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CALIBRATION OF OPTICAL DISPLACEMENT SENSOR SYSTEM

The optical displacement sensor was selected for accurate length measurement. The aim of this article is to determine the mathematical measurement model for displacement measurement using an assembled measuring chain by calibration. The uncertainty balance for the assembled measuring chain is determined in the next part of this article.
Keywords: *uncertainty of measurement, displacement, error, gauge, reliability.*
Fig.: 10. References: 19.

Urgency of the research. In technical and scientific practice, displacement sensors are often used to measure the displacement of moving parts of equipment. Few authors will solve the problem of measurement uncertainty in their applications at the same time. The measurement uncertainty declares the extent to which it is possible to believe the data obtained from the displacement measurement process using the displacement sensor. It often happens that the measurement result has a great measurement uncertainty and thus the measurement is devalued. Therefore, it is necessary to perform an analysis of measurement uncertainty before the actual implementation of the sensor in the target application. The solution is intended for the field of displacement measurement in mechatronic products, where displacement information with high measurement uncertainty can cause product malfunction.

Target setting. Measuring lengths and displacements is one of the most common variables. A large group of sensors measures length by direct contact with a moving object such as a potentiometric sensor, a linear variable differential transformer sensor, a linear encoder sensor, a magnetostrictive sensor, etc. Another group is contactless sensors such as capacitive sensor, inductive sensor, ultrasonic sensor, optical sensor, etc. [1-8].

An optical sensor using the principle of triangulation was chosen to measure the distance. It is a low-cost sensor with an analogue output in the form of voltage up to 5V. According to the data sheet, this sensor has a nonlinear static characteristic. Since it is an optical sensor, this characteristic depends on the color and quality of the reflecting surface of the sensor. The static characteristics of the evaluated sensor will therefore be determined experimentally. The manufacturer of the selected tested sensor does not state the measurement uncertainty or any other form of expression of the maximum measurement error. In this case, experimental verification is the only way to determine the measurement uncertainty.

Analysis of existing research and publications. There are a number of different methods for calibrating displacement sensors. Each calibration method provides a degree of calibration uncertainty and requires certain equipment costs and the actual implementation of the calibration process [1-6].

The development of semi-autonomous metrological devices, capable of calibrating variety of linear displacement sensors has been done, such as Linear Variable Differential Transformers (LVDT), string potentiometers, laser displacement sensors and other. Data acquisition equipment that could be used for measuring objects of various shapes and sizes are already available; however, devices specifically tailored for the calibration of displacement sensors are not currently offered [7].

A new in situ absolute calibration method for a displacement sensor is proposed, and a calibration system is developed. This new method is capable of determining not only the linearity error but also the mean sensitivity (inclination of linear calibration line) on the base of the wavelength. The new measurement system consists of a compact laser interferometer and a previously developed in situ calibration system. The laser interferometer is used only to determine the necessary displacement shift quantity with an integer multiple of half wavelengths of the laser light source [8].

Displacement measuring sensors play an essential role in all aspects of dimensional metrology. They can be used for direct displacement measurements but more often they are part of a measurement system. In order to achieve traceable measurements that can be related to the meter, these sensors must be calibrated against a reference standard that is more noise- and error-free than the sensor under test [9].

The measurement uncertainty and linearity of a bundle fibre-optic displacement sensor were studied on a wide range of displacements using experimental and simulation approaches [10].

The mentioned methodology does not address the complex methodology of evaluation of measurement uncertainties.

Article objective. The aim of the article is to experimentally test the selected sensor and at the same time to solve the problem of measurement errors and measurement uncertainty. The aim is to determine the transformation static characteristic and on its basis it is possible to create a calibration characteristic. It is also possible to determine histograms from the set of measurements to determine the law of probability of distribution of measured values. From the calibration characteristic, a mathematical model is then created to determine the displacement from the measured values of the output electrical voltage of the sensor. The resulting uncertainty of the displacement measurement can then be determined.

General overview of the system. The evaluated sensor consists of an infrared LED and a photosensitive detector. The infrared beam is aimed at the measured object at a certain angle, which impinges on the surface of the measured object and is reflected from it back to the surface of the photodetector. The point of impact of the infrared beam depends on the distance of the measured object, which results from the principle of triangulation (fig. 1). The output of the sensor is then an analogue voltage, which corresponds to the distance of the detected object. The range of the sensor is up to 300 mm, while at shorter distances it is possible to expect ambiguous behaviour of the sensor. Wavelength of the infrared light emitted is (870 ± 70) nm.

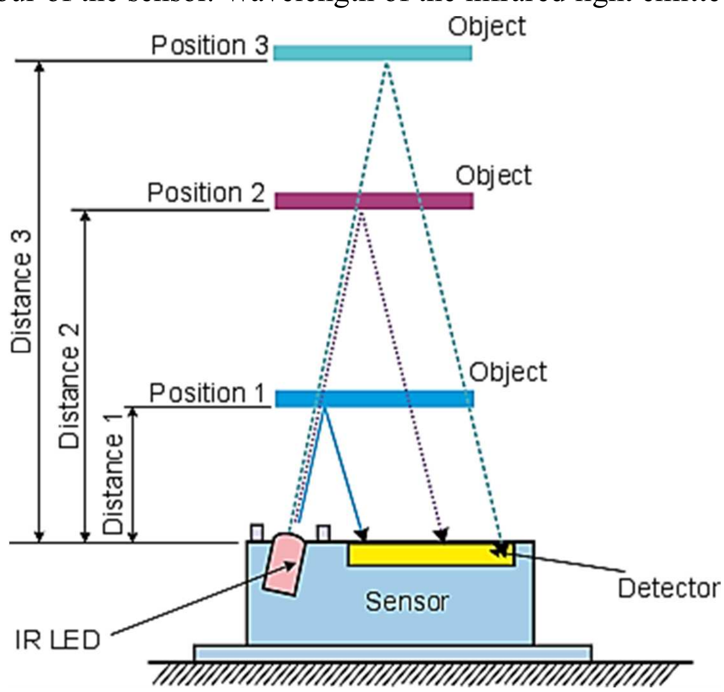

Fig. 1. Triangulation principle of optical distance sensor

The measuring chain was assembled on a sliding mechanism of a linear metroscope, a reflecting surface was placed on a stationary base of the metroscope and the sensor moved on a linear guide of the metroscope. The relative distance between the sensor and the reflecting surface was set using length gauge blocks.

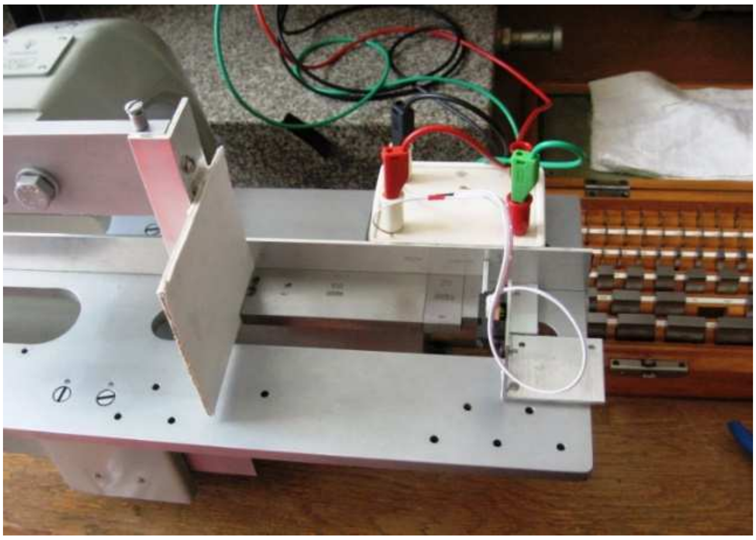

Fig. 2. Measurement chain for distance measurement

The systematic errors and uncertainties of the scale blocks are summarized in the graph (fig. 3).

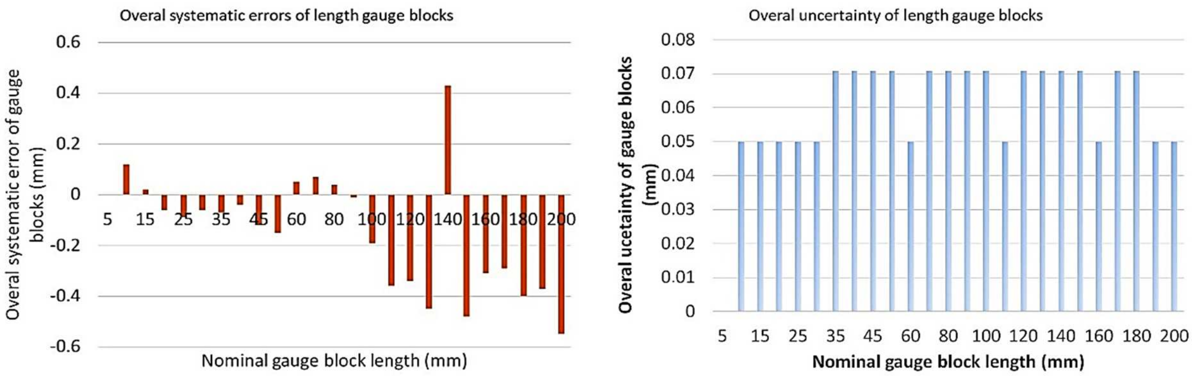

Fig. 3. Systematic errors and uncertainty of the used set of length gauge blocks

Twenty-five distance values set by gauge blocks were selected in the entire range of the sensor. For each such value, ten measurements were performed under unchanged measurement conditions, and the graph shows the mean value of the measured measurements, which is displayed as a point in the graph (fig. 4). It can be seen from the graph that the voltage values have a breaking point for a distance value of 30 mm. The whole range of experimentally determined points is quite complicated. Therefore, a strategy was chosen in which the experimental data were approximated by two functions with a switching point of 30 mm (fig. 4). Polynomial functions were used to approximate both parts of the experimental data. For distance measurement, such a course is disadvantageous because two different values of distance correspond to one value of electrical voltage. This ambiguity can be a problem when processing the measured values. From a practical point of view, it is therefore more advantageous to implement the measuring chain so that only the measuring area from the value of 30 mm is used for the measurement.

The stable properties and good repeatability of the measurement are also indicated by the displayed sequence of measured values (Fig. 5), which deviate only minimally from the mean value of the measured samples. These measured values (Fig. 6) were measured 100 times for 4 selected values of the distance of the reflecting surface from the sensor.

Furthermore, it is possible to evaluate the combined uncertainties for measuring the output voltage of the sensor (Fig. 6), while the maximum value of this uncertainty is 0.0054V [11-18].

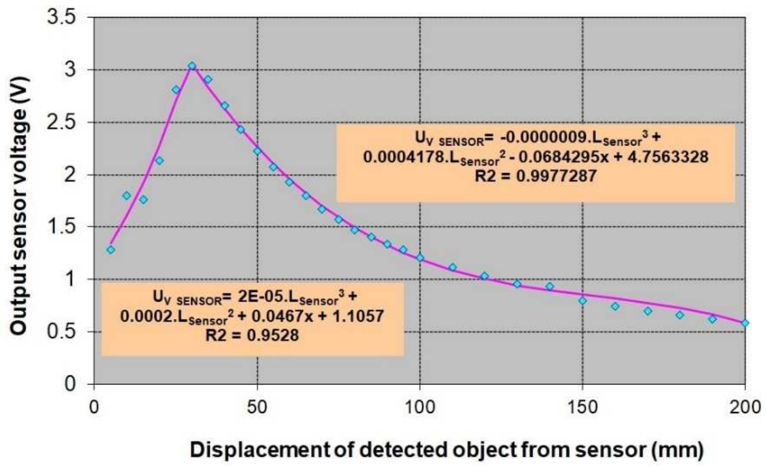

Fig. 4. Voltage values at the sensor output

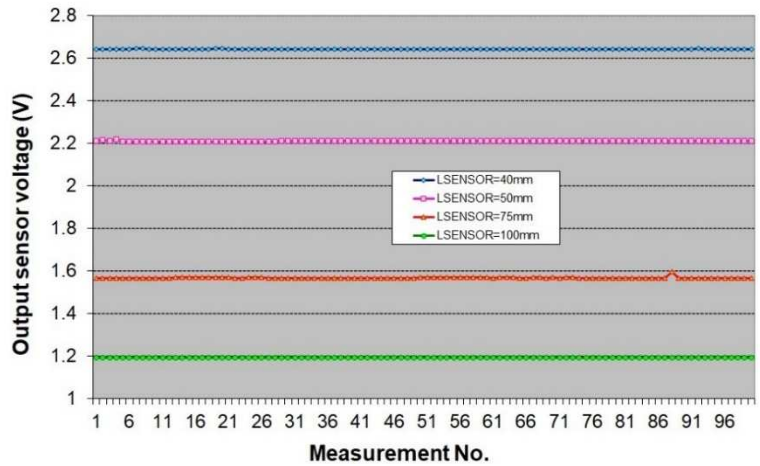

Fig. 5. Sequence of measured values of electrical voltage at the sensor output

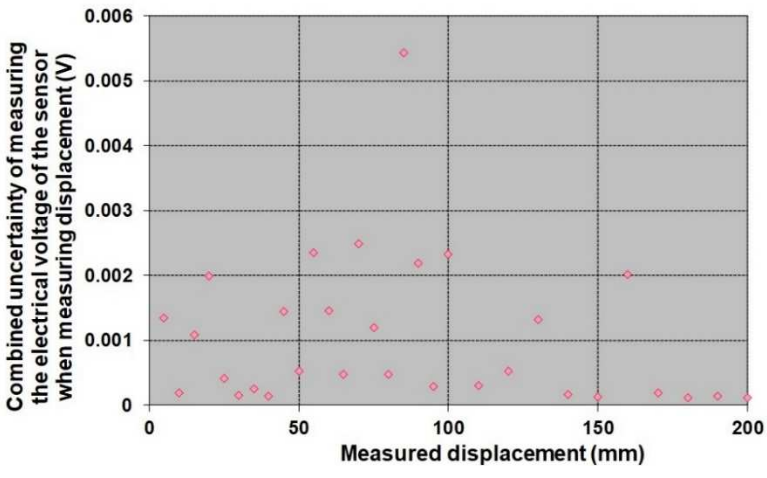

Fig. 6. Combined uncertainty of measuring the output electrical voltage of the sensor when measuring the distance from the reflecting surface

A digital multimeter was used to measure the electrical voltage, for which the manufacturer shows the maximum permissible error of the meter:

$$Z_{\max HP10V} = \pm(0.002\%\_of\_readvalue + 0.0005\%\_of\_range) \quad (1)$$

If the maximum measured value and the measuring range are considered, then the maximum permissible error of measuring the voltage with a multimeter is $Z_{\max HP10V} = \pm 0.00011\text{V}$.

The measured data sets were tested by normality tests, the results of which show that it is possible to reject the hypothesis that the set of measured values follows the normal law of distribution. Distribution of values in displayed histograms Fig. 7 is relatively unstable and thus an approximation by uniform distribution will be used in terms of measurement and evaluation of measurement uncertainties. Thus, the same probability of any deviation in the range of measured values will be assumed. For the purpose of evaluating the measurement, no information is available on the distribution of the probability of occurrence of deviations and therefore there is no reason to prefer certain deviations. In the following, a uniform rectangular distribution of the measured values will be considered.

The optimal number of class intervals for histogram formation (Fig. 7) can be obtained by re-applying Scott's relation [19]:

$$k_{hist} = \frac{R_R}{3.49 \cdot s} \cdot n_M^{\frac{1}{3}} \tag{2}$$

where R_R - range of the set of values; s - standard deviation; n_M - number of measured values.

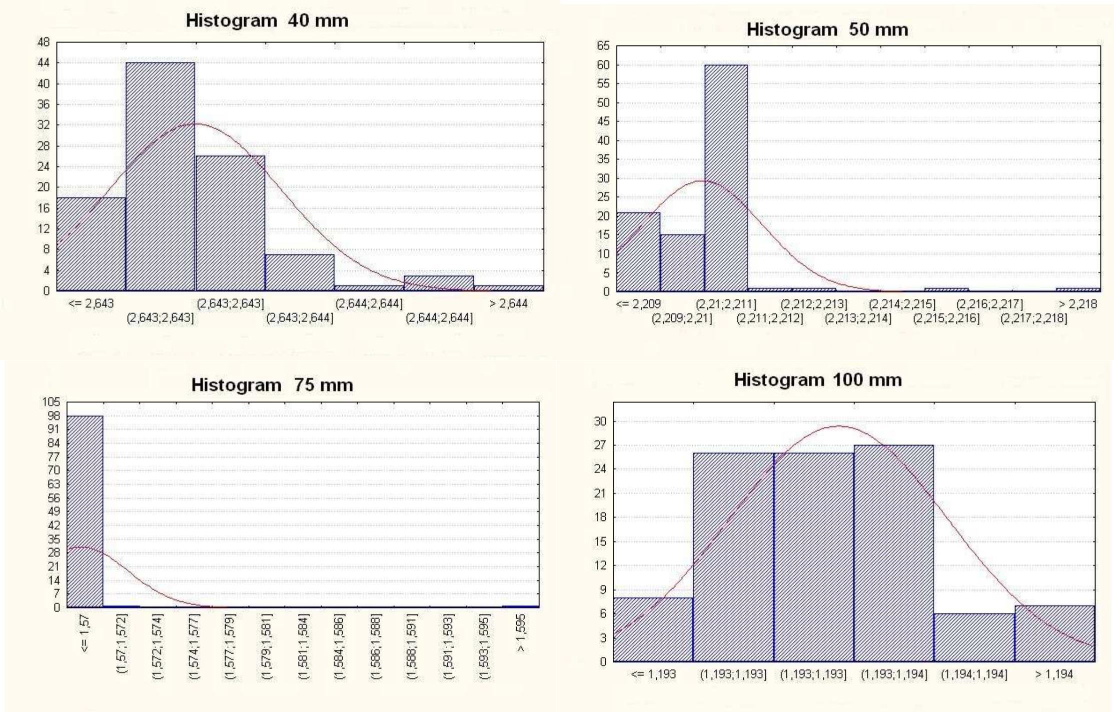

Fig. 7. Histograms of the frequency of measured values at the sensor output

Assuming a uniform rectangular law of distribution of measured values, at the level of significance of 0.95 when considering the coefficient of expansion, then the standard uncertainty determined by method B is equal to:

$$u_{BHP10V} = \frac{Z_{\max HP10V}}{\sqrt{3}} = 0.0000641\text{V} \tag{3}$$

Sampling standard deviations were used to determine the standard uncertainties determined by Method A. The combined uncertainty was evaluated by combining the standard uncertainties determined by Method A and Method B. The expanded uncertainty is affected by one component of the uncertainty for which a uniform distribution is considered. A coefficient of expansion of 1.65 (0.95) was therefore used to provide a confidence level of approximately 95%. Standard measurement uncertainty was determined in accordance with EA-4/02. The maximum expanded uncertainty is at a distance of 85 mm of the sensor from the reflecting surface. At this point, the expanded uncertainty of the measured voltage value at the sensor output becomes 0.0094 V.

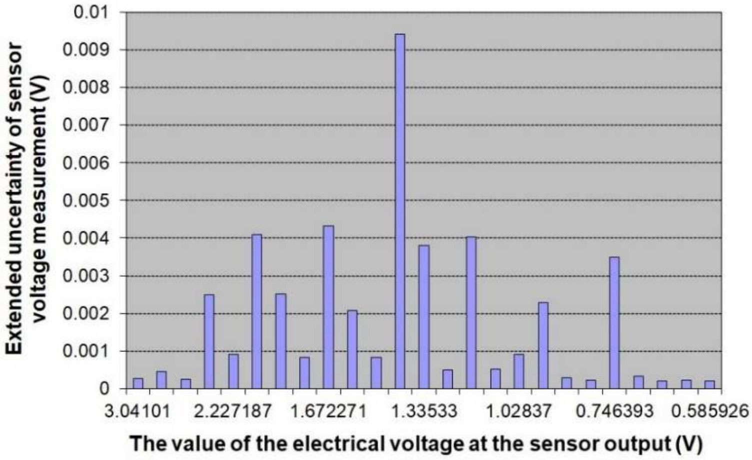

Fig. 8. Dependence of the extended uncertainty of measuring the electrical voltage of the sensor on the value of the electrical voltage at the sensor output

From the measured range of the sensor, a working area (Fig. 9) was selected that can be used to determine the displacement of the measured object (40 to 70 mm): When choosing this area, the expanded uncertainties of measuring the output electrical voltage of the sensor were taken into account (2.65992; 1.67227V), the steepness of the dependence (ie the local sensitivity of the sensor), the residual deviations from the regression mathematical model and the influence of the optical properties of the sensor and the environment on the function of the sensor.

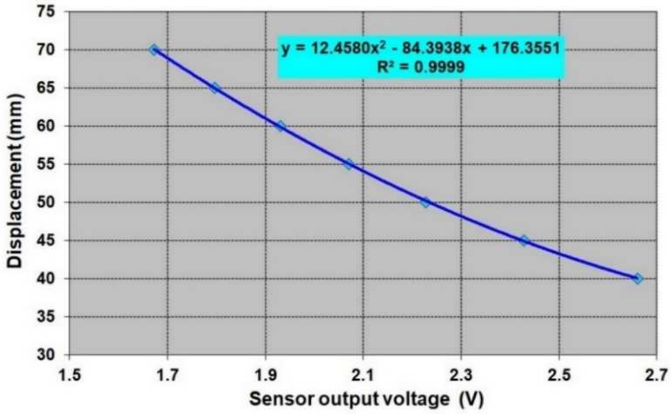

Fig. 9. Calibration characteristic of the selected area from the sensor range

The calibration characteristic (Fig. 9) of this selected working area was approximated by a regression mathematical model in the form of a second degree polynomial. The determination index of this mathematical model (0.9999) confirms the suitability of the selected model.

Based on regression analysis, a second degree polynomial in the form of:

$$y = a + b \cdot x + c \cdot x^2 \tag{4}$$

then it is possible to determine a matrix of estimates of the parameters of the regression dependence model:

$$\hat{a} = \left(A^T A\right)^{-1} A^T t = \begin{pmatrix} 176.35511 \\ -84.39384 \\ 12.45803 \end{pmatrix} \tag{5}$$

The covariance matrix of the vector of model parameter estimates has the form:

$$U_{\hat{a}} = \hat{\sigma}^2 \left(A^T A\right)^{-1} \tag{6}$$

where the selective residual variance has the value: $\hat{\sigma}^2 = 0.017909253$ V.

After substituting it is possible to obtain a covariance matrix:

$$U_{\hat{a}} = \begin{pmatrix} 6.07710 & -5.70027 & 1.30614 \\ -5.70027 & 5.37278 & -1.23663 \\ 1.30614 & -1.23663 & 0.28592 \end{pmatrix} \quad (7)$$

The elements in the diagonal of the covariance matrix are the squares of the standard uncertainties of the model parameters (regression coefficients):

$\hat{a} = 176.35511\text{mm}$	$u_{\hat{a}} = 2.46518\text{mm}$	$u_{\hat{a},\hat{b}} = -5.70027\text{mm}^2/\text{V}$
$\hat{b} = -84.39384\text{mm/V}$	$u_{\hat{b}} = 2.31793\text{mm/V}$	$u_{\hat{b},\hat{c}} = -1.23663\text{mm}^2/\text{V}^3$
$\hat{c} = 12.45803\text{mm/V}^2$	$u_{\hat{c}} = 0.53471\text{mm/V}^2$	$u_{\hat{a},\hat{c}} = 1.30614\text{mm}^2/\text{V}^2$

To determine the uncertainty of measuring *x*, it is necessary to apply the law of uncertainty propagation [17] to the model ($y = a + bx + cx^2$):

potom neistota výstupnej veličiny v obecnom tvare je:

$$u_y^2 = (u_{\hat{a}}^2 + x^2 u_{\hat{b}}^2 + x^4 u_{\hat{c}}^2) + (b + 2x \cdot c)^2 \cdot u_x^2 + 2 \cdot (x \cdot u_{\hat{a},\hat{b}} + x^2 u_{\hat{a},\hat{c}} + x^3 u_{\hat{b},\hat{c}}) \quad (8)$$

wherein the output variable *y* in this case of the calibration characteristic will be the measured distance of the sensor from the reflecting surface. It is possible to substitute the values of the output electrical voltage of the sensor for the input value *x*. From these values, it is then possible to determine the uncertainty determined by method A of the measured distance values.

It is then possible to determine the combined uncertainties (Fig. 10) for measuring the displacement with the sensor. If the sensor is used in a range of values (from 40 mm to 65 mm), the combined uncertainty value will be below 0.16 mm.

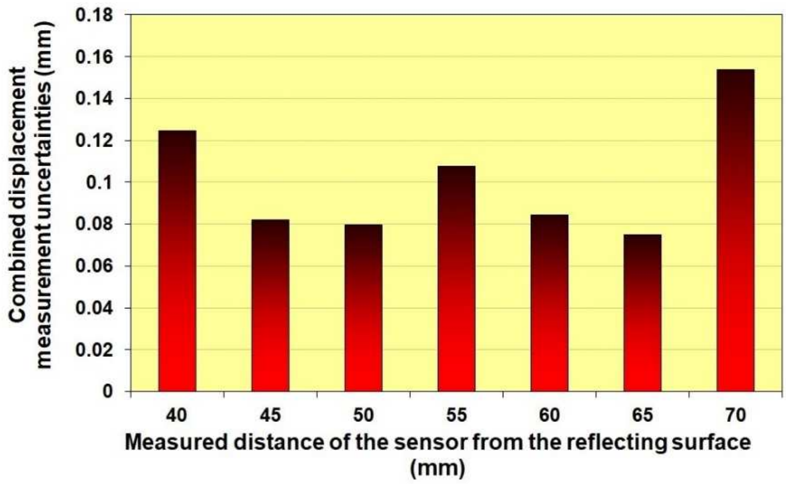

Fig. 10. Combined uncertainties for sensor displacement measurement

Conclusions. Experimental analysis of the tested sensor showed that the built measuring chain with this sensor has a combined measurement uncertainty of at most 0.16 mm. Tests of repeatability of measurement and subsequent graphical histograms showed that the probability of distribution of measured values is governed by the uniform law of distribution of values. In this paper, a mathematical model of the calibration characteristic was also obtained from the experimental data, which can be used to determine the displacement value from the values of the measured output electrical voltage of the sensor. This mathematical model has a practical use, because we can implement it directly into the computer system for data processing and, in addition, we have measurement uncertainty. The resulting measurement uncertainty can be further improved by selecting another meter to measure the output voltage at the sensor output.

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References

1. Doebelin, E. (2003). *Measurement systems Application & Design*, 5th ed.; Mc Graw-Hill College: New York, NY, USA, p. 768.
2. Leach, R. (2014). *Displacement measurement. In Fundamental Principles of Engineering Nanometrology*; Elsevier Science: Amsterdam, The Netherlands, pp. 95–132.
3. Cosijns, S.J.A.G.; Jansen, M.J.; Haitjema, H. (2018). *Advanced Optical Incremental Sensors: Encoders and Interferometers*. In Smart Sensors and MEMS: Intelligent Sensing Devices and Microsystems for Industrial Applications, 2nd ed.; Elsevier Inc.: Philadelphia, PA, USA, pp. 245–290.
4. Hermann, G. (2012). *Design of a calibration system for 1D measuring probes*. In Proceedings of the IEEE 16th International Conference on Intelligent Engineering Systems, INES 2012, Lisbon, Portugal, 13–15 June 2012; pp. 157–160.
5. Jing, □.; Gao, H.T.; Ye, □.Y.; Gu, F.Q.; Li, D.S., (2010). Application of laser sensors for on-line calibration of displacement transducers. *Int. Soc. Opt. Eng*. 2010.
6. Zhang, S.; Kiyono, S. (2001). Absolute calibration method for displacement sensors. *Meas. J. Int. Meas. Confed*. 2001, 29, 11–20.
7. Lagozzino, S., Simic, M., Dudkiewicz, D. (2019). Development of a novel system for linear displacement sensor calibration. *Energy Procedia*. Volume 160, February 2019, Pages 519-525. https://doi.org/10.1016/j.egypro.2019.02.201.
8. Zhang, S., Kiyono, S.: An absolute calibration method for displacement sensors. *Measurement*. Volume 29, Issue 1, January 2001, Pages 11-20. https://doi.org/10.1016/S0263-2241(00)00023-3.
9. Haitjema, H. (2020). The Calibration of Displacement Sensors. *Sensors*, MDPI, Volume 20, 584. https://doi.org/10.3390/s20030584.
10. Nevshupa, R., Conte, M. and van Rijn, C. (2013). Measurement uncertainty of a fibre-optic displacement sensor. *Measurement Science and Technology*. Vol. 24, Number 3, 2013. IOP Publishing Ltd.
11. Taylor, J. R., (1999). *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*. 1999. University Science Books.
12. EA-4/02 M:2013 *Evaluation of the Uncertainty of Measurement In Calibration*. Publication Reference. European Accreditation Laboratory Committee. September 2013 rev 01. cited August, 8th, 2019. Available online: https://european-accreditation.org/wp-content/uploads/2018/10/ea-4-02-m-rev01-september-2013.pdf.
13. JCGM 200:2012, *International vocabulary of metrology –Basic and general concepts and associated terms* (*VIM*), 3rdEdition (BIPM, 2012).
14. JCGM 100 – *Evaluation of measurement data – Guide to the expression of uncertainty in measurement* (ISO/IEC Guide 98-3). First edition September 2008. Available online: http://www.iso.org/sites/JCGM/GUM-JCGM100.htm; http://www.bipm.org/en/publications/guides/gum_print.html.
15. MSA-L/11 *Guidelines on the expressions of uncertainty in quantitative testing* (In Slovak) (EA - 4/16: 2003). Guidelines on the expression of uncertainty in quantitative testing. Slovak national accreditation service, SNAS BRATISLAVA, august 2009.
16. MSA–L/12 *Expression of the uncertainty of measurement in calibration* (In Slovak) (EA-4/02) - Expression of the uncertainty of measurement in calibration, Slovak national accreditation service, SNAS BRATISLAVA, november 2010.
17. Wimmer, G., Palenčár, R., Witkovský, V. (2001). *Stochastic models of measurement*. (In Slovak) Graphic Studio Ing. Peter Juriga, Ľ. Fullu 13, 841 05 Bratislava. 1st. ed., 2001. ISBN 80-968449-2-□.

18. Chudý, V., Palenčár, R., Kureková, E., Halaj, M. (1999). *Measurement of technical quantities* (in Slovak). Edition of STU, 1st. ed., 1999. ISBN 80-227-1275-2.

19. Scott, David W. (1979). "On optimal and data-based histograms". *Biometrika*, Vol. 66, No. 3, pp. 605–610. DOI:10.1093/biomet/66.3.605.

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КАЛІБРУВАННЯ СИСТЕМИ ОПТИЧНОГО ДАТЧИКА ПЕРЕМІЩЕННЯ

У технічній і науковій практиці датчики переміщення часто використовуються для вимірювання зміщення рухомих частин обладнання. Їх можна використовувати для прямих вимірювань зміщення, але частіше вони є частиною системи вимірювання. Невизначеність вимірювання визначає ступінь достовірності даних, що отримані в процесі вимірювання з використанням датчика. Внаслідок великої похибки результат вимірювання знецінюється. Тому необхідно виконати аналіз невизначеності вимірювання до фактичного впровадження датчика в цільовий додаток. Отже, розв'язувана задача призначена для області вимірювання зміщення в мехатронних виробах, де інформація про зміщення з високою невизначеністю вимірювання недопустима.

Для вимірювання відстані був обраний оптичний датчик, який використовує принцип тріангуляції та має нелінійну статичну характеристику. Оскільки це оптичний датчик, його характеристика залежить від кольору і якості поверхні, яку контролює датчик.

Метою статті є експериментальна перевірка оптичного датчика зміщення і одночасно вирішення проблеми похибки вимірювання і невизначеності вимірювання. Завдання роботи полягало в тому, щоб визначити статичну характеристику перетворення сигналу, і з неї створити калибрувальну характеристику. Визначено гістограми з вибірки вимірювань для визначення закону розподілу ймовірності виміряних значень. На основі калібрувальної характеристики створено математичну модель для визначення зміщення по виміряним значенням вихідної електричної напруги датчика. Визначено результуючу невизначеність вимірювання зміщення. У статті не досліджувався вплив температури навколишнього середовища на результат вимірювання, а також не досліджувався вплив кольору контрольованої поверхні виявленого об'єкту, зміщення якого вимірюється. Ефект зміни нахилу поверхні виявленого об'єкту, що відбиває промінь датчика, також не досліджувався. Оптичний датчик зміщення був обраний для точного вимірювання довжини.

Експериментальний аналіз тестованого датчика показав, що побудований вимірювальний ланцюг з цим датчиком має сумарну похибку вимірювань не більше 0,16 мм. Тести повторюваності вимірювань і подальших графічних гістограм показали, що ймовірність розподілу виміряних значень підпорядковується єдиному закону розподілу значень. Математична модель калібрувальної характеристики також була отримана з експериментальних даних, які можуть бути використані для визначення величини зміщення зі значень виміряної вихідної електричної напруги датчика. Отримана математична модель має практичне застосування, оскільки може бути реалізована безпосередньо в комп'ютерній системі обробки даних з відомою невизначеністю вимірювання. Результуючу похибку вимірювання можна додатково поліпшити, вибравши інший вимірювач для визначення вихідної напруги на виході датчика.

Ключові слова: *невизначеність вимірювання; переміщення; похибка; калібр; надійність.*
Fig.: 10. References: 19.

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