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Precision Positioning with Mechanically Amplified Actuator

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Abstract Actuators like PZT or GMA have small stroke and high force at their output. There are several applications, where is necessary to enlarge small stroke. This paper deals with stroke amplifiers. Next part of paper shows the application of amplified actuators.

Keywords: *amplifier, positioning, actuator, stroke, force, displacement*

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1. Introduction

Non-conventional actuators like piezoceramic PZT, magnetostrictive alloy GMA or shape memory alloy SMA has perfect performance, but stroke is too small for many applications. That is the main reason for using of amplifying mechanism with aim to enlarge actuator displacement at the output.

The aim of the paper is analysis of usability of piezoceramic actuators for application of high precision positioning and load.

Displacement amplifying system, also called as enlarging system, is described as transformation system, which is able to transform input mechanical energy (small displacement and high force) to output mechanical energy with desired parameters (higher displacement and lower force) [1].

Consequently, it is necessary to use displacement amplifying system for power transformation. These systems are also called as "displacement amplifier" [1-9].

2. Displacement Amplifiers

Displacement amplifiers can be divided into several groups. - displacement amplifiers based on mechanical principle,

- displacement amplifiers based on fluid principle,
- another displacement amplifiers for indication purposes (aerodynamics principle, pneumatic principle, optical principle, electrical principle) etc.

Displacement amplifiers based on mechanical and fluid principle are classified from the viewpoint of used principle and type of transformation medium for displacement:

1. Levers
2. Flexure bridges
3. Gears and friction gearing for displacement amplifiers.
4. Displacement amplifiers with deformation parts.
5. Hydraulic displacement amplifier.
6. Inchworm motors
7. Ultrasonic travelling – wave motors

Levers are mechanisms which depend on distance ratio between joints and high transverse stiffness of lever. Principle of lever is shown on Figure 1 [1,2].

Levers bring the simplest form of displacement amplifying. Advantage of lever using lies on practical applicability (there is no fluid leakage).However, levers are need very high production precision. Many parts in stage lever mechanisms bring another resonance frequency to the system. These facts cause problems in many mechatronics application [2].

Flexure bridges are gripped with quasi pin – jointed and depend on longitudinal stiffness of parts. This property causes more compact design than levers (Figure 2).

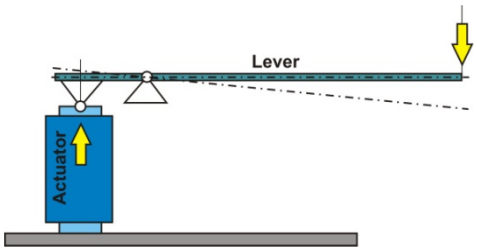

Figure 1. Lever displacement amplifier

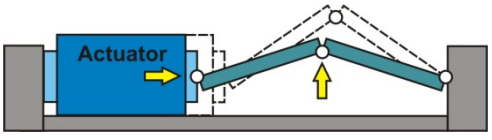

Figure 2. Flexure bridges displacement amplifier

Levers and flexure bridges can be designed as rigid body mechanism with conventional joints or as compliant mechanisms with spring joints. Many mechatronics applications contain compliant mechanisms with spring joints, because conventional rigid bodies and bearings cause several problems. Application of spring joints brings the desired backlash free motion, which is needed for small displacement actuators [3].

Deformation of low stiffness parts is also useful for displacement amplifying. These low stiffness parts can be made as perforated ribbon, which is twisted and pulled in marked direction (Figure 3). It causes rolling and unrolling of ribbon coupled with indicator pointer. This way allows amplifying small displacement with very high precision without backlash (indicator for measurement of geometric deviations).

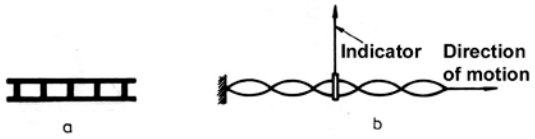

Figure 3. Displacement amplifier with deformation part

Problem with displacement amplifying can be also solved with combination of lever and gearing (Figure 4 left). The main disadvantage of this solution is backlash between gears. Another way is using of friction gearing (Figure 4 right), but slipping can be occurs in this solution.

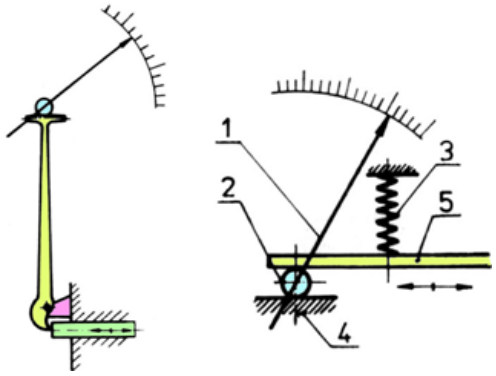

Figure 4. Gearing and friction gearing for displacement amplifying

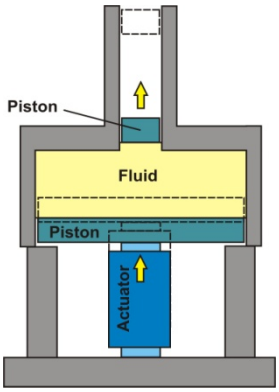

Figure 5. Hydraulic displacement amplifier

Using of elastic medium (rubber, fluids like oil or water) is suitable solution for displacement amplifying. Fluid behaves as non-compressible medium. This property is main advantage for using in displacement amplifying system (Figure 5) [2].

The hydraulic displacement amplifier allows bigger place for flexibility of design and lower loss caused with deformation of amplifier structure. Marginal problem occurs in chamber sealing to avoid the fluid loss.

Dynamic behavior of hydraulic displacement amplifier is determined with time needed for wave transition through the transport medium (fluid) [2].

The term “Inchworm” is registered trademark of Burleigh Instrument, Inc. and it is used as name for structure (Figure 6), which generates motion via using of conception based on three piezoelectric actuators (also called as PZT). Suitable configuration and control algorithm allows the amplified motion against the one piezoelectric actuator. Although it has amplified displacement, it has also extremely high mechanical resolution (about 4 nm) [4].

The term inchworm comes from biological inspiration from biological pattern called with the same name “inchworm”. Principle of the motion is based on three PZT actuators placed on guiding rod. Two actuators place on edges are called as clamp actuator. Middle piezoelectric actuator is able to change distance between both clamp actuators. Suitable designed algorithm of actuator exciting causes forward motion on guiding rod.

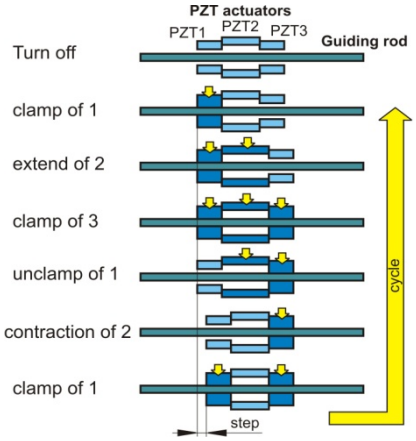

Figure 6. Inchworm motor

Inchworm motors with ultra high resolution are made as various versions with resolution from 1 nanometer (10^{-6}m) to 2.5 angstroms ($2.5 \cdot 10^{-10}$m), what is relative to atom size. These properties are used as positioning systems in raster microscopes [4].

Ultrasonic motor converts ultrasonic mechanical energy to mechanical energy via friction force between the sliding segment and stator. This type of the motion is called as traveling wave. The principle of the ultrasonic motor is described on Figure 7 [5].

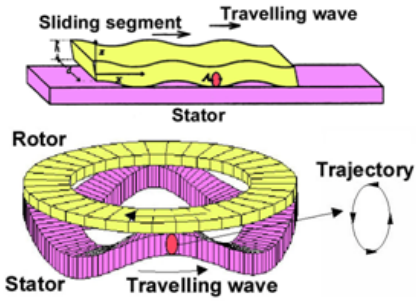

Figure 7. Principle of the planar and rotary ultrasonic motor [5]

Travelling wave traverses through these every elements of surface on the sliding segment and consequently these elements move on elliptical trajectory. If any object will be in contact with the segment, then this object will move through the friction force effect generated between them. Principle of the motion in ultrasonic motor has analogy in surf plate moves on sea waves. The ultrasonic motor has several advantages. It has compact design and it has still force also without exciting. It has bigger torque also in low motion speeds. The main disadvantage is requirement of high frequency power supply [5].

3. Amplified Piezoactuator

Piezoceramic actuators (also called as piezoactuators) are recently used for precision positioning. Piezoactuators are non-conventional actuators, which are today frequently used in mechatronic systems. Thanks to their properties, they are used mainly in miniature systems but also there are many large scale applications.

Piezoactuators use indirect piezoelectric phenomena, which is caused through the crystal polarisation via using the electric voltage applied to their electrodes.

From physical viewpoint it is energy transducer. Electrical energy is converted to mechanical work. Force and displacement are at the output and electrical voltage and current are at the input of the piezoactuators.

A direct piezoelectric phenomenon is inversion and mechanical work is converted to electrical energy. This phenomenon is used for force sensors or vibration sensors.

Consequently, the same material can be used as actuator and as sensor.

Currently, various types of material are used for piezoactuators as PbTiO3, PbZrO3 etc. These materials are also called as PZT (Lead-Zirconate-Titanate).

PZT actuator as fast response time (several μs) and it is suitable for high frequency actuators. Also output force has high value (hundreds of Newtons). One disadvantage is very small mechanical stroke (up to 100μm).

The piezoactivity can be described in simplified form as:

$$\Delta l = d_{33} \cdot U \tag{1}$$

where Δl is deformation (or actuator stroke); d_{33} is piezoelectric strain constant and U is applied electric voltage. Consequently, the deformation does not depend on dimension of piezomaterial.

The piezoelectric strain is generally very small (approx. 10^{-9}m/V). This significant problem can be solved via using of piezostack. The piezostack is composed of many thin piezo layers, which together produce a higher stroke [3,4].

Overall stroke of piezostack can be expressed as:

$$\Delta l = n \cdot d_{33} \cdot U \tag{2}$$

where n is number of piezoelectric layers in piezostack.

Blocked force can be derived in form:

$$F = \frac{\Delta l \cdot A}{n \cdot t \cdot S_{33}^{E}} \tag{3}$$

where Δl is deformation (or actuator stroke); S_{33}^{E} is elastic constant (m^2/N), t is thickness of layers, n is number of piezo layers and F is blocked force (N).

Small stroke of piezoactuator can be solved via using of various type of any amplifying way.

One possible way is to use the stacked piezoelectric actuator also called as piezostacks or multilayer piezoactuator. Piezostack consists of series of thin piezoelectric discs, which are electrically connected in parallel. Final stroke is larger than one solid piezoactuator with the same dimensions as piezostack. Actually it is possible to buy piezostacks with stroke up to 100μm.

Other possible way is to use piezoactuators with amplifying mechanism i.e. with mechanical transformer. Using of amplifying mechanism causes the increasing of stroke and decreasing of output force. Strokes from amplified piezoactuators can achieve the several millimetres.

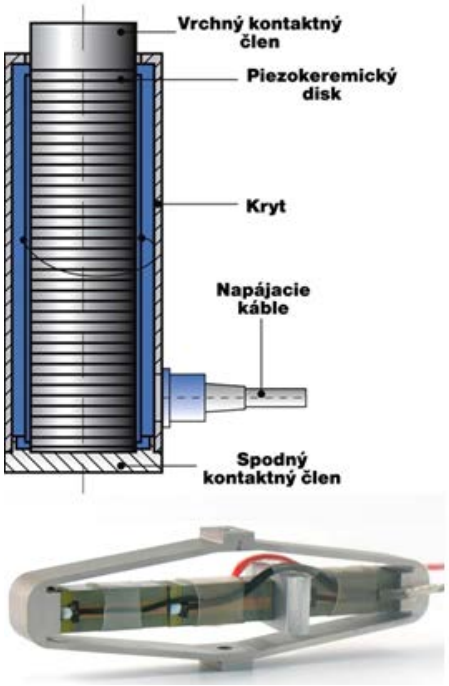

Figure 8. Piezostack and amplified piezoactuator [5]

In this actuator, the shell is used to perform mechanical preloading of the piezoactive elements. This shell also serves the purpose of producing an amplified movement in the direction of the small axis, i.e. the actuating direction, from an actuating point situated on one of the peaks of the small axis. The second actuating point is situated on the opposite peak of the small axis in the usual mode of use [10,11].

This actuator is able to provide two degrees of freedom in the case where the second actuating point is at the centre of the actuator. In addition to main actuation on the direction of the small axis, a non amplified auxiliary movement is produced in the direction orthogonal to the small axis, in the main plane of the shell. This mode of use of the actuator requiring a central actuating point is constraining as it is not compatible with the previous one and does not enable all the deformation of the actuator to be recovered [10,11].

Amplified piezoelectric actuators can cause the problem of an insufficient resistance to dynamic external stresses and of an insufficient mechanical damping capacity. Amplified piezoelectric actuators do in fact sometimes show large quality factors: they can limit the resistance of

the actuators under external dynamic stresses. It may therefore be useful to reduce the mechanical quality factor [10,11].

Moreover, in the case of a shell with a high amplifying factor, the preloading level applied to the piezoactive elements must not exceed the elastic limit of the material of the shell. An auxiliary preloading device can be added on the shell to increase performances [10,11].

4. Concept of Module with Amplified Piezoactuator

The aim is to design actuator with working force 2400N and stroke 1mm. There is no amplified piezoactuator with this output force and stroke. For this reason it inecessary to compose series and parallel composition of more amplified actuators.

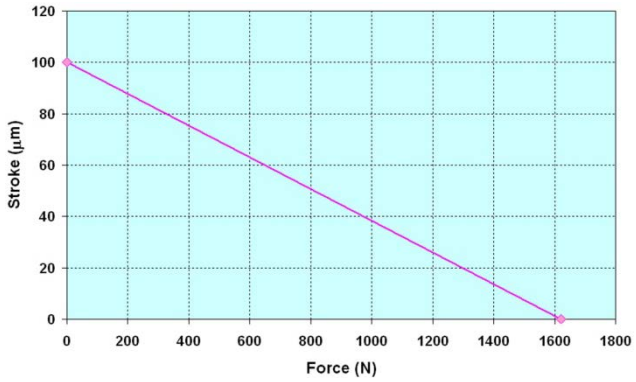

Figure 9. Characteristic of selected amplified piezoactuator

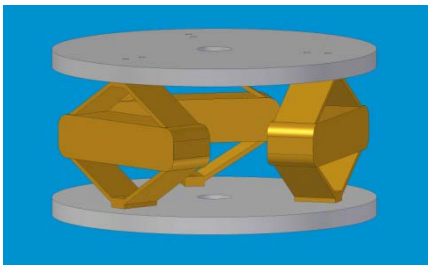

Figure 10. Block of parallel arrangement of 3 pieces of amplified piezoactuator

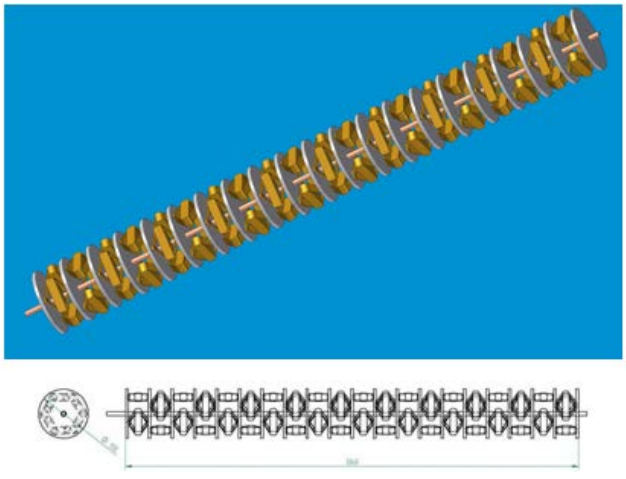

Figure 11. Composition of serial-parallel arrangement of 60 pieces of amplified piezoactuator

One amplified piezoactuator has been selected from available types (Figure 9) with maximum stroke 0.1mm (without load) and maximum blocking force 1600N.

We assume the working point at force with value 800N and stroke will be with value 50µm. For obtaining of the required force and stroke, it is necessary to use block of 3 parallel amplified piezoactuator (Figure 10).

Overall assembly should be composed from 20 pieces of parallel block (Figure 11). The assembly will consist of 60 pieces of selected amplified piezoactuator.

5. Conclusion

The stroke of amplified piezoactuators is still very low for our application. For this purpose the assembly of serial-parallel composition with 60 pieces of selected amplified piezoactuator has been designed.

Overall cost is too high, because also complicated drive unit is necessary for piezoactuators. Also big problem is hysteresis of piezoactuators. Overall length of designed assembly is very long (1368mm).

The piezoactuators are very frequently used for their ability to use as force generator and also as sensors. This actuator is also called as smart material or smart actuator [12-22].

Acknowledgements

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