

A NEW 3D SHAPED, MONOLITHIC PZT BEAM ACTUATOR PRODUCED BY CERAMIC INJECTION MOLDING

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ABSTRACT

A monolithic piezoelectric beam actuator has been produced by ceramic injection molding (CIM). Usually piezoelectric beam actuators are realized by gluing two thin piezo ceramics with different expansion coefficients. This technology is quite complex and cost intensive and the actuators are not shock-resistant.

The goal of this study was to manufacture a real 3D beam actuator made of one solid element in only one forming process. Therefore a non constant cross section in thickness direction was used to transform the material strain into an actuator motion. Different actuator thickness ratios have been simulated to optimize the degree of efficiency. However the final monolithic actuator is robust against shock. This was accomplished by having a high geometrical moment of inertia excited to the thickness ratios. Big advantages of the ceramic injection molding process are more freedom of design, lead-zirconate-titanate (PZT) actuators and sensors with new functional structures and the possibility for low budget mass production. Real 3D PZT elements can be formed with a constant density only by this technology.

To achieve these goals, many researches into material behaviour, especially shrinking caused by debinding and sintering of the ceramic feedstock, have been done. These technical expertises were used for the final design of the injection molding tool and forming process. Because of using a mixed compound piezoelectric ceramic powder with addition of a thermoplastic binder system as injection molding aid, the properties of the finally polarized PZT are equivalent to other processing technologies like dry pressing or thick film.

The CIM principle is used to form special structures (e.g. beams, membranes) with a 3D shaped surface. Therefore the main focus is on deriving precision and optimisation for low cost mass production.

Key words

Monolithic piezoelectric beam actuator, lead-zirconate-titanate (PZT), ceramic injection molding (CIM), Microsystems

INTRODUCTION

Since the piezoelectric effect was found in 1880 by Jacques and Pierre Curie, many actuator and sensor applications have been developed [1]. Due to a very small adjustment travel (e.g. 1.5 μm length variation per 10 mm) with a relative big force they are commonly used in micro positioning systems [2] and sensor applications. But it is possible to realize a stroke increase system with less force and a much higher displacement in one actuator by structuring [3]. That is how these actuators get a new interesting wide range of operation. Today these elements are

used e.g. in automotive applications as ultrasonic distance sensors for parking control systems or as multilayer actuators for diesel injection systems [4]. Because of having a hard financial market, the process in manufacturing has to have a high precision at low manufacturing costs.

To bring ceramics into certain shape many techniques have been established. Most common are the tape casting and dry pressing technologies. For both, the ceramic is milled to fine powders and then mixed with organic, liquid binder or formed under high pressure to bring it into a thick film or bulk shape.

These technologies only allow 2- 2.5 dimensions. After completing the forming step the green parts have to be completed e.g. by using ultrasonic chisels. Because of preparing brittle materials the yield is unprofitable low. That is the reason why we have used ceramic injection molding as a new technology to form piezoelectric ceramics with less finishing, a high accuracy and the ability for low cost mass production. On the base of 3D forming a monolithic beam actuator has been produced.

STANDARD BEAM ACTUATOR - BIMORPH

The principle of a standard piezoelectric bimorph is similarly to a bimetallic strip in a thermostat. Two thin plates with different expansion coefficients or with different polarity are glued. While applying a voltage, one piezo plate contracts and the other one extends. As a result of the induced material strains the bimorph will have a displacement on the non fixed side (Fig. 1). These actuators have a huge displacement while needing a low drive voltage. But a big disadvantage is that they can not sustain significant forces, otherwise they will crack. Also the manufacturing process is complex and cost intensive. Usually these thin ceramics are formed by tape casting followed by sintering. In a next step they were metallised, glued and finally polarized.

METHOD of RESOLUTION for a MONOLITHIC BEAM ACTUATOR

The possibility of forming real three-dimensional piezo ceramic elements by using ceramic injection molding [5] [6] offers a high potential in actuator design. First approach was a beam with a trapezoidal cross section, polarized in z-direction, a clamping at the 1 mm side and a journal bearing at the 4 mm side (Fig. 2 a). FE-simulations (Fig. 2 b) with *Ansys Multiphysics* have shown a significant displacement in polarity direction of 64.4 nm when applying a voltage of 10 V. A standard piezo actuator with a thickness of four millimeters shows a maximum displacement in polarity direction of 4 nm when the same voltage is applied. This means that the new chosen geometry has a 16 times higher displacement. The reason is that the actuator can not expand perpendicular to the applied voltage (d_{31} -effect). Caused by addition of the generated material strains and particularly by the special cross section, the actuator is forced to have a displacement parallel to the applied electrical field.

But in a technical implementation a realization of the journal bearing at the 4 mm side is quite unpractical. The next approach was to mirror the cross section and fix the beam at both sides (Fig. 3a). In this configuration occurs the extension from both bearings to the center of the beam. Simulations

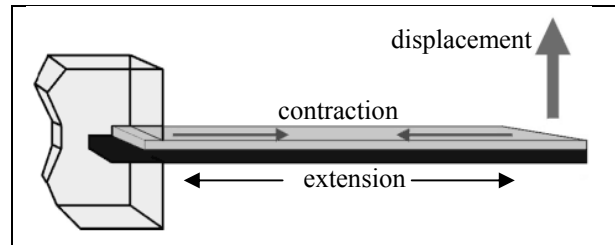


Fig. 1. Principle of a piezo bimorph beam actuator

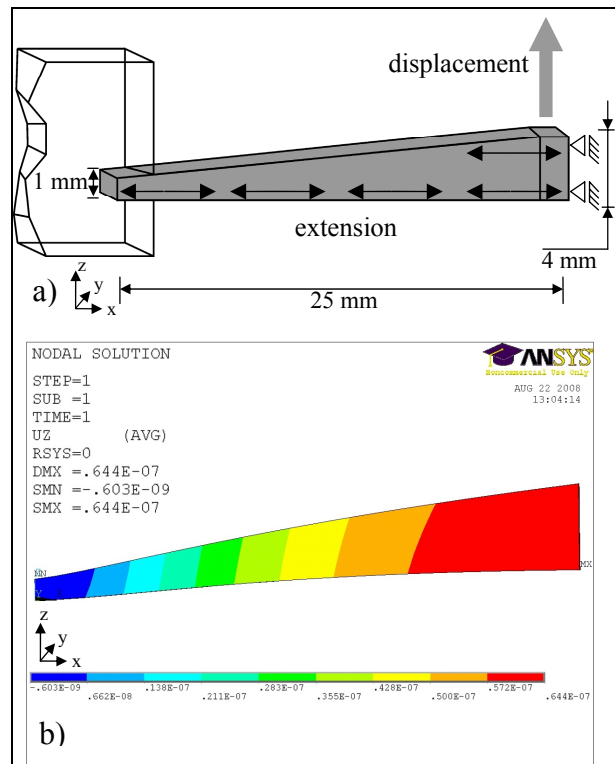


Fig. 2. Schematic of a monolithic beam actuator realized by a non constant cross section in thickness direction (a), FE simulation of monolithic beam actuator displacement while applying 10V (b), final monolithic actuator in a disc shape with an non constant cross section (c)

(Fig. 3b) have confirmed these assumptions and shown that the displacement in the beam center averages 70.2 nm when applying a voltage of 10 V. In comparison to a standard piezo actuator is this displacement in polarity direction about 17 times higher.

To enhance the mechanical stability of the brittle ceramic actuator, the beam from Fig. 2 was rotated around the z-axis at the 4 mm side. The result is an actuator disk with a non constant cross section which is shown in Fig. 4a. The clamping is fixed at the whole outer ring so that the resulting material strains from x and y directions will force the actuator center

to move into z-direction. Simulations confirmed this and show a total actuator displacement of 99.0 nm in z-direction when a voltage of 10 V is applied (Fig.4b). This displacement is 24.75 times higher than the displacement of a standard piezo actuator with a thickness of 4 mm. The resonance frequency of the new trapezoidal disc actuator was determined at 3.4 kHz by simulations. Because of the minimum thickness of one millimeter at the thinnest place the actuator can be driven with up to 1 kV. So the maximum reachable displacement will be theoretically at 9.9 μm .

FABRICATION of the MONOLITHIC DISC ACTUATOR

When using standard forming processes, like dry pressing, a homogenous material density could not be guaranteed by fabricating the piezo disc with a non constant cross section. Therefore the ceramic injection molding process has been chosen. For this process the PZT-powder was mixed with a thermoplastic binder system to a feedstock which could be molded at a temperature of 160°C. The needed molding tool that includes the three-dimensional cavity of the actuator was designed in CAD. Filling behavior of the cavity by using the ceramic feedstock was simulated with the software tool *Moldflow* and the cavity was optimized.

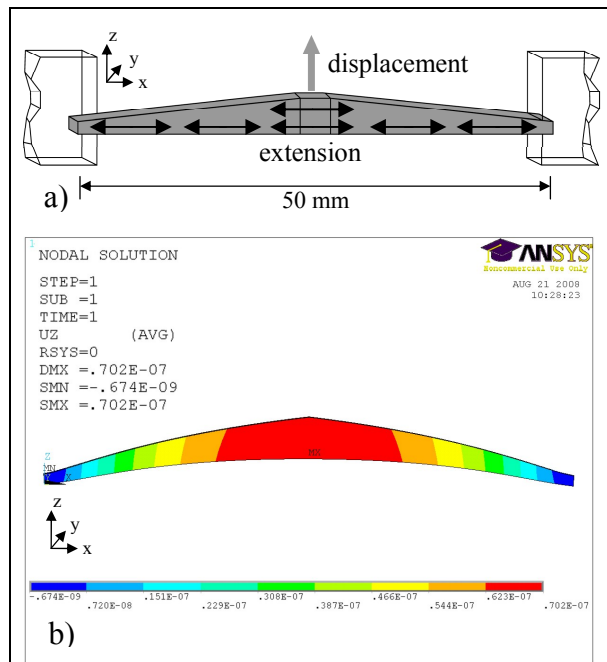


Fig. 3. Schematic the beam actuator with a non constant cross section in thickness direction, clamping on both sides (a), FE simulation of monolithic beam actuator displacement while applying 10V, clamping on both sides (b)

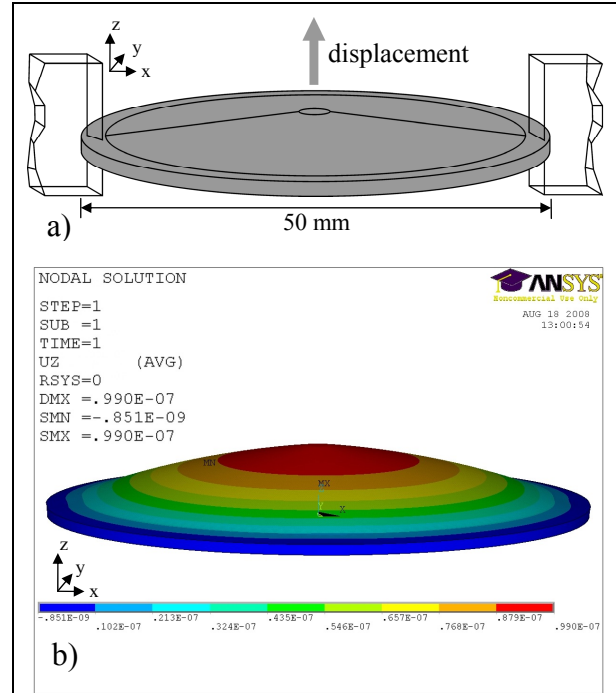


Fig. 4. Schematic of final monolithic actuator in a disc shape with an non constant cross section and clamping on outer ring (a), FE simulation of monolithic actuator in a disc shape and clamping at the whole outer ring (b)

Subsequently the molding tool was made of hardened steel to prevent abrasion caused by the feedstock. After the forming, the binder system was removed by thermal treatment. To compact the piezo grain structure the actuator disc has been sintered at 1300°C. Next process steps were the metallization, which was done by sputtering and polarization with 4 kV at 90°C.

EXPERIMENTAL

To realize the bearings at the outer ring a housing of steel was designed and manufactured (Fig. 5). Significant is that the clamp force in z-direction can be adjusted by the cover screws and the clamp force in x- and y-direction can be adjusted by the screws for the clamping jaws. One advantage of this housing concept is that different actuator designs (e.g. 1 mm or 4 mm thick disc) fit for reference measurements.

Displacement measurements of the trapezoidal actuator disk were done optically with a scanning MEMS analyzer from Polytec GmbH. The used vibrometer supported a signal source up to 10 V_{pp}. That was why the actuator could not be driven at maximum displacement by applying 1 kV_{pp}. Because of the approximate linearity of PZT-actuators [2] a displacement measurement in this lower voltage

range is representative and can be extrapolated to maximum range of 1 kV. At first a white noise was applied to the actuator to detect the real resonance frequencies. A major resonance frequency was detected at 4.5 kHz, while simulations have shown a resonance at 3.4 kHz. This derivation is due to the shrinkage between injection molding and sintering. In these process steps the final actuator shrinks about 16.3 % instead of forecasted 16.1 %. Reason for this shrinkage difference was a different feedstock mixture than used in [5].

Measurements at the resonance frequency of 4.5 kHz with 10 V_{pp} have shown a total actuator displacement of 82.0 nm. This deviation of 17 nm compared to the simulation results of 99.0 nm can be occurred to a non completed sintering step of the ceramics. So the actuator will not have 100% of theoretically density. Considering these described deviation the simulation results of the new course increase system were confirmed.

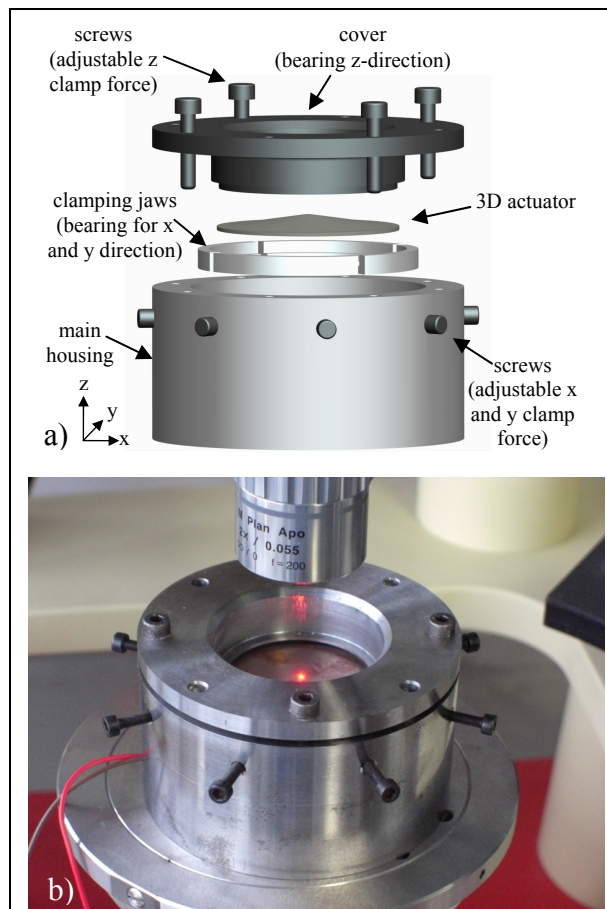


Fig. 5. Schematic of set-up of clamping assembly with adjustable clamp forces (a), experimental set-up with monolithic actuator in a disc shape and a non constant, trapezoidal cross section (b)

RANGE of APPLICATION

The achieved displacement magnification generated by the new actuator design can be used in a wide range of applications. One example is the usage in a piezo speaker (Fig. 6). Here the diaphragm amplifies the small piezo movements to a hearable sound. If the standard planar piezo is substituted by the new actuator design with a non constant cross section, an enormous efficiency increase will be reached with the same manufacturing costs.

A second example is the application of piezo membrane pumps (Fig. 7). Here does the pump suck the medium when the actuator contracts and the inlet valve will open. When the actuator expands the medium will be pushed out through the outlet valve because of the pressure difference.

These are only two examples where the large displacement enlargement of the new presented actuator design can be used. For microsystems applications we have also shown in earlier publications [5] that structures down to some micrometers can be realized by injection molding.

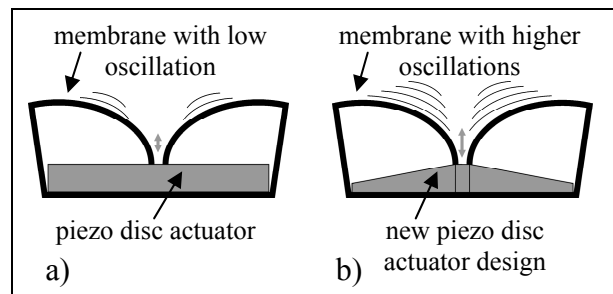


Fig. 6. Functional principle of a standard piezo speaker with a planar membrane (a), example of a new piezo speaker concept with a monolithic actuator in a non constant cross section (b)

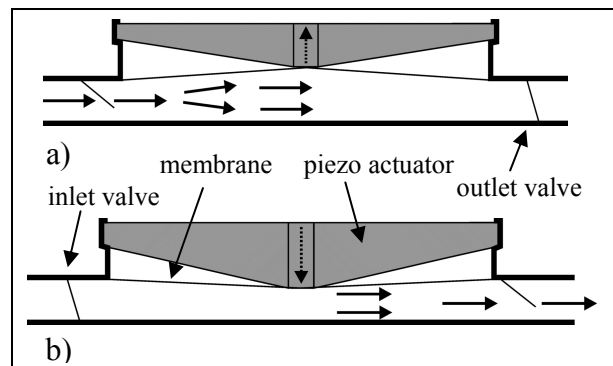


Fig. 7. Application example in a piezo membrane pump; suction when actuator contracts (a), ejection when actuator expands (b)

SUMMARY

A first publication of a real three-dimensional piezoelectric actuator was presented. Process concepts to reach these goals were successfully adapted like the ceramic injection molding. Derivations for the special trapezoidal cross section design were shown theoretically and verified by FE-simulations. Simulation results were successfully approved by optical measurements with a scanning vibrometer. It has been shown that the resulting material strains can be used for a piezoelectric electric stroke increase system with a maximum displacement of 8.2 μm at 1 kV load by a minimum size of only 4 mm thickness.

The published actuator has a 20.5 times higher efficiency in transforming voltage to a z-direction displacement than commercially available piezo-ceramic actuators. All adapted process steps are state of the art and established in mass production. This offers the ability for a low cost production of the special actuator design. Ranges of application were shown with a high market potential.

It might also be possible to manufacture the presented actuator in multilayer technique. Then the efficiency would be lower caused by the damping of the glue between the ceramics.

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