SOME RECENT DEVELOPMENTS IN ACCELERATION SENSORS

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Abstract

The contribution deals with recent development in acceleration sensors, specifically on MEMS sensors and their use. The various noise sources presented are described. Also a short description of so-called Transducer Electronic data Sheet (TEDS) concepts according to emerging standard IEEE P1451 is included.

1. Introduction

Acceleration and associated vibratory variables belong to the vast amount of physical quantities subject to measurement and analysis by various means. There is a continuous quest for improvement of vibration sensor's properties used in this diversified field of measurement science. The basic physical principle is quite simple: the so-called proof mass or seismic mass *m* is supported by an elastic element of stiffness *c*. This element may be in the form of a pre-stressed spring or a cantilever beam. The relative displacement $x(t)$ of this linear oscillatory system is damped by a linear damper whose damping *b* is proportional to the relative velocity $\dot{x}(t)$ of the proof mass *m* in respect to the sensor body. Using Newtonian formalism, the describing linear differential equation (1) can be derived in following form [1]:

$$\ddot{x}(t) + 2\xi\omega_0\dot{x}(t) + \omega_0^2 x = -\ddot{y}(t), \tag{1}$$

where the so-called sensor's natural circular frequency $\omega_0 = \sqrt{(c/m)}$ and dimension-less damping ratio $\xi = b/b_{\mathrm{krit}}$, with critical damping $b_{\mathrm{krit}} = \sqrt{(4cm)}$ are introduced. In this way the acceleration $\ddot{y}(t)$ of the sensor base is converted to relative movement of the proof mass in respect to the body. Then certain mechanical variables are subject to further transformation to electrical quantities and their further processing in acceleration sensors [1-3]:

a. Force $K\cdot x(t)$ in the spring type element via the intrisinic piezo-electric effect,

b. Relative displacement $x(t)$ by a relative displacement sensor,

c. Counter-balancing the elastic force $K\cdot x(t)$ by another force of non-inertial nature, hence establishing a pre-set equilibrium position sensed by a sensitive null-detector.

The first transducing principle is widely used in standard piezo-electric accelerometers, having well known properties - good linearity and wide dynamic range, ruggedness, etc. However, being a charge source has also some disadvantages - very high inner impedance, low output signal and no steady state response. Some miniaturised accelerometers are equipped with build-in integrated pre-amplifier/impedance converter, and in this way above disadvantages are partially removed. Such an accelerometer is connected by a standard coaxial cable to a simple powering front-end unit where the ac vibratory signal is branched of for further processing. This type of accelerometer is generally termed as the Integrated Electronic Piezo-Electric sensor (IEPE sensor) and is marketed under various brand names.

2. MEMS acceleration sensors

The rapid development of semiconductor manufacturing technologies enabled development and mass manufacturing of various sensors and actuators using state of the art technologies. Devices, whose operation principle is based on use of miniature mechanical elements are denoted as Micro Electro-Mechanical Systems (MEMS). Also in the field of vibration measurement such systems have been developed and are marketed [4-7].

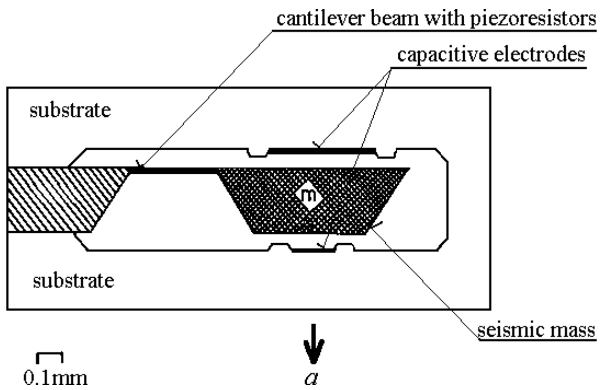

Fig. 1. Principal sketch of MEMS.

The above physical principles and methods of transducing of mechanical variables into electrical ones are used [2, 3]. The principal sketch of MEMS type sensor is in Fig. 1, where also the first two mechano-electrical transducing principles are indicated. Differential capacitor principle is often used in commercial applications [4, 5]; the servo-accelerometer principle is used widely too [5, 6] (Fig. 2):

The servo-accelerometer principle is following [6]: the sensitive element (dashed) is a comb-like structure of 46 differential capacitors arranged in parallel on a beam forming the seismic mass supported by springs etched from silicon substrate. The differential capacitor forms a capacitive half-bridge driven from a high frequency square wave generator by opposite phase pulses. When acceleration is applied perpendicularly to the seismic mass 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 demodulated signal V_{PR} is feedback via the internal loop 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. Further signal processing is provided on-board by a build-in signal conditioning/band-limiting amplifier. Further improvements [7] consist of addition of a temperature sensor to compensate for temperature influence and of using an on-board voltage-to-duty cycle converter to improve connectivity to micro-controller (no ADC is required; instead counter inputs are used).

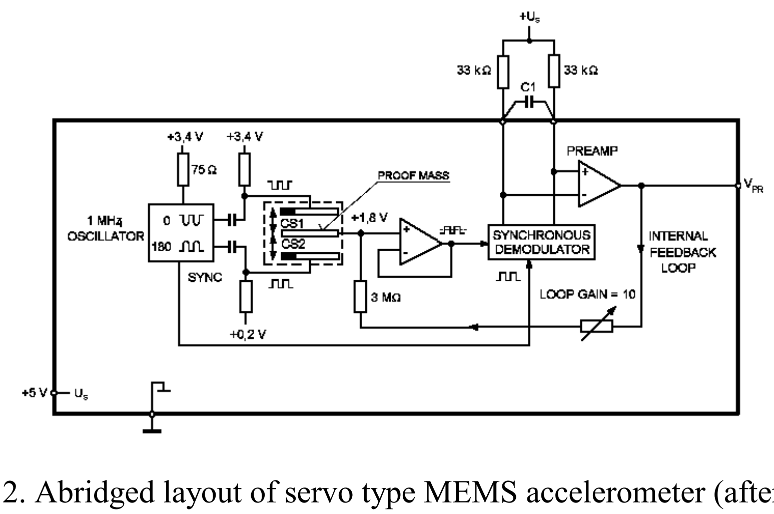

Fig. 2. Abridged layout of servo type MEMS accelerometer (after [6]).

3. Noise and drift issues in MEMS sensors

Due to extreme miniaturisation the noise and temperature drift issues in MEMS sensors are of paramount importance. The MEMS sensor's proof mass m is of the order of 1 μg and is influenced by the Brownian motion of the molecules of the surrounding medium. Following sources of noise are present, which fundamentally limit sensor's performance [5, 8, 9]:

- Thermal noise due to agitation of the proof mass by the surrounding medium,
- Thermal noise in resistors of the semiconductor structure (Johnson noise),
- So called 1/f noise associated to any source of energy in the sensor's structure.

The proof mass thermal agitation can be expressed using thermodynamic approach as the energy of simple damped harmonic oscillator of Eq. (1), 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]. This input mechanical excitation is shaped by the frequency response of the oscillatory system [5, 8] and is manifest at sensor's natural frequency. According to the equipartition principle the average potential energy and the average kinetic energy of the oscillator in thermal equilibrium with it's surrounding are equal to thermal fluctuations ($k_B = 1.38\ 10^{-13}$ J/K is the Boltzmann's constant):

$$\tfrac{1}{2} m\langle v^2\rangle = \tfrac{1}{2} c\langle x^2\rangle = \tfrac{1}{2} k_B T\ . \tag{2}$$

The average squared displacement $\langle x^2\rangle$ of the oscillating mass due to the random thermal force is equal to $G_N/(4bc)$ [8], while, according to generalised Nyquist's theorem, $G_N = 4bk_BT$. Then the signal to noise ratio (SNR) due to thermal agitation is given as the ratio of the square of the rms value of the force due to excitation by acceleration (ma) to the square of the rms value of the force due to thermal agitation at temperature T [8, 9]:

$$SNR = (ma)^2 : (4k_B bT)\ . \tag{3}$$

This source of noise is manifest at sensor's natural frequency, especially if in vacuum and adds to the Johnson type noise generated by the sensor's electronic circuits [5]. For practical purposes a SNR value of 1 is assumed. Then the combined thermal and Johnson noise floor is given as equivalent rms acceleration value for the designed sensor frequency band [5-7].

The 1/f noise source seems to play an important role in acceleration measurement at low frequency [8, 9]. This noise source is termed the Hooge's noise [9]. The power spectral density frequency distribution $G_H(f)$ depends on the biasing voltage across a resistor V_b and the number of carriers n in the resistor, α is a constant (Fig. 3 after [9]):

$$G_H(f) = \alpha V_b^2 / (nf). \tag{4}$$

From the structure of the accelerometer of Fig. 2 follows, that Hooge's noise source is present. This had probably impaired envisaged sensor application [10]. If no dc response is required this effect can be eliminated by proper electronic design [5], which improves SNR by order of magnitude.

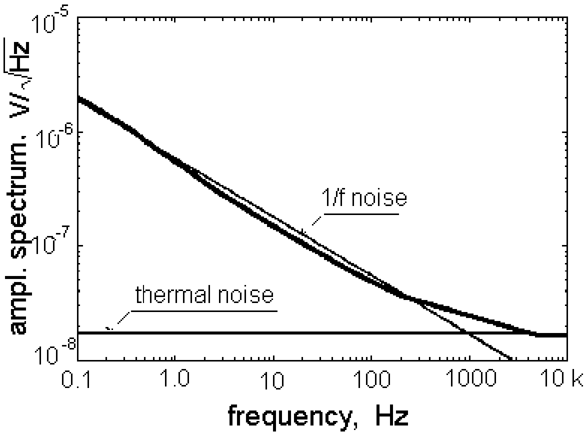

Fig. 3. PSD of the very low frequency noise.

4. The Transducer Electronic Data Sheet (TEDS) concept

In testing and monitoring of large aerospace and engineering structures vast number of sensors are distributed within the structure with star-like cabling connection to the analogue pre-processing unit. The cabling time and costs are rising and errors in sensor's identification may arise. By the emerging IEEE P1451 Standard [12] use of low-cost proven communication means, e.g. Ethernet LAN technology or RS 232 and RS 485 interfaces are standardised. Various sensors with associated pre-processing electronics (e.g. filters, ADCs and pre-processing tasks) are clustered around an Interface Module, which then communicates with the remote PC in standardised way [12]. The task of identifying and calibrating of a particular sensor is furnished by the Transducer Electronic Data Sheet (TEDS), also defined by this Standard. TEDS is a non-volatile memory chip built-in into the IEPE type sensor. The built-in memory contains in 128 bits manufacturer's data on sensor's type and serial number, as well as, a unique sensor identification code. Further 256 bits are in form of EEPROM, which can be programmed in user's calibration laboratory to store sensor's sensitivity, calibration date and parameters, location, etc. So the sensor is uniquely identified. Measured signal is processed in same way as from an ordinary IEPE sensor, whereas digital data are retrieved by reversing supply voltage and connecting the reed-out data to PC's RS 232 interface. Processing software can use sensor identification and calibration data, sawing cost and time.

5. Acknowledgement

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