XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

POSITION MEASUREMENT BY MICRO-ELECTRONIC ACCELEROMETER

G.J. Stein [1] ***and M. Šperka*** [2]
[1] Institute of Materials and Machine Mechanics, Slovak Academy of Sciences
SK-838 12 Bratislava, Slovak Republic
[2] Faculty of Electrical Engineering and Information Technology
Slovak University of Technology, SK-812 19 Bratislava, Slovak Republic

Abstract: Relative displacement measurement by use of absolute acceleration measurement was attempted. A micro-electronic accelerometer, working on the servo-accelerometer principle was tested for this application. The results of extended investigation indicate that this theoretically simple way of relative displacement measurement is not feasible in practice due to large errors introduced by double-integration of the accelerometer output signal corrupted by drift and noise.

Keywords: micro-electronic accelerometer, position measurement, MEMS

1 INTRODUCTION

In robotics, virtual reality, telepresence systems and navigation the knowledge of position of a specific part of the device in three-dimensional space at a given time instant is of prime importance. Especially this is a problem, when no rigid link to the co-ordinate system origin is possible and the measured point is allowed to move free within three-axial Cartesian co-ordinate system.

Most systems used in similar applications are complex, expensive and not readily available. So an attempt was made to solve this task by simple means. The idea was to develop a device similar in appearance to a computer mouse, however not using any mechanical contact with the surface on which it was moving. The device would have to be connected by a wire link or by wire-less means (radio or infra-red link) to a PC [3], equipped with specific software to determine the device position. In the first instant measurement in one axis was sought to test the feasibility of proposed approach. Attempts to solve this problem have been presented on previous similar occasions [1, 2].

2 BASIC IDEA

The idea behind was to use acceleration measurement for determination of the relative position of the device in respect to a set origin. Physically, the idea is based on the simple relation between translation acceleration $a_x(t)$, velocity $v_x(t)$ and displacement $x(t)$ at the time instant t:

$$x(t)=\int_0^t\left(\int_0^t a_x(t)\cdot dt+v_0\right)\cdot dt+x_0 \tag{1}$$

where: v_0, x_0 are the velocity and position respectively at the beginning of measurement. These can be supposed to be zero, so only the measured acceleration has to be integrated twice. For pure harmonic vibration at single frequency f_0 with corresponding circular frequency $w_0 = 2\pi f_0$ the relation between vibration displacement and acceleration is also well known:

$$x(t)=a_x(t)/w_0^2 \tag{2}$$

For vibration measurement the standard way is to use piezo-electric accelerometers with voltage or charge pre-amplifiers with build-in time integrators. However, piezo-electric accelerometers, due to the nature of the piezo-electric effect, are not suitable for measurement of stationary and very low frequency acceleration. For these purposes other types of accelerometers have to be used, employing e. g. strain gauges, piezo-resistance sensors or LVDT or using the so called servo-accelerometer principle. In this class of accelerometers the inertial force of the proof mass moving in respect to the accelerometer body is balanced by a force of non-inertial nature, for example by magnetic or electrostatic force, while a null-detector is employed to detect the original equilibrium state. Signal, corresponding to the driving force, is the measure of the acceleration. So, if the proof mass is at rest this signal is zero or a constant value, corresponding to zero acceleration. The system responds to low-frequency accelerations and tilt. Hence Earth gravity can be used for self-calibration.

Nowadays this class of accelerometers is manufactured by various micro-electronic technologies as the so called micro-electro-mechanical systems (MEMS) and supplied by a couple of vendors either as an IC type component or as an encapsulated transducer/module at very attractive price [4, 5]. Moreover a built in conditioning amplifier and overall circuit design enables to connect such a micro-electronic sensor in a rather simple way to a microcontroller or to an analogue data acquisition system (DAQ) described in [3], connected to a standard PC. Single-, double- and tri-axial models exist, so measurement of translation movement in Cartesian space seems to by in principle feasible. Hence the idea was at hand to test the feasibility of such a sensor for position measurement.

Explanation of one type of this MEMS accelerometer working principle is following (Fig. 1) [6]. The sensitive element (dashed) is a comb-like structure of 46 differential capacitors arranged in parallel on a beam forming the proof mass supported by springs etched from polycrystalline silicon substrate. The differential capacitor forms a capacitive half-bridge (capacitive divider) driven from a 1 MHz square wave generator by opposite phase pulses. When acceleration is applied perpendicularly to the capacitive "comb" due to inertial properties of the beam the differential capacitor is mismatched and a non-zero signal appears on the central plate. This signal is pre-amplified, demodulated in the synchronous detector, amplified and outputted as voltage V_{PR}, corresponding to the applied acceleration. The V_{PR} signal is feed-back via the internal loop through the 3 MΩ resistor to the differential capacitor's central plate, so providing the electrostatic restoring force to move the beam to the original centred position. The output signal bandwidth is determined by the capacitor C_2. The V_{PR} signal could be further conditioned by the built-in buffer amplifier, using external components to establish a pre-set datum for zero acceleration, conveniently approximately 2.5 V, i.e. in the middle of the span of the supply voltage of +5 V. This is convenient for direct connection to a DAQ of a microcontroller. Also the sensor's integrity self-test feature is included: by external signal an internal switch is activated, supplying a DC voltage to deflect electrostatically the differential capacitor in a predetermined way, and so providing a defined V_{PR} output .

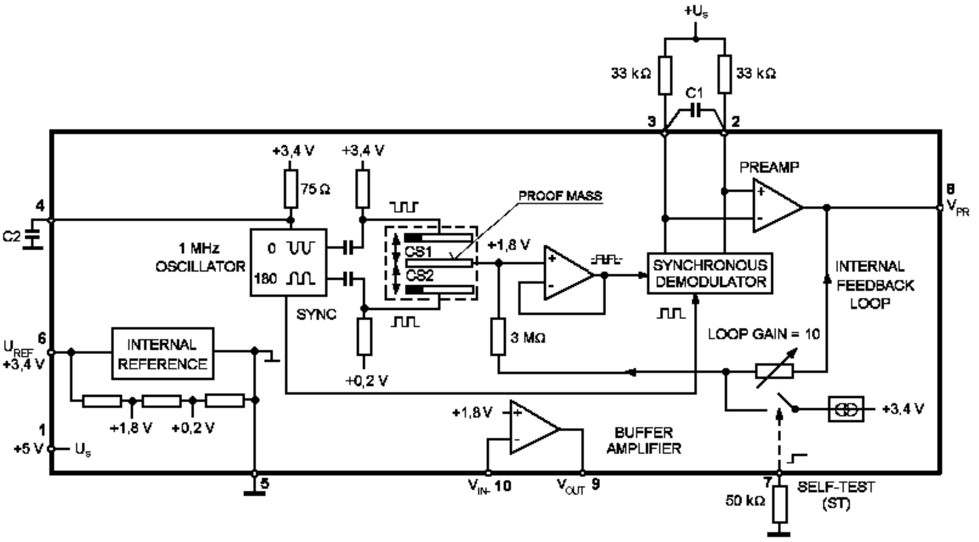

Figure 1. Schematic layout of one type of MEMS accelerometer with external components (after [6]).

This is the first-generation MEMS acceleration sensor. Further improvements, introduced recently [7], consist of improvement in the sensor's internal structure and so also in it's noise and drift performance, addition of a separate temperature sensor or by introduction of voltage-to-duty cycle converter to improve the connectivity to a microcontroller.

In the described application measurement of very low acceleration values is envisaged the noise and DC drift issues are of paramount importance. As the MEMS sensor's proof mass is of the order of 1 µg, it is very much influenced by the Brownian motion of the surrounding medium. Three sources of noise are commonly present, which fundamentally limit the MEMS sensor's performance [8]:

- thermal noise due to thermal agitation of the proof mass,
- shot noise from the P-N junctions of the sensor's transistor structure,
- so called 1/f noise associated to any source of energy in the sensor's structure.

The proof mass thermal agitation can be expressed by the thermodynamical equipartition principle arguments as the energy of simple damped harmonic oscillator, excited by random force due to thermal fluctuations of the surrounding medium at absolute temperature T. The power spectral density frequency distribution $G_N(f)$ of this thermal noise is flat and constant ($G_N(f) = G_N$) [9]. The input mechanical excitation is shaped by the frequency response of the oscillatory system, having mass m, damping constant b and a spring constant c [8, 9]. According to equipartition principle the average potential energy and the average kinetic energy of the oscillator at rest and in thermal equilibrium is equal to the thermal fluctuations ($k_B = 1.38\ 10^{-13}$ J/K is the Boltzmann's constant):

$$\frac{1}{2} m \left\langle v^2 \right\rangle = \frac{1}{2} c \left\langle x^2 \right\rangle = \frac{1}{2} k_B T \qquad (3)$$

It can be shown [8], that the average squared displacement $\left\langle x^2 \right\rangle$ of the oscillating mass due to the random thermal force is equal to $G_N/(4bc)$, so according to the generalised Nyquist's theorem:

$$G_N = 4 k_B b T\ . \qquad (4)$$

The signal to noise ratio (SNR) due to thermal agitation is given as the ratio of the square of the rms signal force due to excitation by acceleration ($m.a$) to the square of the force due to thermal agitation at temperature T. Both are supposed to have flat frequency spectra in the same frequency band [9]:

$$SNR = \frac{(ma)^2}{4 k_B b T}\ . \qquad (5)$$

For practical purposes a SNR value of 1 it is often assumed and the thermal noise floor is given as an equivalent rms acceleration value for the supposed frequency band. For the MEMS type accelerometer described the rms noise floor in acceleration value is given by the manufacturer as 5×10^{-2} m.s^{-2}, for 100 Hz bandwidth at 25 °C, i.e. ≈ 300 °K [6]. For the new generation MEMS accelerometer this value is halved to 2.25×10^{-2} m.s^{-2}, for 100 Hz bandwidth at 25 °C, i.e. ≈ 300 °K [7]. In statistical sense this means that the standard deviation s of the noise with supposed Gaussian normal amplitude distribution with zero mean has this value. So, with probability of approx. 98.8 % the value of $5\times\sigma$ will not be exceeded. If this information is introduced into formula (2) and a circular frequency $\omega_0 = 1$ s^{-1} is stipulated this leads to rms amplitude noise floor of the order of 0.5 mm, i. e. most of the errors will be below 2.5 mm, so for required accuracy of few millimetres the measured data will be extremely close to the required limit. Also the temperature drift of the zero acceleration datum (of the order of 1 mV/ °K, i.e. ≈ 5.10^{-2} m.s^{-2}/°K) is another source of possible errors.

The shot noise of the P-N junctions could be considered to be sufficiently covered by above data. The 1/f noise sources are not well understood [8, 9]. However this type of noise should be also present, due to sensor's operation principle. As explained above, the inertial force due to acceleration is compensated by the electrostatic force. The required balancing energy is injected via the 3 MΩ resistor onto the sensitive element, in parallel to the buffer amplifier input (Fig. 1). The noise and drift issues of the input circuits of the analogue DAQ-system are of importance too. It is also well known that integration methods are prone to cumulative errors. This is pertinent also to this case.

3 MEASURING SYSTEM DESCRIPTION

The MEMS accelerometer IC as such is not well suited for measurement purposes. So a more standard transducer like device was sought. This was furnished by a small box-like module (dimensions: $25 \times 25 \times 19$ mm^3) with encapsulated sensor IC and all external components included. The measurement chain consists of evaluation module of the ADXL05EM1 type connected directly to a proprietary DAQ-system (input range ± 10 V, throughput at 50 kSps, resolution 12 bit). The MEMS module has measurement range of ± 40 m.s^{-2}, output voltage is ≈ 2.5 V for zero acceleration and it's sensitivity is ≈ 50 mV/m.s^{-2}. In some instances the signal was subjected to low-pass filtering by a 4th order Butterworth type analogue filter with cut-off frequency $f_m = 32$ Hz. The accelerometer was calibrated in Earth gravitational field by tilting ± 90° about sensor's sensitive axis. The sampled signal data were subjected to off-line numerical double integration and processing by scripts in Matlab®.

The aim was to measure displacements of the order of 15 ÷ 25 cm with the relative uncertainty of 1÷ 2 %, i.e. with absolute accuracy of the order of few millimetres. To test the feasibility of this idea the accelerometer was moved freely by hand alongside of a fixed ruler for a given distance. The respective acceleration $a_x(t)$, velocity $v_x(t)$ and displacement $x(t)$ were calculated and displayed. A set of same movements was performed and subjected to statistical analysis [10].

4 SOME RESULTS

To test the background thermal noise the signal was measured and evaluated with the accelerometer at rest. To analyse properties of a particular piece of the MEMS accelerometer evaluation module the output time signal was subjected to analysis by means of a FFT signal analyser. The rms value of the noise signal was measured to be equivalent of $5,7\times10^{-2}$ m.s^{-2}, which is close to the value stated by the vendor, with occasional maximal peaks of the order of 30×10^{-2} m.s^{-2}.

Further the necessary sampling rate was determined. If a sampling rate $f_s = 100$ Hz has been selected, in accord with the cut-off frequency of the anti-alliasing filter the measurements revealed an unacceptable worst case displacement error of approx. -1 m without the filter and + 0.5 m with the filter, despite the fact that the acceleration signal seemingly exhibited a random nature. By increasing sampling frequency to 1 kHz and elimination of the analogue filter the worst case error was reduced to +/- 2.5 cm, which was deemed to by still excessive of required positioning accuracy. The supposed very low frequency drift was further attempted to reduce by introduction of a first order high-pass analogue filter with cut-off frequency of $f_l = 0.075$ Hz. This filter eliminated to some extent the drift at rest to below 1 cm, but introduced it's transient response of the order of 15 cm (expressed as displacement), which was also deemed as unacceptable. Other common digital signal processing approaches (i.e. data centering or filtration by FIR filters) did not improve the accuracy either. Also other signal processing approaches to reduce the influence of errors in input signal were fruitless. Detailed signal analysis gave indication that the noise amplitude distribution is not strictly normal, which probably contributes to large biasing errors in integrated acceleration signal.

5 CONCLUSION

The undertaken efforts indicates, that this simple approach to position measurement is not applicable due to large positional errors incurred. The possible cause of errors is probably not only the low signal to noise ratio of the measured acceleration signal, but also the statistical properties of the drift of the MEMS sensor and of the DAQ-system. These conclusions are similar to those of ref. [11].

REFERENCES

[1] Okada, T. et al, Acceleration and Azimuts Utilising Permanent Magnets...., in: *Proceedings of the IMEKO XV World Congress* (Osaka, 13. - 18. June 1999), Japan 1999, Contribution P.17.4.

[2] Bozicievic, J., Theoretical foundation of µP base accelerometer sensor, in: *Proceedings of the IMEKO IX World Congress*, pp. 115 - 124.

[3] Stein, J. - Chmúrny, R. - Koudelka, M. - Klán, P. - Dušek, F., Low cost data acquisition system for a mobile biological object, in: P. Daponte and L. Michaeli (eds.) *Proceedings of the 1st International IMEKO Workshop "ADC Modelling"* (Smolenice castle, 7. - 9. May 1997) Slovak metrological society, Bratislava, Slovak Republic 1996, p. 97-99.

[4] Stein, J., Microelectronic acceleration sensors, in: M. Karovièova and A. Plaèkova (eds.) *Proceedings of the 4th Intl. Workshop "Measurement '95"* (Smolenice castle, 29. - 31. May 1995), Institute of Measurement of SAS, Bratislava, Slovak Republic 1995, p. 44.

[5] Stein, J., New trends in acceleration sensors (*in Slovak*), *Automatizace* **38** (3) (1995) 175-177.

[6] Hutyra, M., Monolytic accelerometer ADXL 50.... (*in Czech*), *Automatizace* **37** (8) (1994) 225-229.

[7] Doescher, J., A High performance Surface Micromachined Accelerometer, Analog Devices Inc., Norwood, Massachusetts, USA, 1999.

[8] Anon., Thermal noise and the detection of gravity waves, *Journal of Physics E (Scientific Instruments)* **6** (5) (1973) 417-422.

[9] Gabrielson T., B., Fundamental Noise Limits for Miniature Acoustic and Vibration Sensors, *Trans. of ASME - Journal of Vibration and Acoustics* **117** (Oct. 1995) 405 - 409.

[10] Mintál, M. and Ivanoviè, ¼., Design of positioning device based on a microelectronic accelerometer (*Diploma project in Slovak*), FEI STU, Bratislava, 1997.

[11] Ribeiro, J. G. et al, Problems in analogue double integration to determine displacements from acceleration data, in: *Proceedings of the "15th Intl. Modal Analysis Conference"* (Orlando, Florida, 3. - 6. Feb. 1997), USA 1997.

AUTHORS: G.J. STEIN, Institute of Materials and Machine Mechanics of the Slovak Academy of Sciences, Raèianska 75, Box 95, SK-838 12 Bratislava 38, Slovakia, Phone Intl. +421 7 5941 2965, E-mail: ummsste@savba.savba.sk and M. ŠPERKA, Dept. of Computer Science and Engineering, FEI - Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, SK-812 19 Bratislava, Slovakia, Phone Intl. +421 7 6029 1847, E-mail: sperka@dcs.elf.stuba.sk