Abstract

The paper deals with the mechatronic arrangement for angle measuring system application. The objects to be measured are the circular raster scales, rotary encoders and coded scales. The task of the measuring system is to determine the bias of angle measuring standard as the circular scale and to use the results for the error correction and accuracy improvement of metal cutting machines, coordinate measuring machines, robots, etc. The technical solutions are given with the application of active materials for smart piezoactuators implemented into the several positions of angular measuring equipment. Mechatronic measuring system is analysed as complex integrated system and some of its elements can be used as separate units. All these functional elements are described and commented in the paper with the diagrams and graphs of errors and examples of microdisplacement devices using the mechatronic elements.

1. Introduction

The main constituents of the measuring system are the air bearing of high precision (uncertainty of the run-out is ~ 0.05 µm), reference angle measure – rotary encoder of high accuracy, piezoelectric drive, rotary adjustable table with possibility to be adjusted at least in three degrees of freedom, the reading devices of angular position of the object to be measured – photoelectric microscopes or autocollimators with CCD matrices, fixtures for their adjusting in radial, tangential and angular directions, signal outputs from all active elements into the PC, hardware and software for system adjustment, control of operation, readings transfer and result processing and presentation.

Angle calibration means have been developed using mechatronic elements. Calibration equipment for angle measurement consists from many constituents that belong to various branches of technique: optics, electronics devices, drives including vibromotors or piezoelectric or step motors, digital information links and data processing technique including computer control of all the processes. So, it is typical

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mechatronic equipment. Photoelectric microscopes and autocollimator, optical standard of angle multiangular prism (polygon), rotary table, driven by step motor and controlled by photoelectric rotary encoder and PC are the technical units of the test bench linked between themselves by informational channels. The PC serves as the main control unit operating not only for the control of the measuring process, but also for the data selection, processing operations including mathematics statistical evaluation and the final results presentation in the form of digital protocol or the diagrams of error distribution [1].

2. PRECISION POSITIONING EVALUATION

It is important to determine the information quantity on an object that has been evaluated providing a more thorough result assessment during the accuracy calibration processes. The problem exists due to the great amount of information that is gained in the calibration of scales, information-measuring systems of the numerically-controlled machines, automated measuring equipment such as coordinate measuring machines (CMMs) in their total volume. The measurement interval of the length in case of its accuracy testing (the calibration) fewer than 20 positions could be measured as it is indicated in CMM technical documentation. These assumptions can help in determination of mechatronic impact on the information-measuring system for the elimination of systematic errors. Piezoplates and simplified bodies from piezomaterial are applied for micrometric displacement for correction of the systematic errors of the raster scale. Correction of errors is accomplished by the control of a potential energy of the piezoplate. From a technical point of view it can be done by changing a voltage supplied to the electrode electromechanically coupled with the raster scale, changing the width of the electrode coating of the piezoplate. According to the principle of minimum of potential energy \( \frac{\partial U}{\partial \epsilon_i} = 0 \), and taking into account that longitudinal displacements are related to deformations by relationship \( \epsilon_i(x) = \frac{du}{dx} \), it is possible to obtain the equation of equilibrium of the piezoplate considered and to control an accuracy of linear raster scale. The distributions of errors for two-dimensional or three-dimensional measuring systems can be expressed by two functions

\[ u(x, y) = -k_1 \delta_i(x, y) \quad \text{and} \quad v(x, y) = -k_2 \delta_i(x, y), \]

where \( u, v \) – the components of displacements at the zone controlled into the direction of appropriate coordinates, \( k_1, k_2 \) – the coefficients of electromechanical coupling. For more exact assessment of error distribution and its possible correction the relative entropy parameters must be evaluated [5].

A piezoelectric system is shown in Fig. 1 for use in the rotary table used for angle measurements. It is useful for circular raster and coded scales measurement with conjunction with scale’s strokes reading instruments as photoelectric microscopes or autocollimators for angle position determination. Information of rotation can be controlled manually or it can be arranged in an automated way when the system is controlled by output signal of rotary encoder. These assumptions can help in determination of mechatronic impact on the information – measuring system for the elimination of systematic errors. A case of scale errors correction is presented in [7, 8]. Piezoplates and simplified bodies from piezomaterial were applied for micrometric displacement for correction of the systematic errors of the raster scale. Correction of errors is accomplished by the control of a potential energy of the piezoplate. In
technical point of view it can be done by changing a voltage supplied to the electrode electromechanically coupled with the raster scale, changing the width of the electrode coating of the piezoplate.

The relative entropy helps to assume the distribution of the random value as $q$ when true distribution of this variable is $p$. Assuming the explanations presented above, the mutual information appears as the most acceptable method to assess the multi-coordinate measuring systems. The mutual information model of 3D measurement is investigated below. $x$, $y$ and $z$ axes are subdivided into $k$, $l$ and $m$ steps (divisions), respectively, and $\Delta$ is the length of a single step of the scale of the information-measuring system. Therefore, the intervals of measurement values extend to

$$0 \leq x \leq k,$$

$$0 \leq y \leq l,$$

and

$$0 \leq z \leq m.$$  \hspace{1cm} (1)

If all dimensions are independent of each other no information is gained about any of the variables by fixing the value in one dimension. The instances of fixing two remaining dimensions produce analogous results using previous equations.

$$I(X; Y | Z) = \sum p(x, y, z) \log \frac{p(X, Y | Z)}{p(X | Z)p(Y | Z)} =$$

$$\sum \frac{1}{klm} \log \frac{1/kl}{1/k \cdot 1/l} = \sum \frac{1}{klm} \log 1 = 0$$ \hspace{1cm} (2)

The general expression for a bivariate normal distribution is given by the formula:

$$p(x, y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-r_{xy}^2}} \times$$

$$e^{-\frac{1}{2(1-r_{xy}^2)} \left[ \left( \frac{x-m_x}{\sigma_x} \right)^2 - 2r_{xy}(x-m_x)(y-m_y) + \left( \frac{y-m_y}{\sigma_y} \right)^2 \right]}.$$

$$e^{-\frac{1}{2} \left[ \frac{(x-m_x)^2}{\sigma_x^2} + \frac{2r_{xy}(x-m_x)(y-m_y)}{\sigma_x\sigma_y} + \frac{(y-m_y)^2}{\sigma_y^2} \right]}.$$  \hspace{1cm} (3)
The expressions for bivariate conditional normal distributions to be placed in the denominator of equation (7) are provided below

\[ p(y \mid z) = \frac{1}{\sigma_y \sqrt{1 - r_{yz}^2} \sqrt{2\pi}} e^{-\frac{1}{2(1-r_{yz}^2)} \left( \frac{y-m_{y}}{\sigma_y} - r_{yz} \frac{z-m_{z}}{\sigma_z} \right)^2}, \]  
\[ p(x \mid z) = \frac{1}{\sigma_x \sqrt{1 - r_{xz}^2} \sqrt{2\pi}} e^{-\frac{1}{2(1-r_{xz}^2)} \left( \frac{x-m_{x}}{\sigma_x} - r_{xz} \frac{z-m_{z}}{\sigma_z} \right)^2}, \]  

where \( r \)'s are correlation coefficients between corresponding random variables, while \( m \)'s and \( \sigma \)'s are means and standard deviations of random variables indicated by the indexes, respectively.

In Fig. 2 the relationship between the total number of strokes on the scale \( m \), its information \( I \) and the number of the strokes position already assessed on the scale \( b \) is displayed. It is assumed that the base of logarithm is 2.

Fig. 2. The relationship between the total and assessed number of strokes with the information quantity of the scale, where \( m \) is the number of strokes on the scale, \( b \) is the number of the assessed strokes on the scale and \( I \) is the quantity of information.
Examples of the transfer from discrete to the analogue information in the measuring system can be presented by angular accuracy calibration of the raster scales. The calibration of the scale stroke-by-stroke (at a predetermined pitch) gives discrete information of the calibration. A possibility to transfer it to the analogue form is presented here and shown in Fig. 3. It is performed by creating Moiré (Fig. 3, a) or Vernier (b) fringe pattern, one of scales serving as a reference. One, two or four analyzing gaps with photocells are located on the optical patterns shown in Fig. 3. For Moiré pattern it is enough to place one photoelectric sensor (in the upper part of the scales, Fig. 3 “a”) on the pattern and rotate it on the table of high accuracy axis [8, 9].

3. THREE-DIMENTIONAL CASE

The measurements of the geometrical parameters of the parts are mostly performed on very expensive 3D measuring equipment – coordinate measuring machines (CMMs) having a high precision mechanical base equipped with very high precision slideways. The CMMs are an example of highly complex, precise and highly expensive equipment. The most precise methods and means are to be used for the assessment of the accuracy parameters of the CMM for the purpose of its correction by mechatronic means. It can be noted that these modern means are to be used only at the initial phase of machine’s production. Further accuracy assurance is transferred to the mechatronic means controlled by the PC of the machine.

The main task of the correction is to determine the correctional displacement values in all co-ordinate displacements by calculations and then to perform the additional movement using the last (conclusive) part of kinematic chain of the machine. For example, it may be the grip of the arm of an industrial robot, the probe of a CMM (measuring robot), the cutting instrument of a metal cutting tool, etc. In this case, piezoelectric plates, cylindrical or spherical components are useful to incorporate into the conclusive machine member for the purpose of accomplishing the correctional microdisplacement required. The final element of CMM, a touch-probe with the piezoelectric cylinder and the electrodes for electric supply, is shown in Fig. 4. The piezoelectric active elements also are implanted into the sliding parts of the machine: I. e., console moving along the y-axis, the carriage moving along the x-axis, and the arm with the touch-probe moving in the direction of the z-axis. New active materials with high piezoelectric or magnetostrictive properties (Terfenol-D, flexible piezoactive materials, etc.) show a wide area of its application with high level of integration and multifunctionality [9]. They are applicable to implement into the piezoactive part’s supports (Fig. 4) giving an opportunity to correct the position of the part in the 3D space compensating the systematic error of the machine’s displacement.
The methods permit to control the accuracy of the displacement of the parts of the machine, of the transducers or the final member of kinematic chain of the machine, such as the touch-probe or the cutting tool of the machine.

4. CONCLUSIONS

The mechatronic constituents for the measurement of angle measuring systems are described giving information on the accuracy of the angular displacement, determining values of errors to be corrected by mechatronic means. Information entropy assessment is given allowing the evaluation of the calibration of the circular scales or rotary encoders supplementing it by the information about which part of the total was assessed during this process. Computer controlled rotary table for angular measurements is developed for the measurement of the circular raster scales, rotary encoders or angle measuring instruments.

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