Advanced Self Balancing Bridge Accelerometer using Sigma Delta Chip

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ABSTRACT
This paper presents an advanced self balancing bridge accelerometer with closed loop digital feedback using the sigma delta-chip. Self-balancing bridge reduces the squeeze film damping by introducing the holes in the structure as add on to the proposed structure. The total area of the electrodes is 7.44*10-6 as compared to the total area of the holes which is 4.80*10-7 with no compromise in the nominal capacitance with holes being incorporated in structure. The main issues that have been achieved are good linearity with respect to the plate deflection and a high dynamic range. Advance self balancing bridge accelerometer has been found to be the optimum solution used to measure plate deflection, symmetrical electrostatic forces on the capacitor plates, its offset and output noise.

Keywords
MEMS, Micro-machine, Bridge Accelerometer.

1. INTRODUCTION
MEMS accelerometers are the simplest and also most applicable micro-electromechanical systems. They became essential in various technologies such as automobile industry, computer and audio-video technology etc.An accelerometer is used to measure electromechanical device that measures acceleration forces such as static, like the constant force of gravity, or they could be dynamic - caused by moving or vibrating the accelerometer. There are many types of accelerometers developed and reported in the literature. The vast majority is based on piezoelectric crystals, but they are too big and too clumsy.

Micro-Accelerometers are micro-machinedacceleration sensors with dimensions ranging from 1m to 1mm. They find a wide range of applications, includingautomotive safety and stability control systems, variousnavigation and guidance systems, vibration monitoring inindustrial environments, movement detection in hand-heldmobile terminals and control devices such as gamecontrollers, and different biomedical applications, forexample. The readout mechanism of a micro-accelerometercan be, for instance, piezoelectric, piezo-resistive orcapacitive

[1]. Capacitive accelerometers have advantagessuch as zero static biasing current, the capability of highsensitivity, and excellent thermal stability, making their usein low-power applications attractive. By using a singlecapacitive accelerometer with a proper configuration,accelerations along all three axes can be measuredsimultaneously [2], [3].

The structural element of these devices, together witheight fixed electrodes, forms four differential capacitorpairs. All three vector components of linear acceleration, x-, y-, and z-directional, can be evaluated by first measuringthese capacitances, and then taking their proper linearcombinations. Additionally, the configuration providesredundancy so that fault conditions can be detected. The use of micro-sensors in battery-powered equipment requiresthe sensor interface to exhibit low power dissipation. Aninexpensive, yet reliable, highly-sensitive and low-power3-axis accelerometer with digital output would have a widerange of applications. In order to realize this kind of asensor, the readout electronics has to be integrated togetherwith the sensor element at chip or module level, forming amicro-electromechanical system (MEMS).

2. ADVANCED SELF BALANCING BRIDGE ACCELEROMETER
Capacitive accelerometers have interesting properties such as high sensitivity, good linearity and low fabrication cost. A vacuum packaged MEMS acceleration sensitive device, i.e., sensor element, has a high quality factor *Q* due to low air damping. The complexities lie in the measurement of the plate deflection. The main problems addressed here are good linearity with respect to the plate deflection and a high dynamic range. That is the measures of the plate deflection are very low, symmetrical electrostatic forces act on the capacitor plates and the electronic circuit was optimized with respect to its offset and output noise. The self balancing bridge has been found to be the optimum solution.

The accelerometer sensor consists of a centralmovable plate with fixed electrodes on each side [4].Together the three electrodes form the capacitors C1 andC2. The plate deflection with respect todistance d_0 between the fixed electrodes may be expressedin terms of the capacitances C1 and C2, by (1)

$$X = \frac{\Delta d}{d_0} = \frac{(C_1 - C_2)}{(C_1 + C_2)} \quad (1)$$

A measurement scheme resulting in a voltageproportional to (c1-c2)/ (c1+c2) leads to a linearrelationship between the plate deflection and the outputvoltage. Such a measurement scheme is realized using theadvanced self balancing capacitive bridge accelerometers.The fixed electrodes of the capacitor C1 and C2 areperiodically switched between the reference voltages V0and the output voltage Vm.
The resulting charge transfersQ1 and Q2 on the capacitors C1 and C2 as well as theirdifferences is given by

$$\Delta Q = Q_1 - Q_2 = C_1(V_0 - V_m) - C_2(V_0 + V_m) \quad (2)$$

The measurement circuits sample the ΔQ from themovable center plate and integrate it to a filter capacitorthereby generating the output voltage Vm [5], that isfeedback to the excitation network in order to establish theequilibrium condition ΔQ=0.

Typical sensor interface topologies for accelerometerscan be divided into two main categories, open-loop andclosed-loop. In the open-loop case, no electrostatic forcefeedback is applied to the sensor element in order tomodify its transfer function from acceleration todisplacement. While open-loop interface is less complex toimplement, it doesn't allow affecting the sensor elementproperties. Thus, input signal bandwidth (BW), dampingand range can be limited by the sensor element. However,an important advantage of the open-loop is that, the outputof the interface is linearly proportional to reference voltageused for signal detection, i.e., ratio-metric. When thisratio-metric output is fed to an ADC, which has the samereference as interface, the reference voltage dependence ofthe sensor output is ideally eliminated.

The schematic of the self balancing capacitor bridgeis as shown in the figure1. The circuit consists of anamplifying stage and an integrator formed by (OperationalTrans-coductance Amplifier) OTA1 and OTA2. The clockscontrol the switches used in the stages. The clock sequencecan be roughly divided into SAMPLE and HOLD state.During the HOLD state output voltage Vm remains constantand the voltage potential C1, C2 and C3 are all dischargedthrough the switches operated by the clock C2.

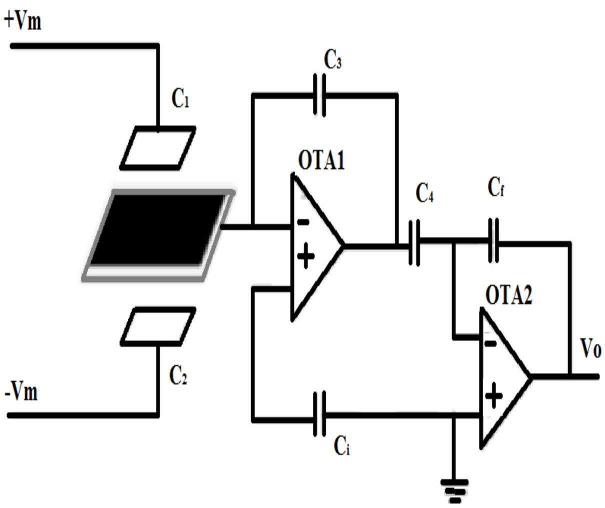


Fig 1: schematic of the self balancing capacitor bridge

In the sample state, the capacitors C1 and C2 are charged upto the values (V0-Vm) and (V0+Vm), respectively. The maximum net flow through the middle electrode as given by the equation is integrated on the capacitor and leads to an error voltage at the output. This error voltage is sampled by capacitor and is integrated on the filter capacitor Cf thereby defining the output voltage Vm of the next measurement cycles.

3. SAMPLE AND HOLD STATE

3.1 Sample State

The capacitors C1 and C2 are charged to the supplyvoltage. The net charge flow through the middle electrodecreates an output voltage given by

$$V_0 = V_m * \left(\frac{C_1 - C_2}{C_1 + C_2}\right) * \frac{(C4C0)}{C3Cf} = V_m * X * \frac{C_4 C_0}{C_3 C_f} \quad (3)$$

where X= normalized plate deflection

3.2 Hold state

The output voltage is fed back to the excitation network,the netcharge on the movable plate is made zero. Here thecapacitors C1, C2 and C3 are all discharged through theswitches operated by the clock ck2. The amplifier offset 1/fnoise; charge injection and KT/C noise are stored oncapacitor C4.

4. CLOSED LOOP ACCELEROMETERS

Open loop accelerometers suffer from cross coupling andare subject to pickoff nonlinearity and hysteresis from theirmechanical springs. Pickoffs are needed to measure largedisplacements so even a low linearity error is crucial. Butin closed loop sensors, the displacement is minimal andtherefore closed loop accelerometers rely less on pickofflinearity than the open loop.

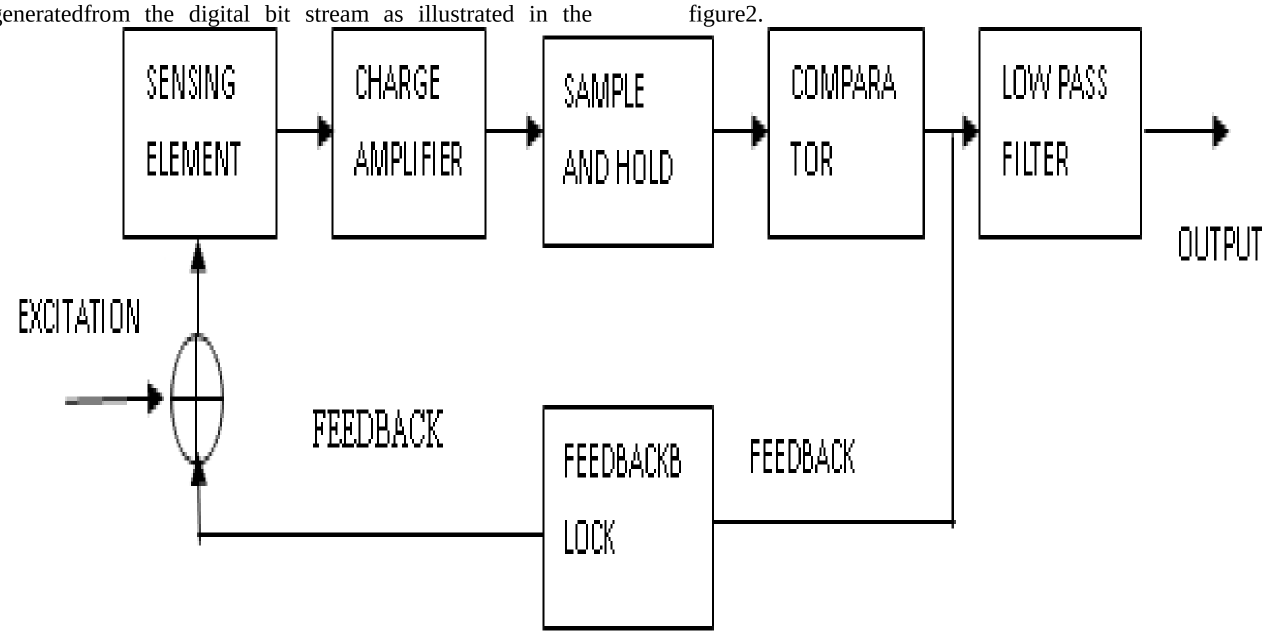
The open loop accelerometers have limitedperformance in terms of bandwidth, linearity and dynamicrange. Also non linear effects caused by damping and theelectrostatic forces required for the signal pickup increasewith the deflection of the seismic mass. A feasible methodfor reducing these nonlinearities is to use closed loopstrategy to provide a reset to the seismic mass to keep it atthe central position between the electrodes, approximatelygiven by

$$\omega_n = \frac{6IE}{mL_{eff}} \quad (4)$$

Now, the force has to be such that it counterbalancesthe accelerating force and provides an accurate measure ofthe acceleration (as an error signal). The sensitivity is notinversely proportional to the natural frequencyapproximated by equation (5) of the accelerometers butdepends on the open loop gain and the form ofcompensation.

$$\omega_n = \sqrt{\frac{K}{m}} \quad (5)$$

Hence one of the biggest advantages is that the nonlinearityintroduced by the spring and damping componentsis reduced considerably if the proof mass stays at thecentral position.The sampled voltage determines the comparatoroutput which indicates that the seismic mass has movedtowards the top plate, the comparator switches levels suchthat feedback voltage is applied to the bottom plate and theseismic mass is pulled back towards its rest position. Thedigital bit stream output of the comparator is sent to thelow pass filter where the input (acceleration) gets generatedfrom the digital bit stream as illustrated in the figure2.



Micro-machined sensing [10] elements have such small dimensions that allow the electrostatic forces to beused as the restoring force. But since the electrostaticforces are inherently positive and attractive (theelectrostatic forces are proportional to the square of thevoltage), a negative feedback is difficult to generate.However this could be overcome by superimposing twoelectrostatic forces on the seismic mass such that theresultant force provides a negative feedback. Negativefeedback relationship is non-linear due to the dependencyof the electrostatic forces on the square of the voltage andinversely related to the square of the gap between theelectrodes. Also care has to be taken that the feedbacksignals do not interact with the excitation signal requiredfor the pick off arrangement.

Drawbacks of the closed loop accelerometers withdigital feedback include limited stability for largedeflections since the voltage is applied continuously to theelectrode and non-linear feedback voltages, since the forcedepends on the square of the feedback voltage, and hencedirect application of a proportional feedback voltage leadsto the non-linear feedback. Two methods of reset actionpossible are separation of the signals in the time domain orin the frequency domain.

4.1 Effects of excitation voltage

The excitation voltage introduces non linearity in thesystem by changing the spring constant. The effectivespring constant is due to the sum of mechanical andelectrostatic feedback forces. The electrostatic feedbackcharges non-linearity with displacement from the restposition and hence introduces the non-linearity [6].
Therefore sensing voltage cannot be increasedbeyond a certain limit which results on the sensitivity thatone can be achieved. The closed loop accelerometersensing elements produces an output proportional to thecapacitive imbalance in the bridge. The charge amplifier outputthus is proportional to the acceleration. The samplersamples this output and decides the direction of feedbackdone by the comparator. If the seismic mass has movedmore towards the top (bottom) plate then a positive voltageis applied on the bottom (top) plate to pull it back towardsthe rest position.

5. SIGMA-DELTA ADC

The AD7732 core consists of a charge balancingsigma-delta modulator and a digital filter. The architectureis optimized for fast, fully settled conversion. This allowsfor fast channel-to-channel switching while maintaininginherently excellent linearity, high resolution, and lownoise. The AD7732 is a high precision, high throughputanalog front end. True 16-bit p-p resolution is achievablewith a total conversion time of 500 µs (2 kHz channelswitching), making it ideally suitable for high resolution multiplexing applications. The part can be configured via asimple digital interface, which allows users to balance thenoise performance against data throughput up to 15.4 kHz.

The analog front end features two fully differentialinput channels with unipolar or true bipolar input ranges to±10 V while operating from a single +5 V analog supply.

The part has an over range and under range detectioncapability and accepts an analog input overvoltage to ±16.5V without degrading the performance of the adjacentchannels.
The differential reference input features "No-Reference" detect capability. The ADC also supports perchannel system calibration options. The digital serialinterface can be configured for 3-wire operation and iscompatible with microcontrollers and digital signalprocessors. All interface inputs are Schmitt triggered. Thepart is specified for operation over the extended industrialtemperature range of –40°C to +105°C.Other parts in the AD7732 family are the AD7734and the AD7738. The AD7734 is similar to AD7732, butits analog front end features four single-ended inputchannels. The AD7738 analog front end is configurable for four fully differential or eight single-ended input channels,features 0.625 V to 2.5 V bipolar/unipolar input ranges, andaccepts a common-mode input voltage from 200 mV toAVDD – 300 mV. The AD7738 multiplexer output ispinned out externally,

allowing the user to implementprogrammable gain or signal conditioning before beingapplied to the ADC.

5.1 Output noise and resolutionspecification

The AD7732 can be operated with chopping enabledor disabled, allowing the ADC to be programmed to eitheroptimize the throughput rate or channel switching time orto optimize the offset drift performance. Noise tables forthese two primary modes of operation are outlined belowfor a selection of output rates and settling times. TheAD7732 noise performance depends on the selectedchopping mode, the filter word (FW) value, and theselected analog input range. The AD7732 noise will notvary significantly with MCLK frequency.

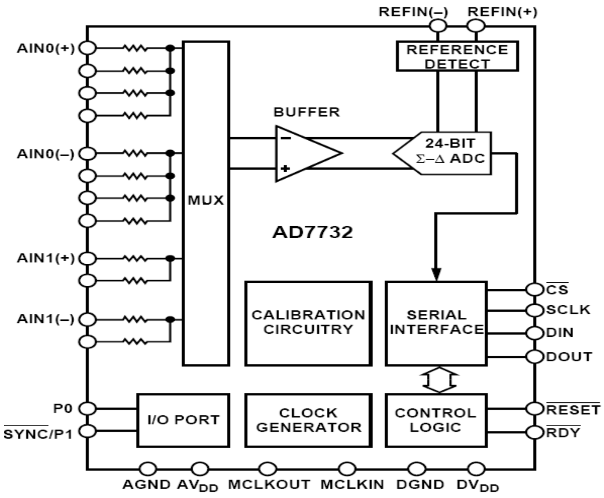


Fig 3: Block diagram of AD7732 sigma-delta chip

- **Chopping Enabled** - The first mode, in which the AD7732 is configured with chopping enabled (CHOP = 1),provides very low noise with lower output rates.
- **Chopping Disabled** - The second mode, in which the AD7732 is configured with chopping disabled (CHOP = 0), provides faster conversion time while stillmaintaining high resolution.

The peak-to-peak resolutions are not calculated basedon rms noise but on peak-to-peak noise. These typicalnumbers are generated from 4096 data samples acquired incontinuous conversion mode with an analog input voltageset to 0 V and MCLK = 6.144 MHz. The conversion timeis selected via the channel conversion time register.

5.2 Frequency response

The sigma-delta modulator runs at ½ the MCLKfrequency, which is effectively the sampling frequency.Therefore, the Nyquist frequency is ¼ the MCLKfrequency. The digital filter, in association with themodulator, features the frequency response of a first orderlow-pass filter. The –3 dB point is close to the frequency of1/channel conversion time.The roll-off is −20dB/dec up to the Nyquistfrequency. If hopping is enabled, the input signal is re-sampledby chopping. Therefore, the overall frequencyresponse features notches close to the frequency of1/channel conversion time. The top envelope is again theADC response of –20dB/dec. The typical frequencyresponse plots are given in Figure 4 and Figure 5. The plotsare normalized to 1/channel conversiontime.

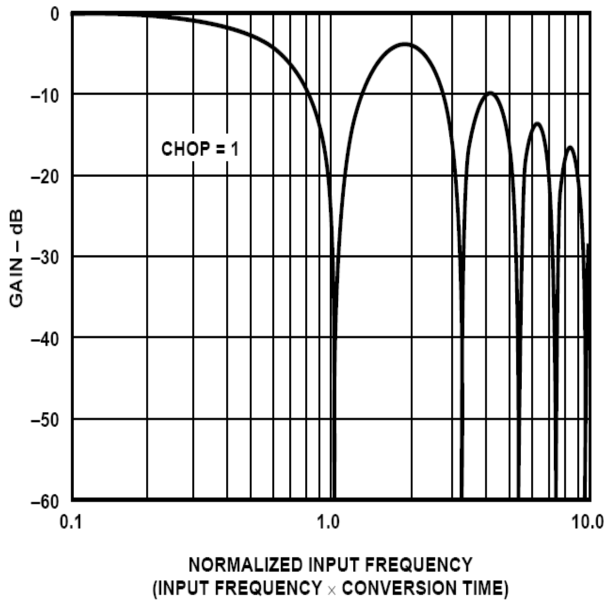


Fig 4: ***ADC Frequency Response, Chopping Enabled***

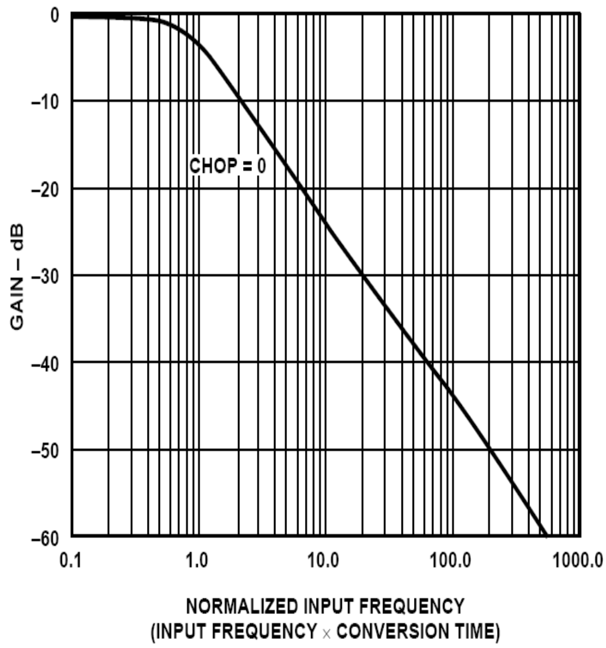


Fig 5: ***ADC Frequency Response, Chopping Disabled***

5.3 ADC Zero-Scale Self-Calibration

The ADC zero-scale self-calibration can reduce the offset error in the chopping disabled mode. If repeated after a temperature change, it can also reduce the offset drift error in the chopping disabled mode.

The zero-scale self-calibration is performed on internally shorted ADC inputs. The negative analog input terminal on the selected channel is used to set the ADC zero-scale calibration common mode. Therefore, either the negative terminal of the selected differential pair or the single-ended channel configuration should be driven to a proper common-mode voltage. It is strongly recommended that the ADC zero-scale calibration register should only be updated as part of a zero-scale self-calibration.

6. RESULTS

Table 1 lists the test results. The drawbacks of the closedloop accelerometers with digital feedback can overcome bythe sigma delta scheme where the feedback is constantvoltage and the pulse width (the time of application) of thefeedback is changed in the form of Pulse WidthModulation. Advantages of the closed loop accelerometersare the improved stability since voltage pulse is applied toonly one electrode, the other electrode being grounded andeven in a shock condition, the mass is eventually restored.

System Specifications

- Sigma delta converter chips (AD7732) is connected to the output of switched capacitor.
- O/P Voltage : 4.5V /2g
- Range : 2g
- Noise : 1mV
- Resolution : 453μg/0.416pF

Table 1. Tested Results

		C1 (pF)	C2 (pF)	C1~C2 (pF)	Observed Vout (V)	Vout PSPICE
Ceramic capacitor		8.353	11.063	2.710	-.339	-1.180
		11.063	8.353	2.710	1.869	1.010
Sensor (S1)	+1g	10.036	12.07	2.034	-.127	-0.815
	-1g	10.979	10.79	0.189	0.705	-0.030
Sensor (S2)	+1g	9.957	11.371	1.414	0.050	-0.638
	-1g	11.542	9.849	1.693	1.280	0.532

From the results shown in figure 6, the lower linearityin the x-direction can be explained by the structure of thesensor. The even order nonlinearity is cancelled in thecases of y- and z-directions. The nonlinearity increased athigher accelerations due to the measurement setup. Themeasured response is shown in Fig. 7. The resultant of theaccelerations to x- and y-directions corresponds to theearth's gravity, because the sensor is slightly slanted on thePCB. The angular acceleration and deceleration cause a tangential acceleration component that can clearly be seenin the y-directional acceleration curve.

The varyingacceleration in y-direction is caused by the cogging torque.

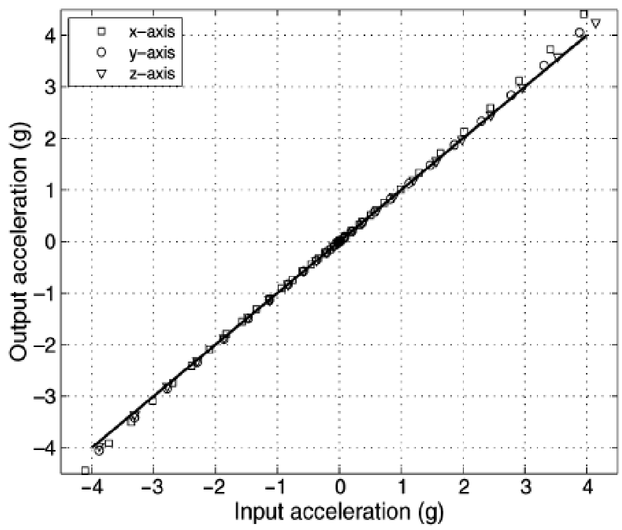


Fig 6: Measured dc acceleration in x-, y-, and z-directions.

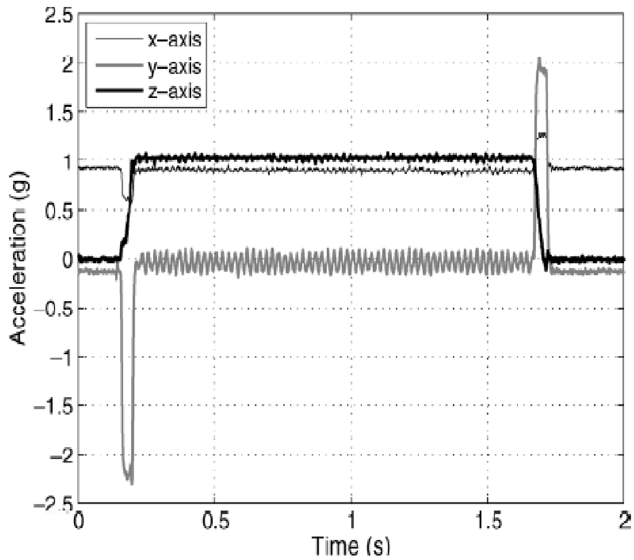


Fig 7: Acceleration pulse in z-direction

7. CONCLUSION

The open loop accelerometer has the limitations interms of bandwidth, linearity and dynamic range.Moreover, non linear effects caused by the damping andthe electrostatic forces required for the signal pick-offincrease with the deflection of the seismic mass. Onemethod of reducing these non linearities and improving theperformance is to use the sensing element in a closed loopsystem in which a reset force is applied t the seismic massto keep it at the central position between the electrodes.

Consequently, the force has to counterbalance theaccelerating force and provide an accurate measure for theacceleration. In Micromachined sensing elements, thedimensions are as such that electrostatic forces can be usedto generate the restoring force. However since electrostaticforces are attractive, it is difficult to maintain negativefeedback. Further complication is that the feedbackrelationship is inherently nonlinear because of thedependency of the electrostatic forces on the square of thevoltage and the inverse square of the gap between theelectrodes.

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