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ACTIVE ERROR COMPENSATION FOR PRECISE MACHINES

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Abstract: The paper deals with the active error compensation effected by using links or components, made from piezoactive (piezoelectric or magnetostrictive) materials. It is shown that by implanting of active links into the technological chain of the measuring equipment both static and dynamic errors can be sufficiently reduced. Some considerations according to new approach to error compensation circuits and actuators are presented. Compensation covers not only generally accepted measurement systems, but also opens new ways of increasing the accuracy of such typical components of technological machines as beddings, slideways, fixing and datum keeping surfaces. Two- and three-dimensional correction methods and means are presented.
Keywords: Error compensation, Piezoactive links, Active kinematic pair, Infinite stiffness, Active supports

1 INTRODUCTION

Experimental investigations show the significance of errors in the output of the transducer and for informational measurement system in large. Technical solution for systematic error correction is used, for example, by applying correctional signal to the output of translational transducer with the interpolator and two outputs (+ and -) connected to commutation circuit. Piezoelectric correctional devices can be effectively used for this purpose [1-3]. The interest in piezoactive (piezoelectric or magnetostrictive) materials has rapidly increased over the last two decades when their potential as transducers for precision actuators and sensors were realised. Recent developments of new active materials with extremely high piezoelectric or magnetostrictive properties (Terfenol-D, PZT, PMN - Lead Magnesium Niobate, flexible piezoactive materials, etc.) have extended the area of their applications, including new systems with a high level of integration and multi-functionality [1,2].

2 CORRECTION USING ACTIVE MATERIALS

The design of correction mechanisms involves the use of rather complicated mechanical or electromechanical programmable systems. These systems are not universally applicable due to considerable size, complexity at large transmission ratios of backlash-free mechanisms, or devices for co-ordination of displacement with a programmable correction system. These problems are especially critical in cases when there is a need to increase the accuracy of a measurement system of a small size, built into vacuum chambers and devices subjected to various external and/or temperature disturbances.

Error correction problems can be solved using measuring scales on the piezoactive, piezoelectric or piezomagnetic substrate. In such systems, the application of electric or magnetic fields generates displacements, which are compensating the errors of the shape or the pitch of rasters. Assuming the displacement to be constant along the width of the piezoplate when components of the electric field in the direction of the axis of the displacement are constant across the thickness, equations of the piezoeffect can be written in the form:

$$s_1(x) = -h_{31} D_3(x) + c_{11}^D e_1(x), \qquad (1)$$
$$D_3(x) = e_{31} e_1(x) + \in_{33}^S E_3$$

Here $D_3(x), E_3(x)$ - displacement and the electric field in the raster plate,

$s_1(x)$, ε_1 (x) - components of elastic stress and deformation in the direction of the axis *x* ,

h_{31} - piezoelectric constant of deformation.

e_{31} - piezoelectric constant,

c_{11}^{D} - modulus of stiffness at constant electric displacement,

$\in_{33}^{S}$- dielectric constant at constant elastic stress.

The potential energy of the piezoplate has the form

$$U=\frac{bh}{2}\int_0^l\left(1-k_{31}^2\right)c_{11}^{D}e_1^2(x)dx-h\int_0^l e_{31}b_1(x)E_3(x)e_1(x)dx-$$

$$-\ h\int_0^l \in_{33}^{S} b_1(x)E_3^2(x)dx.. \qquad (2)$$

where $k_{31}^2=e_{31}h_{31}$ - is coefficient of an electromechanical coupling,

$b_1(x)$ means the width of the electrode coating of the piezoplate.

According to the principle of minimum of potential energy $\frac{dU}{de_1}=0$, and taking into account that longitudinal displacements are related to deformations by relationship $e_1(x)=\frac{du}{dx}$, we obtain the equation of equilibrium of the piezoplate considered

$$e_{31}b_1(x)E_3(x)=b(1-k_{31}^2)c_{11}^{D}\frac{du}{dx}, \qquad x\in[0,l] \qquad (3)$$

Since $u(x)=-kd(x)$ is specified, to satisfy this equation it is necessary to provide the required value of the expression $[e_{31}b_1(x)E_3(x)]$ in every point *x*. It is possible by using three different approaches:

i) By changing $E_3(x)$ along the piezoplate when $b_1=b=$ const. Technically it is performed by means of segmentation of the electrode coating of the piezoplate along the length *l* and by applying different voltage to every segment. The continuous function

$$E_3(x)=-\frac{1}{e_{31}}c_{11}^{D}(1-k_{31}^2)\frac{dd(x)}{dx} \qquad (4)$$

is approximated in this case by a step function. The minimum length of the segment necessary for the satisfactory approximation must not exceed *T*/2 where *T*= period of the higher harmonic of the expansion $E_3(x)$ into a Fourier series;

ii) By changing the width of the electrode $b_1(x)$ along the length of the piezoplate at $E_3=$ const. Besides it is necessary to perform a sectional view of the electrode in the places of the changing sign $\frac{dd(x)}{dx}$ for the connection of the voltages of the opposite polarity to be possible. This method is more suitable, since there is no need for a large number of supply voltages and the number of segments is appreciably smaller than in the first case. A shortcoming of this method is creation of additional distortion of the parallelism of raster scale's lines in case of a considerable width of the piezoplate;

iii) By changing e_{31} along the axis *x* by means of local depolarisation performed. It is less suitable method of error control, because the changes of the properties of piezomaterial is not always acceptable.

When developing of the general approach it is expedient to use finite elements method (FEM) for calculation of the distribution of the external electrical field applied to the piezoplate.

FEM is especially convenient for solving the formulated problem due to a possibility to achieve an analogy of the finite element model with the cellular pattern on the surface of the electrodes of the plate, with each cell connected to the specific voltage. In more general cases implanting of active links into the technological chain of the machines can compensate unwanted displacements, caused by external forces, changing of the position of moving components, unbalance of rotating systems, wear of contacting surfaces, temperature disturbances, etc.

3 ACTIVE KINEMATIC PAIRS

New structure units of precise mechanisms - *active kinematic pairs* there are presented, in which forces or torques are generated in the contact zone between the components. In piezoelectric active kinematic pair, one or both components are made from piezoactive material [4-9]. The relative movement between both components of the pair is generated by transforming resonant multi-component oscillations into continuous or start-stop motion. Usually the number of degrees of freedom (DOF) of such piezoelectric devices lies between 1 and 5, but using flexible piezoactive materials it is possible to design actuators or compensation devises with practically unlimited number of DOF.

When considering the design of piezoelectric multi-degree-of-freedom actuators it is expedient to introduce the concept of active kinematic pair [1,5], in which one or both links are made from piezoactive material, enabling the generation of static displacements, quasi-static or resonant oscillations, resulting in generating forces or torque in contact area between links. It leads to the generation of motion of one link relative to the other. In such definition, active kinematic pair is a kinematic pair with a controllable number of degrees of freedom W, where

$$W = 6 - s(z). \tag{5}$$

Here s is the number of constraint conditions, restricting the relative motion of each kinematic pair ($1 \le s \le 6$); z is a set of the control parameters, changing the constraint conditions. In particular cases, it may be that $s = s(t)$ when the structure of the mechanism is programmable; $s = s(\dot{x})$, $s = s(\ddot{x})$ when the structure of the mechanism in controlled, depending on speed and the acceleration of generalised coordinates x_i; and, in a general case, also depending on constrain reaction magnitudes F_i:

$$s = s(\dot{x}_i, \ddot{x}_i, x_i, F_i, \ldots, t). \tag{6}$$

A number of constrain conditions s can be varied in different ways [8-11]. The simplest is control of the friction, acting in the pair, usually when the elements of the pair are closed by force. Here either the friction coefficient can be varied, or the magnitude of the force executing the closure. This in achieved by the excitation of high frequency tangential or normal vibrations in the contact zone of the pair. The electrorheological and magnetorheological liquids, in which viscosity can be varied in a wide range, can also be used successfully. At $s = 6$, the number of degrees of freedom is equal to zero and the pair becomes stationary.

Active kinematic pair is characterised by:

i) Control of number of degrees of freedom W;
ii) Generation of forces or torque in the contact area between links;
iii) Additional features: self-diagnostic, multi-functionality, self-repair, self-adaptation;
iv) Two levels of degrees of freedom, where the first level is related to big displacements (transformation of resonant frequency oscillations into continuous motion), the second - small displacement (static and quasi-static deformation of active link, generated by using inverse piezoeffect and sectioned electrodes of transducer) [12-14].

Adaptivity of active kinematic pairs. Actuation, sensing and signal processing in intelligent mechanisms are the main functions, embedded in which are energy conversion and information transfer systems [15-17]. Such mechanisms can modify their behaviour in response to change in the dynamics of the process and the disturbances.

An important feature of mechanisms containing links made from active materials (e.g. piezoceramics) is that very often various functions (actuators, sensors, oscillators, generators of static and quasi-static displacements, etc.) can be performed by the same transducer, enabling the development of methods for designing adjustable or adaptive mechanisms, so that multiple tasks can be performed by the same mechanism, including the ability to accommodate manufacturing and part-positioning errors in order to widen applicability. Fig.1 shows three levels of adaptivity of *active kinematic pair* with degrees of freedom.

The lowest - *first level* is characterised by the ability of the mechanism to change its parameters in real time to enable the end-effect or of a given mechanism configuration to accomplish different tasks, depending on the value of the adjustable parameter. It is understood that some prior information regarding the mechanism transfer function is available. The *second level* takes into account full or partial information on external ant state-depend disturbances and the correction of the programme is taking place. On the *third level* such functions as self-diagnosis and self-repair are introduced and multi-functionality of mechanisms with active links are being exploited.

The schematic view of active kinematic pair - piezoelectric actuator with three possible levels of adaptivity is shown in Fig. 1. The generation of resonant travelling wave oscillations in spherical piezoelectric transducer *2* leads to the rotation of link *1* around the corresponding axes x', y' or z'. The position of the axis of rotation is defined by the topology of electrodes, connected to n-phase ($n \ge 3$) electrical signal generator.

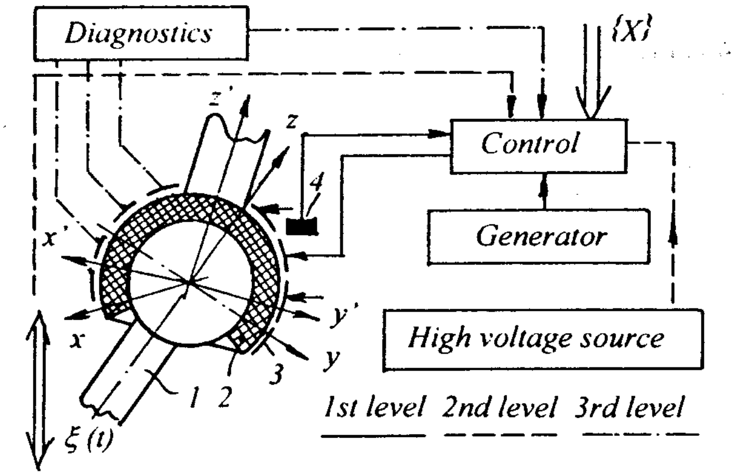

Figure1. Three levels of adaptivity - the example of piezoelectric robot joint three DOF:
1 - passive link; *2* -link- transducer, made of piezoactive material;
3 - sectioned electrodes of transducer; *4* - 3-*D* relative motion transducer

Here, on the first level of adaptivity, the control system defining the actuating torque to produce the desired motion of link *1* has a feedback providing it with information about its parameters. Compensation of disturbances $\xi(t)$ - second level - will include change of state of the contact between links *1* and *2* by changing the diameter of outer sphere (applying high static voltage to certain electrodes) and corresponding change of the control algorithm.

On the third level system diagnostics is included; here an adaptation process, based on full information of mechanism state (including wear, ageing of piezoactive material, etc.) and errors readjust the parameters in the non-linear model until the position and velocity errors of link *1* along the nominal trajectory are minimised. There is a strong correlation between *intelligent* and *adaptive* mechanisms, which can be divided into the three groups:

i) Mechanisms, in which outer excitation or control results in redistribution of strains, stresses, forces, reactions, etc. (as in self-aligning mechanisms);

ii) Mechanisms with controllable parameters, such as mass, moment of inertia, damping, stiffness, friction, etc. Typical examples are mechanisms with redundant degrees of freedom (very often the efficiency of the system is related to the degree of redundancy), self-optimising mechanisms and automatic balancing devices;

iii) Mechanisms with controllable kinematic structure. This is the most advanced class of intelligent mechanisms, in which the kinematic structure of the system can be changed in a very short time, depending only on the natural frequencies of dynamic systems.

More advanced cases can also involve the change of algorithm, e.g. when changing the type of mechanism.

4 INFINITE STIFFNESS

A new concept *of infinite stiffness* of active kinematic pairs (for the specific load range) is introduced and illustrated. To realise the concept both direct and inverse piezoeffects of the active link are used: direct piezoeffect – to measure the displacement or stresses when external forces are applied; inverse piezoeffect – to generate displacements or stresses of opposite sign in the active link.

A classical approach to reduce or eliminate static and dynamic errors of bearings, supports and guides (backlash, hysteresis, dead zones, radial and axial play, vibration, etc.) is to increase the accuracy and stiffness of system elements. This sharply increases the costs of the devices. Further gains in accuracy of high precision elements are gradually reaching its economically acceptable limits. The mechatronic approach to this problem is to integrate mechanical system with electronics and control. Further to reducing the cost and increasing the final accuracy, this alternative introduces new properties in the existing systems. The term *active bearing* here is introduced; it is related to a kinematic pair with n degrees of freedom ($1 \le n \le 5$), in which torque or forces are generated in the contact zone between elements, leading to the relative motion. As in existing devices, one element is fixed, allowing the transmission of forces to the other element.

5 DEVELOPMENT OF ACTIVE BEARINGS

The development of active bearings was made possible through the latest advances in creating new piezoactive materials and the development of various methods to transform high frequency multi-component mechanical oscillations into continuous or step motion [13-19]. The integration of unique properties of piezoactive transducers and actuators (high resolution, low time constant, easy control of forms, types and parameters of oscillations, possibility to generate multi-component static, quasi-static and resonant displacements) with control system made it possible to sharply reduce or even fully eliminate most errors of bearings, supports and guides, used in high precision measuring devices.

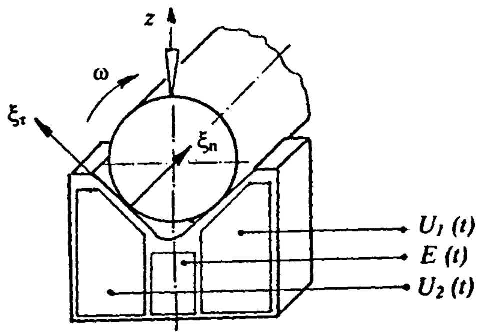

Figure 2. Diagram of active bearing with "infinite" stiffness in *z*-axis direction

The schematic view of active radial and thrust bearings is presented in Fig. 2 with two DOFcontaining active (made from piezoceramics) V-block with sectioned electrodes. Rotation and translational motion of the shaft is achieved by transforming high frequency resonant oscillations into continuous movement, generating additional static or quasi-static displacements of the shaft in the direction of *z* axis (by applying voltage *E(t)* to the central electrode) it is possible to achieve infinite stiffness of the shaft suspension in *z* axis direction.

At a fundamental level, the structures resemble slide bearings with the main difference being that one or both elements are made from piezoactive material with sections of electrodes or constitute part of a piezoelectric transducer. Static and quasi-static displacements are generated by applying voltage to specific electrodes; to achieve rotation or translation motion, high frequency oscillations are generated in the contact zone between two elements.

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