# THE COMPARISON OF PIEZOELECTRIC AND MEM SENSORS INTENDED FOR VIBRATION CONDITION MACHINERY MONITORING

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**Abstract.** The paper offers a comparison between the traditional piezoelectric and modern MEMs based vibration sensors used for machinery condition monitoring and fault diagnostics. The prognoses of what technology and where will be used in the future is discussed.
Group of parameters is selected for defining a capability and perspective of particular sensor to be used for vibration measurements and diagnostics. That group consists of the follow parameters:
1) Required supply power, 2) Cost (parts and assembly),
3) Working frequency range, 4) Working temperature range and
5) Output noise level.
For reference the piezoelectric and MEMs based sensors by the parameters 1) to 4) is presented. For instance it is known that for the vibration machinery protection the frequency range of 10-1000 Hz is commonly used, but for diagnostics goals the high frequency is required to be up to 20 kHz. The experimental data and detailed comparison for output noise level/spectrum density for several popular piezoelectric and MEM vibration sensors are presented.

## 1. MAIN MEMS PARAMETERS IMPORTANT FOR VIBRATION MEASUREMENTS AND DIAGNOSTICS

There is exit a group of parameters which could be used to define will particular accelerometer is perspective to use for vibration measurements and diagnostics. That group consists of the follow parameters: required supply power, cost (parts and assembly), working frequency range, working temperature range and output noise level. The comparison of the piezoelectric and MEMs based accelerometers by the first four parameters is obvious and easily could be done by using the particular specification. For instance it is known that for the vibration machinery protection the frequency range of 10-1000 Hz is commonly used, but for diagnostics goals the up frequency is required to be 10-20 kHz. In the same time the fifth parameter – output noise level – is not always clear shown in the specification and even known for particular application.

Diagram Noise vs Max Working Frequency presented in Figure 1.

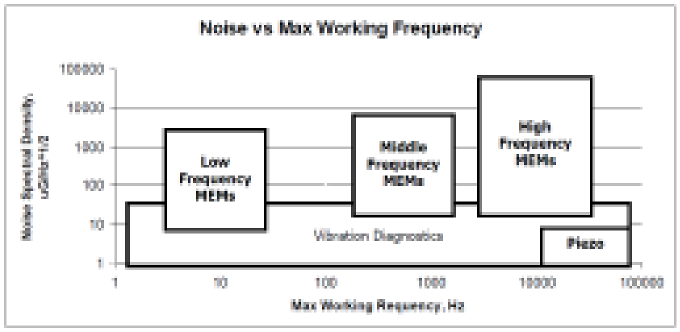


**Figure 1** Diagram Noise vs Max Working Frequency

There are some rectangles crosses area usually used for vibration measurement and diagnostics. It is possible to see that some MEMs with noise going down and frequency range being wider could be used in the vibration field. The typical noise and frequency response plots from modern MEMs accelerometer is shown at Figure 2.

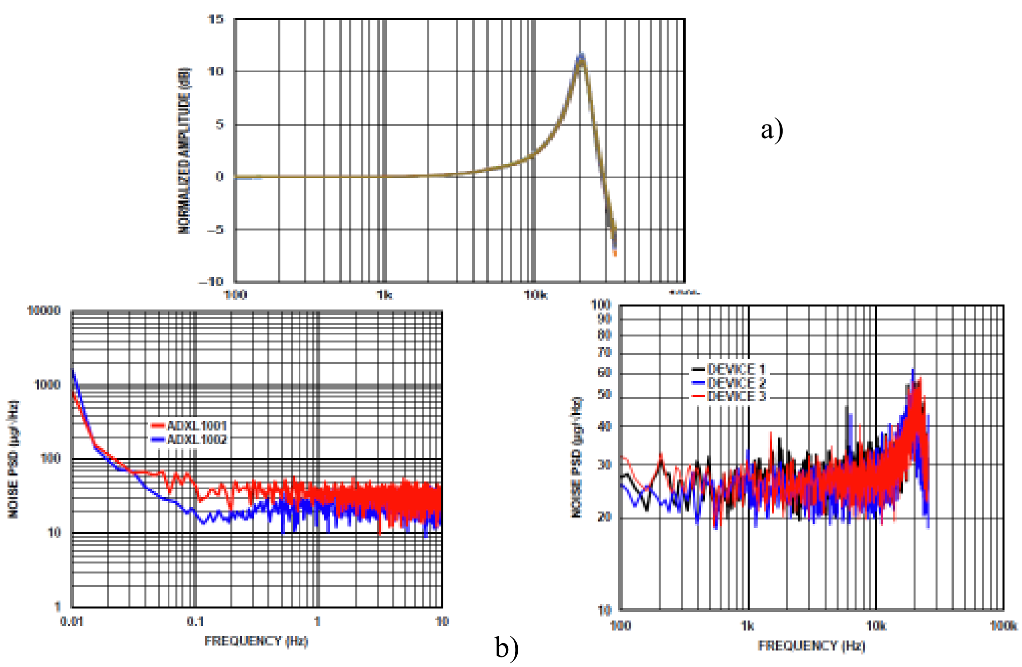


**Figure 2** Example of modern MEM accelerometer frequency response a) and noise density b) vs frequency [1]

Bellow will be discussed the noise level of the MEMs based Accelerometers and Velocity transmitters.

## 2. NOISE OF MEMS ACCELEROMETERS.

The principle of MEMs accelerometer is illustrated by Figure 3. The external vibration is activates a movement of inertial mass. The integrated electronics provides the output in analog or digital form proportional to that movement by measuring the capacitance between movements and fixes sensor parts. That construction might be considered as mechanical resonator. Then the equation described it movement could be written as follow:

$$\mathrm{M}\frac{\partial^2 x}{\partial t^2}+\gamma\frac{\partial x}{\partial t}Kx=F$$

where M – value of inertial mass, x – displacement of inertial mass, K – coefficient of spring elasticity, $\gamma$ - spring damper coefficient, F – external forces applied to the inertial mass and t – time.

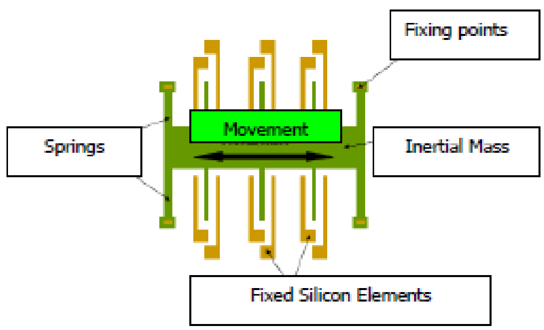


**Figure 3** Diagram of the of MEMs accelerometer working principle

This equation could be transformer to the follow $pMv+\gamma v+K/p=F$

where $v=\frac{\partial x}{\partial t}=px$ and p – Laplace operator.

Thus, the square of velocity of noise generation could be equal to:

$$v_{RMS}^2=\frac{F_{RMS}^2}{\gamma^2+(\omega M-K/\omega)^2}$$ where $\omega$ - circular

frequency of inertial Q- mass movement. Using resonance frequency $\omega_0=\sqrt{K/M}$ and Q-factor $Q=\omega_0 M/\gamma$ the above equition could presented as

$$v_{RMS}^2=\frac{1}{\gamma^2}\frac{F_{RMS}^2}{1+Q^2(\omega/\omega_0-\omega_0/\omega)^2}\quad.$$

The the kinetic energy accumulated in resonator could presented as

$$E = \frac{1}{2}Mv_{RMS}^2 = \frac{1}{4\pi\gamma}\int_0^\infty \frac{F_{RMS}^2 Q d(f/f_0)}{1+Q^2(f/f_0 - f_0/f)^2}$$

where f= $\omega/2\pi$ и f$_0$= $\omega_0/2\pi$. From above equation it is possible to get that $E = F_{RMS}^2/8\gamma$ and $F_{RMS}^2 = 4kT\gamma$ , where k – is Boltzmann constant and T – is absolute temperature. Then the minimum noise level of the accelerometer is $\sqrt{4kT\omega_0/MQ}$ . At the reasonable values of the Q it should be possible to get minimum spectral noise density for the MEM accelerometer about 1 $\mu G/\sqrt{Hz}$ as of today the best results is about 7-10 times higher. Last years progress of reducing the MEMs accelerometers noise allow us proposing of getting the MEMs accelerometers suitable for any vibration measurements in the temperature range up to 125 degree C.

## 3. THEORETICAL NOISE LEVEL OF MEM BASED VELOCITY TRANSMITTERS

Vibration velocity in a range of 10 to 1000 Hz is commonly used and standard parameter for machinery protection. There are norms for different types of machinery used in the industries for emergency machinery shutdown when vibration velocity up over the recommended levels. It is typical request that the minimum velocity have to be measured lay bellow 0.01 IPS PK (about 0.1 mm/s RMS). Then it will be nassery to define what the noise level of MEM based accelerometer allows to provide such measurements. Let us do that analyzes with assumption that spectral noise density is constant in a range of 10 to 1000 Hz, which practically truth for almost all MEMs accelerometers (see Figure 2 a). So, accelerometer acceleration noise density A( $\omega$ )=ND [ $\mu G/\sqrt{Hz}$ ]. The integrator uses to get the velocity from the acceleration with the transfer function:,

$K(\omega) = K_{INT}/\sqrt{\omega_{INT}^2 + \omega^2}$ , where $K_{INT}$ - is integrator gain and $\omega_{INT}$ - is integrator low cutoff frequency. Then the velocity spectral density will be:

$V(\omega) = NDxK_{INT}/\sqrt{\omega_{INT}^2 + \omega^2}$ and noise velocity RMS in the output of velocity transmitter will be:

$$V_{RMS} = NDxK_{INT}\sqrt{\int_{\omega_L}^{\omega_H} d\omega/(\omega_{INT}^2 + \omega^2)} \approx NDxK_{INT}\sqrt{\frac{1}{\omega_{INT}} arctg \frac{\omega_H}{\omega_{INT}}}$$

where $\omega_L$ - is low frequency of the vibration measurement range and $\omega_H$ - is high frequency of the vibration measurement range.

Based on the above equation plots of the velocity noise vs integrator cutoff frequency at different levels of acceleration noise density are presented at Figure 4.

Figure 4 shows that noise density bellow 20 $\mu G/\sqrt{Hz}$ is suitable for most application required vibration velocity measurements.

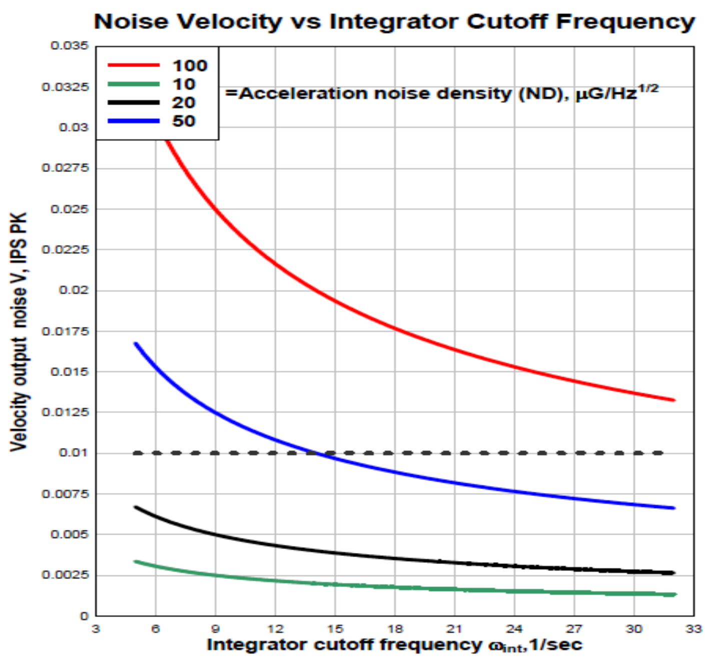


**Figure 4** Velocity noise vs integrator cutoff frequency

## 4 EXPERIMENALE DATA OF NOISE MEASUREMENTS

The some experimental data of self noise measurements for a few popular PZT and MEM based accelerometers is placed bellow.

### 4.1 Acceleration noise vs time

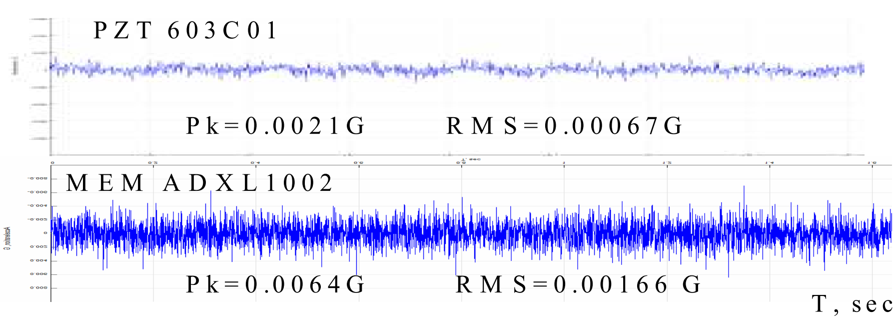


**Figure 5** Output noise vs time for piezoelectric and MEM based 100 mV/g sensors

### 4.2 Acceleration noise spectrum density

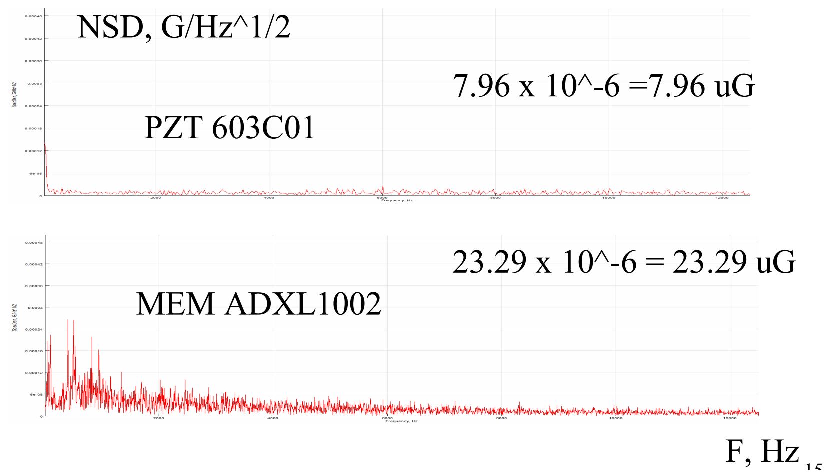


**Figure 6** Acceleration noise spectrum density for piezoelectric and MEM based 100 mV/g sensors

### 4.3 Vibration velocity noise in a range of 10-1000 Hz

The bellow data are produced from acceleration per time signal by digital integration and normalization.

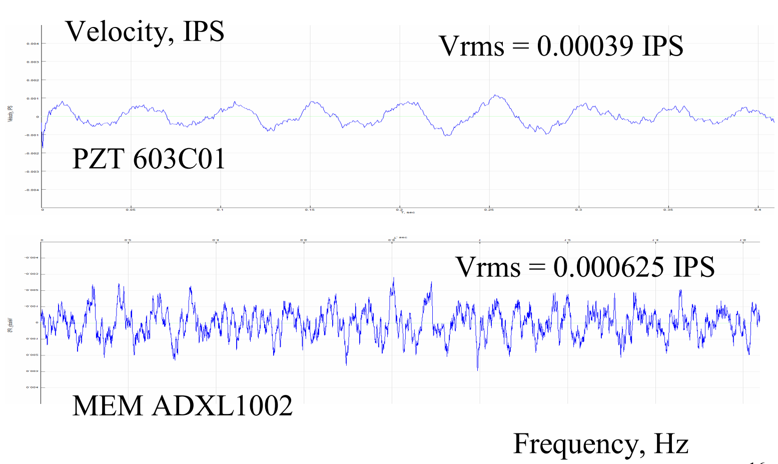


**Figure 7** Vibration velocity noise for piezoelectric and MEM based 100 mV/g sensors

### 4.4 Experimental noise data of several piezoelectric and MEM based sensors

**Table 1**: Noise of several PZT and MEM based sensors sensors

| Model | Original sensitivity, mV/g | Adjusted sensitivity for Noise measurements, mV/g | Acceleration Noise, RMS, g | Acceleration Noise, PK, g | Specified Spectrum Density Acceleration Noise, ug/Hz^1/2 | Measured Spectrum Density Acceleration Noise, ug/Hz^1/2 | Velocity Noise, RMS, IPS |
|---|---|---|---|---|---|---|---|
| **PZT Dynamic Instruments 113** | **100** | **100** | **0.00199** | **0.0078** | **-** | **30.84** | **0.00135** |
| **PZT PCB Piezotronics 352** | **100** | **100** | **0.00037** | **0.0011** | **1.4-11** | **5.07** | **0.000338** |
| **PZT IMI Sensors 603** | **100** | **100** | **0.00067** | **0.0021** | **4-8** | **7.96** | **0.000390** |
| **PZT TE Connectivity 805** | **100** | **100** | **0.00037** | **0.0011** | **-** | **4.07** | **0.000123** |
| **PZT VMS 6200** | **100** | **100** | **0.00063** | **0.0018** | **-** | **9.91** | **0.000340** |
| **MEM ADI ADXL1002 5.0 V DC** | **40** | **100** | **0.0019** | **0.0082** | **25** | **23.29** | **0.000625** |
| **MEM ADI ADXL1002 3.3 V DC** | **25** | **100** | **0.00496** | **0.0146** | **-** | **40.86** | **0.000996** |
| **MEM ADI AXL356** | **80** | **100** | **0.0040** | **0.0107** | **75** | **59.23** | **0.0027** |
| **MEM ADI ADXL321** | **57** | **100** | **0.0211** | **0.0724** | **320** | **334.1** | **0.0878** |
| **MEM STM Electronics LIS344** | **220** | **100** | **0.00235** | **0.00795** | **50** | **63.44** | **0.00239** |

### 4.5 Approximate formulas for noise calculation from/to spectrum density

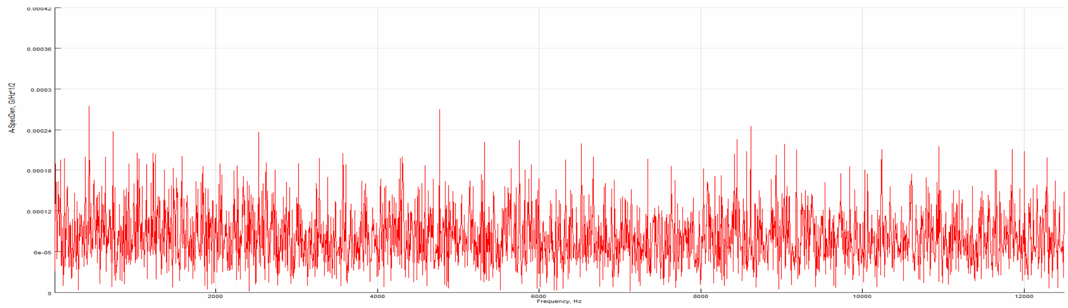

**Figure 8** Sample of vibration sensor spectrum noise density

Accelerometers specification usually included the level of noise spectrum density in ug/Hz^1/2 and the question often appears how then find what is real minimum acceleration or velocity might measured by particular accelerometer. We are offering bellow formulas based on **4.4** measurements results which help to answer above question.

**Noise-Apk[g] =SD[ug/Hz^1/2] /5000**

**Noise-Vrms[ips pk]= SD[ug/Hz^1/2]/28500**

For instance the max SD which provide noise of **V<0.003 IPS** is following

**Max SD = 85.5 uG/Hz^1/2 (actually is in a rage of 45 …123)**

### 4.6 Comparison PZT (top) and MEM sensors at measuring vibration of bearing with inner defect

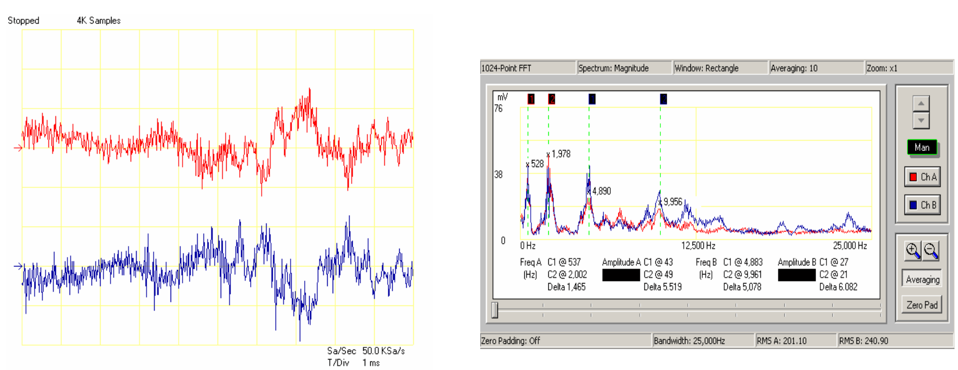


**Figure 9** Comparison PZT (top) and MEM sensors at measuring vibration of bearing with inner defect

## 5 CONCLUSIONS

- The comparison of PZT and MEM vibration sensors is provided.
- The detail data for self noise for PZT and MEN sensors is adduced.
- The experimental formulas which allow finding real noise of acceleration and velocity based on self acceleration noise density are offered.

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