Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 12th International Scientific and Practical Conference. Volume III, 27-31

Method for Measuring Motion Parameters of Moving Objects

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

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

Tsanko Karadzhov
Department of Machine and Precision Engineering
Technical University of Gabrovo
Gabrovo, Bulgaria
Karadjov_st@abv.bg

Nikolay Madzharov
Department of Electronics
Technical University of Gabrovo
Gabrovo, Bulgaria
madjarov@tugab.bg

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

***Abstract*—The paper considers a new method for measuring the angular deviations of moving objects. A specific measuring system is proposed to measure ship roll, pitch, heel and trim. The system consists of two measurement channels operating in parallel. The first channel is built on the position properties of a physical pendulum so as to build the base vertical. The second channel ensures the dynamic accuracy of the system. The principal of operation of the second channel involves correction of the signals from the first channel by using information obtained from linear MEMS accelerometers. To increase system measurement accuracy, a signal processing module is used through the Kalman filter algorithm.**

Keywords*— *Kalman filter; dynamic error; gyro-free measuring system; roll, pitch, heel, trim.

I. Introduction

The dynamic accuracy of measuring instruments and systems mounted on moving objects considerably depends on the intensity of the linear and angular accelerations acting upon them and mainly caused by the fluctuations of the object. Meanwhile the basic parameters of the interference effects and the quantities being measured vary within wide ranges and depend on a number of factors which are determined by the specific moving object and its motion medium. In this respect, there is a great variety available for state-of-the-art means of transport (ships, aircrafts, road transport, etc.).

The above mentioned substantially complicates the development of measuring systems that possess the required accuracy for the whole range of variations of the interference effects and the quantities being measured. This holds true for instruments measuring parameters such as roll, pitch, heel and trim which characterize the ship motion. Namely, the problems related to measuring those parameters are covered by the present study.

A distinguishing feature of the measuring instruments presented in this paper is that they operate under conditions of dynamic effects caused by the motion of the moving objects or by the fluctuations of the ships, aircrafts and road means of transport, as well as by the vibrations in the place where the measuring instruments have been positioned [1] - [3]. Those motions result in producing inertial forces and moments which act upon the measuring instruments thus causing a dynamic error in the measurement result. [4].

To reduce the influence of inertial forces and moments in current measuring instruments, gyro-stabilized systems are mainly used. They model the reference coordinate system in relation to which the position of the moving object upon its rotation with respect to its mass centre and its motion along with its mass centre is measured, as well as the set direction of motion is kept. [5] - [8]. This complicated model for reproducing the direction of the vertical leads to a number of disadvantages such as a complex design resulting in a bigger instrumental error, low reliability under extreme conditions, need for special systems ensuring the operation of the gyro-vertical, larger dimensions, higher price of the instrument or system, etc. [9], [10].

Thus, the present paper proposes a new method for developing measuring instruments and systems which define the parameters of moving objects. That method is able to overcome the drawbacks of the current measuring instruments since, on one hand, it is based on a considerably simplified mechanical module, and on the other hand, on the advanced achievements in the area of nanotechnologies, microprocessor and computer equipment.

A specific measuring system has been developed in compliance with the basic principles of the proposed method so as to measure ship roll, pitch, heel and trim.

II. Description of the measuring method

The general concept of the proposed method is presented by means of a block diagram shown in Fig. 1. The

Print ISSN 1691-5402
Online ISSN 2256-070X
http://dx.doi.org/10.17770/etr2019vol3.4131

block diagram consists of a main measurement channel, an additional channel, interfaces to be connected to a computer and software modules for processing and presenting measurement information. The main channel is designed to measure the current values of the quantities being measured.

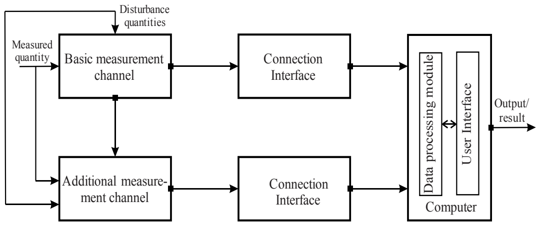

Fig.1. Block diagram illustrating the principle of modeling of measuring systems

Due to its simplified design and lack of stabilization systems, the signal at the channel output contains a dynamic error caused by the deviation of the physical pendulum from the astronomical vertical. The procedure for obtaining the measurement information required for defining the current values of the dynamic error is performed in the additional channel (Fig. 1). The latter operates in parallel with the main one, which makes possible the elimination of the dynamic error from the measurement result in real time. The design of the additional channel and the type of the constituent devices are specified according to the model chosen to determine the current values of the dynamic error and the correction algorithm of the signal from the main measurement channel.

III. Measuring system for defining ship roll, pitch, heel and trim

To illustrate the features of the proposed method, the characteristics of a specific measuring system built in compliance with the above concept are considered. The system has been developed to measure ship roll, pitch, heel and trim.

The block diagram of the system is shown in Fig. 2. The main measurement channel consists of a mechanical module intended to provide gyro-free modelling of the local vertical and a system for recording the angles of the heel and trim, which includes two code photoelectric converters mounted along the respective measurement axis. The design model of the mechanical module of the main measurement channel (Fig. 3) has been developed according to the block diagram in Fig. 2.

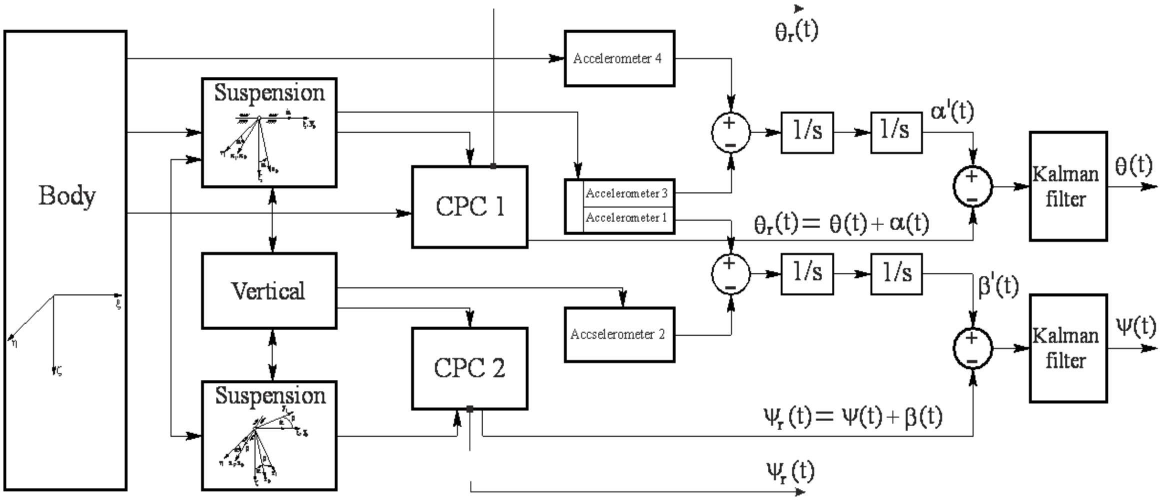

Fig.2. Operating diagram of the measuring system

The development of the main measurement channel is focused on a simplified technical implementation of the vertical in the form of a physical pendulum. Therefore, this comparatively easy technical implementation of the mechanical module, which consists of a small number of components, results in reducing the magnitude of the instrumental error.

The body of the mechanical module is permanently connected to the ship. A 2-degree-of-freedom physical pendulum reproducing the device vertical is mounted on the body by means of a suspension system (Fig. 3). The latter consists of an outer and inner frame, connected in series by cylindrical joints. A physical pendulum is attached to the inner frame. The two frames have inter perpendicular axes of rotation, which intersect at one point. The measurement information about the heel and trim angles is obtained from two code photoelectric converters (CPC1 and CPC2), mounted on the respective measurement axis.

The measurement accuracy in dynamic mode is ensured by an additional channel for determining the dynamic error. It consists of two pairs of identical MEMS accelerometers used for measuring the linear acceleration. The accelerometers are mounted respectively on the body of the mechanical module, on the first cylindrical joint (two accelerometers), and on the physical pendulum. The first two accelerometers are mounted in such a way that their measurement axes are sensitive to the accelerations generated by the roll whereas the measurement axes of the other two accelerometers are sensitive to the accelerations generated by the pitch. This scheme of mounting of the MEMS sensors ensures the sensitivity of the first accelerometer of each sensor pair to all accelerations generated by the roll and pitch. Every second accelerometer is sensitive not only to the accelerations of the first sensor but also to those generated by the pendulum motion with respect to its degree of freedom. This makes possible the development of a procedure involving the subtraction of the signals from the first and second accelerometer of each sensor pair where the output signals are proportional to the accelerations generated by the pendulum motion with respect to its degree of freedom. By means of a data processing algorithm a double integration of the accelerations is performed, where signals defining the pendulum deviations from the vertical with respect to its two degrees of freedom are obtained.

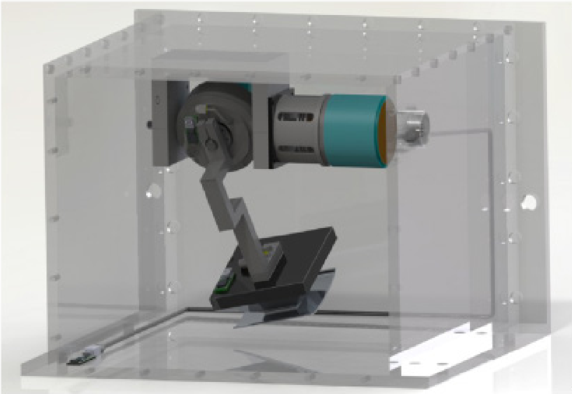

Fig.3. Design model of the main measurement channel

Because the device body is permanently fixed to the ship and its measurement axes are sensitive to ship fluctuations with respect to the heel θ and trim ψ , the measurement information on the change of those quantities is obtained at CPC1 and CPC2 outputs. That information is recorded with respect to the time coordinate in the form of functions $\theta_r(t)$ and $\psi_r(t)$. The instability of the physical pendulum in the inertial space leads to a dynamic error in the result whose characteristics are defined by functions α(t) and β(t). The latter are formed by the pendulum deviations from the ideal astronomic vertical emerging along the two measuring coordinates of the device. In this case the values obtained from the two measurement channels are equal to the sums of the desired signals and the respective dynamic errors, i.e. $\theta_r(t) = \theta(t) + \alpha(t)$; $\psi_r(t) = \psi(t) + \beta(t)$, where θ(t) and ψ(t) are the signals determining the true values of the heel and trim along the time coordinate.

Due to the presence of interference sources of random characteristics, additional secondary processes of unpredictable behavior and possible occurrence of errors as a result of system conversion processes, additional errors may occur thus considerably reducing accuracy when defining the dynamic error [11] - [14]. Therefore, in order to eliminate the influence of the above listed sources, adaptive algorithms (such as Kalman filter) need to be introduced in the measurement procedure [15] - [17]. They make possible the automatic adjustment of the measuring system when searching for optimal solutions according to the minimum mean square criterion. In this sense, the result from the precise solution of the algorithmic synthesis problem can be formulated by target inequalities of the form

$$\varepsilon_{\alpha_{de}}(t) - \alpha(t) \le q_{доп}\ ; \qquad \varepsilon_{\beta_{de}}(t) - \beta(t) \le q_{доп}\ , \qquad (1)$$

where $\varepsilon_{\alpha_{de}}(t)$, $\varepsilon_{\beta_{de}}(t)$ - the dynamic errors obtained as a result at the output of the adaptive filters; *α(t)*, *β(t)* – the true values of the respective dynamic error; $q_{доп}$ – admissible deviation.

IV. Mathematical model of the measuring system

The measuring system can be developed only on the basis of a complete and precise mathematical model because this model is used to determine the main dependences of the parameters of the measuring system, the quantities being measured, and the influence quantities in a form appropriate for the analysis of the required characteristics.

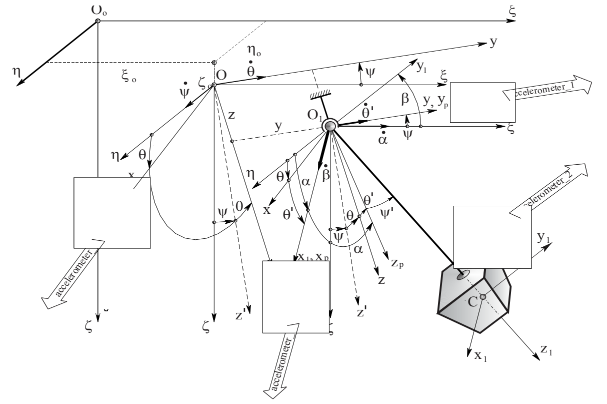

Fig.4. Diagram of the dynamic system moving object - measuring instrument

The differential equations are worked out on the basis of the design model and the diagram showing the arrangement of the accelerometers. The dynamic system is shown in fig. 4. Ship motions are defined as angular and linear fluctuations of a rigid body around or along with its centre of gravity. The moving object (the ship) to which the coordinate system O*xyz* is connected moves randomly with respect to the reference system $O_o\xi\eta\zeta$. A measuring instrument is mounted on the ship and its sensitive element (a physical pendulum) is connected to coordinate system $Cx_1y_1z_1$. The suspension point O_1 of the instrument sensor coincides with the diametral plane of the ship and its position with respect to the centre of gravity of the moving object O is defined by the *z* and *y* coordinates.

The position of the moving object with respect to the reference system $O_o\xi\eta\zeta$ is set by the three coordinates of its centre of gravity O - ξ_o, η_o, ζ_o and the matrix $A = \left\| a_{ij} \right\|$ (*i,j=1,2*) of the given angle cosines of the trim *ψ* and the heel *θ*, defining the angular displacement between the axes of the systems $O_o\xi\eta\zeta$ and Oxyz. The dynamic system consists of two bodies - a physical pendulum which is free to rotate with respect to the coordinate axes O_1x_1 and O_1y_1, and an accelerometer mounted in the centre of gravity C of the physical pendulum. The accelerometer inertial body of a mass m_2 stays at an equilibrium position in relation to the y_1 coordinate by means of two horizontal springs of an elastic constant c.

Therefore, the system has three degrees of freedom and the generalized coordinates are, respectively, *α*, *β* and y_1. The *α* and *β* coordinates define the angular displacement of the physical pendulum from the vertical in relation to, respectively, O_1y_1 and O_1x_1 axes whereas y_1 determines the relative motion of the inertial mass m_2. By means of coordinate β the inertial component of the dynamic error for the measurement channel under consideration is defined. The latter determines the trim values of a ship.

After performing the required mathematical operations and reducing the obtained equations to a simplified form by linearizing the quantities that define the motion of the system points and including only small first-order quantities, the following system of differential equations is obtained:

$$\left|\begin{array}{l}\left(J_{y_1}+m_1.l^2\right).\ddot{\alpha}+k_\alpha.\dot{\alpha}+m_1.g.l.\alpha= \\ =m_1.l.\ddot{\eta}_o-\left(J_{y_1}+m_1.l.z\right).\ddot{\theta}; \\ \left(J_{x_1}+m_1.l^2\right).\ddot{\beta}+k_\beta.\dot{\beta}+m_1.g.l.\beta= \\ =-m_1.l.\ddot{\xi}_o-\left(J_{x_1}+m_1.z.l\right).\ddot{\psi}; \\ m_2.\ddot{y}_1+k_{y_1}.\dot{y}_1+c.y_1= \\ =-\frac{1}{2}m_2.\left(l.\ddot{\beta}+\ddot{\xi}_0+z.\ddot{\psi}\right),\end{array}\right. \tag{2}$$

where k_α, k_β and k_{y1} are damping factors along the three generalized coordinates α, β and y_1; l – the length of the physical pendulum.

The third equation in (2) defines the link between the readings of the accelerometer mounted on the physical pendulum and the quantities entering at the input of the instrument. A differential equation representing the motion of the sensitive element of the second accelerometer can be easily worked out from this equation, taking into account the identical design characteristics of the two sensors and the fact that this accelerometer is not sensitive to the motion of the physical pendulum. Then the differential equation sought will be:

$$m_2\cdot\ddot{y}_p+k_{y_p}\cdot\dot{y}_p+c\cdot y_p=-\frac{1}{2}m_2\cdot\left(\ddot{\xi}_0+z\cdot\ddot{\psi}\right), \tag{3}$$

where y_p is the coordinate of the motion of the sensitive element of the second accelerometer.

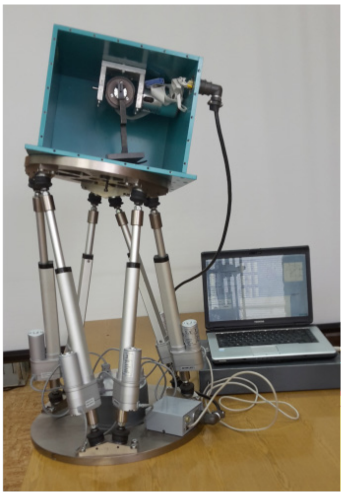

Fig.5. Photos from the experiments

In this case the difference between the readings of the two accelerometers will be proportional to the function $\ddot{\beta}(t)$, by means of which we can easily determine the quantity β(t) defining the dynamic error. However, additional interferences are accumulated to the $\ddot{\beta}(t)$ signal. They can be easily identified if equations (2) are reduced to a form which consists of first- and second-order quantities. Then on the right side of the third differential equation from (2) functions $\ddot{\xi}_o\cdot\beta$ and $y\cdot\ddot{\psi}\cdot\beta$ appear and they are superposed on signal $\ddot{\beta}(t)$. Although the values of those functions are formed as small second-order quantities with respect to $\ddot{\beta}(t)$, they cause an additional error when determining quantity $\beta(t)$. Hence, they should be eliminated from the signal before the final formation of function $\beta(t)$. In this case the use of Kalman filter, whose location in the measurement procedure is given in the block diagram in fig. 2, is very relevant.

V. Experiments and results

To carry out the experiments, the required stand equipment has been developed. It possesses reference properties and makes possible the implementation of all metrological tasks related to checks, calibration, definition of dynamic characteristics and investigation of dynamic accuracy. The equipment is in the form of a 6-degree-of-freedom hexapod and photos from the experiments are shown in fig. 5.

To illustrate the quality of the measuring system, the results from the investigation of the channel measuring the ship pitch and trim are presented in fig. 6. The figure shows: the reference motion of the hexapod operating platform $\psi(t)$; the recorded signal before Kalman filter $\psi_{bk}(t)$; the pitch measurement result obtained at the output of Kalman filter $\psi_{bk}(t)$; the dynamic error $\varepsilon_{\beta_{de}}(t)$. Figure 5 indicates that the measuring system possesses high measurement accuracy in dynamic mode, since error $\varepsilon_{\beta_{de}}(t)$ does not exceed *4%* of the variation range of the quantity being measured. Similar results are obtained upon investigating the second measurement channel (measuring roll and heel). In static mode the system operates at approximately two times higher accuracy because of its simplified design diagram, which is used in the mechanical module for modeling the vertical.

VI. Conclusions

The proposed measurement concept is designed for developing gyro-free measuring systems that determine the parameters of moving objects. This modelling approach overcomes the disadvantages of the existing measuring instruments since it is based, on one hand, on a very simplified mechanical module, and on the other hand, on the advanced achievements in the area of nanotechnologies, microprocessor and computer equipment.

The high dynamic accuracy of the proposed measuring system is ensured by an additional measurement channel operating in parallel with the main channel. The metrological procedures in the additional channel are based on an appropriate correction algorithm using signals from linear MEMS accelerometers.

The experimental results confirm the effectiveness of the proposed measurement concept in relation to the dynamic accuracy of systems measuring moving objects. As a result of the operation of the additional channel and the Kalman algorithm the accuracy characteristics of the measuring system under conditions of dynamic influences are improved to a great extent. This can be implemented without using expensive elements and stabilization systems.

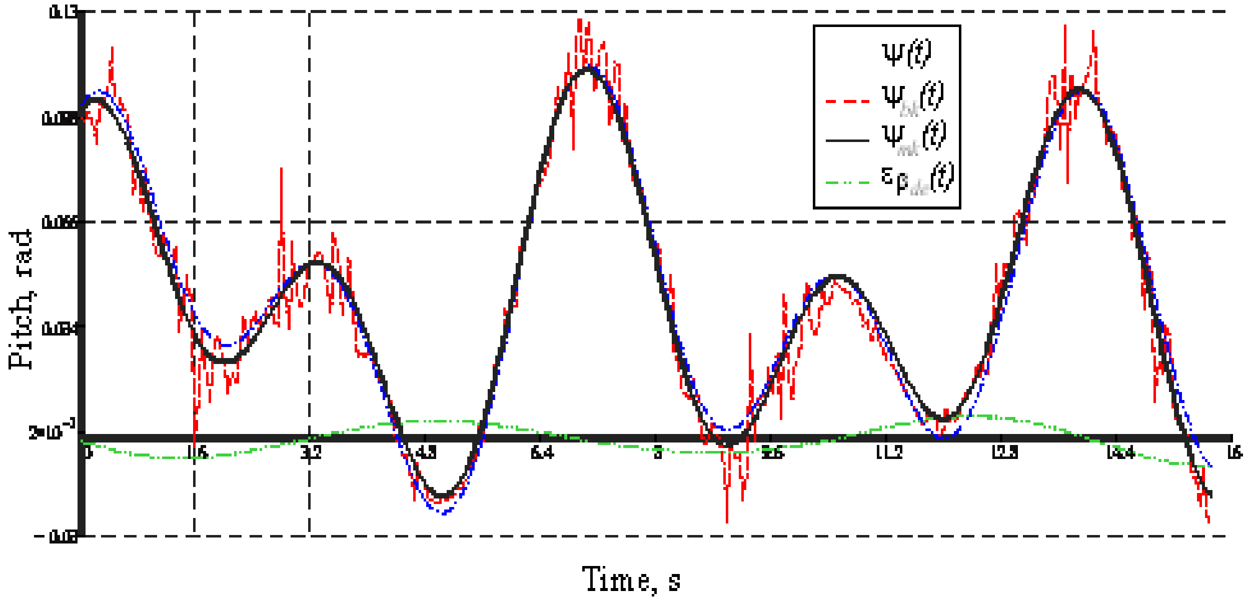

Fig.6 Experimental results

Acknowledgment

This work was supported by the European Regional Development Fund within the OP "Science and Education for Smart Growth 2014 - 2020", Project CoC "Smart Mechatronic, Eco- And Energy Saving Systems And Technologies", № BG05M2OP001-1.002-0023.

References

[1] H. Pan, S. Tian and P. Ye, "An Adaptive Synthesis Calibration Method for Time-Interleaved Sampling Systems" in Metrol. Meas. Syst., Vol 17, issue 3, 2010, pp. 405-414.

[2] L. Song, Z. Chen, Y. Mao, Z. Dong and Z. Xiang, "Error Mitigation Algorithm Based on Bidirectional Fitting Method for Collision Avoidance of Unmanned Surface Vehicle", in Polish Maritime Research, Vol. 25, issue 4, 2018, pp. 13-20.

[3] D. Borkowski and S. Barczentewicz, "Power Grid Impedance Tracking with Uncertainty Estimation Using Two Stage Weighted Least Squares", in Metrol. Meas. Syst., Vol. 21, issue 1, 2014, pp. 99-110.

[4] D. Dichev, F. Kogia, H. Nikolova and D. Diakov, "A Mathematical Model of the Error of Measuring Instruments for Investigating the Dynamic Characteristics", in Journal of Engineering Science and Technology Review, Volume 11, Issue 6, 2018, pp. 14-19.

[5] R. Zhu, D. Sun, Z. Zhou and D. Wang, „A linear fusion algorithm for attitude determination using low cost MEMS-based sensors", in Measurement, Vol. 40, issue 3, 2007, pp. 322–328.

[6] J-O. Nilsson and I. Skog, "Inertial Sensor Arrays - A Literature Review", presented at 24th European Navigation Conference, IEEE, Finland, 2016, pp. 1-10.

[7] I. Malakov, V. Zaharinov and V. Tzenov, "Size Ranges Optimization", in Procedia Engineering, Vol. 100, 2015, pp. 791-800.

[8] I. Malakov, T. Georgiev, V. Zaharinov, A. Tzokev and V. Tzenov, "Demand modeling for the optimization of size ranges", presented at 26th DAAAM International Symposium, Vienna, Austria, 2015, pp. 0435-0444.

[9] D. Dichev, F. Kogia, H. Koev and D. Diakov, "Method of Analysis and correction of the Error from Nonlinearity of the Measurement Instruments", Journal of Engineering Science and Technology Review, Vol. 9, Issue 6, 2016, pp. 116-121.

[10] A. Volosnikov and E. Yurasova, "Dynamic Measurement Error Evaluation and Minimization based on FIR-filter", presented at 2018 Global Smart Industry Conference (GloSIC), Chelyabinsk, Russia, 2018, pp. 1-7.

[11] D. Dichev, H. Koev, T. Bakalova and P. Louda, "A Model of the Dynamic Error as a Measurement Result of Instruments Defining the Parameters of Moving Objects", in Measurement Science Review, Vol. 14, issue 4, 2014, pp. 183-189.

[12] E. Yurasova and A. Volosnikov, "Dynamic measurement errors correction adaptive to noises of a sensor", Series on Advances in Mathematics for Applied Sciences, vol. 89, 2018, pp. 427-438.

[13] H. Pan, S. Tian and P. Ye, "An Adaptive Synthesis Calibration Method for Time-Interleaved Sampling Systems", in Metrol. Meas. Syst., Vol. 17, issue 3, 2010, pp. 405-414.

[14] M. Jiang, J. Luo, D. Jiang, J. Xiong, H. Song and J. Shen, "A cuckoo search-support vector machine model for predicting dynamic measurement errors of sensors", in IEEE Access, Vol. 4, 2016, pp. 5030-5037

[15] K. Ormandzhiev, S. Yordanov and S. Stoyanov, "Synthesis of Fuzzy Controller for Cross-Flow Water Turbine", in Information Technologies and Control, Vol. 15, issue 1, 2017, pp. 9-16.

[16] Y. Zhang, C. Peng, D. Mou, M. Li and W. Quan, "An Adaptive Filtering Approach Based on the Dynamic Variance Model for Reducing MEMS Gyroscope Random Error", in Sensors, Vol. 18, issue 11, 2018, pp. 1-14.

[17] M. Jiang, L. Jiang, D. Jiang, J. Xiong, J. Shen, S. H. Ahmed, J. Luo and H. Song, "Dynamic Measurement Errors Prediction for Sensors Based on Firefly Algorithm Optimize Support Vector Machine", in Sustainable Cities and Society, Vol. 35, 2017, pp. 250-256.