Accuracy Evaluation of Flat Surfaces Measurements in Conditions of External Influences

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***Abstract*— A theoretical model for research the accuracy of a method for measuring deviations from flatness is considered in the publication. The measurement method is based on the concept of the Kalman filter and is particularly effective against the action of various types of external influences, such as vibrations and shocks, noises of electromagnetic origin, temperature deformations, etc. It is adapted to measurements in static mode. Based on the measurement method, specialized algorithms can be developed to automatically correct measurement errors of shape and placement deviations, which can significantly improve accuracy characteristics, simplify the construction of measuring instruments, and reduce metrological requirements for their components and elements. Based on the structure of the measurement method, the concept of the research model is developed, which is based on the mutual conditioning of the statistical characteristics of the errors of model and measurement, derived as standalone components in the base system of equations.**

***Keywords*— Kalman filter; Flat Surfaces Measurements; Dynamic measurement error; measurement in dynamic mode.**

I. Introduction

The modern development of industry, the high level of automation and intellectualization of technical processes, including measurement processes, allow nowadays to solve the problems of ensuring the unity and necessary accuracy of measurements, the allocation of the metrological load between the hardware and informational parts of the measurement systems [1]. The development and application of specialized algorithms for automatic error correction in a number of cases can significantly improve the accuracy characteristics, simplify the construction of measuring instruments and reduce the metrological requirements for their components and elements [2].

For example, in the field of mechanical engineering, the metrological task related to the measurement of the deviation from flatness is particularly relevant [3]. This task arises both in the development and creation, as well as in the calibration and attestation of machine-building equipment (multifunctional CNC machines, coordinate measuring machines, 3D printers, etc.) [4]. One of the main accuracy parameters of all the machines and systems listed above is the deviation from flatness of the working and measuring surfaces.

The importance it has the measurement of deviation from flatness both for the shape of the manufactured products and for the quality indicators of the technological equipment and measuring systems in coordinate metrology leads to the appearance of a large amount of measuring tools in this direction [3]. All known methods in this field are based on comparing the controlled plane with the reference plane [5, 6]. At the same time, the methods for reproducing the reference plane and the ways for determining the deviations of the measured surfaces from the reference plane can be of a different nature [7-25]. It is in this direction, the development of specialized mathematical models and algorithms can increase the level of automation of metrological processes, expand the spectrum of input-output processes and lead to improvement of the characteristics of measurement accuracy.

On the other hand, a large part of the technological equipment and measuring systems work in the conditions of external influences, which lead to the appearance of significant errors, having a dynamic nature for the most part. External influences can be sign-changing mechanical influences such as vibrations and shocks, noises of electromagnetic origin, temperature deformations, etc. All these influences are determined by the conditions in a real working environment. That is why, in these cases, the task of removing or reducing the influence of external factors on the measurement result becomes important meaning. One of the most effective ways to solve this task is through the development of adaptive stochastic optimization algorithms, which include evaluation search and iterative optimization of the solution. Along with this, it is necessary to evaluate the accuracy of the obtained solutions, which will be the main task in the present publication.

II. Measurement Algorithm

When measuring deviations from flatness in conditions characterized by the action of factors of different nature, it is appropriate to use the following measurement model, representing a powerful tool for combining information from different sources:

$$\mathbf{z_{k+1}} = \mathbf{F_k} \cdot \mathbf{X_{k+1}} + \boldsymbol{\varepsilon}_\mathbf{k}$$

$$\mathbf{q_{k+1}} = \mathbf{H_{k+1}} \cdot \mathbf{z_{k+1}} + \boldsymbol{\rho}_\mathbf{k+1}, \qquad (1)$$

where $\mathbf{F_k}$ is the matrix defining the transition from the values of the measured magnitude, grouped in the vector $\mathbf{z_{ij}}$, from the previous position $(x_k y_j)$ to the current position $(x_{k+1} y_j)$; $\mathbf{X_{k+1}}=[X, Y, 1]^T$ – matrix with the values of the coordinates in the current position determined by the ordered pair of numbers $x_{k+1}y_j$; $\boldsymbol{\varepsilon}_\mathbf{k}$ – a random vector specifying the model; $\mathbf{q_{k+1}}$ – a vector formed by the measured values at the current position $(x_{k+1}y_j)$; $\mathbf{H_{k+1}}$ – a transformation matrix that converts the measurement units from the measurement vector $\mathbf{q_{k+1}}$ to the model vector $\mathbf{z_{k+1}}$; $\boldsymbol{\rho}_\mathbf{k+1}$ – random vector defining the measurement error.

vector $\mathbf{q_{k+1}}$, a correction based on the minimum of the mean squared error from the prediction and measurements is performed for the values of the deviations z in the current step $k+1$.

In static measurements, what are the measurements of deviations from flatness, there are a number of specific features related to the characteristics of the elements of the system (1). Thus, for example, the transition matrix $\mathbf{F_k}$ can take a different form depending on the chosen approach for defining the theoretical model by which the values are predicted from step k in the next step $k+1$. One of the frequently used theoretical models is a plane of the form $\alpha_k : a_k X + b_k Y + c_k = Z$, whose coefficients a_k, b_k and c_k are calculated by the method of least squares for each iteration. Another specific feature is that in linear measurements the

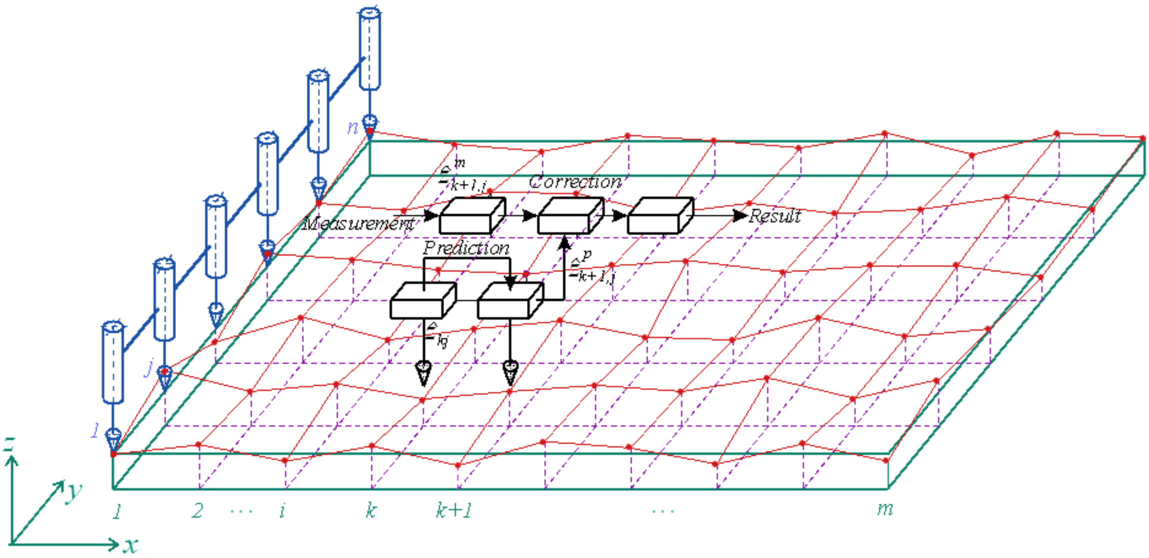

Fig. 1. Measurement scheme and block scheme of the algorithm

transformation matrix $\mathbf{H_{k+1}}$ can be easily determined, since the theoretical model usually works in the same measurement units in which the measurement procedures are performed. Moreover, the measurement algorithms have wide possibilities to configure their parameters so that the model errors $\boldsymbol{\varepsilon}_\mathbf{k}$ and the measurement $\boldsymbol{\rho}_\mathbf{k+1}$ represent one-dimensional random vectors.

Based on the model (1), numerous algorithms can be created for automatic correction of errors made in real working conditions when measuring deviations from flatness, parallelism, perpendicularity and other geometric inaccuracies of shape and placement. Through this model, error correction is embedded in the structure of the measurement procedure in the form of a filter, at the output of which the best estimate is obtained. When determining deviations from flatness, all algorithms based on model (1) work on the basis of data obtained from coordinate measurements, the structural organization of which is shown in the scheme of Fig. 1. The basic coordinate system that defines the measurement-calculation operations in three-dimensional space is denoted by *xyz*. The deviations of the flat surface 1 in the direction of the *z* axis are measured by the sensors 2. The sensors are spaced equally apart in the *y*-axis direction, and their sequential number is denoted by the variable $j=1,2,\ldots,n$. When performing the measurement procedure, all sensors are moved simultaneously along the *x*-axis and reports are made at each successive position indicated by $i=1,2,\ldots,m$.

Algorithms based on equations (1) work in two steps within the prediction-correction model, which is shown schematically in Fig.1. In the first step, determined by the first equation in system (1), the predicted estimates of the values of deviations z in step $k+1$, as well as their uncertainties, are calculated. After receiving the measurement data forming the

III. A MATHEMATICAL MODEL FOR ESTIMATING THE ACCURACY OF THE MEASUREMENT ALGORITHM

One of the tasks having important practical importance for the applicability of the model (1) is related to the accuracy of the estimation of the measured magnitude. The model (1) has the advantage that model and measurement errors are separated as independent components. In fact, the errors $\boldsymbol{\varepsilon}_\mathbf{k}$ and $\boldsymbol{\rho}_\mathbf{k+1}$ represent one-dimensional random vectors whose elements can be defined as random variables characterizing the uncertainty at each coordinate point $x_k y_j$ and $x_{k+1} y_j$.

Unlike other similar filters, model (1) works not only with the estimation of the measured magnitude, but also with the estimation of the statistical probability density, based on the Bayes formula for the conditional probability.

If at the coordinate point $x_k y_j$ an estimate $\hat{z}_{kj}$ is obtained with a probability density function (PDF) shown in Fig. 2 with position 1, the predictive estimate $\hat{z}^{p}_{k+1,j}$ and its corresponding PDF (position 2 of Fig. 2) for the next coordinate point $x_{k+1}y_j$ x can be obtained based on the equation of the model. It can be seen from Fig. 2 that the dispersion of the estimate is larger, which is due to the uncertainty defined by the model error $\boldsymbol{\varepsilon_k}$. The probability density function of the predicted estimate can be determined by a Gaussian model

$$P_{\varepsilon_{k+1}}\left(z,\hat{z}^{p}_{k+1,j},\sigma_{\varepsilon_{k+1}}\right)=\frac{1}{\sigma_{\varepsilon_{k+1}}\sqrt{2\pi}}e^{-\frac{\left(z-\hat{z}^{p}_{k+1,j}\right)^2}{2\sigma^2_{\varepsilon_{k+1}}}}. \qquad (2)$$

As a result of measuring the magnitude z at the coordinate point $x_{k+1}y_j$, a second estimate $\hat{z}^{m}_{k+1,j}$ is obtained, the statistical characteristics of which are presented in Fig. 2 of curve 3. The probability density function of this estimate is defined by

$$P_{\rho_{k+1}}\left(z,\hat{z}^{m}_{k+1,j},\sigma_{\rho_{k+1}}\right)=\frac{1}{\sigma_{\rho_{k+1}}\sqrt{2\pi}}e^{-\frac{\left(z-\hat{z}^{m}_{k+1,j}\right)^2}{2\sigma^2_{\rho_{k+1}}}}. \qquad (3)$$

The best estimate $\hat{z}_{k+1,j}$ of the measured magnitude z is obtained by combining the predicted estimate $\hat{z}^{p}_{k+1,j}$ and the measurement estimate $\hat{z}^{m}_{k+1,j}$ based on the criterion for a minimum of mean squared error.

From where, the new function defining the statistical characteristics of the estimation accuracy $\hat{z}_{k+1,j}$, will be [26]:

$$P_{\hat{z}_{k+1,j}}\left(z,\hat{z}_{k+1,j},\sigma_{k+1,j}\right)=\frac{1}{\sigma_{k+1,j}\sqrt{2\pi}}e^{-\frac{\left(z-\hat{z}_{k+1,j}\right)^2}{2\sigma^2_{k+1,j}}}, \qquad (5)$$

where

$$\hat{z}_{k+1,j}=\frac{\hat{z}^{p}_{k+1,j}\sigma^2_{\rho_{k+1}}+\hat{z}^{m}_{k+1,j}\sigma^2_{\varepsilon_{k+1}}}{\sigma^2_{\varepsilon_{k+1}}+\sigma^2_{\rho_{k+1}}}= =\hat{z}^{p}_{k+1,j}+\frac{\sigma^2_{\varepsilon_{k+1}}\left(\hat{z}^{m}_{k+1,j}-\hat{z}^{p}_{k+1,j}\right)}{\sigma^2_{\varepsilon_{k+1}}+\sigma^2_{\rho_{k+1}}}; \qquad (6)$$

$$\sigma_{k+1,j}=\frac{\sigma^2_{\varepsilon_{k+1}}\sigma^2_{\rho_{k+1}}}{\sigma^2_{\varepsilon_{k+1}}+\sigma^2_{\rho_{k+1}}}=\sigma^2_{\varepsilon_{k+1}}-\frac{\sigma^4_{\varepsilon_{k+1}}}{\sigma^2_{\varepsilon_{k+1}}+\sigma^2_{\rho_{k+1}}}. \qquad (7)$$

The above formulas make it possible to study the influence of the statistical characteristics of the errors allowed in the prediction and measurement on the accuracy of the estimate when measuring the deviation from flatness.

IV. ANALYSIS AND RESULTS

The analysis was performed on the basis of the mathematical models presented in the previous point of the statistical characteristics of the parameters determining the

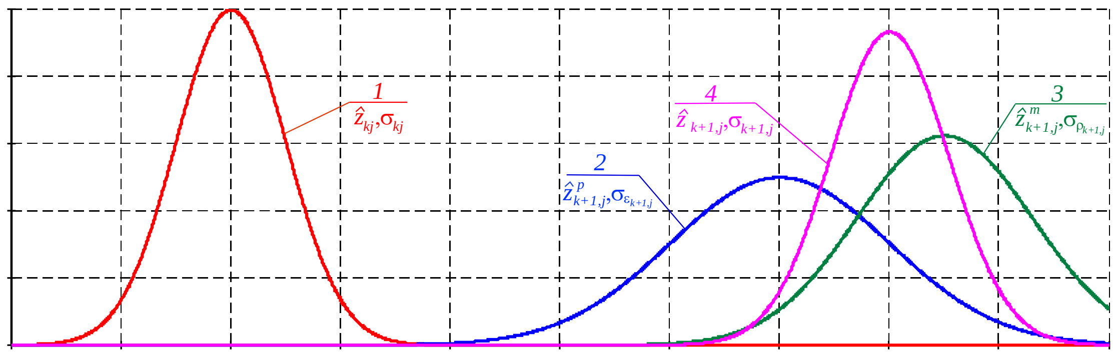

Fig. 2. Layout of the probability density functions of the parameters of the prediction-correction system

The graphical interpretation of the statistical characteristics of this estimate is shown in Fig. 2 through curve 4. In this case, the property that the multiplication of two Gaussian functions equals a third Gaussian function can be used [26]. From where it follows that the statistical characteristics of the estimation accuracy $\hat{z}_{k+1,j}$ at the current point $x_{k+1}y_j$ are determined by the multiplication

$$P_{\hat{z}_{k+1,j}}\left(z,\hat{z}^{p}_{k+1,j},\sigma_{\varepsilon_{k+1}},\hat{z}^{m}_{k+1,j},\sigma_{\rho_{k+1}}\right)= =\frac{1}{\sigma_{\varepsilon_{k+1}}\sqrt{2\pi}}e^{-\frac{\left(z-\hat{z}^{p}_{k+1,j}\right)^2}{2\sigma^2_{\varepsilon_{k+1}}}}\times\frac{1}{\sigma_{\rho_{k+1}}\sqrt{2\pi}}e^{-\frac{\left(z-\hat{z}^{m}_{k+1,j}\right)^2}{2\sigma^2_{\rho_{k+1}}}}= =\frac{1}{2\pi\sigma_{\varepsilon_{k+1}}\sigma_{\rho_{k+1}}}e^{-\left[\frac{\left(z-\hat{z}^{p}_{k+1,j}\right)^2}{2\sigma^2_{\varepsilon_{k+1}}}+\frac{\left(z-\hat{z}^{m}_{k+1,j}\right)^2}{2\sigma^2_{\rho_{k+1}}}\right]}. \qquad (4)$$

prediction and correction in the platform (1) for stochastic optimization.

The results of the study of the influence of the statistical parameters of the prediction and measurement on the formation of the result estimate $\hat{z}_{k+1,j}$ in the current step $k+1$ are shown in Figures 3 and 4. It can be seen from Fig. 3 that when increasing the values of the mean squared deviation $\sigma_{\rho_{k+1}}$ from the probability density function of measurement $P_{\rho_{k+1}}$, the value of the estimate $\hat{z}_{k+1,j}$ shifts in the direction of decreasing its values. This shift is stronger pronounced for smaller values of the mean squared deviation $\sigma_{\varepsilon_{k+1}}$ of the statistical characteristics defining the estimate prediction. From a mathematical point of view, this is explained by the stronger influence of the second term in equation (6). The probabilistic interpretation of this circumstance is related to the broadening of PDF span from measurement, which leads to a shift of the value of to $\hat{z}_{k+1,j}$ the left area of the graphic of Fig. 2.

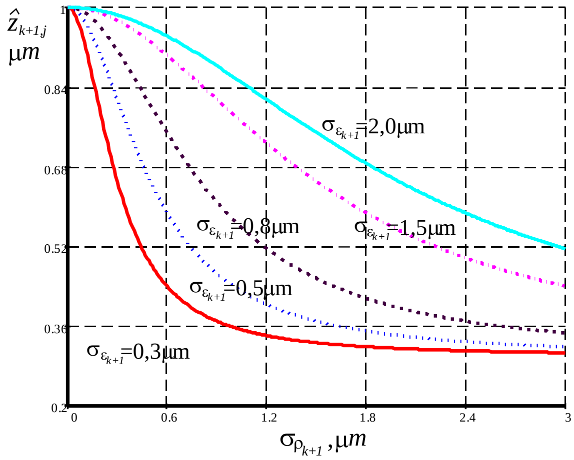

Fig. 3. Results of the research of the influence of the statistical parameters of the prediction and the measurement on the evaluation of the result

Reverse to the influence of $\sigma_{\rho_{k+1}}$, the increase in the values of the mean squared deviation $\sigma_{\varepsilon_{k+1}}$ leads to a substantial change in the values $\hat{z}_{k+1,j}$ of in the direction of increasing its values, i.e. in the direction to the right with respect to the arrangement of the graphs of Fig. 2. The most complete idea of the influence of the statistical parameters of the prediction and measurement on the evaluation of the result $\hat{z}_{k+1,j}$ can be obtained from the three-dimensional graph shown in Fig. 5. The function from fig. 5 expresses not only the influence of the mean squared deviations of the prediction and the measurement, but in this case the values determining the difference between the estimates are also taken into account, i.e. $\hat{z}^{m}_{k+1,j} - \hat{z}^{p}_{k+1,j}$.

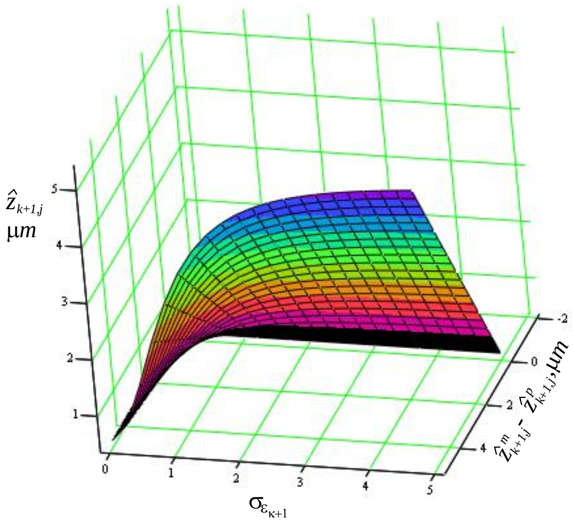

Fig. 5. Results on a three-dimensional scale obtained in research of the outcome assessment

Results of the analysis related to the change in the mean squared deviation $\sigma_{k+1,j}$ of the estimate $\hat{z}_{k+1,j}$ obtained in the $k+1$-th iteration are presented in Figures 6 and 7 on a graphical scale. It can be seen from the figures that for smaller values

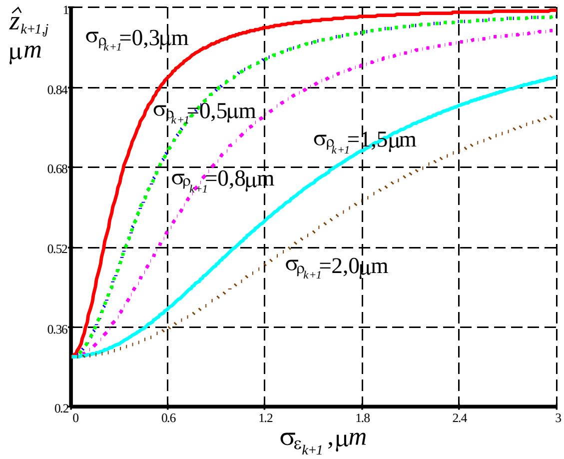

Fig. 4. Results of the research of the influence of the statistical parameters of the prediction and the measurement on the evaluation of the result

$\sigma_{\varepsilon_{k+1}}$ of the increase of $\sigma_{k+1,j}$ is not substantially, and the curves in this case reach certain limit values (Fig. 6). In contrast to this, at larger values of $\sigma_{\varepsilon_{k+1}}$ the increase of the mean squared deviation $\sigma_{k+1,j}$ is unbounded (Fig. 7).

V. Conclusions

A model to investigate the accuracy of a flatness measurement method is presented. The measurement method makes it possible to build specialized algorithms that are particularly effective against the action of various types of external influences, such as vibrations and shocks, noises of electromagnetic origin, temperature deformations, etc. The operation of the algorithms is performed in two steps within the prediction-correction model. The resulting estimate is corrected substantially based on a criterion based on the minimum of the mean squared error from the prediction and measurements. The concept of the research model is based on the mutual conditioning of the statistical characteristics of the errors of model and measurement, derived as independent components in the basic system of equations. The model works not only with the estimation of the measured magnitude, but also with the estimation of the statistical probability density, based on the Bayes formula for the conditional probability.

The analysis carried out based on the model presented in the work reveals important properties of the statistical parameters of the prediction and the measurement on the accuracy of the estimate when measuring the deviation from flatness.

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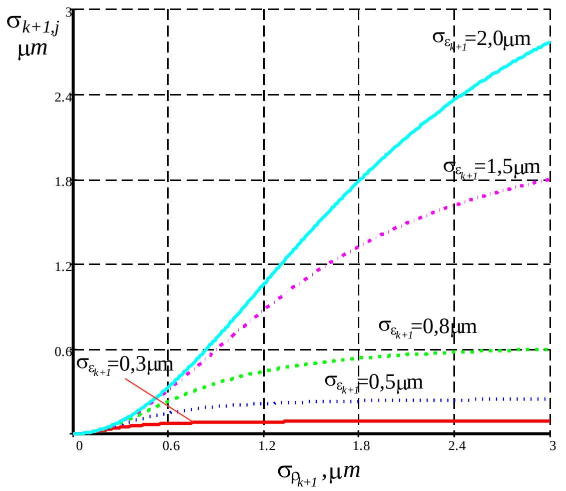

Fig. 6. Results of a research of the influence of statistical parameters on the uncertainty of the assessment

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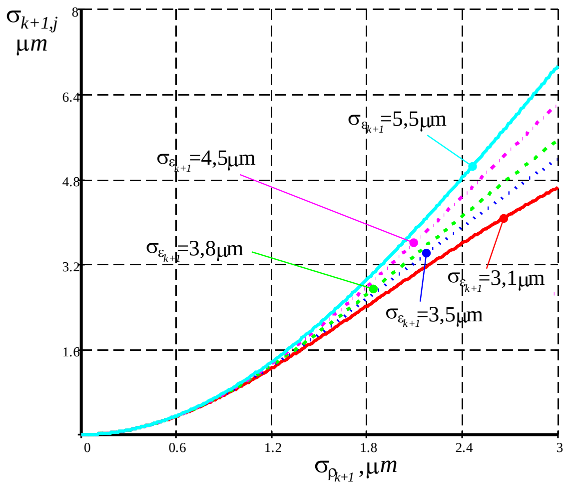

Fig. 7. Results of a research of the influence of statistical parameters on the uncertainty of the assessment

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