Analysis of instrumental errors influence on the accuracy of instruments for measuring parameters of moving objects

Dimitar Dichev
Department of Machine and Precision Engineering
Technical University of Gabrovo
Gabrovo, Bulgaria
dichevd@abv.bg

Dimitar Diakov
Department of Precision Engineering and Measurement Instruments
Technical University of Sofia
Sofia, Bulgaria
diakov@tu-sofia.bg

Ralitza Dicheva
Department of Precision Engineering and Measurement Instruments
Technical University of Sofia
Sofia, Bulgaria
ralitza94@abv.bg

Iliya Zhelezarov
Department of Machine and Precision Engineering
Technical University of Gabrovo
Gabrovo, Bulgaria
izhel@tugab.bg

Oleksandr Kupriyanov
Department of Information Computer Technologies and Mathematics
Ukrainian Engineering Pedagogics Academy
Kharkiv, Ukraine
a_kupriyanov@uipa.edu.ua

***Abstract*— This paper presents the results of the analysis of the influence of instrumental and methodical errors on the accuracy of instruments for measuring parameters of moving objects. The analysis is based on a new method for examining those errors which allows the static measurement mode to be considered as a separate measuring procedure. Based on that method there have been derived mathematical models for determining and investigating the probabilistic characteristics of the instrumental error of measuring instruments, whose output signal is quantized in value. In addition, the paper presents the results from experimental investigation of the methodical and instrumental components of an instrument for measuring ship pitch.**

Keywords*— *Dynamic measurement error; measurement in dynamic mode, inertial impacts, moving objects parameters.

I. INTRODUCTION

The task related to improvement of measurement accuracy is among the major ones in metrological science. Successful solution of this task is one of the most important prerequisites for further improvement of measuring instruments. Very often the problem related to ensuring the necessary measurement accuracy requires the solution of tasks different in type and nature. For example, measurements of moving objects parameters carried out in dynamic mode of operation are characterized by a dynamic error which is largely due to the inertial impacts related to the primary transducer and the existing random output noises [1, 2]. This particular component of the error of the measuring instruments very often turns out to be much greater than all the other components. This is the reason why research in this area focuses primarily on the inertial component of dynamic error and its noise components [3-6].

Alternatively, underestimating the influence of the instrumental and methodical errors on the measurement accuracy in dynamic mode can lead to a significant deviation in the result. In addition, it is necessary to keep in mind that the parameters of moving objects being measured are dynamically changing time dependent quantities and their values are most accurately defined by random functions of time [7-9]. The random nature of instrumental errors of measuring instruments and their random projection on the time coordinate of the measured dynamic quantity lead to a number of difficulties of theoretical and experimental nature in determining the influence of these inaccuracies on the measurement accuracy [10].

All of the above proves the need for defining a mathematical model of the error component in measuring dynamically changing quantities, caused by methodical and instrumental errors of measuring instruments.

II. DIAGRAM FOR DEFINING AND INVESTIGATING MEASURING INSTRUMENTS ACCURACY IN DYNAMIC MODE OF OPERATION

Measurements in dynamic mode differ from those carried out in static mode of operation. To define the unit of measurement in dynamic mode it is necessary to define not only the unit of the quantity being measured but also its exact fixation on the time coordinate and to present the result as a function of time with all necessary characteristics that determine its properties [11].

Generally, devices for measuring moving objects parameters have sensitive elements whose inertial characteristics are significantly influenced by the rate of change of the quantity being measured and the additional impacts involved in the measuring process. Due to the dynamic character of the quantity being measured and all the other impacts the sensitive elements change their relative motion or their zero coordinate beyond the tolerances. All this leads to the appearance of dynamic errors, the values of which in some cases are commensurate with the values of the quantity being measured [12].

978-1-7281-2213-7/19/$31.00 ©2021 IEEE

At the same time, however, errors of instrumental or methodical origin accrue in the measurement result [13-17]. In most cases, these errors have values that are significantly smaller than the dynamic errors. However, undetected and uninvestigated instrumental and methodical errors in the process of measuring instruments design can cause significant difficulties and unpredictable deviations of the measurement result during operation, inspection and calibration of the instruments [18-20].

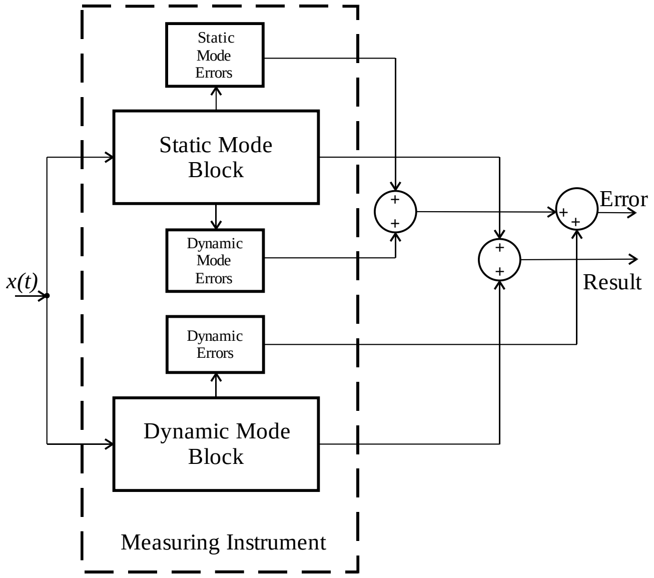

Fig.1. Block diagram for determining and investigating accuracy of measuring instruments in dynamic mode of operation

Therefore, the present paper proposes a new scheme for determining and investigating measuring instruments accuracy in dynamic mode of operation. In the block diagram presented in fig. 1, the measuring instrument is structured, though conditionally, in two parallel channels. The first channel allows investigation and definition of accuracy in static mode. Measurement accuracy in this channel depends on two types of errors. Errors of the first type allow their definition and investigation to be carried out in static mode and their projection in the measurement result does not depend on the dynamically changing function of the signal being measured. In contrast, the second type of errors can be defined in static mode, but their projection in the measurement result depends on the temporal change of the signal being measured.

The second channel is for defining and investigating the dynamic error, which does not take into account instrumental and methodical errors of measuring instrument. The present paper does not aim to investigate this channel.

III. CHARACTERISTICS OF METHODICAL AND INSTRUMENTAL ERRORS

The main part of methodical errors of instruments for measuring moving objects parameters are due to quantization and discretization of measuring signals. Depending on the nature of change of the informative parameter the signals used in instruments for measuring moving objects parameters are divided into four groups:

- continuous-time and continuous-value signals;
- continuous-time and quantized-value signals;
- discrete-time sampling and continuous-value signals;
- discrete-time sampling and quantized-value signals.

A large part of modern measuring instruments for defining moving objects parameters use digital encoders in their measuring circuits. Absolute rotary encoders have significant advantages given the conditions in which they operate. They possess high accuracy, high speed, noise resistance and informative function conversion reliability. This is the reason why the present paper will consider methodical errors caused by value quantization of continuous-time measuring signals. Fig.2 shows that the projection of this type of errors in the measurement result depends on the temporal change of the signal being measured.

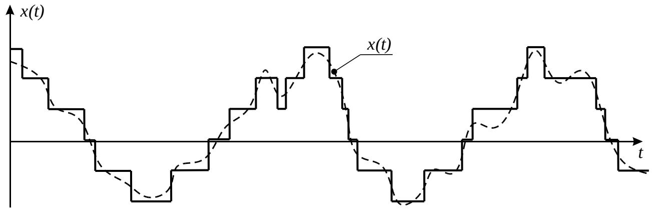

Fig.2. Continuous, value quantized signal

Characteristics of instrumental errors can normally be determined in static mode based on the relative standard and the existing calibration hierarchy.

IV. MATHEMATICAL MODEL

The result obtained after quantization of continuous-time function $x(t)$, can be represented as sequences of intervals located at levels $k.\varDelta$, i.e.

$$y_q(t) = k(t_i) \cdot \Delta \cdot 1(t - t_i), \tag{1}$$

where $y_q(t)$ – quantized signal; $k(t_i)$ – quant number; $1(t - t_i)$ – Heaviside step function.

The probability of function $x(t)$ ending up in $k-$th interval can be expressed in the time domain by the ratio

$$P_t^k = \frac{T_k}{T}, \tag{2}$$

where T_k – time in which function $x(t)$ falls in interval $(k \pm 0{,}5) \cdot \Delta$; T – period of realization.

The expression of the likelihood ratios in the time domain is associated with a number of computational difficulties. On the other hand, the stationary random processes allow the expression of their probabilistic characteristics to be performed on the basis of the statistical functions of the ordinates x of the corresponding processes $x(t)$. Moreover, any stationery process can be expressed by function

$$\eta_k(t) = \begin{cases} 1, & if\ k - 0{,}5 < x(t) \le k + 0{,}5 \\ 0 & in\ all\ other\ cases. \end{cases}$$

Then

$$\frac{T_k}{T} = \frac{1}{T} \cdot \int_0^T \eta_k(t) dt. \tag{3}$$

Based on the concept presented by (3), it is possible to determine the probability of process $x(t)$ falling into interval $[(k - 0{,}5)\Delta \div (k + 0{,}5)\Delta]$

$$P_k = \int_{(k-0{,}5)\Delta}^{(k+0{,}5)\Delta} f_x(x) dx, \tag{4}$$

where $f_x(x)$ – probability density function of ordinates of process $x(t)$.

Many of the quantities that characterize the movement of moving objects (ships, aircraft, land vehicles, etc.) are stationery random processes with Gaussian distribution. Therefore formula (4) can be presented as follows

$$P_k = \int_{(k-0,5)\Delta}^{(k+0,5)\Delta} \frac{1}{\sigma_x\sqrt{2\pi}} \cdot exp\left[-\frac{1}{2\sigma_x^2} \cdot (x - m_x)^2\right] \cdot dx, \quad (5)$$

where σ_x is Standard deviation; m_x – expected value of ordinates x.

The expected value with level-quantization will be:

$$M_x = \sum_{k=-\infty}^{\infty} k\Delta \int_{(k-0,5)\Delta}^{(k+0,5)\Delta} \cdot exp\left[-\frac{1}{2\sigma_x^2}(x - -m_x)^2\right] dx. \quad (6)$$

The characteristics of methodical and instrumental error of measuring instruments which quantize the signal by level are defined by their transfer function (fig.3). With symmetrical setting of the transducer and presence of only a methodical error the interval between the successive values of the measured quantity x_i (fig.3, 1) remains constant which is equivalent to the linear transfer function. The total effect of the instrumental inaccuracies is expressed in the shift of the code sectors relative to their nominal location. The shift can be defined by the deviations δx_{uo_i} of the median of discrete values x_i', to which the transducer readings are set, relative to their nominal values x_i (fig.3, 2).

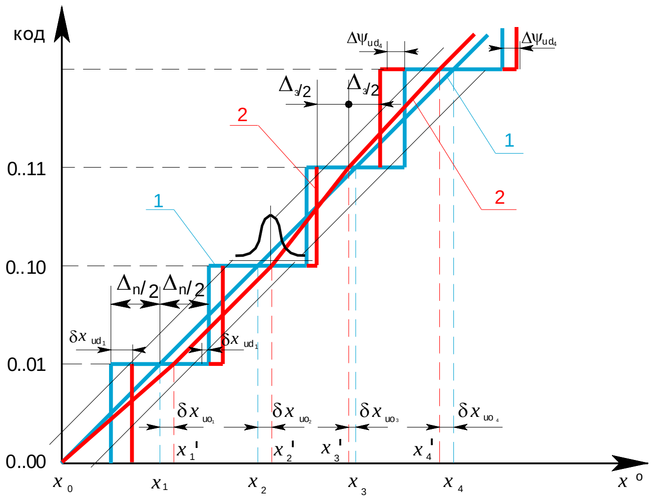

Fig.3. Transfer function

This causes changes in the linear nature of the transient characteristics of the measuring instrument and the actual value of x_i' projected on the number-scale axis of the measured quantity x will be:

$$x_i' = x_i + \delta x_{uo}. \quad (7)$$

Moreover, instrumental inaccuracies cause changes in the discrete values, which affects the above described methodical error characteristics. The actual operating size of discrete values Δ_i and the deviation from their nominal values depends on a number of technological factors, therefore it acquires a random nature and adds an additional component of instrumental nature δx_{ud} to the methodical error and half of the actual value of the quantizing will be:

$$\frac{\Delta_i}{2} = \frac{\Delta_k}{2} \pm \frac{\delta x_{ud}}{2}. \quad (8)$$

In this paper, however, this type of errors will be considered as instrumental errors, therefore the summary instrumental error will be:

$$\delta x_u = \delta x_{uo} + \delta x_{ud}. \quad (9)$$

Then, the likelihood of function $x(t)$ falling into k-th interval, corrected with the value of the summary instrumental error δx_u, will be:

$$P_t^{k\delta} = \frac{T_{k\delta}}{T}, \quad (10)$$

where $T_{k\delta}$ is the time for which the realization of process $x(t)$ is in the interval $[(k-0,5)\Delta - 0,5\delta x_{uo} - 0,5\delta x_{ud}] \div [(k+0,5)\Delta + 0,5\delta x_{uo} + 0,5\delta x_{ud}]$.

All this gives grounds to write the following formula for the probability $P_{k\delta u}$, which differs from $P_t^{k\delta}$ in that the time t is excluded:

$$P_{k\delta u} = \int_{[(k-0,5)\Delta - 0,5\delta x_{uo} - 0,5\delta x_{ud}]}^{[(k+0,5)\Delta + 0,5\delta x_{uo} + 0,5\delta x_{ud}]} \frac{1}{\sigma_x\sqrt{2\pi}} \cdot exp\left[-\frac{1}{2\sigma_x^2} \cdot \times (x - m_x)^2\right] \cdot dx. \quad (11)$$

(5) and (11) make it possible to determine the probability of instrumental errors occurring regarding the ordinates of process $x(t)$.

$$P_{\delta u} = P_{k\delta u} - P_k = = \int_{[(k-0,5)\Delta - 0,5\delta x_{uo} - 0,5\delta x_{ud}]}^{(k-0,5)\Delta} \frac{1}{\sigma_x\sqrt{2\pi}} \cdot exp\left[-\frac{1}{2\sigma_x^2} \cdot (x - -m_x)^2\right] \cdot dx + \int_{(k+0,5)\Delta}^{[(k+0,5)\Delta + 0,5\delta x_{uo} + 0,5\delta x_{ud}]} \frac{1}{\sigma_x\sqrt{2\pi}} \cdot .exp\left[-\frac{1}{2\sigma_x^2} \cdot \times (x - m_x)^2\right] \cdot dx. \quad (12)$$

If the limits of integration in (12) are changed, so that instead of the two components δx_{uo} and δx_{ud} the summary instrumental error δx_u is used, the following formula will be obtained:

$$P_{\delta u} = \int_{(k-0,5)\Delta - 0,5\delta x_u}^{(k-0,5)\Delta + 0,5\delta x_u} f_x(x) + \int_{(k+0,5)\Delta - 0,5\delta x_u}^{(k+0,5)\Delta + 0,5\delta x_u} f_x(x) dx. \quad (13)$$

Considering (13) the instrumental error variance can be determined

$$D_{\delta u} = \sum_{k=-\infty}^{\infty} (k \cdot \Delta - M_x)^2 \cdot P_{\delta u}, \quad (14)$$

where M_x is the expected value defined by (6).

It should be noted that in (13) error δx_u can participate only with one of its values, for instance – its estimate for the k-th interval. In fact error δx_u is a random variable with its own probability density functions $f_k(z)$ in k-th interval. Probability $P_{\delta u}$ can be determined on the basis of double integrals of the type:

$$P_{\delta u} = \int_\alpha^\beta \int_\delta^\mu \frac{\rho^2}{\pi E_x E_z} e^{-\rho^2\left(\frac{x^2}{E_x^2} + \frac{z^2}{E_z^2}\right)} dxdz, \quad (15)$$

where ρ is an argument in the Laplace function, i.e. $\Phi\left(\frac{E}{\sigma\sqrt{2}}\right) = \Phi(\rho)$; $E_x = \rho\sigma_x\sqrt{2}$; $E_z = \rho\sigma_z\sqrt{2}$.

On the other hand, solving integrals of type (15) is extremely difficult, since functions $f_x(x)$ and $f_k(z)$ do not have primitive functions that can be expressed by elementary functions. Of course, functions of type $\Phi(x) = \frac{2}{\sqrt{\pi}}\int e^{-x^2}dx + C_1$ are well enough studied and to solve (14) Laplace function $\Phi(x)$ can be used. In addition, when probabilities $f_k(z)$ and $f_x(x)$ are distributed by law different from the normal one, the solutions of (14) are expressed by elementary functions.

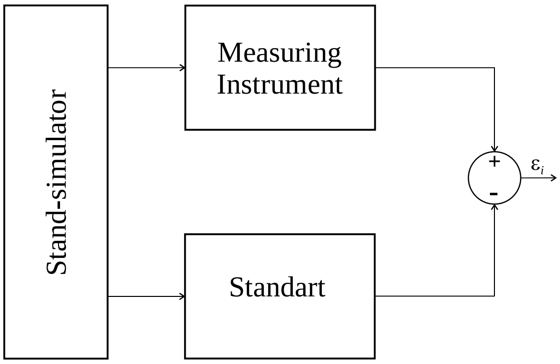

Fig.4. Block diagram for experimental investigation

Therefore, it is most appropriate to perform the analysis of instrumental error δx_u experimentally. This can be done following the diagram shown in fig. 4. In fact, the diagram in fig. 4 is used to determine the influence on measurement accuracy not only of the instrumental component δx_u, but also of the summary error δx_Σ^s allowed in static mode of measurement. The latter is determined by the expression

$$\delta x_\Sigma^s = \delta x_u + \delta x_m, \tag{16}$$

where δx_m is the methodical component.

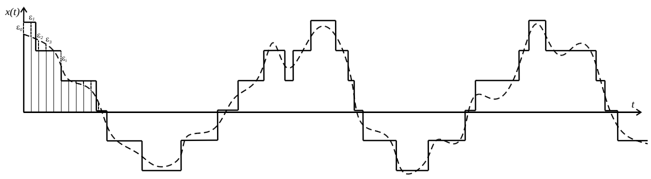

Fig. 5. The set of values ε_i

The measurements following the diagram in fig. 4 are performed along two parallel measuring circuits. The first circuit includes the studied measuring instrument at the output of which a value-quantized signal is obtained. The signal from the second circuit passes through reference measuring instrument at the output of which a discrete-time signal is obtained. The difference between the output signals of the two measuring circuits represents a set of values ε_i, arranged in successive time intervals t_i, which is illustrated in fig. 5. The set of values ε_i represents random variable ε, which defines the characteristics of summary error δx_Σ^s. The properties of error δx_Σ^s are determined by the first moment M_ε and the second moment D_ε of the random variable ε.

Experimental studies were performed with a prototype of an instrument for measuring ship pitch at the output of which a value quantized signal is obtained. The reference signal is set by a simulation stand which is a hexapod with six levels of freedom. The results of the experimental study are presented in fig. 6 in relative units. Fig. 6 shows that with small variances and expected values of the ordinates of measured quantity $x(t)$ error variance δx_Σ^s has values close to zero. The limit value of the variance of summery error δx_Σ^s is reached by increasing the variance value of $x(t)$.

V. CONCLUSIONS

There has been proposed a novel method for investigating methodical and instrumental error of measuring instruments operating in dynamic mode. The concept of the method is based on a generalized scheme of the measuring instrument in which the measuring signal is divided, though conditionally, in two channels. The first channel characterizes the static mode of measurement, while the second one – the dynamic mode of measurement. This makes it possible to distinguish the dynamic error from the components of the summery error caused by instrumental and methodical inaccuracies of the measuring instrument.

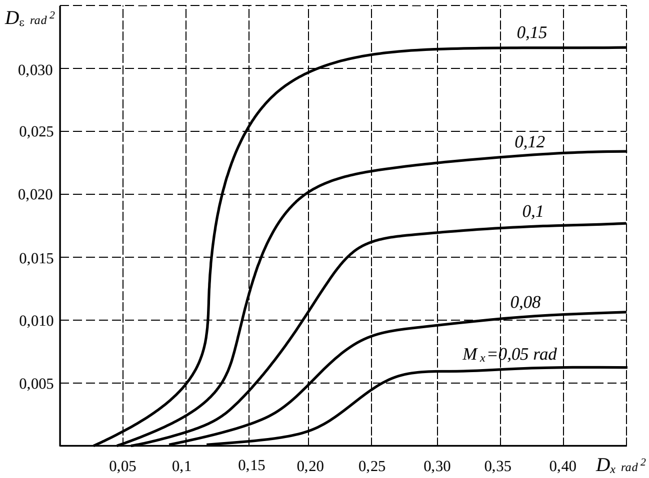

Fig.6. Results from the experimental investigations

The paper presents mathematical models for defining and investigating the probabilistic characteristics of the instrumental error of measuring instruments with converters quantizing the signal. The models are developed on the basis of the probabilistic characteristics of the signals involved in the measuring process. A block diagram for experimental determination of the methodical and instrumental components of the summery error of instruments for measuring moving objects parameters has been drawn. Also presented are the results from the experimental investigation of the methodical and instrumental components of an instrument for measuring ship pitch.

ACKNOWLEDGMENT

This work has been accomplished with financial support by the Grant № BG05M2OP001-1.002-0011 "MIRACle (Mechatronics, Innovation, Robotics, Automation, Clean technologies)", financed by the Science and Education for Smart Growth Operational Program (2014-2020) co-financed by the European Union through the European structural and Investment funds and supported by the European Regional Development Fund within the Operational Programme “Science and Education for Smart Growth 2014 - 2020” under the Project CoE “National center of mechatronics and clean technologies“ BG05M2OP001-1.001-0008-C01".

References

[1] Tomczyk, K., Piekarczyk, M., Sokal, G., “Radial basis functions intended to determine the upper bound of absolute dynamic error at the output of voltage-mode accelerometers”, Sensors, Vol. 19, Issue 19, 2019. DOI:10.3390/s19194154

[2] Tomczyk, K., “Procedure Proposal for Establishing the Class of Dynamic Accuracy for Measurement Sensors Using Simulation Signals with One Constraint”, Measurement, Vol. 178, 2021. DOI:10.1016/j.measurement.2021.109367

[3] Yurasova, E. V., Rusanova, A. C., “Implementation of the Genetic Algorithmfor Correcting the Dynamic Error of the Measuring Systems”, In 2020 Global Smart Industry Conference (GloSIC), November 2020, 240-245. DOI:10.1109/GloSIC50886.2020.9267875

[4] Dichev, D., Koev, H., Bakalova, T., Louda, P., “A model of the dynamic error as a measurement result of instruments defining the parameters of moving objects”, Measurement Science Review, Vol.14, Issue 4, 2014. pp. 183-189. DOI:10.2478/msr-2014-0025

[5] Kvedaras, R., Kvedaras, V., Ustinavičius, T., Masiulionis, R., “Digital Signal Processing Algorithm for Measurement of Settling Time of High-Resolution High-Speed DACs”, Measurement Science Review, Vol. 19, Issue 3, 2019, 86-92. DOI:10.2478/msr-2019-001

[6] Zaharinov, V., Malakov, I., Nikolov, S., Dimitrova, R., Stambolov, G., “Classification of parts used in mechatronic products and produced by permanent-mold casting methods”, In IOP Conference Series: Materials Science and Engineering, June, 2020, Vol. 878, No. 1., DOI: 10.1088/1757-899X/878/1/012063

[7] Wang, X., Cao, H., Jiao, Y., Lou, T., Ding, G., Zhao, H., Duan, X., “Research on Novel Denoising Method of Variational Mode Decomposition in MEMS Gyroscope”, Measurement Science Review, Vol. 21, Issue 1, 2021, pp. 19-24. DOI: 10.2478/msr-2021-0003

[8] Dyomko, A. I., Semenov, O. Y., Churilova, I. N., “Quasi-optimal processing simulation of ultrasonic signals“, In Journal of Physics: Conference Series, Vol. 1488, No. 1, 2020. DOI: 10.1088/1742-6596/1488/1/012004

[9] Du, B., Song, J., Shi, Z., “An Anomaly Diagnosis Method for Redundant Inertial Measurement Unit and Its Application with Micro-Electro-Mechanical System Sensors”, Applied Sciences, Volume 9, Issue 8, 2019. DOI: 10.3390/app9081606

[10] Rogne, R., Bryne, T., Fossen, T., Johansen, T., “Redundant MEMS-based inertial navigation using nonlinear observers”, Journal of Dynamic Systems, Measurement, and Control, Vol. 140, Issue 7, 2018. DOI:10.1115/1.4038647

[11] Kok, M., Wahlström, N., Schön, T. B., Gustafsson, F., “MEMS-based inertial navigation based on a magnetic field map”, In 2013 IEEE International Conference on Acoustics, Speech and Signal Processing, May, 2013, pp. 6466-6470. DOI: 10.1109/ICASSP.2013.6638911

[12] Vasilevskyi O. M, “A frequency method for dynamic uncertainty evaluation of measurement during modes of dynamic operation”, International Journal of Metrology and Quality Engineering, Vol. 6, No 2, 2015. DOI: 10.1051/ijmqe/2015008

[13] Volosnikov, A., Yurasova, E., “Dynamic Measurement Error Evaluation and Minimization based on FIR-filter”, presented at 2018 Global Smart Industry Conference (GloSIC), Chelyabinsk, Russia, 2018. DOI: 10.1109/GloSIC.2018.8570128

[14] Lazov, L., Teirumnieks, E., Karadzhov, T., Angelov, N., “Influence of Power Density and Frequency of the Process of Laser Marking of Steel Products”, Infrared Physics & Technology, Vol. 116, 2021. DOI: 10.1016/j.infrared.2021.103783

[15] Pencheva, T., Pulov, D., Gyoch, B., Nenkov, M., “Design of CCD Optical System for Thermal IR Spectral Region”, In 2006 29th International Spring Seminar on Electronics Technology, May, 2006, pp. 173-178. DOI: 10.1109/ISSE.2006.365380

[16] Dichev, D., Zhelezarov, I., Karadzhov, T., Madzharov, N., Diakov, D., Method for Measuring Motion Parameters of Moving Objects. In ENVIRONMENT. TECHNOLOGIES. RESOURCES. Proceedings of the International Scientific and Practical Conference, Vol. 3, 2019, June, pp. 27-31. DOI: 10.17770/etr2019vol3.4131

[17] Angelov, N., Teirumnieks, E., Lazov, L., “Influence of pulse duration on the process of laser marking of CT80 carbon tool steel products“, Laser Physics, Vol. 31, issue 4, 2021, DOI: 10.1088/1555-6611/abe5af

[18] Zhang, Y., Peng, C., Mou, D., Li, M., Quan, W., “An adaptive filtering approach based on the dynamic variance model for reducing MEMS gyroscope random error“, Sensors, Vol. 18, Issue 11, 2018. DOI: 10.3390/s18113943

[19] Dichev, D., Zhelezarov, I., Dicheva, R., Diakov, D., Nikolova, H., Cvetanov, G., “Algorithm for estimation and correction of dynamic errors”. In 2020 XXX International Scientific Symposium'Metrology and Metrology Assurance, 2020, September, DOI: 10.1109/MMA49863.2020.9254261

[20] Dichev, D., Koev, H., Diakov, D., Panchev, N., Miteva, R., Nikolova, H., “Automated System for Calibrating Instruments Measuring Parameters of Moving Objects”, in 59th International Symposium ELMAR, Zadar, Croatia, 2017, pp. 219-224. DOI: 10.23919/ELMAR.2017.8124472