensor output will be filtered and downsampled to a smaller useful bandwidth. For this sensor the downsampling ratio is on the order of one-thousand times. The top plot, without drift cancellation, shows coupling of low frequency noise directly to the output in typical sensor bandwidths of up to 1 kHz. The inner feedback loop attenuates this noise as shown in the bottom plot.

MEASUREMENT RESULTS

A die photo of the differential test accelerometer is shown in Figure 6. Table 1 lists important accelerometer specifications. For evaluation the accelerometer is mounted on a vibration table and excited with a sinusoidal input signal. A reference accelerometer mounted beside the test accelerometer is used for calibration of the test accelerometer. The one-bit output is decimated with a digital signal processing card connected to a workstation. Data analysis to determine signal to noise ratio and generate power spectral density plots is done off line with MATLAB.

This accelerometer has been tested with and without drift cancellation circuitry enabled. Figure 7a shows measured power spectral density of the sensor output with drift reduction circuitry disabled. A 110 mg RMS input signal at 16 Hz is used as a reference. Flicker noise from the preamp input dominates the noise floor below 3.2 Hz. At 0.1 Hz the noise floor due to 1/f noise in the

Figure 7 Measured output spectrum. The top plot (a), without drift cancellation, shows coupling of preamp noise directly to the output. The inner feedback loop cancels this noise as shown in the bottom plot (b), providing 13 dB improvement in the noise floor at 0.1 Hz. The two peaks are 110 mg RMS reference inputs at 16 Hz used for calibration. PSD constructed from 415 second data train.

preamp has risen 13 dB to 5 mg/√Hz. To obtain this plot an offset voltage added to the auxiliary stage of the preamp had to be manually adjusted to bring the sensor output to mid-scale, since mismatch in the sense interface caused the sensor output to saturate.

Figure 7b shows the measured sensor PSD with drift reduction enabled. The elimination of 1/f noise in the output is clearly demonstrated by the flat power spectrum. The offset necessary to bring the output to the center of its range was automatically provided by the inner feedback loop.

CONCLUSIONS

The relatively high resonant frequency typical of surface micromachined accelerometers reduces attenuation of low frequency noise and DC offset from the electrical position sense interface. This noise and offset appear in the output and reduce bias stability as well as dynamic range. A time multiplexed, dual

Table 1: Accelerometer Specifications

Parameter	Value
Process	3μm BiCMOS
Power Supply	3.7 mA @ 5V
Die Size	3mm x 3mm
Full Scale	+/- 3.5 g
Noise Floor (fs = 500 kHz) Sense Pulse = 2.5V	500 μg/√Hz
Noise Floor (fs = 250 kHz) Sense Pulse = 1.25V	1.6 mg/√Hz
Resonant Frequency	8.1 kHz
Proof-Mass	0.2 μgram
Total Sense Capacitance	84 fF
Sensitivity	64 fF/μm

feedback loop $\Sigma\Delta$ topology has been presented using an electrical voltage integrator to provide cancellation of noise, offset and drift in position sense electronics. Proof of efficacy has been demonstrated both through simulation and measurements from a fabricated device, with an observed 13dB improvement in output noise at 0.1 Hz.

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