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Algorithm for estimation and correction of dynamic errors (Conference Paper)

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Abstract

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This paper presents a mathematical model which can be used to develop algorithms for estimation and correction of dynamic errors of instruments for measuring parameters of moving objects. The dynamic error of the measuring instruments discussed in the present paper is mainly due to the inertial effects relative to the primary measuring transducer. The algorithm model is designed to determine the optimal estimate of the dynamic error by the criterion of minimum standard deviation of current and previous estimates. The developed algorithm significantly increases the accuracy of the measuring system because it is based on the actual model of the sensitive element dynamics and the analysis of each new time sequence measurement. © 2020 IEEE.

Author keywords

Dynamic measurement error | inertial impacts | measurement in dynamic mode | moving objects parameters

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***Abstract*— This paper presents a mathematical model which can be used to develop algorithms for estimation and correction of dynamic errors of instruments for measuring parameters of moving objects. The dynamic error of the measuring instruments discussed in the present paper is mainly due to the inertial effects relative to the primary measuring transducer. The algorithm model is designed to determine the optimal estimate of the dynamic error by the criterion of minimum standard deviation of current and previous estimates. The developed algorithm significantly increases the accuracy of the measuring system because it is based on the actual model of the sensitive element dynamics and the analysis of each new time sequence measurement.**

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

I. Introduction

The accuracy of systems and instruments positioned on moving objects and measuring some of their parameters is mainly determined by the values of their dynamic error [1, 2, 3]. The latter is due to the inertial effects relative to the primary measuring transducer, as well as to random noises present in the measuring circuit of the instrument [4]. The main parameters of inertial effects depend mainly on the intensity of the linear and angular accelerations acting in the place of installation of the measuring instruments, caused by the oscillating motion of the object [5, 6]. The magnitude of the linear and angular accelerations is determined by the specificity of the moving object, the instantaneous values of motion parameters and the surrounding environment, however for modern vehicles (ships, aircraft, land vehicles, etc.) there is a great variety in this respect [7, 8].

Sensitive elements developed on the basis of gyroscope properties are used to reduce the effects of inertial forces and momentum in existing measuring instruments [9, 10]. This method achieves an increase in the resistance of primary transducer to inertial effects. However, it has a number of shortcomings, such as complex structure resulting in an increase in the magnitude of the instrumental error; insufficient reliability in extreme conditions; need for special systems to ensure gyrovertical operation; large dimensions; high instrument cost or high system cost, etc.

To eliminate the above mentioned shortcomings, the present paper proposes a mathematical model which allows algorithms that can be adapted to specific measurement conditions to be developed. In this case, high dynamic accuracy is achieved by eliminating the dynamic error in real time. To build such procedures it is necessary to use information from different sensors combined in a common platform working with an algorithm based on the mathematical model presented in this paper.

II. Model of the Measuring Instrument

The mathematical model presented in this paper is intended for development of algorithms as part of measuring instruments whose high, dynamic accuracy is ensured by eliminating the dynamic error in real time. A generalized block diagram of such a measuring instrument is shown in fig.1. The presented scheme solves the problem of determining the measuring vector on the basis of the results from measuring its projection on sensors sensitivity axis which are part of the basic block (BB). The operation procedure of the measuring instrument consists of three main parts. In the first part the measuring vector is directly determined by the sensors in block BB [11]. Due to the weak resistance of the sensitive element of the primary transducer of inertial disturbances caused by the movement of the moving object, a dynamic error will be accumulated at the output of block BB. Therefore, the result $q(t)$ at the output of block BB will differ from the measured quantity $x(t)$ entering the input of the measuring instrument.

The second part is a hardware-software block designed to determine the current values of the dynamic error $\varepsilon_{de}(t)$. In this part the sensitive element of the primary transducer is separated as a separate unit by the parameters of the operating part of its transmitting function $W_{pt}(p)$. In this way the specific dynamic characteristics of the sensitive elements, as well as the effect of the disturbances on their dynamics can be accounted for in the mathematical models and algorithms for dynamic error correction. This way of working significantly increases the accuracy in determining the dynamic error. An application-oriented platform consisting of a combination of different micro-electromechanical systems (MEMS) is used to obtain the measurement signals required for the operation of the processing algorithm.

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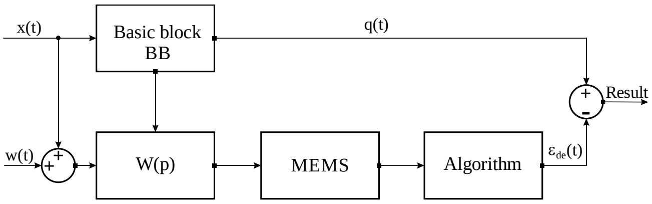

Fig.1. Block diagram of the measurement system

The third part corrects *q(t)* signal from block BB with the current values of dynamic error $\varepsilon_{de}(t)$ defined in hardware-software block.

III. A MATHEMATICAL MODEL OF THE ALGORITHM

The statement of the problem for complex information processing and dynamic error determination is reduced to estimating the parameters of the error model caused by sensitive element deviations of primary transducer due to the inertial effects.

$$\dot{\boldsymbol{E}} = \boldsymbol{A}(t) \cdot \boldsymbol{E} + \boldsymbol{G}(t) \cdot \boldsymbol{w}(t), \tag{1}$$

where $\boldsymbol{E}$ – state vector determining the dynamic error; A – matrix determining sensitive element dynamics; $\boldsymbol{G}$ – matrix defining the disturbance effects; $\boldsymbol{w}(t)$ – vector, usually set as a white noise.

$$\boldsymbol{Y} = \boldsymbol{H}(t) \cdot \boldsymbol{E}, \tag{2}$$

where $\boldsymbol{H}(t)$ – matrix characterizing the measurement parameters.

In fact, the measurement takes place in the presence of errors, i.e.

$$\boldsymbol{z}(t) = \boldsymbol{Y}(t) + \boldsymbol{v}(t) = \boldsymbol{H}(t) \cdot \boldsymbol{E} + \boldsymbol{v}(t), \tag{3}$$

where $\boldsymbol{v}(t)$ – vector in the form of white noise characterizing measurement errors.

The task of state estimation, i.e. the task of determining dynamic error current values $\varepsilon_{de}(t)$ consists in the following: to use measurement data $\boldsymbol{z}(\tau)$ in observation interval (t_0, t) and the model corresponding to (1) as a basis to determine the best estimate $\hat{\boldsymbol{\varepsilon}}$ of the state vector $\boldsymbol{E}$ meeting a certain quality criterion; the solution of the task of determining the optimal estimate is an operator allowing vector $\boldsymbol{z}(\tau)$ to connect to vector$\boldsymbol{E}$.

IV. WORK ALGORITHM MODEL

The work algorithm model is based on the assumption that the equations determining the dynamics of the sensitive element are unknown. Then, the equation on which the present algorithm is based will be equation (3). It can be assumed that the measurement errors are distributed by normal law with covariance matrix $\boldsymbol{P} = \sigma^2 \cdot \boldsymbol{I}$, where $\boldsymbol{I}$ is the unit diagonal matrix [12, 13].

According to the method used in this paper the optimal estimate $\hat{\boldsymbol{\varepsilon}}$ is determined by the criterion of minimum standard deviation of current and previous estimates.

$$J = (\boldsymbol{z} - \boldsymbol{H} \cdot \hat{\boldsymbol{\varepsilon}})^T \cdot (\boldsymbol{z} - \boldsymbol{H} \cdot \hat{\boldsymbol{\varepsilon}}) = min. \tag{4}$$

Finding that minimum is equivalent to resetting the first derivative to the right of (4), i.e.

$$\frac{\partial J}{\partial \hat{\boldsymbol{\varepsilon}}} = -2 \cdot \boldsymbol{H}^T \cdot (\boldsymbol{z} - \boldsymbol{H} \cdot \hat{\boldsymbol{\varepsilon}}) = 0. \tag{5}$$

The following can be derived from (5)

$$\hat{\boldsymbol{\varepsilon}} = (\boldsymbol{H}^T \cdot \boldsymbol{H})^{-1} \cdot \boldsymbol{H}^T \cdot \boldsymbol{z}. \tag{6}$$

To obtain the final algorithm, we assume that *i-th* measurement has been carried out.

$$\boldsymbol{z}_i = \boldsymbol{H}_i \cdot \hat{\boldsymbol{\varepsilon}}_i + \boldsymbol{v}_i. \tag{7}$$

System (7) contains *i* equations in number and the estimate $\hat{\boldsymbol{\varepsilon}}_i$ is derived on the basis of *i-th* measurement. After $(i+1)$ −th measurement has been performed, the following equation is obtained

$$\boldsymbol{z}_{i+1} = \boldsymbol{H}_{i+1} \cdot \hat{\boldsymbol{\varepsilon}}_{i+1} + \boldsymbol{v}_{i+1}. \tag{8}$$

Then the system can be written as follows

$$\left|\begin{matrix} \boldsymbol{z}_i \\ z_{i+1} \end{matrix}\right| = \left|\begin{matrix} \boldsymbol{H}_i \\ \boldsymbol{h}_{i+1}^T \end{matrix}\right| |\hat{\boldsymbol{\varepsilon}}_{i+1}| + \left|\begin{matrix} \boldsymbol{v}_i \\ \boldsymbol{v}_{i+1} \end{matrix}\right|. \tag{9}$$

The iterative form of the estimate will be

$$\begin{aligned} \hat{\boldsymbol{\varepsilon}}_i &= \boldsymbol{P}_i \cdot \boldsymbol{H}_i^T \cdot \boldsymbol{z}_i, \\ \hat{\boldsymbol{\varepsilon}}_{i+1} &= \boldsymbol{P}_{i+1} \cdot \boldsymbol{H}_{i+1}^T \cdot \boldsymbol{z}_{i+1}, \end{aligned} \tag{10}$$

where

$$\boldsymbol{P}_{i+1} = \boldsymbol{P}_i - \boldsymbol{P}_i \boldsymbol{h}_{i+1} (\boldsymbol{I} + \boldsymbol{h}_{i+1}^T \boldsymbol{P}_i \boldsymbol{h}_{i+1})^{-1} \boldsymbol{h}_{i+1}^T \boldsymbol{P}_i. \tag{11}$$

The final form of the estimate of the dynamic error will be:

$$\hat{\boldsymbol{\varepsilon}}_{i+1} = \hat{\boldsymbol{\varepsilon}}_i + \boldsymbol{P}_{i+1} \boldsymbol{h}_{i+1} (z_{i+1} - \boldsymbol{h}_{i+1}^T \hat{\boldsymbol{\varepsilon}}_i). \tag{12}$$

Fig.2. Stand equipment

Equations (11) and (12) allow us to calculate recurrently the estimate of the unknown vector of dynamic error$\varepsilon_{de}(t)$, i.e. to calculate the new estimate $\hat{\boldsymbol{\varepsilon}}_{i+1}$ based on the known value of the previous estimate $\hat{\boldsymbol{\varepsilon}}_i$ and the information from the new measurement z_{i+1}. At the beginning of the iterative process it is necessary to set the values $\hat{\boldsymbol{\varepsilon}}_0$ and $\boldsymbol{P}_0$. The first one is chosen in accordance with the existing a priori information, while matrix $\boldsymbol{P}_0$ is chosen so that it is proportional to the single matrix.

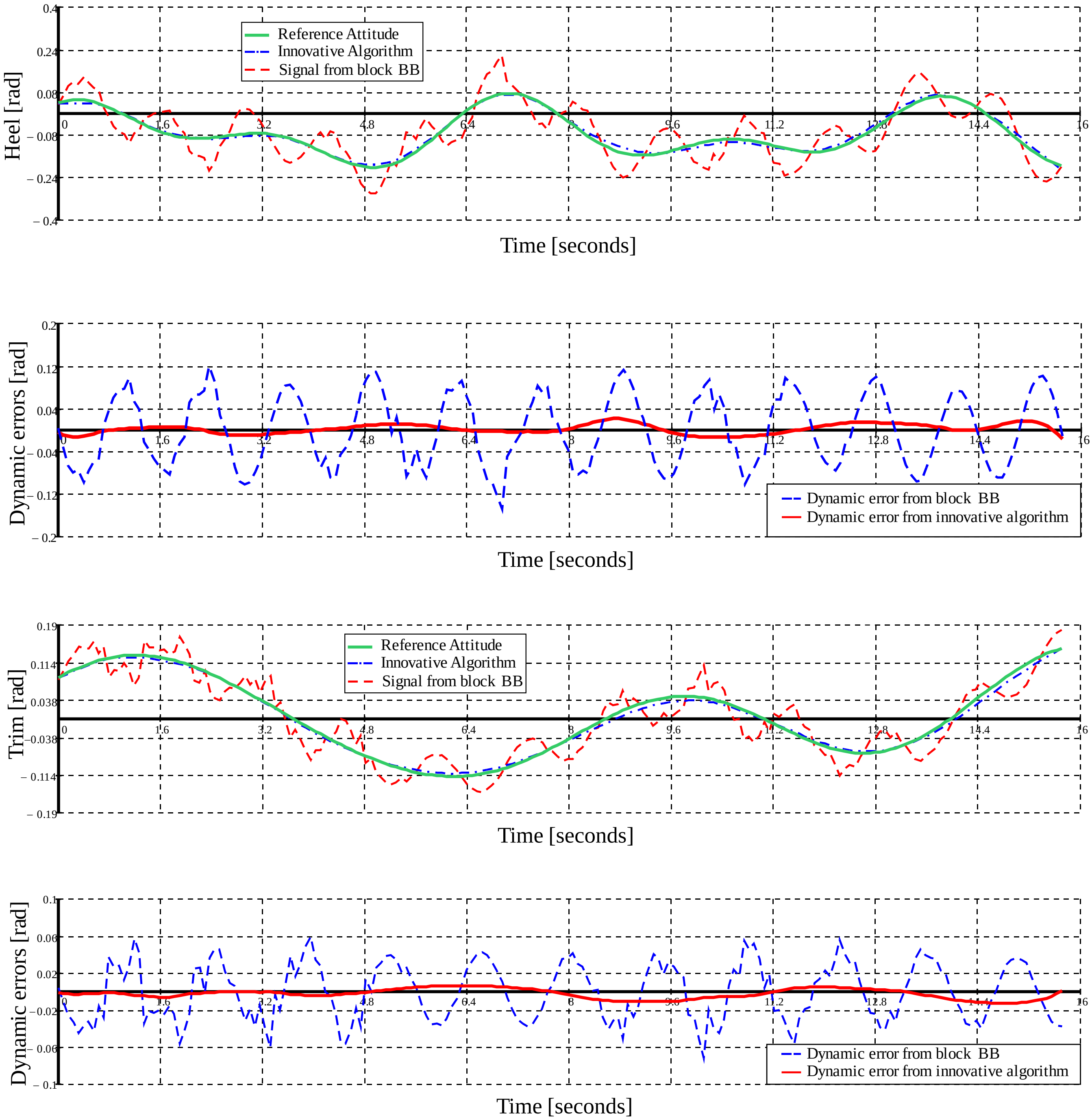

Fig.3. Results from experimental investigations

V. Experiment and Results

The experimental studies were conducted in order to verify the developed mathematical model and algorithm. A prototype of a system for measuring roll, pitch, heel and trim of a ship was used. The primary transducer, which is part of block BB, consists of a sensitive element and two absolute rotary encoders measuring the angular position of the moving object relative to the vertical in two mutually perpendicular directions. The sensitive element is a physical pendulum with two degrees of freedom. A stand simulator [14] consisting of a hexapod with six degrees of freedom was used to reproduce reference motion of the moving object (fig.2).

The results of the experimental studies carried out are presented in fig.3. It can be seen that due to the inertial effects the sensitive element of the primary transducer deviates significantly from its nominal position, which leads to the occurrence of a dynamic error in the result. This is illustrated by the broken curve defining the signal at the output of block

BB. In this case, the maximum error in measuring the roll and pitch motion ranges between 3° and 5°. In contrast, the results obtained by using the algorithm developed and presented in this paper show a considerable accuracy. The maximum values of the dynamic error are in range of $30'$ to $40'$.

VI. CONCLUSIONS

The mathematical model and algorithm for increasing dynamic accuracy proposed in this paper can be used to develop new generation measurement instruments with significantly better quality indicators and metrological characteristics than the existing ones. The algorithm is based on the criterion of a minimum of standard deviation of current and previous estimates whose values are derived by means of a hardware platform consisting of a combination of different micro-electromechanical systems.

The obtained experimental results prove the effectiveness of the proposed algorithm with respect to the dynamic accuracy of systems measuring parameters of moving objects.

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