DIAGNOSTYKA, 2023, Vol. 24, No. 4

e-ISSN 2449-5220
DOI: 10.29354/diag/172581

IDENTIFICATION AND EVALUATION OF THE CHARACTERISTICS OF A SELECTED COMMERCIAL MEMS BASED VIBRATION SENSOR FOR THE MACHINE CONDITION MONITORING

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Abstract

With the emergence of the Industry 4.0 concept, machine vibration monitoring and diagnostics systems based on the so-called smart vibration sensors using MEMS accelerometers become very popular on the market. Many automation companies use specifically designed for CbM industrial vibration sensors based on electronic chips with enclosed MEMS accelerometers. However, in the commercial vibration sensors datasheets very often are not provided detailed metrological parameters like frequency response in the declared frequency band. The article presents the results of research concerned to identification of frequency response of an exemplary available on market digital accelerometer dedicated to machines condition monitoring. The determined characteristics indicate that the sensor can be used for basic diagnostics of machines in accordance to the series of vibration standards ISO 10816 and ISO 20816. On the basis of the determined characteristics, it can be concluded that there are some non-linarites of the frequency response functions at the boundaries of the declared measurement band. It shows that application of that sensor to precise measurements conducted during scientific research could be limited.

Keywords: digital accelerometers, MEMS accelerometers, machine diagnostics, vibration measurements, CbM

List of Symbols/Acronyms

CbM – Condition Based Maintenance
ICP/IEPE – Integrated Circuit-Piezoelectric
IIoT – Industrial Internet of Things
MEMS – Micro Electro-Mechanical System
PCB – Printed Circuit Board
PdM – Predictive Maintenance
RMS – Root Mean Square
RxM – Prescriptive Maintenance

1. INTRODUCTION

With the emergence of the Industry 4.0 concept, maintenance departments are increasingly implementing machine maintenance strategies based on the machine conditions based maintenance CbM and prediction of their conditions PdM and RxM [6].

The use of the above-mentioned strategies is closely related to the monitoring and diagnostics of machines, which is carried out both using hand held instruments (Route based diagnostics) and continuous monitoring systems. Until recently, due to the cost a continuous monitoring and machine diagnostics systems were mainly used for critical machines and were based on classic piezoelectric accelerometers (IEPE, ICP) connected to analog to digital processing units. With the emergence of the IIoT technology, a whole range of various and affordable measuring systems for continuous monitoring appeared on the market. Contemporary monitoring systems are very often based on the so-called "smart sensors", wireless interfaces, edge processing units and "cloud" data storage and processing systems. Common feature of such sensors are integrated a measuring transducer, a conditioning system (filters, AD converter), a microprocessor, and a digital interface allowing sensor programming as well as transferring data in digital format using industrial protocol like Modbus RTU, IO Link, etc. to supervisory units (Fig. 1).

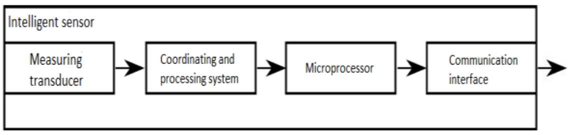


Fig. 1. A block diagram of the digital accelerometer

In the field of vibration condition monitoring market offers different types of commercially available vibration sensors with digital communication interface. Most of them are based on MESM accelerometers [3].

Received 2023-05-08; Accepted 2023-09-20; Available online 2023-09-27

1.1. MEMS vibration sensors – construction, operation and application

MEMS accelerometers are increasingly used to measure vibrations. We can distinguish two types of MEMS accelerometers: capacitive and piezoresistive [18].

Capacitive transducers are most often used in sensors dedicated to machine vibration monitoring.

MEMS accelerometer contains a polysilicon surface-micromachined structure contained fixed cantilever beams and movable beams connected to inertial mass suspended to elastic springs (Fig. 2) [4]. Fixed and movable beams are sensing electrodes of capacitors. Deflection of the inertial mass changes the capacitance between the movable and the adjacent fixed beams. The transducer structure is surrounded by supporting electronics, which converts the capacitance changes due to acceleration into an analog voltage signal [16] [4].

The output voltage is processed by the A/D converter and the microcontroller. The micromechanical structure and electronics are integrated into small electronic chip ready to mount to PCB.

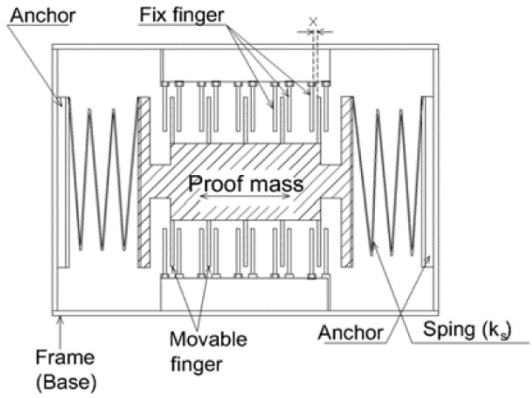


Fig. 2. Figure shows a diagram of the construction of an MEMS capacitive accelerometer [4]

An example of MEMS accelerometers designed specifically for CbM applications are presented in Fig. 3.

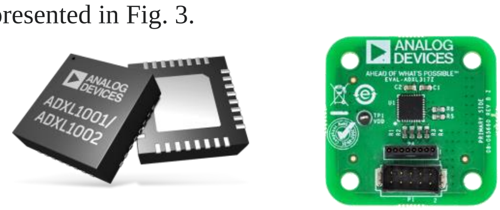


Fig. 3. Examples of MEMS capacitive accelerometers dedicated to CbM (Source: Analog Devices, www.analog.com)

Capacitive type MEMS accelerometers [1] [8] [15] [17] has sufficient parameters for many industrial applications [2] including vibration condition based monitoring [12]. Table 1 presents a comparison of the parameters of MEMS accelerometers chips currently available on the market and dedicated to machine condition based monitoring applications [7] [5] [12]. Compared to piezoelectric sensors, mems capacitive sensors are cheaper, do not have the effect of "ski slope" caused by piezo element saturation in case of impacts, are less prone to damage and have greater self-diagnosis capabilities, but on the other hand have a large noise level that increases with frequency [10] [12] [13]. However, this problem has gradually eliminated along with technological progress in the field of design and production of this type of structures [12].

Table 1. Exemplary parameters of contemporary MEMS accelerometers suitable for CBM [12]

	ADXL1002	ADXL317
No. Axes	1	3
Sensitivity	40 mV/g	500 LSB/g (500 Hz Cascaded filter)
±3 dB Bandwidth	11 kHz	4 kHz (x, y) 2 kHz (z)
Resonance	21 kHz	5.1 kHz (x, y) 3.1 kHz (z)
Noise Density	$25\ \mu g\sqrt{Hz}$	$55\ \mu g\sqrt{Hz}\ (x,y)$ $120\ \mu g\sqrt{Hz}\ (z)$
g-Range	50 g	16 g
Cross-Axis Sensitivity	1%	1%
Temperature Range	-40 °C to +125 °C	-40 °C to +125 °C

On the basis of the electronic chips with integrated MEMS accelerometers offered by microelectronics manufacturers, commercial sensors dedicated to industrial applications, in particular for machine condition based monitoring, have appeared on the market. Exemplary solutions are presented in Fig. 4.

Fig. 4. Examples of "smart sensor" available on the market (Source: Banner, www.bannerengineering.com; Sick, www.sick.com; Balluff, www.balluff.com; IFM, www.ifm.com)

Available commercial solutions allow detection of the potential damages of motors, pumps, and fans like imbalance and misalignment. Some sensors offer ability to diagnose of bearings and gear defects [11].

Manufacturers place the basic parameters in datasheet of the sensors however they not provide information devoted to sensor frequency response. Even if the producer applied MEMS accelerometer with linear frequency response after it integration into PCB and in a sensor housing the frequency response of the entire measurement system could be different than those declared by electronic chip manufacturer and some non-linearities could appear. [9] It could cause certain measurement errors, especially in scientific applications that require high measurement accuracy. The purpose of the research was to verify the measurement parameters of the selected MEMS based vibration sensor to assess its suitability both for machine diagnosis and scientific research.

2. PARAMETERS OF CONTEMPORARY VIBRATION SENSORS FOR CBM

Contemporary MESM based vibration sensors with digital interface, also known as "smart sensors," allow for measuring vibrations in a wide frequency range, from 10 to even 10000 Hz, simultaneously in up to three directions. Many of them also allow for the measurement of other physical parameters such as temperature, humidity, and pressure. Temperature measurement is also carried out in a relatively wide range, from -40 to 125°C. Sensors have various communication interfaces to connect to other devices. Contemporary vibration sensors usually have interfaces such as USB, RS232, RS485, CAN, Ethernet, and wireless Bluetooth, WiFi, or GSM. The interface enables sensor configuration and reading of data from memory registers. Built-in microcontrollers allow for determining many vibration parameters for each measurement direction in a given frequency range in metric and imperial units.

Manufactures of the sensors declare low noise levels and sufficient measurement accuracy, usually less than 10% error with an adequate sampling frequency in most applications. Many of them have built-in diagnostic functions for detecting damage and auto-calibration. The housing of many sensors has a low-profile design, which allows for their installation in places with limited space. The housing is typically made of metal to reduce interference and increase reliability in harsh environmental conditions.

2.1. Tested sensor

The tested sensor allows to measure vibrations in the frequency range from 10 to 4000 Hz simultaneously in two directions. Additionally the sensor is capable to measure a temperature between -40 ° C and +105 °C. Declared accuracy for vibration measurements is ±10% at 25 °C. The sensor has an RS485 digital interface and enables communication in accordance to the Modbus RTU protocol. Using the interface is possible to configure the sensor as well as read data from memory registers. Embedded microcontroller allows to determine almost 8 vibration parameters for two measurement direction in a two frequency bands 10-1000 Hz and 1000-4000 Hz in metric and imperial units. The parameters are listed in the table 2.

Table 2. Main vibration parameters measured by tested digital accelerometer

10-1000 Hz band	**1000-4000 Hz band**
RMS Velocity (mm/s)	Peak Acceleration (G)
Peak Velocity Component Frequency (Hz)	Kurtosis
RMS Acceleration (G)	Crest Factor
Peak Velocity (mm/s)	High-Frequency RMS Acceleration (G)

Parameters for the 10-1000 Hz band allow for a general assessment of the condition of machines according to the vibration standards. For example, the low frequency velocity RMS parameter allows to assess the rotating machinery condition according to the series of standards ISO 10816 and ISO 20816. According to sensor specification, a measuring range for these parameters is from 0 to 46 mm/s.

3. TEST BENCH AND MEASUREMENTS PROCEDURE

A test stand has been prepared for the purpose of the research. The testing method was based on the concept of a reference sensor described in part 21 of the ISO 16063 standard. The standard describes the calibration process, the apparatus, and environmental conditions, as well as the process of calculating the measurement uncertainty. The block diagram of the test stand is presented in Figure 5. The test stand included elements such as: an electrodynamic shaker driven by a power amplifier, a NI9263 module was used to generate an appropriate input excitation signal, and the NI9234 module allows to collect data from reference accelerometer. As a reference sensor we use accelerometer PCB 301A10 especially dedicated for calibration purposes [14]. Its sensitivity is 100mV/g, measurement range is ±50 g pk and Frequency Range (±5%) is in range 0.5 – 10000 Hz. Data acquisition modules were part of the NI CompactDaq system mounted in chassis cDAQ-9174 which was connected to a PC computer. The digital accelerometer was connected to a computer using a dedicated serial RS485 to USB converter. Measurement system allow to close loop control of shaker vibration according to measured parameters.

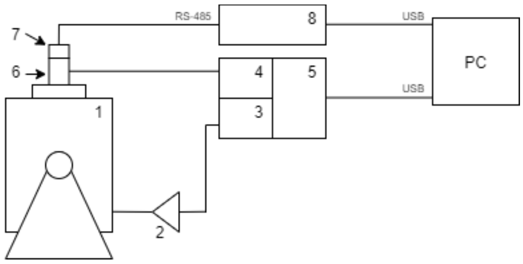


Fig. 5. Figure shows diagram of the measuring system, where,1- shaker, 2-power amplifier, 3-C Series Voltage Output Module NI-9263, 4- C Series Sound and Vibration Model NI-9234, 5- CompactDAQ Chassis cDAQ-9174, 6- reference accelerometer PCB 301A10, 7- digital accelerometer, 8- converter RS-485 to USB

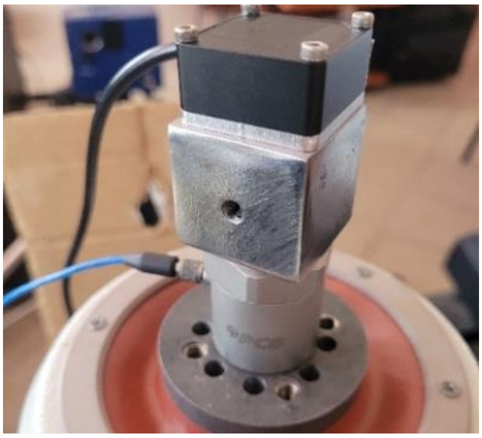


Fig. 6. Figure shows an example of a test and reference sensor mounted on an exciter

A program in the MATLAB environment was created to acquire and analyse the data from measurement system. Three sensors were used for the tests. Each sensor was tested for two measuring axes according to the same procedure. The measurement procedure was presented in block diagram (Fig. 7). Firstly based on the signal from the reference accelerometer, the peak vibration value of 0.4G was determined using a feedback loop to amplitude control. When the determined value was reached then 10 values were read from the tested accelerometer. The following parameters were read from the sensor: Z-Axis RMS Velocity (mm/s), Z-Axis RMS Acceleration (G), Z-Axis High-Frequency RMS Acceleration (G), Z-Axis Peak Acceleration (G), Z-Axis Peak Velocity (mm/s). The data were processed after acquisition process in the following way: Outliers were rejected and the mean value of the three maximum scores was calculated. At the end, the results were stored on a computer hard drive. After completing the tests for the Z-axis, the procedure was carried out again for the X-axis reading the following parameters: X-Axis RMS Velocity (mm/s), X-Axis RMS Acceleration (G), X-Axis High-Frequency RMS Acceleration (G), X-Axis Peak Acceleration (G), X-Axis Peak Velocity (mm/s).

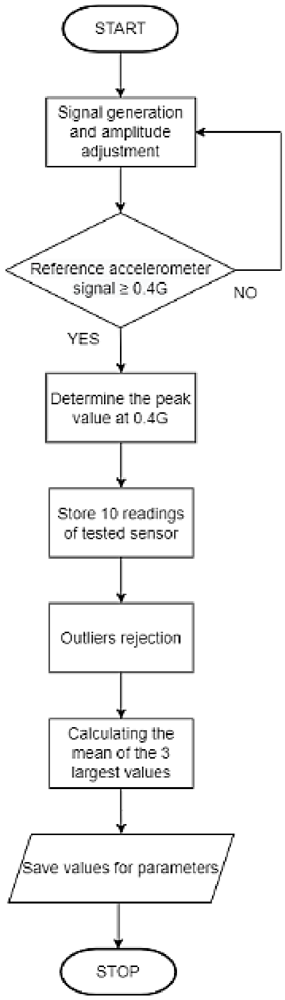


Fig. 7. Figure shows block diagram of the program algorithm

4. SENSOR CHARACTERISTICS AND ITS EVALUATION

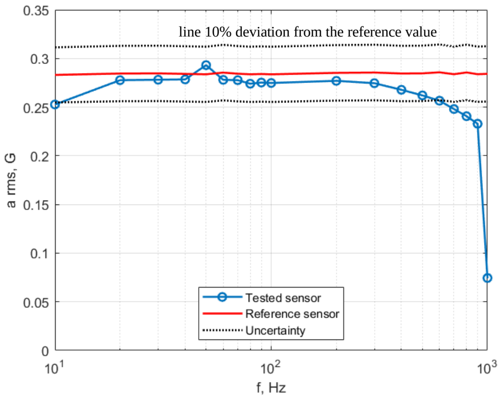
The purpose of the study was to identify the frequency characteristics of the digital accelerometer and compare them with the reference characteristics of the calibration piezoelectric accelerometer. The following part of the article presents the characteristics resulting from the averaging of data collected from the three digital accelerometers under test. The standard deviations of the measured values as a function of frequency were also determined to assess the accuracy of the measurements.

4.1. Identification of digital accelerometer characteristics in low frequency band

Evaluation of sensors characteristic was started from low frequency band 10-1000 Hz for Z and X-axes (Figs. 8 – 11).

Fig. 8a and 8b show plots of RMS vibration acceleration amplitudes as a function of frequency obtained for the Z and X directions, respectively (blue lines) in the frequency range of 10-1000 Hz. For comparison, the characteristics of the reference sensor (red line) and the 10% error lines are plotted on the graphs.

a)



b)

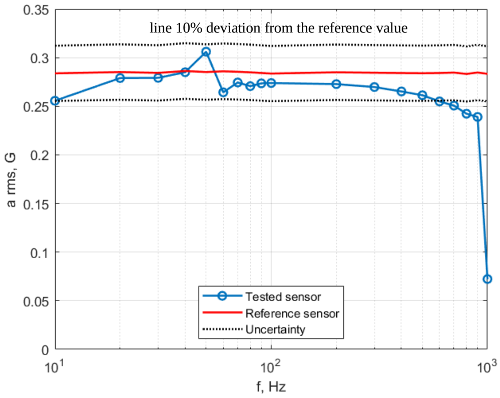


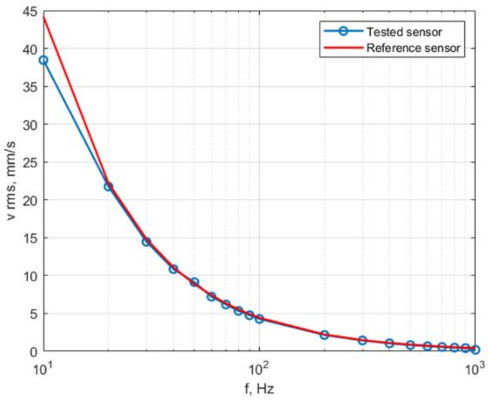
Fig. 8. Comparison of frequency characteristics of the acceleration rms values of the reference and digital accelerometer in the 10-1000 Hz band for (a) Z-axis and (b) X-axis

The characteristics of tested digital accelerometer revealed deviations from linearity at the band boundaries, where the measurement error is greater than 10%. For 10 Hz it is 12.03% and 11.02% for Z and X-axes, respectively. For frequencies of 700, 800, 900 Hz and 1000 Hz, the errors for Z-axis is 14.43, 18.67 ,21.86 and 281.7%, respectively. On the X-axis the errors are 13.55, 16.87, 19.12 and 291.72%, respectively. The average error of RMS acceleration measurement in the considered band 10-1000 Hz for Z and X-axes are 21.42% (6.96% for 10-900 Hz) and 22.4% (7.44% for 10-900 Hz) respectively.

The average standard deviation of rms vibration acceleration measurements in the 10-1000 Hz band was close to zero and was 0.0057 for Z-axis and 0.0053 for X-axis. The measurement uncertainty increased for the frequency of 1000 Hz, with the largest measurement error being 0.086 for the Z-axis and 0.083 for the X-axis. For comparison, the smallest error was 0 at a frequency of 200 Hz for the Z-axis and 0.0003 at a frequency of 300 Hz for the X-axis.

In Fig. 9 and 10 respectively, the plots of the RMS velocity amplitudes for Z and X-axes in the frequency band 10-1000 Hz are presented. RMS velocity in frequency band 10-1000 Hz is a fundamental parameter considered in standard ISO 10816 (20816) and another standards for condition assessment of industrial machinery. From that reason, we presented results of measurements.

a)



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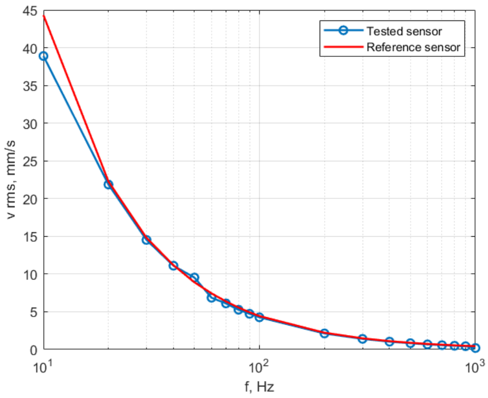


Fig. 9. Comparison of frequency characteristics of the velocity rms values of the reference and digital accelerometer in the 10-1000 Hz band for (a) Z-axis and (b) X-axis

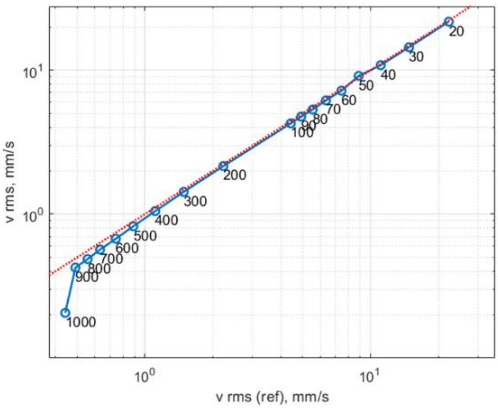
The RMS velocities values as function of frequency in the band 10-1000 Hz for reference and tested accelerometers were compared and shown in Figure 9. In addition, in order to better represent the deviation from linearity, the values measured from the digital accelerometer were compared with the values of the reference accelerometer and are shown in Fig. 10. The average measurement error of the rms value of the vibration velocity of the digital accelerometer for the Z-axis and X-axis in the 10-1000 Hz band was 12.04% and 12.89%, respectively. The largest impact on the average measurement error is the deviation from linearity recorded at the band boundaries for frequencies of 10 and 1000 Hz as seen in Fig. 9 and 10. The error for frequencies of 10 Hz and 1000 Hz is 14.92% and 115.37%, respectively, for the Z-axis, and 13.94% and 124.18%, respectively, for the X-axis.

The average standard deviation of rms vibration velocity measurements in the 10-1000 Hz band was close to zero and was 0.036 for Z-axis and 0.033 for X-axis. The values of the standard deviation of vibration velocity measurements in the frequency function are presented in Fig. 11. In this case, the measurement uncertainty also increased at the limits of the measurement band. Table 3 compares the average measurement errors for peak and rms values of velocities in frequency band 10-1000 Hz.

Table 3. Comparison of mean measurement error of rms and peak velocity values in frequency band 10-1000 Hz

	Z	X
Peak	12.03%	12.93%
RMS	12.04%	12.89%

a)



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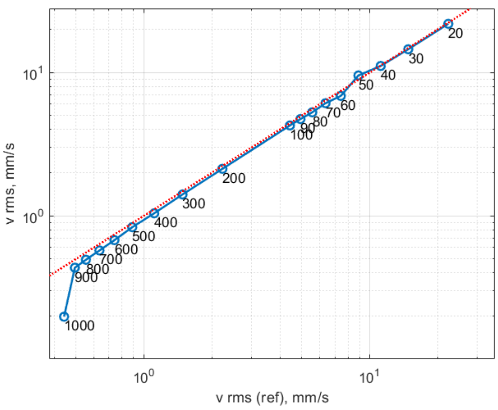


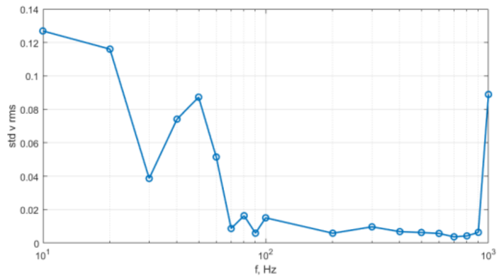
Fig. 10. Comparison of RMS Velocity (mm/s) values of reference and investigated sensors for (a) Z-axis and (b) X-axis

4.2. Identification of digital accelerometer characteristics in high frequency band

Identification of the dynamic characteristics of the accelerometer was also performed for the high-frequency band 1000-4000 Hz. Measurements of the acceleration peak and RMS value of the vibration were made. Due to the relationship of the measured parameters and the similarity of the determined characteristics, only the plots of peak values as a function of acceleration frequency are presented in the Fig. 12a and 12b, for the Z and X-axes respectively.

For both directions of measurement, the determined characteristics have discernible non-linearities in almost the entire measurement band. At a frequency of 3800 Hz, the resonance of the sensor for both measurement directions is clearly visible, with the resonance for the X direction being three times greater than for the Z direction.

a)



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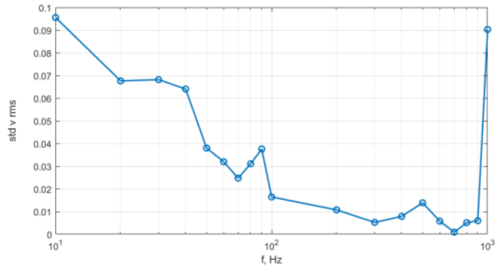


Fig. 11. Comparison of standard deviations of the velocity rms values of the reference and digital accelerometer in the 10-1000 Hz band for (a) Z-axis and (b) X-axis

Measurement error is already significantly greater than 10% and exceeds 20%. For 10 Hz it is 110.4% and 102.04% for Z and X-axes, respectively. For the range of 1100-3100, the characteristic flattens out, and for the Z-axis, the average measurement error is 40.42%, while for the X-axis, the situation is better, and the measurement error is 25.81%. At the end of the measurement range where resonance occurs, measurement errors for frequencies 3700, 3800, 3900 Hz and 4000 Hz for Z-axis are 5.36, 7.11, 4.53 and 62.92%, respectively. In X-axis for those frequencies the errors are 70.11, 63.59, 51.63 and 13.99%, respectively. The average error of peak acceleration measurement in the considered band 1000-4000 Hz are 36.35% and 33.83% for Z and X-axes, respectively.

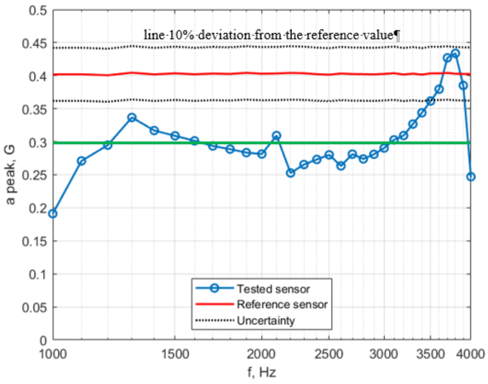
Table 4 compares the average measurement errors for peak and rms values of accelerations in frequency band 1000-4000Hz.

Table 4. Comparison of mean measurement error of rms and peak acceleration values in frequency band 1000-4000 Hz

	Z	X
Peak	36.35%	33.83%
RMS	48.36%	41.79%

The average standard deviation of peak vibration acceleration measurements in the 1000-4000 Hz band was close to zero and was 0.0151 for Z-axis and 0.0968 for X-axis. The values of the standard deviation of vibration acceleration measurements in the frequency function are presented in Fig. 13.
For RMS, the average standard deviation had similar values and was 0.0103 and 0.0671 for the Z and X directions, respectively.

a)



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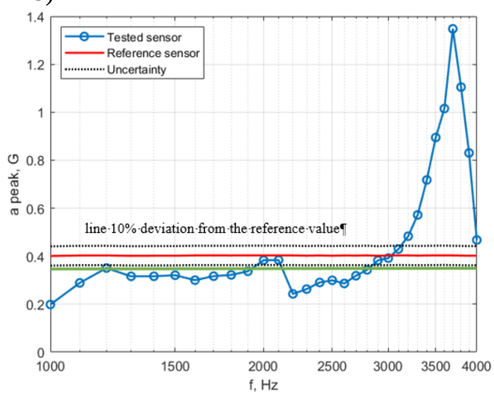
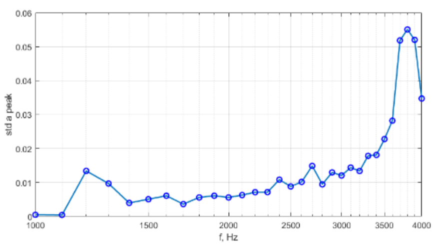


Fig. 12. Comparison of frequency characteristics of the acceleration peak values of the reference and digital accelerometer in the 1000-4000 Hz band for (a) Z-axis and (b) X-axis

a)



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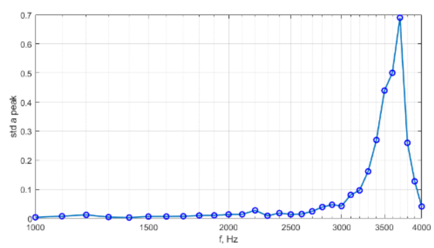

Fig. 13. Comparison of standard deviations of the acceleration peak values of the reference and digital accelerometer in the 1000-4000 Hz band for (a) Z-axis and (b) X-axis

4. CONCLUSIONS

The research devoted to identification and evaluation of digital accelerometer characteristic was carried out.

The low values of the standard deviation of the measurements testify both to the repeatability of the experiment and to the repeatability and correctness of the performance of the digital accelerometers tested. It was noted that the values of the standard deviation increase at the borders of the bands, that is, where the largest measurement errors of the tested accelerometer were recorded.

A study of the characteristics of the digital accelerometer shows that it has a larger measurement error than that defined by the manufacturer. The measurement error is different for each of the measured parameters on each measurement axis. The least error is in the rms value of the vibration velocity for the Z direction in the 10-1000 Hz band. The largest measurement error is characterized by the rms value of accelerations in the X-direction which is related to the occurrence of resonance of the sensor at 3800 Hz.

From the metrological point of view, the sensor is suitable for measuring the rms value of vibration velocity in accordance with ISO standards, but the measurement error of 12% must be taken into account. This error can increase when the sensor is mounted incorrectly, such as a magnetic mount on an uneven and contaminated surface.

As could be expected, enclosing the MEMS accelerometer and electronics in the housing suitable for industrial applications has influence on final frequency response of the digital accelerometer, which confirms non-linearities of bands boundaries visible especially in frequency band 1000-4000Hz.

Despite inferior metrological properties compared to piezoelectric accelerometers, the tested sensor can be effectively used in systems for continuous monitoring and evaluation of changes in technical condition based on trend analysis of measured values. In such a case, state changes depend on the relative changes in values over time, and the existence of a constant even significant measurement error will not be very important results of state change assessment. The variation of values resulting from non-linearity at the boundaries of measurement ranges can be limited by using averaging, which will allow for smoothing of time series and facilitate interpretation of the collected data.

Author contributions: *research concept and design, D.A., M.F.; Collection and/or assembly of data, D.A.; Data analysis and interpretation, D.A.; Writing the article, D.A; Critical revision of the article, M.F.; Final approval of the article, M.F.*

Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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