ACCELEROMETER DESIGN

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Much effort is being applied to the development of intelligent, autonomous Micro Electro Mechanical Systems (MEMS). One kind of such devices, these are Accelerometers. Nowadays, they find very large applications in different areas of life, science and techniques. Contemporary microelectronics and microelectronic technologies give the possibility to design and to produce an acceleration sensing device, together with the data processing system in the same production cycle, on the same semiconductor substrate, so called "smart sensors". In the present paper, an explanation of the principles of operation, technological ways of production and application are given. A Microsystems Accelerometer is designed and presented.

Keywords: Accelerometer, Microsystems, MEMS, Accelerometer Design

1. INTRODUCTION

The sophisticated manufacturing process is entirely controlled and carried out by machines. Such complex artificial systems rely heavily on an interaction between the environment and the machine, which reacts according to changing parameters in its environment. Consequently, the sensing of these parameters is of utmost importance. These sensing devices are commonly referred to as sensors or transducers.

One important class of transducers is the group of mechanical sensors for measuring acceleration, velocity, position, pressure, weight, flow rate, force, sound, etc. The demand for these sensors has increased recently quite considerably, because of the growing number of applications, dependent on accurate measurements of physical quantities, such as in plant and process control, monitoring systems, medical applications, etc. These sensors should provide high precision measurement data at both low cost and low power consumption.

Two technical advances can be identified to be of importance in the search for new concepts: first, the ever increasing use of digital signal processing (DSP), for which powerful tools are available and the enormous advantages of digital data transmission, providing a robust signal, even in an electrical noisy environment; second, the progress in micromechanics which, it is claimed, has similar potential for development as microelectronics.

Micromachined sensors often have a superior performance to their conventional counterparts in terms of robustness, reliability, accuracy, flexibility and sensitivity at reduced weight, dimensions and power consumption. Since the microfabrication process offers the possibility to manufacture in a batch process, in which hundreds of sensors can be fabricated on a wafer, the cost of these devices is expected to fall to similar levels to that of components, produced by the microelectronic industry.

A combination of micromachined sensors with the above mentioned advantages of digital signal processing yield "intelligent" or "smart" sensors. The availability of such transducers will enable applications to become feasible, which in the past were impossible or at least economically unjustified.

One important mechanical transducer, already mentioned above, is the accelerometer. It provides a measure of acceleration in form of an electrical output signal. One reason this sensor to be of special significance is the fact, that by integrating the output signal, an accelerometer can also provide a measure of velocity and position. As a result, these devices are widely used in all sorts of terrestrial, marine and aerospace applications. Recently, the automotive industry has shown extremely high demand for accelerometers, where the release of the airbag is the most well known application, but also for active suspension control, brake control, fuel cut-off and engine knock. High precision inertial navigation and guidance systems are based upon accelerometers; they are also used in vibration control, e.g. if containers with fragile goods are shipped, to monitor the vibration of the hard disk in portable computers, to measure the vibration of machines and in the investigation of earthquakes. In aerospace, accelerometers are used to sense microgravity in space laboratories. In medical applications, accelerometers can help to monitor the motion of a patient, e.g. suffering from Parkinson disease. The variety of applications for accelerometers is enormous and this list is far from complete.

To date the main limitations have been the cost, size, weight and power consumption of these devices. Consequently, accelerometers have an especially high potential for improvements through new developments in micromachining, because this technique addresses the problems mentioned above.

2. THEORY

The measurement of acceleration always relies on classical Newton's mechanics. The transducers make use of a sensing element, consisting of a proof mass (also referred to as seismic mass), which is suspended by a spring; acceleration causes a force to act on the mass, which is consequently deflected by a distance 'x', as shown in fig. 1. Some form of damping is required, otherwise the system would oscillate at its natural frequency 'ω_n' for any input signal.

To derive the motion equation of the system, D'Alembert's principle is applied, where all real forces, acting on the proof mass, are equal to the inertia force on the proof mass. Let x be the displacement of the mass m relative to the body. When the body has acceleration a, the equation of motion for the mass is:

$$m\ddot{x} + \beta\dot{x} + kx = -ma, \qquad (1)$$

where β and k are the damping coefficient and spring constant, respectively. Thus, the acceleration can be determined by measuring x, i.e., the net stretch or compression of the spring.

The behavior of this dynamic system is determined by two parameters: the natural frequency $\omega_n = \sqrt{k/m}$, and damping ratio $\zeta = \beta/\sqrt{4mk}$. Using these parameters, the equation of motion becomes:

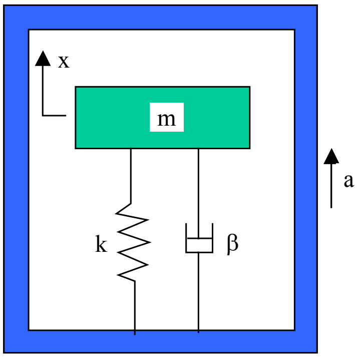

Fig.1. Principle of Operation of an Accelerometer

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = -a. \tag{2}$$

The solution to this equation consists of a *transient response*, which depends on the specific initial conditions, and a *steady-state response*, which is independent of initial conditions. If the response of the system is sufficiently fast, it is reasonable to ignore the transient response.

In the **steady state condition** - with constant acceleration '*a*' and constant deflection '*x*', the above equation yields:

$$ma = kx \qquad \text{or} \qquad a = \frac{kx}{m}$$

Here, the sensitivity "*S*" of an accelerometer is defined by:

$$S = \frac{x}{a} = \frac{m}{k} \tag{3}$$

For the **dynamic performance** it is easier to consider the Laplace transform of $\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = -a.$:

$$\frac{x(s)}{a(s)} = \frac{1}{s^2 + \frac{\beta}{m}s + \frac{k}{m}} \tag{4}$$

As stated, the natural frequency is $\omega_n = \sqrt{k/m}$

An upper boundary of the bandwidth of an open loop accelerometer is its natural frequency. It can be seen, that the bandwidth of an accelerometer sensing element has to be traded off with its sensitivity since $S = \frac{1}{\omega_n^2}$.

For the dynamic performance of an accelerometer the damping coefficient 'β' is crucial. For maximum bandwidth the proof mass should be critically damped; it can be shown that for $\beta = 2m\omega_n$ this is the case. It should be noted here, that in micromachined accelerometers, the damping originates from the movement of the proof mass in a viscous medium. However, depending on the mechanical design, the damping coefficient 'β' cannot be assumed to be constant.

3. MEMS ACCELEROMETER STRUCTURE

The accelerometer has a configuration, shown in Figure 2 (top and cross-sectional views). Using micromachining technology, the silicon mass is shaped like a truncated pyramid, as shown in Figure 3. Note that the mass is shown upside down for convenience in visualization. By the nature of the micromachining process used, the edge lengths of the two horizontal surfaces of the silicon mass are a_1 and $a_2 = a_1 - t/\sqrt{2}$, where t is the thickness of the mass. Note that the thickness t of the silicon mass is given by that of the silicon wafer (525 μm), from which the accelerometer is fabricated.

As shown in Figure 2, the mass is suspended by eight beams, which are also fabricated from silicon. Integrated strain gauges are fabricated on the surface of each beam (at the end of the beam, near the frame, where strain, due to bending, achieves a maximum), and are used to measure the deflection of the beam. The damping in the sensor, mainly arises from squeeze-film effects in the air gap between the silicon mass and the bottom encapsulation.

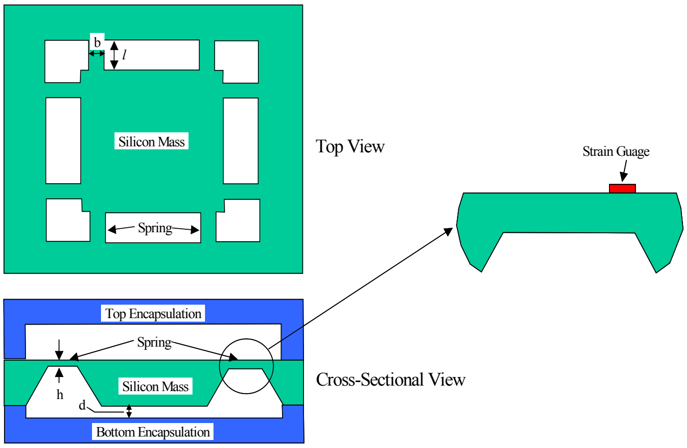

Fig.2 Schematic of a micromachined accelerometer (top and cross-sectional views)

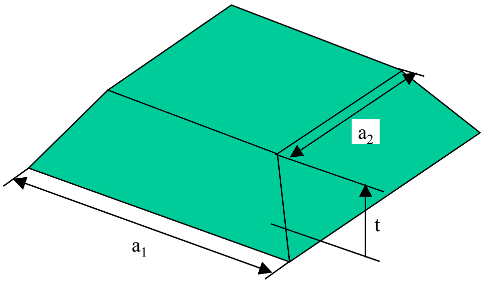

Fig.3 Three-dimensional view of the silicon mass in the micro accelerometer

4. DESIGN PROCEDURE

Focusing on the steady state response, we introduce two important performance parameters as follows.

1. *Minimum detectable acceleration*. Let the applied acceleration be a constant. The steady state response is then $x = a/\omega_n^2$. In other words, the steady-state net stretch or compression of the spring is directly proportional to the applied acceleration. Suppose that the minimum measurable spring deflection is $x_{\min}$, then the minimum detectable acceleration of the accelerometer is given by $a_{\min} = x_{\min}\omega_n^2$.
2. *Bandwidth*. Let the applied acceleration be a sinusoid with circular frequency ω, i.e., $a = a_0\cos(\omega t)$. The steady-state deflection of the spring is of the form $x = x_0\cos(\omega t + \phi)$. The deflection magnitude x_0 is related to the magnitude of the applied acceleration a_0 by:

$$x_0(\omega) = \frac{a_0}{\omega_n^2}\cdot\frac{1}{\sqrt{[(\omega/\omega_n)^2 - 1]^2 + 4\zeta^2(\omega/\omega_n)^2}}$$

As indicated by the notation, x_0 depends on the driving frequency ω. In particular, x_0 becomes diminishingly small, when ω is sufficiently large, and the accelerometer will cease to be useful for accelerations at such a frequency. In practice, the bandwidth, within which the accelerometer is useful, is given by the *cutoff frequency* ω_c, which could be defined from $x_0(\omega_c)/x_0(0) = 1/\sqrt{2}$, and is given by: $\omega_c = \gamma\omega_n$, where $\gamma = \sqrt{1 - 2\zeta^2 + \sqrt{(1 - 2\zeta^2)^2 + 1}}$.

5. MICRO ACCELEROMETER PERFORMANCE SPECIFICATIONS

The accelerometer is to be designed to satisfy the following specifications:

1. The minimum detectable acceleration, should be smaller than 0.0025g, where g is gravitational acceleration.

2. The bandwidth, given by the cutoff frequency for sinusoidal accelerations, should be greater than 4 kHz.

3. The damping ratio should be in the range $0.6 \le \zeta \le 1.1$, so that the transient response of the accelerometer has desired characteristics.

6. MICRO ACCELEROMETER DESIGN PARAMETERS

The design of the accelerometer involves the selection of the following parameters. The dimensions of the silicon mass (a_1), the dimensions of the silicon beams (l, b, and h), and the depth (d) of the air gap between the silicon mass and the bottom encapsulation. These design parameters are to be chosen from the following practical ranges allowed by micromachining technology:

$1\,\text{mm} \le a_1 \le 5\,\text{mm}$, $300\,\mu\text{m} \le l \le 600\,\mu\text{m}$, $100\,\mu\text{m} \le b \le 300\,\mu\text{m}$, $2\,\mu\text{m} \le h \le 10\,\mu\text{m}$, $5\,\mu\text{m} \le d \le 40\,\mu\text{m}$.

7. DESIGN PROCEDURE. CALCULATION STEPS

The micro accelerometer design is to be accomplished by exploring the design parameter space using appropriate design equations. The following procedure is suggested.

a) mass m:

The mass can be calculated from the formula $m = \frac{1}{3}\rho t(a_1^3 - a_2^3)/(a_1 - a_2)$,

where ρ=2300 kg/m^3 is density of silicon and t = 525 μm.

b) spring constant k:

The spring constant k can be calculated, using the formula: $k = \frac{12EI}{l^3}$, and $I = \frac{bh^3}{12}$ is the moment of inertia for a beam.

As shown in Figure 2, the mass is suspended by eight beams, therefore: $k = \frac{8Ebh^3}{l^3}$.

c) damping coefficient β:

The damping force arises from the squeeze-film effect, i.e., the interaction of the silicon mass and the air film, trapped in the gap between the mass and the bottom encapsulation. The "squeeze number" is: $\sigma = \frac{12\mu A\omega}{P_a d^2}$, where μ = 1.85×10^{-5} N/m^2·s is the dynamic viscosity of air, and P_a = 10.13×10^5 Pa is the atmospheric pressure, $A = a_2^2$ is the area of the air film, and ω is the driving frequency of a sinusoidal excitation. The squeeze-film effect can be neglected for σ<<1.

d) the natural frequency $\omega_n = \sqrt{k/m}$;

e) the damping ratio $\zeta = \beta/\sqrt{4mk}$;

f) minimum measurable spring deflection $x_{\min} = \varepsilon_{\min} l$, where the minimum measurable strain of the silicon beams allowed by the strain gauges is $\varepsilon_{\min}$=5×10^{-7};

g) the minimum detectable acceleration $a_{\min} = x_{\min}\omega_n^2$.

h) bandwidth $\omega_c = \gamma\omega_n$, where $\gamma = \sqrt{1 - 2\zeta^2 + \sqrt{(1-2\zeta^2)^2 + 1}}$.

Substituting in the above equations and using Excel Sheet, we receive that:

Acceleration a = 0,0023g. Cut-off frequency ω$_c$ = 9,6 kHz. Damping Ratio ξ = 0,62

All these values are within the required design specifications.

8. CONCLUSIONS

The theory of explanation of the action of the acceleration sensors is studied, systematized and formulated. A specialized design procedure is proposed. The pilot calculations are done. The results are in good accordance with the expectations and the initial specification.

9. REFERENCES

[1] Muller S., A. Pisano, *Microactuators*, CRC Pr I Llc, October 2000, ISBN-10: 0780334418.

[2] Elwenspoerk M., R. J. Wiegering, *Mechanical Microsensors,* Springer Verlag, January 2001, ISBN-10: 3540675825.

[3] Hsu Tai-Ran, *MEMS and Microsystems : Design and Manufacture*, McGraw-Hill College, October 2001, ISBN-10: 0072393912

[4] Maluf N., K. Williams, *An Introduction to Microelectromechanical Systems Engineering*, Artech House, June 2004, ISBN-10: 1580535909