Mechatronic Systems 2

Applications in Material Handling Processes and Robotics

Edited by
Leonid Polishchuk
Orken Mamyrbayev
Konrad Gromaszek

ROUTLEDGE

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Routledge
Taylor & Francis Group
LONDON AND NEW YORK

Cover image: Andrzej Kotyra
First published 2021
by Routledge/Balkema
Schipholweg 107C, 2316 XC Leiden, The Netherlands
e-mail: enquiries@taylorandfrancis.com
www.routledge.com – www.taylorandfrancis.com

Routledge/Balkema is an imprint of the Taylor & Francis Group, an informa business

Library of Congress Cataloging-in-Publication Data
A catalog record has been requested for this book

ISBN: 978-1-032-10585-7 (Hbk)
ISBN: 978-1-032-12621-0 (Pbk)
ISBN: 978-1-003-22544-7 (eBook)

DOI: 10.1201/9781003225447

Typeset in Times New Roman
by codeMantra

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Chapter 23

Improving the precision of the methods for vibration acceleration measurement using micromechanical capacitive accelerometers

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23.1 GENERAL INSTRUCTIONS

The rapid development of systems for control and diagnostics of high-power electric machines (including turbine- and hydro-generators) results from the increase in unit power of the latter and by the amount of equipment installed, as well as by wider opportunities for control using up-to-date measurement methods and computers (Belik, 2018a). In addition, the need for the improvement of methods and means of control and diagnostics rapidly grows due to the increase in the amount of equipment, the rated service life that has expired, while operation thereof continues. Notably, the share of such equipment among high-bower turbine- and hydro-generators has exceeded 50% in the majority of industrialized countries as of early twenty-first century (Alekseev, 2002).

Since vibration-based diagnostics is one of the most promising types of rotating electrical machines' technical state monitoring and diagnostics (Alekseev, 2002; Kukharchuk, 2015; Rao, 2007), while the overwhelming majority of existing vibration velocity and vibration displacement sensors cannot allow measuring low-frequency vibration signals (of just sporadic Hz) (Kukharchuk, 2014), the need emerges in development of brand-new approaches to the solution of this scientific-and-technical problem. Moreover, taking into account the existing trend for digitization of intermediate signals and standardization of data transmission channels between structural units of control and diagnostics systems (Belik, 2018b), which requires the introduction of intermediate programmable low-level units for digital preprocessing

DOI: 10.1201/9781003225447-23

of measured information, the possibility arises to apply analytical methods of these parameters' calculation based on the temporal implementation of vibration acceleration (Kukharchuk, 2015). This allows using, as the means for measurement of such systems' vibro-acoustic signal, exactly the measuring channels of vibration acceleration, the increase in precision of which is a crucial applied-scientific task of practical significance (Belik, 2018b; Kukharchuk, 2019; Hraniak, 2017).

23.2 SETTING THE TASK

Among known primary measuring converters of vibration acceleration, the converters based on micromechanical capacitive accelerometers (sensitive elements) have gained widespread use. The specificity that sets them apart from the sensors based on other operating principles (piezoelectric, mechanical, etc.) lies in the combination of relatively high sensitivity, the linearity of static characteristics, high overload capability, and low weight and dimensions (Kukharchuk, 2019). In such converters, under the action of linear acceleration, the inertial force

$$F = m \cdot a, \tag{23.1}$$

is counterbalanced by spring pressure

$$F = k \cdot x, \tag{23.2}$$

where m – weight, a – acceleration; x – weight displacement relative to the initial position.

By equating (23.1) and (23.2), we obtain

$$a = \frac{k}{m} x = S_a \cdot x \tag{23.3}$$

where $S_a = k/m = const$ – sensitivity, the value of which depends on the sensor's structural parameters (k and m).

As it appears from (23.3), the signal at the output of vibration acceleration sensor that is based on micromechanical capacitive accelerometers will have the additive component associated with gravitational effect of the non-perpendicularity of the installation of an accelerometer on the site. And since it is extremely difficult to ensure strictly vertical position of the sensor during its on-site fastening, a significant error arises during operation of the measuring channels based on micromechanical capacitive sensors of vibration acceleration, where error impairs both the measurement channel's precision and the probability of control and diagnostics in general.

In view of the aforesaid, the objective of the chapter lies in development of a new method for deletion of additive error component during installation of capacitive micromechanical sensors of vibration acceleration, which allows the increase of the precision class of digital measurement means based thereon (Vasilevskyi, 2013; Vasilevskyi, 2015; Vasilevskyi et al., 2018).

23.3 EXPERIMENTAL INVESTIGATION OF VIBRATION ACCELERATION SENSOR AND DIGITAL CHANNEL

In order to carry out an experimental investigation of vibration acceleration sensor, which is based on capacitive micromechanical accelerometers, we used the vibration sensor based on commercially produced accelerometer ADXL322, which has two mutually perpendicular measuring axes and ensures the opportunity to measure vibration accelerations in two mutually perpendicular projections. A batch of sensors so structured currently undergoes pilot operation within vibration monitoring system of Lower Dniester HPP. The generalized structural diagram of proposed vibration acceleration sensor is shown in Figure 23.1.

The following abbreviations are used in Figure 23.1: SEA denotes the sensitive element, in which capacity accelerometer ADXL322 is used; CA-X, CA-Y denote conditioning amplifier units of X and Y measuring axes, respectively; TL – termination set.

In view of the necessity to carry out the entire range of vibration acceleration measurements, the magnification coefficients are chosen for conditioning amplifier units of measuring axes to ensure the sensor's sensitivity along measuring axes X and Y at the level of 0.08 V·s^2/m.

The essence of the experiment consisted in determination of real readings of the primary measuring converter of vibration acceleration at different turning angles of the latter in relation to the axis, which is perpendicular to measuring axes X and Y. In this case, the actual value of static acceleration for measuring axes will be theoretically defined as follows:

$$a_x = -9.81 \cdot \sin(\beta), \tag{23.4}$$

$$a_y = 9.81 \cdot \cos(\beta), \tag{23.5}$$

where a_x and a_y – static acceleration along measuring axes X and Y, respectively; β – the angle of the sensor's incremental turn.

Results of superimposition of theoretical and experimental dependence of error along measuring axes X and Y are shown in Figures 23.2 and 23.3.

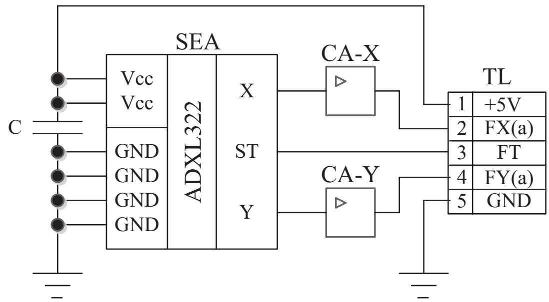

Figure 23.1 Generalized structural diagram of capacitive micromechanical sensor of vibration accelerations.

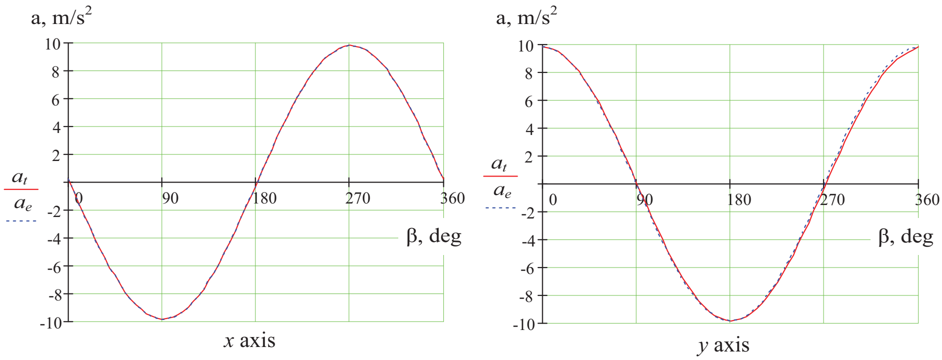

Figure 23.2 Theoretical (at) and empirical (ae) errors of capacitive micromechanical sensor of vibration accelerations associated with the influence of error during installation of vibration acceleration sensor.

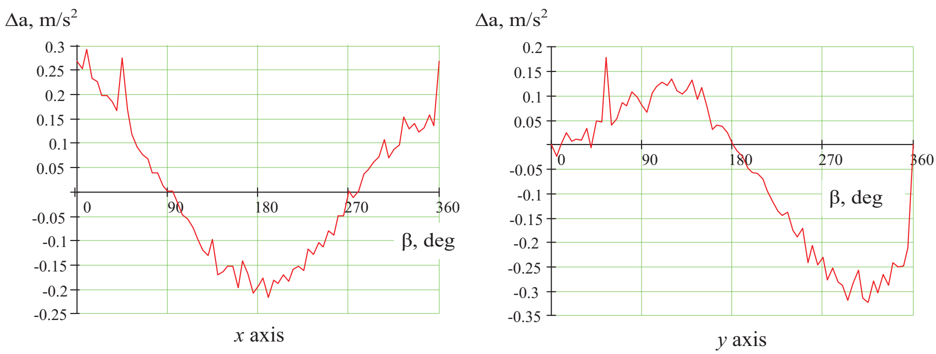

Figure 23.3 Curves of errors of capacitive micromechanical sensor of vibration accelerations.

As it is seen in Figure 23.2, a significant additive error component arises in case of deviation from installation perpendicularity. Such being the case, given the fact that the deviation of ±5 degrees of flat angle between the axis of primary measuring converter and guiding axis of coordinates system (Hraniak, 2017) is deemed normal deviation from perpendicularity of accelerometer installation in production conditions, this error component may reach $0.855\,m/s^2$, being maximal in the horizontal measuring axis (Azarov, 2011, Azarov et al., 2016).

For empirical and theoretical dependencies so obtained, we assessed the absolute error of the theoretical model:

$$\Delta a = a_t - a_e. \tag{23.6}$$

Similarly, we also experimentally established the dependence of an additive component in the absolute error of vibration acceleration's digital channel, which operates jointly with the primary measuring converter under investigation. The generalized structural diagram of vibration accelerations channel is shown in Figure 23.4.

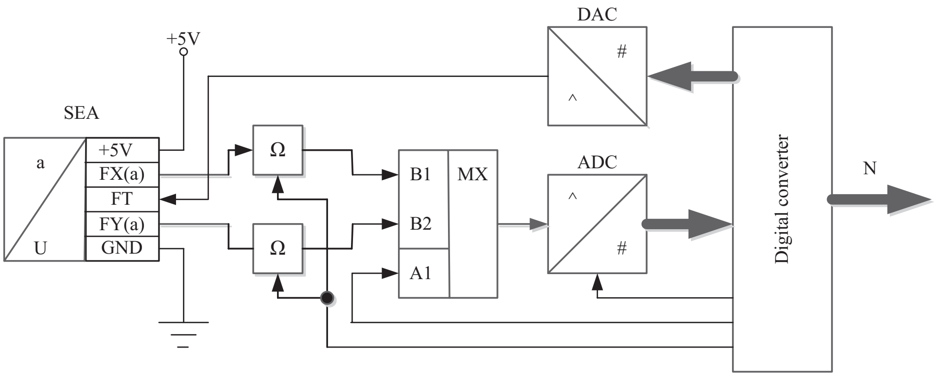

Figure 23.4 Generalized structural diagram of the digital channel of vibration accelerations.

The following abbreviations and legends are used in Figure 23.4: SEA denotes the capacitive micromechanical sensor of vibration accelerations; Ω denotes the analogue memory unit; MX denotes the analogue multiplexer; DAC denotes the digital-to-analogue converter; ADC denotes the analogue-to-digital converter.

The proposed digital channel, the pilot batch of which also undergoes commercial operation within vibration monitoring system of Lower Dniester HPP, has ten-digit ADC and quantizes vibration acceleration along measuring axes X and Y, also having a self-testing mode, which is ensured by supplying the analogue signal of +5 V voltage from the output of digital-to-analogue converter, resulting in a standard output signal of known voltage value being generated at the output of capacitive micromechanical sensor of vibration accelerations, the signal of which allows for self-testing of measuring channel in the process of its operation.

The results of experimental investigation of proposed digital measuring channel of vibrations are shown in Figure 23.5.

It follows from Figures 23.3 and 23.5 that introduction of theoretical adjustments

$$q_x = 9.81 \cdot \sin(\beta), \tag{23.7}$$

$$q_y = -9.81 \cdot \cos(\beta), \tag{23.8}$$

does not make it possible entirely to delete the additive component of error during installation of primary measuring converter. As is seen from the experimental investigations completed, even after introduction thereof the highest value of additive error component will continue to manifest itself in the horizontal axis (this may be axis X or Y depending on the type and spatial orientation of the electrical machine under investigation, and spatial arrangement of capacitive micromechanical accelerometer will also depend on this type and orientation). Yet, within normal range of deviation between the axis of primary measuring converter and the guiding axis of coordinates system not exceeding ±5 degrees of flat angle upon introduction of adjustments (7) and (8), the precision class of measuring channel with absolute error $K_\Delta = \pm\, 0.2\,\mathrm{m/s^2}$ will be achieved (Hraniak, 2017).

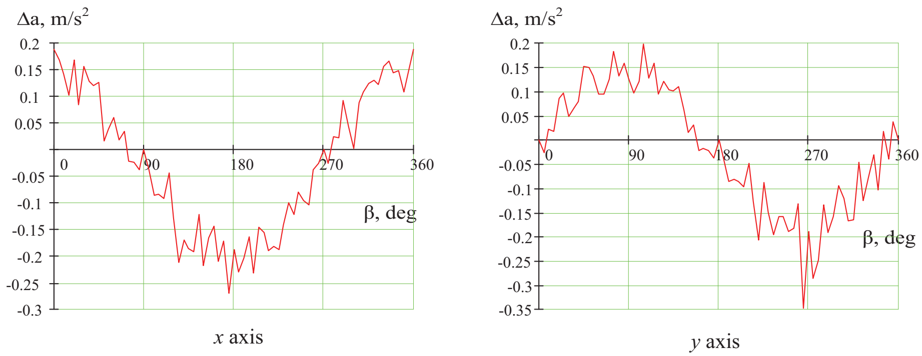

Figure 23.5 Curves of errors of digital channel of vibration accelerations.

Another weak point of using the method of errors calculated based on (23.7) and (23.8) lies in the technical complexity of high-precision determination of β angle at the measurement site, which represents another source of error's growth during the aforementioned measurement means and determines the necessity of search for other ways to delete this error component from the measurement result (Osadchuk et al., 2011a, 2011b, 2012).

23.4 DEVELOPMENT OF HIGH-PRECISION DIGITAL MEASURING CHANNEL OF VIBRATION ACCELERATION

Since the use of theoretical adjustment factors (23.7) and (23.8) does not ensure maximum improvement in precision of the methods of vibration acceleration measurement, we proposed a brand-new approach to deletion of sensor error's additive component that is based on the use of automatic self-calibration algorithm. The generalized structural diagram of intelligent self-calibrating measuring channel of vibration acceleration, which implements the said algorithm, is shown in Figure 23.6 (Osadchuk et al., 2015b).

The measuring channel that provides maximum possible number of measuring axes – three, the number of which may be adjusted depending on the technical requirement applied, is shown in Figure 23.6.

The device operates in the following way (Osadchuk et al., 2015a; Vedmitskyi et al., 2018). Measurement of signal levels at outputs of vibration acceleration sensors 1, in its essence being three-axis modification of primary measuring converter of vibration acceleration shown in Figure 23.1. From the first, second and third outputs of vibration acceleration sensors 1 to the first input of, respectively, the first 2, second 3, and third 4 conditioning amplifiers, the signals are accepted that correspond to the current level of vibration acceleration along the three coordinates axes (X, Y, Z). In the first 2, second 3, and third 4 conditioning amplifiers, the said signals are reduced to the level suitable for operation of analogue-to-digital converter 13 and supplied to the first inputs of the first 5, second 6, and third 7 analogue adder. In analogue adders 5–7, the signals from outputs of sensors of conditioning amplifiers 2–4 are complemented with adjustment

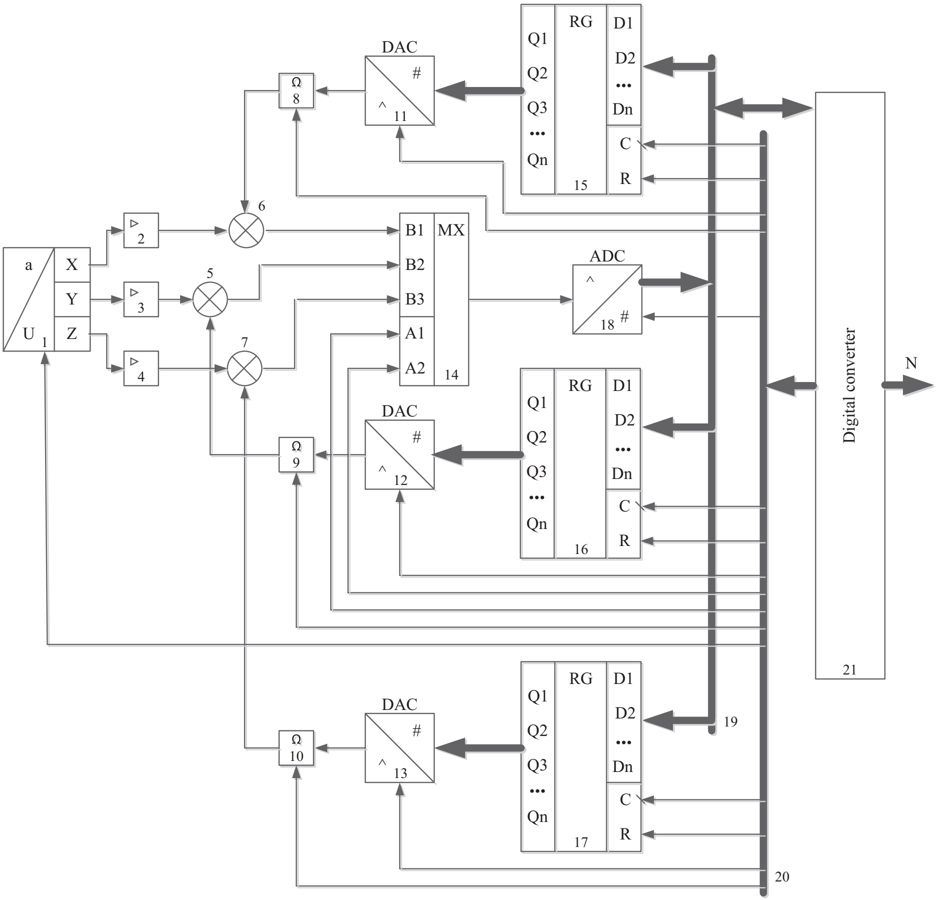

Figure 23.6 The general structural diagram of intelligent self-calibrating measuring channel of vibration acceleration.

signals accepted at the second inputs of analogue adders 5–7. From the outputs of analogue adders 5–7, the signals are supplied to, respectively, the first, second, and third informational inputs of analogue multiplexer 14. Depending on the value of digital signals supplied to the first and second address inputs of analogue multiplexer 14 from of control bus 20, the output of analogue multiplexer 14 accepts a signal from its first, second, or third informational input. From the output of analogue multiplexer 14, the signal arrives at the first input of analogue-to-digital converter 18, in which, upon arrival of triggering signal at its second input from control bus 20, the signal that arrives at its first input undergoes analogue-to-digital conversion. Upon completion of analogue-to-digital conversion, the signal of measuring conversion completion and obtained numerical code are supplied through the output of analogue-to-digital converter 18 to data bus 19, from where it is read by microcontroller 21 through its input-output. In microcontroller 21, obtained digital code is further processed and the current mode of measurement device is selected depending on software-defined algorithm. Guiding signals are supplied to control bus 20 through the first output of microcontroller 21, the signals of which regulate the operation of measurement devices (Yuchshenko & Wójcik, 2014).

The mode of compensation of the error is determined by the error during installation of vibration acceleration sensor 1. The mode of compensation of the installation error is implemented in the beginning of measurement device operation at zero value of vibration acceleration along all three coordinates axes (X, Y, Z). In this mode, levels of signals from the outputs of vibration acceleration sensor 1 are measured at zero signals at other inputs of analogue adders 5–7 according to the algorithm described above. Upon obtaining of the binary code, which is proportional to the signal at the first output of vibration acceleration sensor 1 (coordinate axis X), microcontroller 21 compares this binary code with the standardized value that corresponds to a half of the reference voltage of analogue-to-digital converter 18, and digital adjustment signal is generated. After that, one stepwise signal is supplied to the third input of register 15 through control bus 20, being in its essence the signal of the first register 15 zeroing. Further on, through the input/output of microcontroller 21, the digital adjustment code arrives at data bus 19, through which it is supplied to the first input of the first register 15. With a minimum delay after that, one stepwise signal is supplied through control bus 20 to the second input of the first register 15, this signal serving for it as the signal for memorizing of the digital adjustment signal. From the output of the first register 15, the recorded digital adjustment code constantly arrives at the first input of the first digital-to-analogue converter 11. Upon arrival of the triggering signal from control bus 2 at the second input of the first digital-to-analogue converter 11, the binary code that arrived at its first input undergoes analogue-to-digital conversion. The analogue signal obtained as a result of digital-to-analogue conversion by the first digital-to-analogue converter 11 arrives at the input of the first analogue memory unit, where, upon the signal to its second input from control bus 20, it is memorized and stored during a certain technically justified period, until the next digital-to-analogue conversion. The signal from the output of the first analogue memory unit 8 arrives at the second input of the first analogue adder 6. In such a manner, an adjusted signal is established at the output of the first analogue adder 6, the signal of which equals to a half of the reference voltage of analogue-to-digital converter 18 and contains no error associated with improper installation of vibration acceleration sensor 1.

In a similar way, using the second register 16, the second digital-to-analogue converter 12, and the second analogue memory unit 9, the bias error associated with improper installation of vibration acceleration sensor 1 is deleted from the signal at the second output of vibration acceleration sensor 1 (coordinate axis Y), and using the third register 17, the third digital-to-analogue converter 13, and the third analogue memory unit 10, the error associated with improper installation of vibration acceleration sensor 1 is deleted from the signal at the third output of vibration acceleration sensor 1 (coordinate axis Z)

Measurement mode. In this mode, instantaneous values of vibration acceleration are actually measured. This mode provides for measurement of analogue values of signals proportional to the instantaneous values of vibration acceleration along coordinate axes X, Y, Z, which arrive from the outputs of vibration acceleration sensors 1 according to the algorithm described above. Upon obtaining the binary code by microcontroller 21 according to known transformation equations, it calculates the current value of vibration acceleration. Obtained value of vibration acceleration is extracted through the second output of microcontroller 21. Upon completion of the procedure for extraction of the obtained value of vibration acceleration, vibration acceleration measurement for the next coordinate axis is launched in the current coordinates axis. Upon completion of vibration acceleration measurement in all three coordinate axes, the measurement procedure is repeated in a cyclic manner.

Self-testing mode. In this mode, the guiding signal arrives at the input of vibration acceleration sensor 1 from control bus 20, and after supply of this signal, the voltage of a priori known amplitude is established at all outputs of vibration acceleration sensor 1. After that, signals are measured at each output of vibration acceleration sensor 1 according to the algorithm described above, and the measurement result is compared with a priori known voltage value. Should these values disagree, the decision is made about system failure with a respective signal sent through the second output of microcontroller 21. Should a measured value agree with a priori known voltage value, the decision is made about the measurement device's suitability for further operation.

23.5 CONCLUSIONS

Obtained were the mathematical models of additive error components for non-perpendicularity of capacitive micromechanical accelerometer installation. It was shown that, within a normal range of deviation between the axis of the primary measuring converter and the guiding axis of coordinates system, the deviation of which should not exceed ±5 degrees of flat angle in case of correct installation, the value of its error will be maximum in the horizontal measuring axis and may reach $0.855\,m/s^2$.

Investigated was the possibility to use calculated values of errors to improve the precision of the vibration acceleration measurement methods based on capacitive micromechanical accelerometers. It was experimentally proved that, when using the calculated values of errors, an unaccounted error component remains, with its maximum value in the horizontal measuring axis to reach the values of $\pm 0.2\,m/s^2$.

Proposed was the operation algorithm and structural diagram of the intelligent self-calibrating measuring vibration channel that ensures an entire automatic deletion of the additive error component from vibration measurement results and provides for an opportunity of self-testing in the process of operation.

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