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STATE-OF-THE-ART AND NEW DEVELOPMENTS OF MULTI-DEGREE-OF-FREEDOM PIEZOELECTRIC MOTORS FOR EXPERIMENTAL MECHANICS AND MEASURING DEVICES

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Abstract – The paper covers state of the art and latest development of piezoelectric motors at Kaunas University of Technology (Lithuania), that are related to the R&D of laser scanning and deflecting devices, measuring systems, nano-resolution positioning devices on the plane, various applications including teaching aids for Mechatronics studies and even "intelligent" toys. All presented motors are one- or multi-degree-of-freedom (multi DOF) resonant devices and generate continuous or step motion of the positioning object.

Keywords: Piezoelectric motors, Laser beam scanners, Multi DOF devices, Nano-resolution positioning

1. INTRODUCTION

According to the report on a Global Industry and Market Analysis, related to piezoelectric operated actuators and motors [1], the global market for piezoelectric operated actuators and motors will double from $5.3 billion in 2006 to $10.7 billion by the year 2011 at an average annual rate of growth (AARG) of 15.1%. New applications are emerging for piezoelectric operated actuators and motors in applications including aircraft, automobile hydraulics and drug delivery. The report includes several major findings. For example, among the five markets, the ceramic servo motor is the largest and most mature. It is likely to grow at an annual rate of 11%. However, the piezoelectric multilayer actuators and motors will see the highest growth rate, estimated to be 19.2% annually.

The report [1] also found that the life science and medical technology fields also constitute a high-growth segment of piezoelectric-operated actuators and motors. This market is expected to grow at 18.7% annually and could record an even higher growth rate if there is wider acceptance by end users.

R&D activity in developing piezoelectric motors began in Kaunas University of Technology as early as 1975 [2, 3] and resulted in developing basic schematics of one- and several DOF piezoelectric motors and piezoelectric robots [4…8]. Further research resulted in the development of precise devices, unified by the concept of *active bearings and supports* [9…11].

Latest R&D activity of The Mechatronics Centre for Research, Studies and Information (Kaunas University of Technology) is directed to the development of several types of multi DOF piezoelectric motors, based on various operating principles. Introduced piezoelectric devices can be characterized by specific areas of application, high resolution and short time response. New types of piezoelectric transducers (e.g. with alternating poling vector) allow to considerably simplify the design of positioning devices or laser scanning systems due to eliminating intermediate links and additional piezoelectric transducers in case of multi DOF systems.

2. ACTIVE KINEMATIC PAIRS

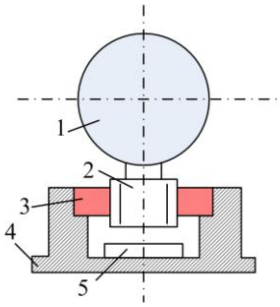

Fig.1. One DOF laser beam deflector, based on active kinematic pair *screw – active nut*: *1* – mirror; *2* – screw; *3* – piezoelectric disk/nut with sectioned electrodes; *4* – housing; 5 – permanent magnet.

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. Active kinematic pair can change its kinematic structure or parameters as the external conditions or dynamic excitation characteristics vary. The multi-functionality of the mechanisms can be achieved applying direct or inverse piezoelectric effects. In other words, several different functions as motion generation, measurement of parameters of motion, control of friction forces in the contact zone can be implemented into one instrument. Excitation of static or quasi-static deformations, multi-directional and various modes/forms resonance oscillations, generation of motion in the contact zone, transformation of oscillations into continuous motion are just several examples of application. Active kinematic pairs enable:

(a) Control of the number of DOFs 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;

(b) Generate forces and moments in the contact zones;

(c) To effect additional functions – self-diagnostics, multi-functionality, adaptivity, self-assembly;

(d) To implement two levels of degree-of-freedom. The first level comprises large deflections or displacements, produced by transformation of resonance oscillations of pair's links into continuous motion. The second level deals with small displacements (in micrometre and nanometre range), implemented by means of direct piezoelectric effect and specific sectioning of electrodes.

New type of multi-degree-of-freedom piezoelectric actuators based on *active kinematic pairs* has been developed [3, 6, 9…11]. The contact zone of this type of actuator is formed by one or two oscillating transducers in a form of a rod, plate, disk or cylinder. Depending on a phase of oscillations 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. Thus, schematics of piezoelectric motors, using two active elements in the contact zone and comprising the number of degrees-of-freedom up to 5, can be realized. Some of them are related to specific applications for laser beam deflection and positioning devices in the plane.

The concept of *active bearing* [3, 11] enable to develop bearings and supports, that have no processing datum surface errors and are effective in the design of multi-degree-of-freedom actuators and 3-*D* positioning systems. Such concept is especially useful in the design of high accuracy positioning systems.

3. TWO ACTIVE ELEMENTS IN CONTACT AREA

Oblique impacts in contact area can be generated by summing two orthogonal oscillations of transducers (Fig.2) and controlling phase shift φ. Symmetrical reverse of motion is obtained by changing the phase of

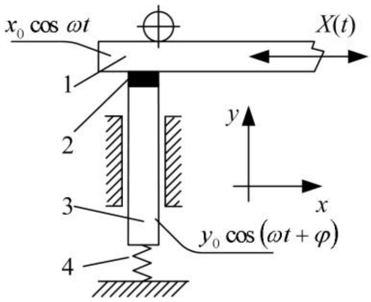

Fig.2. Translation of link *1* is realized due to oblique impacts in contact zone *2,* in which orthogonal resonant oscillations of piezoelectric rods *1* and *3* are being summed-up (*4* – spring).

oscillation by π. The application of two active elements in contact area is effective in multiDOF actuators due to possibility to separately control amplitudes, phases and even forms and modes of oscillations, as shown in Fig.3, where the sign of oblique impact is the same for both contact zones.

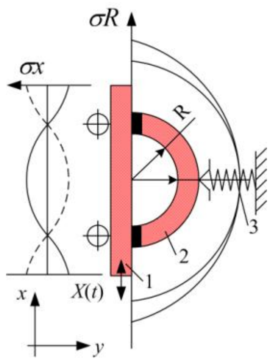

Fig.3. A case of generating translation, exploiting second mode of longitudinal resonant oscillations of active link *1* and first mode of flexural oscillations of active link *2*.

4. ONE ACTIVE LINK IN TWO KINEMATIC PAIRS

By controlling excitation zones of typical piezoelectric transducers, resulting in different forms and modes of oscillations, it is feasible to use one active link in two kinematic pairs (Fig. 4 and 5). The effect is evident – reducing the number of serially connected links in mechanism is not more cost effective, but also results in increase of stiffness and total accuracy.

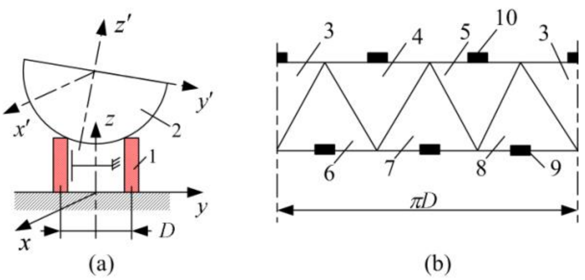

Fig. 4. Piezoelectric cylinder *1* can position mirror *2* on the plane (3 DOF – first mode of operation); second mode of operation – rotating mirror *2* in relation to piezoelectric cylinder *1* (3 DOF). Here *3…8* – electrodes; *9,10* – contact points.

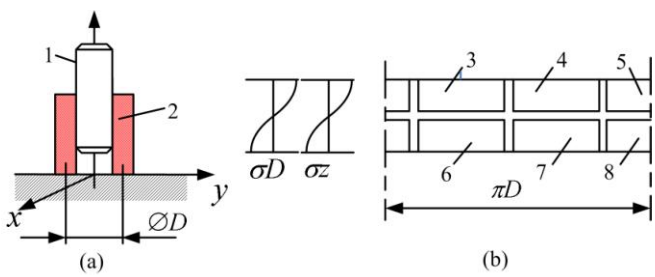

Fig.5. Link *1* can be actuated by piezoelectric cylinder *2* in two directions (2 DOF) and positioned on the plane (3 DOF). Here *3…8* – electrodes.

5. NEW APPROACH TO GENERATE FLEXURAL OSCILLATIONS OF THE PLATE

Existing methods to generate flexural oscillations of piezoelectric plates in the plane, perpendicular to it, are limited by the use of bimorphs. We proposed new method [12] based on the application of passive masses, symmetrically positioned in specific points, coinciding with oscillation nodes. In case when longitudinal resonant oscillations of the first or second form are generated, induced moments generate flexural oscillations. By controlling the form of longitudinal oscillations it is possible to control the form of flexural oscillation, thus, e.g., reversing the sign of speed, etc. Method can be applied for all classical schematics of piezoelectric motors; in case of screw-type actuator, shown in Fig. 6, two types of resonant oscillations are exploited: first form of bending vibrations in *x0y* plane (obtained by sectioning electrode in two longitudinally situated sections) and first form bending oscillations (*y0z* plane).

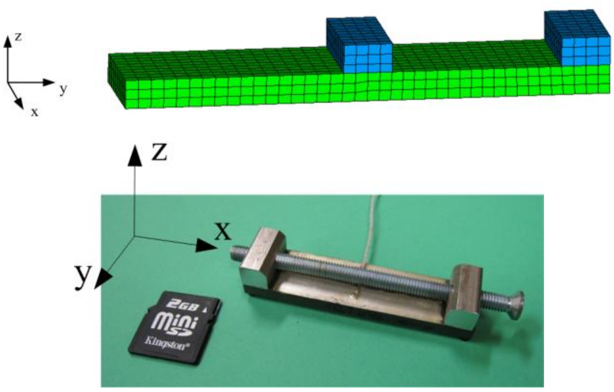

Fig.6. Schematic and the example of application of new approach to generate in-plane and bending oscillations of the piezoelectric plate.

6. PIEZOELECTRIC LASER SCANNING AND DEFLECTING DEVICES

The problem to scan or deflect optical or laser beam is frequently met in measuring devices and systems. Latest developments in piezoelectric laser scanning and deflecting devices are based on the transformation of multi-component resonant oscillations into continuous or start-stop motion. Usually three types of mechanisms to transform oscillations into continuous motion are used:

(*a*) The application of non-harmonic resonant oscillations;

(*b*) Transforming internal (in relation to mirror) oscillations into *2*-D (or even *3*-D) rotation of the mirror;

(*c*) Transforming external harmonic resonant oscillations into *2*-D rotation (Fig.7 and 9). All three methods can be characterized by specific areas of application, including different accuracy, resolution and time constant.

Initial experiments with one DOF scanners revealed dramatic influence of the type of supports to resolution, especially in nano range. Very promising results were obtained using schematic shown in Fig.8, containing just two kinematic pairs, based on the magnetic attraction forces in the contact zones of cylindrical neodymium magnets and spherical supports.

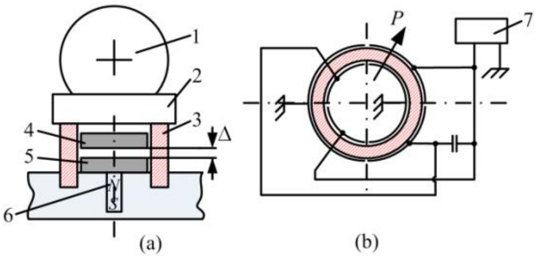

Fig.7. Using axial traveling waves in one DOF reflector: *1* – mirror; *2* – rotor/contacting disk; piezoelectric cylinder; *4, 5* – capacitive transducer; *6* – permanent magnet to ensure axial force in contact area; *7* – signal generator.

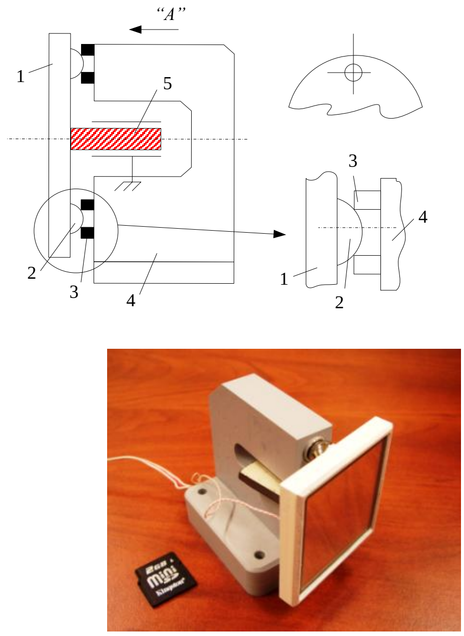

Fig.8. Schematic and model of laser deflector. *1* – mirror; *2* – spherical support; *3* – cylindrical permanent magnet; *4* – housing; *5* – piezoceramic plate with sectioned electrodes.

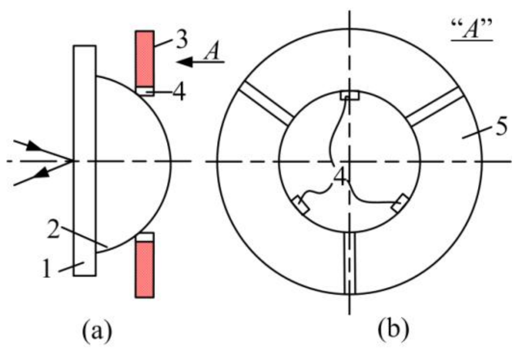

Fig.9. Realizing rotation of the mirror *1* in three directions: *2* – segment of ferromagnetic sphere, contacting with piezoelectric disk; *3.* *4* – permanent magnets; *5* – electrodes.

7. SPECIFICS OF MODELLING

Numerical study of piezoelectric actuators was performed to investigate vibration shapes and trajectories of contact point oscillation through the modal and harmonic response analysis. FEM package ANSYS was employed for the simulation [4, 5, 8]. Three-dimensional finite element model was built. Modal analysis of piezoelectric actuator was done to find applicable modal shapes and natural frequencies of the actuator. Results of structural displacements of the piezoelectric actuator, obtained from harmonic response analysis, were used for determining the trajectory of contact point movement [12]. The example of visualizing the forms of oscillations in case, shown in Fig.6, is given in Fig.10.

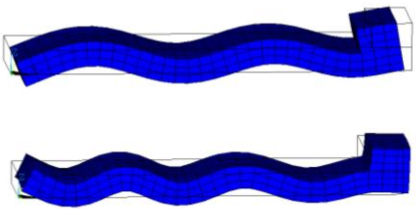

Fig.10. Bending oscillations of the monolithic plate with resonant frequencies 30.19 kHz and 63.2 kHz [12].

In case of a system with two degrees-of-freedom the problem is to define the topology of sectioned electrodes of a piezoelectric cylinder, capable of effecting two independent rotations about perpendicular axes. In this case the design of piezoelectric motors can be simplified, leading to the application of two contacting links: piezoelectric cylinder with radial poling vector and sectioned electrodes, contacting with passive sphere made of glass or ferromagnetic material (in latter case it allows simplification of controlling contact forces with the help of neodymium magnets).

8. POSITIONING SYSTEMS ON THE PLANE

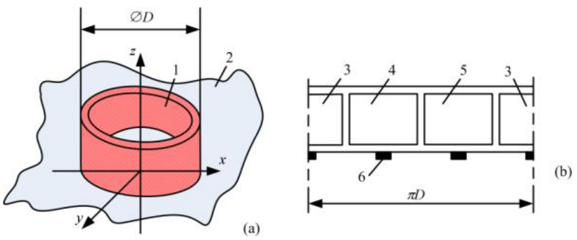

Fig.11. Radially polarized piezocylinder *1* on the plane *2* (3 DOF). 3…5 – electrodes, 6 – contact points.

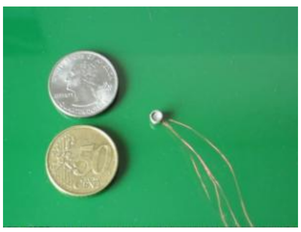

Fig.12. The smallest positioning device (4 x3 x 4mm).

Piezoelectric cylinder with special topology of electrodes (Fig. 11 and 12) is simple but effective positioning device on the plane, effecting three DOF [2, 9, 10]. The same high resolution and wide speed range can be obtained with the disk type transducer (Fig. 13). Here the main advantage – small height if compared with piezocylinders and the possibility to mount object (e.g. miniature laser) inside the hole.

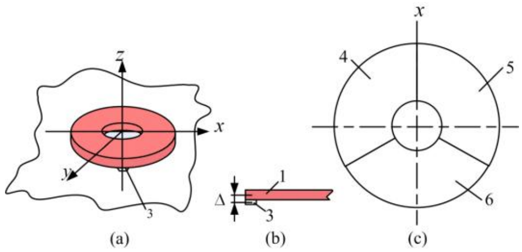

Fig.13. Generating the *z*-axis component of resonant oscillations of disk or washer type transducer *1* situated on the plane *2* by applying passive masses/contact points *3*. Distance Δ defines the 2-*D* trajectory of the contacting points.

New system to realize simplified nano-resolution positioning on the plane was suggested and demonstrated on a model level. This system is based on the application of piezoceramic hemispheres and focal bowls with special topology of electrodes, oscillating on higher forms of asymmetric oscillations. These oscillations in the contact areas are transformed into continuous or start-step motion of the object; speed and direction (or rotation) of the object is related to the connection of multi-phase power supply to specific electrodes of the transducer.

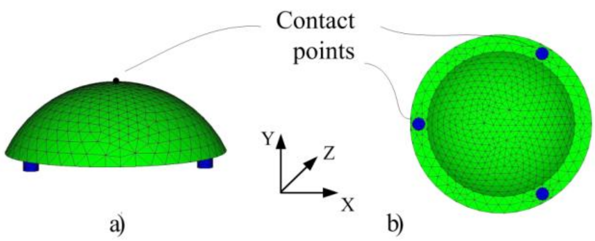

Fig.14. Typical focal bowl transducer and its application for positioning systems.

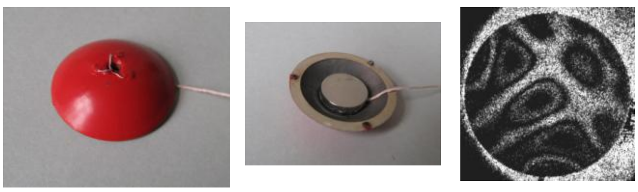

Fig.15. Photo and distribution of oscillations nodes of miniature bowl (diameter – 10mm), registered with digital holographic system PRISM. Piezoelectric bowl contains neodymium magnet to guarantee initial preload in contact areas.

Application of hemispheres/focal bowls (Fig.14) allows realizing various devices for positioning on the plane, to generate rotation of the shafts, etc. One of possible applications is for precise shaft measuring systems, when rotation of the shaft is generated without introducing datum surface errors – using *active centers.* In this case no classical bearings or supports are applied; rotation of the shaft is realized by "active" non-rotating centers, supporting the shaft.

9. APPLICATION OF VARIABLE POLING VECTOR

Very important feature of piezoelectric transducers is the possibility to easily control forms and modes of oscillations, including their direction, amplitudes and frequencies. Usually it is done by selecting specific areas of transducer electrodes and actuate them by connecting to signal generator. Simplest example is piezoelectric cylinder (Fig. 11), in which internal or external electrodes are sectioned into several parts (total number 3 in Fig.11), connected to signal generator in a specific way and related to the direction of positioning.

The schematics of new monolithic piezotransducers with variable poling vector have been proposed and investigated. The example is presented in Fig.16a,b, where piezoceramic bar with circular cross section contains central electrode (wire), together with external electrode used in poling operation. After poling in radial direction, external electrode is sectioned into several parts and following modes of operation can be realized:

(a) Longitudinal oscillations of transducer along *x* axis;
(b) Flexural oscillations of transducer in *z0x* or *z0y* planes;
(c) Simultaneous generation of longitudinal (along *x* axis) and flexural oscillations in *z0x* or *z0y* planes with controlled phase shift between both forms of oscillations.

The last mode of operation can be used to design *2*-D positioning system on the plane (Fig. 16a), in which the direction of motion is controlled by changing the phase between longitudinal and flexural oscillations of the transducer.

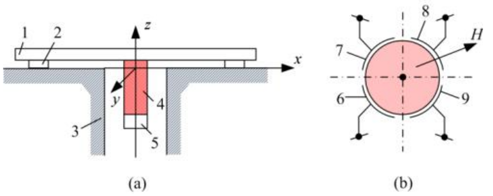

Fig.16. Two DOF positioning device on the plane: *1* – table; 2 – permanent magnet; 3 – ferromagnetic housing; 4 – piezoelectric rod with passive mass 5; 6…8 electrodes.

It is worth to mention that the type of transducer with variable poling vector could allow to realize continuous manufacturing process (presently it consists of discrete technological steps) and, thus, dramatically reduce the cost of transducer. This approach can simplify the design and reduce the cost of some piezoelectric motors.

10. CONCLUSIONS

High resolution and small response time piezoelectric motors with several degrees-of-freedom are capable of covering wide area of specific applications, gradually in some areas reducing the application of classical electric actuators.

ACKNOWLEDGEMENTS

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