

Simulation of a Micromachined Digital Accelerometer in SIMULINK and PSPICE

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Keywords: Mechatronics, Simulation, Measurement and instrumentation

1. INTRODUCTION

The development of a mathematical model of a closed loop micromachined silicon accelerometer is a very important consideration in the design of such a transducer. The sensing element being used for this work consists of a seismic or proof mass which is suspended between two sensing electrodes forming two capacitors in series, fig. 1. The acceleration force acting on the sensing element will cause the proof mass to deflect from its rest position resulting in a differential change in capacitance proportional to the acceleration. In this paper a model is derived for a silicon micromachined accelerometer and as well as the control strategy to provide a closed loop operation with a direct digital output signal. The model has been implemented both in MATLAB with SIMULINK and the MicroSim Design Centre (PSPICE for Windows). The simulation process models the dynamic performance of the sensing element itself, the control electronics and the effects introduced by the method of reset employing electrostatic forces. This joint approach of employing a high level simulator in the s domain and a much lower level electronic component simulator proved a useful design approach.

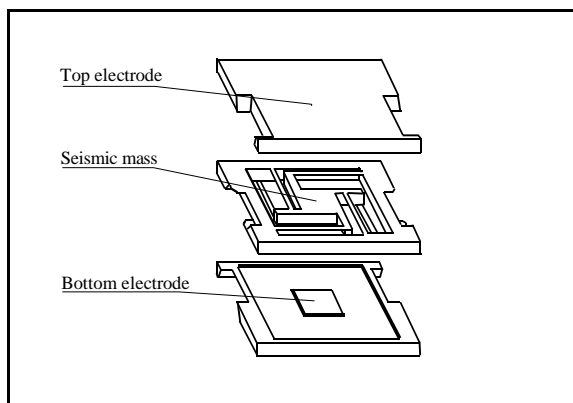


Fig. 1: Micromachined sensing element.

2. DIGITAL TRANSDUCER CONCEPT

Before describing the accelerometer system it is necessary to consider the basic concept of a digital

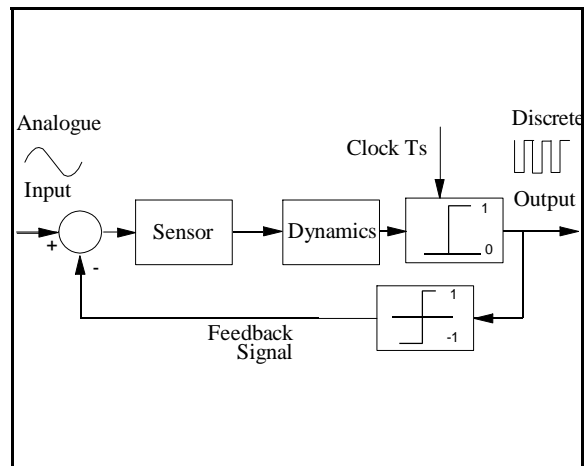


Fig.2: Digital transducer structure

transducer. It is based upon a form of oversampling converter more commonly known as a sigma-delta modulator. This device is widely employed in areas such as audio, instrumentation and telecommunications and may be used to convert an analogue signal to a train of constant height pulses. The rate of production of the pulses is determined by an external clock which is of a much higher frequency than the required signal bandwidth.

The system uses single bit quantisation which implies that only one accurate voltage reference is required, consequently the conversion process can be very accurate, [1]. Another important feature is that when subjected to a zero input the modulator oscillates continuously in a limit cycling mode. The serial output bit stream is in a form of a pulse density modulated signal. This robust signal may be transmitted directly over a standard digital bus system or as is common, passed through a decimating filter which removes the quantisation noise and provides a n-bit word.

A sigma delta modulator together with a sensor can be used to produce an inherently digital transducer. A block diagram of such a system employing oversampling in which the sensor is embedded within the feedback loop is shown in fig. 2. This concept can be applied to a range of sensors, one which has been developed recently at Coventry University is a current transducer for very high accuracy applications, [2]. Such devices exhibit a flat frequency response down to 0 Hz as would be expected in this type of transducer. Besides the advantage of

having a direct digital output signal the limit cycling property can be used for self-testing purposes which are vital especially in the case of an accelerometer in crucial application e.g. release of airbags or navigation systems.

3. THE DIGITAL ACCELEROMETER

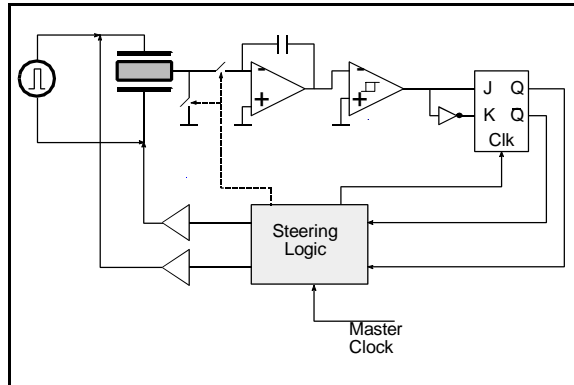


Fig. 3: Digital accelerometer system.

- The digital accelerometer system, fig.3 comprises:
- , the micromachined sensing element,
 - , a pick-off circuit converting the differential change of capacitance into a voltage,
 - , a comparator and a sample and hold to provide the oversampling conversion,
 - , a steering logic to provide all digital clock and control signals,
 - , a feedback system using electrostatic forces to reset the proof mass to its centre position.

For simplicity the sensing element is depicted as two capacitors in series. In this design care must be taken to ensure that the sensing and feedback signals do not interact because the micromachined accelerometer has only three contacts, top and bottom electrodes and proof mass. Consequently the two phases of operation are separated in time. Only during the sensing phase is the charge amplifier connected to the seismic mass. The output of the amplifier is either a proportional, integral or a combination of both of the differential change in capacitance. One aim of this paper is to investigate whether a pure integrator pick-off results in stable system operation (this is easier to realise in hardware) or whether a proportional term is required. For accurate coding a type 1 control system is required, consequently a pure proportional pick-off was not considered. Other types of digital accelerometer based upon oversampling conversion processes have been described, [3,4,5] however, they are not of a true type 1 control structure. The comparator and the sample and hold are realised as an open loop operational amplifier and a JK-flipflop. The steering logic determines to which plate an electric potential is applied depending on the state of the flipflop. The potential is applied to the plate on the opposite side of the plane of equilibrium to which the seismic mass is positioned at this instant of time. Consequently an

electro-static force is generated pulling the proof mass back to the centre position. This results in another major advantage of this approach over a conventional closed loop analogue accelerometer strategy, [6], in which a bias voltage is required to provide linearised negative feedback for small displacements of the proof mass from its centre position. If a shock causes the seismic mass to leave this linear region, the feedback can change polarity, the seismic mass is then attracted to one electrode and 'locks-up', [7]. To reset the transducer it has to be switched off which is not acceptable for many applications.

The voltage applied to the electrodes is of a constant magnitude and duration. This solves the problem that the generated electro-static force has a square law dependency on the voltage, the net force is now a linear function of the number of pulses per time period. However it also depends on the distance between the energized electrode and the proof mass (proportional to the inverse of the distance) consequently a strictly linear relationship is only valid for very small displacements of the proof mass from its rest position.

The sensing period is of a much shorter duration than the feedback period, in practice a ratio of the order of 1 to 10 is suggested.

At the time of preparing this paper a prototype hardware realisation is about to be tested.

4. MATHEMATICAL MODEL

One requirement to simulate the system described above is to develop a mathematical model. To achieve this it is sensible to develop a model for the micromachined sensing element first and incorporate this into the model for the entire transducer system.

4.1 Model of the Sensing Element

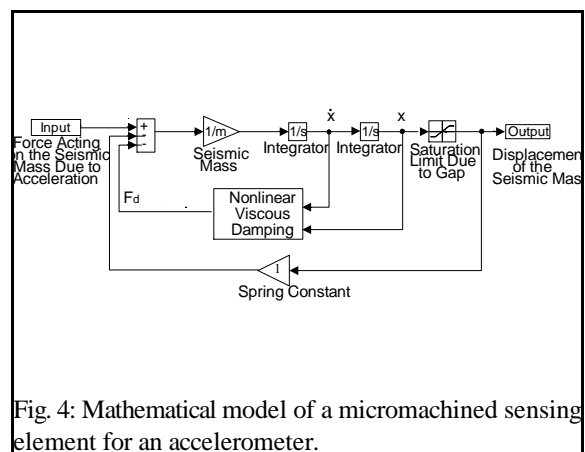


Fig. 4: Mathematical model of a micromachined sensing element for an accelerometer.

The sensing element is basically a second order system with a mass, spring and a form of damping caused by the motion of the proof mass in a gaseous medium, air in this case. The damping cannot be assumed to be linear because the gap between the electrodes and the proof mass is much smaller than the area of the plates. As the

mass moves towards an electrode the air cannot escape fast enough, pressure is built up resulting in a dependency of the damping coefficient on the position of the proof mass, [8]. A model for the sensing element incorporating this effect is shown in fig.4. The saturation block represents the physical restraint in movement of the seismic mass due to the top and bottom electrodes. The input to the system is the acceleration force acting on the proof mass causing to deflect it from the rest position; the output signal is a measure of the position of that mass. It is interesting to note that, although this kind of accelerometer is normally referred to as open loop, it is a closed loop system in its own right with the spring of the suspension providing negative feedback.

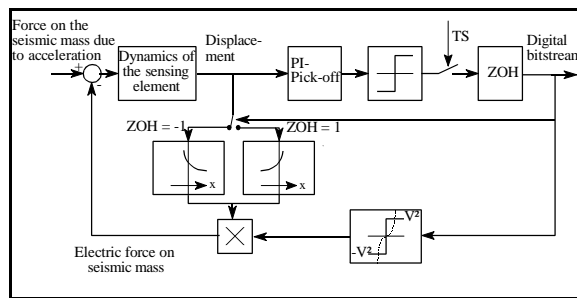


Fig. 5: Mathematical model of the digital accelerometer.

4.2 Model of the transducer

The model of the entire system is shown in fig.5. The pick-off can be modeled as a proportional plus integral gain factor that converts the displacement of the proof mass into a voltage. The JK-flipflop can be represented as a zero order hold. The dependency of the generated electric force on the position of the seismic mass is modeled by a switch the state of which is determined in turn by the signal of the zero-order-hold. An electrical

generated force proportional to the square of the hold signal provides the feedback force. Another gain block is required to convert the signal at the output of the hold into a voltage generating a sufficient electric feedback

force. For simplicity it is assumed that the feedback voltage is applied to one electrode for an entire cycle, in reality, one cycle is divided into sensing and feedback periods.

5. SIMULATION

The mathematical model described above can be readily implemented in SIMULINK. However as a comparison it was also implemented in PSPICE. This package is normally used to simulate at an electronic component level, but also contains 'behavioural modelling' capabilities which facilitate simulation at block diagram level. The advantage of simulating in PSPICE is that the designer can start at a mathematical block diagram level and then gradually refine the simulation by introducing electrical components. In this case this was done in two steps: firstly by replacing the ideal sample and hold with a JK-flipflop and secondly by replacing the ideal comparator with a open-loop operational amplifier. Another step to a more realistic simulation was to assume that the voltage is not applied to one electrode during the entire cycle but only during the feedback phase. In this way the designer can check after each refinement the influence of using non-ideal components on the performance of the system.

5.1 SIMULINK Simulation

Fig. 6 shows the SIMULINK simulation diagram which is basically a direct equivalent to the mathematical model of fig.5.

To characterize the system a zero acceleration signal was assumed from 0 to 0.1s then a step in acceleration to a value of 1g. Fig. 7 shows the step in acceleration,

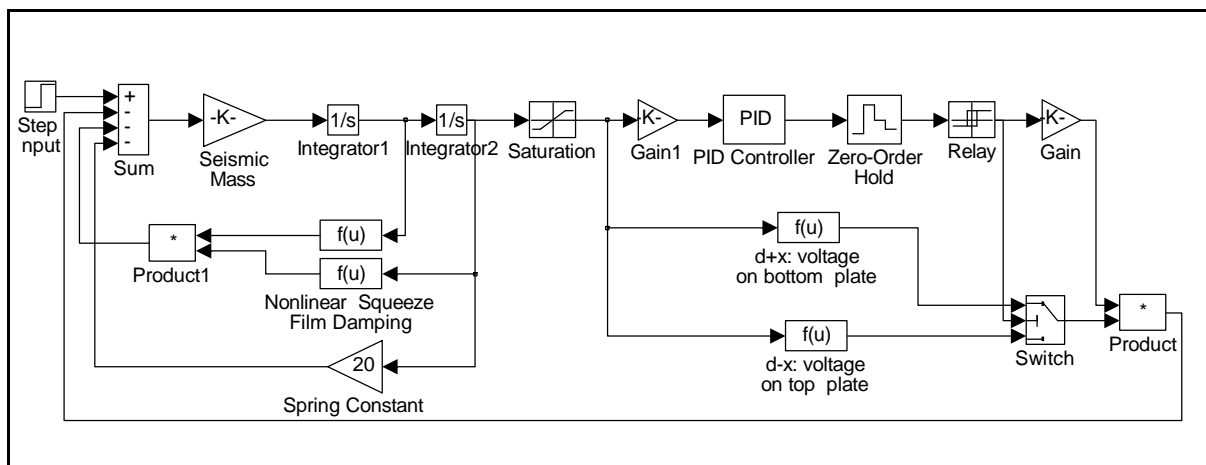


Fig. 6: SIMULINK simulation diagram.

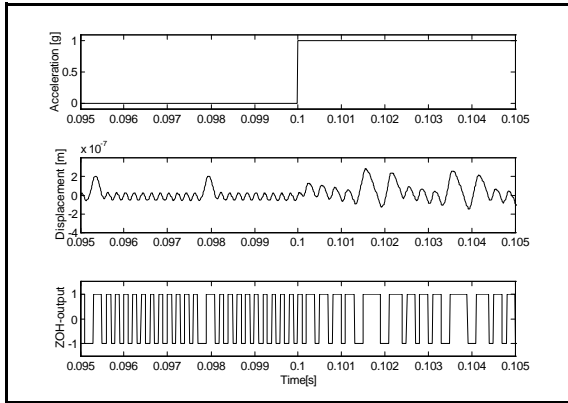


Fig. 7: SIMULINK simulation for PI-pick-off.

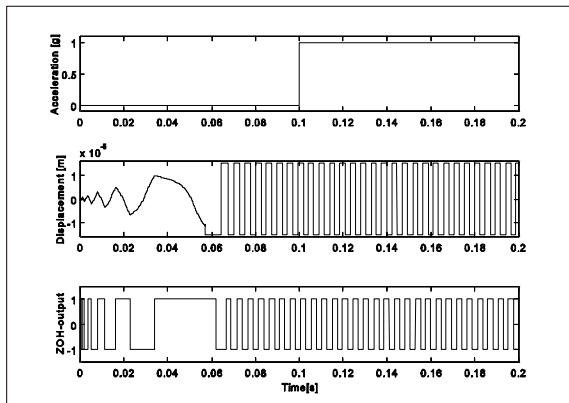


Fig. 8: SIMULINK simulation for I-pick-off.

the displacement of the seismic mass and the pulse density modulated output signal for a PI-pick-off configuration. This signal is then normally subjected to a decimating filter to provide an n-bit word by removing the quantisation noise. It can be seen that the seismic mass is kept very closely to its centre position which is desirable to maintain a linear feedback relationship. Additionally the effect of the nonlinear viscous damping increases in a cubed relationship with the displacement of the seismic mass, if the mass can be kept close to the centre position the damping can be neglected. In the second simulation, fig. 8, a purely integral pick-off is assumed; this results in an unstable system, the seismic mass is moving from the top to the bottom electrode in a very high order limit cycling mode consequently this system is not suitable for this application.

5.2 PSPICE Simulation

Fig.9 shows the PSPICE simulation diagram where the ideal zero-order-hold is now replaced by a JK-flipflop constituting the pulse density modulated output signal. Also the fact that one cycle is split into a sensing and feedback period is taken into consideration by using a digital stimulus providing the right timing and two AND gates. The comparator is still assumed to be ideal and is realised as a look-up table. PSPICE can only simulate linear processes therefore the transition region of the look-up table between the high and low state has

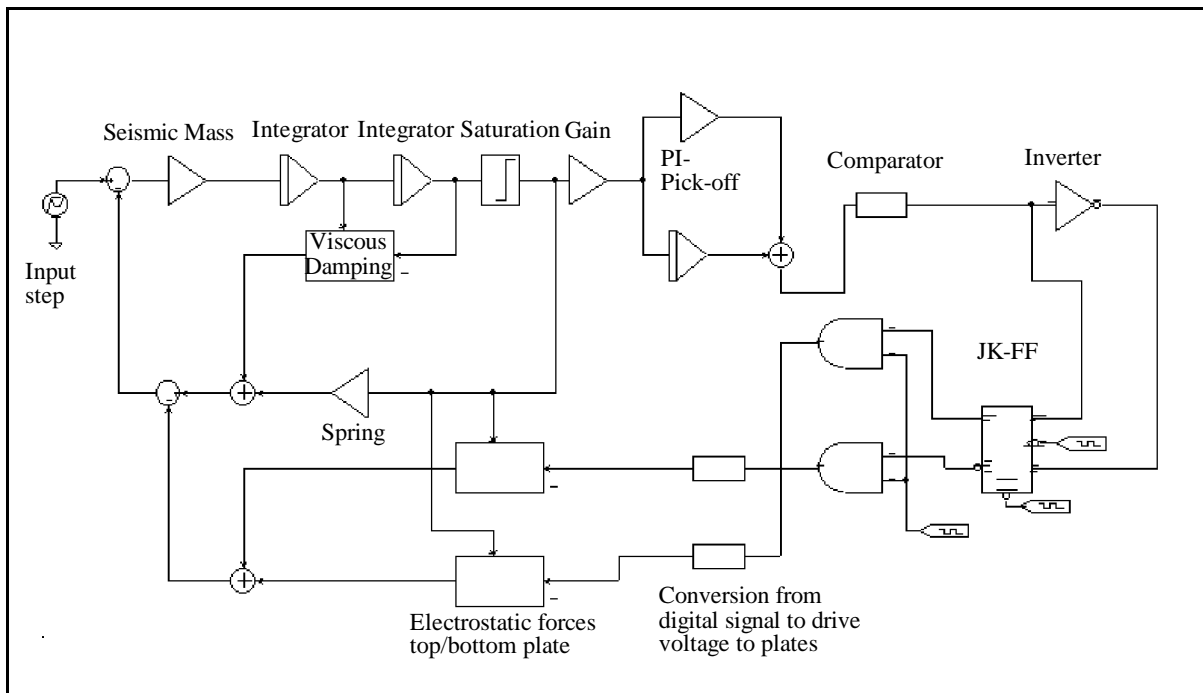


Fig. 9: PSPICE simulation diagram with JK-flipflop.

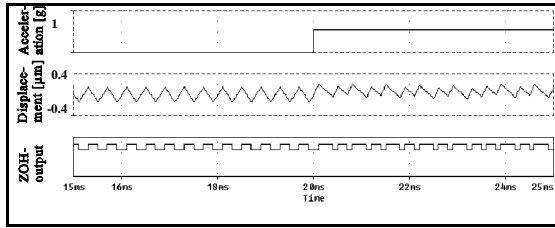


Fig. 10: PSPICE simulation with a JK-flipflop instead of an ideal zero-order-hold.

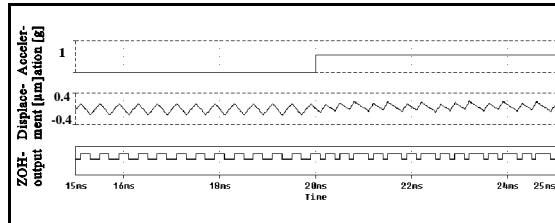


Fig. 11: PSPICE simulation with a JK-flipflop and a non-ideal comparator.

to be chosen carefully. If it is too small convergence problems occur.

Again a step function in acceleration was assumed of a magnitude of 1g, fig.10. A good agreement with the SIMULINK simulation is obvious, the sensing element is moving only $\pm 0.3\mu\text{m}$ from its rest position. In the second simulation, fig.11, additionally a non-ideal comparator was assumed. Again a good agreement with the previous simulation is apparent.

A further refinement would be to simulate the pick-off circuit at an electronic component level. However the simulation time increases enormously in PSPICE. The simulations shown above already took 8-9 hours, with the pick-off circuit this could easily be several days.

6. CONCLUSIONS

The top down design process of a mechatronic system as in a digital accelerometer can be verified by simulation at different levels. The first step is to simulate the system at a block diagram level including the effects inherent in the sensing element, the pick-off, the control strategy and the feedback mechanism. This model can then be implemented in PSPICE which is used to simulate at an electronic component level allowing the model to be refined gradually. The model considered involves both nonlinearities and sampling, this is a severe test for a simulation package. The results obtained by the different approaches are sufficiently in agreement for confidence in the results to be justified. Although the results have not been compared with actual measurements, the testing on the sensing element at an earlier stage, [7], resulted in a satisfactory outcome.

7. REFERENCES

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