A Micropower Arcsine Circuit for Tilt Processing

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Abstract: This letter describes an analogue circuit for producing an arcsine transfer based on a differential pair with source degeneration. The application uses this circuit to post-process an accelerometer signal by normalising with respect to the gravitational acceleration vector to extract inclination. Using diode-connected MOS devices operating in weak inversion, the appropriate trigonometric function, i.e. an arcsine, has been realised to compute tilt. The hardware has been implemented in AMS 0.35 μ m 2P4M CMOS technology.

Introduction: An increasing number of medical devices including implantable prosthetics and body worn instrumentation are incorporating sense systems within and around the body. One such sensor is the inclinometer (or tilt sensor), which senses its orientation with respect to gravity. Tilt sensors have typically been implemented using hybrid structures incorporating a stationary reference and movable mass. Traditionally these have been realised using electrolytic fluid-filled cavities. More recently a breed of modern silicon-based inclinometers have emerged implemented in various MEMS technologies [1–3]. It has also been shown how to derive inclination using an unmodified accelerometer [4].

In this letter, we present a novel analogue circuit to convert an accelerometer output to a tilt signal, implementing the arcsine function at transistor level. This letter describes the concept of extracting tilt from acceleration in addition to how the arcsine function is realised in analogue microelectronics. The circuit implementation and simulated results are then presented for a system using an off-the-shelf MEMS-based accelerometer.

System Overview: The circuit presented in this paper is based on the concept that for any sensed acceleration there exists a component due to the gravity, except in the case that the axis of reference is perpendicular to the gravitational acceleration vector. This concept is

illustrated in Fig. 1. Consequently, this means that any accelerometer can be used as a tilt sensor provided the following criteria are met: (1) the accelerometers range is equal to or greater than the gravitational constant and (2) the accelerometer does not exhibit any out-of-plane non-linearities, i.e. due to proof mass sagging. However most MEMS-based capacitive accelerometers fulfil this criteria as they are typically designed to be stiff in the out-of-plane axis.

The circuit presented has been designed to be used with an off-the-shelf accelerometer taking a voltage output centred between the supply rails. Specifically the Analog Devices ADXL330 has a nominal output (i.e. at 0g) of $0.5V_{DD}$ and sensitivity of $0.1V_{DD}/g$. From this ratiometric voltage the circuit is required to compute the arcsine of the normalised input, i.e. for an input corresponding to a $\pm 1g$ linear acceleration range.

Arcsine concept: It has been shown possible to generate a sinusoidal transfer characteristic based on an exponential circuit primitive. Meyer et al. [5] were amongst the first to report that a differential pair with emitter degeneration could be used as a triangle-sine wave converter in bipolar technology. Gilbert [6] extended this technique to provide realisations of other trigonometric functions including their inverses. With weak inversion CMOS technology it has been shown possible to achieve the sine function [7]. We use this technique in reverse to realise the inverse function. This requires driving the differential pair with a current and reading out the voltage at what was previously the input node. The proposed circuit concept is shown in Fig. 2.

The differential output voltage is defined as:

$$V_{OUT2} - V_{OUT1} = I_{IN}R + nV_T \ln\left(\frac{1 + I_{IN}/I_{BIAS}}{1 - I_{IN}/I_{BIAS}}\right) \quad (1)$$

This assumes devices Q1 and Q2 are perfectly matched and operating in weak inversion.

The logarithmic term can subsequently be expanded as a power series (for $|I_{IN}| \leq I_{BIAS}$) to give:

$$\frac{V_{OUT2} - V_{OUT1}}{nV_T} = \left(\frac{I_{BIAS}R}{nV_T} + 2 \right) \left[\left(\frac{I_{IN}}{I_{BIAS}} \right) + \frac{2}{3} \left(\frac{I_{IN}}{I_{BIAS}} \right)^3 + \frac{2}{5} \left(\frac{I_{IN}}{I_{BIAS}} \right)^5 + \dots \right] \quad (2)$$

This can now be rearranged to fit the coefficients of a power expansion of the arcsine function giving the transfer characteristic:

$$V_{OUT2} - V_{OUT1} = (I_{BIAS}R + 2nV_T) \arcsin \left(\frac{I_{IN}}{I_{BIAS}} \right) \quad (3)$$

Circuit description: The circuit implementation is shown in Fig. 3. A linearised fully-differential operational transconductance amplifier (OTA) has been used to implement the resistive degeneration (i.e. V to I) within the arcsine processor. This takes a differential voltage input (i.e. consisting of the accelerometer output and zero-g DC bias) and generates a fully-differential current output using a linearised OTA. The OTA itself uses resistive degeneration to achieve a linearised response for an input range of $\pm 330\text{mV}$. The circuit feeds a split tail current of 660nA into the differential pair (Q5, Q8) and using scaled current mirrors (Q9-11 and Q14-16) at a 10:1 ratio, an output range of $\pm 45\text{nA}$ is achieved for the linear input range.

The arcsine characteristic is then produced by using this V to I conversion to degenerate a differential pair (Q6-7). These have been diode-connected to have a logarithmic input current to output voltage transfer. Thus to achieve a good arcsine characteristic, this pair must remain biased in weak inversion throughout the complete signal range. For this condition to hold a nominal bias of 50nA is applied and the diode-connected MOS devices (Q6-7 and Q12-13) are all sized $W/L=100\mu\text{m}/5\mu\text{m}$.

Simulation Results: The circuit was simulated using the Cadence Spectre (5.1.41isr1) simulator with foundry supplied BSIM3v3 models. The arcsine transfer function has been simulated by providing a differential sinusoidal stimulus to the circuit and observing the differential voltage output. The transient simulation results are shown in Fig. 4. It can be seen

that for a differential input voltage of amplitude 330mV, the differential output is a triangular wave of $\pm 225\text{mV}$ amplitude. Furthermore, the error of the output from an ideal triangle wave is observed to be below 5%. This error is due to a limited dynamic range of pure exponential characteristic for MOS devices operating in weak inversion.

Conclusion: In this letter we have presented a compact, micropower integrated circuit for use in generating a tilt signal from an accelerometer output by implementing an arcsine processor. The system has been designed to take a differential voltage input compatible with an off-the-shelf accelerometer. We have aimed to produce a fully analogue implementation for applications requiring an analogue tilt signal such as in biomedical devices.

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Figure Captions:

Fig. 1. The concept of obtaining tilt from an accelerometer using the gravitational acceleration vector.

Fig. 2. The arcsine transimpedance converter using diode-connected MOS devices operating in weak inversion.

Fig. 3. Circuit schematic of the fully differential arcsine processor combining linearised input transconductor and transimpedance arcsine converter.

Fig. 4. Simulated transient response for the arcsine transfer function. Shown are (from top to bottom): (a) differential input voltages, (b) differential output voltages, (c) single-ended output (i.e. difference) voltage, and (d) output error.

Figure 1:

Figure 2:

Figure 3:

Figure 4: