MECHANICAL AND ELECTRONICS DESIGN OF CAPACITIVE ACCELEROMETERS USING SUGAR TOOL

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ABSTRACT: In this paper, we focused on modeling the structure of the capacitive accelerometer by using SUGAR in MATLAB environment. SUGAR is such a powerful and flexible language that MEMS designer can get the equivalent results to classical methods (FEM, BEM). The accelerometers having the vertical structure with four diagonai spring beams were designed and simulated. In other way, we built a closed-loop system which can be applied for this structure. The system used sigma-delta modulation method because of its noise shaping properties and its direct digital output signal.

1. INTRODUCTION

There is a great need for an accelerometer on specific application ranging from guidance and stabilization of the spacecrafts to research on vibrations of the Parkinson patient's fingerers [1, 2]. We want a linear response without noise to characterize movements correctly. The silicon capacitive accelerometers have advantages that make them very attractive for these applications. They have high sensitivity, good dc response and noise performance, low drift, low temperature sensitivity and low power dissipation. Furthermore, additional capacitors can be integrated and used in a closed-loop feedback configuration for electrostatic force rebalancing [3, 4].

The structure is designed by using SUGAR language in MATLAB environment and the closed-loop system is simulated in MATLAB with SIMULINK or M-file functions. SUGAR is a tool which applies modified nodal method to implement simulation programs. The derived results are equivalent to that of classical methods. The closed-loop force feedback structure incorporated in the sensor is sigma-delta type structure [5]. Using sigma-delta technique, we can get many advantages such as a direct digital output signal in form of a pulse density modulated bitstream suitable for digital processing, improving system stability and reduce the quantization noise by increasing the sampling frequency of the modulator.

2. STRUCTURE AND OPERATION

The accelerometer is a vertical structure which suggests the use of bulk micromachining. The bulk micromachined capacitive accelerometers provide larger proof mass and larger capacitive area that lead to a higher resolution and greater sensitivity. This silicon accelerometer consists of a proof mass (M) attached to a fixed frame by four suspension beams which have an effective spring constant of K.

The operation of the device is based on Newton's second law of motion. An external acceleration results in a force being exerted on the mass. This force results in a deflection x of the proof mass, where a is the frame acceleration. The following second-order mechanical transfer function from acceleration to a displacement of the mass can be obtained:

$$H(s) = \frac{x(s)}{a(s)} = \frac{1}{s^2 + \frac{D}{M}s + \frac{K}{M}} = \frac{1}{s^2 + \frac{\omega_r}{Q}s + \omega_r^2} \quad (1)$$

where $\omega_r = \sqrt{K/M}$ is the resonant frequency and $Q = \omega_r M / D$ is quality factor.

Fig. 1 shows the frequency response of the open loop accelerometer that depends on damping factor D. We need our device to be critically damped because when the system is critically damped, it has the least amplitude distortion, and the output follows the input over the widest frequency range. This limitation is that D = 0.707. Unfortunately, it's quite difficult to control the damping effect so it is suggested that we should use the closed loop accelerometer. Using closed loop accelerometers, we not only overcome the damping problem but also other nonlinearity effects [6].

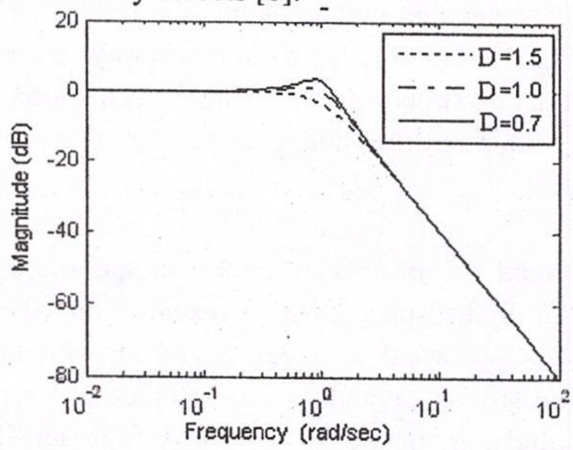

Fig.1 Frequency response of the open loop accelerometer

3. DESIGN THE STRUCTURE BY USING SUGAR

SUGAR is a tool that developed at Berkeley University in order to create powerful and flexible software for MEMS designers. SUGAR applies modified nodal method to implement simulation programs which a MEMS designer can describe a device in a compact netlist format and quickly simulate the device's behavior [7, 8]. Later in the design process, a designer might run more detailed simulations to check for subtle second-order effects. We use SUGAR to design the capacitive accelerometer whose geometry parameters are specified in Table 1.

Table 1: Specifications of the structure whose four diagonal spring beams

Item	Specification
Proof mass dimensions	4 mm × 4mm × 320 μm
Proof mass	12 mg
Beam length	2 mm
Beam width	200 μm
Beam thickness	30 μm
Electrode dimension	$4 \times 4mm^2$
Sensing gap	10 μm

The free body of the structure is shown in Fig.2. SUGAR abstracts the MEMS structures in terms of three basic elements (i.e. beams, gaps, and anchors), and builds the ordinary equation models for each kind. The system equations can be formulated according to the node connectivity information provided in the input file, and solved using nodal analysis

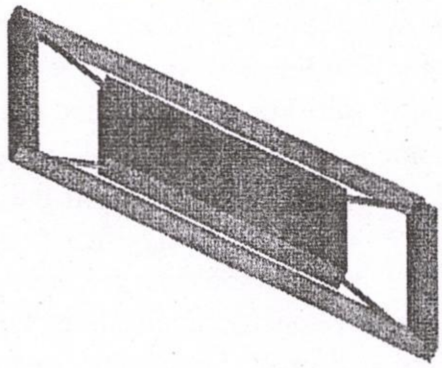

Fig. 2: The free body of the designed accelerometer

Fig.3 demonstrates the use of three dimensional modal analyses performed on this accelerometer. The mode shapes and frequencies of mode 1 and 2 are shown in Fig.3 a and Fig.3 b respectively.

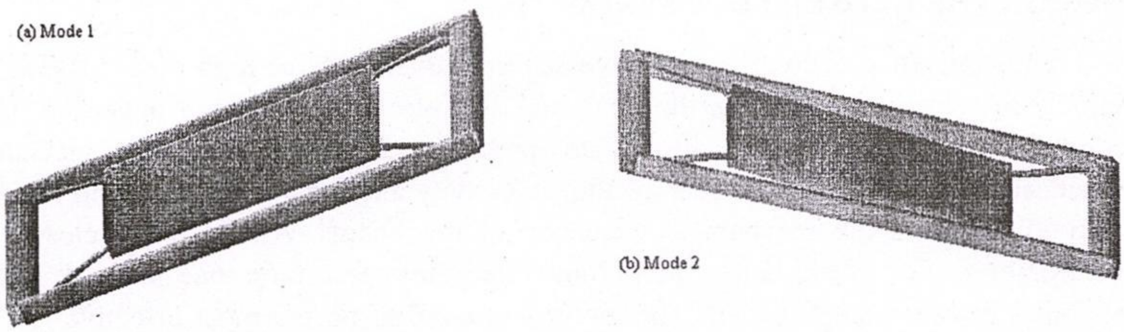

Fig. 3: 3D mechanical mode analysis of the designed accelerometer. Frequency of modes 1 and 2 are 980 Hz and 2.3 kHz respectively

Fig.4 is magnified to show static analysis applied to the designed accelerometer. In this case, we applied an external acceleration (or external force) to the proof mass, grounded the mass and put a voltage V+ to other electrodes. The balance was obtained when sum of the external force, electrostatic forces and the elastic force is zero. The defection of the proof mass reflected how strong the external acceleration was.

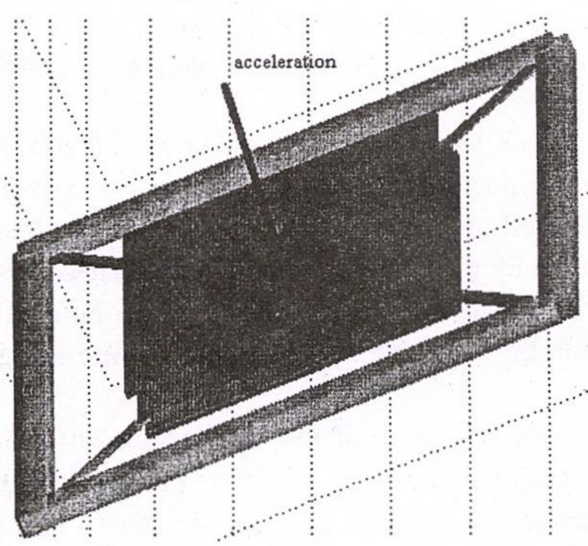

Fig. 4: A DC simulation involving mechanical and electrostatic analysis couple together.

Comparing the present structure of the accelerometer with four symmetrical beams reported in [8] (see Fig. 5), we found that the accelerometer with four diagonal spring beams will give a higher sensitivity if their die sizes are equal. It's significant in improving the accelerometer's sensitivity which suitable for specific applications but still keeps the size small. Simulation results give important parameters such as sensitivity (0.4 pF/g), Brownian noise floor ($0.13\,\mu g/\sqrt{Hz}$) and resonant frequency (980 Hz).

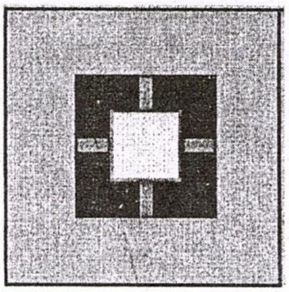

Fig. 5: The sensor with four symmetrical beams fabricated at ITIMS

4. DESIGN THE CLOSED LOOP SYSTEM

The capacitive accelerometer have several advantages of high output signal, low temperature sensitivity, excellent linearity and suitable for closed loop operation. Using feedback can reduce the sensitivity to process variations, eliminate mechanical resonances, and increase sensor bandwidth, selectivity and dynamic range. The feedback effectively reduces the mechanical excursion of the beams. Although the closed loop accelerometer has much better properties than the open loop one but the control electronics is very complex [10]. The method seemed to be the most effective is sigma delta modulation (see Fig.6). Sigma-delta modulation, also called the pulse density modulation or oversampling conversion, is a digital feedback technique. The proof mass is enclosed in the feedback loop which provides force balancing in addition to one bit A/D conversion [11].

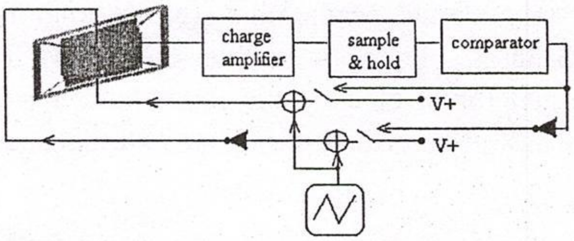

Fig. 6: Closed loop structure using Δ-Σ modulation

High frequency sinusoidal signals are applied in anti phase to the top and bottom electrodes to determine the position of the proof mass. The amplitude of the signal from the seismic mass is measured by the imbalance in capacitance. Then, it is fed to a charge amplifier which is followed by a sample and hold circuit. These discrete signals are fed to a comparator whose output is logic signal. If it is one, it implies that the seismic mass is above the central position between the two electrodes while a logic zero shows that it is below the centre position.

In the feedback path, the state of the comparator will determine a pulse whose constant voltage and constant duration is added to the high frequency excitation signal then applied to the electrode furthest away from the mass. The magnitude of the pulse signal is much greater than that of the excitation signal and the duration of the pulse signal is much longer than that of the excitation signal.

The sampling frequency is much lower than the frequency of excitation signal because the charge amplifier output signal saturates on the leading and trailing edges of the feedback voltage pulse. This ensures that the sample occurs after the decay of the transient condition. We often choose a ratio of 10:1 between excitation and sampling frequencies.

The output signal of the comparator is also the output signal of the system that has the form of a pulse density modulated serial bitstream. This digital signal is suitable for digital processing. It is often converted into a digital parallel word by a decimation filter which can remove the quantization noise that is introduced by the one bit quantization in the forward path.

The mathematic model of the closed loop system is shown in Fig.7. The model was written in MATLAB with M-file functions in which the voltage on the mass's electrode is sampled every T seconds (much faster than the required output of the digital signal), then filtered by a lead compensator $H_c(z)$ (an FIR filter), and fed to an one-bit A/D converter. The outputs of the A/D converter are converted to force and fed back to the sensor. The linearity of the system is determined solely by the feedback, thus, is insensitive to the circuit imperfections on the forward path (i.e the filter $H_c(z)$ and the low resolution A/D). The outputs are also counted and averaged every N*T seconds to produce the digital output. In our program, the external acceleration is a 100 Hz sine wave whose range is ±1g.

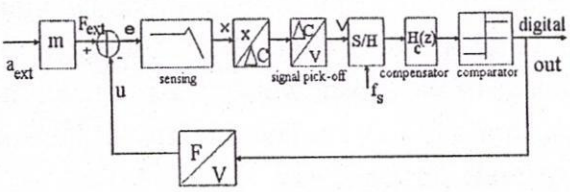

Fig. 7: The mathematic model of the closed loop system using Δ-Σ modulation technique

The model consisted of the sensing element and the control electronics. The sensing element is a second order system consisting of a proof mass, spring and some type of damping which in many cases can not be assumed to be linear. The nonlinear effect from the electrostatic forces which are a function of the square of the voltage and inversely proportional to the square of the distance have also to be include. An accelerometer employing oversampling conversion will display the characteristics of a flat frequency response down to 0 Hz and a linear transfer characteristic.

The proof mass acts as double integrator above its resonant frequency by integrating acceleration twice to position. Since the proof mass is used for noise shaping in the sigma delta loop, quantization noise from the sigma delta loop is lower than both mechanical and electronic noise sources. However, quantization noise can be observed by decreasing the sampling frequency. The filter $H_c(z)$ provides compensation to the two pole proof mass/ spring/ damper structure to ensure the loop have sufficient stability margin. If the filter $H_c(z)$ contains L integrators, the modulator order is L+2.

Fig.8 shows the sinusoidal acceleration input and the pulse density modulated output signal. In this simulation, the order of the modulator is 5, the oversampling rate is 32 and the external acceleration is a 100 Hz sine wave whose range is ±1g. This result agrees with the theoretical prediction. Sigma delta technique minimizes the difference between the external acceleration signal and the feedback acceleration signal. The means of the feedback acceleration signal and the mean of bit stream output track the external acceleration signal. The external acceleration signal can be recovered by computing mean of bit stream data. Fig.9 depicts the spectrum of the digital output which acceleration signal's spectrum is separated. We can calculate the SNR is 82.5 dB and NBW is 0.00018. Putting bit stream into a decimation filter (i.e. computes the means of bit stream data), we can retrieve accurate signal (see Fig.10).

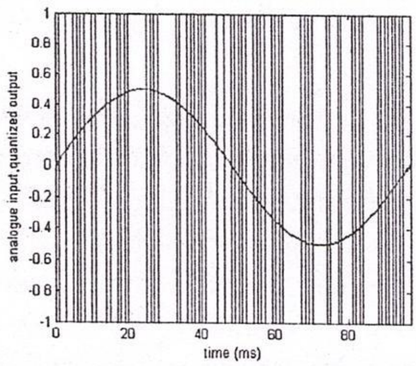

Fig. 8: Analogue input and digital output of the closed loop accelerometer

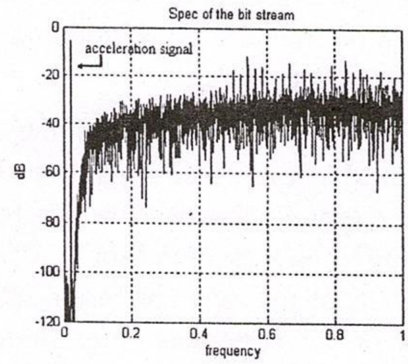

Fig. 9: Output signal's spectrum of the closed loop accelerometer

Fig.11 shows the simulation result for the unforced condition. It is easy to see that the mean of bit stream output is zero. It is our desired result in the unforced condition. Fig. 12 shows the static response of the sensor which was rotated in the earth's gravitation field to generate acceleration from -1g to +1g. The linearity of the simulation is quite good and suitable to the desired result in this condition.

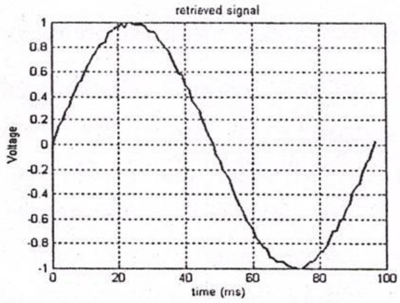

Fig. 10: Acceleration signal retrieved

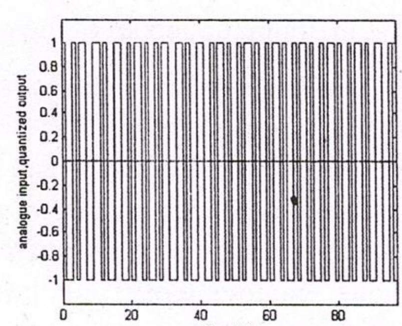

Fig. 11: Unforced condition (a=0)

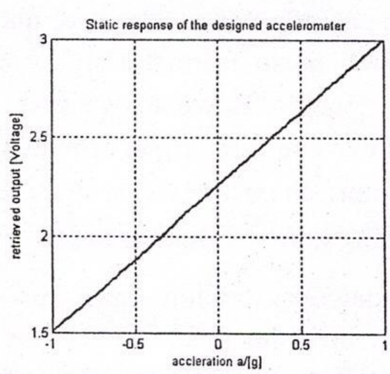

Fig. 12: Static response of the designed accelerometer

Table 2. Desired specification of the sensor and interface IC

Sensor Specification	
Device size	4 mm × 4mm × 320 µm
Rest capacitance	14 pF
Sensitivity	0.4 pF/g
Brownian noise	$0.13\ \mu g/\sqrt{Hz}$
Resonant frequency	980 Hz
Transverse sensitivity	0.05 %
IC specification	
Sampling clock	20 kHz
Sensitivity	0.8 V/g
IC core size	$4\ mm^2$
Range	± 1g, ± 2g
Absolute maximum acceleration	500 g

Table 2 summarizes the specification of the designed sensor and IC. This closed loop accelerometer has several advantages when comparing with other bulk accelerometers such as low Brownian noise, high sensitivity, small transverse sensitivity [12,13]. In other way, applying the sigma-delta modulation technique to this sensor can obtain lower quantized noise and digital output.

5. CONCLUSIONS

A specific accelerometer designed by SUGAR and a feedback system was present. SUGAR is such a flexible and powerful tool which allows MEMS designed to create various structures. Air gaps between the sense capacitors must be reduced to obtained larger changes in capacitance for a given input acceleration. The sigma delta modulator has the ability of interfacing to different capacitive sensor with optimized characteristics. The simulation result is very agreed with the theoretical prediction and it results in a digital closed loop accelerometer.

THIẾT KẾ CẤU TRÚC CƠ HỌC VÀ ĐIỆN TỬ CỦA CÁC CẢM BIẾN GIA TỐC KIỂU TỤ SỬ DỤNG SUGAR

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TÓM TẮT: Bài báo này trình bày về mô hình hoá các cấu trúc cảm biến gia tốc kiểu tụ sử dụng ngôn ngữ SUGAR trong môi trường MATLAB. SUGAR là ngôn ngữ mạnh mẽ và linh hoạt cho phép các nhà thiết kế MEMS thu được kết quả tương đương với các phương pháp truyền thống (phương pháp phần tử hữu hạn, phương pháp phần tử biên). Bài báo đã tập trung vào thiết kế và mô phỏng các cấu trúc cảm biến gia tốc bốn thanh dầm đối xứng chéo. Bên cạnh việc thiết kế cấu trúc cơ học của cảm biến, bài báo còn xây dựng

hệ thống phản hồi điện tử sử dụng phương pháp điều chế mật độ xung với những tính năng ưu việt như giảm thiểu nhiễu lượng tử hoá và cho phép tín hiệu lối ra là số.

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