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DEVELOPMENT OF WIRELESS VIBRATION TRANSDUCER BASED ON MEMS ACCELEROMETER

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Представлено бездротовий датчик вібрації, створений на основі MEMS акселерометра. Описано застосовані схемотехнічні рішення, структуру програмного забезпечення датчика, алгоритм корекції АЧХ MEMS акселерометра та обробки даних, розглянуто питання впливу на датчик електромагнітних полів. Результати проведених випробувань підтверджують працездатність датчика та можливість забезпечення за його використання вимірювань з точністю, порівняною з промисловими п’єзоакселерометрами

Ключові слова: вібрація, MEMS акселерометр, бездротовий датчик вібрації, Wi-Fi, моніторинг обертового обладнання

Представлен беспроводный датчик вибрации, созданный на основе MEMS акселерометра. Описаны примененные схемотехнические решения, структура программного обеспечения датчика, алгоритм коррекции АЧХ MEMS акселерометра и обработки данных, рассмотрен вопрос влияния на датчик электромагнитных полей. Результаты проведенных испытаний подтверждают работоспособность датчика и возможность обеспечения при его использовании измерений с точностью, сравнимой с промышленными пъезоакселерометрами

Ключевые слова: вибрация, MEMS акселерометр, беспроводный датчик вибрации, Wi-Fi, мониторинг вращающегося оборудования

1. Introduction

When measuring vibration of the heavy machinery (generators, turbines), connection of transducers is one of the critical issues. As a rule, classical piezoaccelerometers with charge output aren’t used for that task due to their inherent limitations. As cable capacity has a significant influence on the piezoaccelerometer voltage sensitivity coefficient and on the frequency response slope at high frequencies, cable length is typically not higher than 1–3 m, which is insufficient for measurement of vibration of heavy machinery. Moreover, the cable of piezoaccelerometer has to be properly fixed on the object (machine) in order to decrease triboelectric noise. Accelerometers with ICP output are free of limitations mentioned, but when measuring vibration of the heavy machinery, one has to use shielded cable tens of meters long. Using such a cable is unhandy because of its length and mass; except that, personnel often works with the cable carelessly, and that results in breakdown of both cable and connectors of cable and equipment. One of possible solutions of the problems mentioned is the use of Wi-Fi for measured data transfer, but the use of Wi-Fi in conjunction with ICP or charge transducer requires a heavy-duty power supply. As a result, one tends to consider microelectromechanic system (MEMS) based sensors as primary vibration transducers in stationary systems and diagnostic study stations. MEMS have a number of advantages compared to industrial piezoaccelerometers: smaller size and mass, lower power consumption and tens of times less cost. Therefore, development of MEMS-based vibration transducer would make it possible to decrease the cost, mass and power consumption of rotating machinery monitoring systems. That would allow one to use monitoring systems on the machinery, on which use of such systems is considered inappropriate up to this time, and to increase the safety of an operation of such machinery. Thus, development of MEMS-based vibration transducer is an actual task.

2. Analysis of publications and problem statement

Study of application of MEMS accelerometer as a primary vibration transducer is done for a long time. Back in 2006 experiments in measurement of pump vibration with piezoelectric accelerometer and MEMS one were carried out [1]. In [2], comparison of data, measured with piezoelectric accelerometer and MEMS at the same test conditions (frequency range of 0–10 kHz, vibration acceleration level of 5 g) is presented. According to [2], MEMS accelerometer doesn't provide a stable sensitivity coefficient and phase shift even when the sine signal is measured, not to mention low-frequency response flatness: frequency response unevenness can be up to 6 dB in 300 Hz range. Similar comparison, made in [3], confirms the results, presented in [2].

Measurement of tilt of an object and its vibration in 0–500 Hz frequency range with the use of ADXL202 accelerometer is described in [4]. In paper [5], a MEMS-based accelerometer with RMS detector is presented, at that schematics is provided, but there are no data about transducer tests; therefore one cannot estimate its efficiency. MEMS-based transducer, described in [6], has a limited frequency range, which makes it useful only for structure health monitoring and monitoring of some low-speed machinery, like hydroturbines and paper mill equipment. In work [7], development of MEMS-based transducer is described; transducer is designed using an ARM7 processor, and that increases its cost and power consumption. Besides that, according to the authors of [7], the problem of tansducer's noise cancellation is not solved.

Application of MEMS accelerometer for monitoring of rotating machinery is studied in several works. In [8], state-of-the art designs created by Analog Devices, which can be used in monitoring and diagnostics systems, are described. Authors of [9] developed an accelerometer for vibration measurement based on ADXL322 and used autocorrelation function and adaptive rule-based filters in order to increase signal-to-noise ratio. The drawback of such an approach is the rejection of both noise and high-frequency signal, which contains, among other, information about rolling element bearing defects.

Wireless rotation machinery monitoring system based on MEMS is described in [10]. Authors of [10] focused their study on the task of synchronization of measuring modules and compensation of difference between their oscillator clock frequencies. The drawback of the system, described in [10], is its considerable complexity, and, as a consequence, high requirements to the computational power of the controllers used.

So, development of MEMS-based vibration transducer, which can be used in monitoring systems, is a complex problem, that calls for the solution of several accompanying problems, related to both signal processing and features of MEMS accelerometers themselves. Up to now, the problem of development of MEMS-based vibration transducer, in which problems of guaranteeing frequency range, suitable for vibration monitoring (10–1000 Hz at least), compensation of frequency response unevenness and noise cancellation are tackled on the assumption of limited power consumption and computational power, is not solved.

3. Objective and goals of the research

The objective of the present work is the development of the vibration transducer based on MEMS that could be used in the rotating machinery vibration monitoring system instead of industrial accelerometers.

In order to achieve that objective, the 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 MEMS accelerometer frequency response unevenness correction;

– to provide the solution of accompanying problems, including synchronization of data measurement from different transducers and electromagnetic compatibility of the transducer.

4. Schematics of the transducer and its electronic components

First of all, analysis of available MEMS sensors with analog output is made, and they are compared with industrial ICP transducer (Bruel&Kjaer 8325 [11]). Digital MEMS sensors, for instance ADIS16223, are not considered, as their claimed characteristics are lower than ones of industrial ICP accelerometers, and the ability of correction of the output signal is minimal, as corresponding algorithms are "flashed" by the manufacturer. Specifications of the accelerometers considered according to information, provided by their manufacturers [11–14], are given in Table 1.

As one can see from Table 1, present-day MEMS accelerometers have technical features close to industrial piezoaccelerometers. The main drawback of those accelerometers, as before, is significant frequency response unevenness; due to that frequency range of vibration measurement narrows. For example, significant (>10 %) deviation of the frequency response of ADXL001–70 [15] from the horizontal line starts at 5–6 kHz, in spite of the fact, that the resonant frequency of the accelerometer is 22 kHz; significant deviation of B&K 8325 frequency response starts at 10 kHz. Frequency responses of other accelerometers are even worse. Moreover, in contrast to piezoaccelerometers, which are insensitive to static accelerations (e. g. gravity), MEMS sensors measure both dynamic and static accelerations, and so when measuring vibration data, analog signal filtering must be applied.

When using the monitoring system, one often has to measure vibration of a bearing on three axes. Use of three one-axis accelerometers (or of two-axis and one-axis ones) in the transducer increases its power consumption and cost. Therefore, in spite of the advantages of accelerometers with a wide frequency range of ADXL001-70 type, LIS 344 accelerometer is selected for use in the transducer developed, as that accelerometer provides a high sensitivity coefficient and low transverse sensitivity. Besides that, the price of the sensor mentioned is lower compared to ADXL316.

cial features are the ability to control it via AT commands through serial interface and low power consumption (less than 1mA to stay connected to the access point). ESP8266's significant shortcoming is the fact, that ADC, built into its processor, cannot operate while module is transmitting data; because of that, it was decided to use C8051F120 MCU for data measurement, synchronization of measurement start and computations, and leave only operation of network protocol stack to ESP8266's processor.

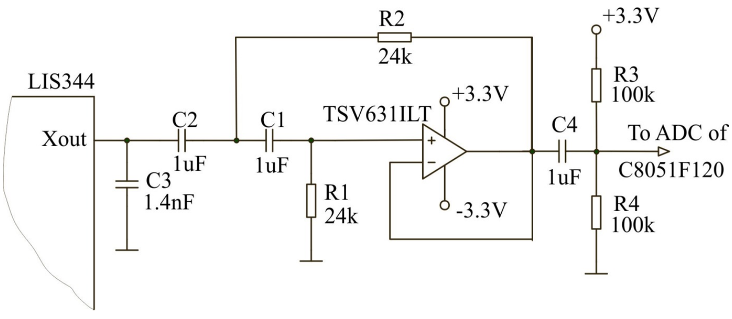

Fig. 1. Analog part of the transducer (channels Y and Z aren't shown)

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
Sensitivity	570 mV/(m/s^2)	80 mV/(m/s^2)	660/220 mV/(m/s^2)	10 mV/(m/s^2)
Measurement range	±160 m/s^2	±500 m/s^2	±20 / ±60 m/s^2	±500 m/s^2
Resonant frequency	4.2 kHz	–	1.8 kHz	25 kHz
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
Transverse sensitivity	1 %	3 %	2 %	< 4 %
Shock (max.)	100000 m/s^2	50000 m/s^2	100000 m/s^2	50000 m/s^2
Temperature range	–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 microchip pins; resonance frequency data of SD 1510L–050 accelerometer are not provided by its manufacturer

The transducer is fed by an external accumulator (up to 8–10 hours of continuous measurement with 2000 mA·h capacity accumulator) or another power source. When using transducer on heavy machinery, one can also use piezoelectric energy harvester [17] as a power source. However, the effectiveness of such a power source directly depends on the machine vibration level, and, therefore, an additional study is required.

5. Firmware of the transducer developed

For the transducer, specialized firmware is developed, which performs a range of tasks:

1) Synchronization of measurement with other transducers in the monitoring system (using PTP protocol).

2) Measurement and processing of data from ADC (accelerometer frequency response correction, calculation of vibration acceleration or velocity RMS) with the given time interval.

3) Detection of the vibration signal exceeding the preset boundary levels.

4) Transfer of the measured data and determined machine state, data exchange with higher level systems.

5) Setup and change of the transducer configuration.

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

The core element of the firmware is a control program, which organizes transducer operation in configuration set–up mode, data measurement and data estimation modes, and also in the mode of data transfer to higher level systems. Data transfer is implemented using TCP protocol, which ensures measured data delivery. Connection of the transducer to the monitoring system is fully automated; when the trans-

As the value of vibration velocity root mean squared (RMS) in the range of 10–1000 kHz is a fundamental data used by the monitoring system, the higher boundary of a frequency range is limited by built-in LPF of the accelerometer; its cut-off frequency is set equal to 1 kHz. In order to eliminate the influence of low-frequency component, active Sullen-Key filter with 10 Hz cut-off frequency is used; use of a higher order filter is considered to be inappropriate, because the data processing algorithm allows one to eliminate vibration data at low frequencies in the course of its operation.

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

As the cost of the transducer was a crucial factor during its development, Espressif systems ESP8266 board [16] was selected as a Wi-Fi module. ESP8266 is available in several modifications, including shielded modules and modules with the ability to connect an external antenna. Module's speducer is powered on, it makes a search of the monitoring system according to the identifier, set in its configuration, connects to the monitoring system, synchronizes its internal clock and switches to measurement mode.

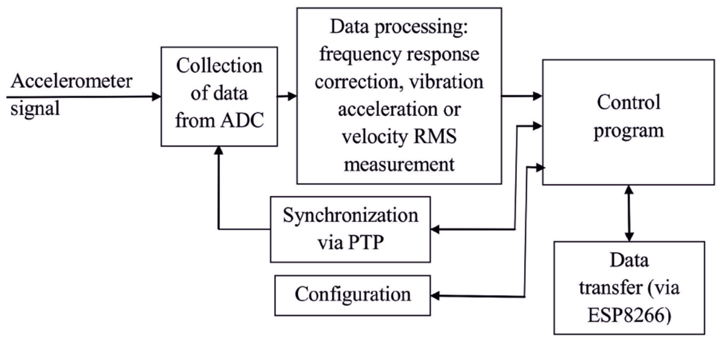

Fig. 2. Transducer's firmware structure

Synchronization of measurement time via PTP (Precision Time Protocol) is an important feature of the transducer. In the process, an internal clock of the transducer is synchronized with the monitoring system clock with the precision up to 100 µs, and measurement start is initiated by monitoring system command. That allows one to ensure synchronous data measurement form all the sensors of the monitoring system. Synchronization of sensors during data measurement is done periodically, once in 10 minutes.

In order to correct frequency response unevenness, one could use a digital filter similar to the one described in [18]; however, computational power of the MCU used proved to be insufficient for that task due to the high number of zeros and poles of such a filter (e. g., order of a filter, described in [18], is equal to 21). Because of that, frequency response correction is done using the following algorithm:

1) Measure vibration acceleration data buffer, which is long enough for RMS measurement.

2) Calculate fast Fourier transform of the buffer measured and calculate an array of vibration acceleration power spectrum lines a_i.

3) Reject spectrum lines with medium frequencies lower than 10 and higher than 1000 Hz.

4) If vibration acceleration RMS has to be measured, calculate it using the formula

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

where q_i is the corrective multiplier of spectrum line with medium frequency f_i (frequency response correction).

5) If vibration velocity RMS is measured, calculate velocity power spectrum using the formula

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

6) Calculate vibration velocity RMS using the formula

$$V=\sqrt{\sum_i v_i^2}.$$

In the proposed algorithm, frequency response correction is done concurrently with the integration of the measured acceleration, calculation of measured vibration acceleration RMS and vibration velocity RMS according to formulae (1) and (2).

In order to determine corrective multipliers q_i for spectrum lines the following method is applied: frequency response of the LIS 344 sensor, installed on the shaker table "back to back" with etalon transducer, is measured. Corrective multiplier for a spectrum line with medium frequency f_i is calculated using the formula

$$q_i = \frac{A_{LIS344i}}{A_{ETi}}, \tag{3}$$

where $A_{LIS344i}$ is the vibration acceleration magnitude, measured by the LIS344 sensor at frequency f_i, A_{ETi} is the vibration acceleration magnitude, measured by the etalon transducer at frequency f_i.

In order to obtain corrective multipliers in the whole frequency range, one can use shaker excitation with linear frequency sweep (chirp signal), take signal spectrums from etalon and tested transducers, and then calculate the ratio of magnitudes of their lines according to (3), thus obtaining a spectrum of multipliers Q . As the spectrum of multipliers Q, obtained even from averaged spectrums of measured signals, contains noise, one should obtain coefficients q_i that are to be used in the correction algorithm via least squares approximation of the obtained graph with a polynomial.

In Fig. 3, experimentally obtained spectrum of multipliers Q and its approximation with a 3-rd order polynomial $\hat{Q}$ is plotted.

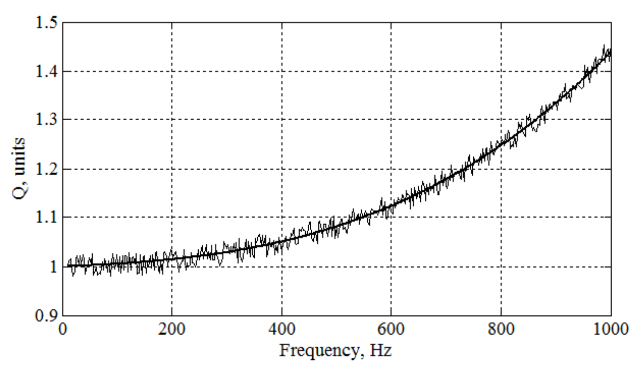

Fig. 3. Spectrum Q of multipliers (thin line) and its approximation with 3-rd order polynomial $\hat{Q}(f)$ (thick line)

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

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

Approximation error of the experimentally found spectrum with polynomial is not higher than 0.03 units. In order to check the efficiency of the correction method, modeling of correction of several spectra with different frequency contents, measured on real-world equipment, was done. To that end, measured spectrum was multiplied by the experimentally found spectrum Q, then corrected using formula (3), and after that RMS and relative measurement errors were calculated using 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 of the correction method are summarized in Table 2.

Table 2

Results of modeling 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, %
Low frequencies (up to 100 Hz)	1.0514	1.0608	0.89	1.0545	0.28
Low (up to 100 Hz) and high frequencies (higher than 500 Hz)	1.1313	1.1713	3.54	1.1237	0.67

As one can see from Table 2, relative error both when high-frequency vibration is present and when it's absent is several times lower when correction is applied; that confirms the efficiency of the correction method.

In order to simplify operation of the vibration monitoring system, ability to set three boundary levels for a sensor is provided; those levels are "change" (boundary between A/B zones according to ISO 10816–1 [19]), "alarm" (boundary between B/C zones) and "breakdown" (boundary between C/D zones). If vibration signal RMS exceeds a specific boundary level, machine condition ("change", "alarm" or "breakdown" correspondingly) is transferred to monitoring system, and measured RMS data are transferred with the period, set for the last determined condition (e. g. once in a minute for "alarm" state and one in 10 minutes for "change" state). That allows one to decrease power consumption of the transducer and load on the Wi-Fi network. If boundary levels are not set, measured data are simply transferred to higher level system with a preset period; one can get signals about exceeding of the boundary level and current measured data both into database on the stationary PC and on a tablet PC or smartphone, if Wi-Fi network is available.

6. Effect of the electromagnetic fields of the transducer developed

One of the widely used vibration transducer mounting methods [20], along with stud mounting, is magnetic mounting. The cardinal problem of magnetic mounting of the transducer developed was the influence of electromagnetic fields on its output signal and on the operation of Wi-Fi module. Tests of the transducer with plastic casing and non-shielded Wi-Fi module board revealed that the measured data transfer was inoperable due to magnetic field influence. Moreover, during operation of Wi-Fi board in transmission mode, the influence of transmitter's electromagnetic field on the accelerometer readings was detected in the form of peaks in the output signal. Those peaks disappeared when shielded FCC certified Wi-Fi module was used, and so it's shown that shielded Wi-Fi transmitter has to be used.

7. Results of transducer tests

The transducer developed is calibrated using the comparison method [20, 21] 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 %.

As a practical test of transducer functionality, measurement of electric motor vibration is done. The results of measurement at points on the first engine's bearing in vertical (1V) and transverse (1P) directions in the frequency range of 10–1000 Hz are shown in Fig. 4; measurement is done with the period of 2 minutes. Data, measured both with the use of the transducer developed and with the use of industrial piezoaccelerometer B&K 8325 are shown for comparison.

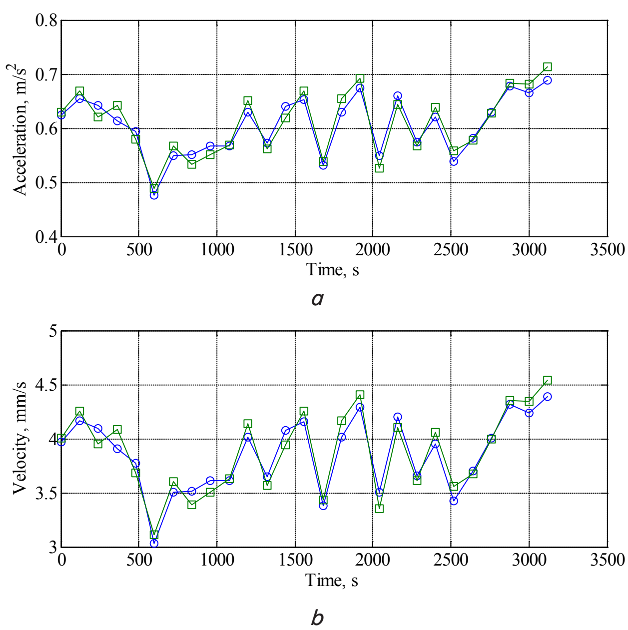

Fig. 4. Electric motor vibration measurement results (blue circles — transducer developed, green squares — vibrometer with B&K 8325 transducer): *a* — acceleration in 1V point; *b* — velocity in 1P point

As one can see from Fig. 4, the measurement accuracy of the transducer developed is comparable with the industrial transducer's one; the difference between the readings of those transducers is not higher than 7 %.

8. Results of transducer development and discussion

As one can see from the test results, the transducer has an acceptable precision and is suitable for use in vibration monitoring systems, in particular, in systems for rotating machinery vibration monitoring.

The transducer developed has many undeniable advantages:

– low power consumption of the sensor owing to the schematics used;

– simple method of frequency response unevenness correction, which allows one to use a relatively cheap processor with low computational power;

– measurement precision,comparable with industrial piezoaccelerometers;

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

Vibration transducer developed also has some drawbacks, namely:

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

– it's desirable to extend the frequency range of vibration measurement;

– for use in diagnostic systems, waveform measurement and its transfer (maybe, real-time one) to the high-level system has to be provided.

Future research will deal with those drawbacks.

9. Conclusions

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

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

2. A simple method of MEMS frequency response unevenness correction based on spectral analysis is proposed; that method is suitable for use in the measurement of vibration RMS and power spectra.

3. Synchronization of data measurement in monitoring systems with the transducers developed with the precision, sufficient for practical use, is provided via the use of PTP.

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METHOD OF STUDYING CORROSION PROCESSES OF METAL ELECTRODES BY SURFACE VOLTAGE FLUCTUATIONS

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Запропоновано спосіб дослідження корозійних процесів на поверхні металевого електрода за результатами спостереження флуктуацій напруги на ньому. Розроблено пристрій для обробки цих сигналів. Виявлено, що найбільш інформативним параметром при дослідженні сигналів, пов'язаних із корозійними процесами на поверхні металевого електрода, є форма розподілу ймовірностей миттєвих значень та оцінка їх інформаційної ентропії

Ключові слова: електрохімічна корозія, напруга електричного шуму, форма розподілу ймовірності миттєвих значень сигналу, інформаційна ентропія миттєвих значень сигналу

Предложен способ исследования коррозионных процессов на поверхности металлического электрода по результатам наблюдения флуктуаций напряжения на нем. Разработано устройство для обработки этих сигналов. Выявлено, что наиболее информативным параметром при исследовании сигналов, связанных с коррозионными процессами на поверхности металлического электрода, является форма распределения вероятностей мгновенных значений и оценка их информационной энтропии

Ключевые слова: электрохимическая коррозия, напряжение электрического шума, форма распределения вероятности мгновенных значений сигнала, информационная энтропия мгновенных значений сигнала

1. Introduction

Metals and alloys are important modern construction materials. Wherever metal constructions are operated, substances interacting with metals are present that destroy them gradually. During operation most metals have greater stability in oxidated state that is the result of corrosion. Iron oxides resulting from corrosion of steel constructions have substantially different mechanic properties, so metal constructions can fail to withstand mechanical stress that they are designed for.

Corrosion of metals does great harm to economic activity of enterprises. Equipment for industry collapses due to aging or corrosion. It brings not only great economic losses, but also leads to a global ecological catastrophe.

Various research methods of corrosion processes make it possible to control the electrochemical reactions associated