Designing of a Laboratory Complex for Spectral Analysis of Measurement Data of Different Materials

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Abstract The article describes the process of development and testing of a laboratory complex for spectral analysis of measured data, which is based on a signal processing method based on measuring the frequency and amplitude of the signal (spectral method) with further evaluation using fast Fourier transform. The described laboratory complex consists of a spectrum analyzer connected to a personal computer with special software installed on it, a loudspeaker and a laser sensor. The this substantiates the relevance of the development, due to the fairly wide use of spectral analysis methods in science, technology and production, the advantages of using a laboratory complex in comparison with analogues were shown. the description of the experiments to measure the speed of objects, control their location, vibration measurement, the procedure of verification and calibration that is performed with the use of this complex, as well as the use of the system of automatic regulation and stabilization of production processes.

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1 Introduction

One of the important stages of the production process is the quality control of raw materials, semi-products and completed products, consisting of measurements—a process where the value of a feature is set—and further comparison of the measurement results with the specified parameters [1]. Depending on the specifics of the controlled parameter, it is possible to use different control methods, in particular, the spectral method [2, 3], non-destructive testing method [4, 5], its essence consists in determination of the spectral content (i.e. power frequency distribution) of a time series from a finite set of measurements using nonparametric or parametric methods [6, 7]. Nowadays this method is widely used in science and production; in particular, it is used in the assessment of product quality in food industry in the detection of chemical, biological and physical hazards [8], pharmaceuticals [9], the oil refining industry [10] and a number of other areas [11]. The reason for the high popularity of the spectral method is due to high visibility of the measurement results (the form the measurement results can be presented is the graph), it is easily to detect frequencies, the value of which is different from the standard values, and quickly identify and correct the fault during the process [12].

2 Research Method

Spectral analysis is a method of signal processing—material carriers of information,—based on the evaluation of the frequency and amplitude of the signal. There are various methods for estimating the vibration spectrum, one of which is the method based on using fast Fourier transform, which is based, in its turn, on representation of the original signal function from time as the sum of an infinite series of trigonometric functions with certain amplitudes and phases [13].

The Fourier series can be represented as: $f(x) = \sum_{k=-\infty}^{+\infty} X_n * e^{i*2\pi*\frac{k}{T}*x}$, where $f\ (x)$ is the function of the analyzed signal; k is the number of the trigonometric function; T is the segment where the function is defined; Xn is the complex amplitude of the signal n.

Graphically, the Fourier series is represented as a Fourier spectrum, where it is possible to trace the dependence of the signal amplitude on the frequency on it [14].

The method of signal processing by their representation in the form of Fourier spectrum underlies the work of modern spectrum analyzers-devices designed to observe and measure the relative energy distribution of electric (electromagnetic) oscillations in the frequency band [15]. Spectrum analyzer allows determining the frequency and amplitude of the analyzed signal. In general, the mechanism of its operation can be described as follows: the input of the analyzer receives a digital signal. The analyzer selects successive intervals from the signal, where the spectrum will be calculated, and converts the received signal using the Fourier transform [16].

The calculated spectrum is displayed as a graph of amplitude versus frequency. Spectrum analyzers allow measuring the signal frequency, its amplitude, power, modulation, distortion and noise, their using shows a complete picture of the signal nature and its characteristics, the knowledge of which is important for solving the problems facing modern science and technology [17, 18].

Currently, spectrum analyzers, in addition to converting a digital signal to an analog signal for subsequent processing, are able to convert an input digital signal read from various sensors into an analog signal for its subsequent transmission to analog electronic devices.

3 Description of the Installation

In the work, a laboratory complex was developed that allows spectral analysis of measurement data of various materials. The complex includes a computer with specialized software installed, a spectrum analyzer ZET 017-U4, a column and a RF 603 laser displacement sensor. It is also possible to additionally connect various sensors, for example, displacement sensors or force sensors, to one of the four analog–digital inputs of the analyzer Spectrum ZET 017-U4. The basic installation diagram is shown in Fig. 1.

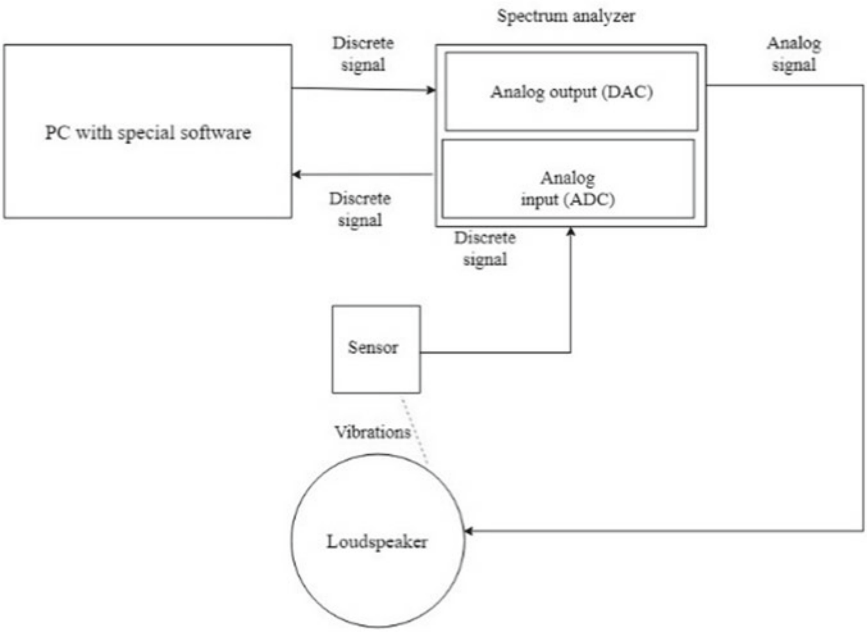

Fig. 1 Scheme of the laboratory complex

The spectrum analyzer used consists of two modules, such as an Analog output (DAC) and an Analog input (ADC). An ADC converts an analog signal into a digital one and is an analog output, and a DAC converts an analog signal into a digital one and is an analog output. The uncertainty of measurements made using the analyzer is best described by the Gaussian distribution, which indicates the possibility of using the analyzer for measurements with high accuracy. All analyzer settings are made on the computer, which is part of the laboratory complex, before starting work in a specialized software product, in which data is subsequently processed and the signal analyzed with its parameters determined.

Consider the algorithm of the laboratory complex for generation and spectral analysis of measurement information:

(1) a control command is sent to the generator from the computer via software by the USB interface to generate a specific waveform with a spectrum analyzer;
(2) the spectrum analyzer of the analog output transmits a signal to the column, which converts it into the form of vibrations, sounds or noise;
(3) the laser motion sensor reads vibrations from the column and transmits them to one of the four analog inputs of the spectrum analyzer;
(4) the received signal is converted by the ADC and fed to a computer in software that issues a report in the form of a measured signal.

To check the operability of the complex, a series of tests were conducted to generate a signal of a given frequency and amplitude in order to receive a filtered signal with the same parameters at the output. Part of the tests was carried out using one motion sensor; in other experiments, a second similar sensor was included in the laboratory complex. The set frequencies and voltage of the signals and the output parameters of the signals are shown in Table 1. The noise level in all experiments was equal to 0.001 mm.

In the first series of experiments a signal with a constant voltage of 7 V and frequencies equal to 1 Hz, 10 Hz, 50 Hz, 100 Hz, and 200 Hz, respectively, was supplied to the spectrum analyzer. At output in the first three experiments, a signal was obtained having a frequency similar to the frequency of the supplied signal (2 Hz, 9.8 Hz, 51 Hz), however, at frequencies exceeding 50 Hz, the noise component of the signal did not allow us to determine the useful signal read by the sensor. When exceeding the value of the frequency values of the signal mark at 50 Hz, the noise did not allow accurate measurements. According to the results of the experiments, we can conclude that the laboratory complex is advisable to use for tests performed at low frequencies. In these conditions, the installation allows you to take the necessary measurements and analyze the result using various software modes.

The laboratory complex also allows to produce flat, band, pink and defined noise at the DAC output. As we can see, the laboratory testing with using the laboratory complex is quite similar to real impacts, to which the specimen is exposed in the course of its operation.

Table 1 Experimental results

The frequency of the first harmonic [Hz]	The voltage of the first harmonic [V]	Second harmonic frequency [Hz]	Second harmonic voltage [V]	Frequency 1 of the RF sensor 603 [Hz]	Amplitude of 1 sensor RF 603 [mm]	Frequency 2 sensors RF 603 [Hz]	Amplitude 2 sensors RF 603 [mm]
1	7	–	–	2	0.100	–	–
10	7	–	–	9.8	0.200	–	–
50	7	–	–	51	0.250	–	–
100	7	–	–	–	0.001	–	–
200	7	–	–	–	0.001	–	–
1	2	10		1.9	0.024	10	0.032
1	2	50	5	2.1	0.025	49.5	0.030
10	2	10	5	10.1	0.024	9.9	0.031
10	2	50	5	10	0.025	50	0.029
10	2	100	5	–	0.001	–	0.001
10	2	100	5	–	0.001	–	0.001

4 Results and Considerations

The scope of this complex is wide enough, since the complex is based on the spectral method, which is widely used in various fields of modern science and technology. Thus, the assembly of various modifications of the laboratory complex allows it to be used to detect cracks in concrete and damage in building structures [19, 20], while continuously monitoring the tightness of various containers and pipelines.

It is also possible to use a laboratory complex to control the location of various objects and the speed of their movement, moreover, it is possible to measure values of both angular and linear velocities and values of displacements in the space of the studied object.

The developed laboratory complex can also be used in mechanical engineering during vibration analysis during dynamic testing of machines and various mechanisms. During this operation, a force sensor is connected to the spectrum analyzer through a charge amplifier and with its help vibrations emanating from moving parts of machines and mechanisms are measured.

It is possible to use the complex, creating systems for protecting production facilities based on voice recognition [21]. It is also advisable to include the laboratory complex under consideration in the equipment when conducting various scientific studies of the properties of substances and materials, as well as noted above, in assessing the quality of food products [22].

Another direction in which it is advisable to use this complex is the testing and calibration of vibration sensors by comparing the device to be verified with a reference device. To carry out this operation, verifiable sensors are connected to the spectrum

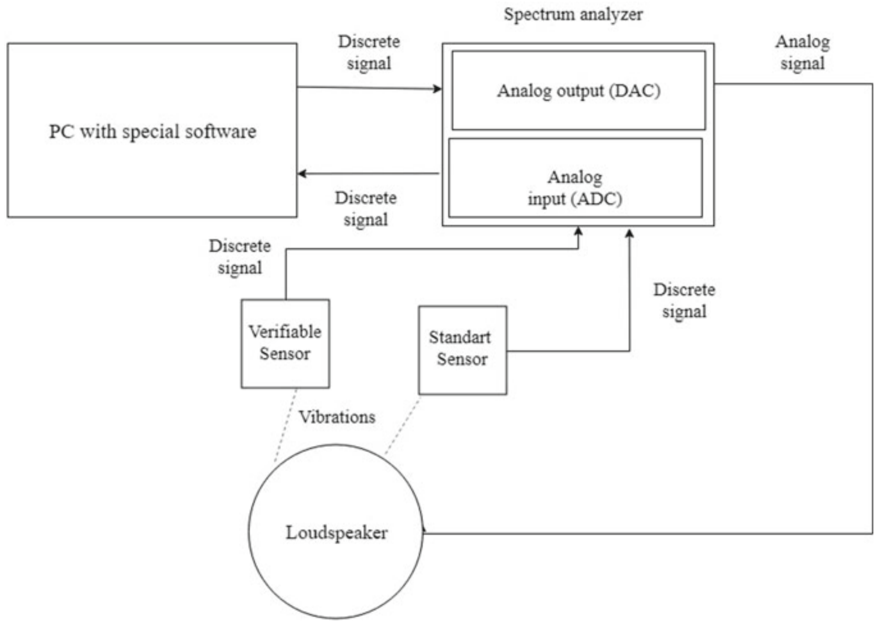

Fig. 2 Installation diagram for sensor verification

analyzer, which is installed on the loudspeaker. The installation diagram for sensor verification is shown in Fig. 2. On the computer, vibration parameters are set, which are reproduced by the loudspeaker, and the system is brought into operation and the device is automatically calibrated: the ADC receives signals from the reference and verified devices, transfers data to the computer, to the software, in which there is a comparison of the readings of devices, determination of the amplitude characteristic, the removal of the amplitude-frequency characteristics of the sensor being calibrated [23].

Based on the results of measurements and comparisons of instrument readings, a protocol is compiled containing information on the suitability of the sensor being verified. Since the verification procedure is carried out in automatic mode, its results are not affected by errors caused by the work of the employee performing the verification, due to high accuracy of measurements and the obtained results are achieved.

Presented laboratory complex can be used not only during control measurements, but also when creating automatic regulation and stabilization of production processes. At the same time, the laboratory complex takes a part of a proportional-integral-differentiating (PID) feedback regulator. PID control is carried out by applying a control signal to the control object, the value of which depends on the difference between the measured parameter and the set value, on the integral of the difference and on the rate of change of parameters. As a result, the PID controller transmits a signal providing such a state of the device at which the measured parameter is equal to the specified one, stable and maintained during the course of the process at a given level with fairly high accuracy. Because of the production process stability, labor productivity increases, product quality, process efficiency and effectiveness indicators increase, which is important in modern market economies and constant competition [21]. The control signal for the PID controller is determined by three components: proportional, integral and differential, and depends on how large the mismatch (proportional component) is, how long the mismatch (integral component) lasts, and finally, how quickly the mismatch (differential component) changes. The regulator can hold the set level or work on the set profile. Additionally, the software product of the complex can graphically display form the set level, the current value of the parameter, and the output signal.

5 Conclusion

In the course of the work, a laboratory setup was developed and implemented for the spectral analysis of measurable data of various materials with a fairly wide range of applications. In particular, it is possible to use the installation for conducting non-destructive testing in production, for detecting cracks in concrete, damage in building structures, with continuous monitoring of the tightness of various containers and pipelines, monitoring the location of various objects and the speed of their movement, during vibration analysis during dynamic tests machines and various mechanisms, during various scientific studies of the properties of substances and materials, in assessing the quality of food products, for the existence of verification of non-destructive testing means, as well as in the training of employees whose activities are directly related to the measurement and analysis of their results. A high degree of automation ensures high measurement accuracy, therefore it is advisable to include the developed laboratory complex in the laboratory base of industrial enterprises.

References

1. Kulz, M.: Mechanical Engineers Handbook, vol. 2: Design, Instrumentation, and Controls. Wiley, Hoboken (2015)
2. Surzhikov, A.P., Galtseva, O.V., Vasendina, E.A., Vlasov, V.A., Nikolaev, E.V.: Processing line for industrial radiation-thermal synthesis of doped lithium ferrite powders. IOP Conf. Ser.: Mater. Sci. Eng. **110** (1), 012002 (2016). https://doi.org/10.1088/1757-899X/110/1/012002
3. Im, S.B., Hurlebaus, S.: Non-destructive testing methods to identify voids in external post-tensioned tendon. KSCE C.E.J **16**(3), 388–397 (2012). https://doi.org/10.1007/s12205-012-1295-0
4. Li, N., Cao, M., Liu, K., He, C., Wu, B.: A boundary detecting method for post-tensioned pre-stressed ducts based on Q-factor analysis. Sens. Actuators, A **248**, 88–93 (2016). https://doi.org/10.1016/j.sna.2016.07.024

5. Krause, M., Milmann, B., Mielentz, F., Streicher, D., Redmer, B., Mayer, K., Langenberg, K.J., Schicker, M.: Ultrasonic imaging methods for investigation of post-tensioned concrete structures: a study of interfaces at artificial grouting faults and its verification. J. Nondestruct. Eval. **27**, 67–82 (2008). https://doi.org/10.1007/s10921-008-0033-5
6. Surzhikov, A.P., Pritulov, A.M., Lysenko, E.N., Sokolovskiy, A.N., Vlasov, V.A., Vasendina, E.A.: Calorimetric investigation of radiation-thermal synthesized lithium pentaferrite. JTAC **101**(1), 11–13 (2010). https://doi.org/10.1007/s10973-010-0788-7
7. Astanov, SKh., Kasimova, G.K., Sharipov, M.Z.: Optical systems for removal of polarization spectra. Eurasian Phys. Tech. J. **16**(31), 83–88 (2019). https://doi.org/10.31489/2019No2/83-88
8. Stoica, P., Moses, R.: Spectral Analysis of Signals. Prentice Hall, New Jersey (2005)
9. Fu, X., Ying, Y.: Food safety evaluation based on near infrared spectroscopy and Imaging a review. Crit. Rev. Food Sci. Nutr. **56**(1), 1913–1924 (2014). https://doi.org/10.1080/10408398.2013.807418
10. Roggo, Y., Chalus, P., Maurer, L., Lema-Martinez, C., Edmond, A., Jent, N.: A review of near infrared spectroscopy and chemometrics in pharmaceutical technologies. J. Pharm. Biomed. Anal. **44**(1), 683–700 (2007). https://doi.org/10.1016/j.jpba.2007.03.023
11. Yesbaev, A.N., Yessenbayeva, G.A., Ramazanov, M.I.: Investigation of the model for the essentially loaded heat equation. Eurasian Phys. Tech. J. **16**(1), 113–120 (2019). https://doi.org/10.31489/2019No2/105-112
12. Xu, S., Zhao, Y., Wang, M., Shi, X.: Comparison of multivariate methods for estimating selected soil properties from intact soil cores of paddy fields byViseNIR spectroscopy. Geoderma **310**, 29–43 (2018). https://doi.org/10.1016/j.geoderma.2017.09.013
13. Surzhikov, A.P., Pritulov, A.M., Lysenko, E.N., Sokolovskii, A.N., Vlasov, V.A., Vasendina, E.A.: Dependence of lithium-zinc ferrospinel phase composition on the duration of synthesis in an accelerated electron beam. J. Therm. Spray Technol. **110**(2), 733–738 (2012). https://doi.org/10.1007/s10973-011-1947-1
14. Doobae, J., Changmo, A., Jinsu, K., Gwangil, K.: Signal analysis of global financial crises using Fourier series. Physica A **526**, 1212015 (2019). https://doi.org/10.1016/j.physa.2019.04.251
15. Lizhe, T., Jean, J.: Discrete Fourier transform and signal spectrum Chap. 4 in digital signal processing (3rd ed.). Fund. Appl. 91–142 (2019). https://doi.org/10.1016/B978-0-12-815071-9.00004-X
16. Joseph, C., Joseph, J.C.: Practical Radio Frequency Test and Measurement: A Technician's Handbook. Newnes, New York (2002)
17. Meng, C., Hong, S., Xiaoshuai, P., Minzan, L., Qin, Zh., Man, Zh.: Spectrum analyzer development for oxidation diagnosis of Potato semi-finished products. IFAC-Papers On-Line **49**(16), 320–323 (2016). https://doi.org/10.1016/j.ifacol.2016.10.059
18. Turon, V., Janik J., Spetik, R., Sovka, P., Vlcek, M.: Study of ADZT properties for spectral analysis. In: Proceedings of the 11th WSEAS International Conference on Signal Processing, Computational Geometry and Artificial Vision, and Proceedings of the 11th WSEAS International Conference on Systems Theory and Scientific Computation, pp. 171–176 (2011)
19. Franček, P., Petošić, A., Budimir, M., Hrabar, I.: Electrical resonance/antiresonance chaacterization of NDT transducer and possible optimization of impulse excitation signals width and their types. NDT E Int. **106**, 29–41 (2019). https://doi.org/10.1016/j.ndteint.2019.05.005
20. Chen, J., Wu, Y., Yang, C.: Damage assessment of concrete using a non-contact nonlinear wave modulation technique. NDT & E Int. **106**, 1–9 (2019). https://doi.org/10.1016/j.ndteint.2019.05.004
21. Sánchez-Aparicio, L.J., Bautista-De Castro, Á., Conde, B., Carrasco, P., Ramos, L.F.: Non-destructive means and methods for structural diagnosis of masonry arch bridges. Autom. Constr. **104**, 360–382 (2019). https://doi.org/10.1016/j.autcon.2019.04.021

22. Han, Z., Yang, S.: Analysis of voice of healthy aged persons with narrow band spectrum analyzer. Auris Nasus Larynx **17**(1), 45–48 (1990). https://doi.org/10.1016/s0385-8146(12)80020-4
23. Cheng, M., Sun, H., Pei, X., Li, M., Zhang, Q., Zhang, M.: Spectrum analyzer development for oxidation diagnosis of Potato semi-finished products. IFAC-Papers On-Line **49**(16), 320–323 (2016). https://doi.org/10.1016/j.ifacol.2016.10.059