NEW TYPE OF MULTI-DEGREE-OF-FREEDOM PIEZOELECTRIC ACTUATORS, BASED ON ACTIVE KINEMATIC PAIRS

Ramutis Bansevicius, Arunas Lipnickas
Kaunas University of Technology, The Mechatronics Center for Research, Studies and Information
Kestucio 27, Kaunas, Lithuania

Minvydas Ragulskis
Kaunas University of Technology, Research Group for Mathematical and Numerical Analysis of Dynamical Systems
Studentu 50-222, Kaunas, Lithuania

Keywords: Mechatronics, Piezoelectric Actuators, Active Kinematic, Active Bearing, Modelling.

Abstract: New type of multi-degree-of-freedom piezoelectric actuators based on active kinematic pairs is presented. The contact zone of this type of actuator is formed by two oscillating transducers in a form of rod, plate, disk or cylinder. Depending on a phase of both transducers in a contact zone and their amplitudes, either high frequency oblique impacts or periodic change of normal reaction in the contact zone are generated, leading to continuous motion of one of the links. Schematics of piezoelectric motors, using two active elements in the contact zone and comprising the number of degrees-of-freedom up to 5 are presented. Several applications for laser beam deflection and positioning devices in the plane are considered. The concept of active bearing is introduced; this type of support has no processing datum surface errors.

1 INTRODUCTION

It is worthwhile to introduce the concept of *active kinematic pair* in the design of multi-degree-of-freedom actuators and 3*D* positioning systems. Such concept is especially useful in the design of adaptive positioning systems (Ragulskis, 1988; Bansevicius, 2002a). The characteristic feature of active kinematic pair is that one or both elements of it are manufactured from active or smart materials such as piezoelectric, magnetostrictic or shape memory materials (Bansevicius, 2002a). Active kinematic pair can change its kinematic structure or parameters depending on external conditions or excitation characteristics (Bansevicius, 2002b). The multi-functionality of the mechanisms can be achieved applying direct or inverse piezoelectric effects. In other words, several different functionalities as motion generation, measurement of parameters of motion, control of friction forces in the contact zone can be implemented into one instrument (Bansevicius, 2000a; Ko and Kimb, 2006, Chu and Fan, 2006). Excitation of static or quasi-static deformations, multi-directional and multi-shape resonance oscillations, generation of motion in the contact zone, transformation of oscillations into continuous motion are just several examples of application of active kinematic pairs (Bansevicius, 2000b; Bansevicius and Ahmed, 2000ab; Bansevicius, 2001).

Active kinematic pairs enable:

- Control of the number of degrees-of-freedom of the kinematic pair by means of friction force control in the contact zone or generation static or quasi-static deformations of the element of the pair;
- Generate forces and moments in the contact zones;
- To effect additional functions – self-diagnostics, multi-functionality, adaptively, self-assembly;
- To implement two levels of degree-of-freedom. The first level comprises large deflections or displacements, produced by transformation of

Bansevicius R., Lipnickas A. and Ragulskis M. (2009).
NEW TYPE OF MULTI-DEGREE-OF-FREEDOM PIEZOELECTRIC ACTUATORS, BASED ON ACTIVE KINEMATIC PAIRS.
In *Proceedings of the 6th International Conference on Informatics in Control, Automation and Robotics - Robotics and Automation*, pages 159-164
DOI: 10.5220/0002180401590164

resonance oscillations of pair's links into continuous motion. The second level deals with small displacements (in nanometre range), implemented by means of direct piezoelectric effect and specific sectioning of electrodes.

2 TWO ACTIVE ELEMENTS IN THE CONTACT ZONE

Applying two active elements in the contact zone of piezoactuator enables enlargement of the generated force or torque and transforming oscillations into continuous motion. High frequency oblique impacts are generated in the contact zone between two rod type transducers (Fig. 1). Only longitudinal resonance oscillations are generated in these rods. Specific phase differences between the oscillations in these rods enable variation of the continuous motion parameters. Zero phase difference generates direct continuous motion, 180 degree phase difference enables reverse continuous motion. Phase difference between 0 and 90 degrees (or between 180 and 270 degrees) changes the normal force component in the contact zone and helps to tune dynamical parameters of the whole system with the rheological parameters of the contact zone.

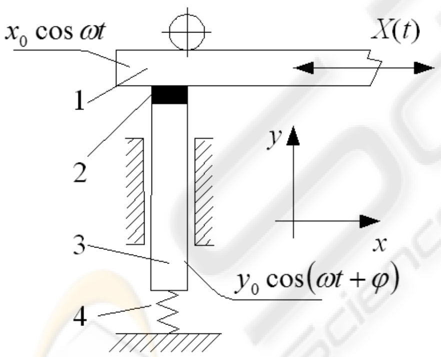

Figure 1: Piezoelectric motor. *1* – the first piezoelectric transducer (slider); *2* – contact element; *3* – the second piezoelectric transducer (active support); *4* – spring.

Several schematics of such piezomotors are presented in Figures 2, 4 and 6. Symmetric scheme (Fig. 2) enables sufficient increase of the generated force. Combination of different Eigen modes helps to achieve larger deflections or displacements of the sliding element. It must be noted that the reverse mode is symmetric in all schemes and can be realised by altering the phase of one of the transducers by 180 degrees. The scheme presented in Fig. 2b is implemented in the design of miniature longitudinal small stroke (2 mm) piezomotor and well illustrates the technological advantages of such an approach.

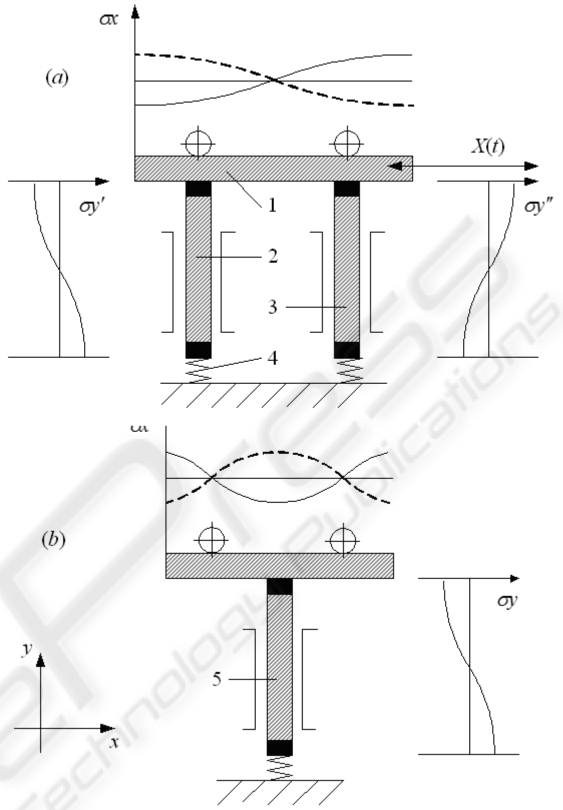

Figure 2: Two cases of piezoelectric motors with two active elements in the contact zone: *(a)* - symmetric scheme; only longitudinal first Eigen shape resonance vibrations are generated in all actuators (the node is located in the middle point of the actuator); *(b)* - application of different Eigen shapes to increase the stroke: longitudinal resonance oscillations (second Eigen shape) are excited in the slider (two nodal points); longitudinal resonance oscillations (first Eigen shape) are excited in the supporting actuator (one nodal point).

2.1 Numerical Analysis of Active Kinematic Pair comprising Two Active Elements in the Contact Zone

The active kinematic pair shown in Fig. 1 is modelled using finite element techniques (Zienkiewitcz and Taylor, 1991). We used hybrid elastic body – piezoelectric material finite element formulations, described in (Ragulskis, 1998). Non-adaptive uniform finite element meshes were used for the slider and the active support in order to secure the best stability and convergence of the numerical solution, while an adaptive mesh was used for the contact element (Fig. 1).

The effect of the pressing spring was assumed as constant forces, acting to nodes of the outside surface of the contact element. Limiters for the slider were modelled as kinematic constrains for the nodes of the external surface of the slider, permitting longitudinal but impeding transverse displacements.

Eigen shapes of the slider and the contacting element were calculated. Then the electrical excitation of the piezoelectric material was selected in such a way that the oscillations of the slider and the active support element would follow their Eigen shapes (and resonance Eigen frequencies) as close as possible.

The time step was selected to accommodate accurate integration of the fifteenth Eigen mode (the first fifteen Eigen modes were sufficient to represent complex dynamical processes taking even in the contact zone). Schematically, the piezoelectric excitation can be represented as:

$$\begin{aligned} F_S(i,j) &= \Phi_S(\delta x_i, \delta y_j)\sin(\omega t) \\ F_A(i,j) &= \Phi_A(\delta x_i, \delta y_j)\sin(\omega t + \varphi) \end{aligned} \quad (1)$$

where F_S is a matrix of dynamical forces acting to the nodes of the slider; F_A are forced acting to the nodes of the active support; Φ_S and Φ_A are first Eigen shapes of the slider and the active support (Eigen shape depends from the allocation of electrodes); ω is the resonance frequency (both for the slider and the active support); φ is the phase difference of the electric excitation. Numerical simulations produce a large dataset of results. Only the trajectory of the middle contact point of the slider is shown in Fig. 3 in the *x*-*y* phase plane in order to represent main dynamical features.

It can be seen that optimal longitudinal motion of the slider is achieved at φ = 0, or φ = 180 (the reverse mode). Other phase differences result into chattering mode when the oblique impact energy is not optimally transferred into the continuous longitudinal motion of the slider.

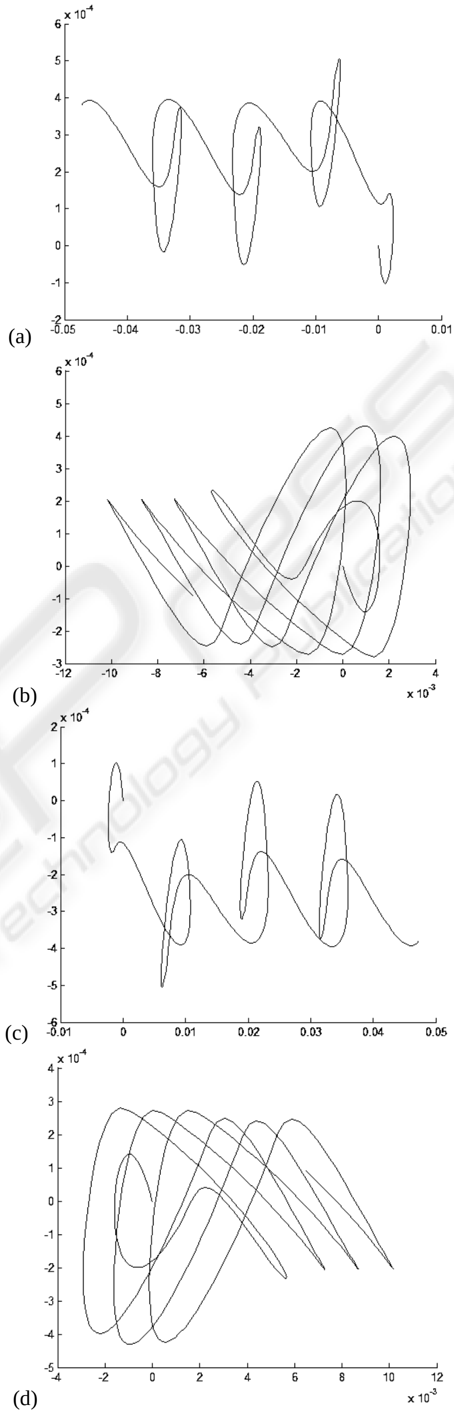

Figure 3: Numerically reconstructed transient dynamical processes taking place at different phases: (a) φ = 0; (b) φ = 90; (c) φ = 180; (d) φ = 270 degrees. Note different scales of *x*-axis.

3 APPLICATIONS OF MULTI-DEGREE-OF-FREEDOM PIEZOELECTRIC ACTUATORS

Piezoelectric actuators based on active kinematic pairs enable realisation of different types of motion. Schematic of piezoelectric rotary motor is presented in Fig. 4. Dynamical processes taking place in the contact zone are analogous to the basic type mechanism shown in Fig. 1 and depend on the phase difference and rheological properties of the contact surfaces. As in the previous schemes, the resonance frequencies of the radial oscillations of the disk type transducer and longitudinal oscillations of the rod piezotransducer can differ in the range of few percents. In fact, the range of tolerable differences depends on the damping in the transducers and in the whole system in general.

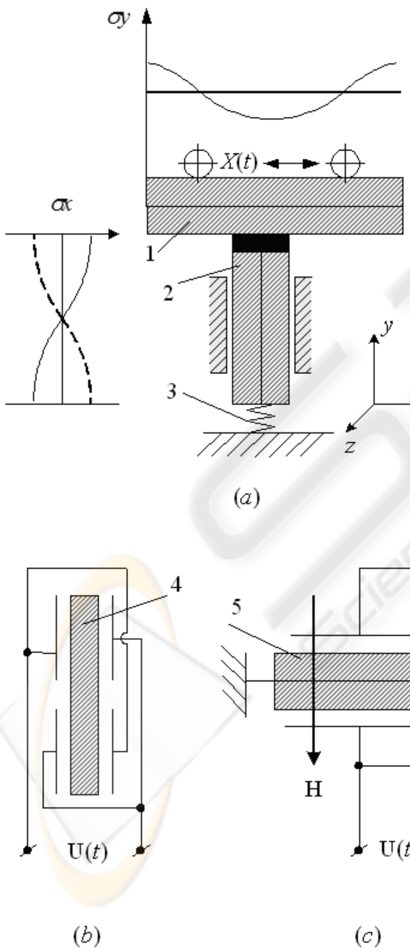

Figure 4: Increasing the velocity by using bimorphic transducers. *1, 2* – bimorphic piezotransducers; *3* – spring; 4 – schematics of the electrodes; *5* – excitation wiring diagram; *H* – poling vector.

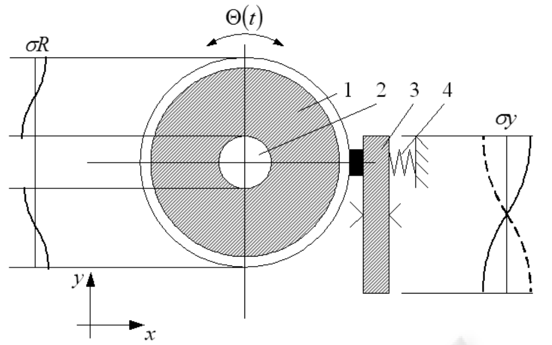

Figure 5: Schematics of angular motion piezomotors with increased torque. *1* – piezoceramic ring; *2* – fixing element; *3* – rod type piezotransducer; *4* – spring.

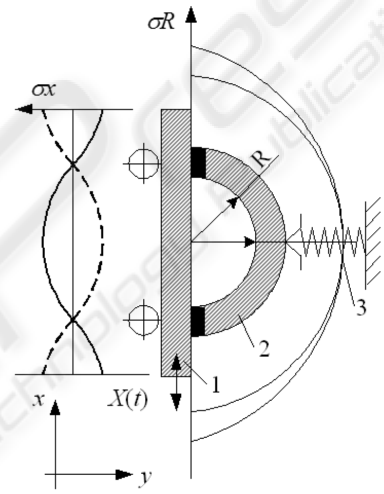

Figure 6: Schematic diagram of translational motion piezomotor analogous to symmetric scheme presented in Fig. 4.

Two new instrumentation schemes shown in Fig. 7 and Fig. 8 have been implemented practically. Initial experiments have shown their effectiveness for implementation small one-degree-of-freedom positioning systems dedicated for precision instrumentation. Such schemes can be easily manufactured using low cost piezotransducers.

Piezomotors with two active elements in the contact zone can be effectively applied in the design of optical beam reflection and scanning equipment. Two cases of such instrumentation are presented in Fig. 9 and 10. Oblique high frequency impacts are generated in the contact zone between the cylinder section and rod type transducer (Fig. 9).

The scheme showed in Fig. 10 enables implementation of two-degrees-of-freedom motion of the mirror by electric control of different disk or plate type piezotransducers' electrodes.

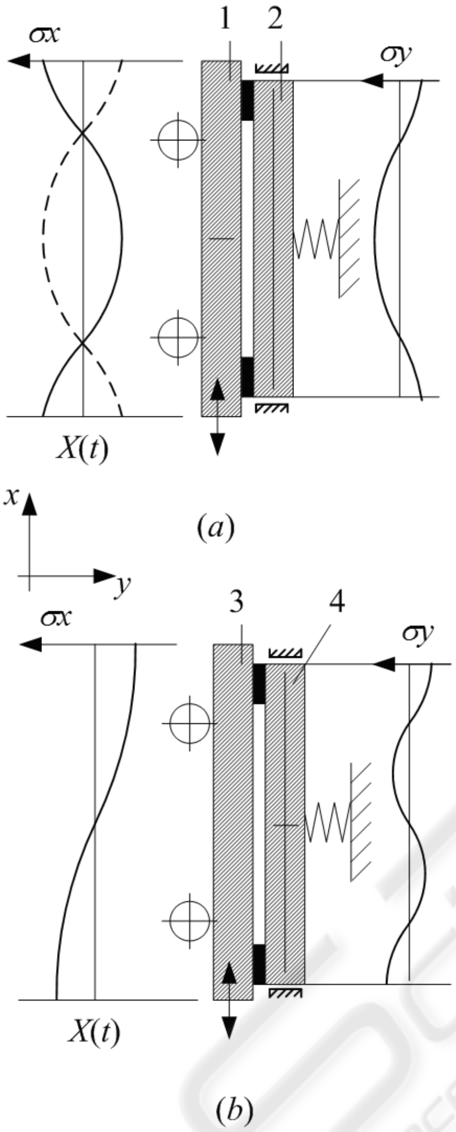

Figure 7: Schematics of translational motion piezomotors with two active elements in the contact zone. *(a): 1* – piezoceramic transducer (longitudinal resonance second Eigen shape oscillations; two nodal points); *2* – piezoceramic bimorphic bending resonance oscillation transducer (first Eigen shape; two nodal points). *(b): 3* – longitudinal vibration transducer (first Eigen shape; one nodal point); *4* – bending vibration transducer (second Eigen shape; three nodal points).

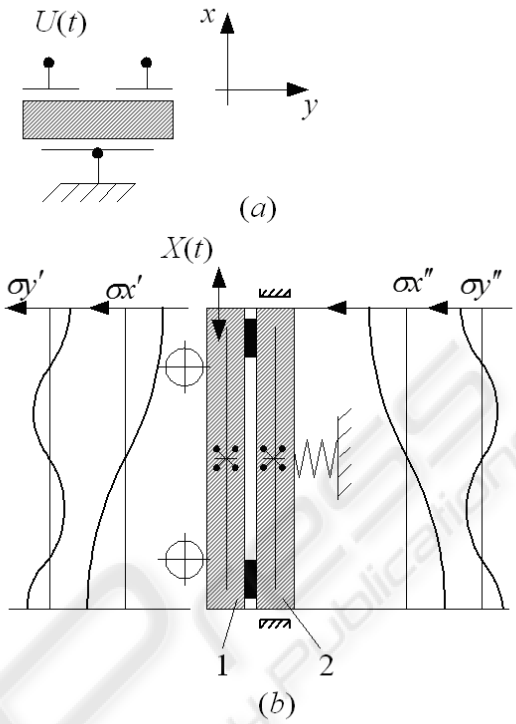

Figure 8: Symmetric translational motion piezomotor with two active elements in the contact zone. *(a):* sectioning of the electrodes; *(b): 1, 2* –longitudinal resonance oscillations (first Eigen shape) and in-plane bending oscillations (second Eigen shape) are generated in two identical piezotransducers.

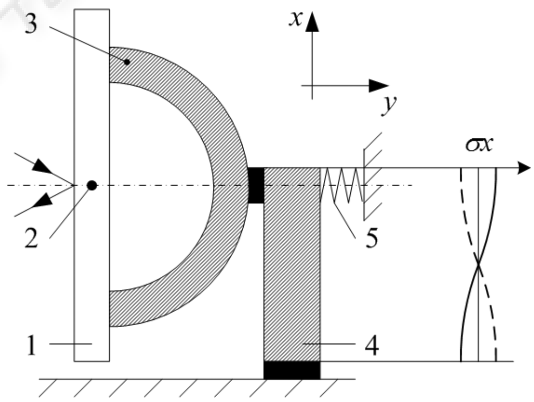

Figure 9: Optical beam reflector. *1* – mirror; *2* – fixing elements; *3* – piezoceramic sector; *4* – piezoelectric rod, generating longitudinal resonance first Eigen shape oscillations.

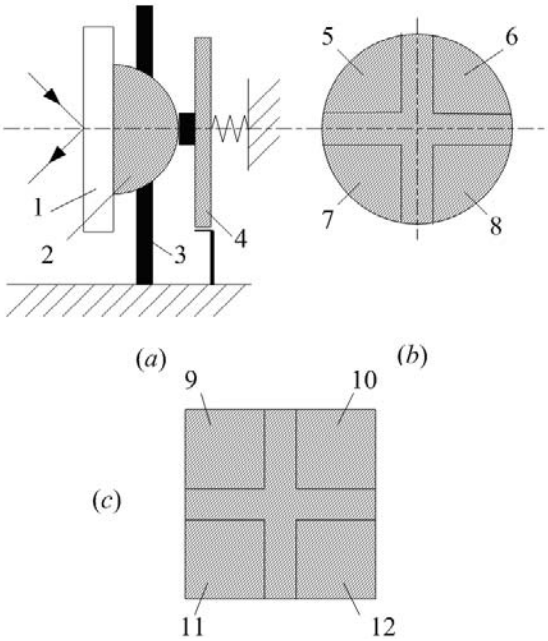

Figure 10: Two-degree-of-freedom optical beam reflector/scanner. *1* – mirror; *2* – segment of spherical piezotransducer; *3* – fixing element (scheme is not specified); *4* – plate type piezotransducer; *5…12* – sectioned electrodes.

4 CONCLUSIONS

New type of multi-degree-of-freedom piezoelectric actuators, based on active kinematic pairs, is presented in this paper. Schematics of piezoelectric motors, using two active elements in the contact zone and comprising the number of degrees-of-freedom up to 5 are presented. Several applications for laser beam deflection and positioning devices in the plane are described. The concept of active bearing is introduced.

The contact zones of these actuators are formed by oscillating pairs of piezoelectric transducers. Control of the phase difference between the transducers enable transformation of oblique impacts into continuous motion. Such types of actuators are characterised by high resolution, low time constant, and are applicable in different areas of precision mechatronics.

ACKNOWLEDGEMENTS

Research has been financed by Lithuanian State Science and Studies Foundation (High-Tech Development program's research project PjezoAdapt).

REFERENCES

Ragulskis, K., et al., 1988, Vibromotors for Precision Microrobots, Hemisphere Publishing Corp., New York, 310 p.

Bansevicius, R. et al., 2002a, *The Mechatronics Handbook*, CRC Press, Boca Raton.

Bansevicius, R., 2002b, Latest trends in the development of piezoelectric multi-degree-of-freedom actuators/ sensors. Responsive systems for active vibration control, NATO Science Series, Vol. 85, Kluwer Academic Publishers, Dordrecht, p.207-238.

Bansevicius, R., et al., B., 2000a, Design and control of precise robots with active and passive kinematic pairs, Mechatronics 2000: Proceedings of the 7-th Mechatronics Forum, Atlanta, Georgia, U.S.A., Pergamon, p.10-16.

Ko, H-P., et al., 2006, A novelty in ultrasonic linear motor using the radial mode of a bimorph, Sensors and Actuators A 125, p.477–481.

Chu, C-L. and Fan, S-H., 2006, A novel long-travel piezoelectric-driven linear nanopositioning stage, Precision Engineering 30, p.85–95.

Bansevicius, R., et al., 2000b, Active error compensation for precise machines, IMEKO 2000: XVI IMEKO World Congress Proceedings, Vienna, Vol. 8, p.21-26.

Bansevicius, R. and Ahmed, S., 2000a, Piezoelectric Active Supports, U.K. Patent 2313982, Patented by Smart Technology Ltd., U.K..

Bansevicius, R. and Ahmed, S., 2000b, Piezoelectric Actuators, U.K. Patent 2332090, Patented by Smart Technology Ltd., U.K..

Bansevicius, R. and Ahmed, S., 2001, Bearings and Support, USA Patent 62625114B1, Patented by Smart Technology Ltd., U.K..

Zienkiewicz, O.C. and Taylor, R.L. 1991, Finite Element Method – Solid and Fluid Mechanics: Dynamics and Nonlinearity, Vol. 2, McGraw-Hill: New York.