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MEMS-BASED WIRELESS VIBRATION TRANSDUCER FOR CONDITION MONITORING

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Background. When monitoring vibration of rotating machines, especially heavy ones, problems with cables of transducers often emerge. Those cables are usually long, heavy and prone to damage.

Objective. The purpose of the paper is to develop a wireless vibration transducer, which is free of those problems, on the base of MEMS accelerometer. Sensor developed should provide low power consumption, linear frequency response at least in 10…1000 Hz range, calculate vibration RMS and detect machine condition based on it.

Methods. Develop wireless sensor design based on 8-bit MCU. Develop method of MEMS frequency response correction, based on spectral analysis. Compare sensor developed with industrial piezoelectric ones.

Results. Transducer developed can be used instead of the industrial piezoelectric vibration transducers. Moreover, MEMS-based transducer allows one to move basic machine condition detection process from the high–level system to transducer level. That, in turn, allows one to reduce network traffic and simplify condition monitoring system as a whole.

Conclusions. MEMS-based wireless vibration transducer for condition monitoring is developed. Tests conducted showed that the transducer developed is well–behaved and its precision is comparable to one of industrial piezoelectric transducers.

Keywords: *vibration; MEMS accelerometer; wireless vibration transducer; Wi–Fi; monitoring of rotating machinery.*

1. Introduction

In condition monitoring systems of heavy machinery (steam turbines, generators, paper machines) connection of transducers poses a problem. Classic piezoaccelerometers with charge output currently are not used, as their cable length (via cable capacity) and even cable mounting (because of triboelectric noise) have an impact on sensor's output signal. Accelerometers with ICP output are free of limitation of classic ones, but use of shielded cable tens of meters long is required when installing those transducers on heavy machines. Use of such cabling because of its length and mass is unhandy. Moreover, long cables, as well as their connectors are often broken by the personnel in the process of machine maintenance. One of possible solutions of that problem is the use of wireless communications to transfer measured vibration data. However, measurement module with wireless transmitter and ICP transducer requires heave-duty power source in order to ensure its operation. As a result, one has to consider use of microelectromechanic system (MEMS) accelerometer-based sensors in order to provide condition monitoring and diagnostic systems with a small-sized, low-power consumption alternative to classic industrial measurement systems. Except for small mass and low power consumption, MEMS-based transducer will be significantly cheaper than industrial one, thus enabling use of condition monitoring systems on machines, for which classic monitoring system is too expensive to use. That, in turn, will improve safety of operation of such machinery. Thus, development of MEMS–based vibration transducer is an actual task.

2. Analysis of publications and problem statement

Application of MEMS accelerometer as a vibration transducer is studied from at least 2000's. Pump vibration measurement with piezoelectric accelerometer and MEMS one were carried out by Thanagasundram and Schlindwein [1] in 2006. Albarbar et al. (2008) [2] compared data measured with MEMS and piezoelectric accelerometer under the same test conditions (frequency range 0…10 kHz, acceleration level 5g), and found, that MEMS accelerometer doesn't provide a stable sensitivity coefficient and phase shift. The problem stated is present even when even sine vibration signal is measured; moreover, for the sensor used frequency response unevenness was up to 6 dB in 300 Hz range. Similar analysis, performed by Albarbar et al. (2009) [3] confirms the results, presented in [2].

Wahid and Anuar (2008) in [4] presented measurement of tilt of an object and its vibration in 0…500 Hz range using ADXL202 accelerometer. Jagadeesh et al (2006) presented a MEMS-based transducer with RMS detector in [5]; in that paper transducer's schematics is provided, but there are no data about its tests, so one cannot estimate transducer's efficiency. MEMS-based transducer, designed by Kwon et al. (2006) [6] has a limited frequency range, so it can be used only for structure health monitoring and measurement of low-speed machinery (e.g. hydroturbines, paper mill equipment, etc.). Marne, Nagmode and Komati (2014) developed MEMS–based vibration transducer based on ARM7 microcontroller [7]; main drawbacks of that transducer are its high power consumption and noise.

Application of MEMS accelerometer for condition monitoring of rotating machinery is studied in several works. In [8], Loony (2014) described designs, created by Analog Devices. Chaudhury., Sengupta and Mukherjee (2014) [9] developed vibration accelerometer based on ADXL322 accelerometer and in order to increase signal-to-noise ratio used autocorrelation function and adaptive rule–based filters. The drawback of such a design is the rejection of both noise and high-frequency vibration signal that contains vital diagnostic information (e.g., information about rolling bearing defects).

Huang, Tang and Deng (2015) described MEMS-based condition monitoring system in [10]. Paper mentioned is focused on synchronization of standalone measuring modules and compensation of differences between their clock frequencies. The solution proposed by authors of [10] is rather complex; therefore, monitoring system requires use of high-performance controllers.

Holovatyy et al. (2017) created MEMS-based monitoring system [11] based on ADXL435 accelerometer and Raspberry Pi 3 board. The main drawback of the system is its narrow bandwidth (0…100 Hz) and absence of frequency band correction; that means that sensor can be used only on low-frequency machines (e.g. paper mills). Moreover, use of Raspberry Pi and custom board increases size of the sensor and is more suitable for prototype than for production system.

Suukenda et al. (2020) used SW420 MEMS vibration sensor as a train detector for railway monitoring [12]; the system proposed, however, cannot be used for condition monitoring of rotation machinery due to limitations of the SW420 sensor, which is intended to be used in security and anti-hijack systems.

Ghazali and Rahiman (2022) tested an compared SW420 and ADXL345 accelerometers as a base for condition monitoring [13]. The pros and cons of their systems are the same as in [11] and [12].

As one can see, development of MEMS–based vibration transducer, which can be used in condition monitoring, is a complex problem. To solve that problem, several accompanying problems have to be solved; those problems are related to both signal processing and features of MEMS accelerometers themselves. Up to now, the problem of development of low-power consuming MEMS-based vibration transducer which provides a guaranteed linear frequency range of at least 10…1000 Hz and features noise cancellation is not solved.

3. Objective and goals of the research

The aim of the work is the development of the vibration transducer based on MEMS accelerometer which could be used for condition monitoring of the rotating machinery.

In order to achieve the objective, following goals were set:

– to develop transducer design that will ensure effective noise cancellation and frequency range of 10…1000 Hz;

– to develop simple and effective method of correction of MEMS accelerometer’s frequency response unevenness;

– to provide the solution of other problems, including electromagnetic compatibility and synchronization of measurements between many transducers.

4. Schematics of the transducer and its electronic components

As a starting point, analysis of available MEMS sensors with analog output is made, along with their comparison with industrial transducer (Bruel&Kjaer 8325 [14]). Digital MEMS sensors (e.g. ADIS16223) were not considered, as their claimed characteristics are lower than ones of industrial ICP accelerometers; moreover, signal processing in those sensors is “hard-coded” by the manufacturer, thus disabling any correction by the system developer. Specifications of the accelerometers according to their datasheets [14-17] are shown in Table 1.

Table 1. Specifications of accelerometers

Parameter	Accelerometer			
	ADXL316	SD 1510L–050	LIS344 ALH	B&K 8325
Manufacturer	Analog Devices	Silicon Designs Inc.	ST Microelectronics	Bruel&Kjaer
Measurement axes count	3	1	3	1
Measurement range	±160 m/s^2	±500 m/s^2	±20 / ±60 m/s^2	±500 m/s^2
Sensitivity	570 mV/(m/s^2)	80 mV/(m/s^2)	660 / 220 mV/(m/s^2)	10 mV/(m/s^2)
Frequency response flatness	3 dB, 0 Hz – 1,6 kHz	3 dB, 0 Hz – 2 kHz	3 dB, 0 Hz –1,4 kHz	±10%, 1 Hz – 10 kHz
Resonant frequency	4.2 kHz	–	1.8 kHz	25 kHz
Transverse sensitivity	1 %	3 %	2 %	< 4 %
Shock (max.)	100000 m/s^2	50000 m/s^2	100000 m/s^2	50000 m/s^2
Operating temperature	–40…+105 °C	–40…+85 °C	–40…+80 °C	–50…+125 °C

Note: measurement range and sensitivity of LIS344 accelerometer is selected by connection of chip pins.

As one can see from Table 1, parameters of present–day MEMS accelerometers are close to ones of industrial piezoaccelerometers. The main drawback of MEMS sensors is their significant frequency response unevenness, which effectively narrows frequency range. For example, B&K 8325 frequency response deviation from the horizontal line of more than 10% starts at 10 kHz; at the same time ADXL001–70 MEMS accelerometer [15] shows the same deviation at 5–6 kHz, in spite of the fact, that its resonant frequency is 22 kHz. Frequency responses of other MEMS accelerometers are even worse. Moreover, MEMS accelerometers are sensitive to static accelerations (e.g. gravity), while piezoelectric ones are not. Therefore, MEMS accelerometer requires not only frequency response correction, but the use of high-pass analog filter in order to be used for vibration measurement.

In condition monitoring system, vibration of bearing is often has to be measured along three axes, so use of a three-axis accelerometer is desired. In spite of advantages of accelerometers with a wide frequency range (ADXL001–70 and the like), LIS 344 accelerometer was selected, as it provides high sensitivity coefficient and transverse sensitivity as low as 1%. In addition to that, price of the LIS 344 sensor is lower than that of ADXL316.

A basis measurement of any condition monitoring is the root mean squared (RMS) value of vibration velocity in 10..1000 Hz frequency range. The higher boundary of that frequency range is limited by built–in LPF of the accelerometer itself. In order to eliminate influence of any vibration below 10 Hz, active Sullen–Key HPF with 10 Hz cut–off frequency is used. Use of a higher-order filter is inappropriate, as data processing algorithm allows one to eliminate low-frequency data in the course of its operation.

Circuit diagram of the analog part of the transducer developed is shown in Fig. 1; channels Y and Z aren't shown.

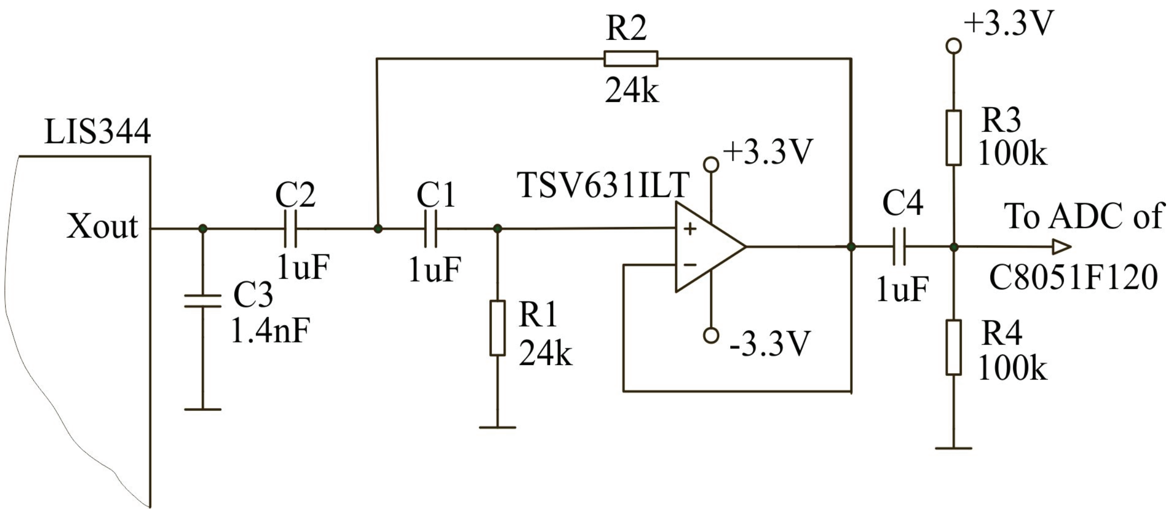


Fig. 1. Analog part of the transducer (channels Y and Z aren't shown)

Cost of the transducer was a crucial factor during its development, so in order to provide wireless capability of the sensor, Espressif systems ESP8266 board [16] was selected. That Wi-Fi board is available in several modifications, including shielded modules and ones with connector for an external antenna. ESP8266 allows one to control its operation via serial interface using AT commands, and features low power consumption (less than 1 mA when connected to access point). Its significant shortcoming is its ADC operation: when transmitting data, built-in ADC is inoperable. That, in turn, forced authors to use C8051F120 MCU for data measurement, synchronization of measurement startup and computations, leaving operation of network protocol stack to ESP8266 board's processor.

Transducer is powered by an external accumulator of 2000 mA·h capacity (up to 8–10 hours of continuous measurement), other power source may be used. On heavy machinery, piezoelectric energy harvester [20] may also be used as a power source. The effectiveness of energy harvester, however, directly depends on the machine vibration level, so additional study is required.

5. Firmware of the transducer developed

Transducer is controlled by a specialized firmware, which does the following:

1) Synchronization of measurements in the whole monitoring system (using PTP protocol).

2) Measurement and processing of measured data (MEMS sensor frequency response correction, calculation of RMS of vibration acceleration or velocity).

3) Detection of the vibration RMS value exceeding the preset boundary levels and determination of state of the machine.

4) Transfer of the measured data and determined machine state to the condition monitoring system.

5) Setup and changes in the transducer configuration.

Transducer's firmware structure is shown in Fig. 2.

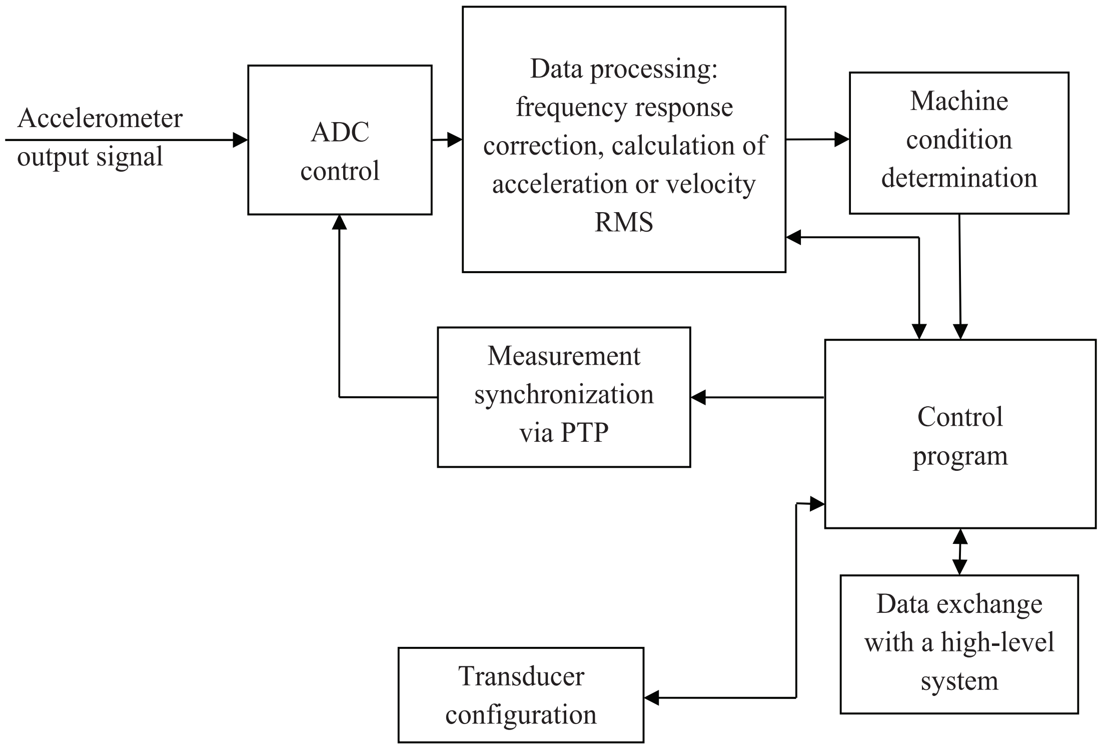


Fig. 2. Transducer's firmware structure

The heart of transducer's firmware is its control program, which provides its operation in set-up mode, data measurement and machine condition determination, and also implements transfer of measured data to higher-level system. In order to ensure measured data delivery, TCP protocol is used; connection to the higher-level monitoring system is fully automatic. When transducer is powered on, it searches for the monitoring system's wireless network according to the preset identifier, connects to the monitoring system, synchronizes its internal clock with master clock of the system and switches into the measurement mode.

Measurement time synchronization is implemented using Precision Time Protocol. Internal clock of the transducer is synchronized with the master clock with precision of up to 100 µs, and measurement is started by monitoring system command with a preset timestamp, which is sent beforehand. Such an approach guarantees synchronous data measurement from all transducers in the system. Clocks are synchronized once every 10 minutes.

Frequency response unevenness can be corrected using a digital filter. Such an approach is used in [21] but attempt to use it in the transducer developed failed. Computational power of the MCU proved to be insufficient, as number of zeros and poles of corrective filter is rather high (e.g., order of a filter, described in [21], is equal to 21). As a result, following algorithm was used to correct MEMS accelerometer's frequency response:

1) Measure data buffer of vibration acceleration values, which is long enough to compute vibration RMS.

2) Perform fast Fourier transform of the buffer and calculate array of acceleration power spectrum lines a_i.

3) Reject spectrum lines with medium frequencies that are out of 10…1000 Hz range.

4) If needed, calculate acceleration RMS using formula

$$A = \sqrt{\sum_i \left(a_i q_i\right)^2}, \tag{1}$$

where q_i is the corrective multiplier for spectrum line with medium frequency f_i.

5) If vibration velocity RMS is needed, calculate velocity power spectrum as follows:

$$v_i = a_i q_i \frac{1}{2\pi f_i}, \tag{2}$$

then calculate vibration velocity RMS using the formula $V = \sqrt{\sum_i v_i^2}$.

Frequency response correction in the algorithm proposed is done along with integration of measured acceleration and calculation of acceleration and velocity RMS according to formulae (1) and (2).

Corrective multipliers q_i for spectrum lines are estimated as follows. First, transducer without any correction applied is installed on the shaker table "back to back" with the etalon transducer (e.g. Bruel&Kjaer 8305) and its frequency response is measured. Corrective multiplier for a spectrum line with medium frequency f_i is calculated as

$$q_i = \frac{A_{TRANSi}}{A_{ETi}}, \tag{3}$$

where A_{TRANSi} is the vibration acceleration magnitude, measured by the transducer at frequency f_i, A_{ETi} is the vibration acceleration magnitude, measured by the etalon transducer at the same frequency.

To obtain corrective multipliers in the whole 10…1000 Hz frequency range, one can excite shaker with a chirp signal (i.e. signal with linear frequency sweep) and simultaneously measure data arrays of output signals of the transducer developed and of the etalon transducer. Then, spectra of the output signals are taken and ratio of magnitudes of their lines according to (3) is calculated, thus obtaining a spectrum of multipliers Q. However, spectrum of multipliers, even calculated from averaged spectra of measured signals, contains noise; thus, corrective multipliers q_i are obtained as a least-squares approximation of the obtained Q graph with a polynomial.

In Fig. 3, spectrum of multipliers Q obtained during transducer development, and its least-squares approximation with a 3–rd order polynomial $\hat{Q}$ is shown.

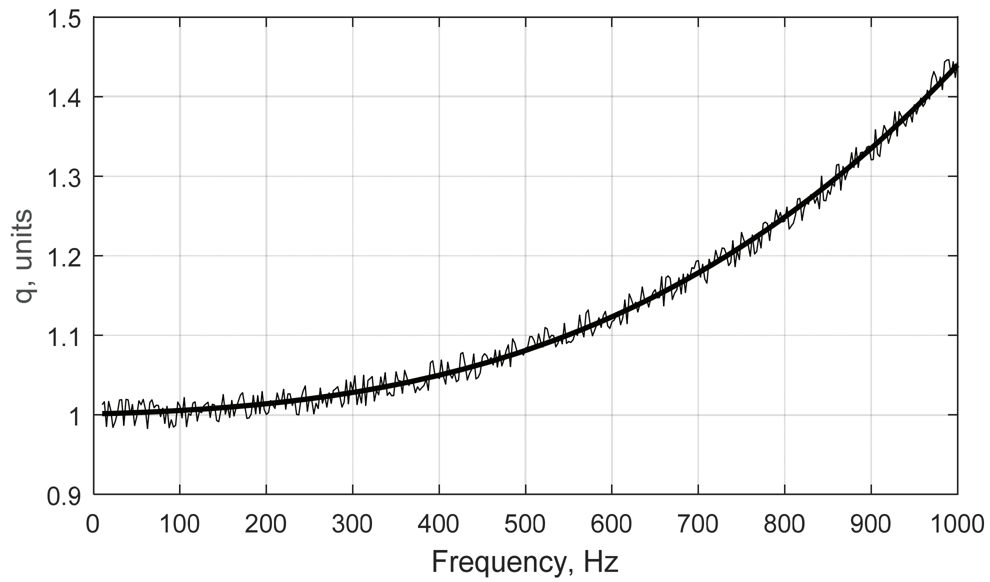


Fig. 3. Spectrum of multipliers Q (thin line) and its approximation with 3–rd order polynomial $\hat{Q}(f)$ (thick line)

Corrective multipliers q_i are obtained as values of a polynomial $\hat{Q}(f)$ at corresponding medium frequencies of spectrum lines f_i:

$$q_i = \hat{Q}(f_i)\,. \qquad (4)$$

Approximation error of the experimentally found spectrum with polynomial is not higher than 0.03 units. In order to check the correction method errors, modelling of correction of several spectra, which are measured with piezoelectric transducer on real-world machines and have different frequency content, was performed. Spectrum of measured signal was multiplied by frequency reference function spectrum Q of the developed transducer line by line (in order to take LIS344 frequency response into account), then corrected using expression (3), and after that RMS and relative measurement errors were calculated using following MATLab code:

```
p1=polyfit(Freq,Q,3);
Qs=polyval(p1,Freq);
Ampl_err=Ampl.*Q;
Ampl_corr=Ampl_err./Qs;
RMS=sqrt(sum(Ampl.*Ampl));
RMS_err=sqrt(sum(Ampl_err.*Ampl_err));
Err_err=abs(RMS_err–RMS)/RMS*100;
RMS_corr=sqrt(sum(Ampl_corr.*Ampl_corr));
Err_corr=abs(RMS_corr–RMS)/RMS*100.
```

Results of modeling are summarized in Table 2.

Table 2. Results of modelling of the frequency response correction method proposed

Spectrum contents	Output signal RMS, m/s^2	Signal with frequency response of LIS344 taken into account		Signal after correction	
		RMS, m/s^2	Error,%	RMS, m/s^2	Error,%
Frequencies below 100 Hz	1.1040	1.1151	1.00	1.1060	0.18
Frequencies below 100 Hz and higher than 500 Hz	1.1415	1.1826	3.60	1.1495	0.7

From Table 2 one can see that relative error both for spectra with and without high–frequency vibration is several times lower when correction is applied. That confirms that correction method is efficient.

In order to simplify operation of the vibration condition monitoring system, each sensor after calculation of RMS determines machine condition according to ISO 10816–1 [22]. To that end, sensor allows one to set three levels: "change" (boundary between A/B zones), "alarm" (boundary between B/C zones) and "breakdown" (boundary between C/D zones). If RMS of vibration signal exceeds a specific boundary level, machine condition ("change", "alarm" or "breakdown" correspondingly) is transmitted to monitoring system; at that measured data may be transferred to high-level system at the specific time interval (e.g. once a minute for "alarm" state, once each 15 minutes in "change" state). Such an approach allows one to further decrease power consumption and network traffic. If boundary levels are not set, measured data are transferred to higher level system with a preset period. Further data processing is done by the high-level condition monitoring system; it may include data registration in database, data visualization, trend-analysis and report creation.

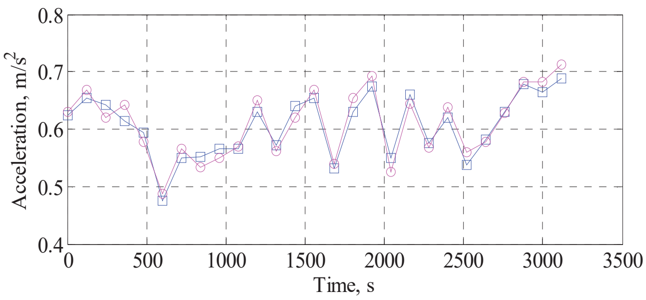
6. Effect of the electromagnetic fields of the transducer developed

Magnetic mounting of vibration transducer along with stud mounting are two most widely used mounting methods [23]. Thus, vibration transducer must be insensitive to influence of electromagnetic fields. In the process of development, two problems related to electromagnetic fields had to be solved. First, transducer with plastic casing and non–shielded Wi–Fi module could not send measured data when installed on an industrial magnet with 150 N force. Second problem was the fact, that Wi-Fi electromagnetic field during transmission had influence on the accelerometer readings in the form of peaks in the output signal. Both those problems were solved when shielded FCC certified Wi–Fi module was used.

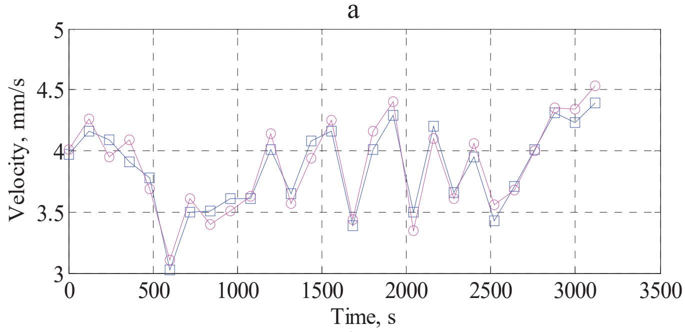
7. Results of transducer tests

The transducer developed is calibrated using the comparison method [23, 24] with the use of B&K8305 etalon transducer. Sensitivity of the analog part of the transducer is 22.43 mV/(m/s^2) or 0.036 (m/s^2)/LSB (least significant bit of ADC), frequency response flatness in the measurement range of 10–1000 Hz is 10 %.

To test transducer functionality, measurement of electric motor vibration was done. Histories of measured vibration on the first engine's bearing in vertical (point 1V) and transverse (point 1P) directions in the frequency range of 10…1000 Hz are shown in Fig. 4; measurement was done once every 2 minutes. For comparison, data measured with the use of industrial piezoaccelerometer B&K 8325 are also shown.



a



b

Fig. 4. Electric motor vibration measurement results (blue squares – transducer developed, violet circles – vibrometer with B&K 8325 transducer): a – acceleration in 1V point; b – velocity in 1P point.

It's evident from Fig. 4, that measurement accuracy of the transducer developed is comparable to one of the industrial transducer; the difference between the readings of those transducers is not higher than 7 %.

8. Results of transducer development and discussion

From results of the tests one can see that the transducer has an acceptable precision and is suitable for use in condition monitoring systems of rotating machinery.

The transducer developed has many advantages:

– low power consumption;

– simple method of frequency response correction, which can be implemented using a cheap 8-bit processor with low computational power;

– measurement precision, comparable with industrial piezoaccelerometers;

– moving of the machine condition detection process to the transducer level allows one to simplify monitoring system as a whole.

Vibration transducer developed also has some drawbacks:

– frequency response flatness of 10 % is insufficient for use in detailed diagnostic monitoring and diagnostics tasks, so a more through frequency response correction is needed;

– for use in detailed diagnostic monitoring, it's desirable to extend transducer's frequency range;

– for use in diagnostic systems, waveform measurement and its transfer to the high-level system has to be provided.

Future research will deal with those drawbacks.

9. Conclusions

As a result of the research, low–cost wireless vibration transducer, based on MEMS accelerometer, with Wi–Fi interface is developed. The transducer is meant to be used in the condition monitoring system. As a result of the research:

1. Schematics of the transducer, based on existing electronic components is proposed. Schematics guarantees a 10…1000 Hz frequency range of vibration measurement, while providing low power consumption and noise cancellation.

2. A simple method of MEMS frequency response correction based on spectral analysis is proposed. The method proposed is suitable for measurement of RMS and power spectrum of machine's vibration.

3. Synchronization of data measurement with the precision, sufficient for practical use, is provided via the use of PTP.

As a whole, the transducer developed can be used as a vibration sensor in basic condition monitoring systems. For use in advanced systems (e.g. diagnostic monitoring systems), transducer should be improved, and that can be the goal of the future research.

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Безпровідний датчик вібрації для моніторингу стану на основі mems

Постановка задачі. При моніторингу вібрації обертового обладнання, особливо важкого, часто виникають проблеми з кабелями. Згадані кабелі зазвичай довгі, важкі та легко пошкоджуються.

Завдання дослідження. Розробка безпровідного датчика вібрації, вільного від згаданих проблем, на основі MEMS акселерометра. Розроблений датчик повинен мати низьке енергоспоживання, лінійну амплітудно-частотну характеристику принаймні в діапазоні 10…1000 Гц, обчислювати СКЗ вібрації і на його основі визначати стан машини.

Метод реалізації. Розробити конструкцію датчика на основі 8-бітного мікроконтролера. Розробити метод корекції амплітудно-частотної характеристики MEMS на основі спектрального аналізу. Порівняти розроблений датчик з промисловими п'єзоелектричними датчиками.

Результати дослідження. Розроблений датчик може бути використаний замість промислових п'єзоелектричних датчиків вібрації. Більше того, датчик на основі MEMS дозволяє перемістити процес базової оцінки стану обладнання

з системи верхнього рівня на рівень датчика. Це, в свою чергу, дозволяє знизити трафік у мережі і спростити систему моніторингу в цілому.

Резюме. Розроблено безпровідний датчик вібрації для моніторингу стану на основі MEMS. Проведені випробування показали, що датчик функціонує правильно і його точність порівняна з точністю промислових п'єзоелектричних акселерометрів.

Ключові слова: *вібрація; MEMS акселерометр; безпровідний датчик вібрації; Wi–Fi; моніторинг обертового обладнання.*