Novel Linear Piezo Actuator

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Abstract: This publication presents a novel concept for an electromechanical piezoelectric actuator. This concept is intended to enable a piezoelectric actuator that exceeds the current state of the art in terms of achievable deflection at operating frequencies in the range of 0 Hz to 100 Hz. This will be realised by merging the strokes of individual piezo stacks. The concept enables linear or rotational movement. The linear version will be discussed here. An actuator of this type enables high-speed positioning of, for example, shafts, valves or lasers.

Additional keywords: Piezo - Actuator - Linear/Rotational Motion - High Speed Actuation - Precise deflection

1 Introduction

The idea to develop this novel piezo actuator arose during the course of a research project, which aimed to develop a fully variable valve control system for internal combustion engines. This valve control system had a piezo actuator, which operated a hydraulic valve via a hydraulic transmission. This valve was used to control hydraulic streams that could hold a poppet valve in position, or retract it or extend it. Further information regarding the previous system can be found in the publication "An indirectly controlled high-speed servo valve for IC engines using piezo actuators"[1]. The system developed beforehand in this project is shown in figure 1.

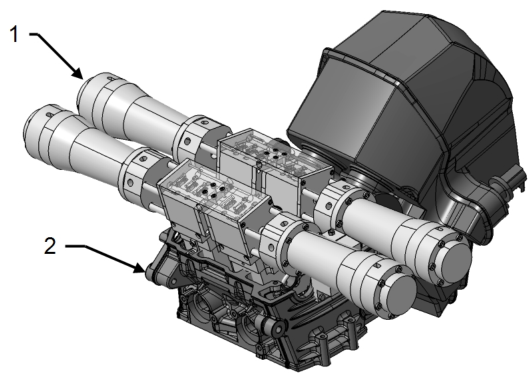

Figure 1 Fully variable valve train, Ostfalia
1*: Piezo stack*
2*: Cylinder head two-cylinder combustion engine*

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Although it was possible to demonstrate satisfactory function of the fully variable valve train system by means of a prototype up to a motor speed of 8000 rev/min, it was not possible to reduce the dimensions of this system with a view to a usable package. The dimensions of the system are essentially determined by the required length of the piezo stacks (1), which predetermines the deflection of the piezo actuators that can be generated by the actuator, and they cannot be significantly reduced. Because of this, we looked for an alternative system for controlling the exchange of gas that had lower requirements with regard to the actuating force and displacement path through an actuator.

One approach that would enable a significant reduction of the actuating forces and, thus, of the package, is controlling the exchange of the gas by means of rotary valve. A rotary valve is a valve which opens or closes an opening cross-section by turning a mechanical body. In direct comparison with a poppet valve, this leads to a significant reduction of the actuating force, since the required force is predetermined only by the rotation of the rotary valve and not by opening the valve in a translational manner against the existing gas pressure, and against the force of the valve spring.

With regard to rotary valve controls, there have been numerous attempts in the past of combustion engine development to integrate such a system; however, this never succeeded in reaching series production due, among other things, to leakage problems. Whether the use of a rotary valve control system is possible using today's materials and manufacturing techniques is intended to be one of the focal points of this new research project. This will be investigated after the development of the actuator which is discussed here.

Parallel to the development of the rotary valve control system, the aim of this research project is to develop an electromechanical actuator which can control the actuation or positioning of a rotary valve of this kind without the use of a hydraulic system while adhering to the given requirements. This desire arose because of the elaborateness and complexity of the control system to be developed for the previous system, since numerous parameters such as the temperature or viscosity of the oil have a strong influence here on the deflection of the poppet valve. Elimination of the hydraulics would thus simplify the system significantly.

The requirements for an actuator of this kind were defined on the basis of simulations of concepts of a potential rotary valve control in which the rotary valve had a mass of 94 g and was to be operated up to a maximum speed of 8000 rev/min. The requirements for the actuator to be developed could be defined on the basis of these parameters. These are:

- Linear or rotational movement
- Working frequency 66.67 Hz
- Actuator force 100 N

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- Deflection 2.5 mm

Due to the required operating frequency, the precision, and the required force this actuator needs to generate, piezo actuators should again be used for this actuator.

The aim of this publication is to present the insights gained during the development of the linear actuator and the prototype experiments. Although this actuator was developed with the intention of controlling a valve for changing the gas of an internal combustion engine, such an actuator could also be used in other fields of application. These could be:

- Positioning lasers and optics
- Controlling hydraulic or pneumatic valves
- Dosing systems

2 Fundamentals

Due to the high potential regarding velocity, accuracy and actuation force piezo actuators are highly attractive for application cases like the planed actuator. Other aspects, like the limited displacement or the economy, at first glance speak against the use of piezo ceramics. With regard to the displacement, there are three approaches based on current state of the art technology that can increase this. First of all, one needs to consider the different materials that are used in this technology. Nowadays, PZT* ceramics are mainly used for displacement tasks using piezo ceramics, because this material currently shows the best performance profile alongside doping possibilities when combining technically relevant parameters. Particularly important characteristics here are the Curie temperature T_C of the material, above which no piezoelectric effect occurs, the piezoelectric charge constant d (1), and the coupling factor k (2). In view of the large number of different materials that are used for these ceramics, there are great differences, especially for these three parameters [2].

$$d = \frac{m}{V} = \frac{\text{Generated elongation}}{\text{Applied electric field strength}} \tag{1}$$

$$k = \sqrt{\frac{w_{12}^2}{w_1 \cdot w_2}} = \sqrt{\frac{\text{Energy stored mechanically}}{\text{Total absorbed energy}}} \tag{2}$$

The second option to increase the displacement of a piezoelectric actuator is adjusting the length of the piezo stack L_{STACK}. The maximum achievable expansion of piezo stacks depends on the stack length and on the material. It is about $1‰ - 1.5‰$. A stack with the length L_{STACK}=50 mm is able to reach a maximum displacement of about 50 μm-70 μm. For some applications, these stroke ranges are sufficient. However, with regard to the compactness of the systems, this method of achieving larger strokes is limited. At an earlier stage of the research project 'Fully variable valve train for internal combustion engines'[1], several 250 mm long piezo stacks were used. The lack of compactness this system now has is shown in Figure 1. A major problem of such long piezo stacks is the breaking strength of the ceramics. This can be remedied by a larger diameter, for example, when using a cylindrical ceramic, but this also increases the cost.

The third option is to use a mechanical or hydraulic transmission. For mechanical transmissions, especially, there is a wide range of different manufacturers. These systems consist of a piezo actuator and a mechanical lever. These systems allow travel ranges of up to 1 mm. With regard to the requirements for the problem mentioned here, these systems are not suitable due to their reduced stiffness [3].

When planning to use piezo technology in actuators, economy is often one of the main problems. When applying piezo actuators, the stacks are selected based on the given demands, for example, the blocking force or the displacement. For the manufacturers of these ceramics, this means that they need to adjust production seeing as they need to produce stacks with different dimensions, according to the demands of customers [4]. It is therefore difficult for the manufacturers to produce standard ceramics in high quantities. Nevertheless, the price of piezo stacks depends strongly on the quantity of units made. If we consider common ceramics from a German manufacturer with the dimensions $18 \times 5 \times 5$ mm, this currently costs approximately 160 Euro based on an annual production of a few hundred ceramics. When the quantity of units is in the region of several thousand units per year, the costs reduce dramatically to the level of a few tens of euros [5]. Based on that fact, the costs of piezoelectric ceramics could be significantly reduced if customers were able to use standardised stacks. A concept that enables customers to use standardised stacks will be introduced here.

3 Novel Mechanism for Piezo Actuators

The function of the concept that was developed to solve the problem mentioned here is shown in figure 2 and figure 3. The concept is simplified to illustrate the function, represented by a spring reset. One can also reset to the starting position, as shown in figure 4, using actuators, in this case piezo stacks. This would allow the actuator, and thus the valve, to run at a higher speed.

As can be seen from figure 2, the actuator consists of one or more piezo stacks (1), pressure pieces (2), a piston (3), a spring (4) and the housing (5). At rest, the piezo actuators are de-energised and have their idle length. The pressure pieces are held in their basic position by the piston and the spring. One level of the pressure pieces lies in such a way that the bodies are in direct contact with the piezo actuators (level 1). The other bodies are on the lower level (level 2). The pressure pieces are all in contact with each other.

If the valve now needs to be stroked, the piezo actuators need to be energised. This is shown in figure 3. The piezo stacks push the upper pressure pieces down due to their stroke. However, since the upper bodies (level 1) are in contact with the lower bodies (level 2), the entire row of bodies in the figure is moved to the right, in the direction of the piston. The piston is thus now stroked ($s_0 \longrightarrow s_1$). After the piston (3) has been stroked, the piezo stacks must be discharged. This gives the piezo stacks their idle length again. The spring (4) is not used to reset the piezo stacks. When the actuator is equipped with piezo stacks, the spring serves only to reset the pressure pieces and the piston. In principle, resetting the actuator by spring would be possible, for example when using hydraulic pistons. However, this is not the case when using piezo stacks.

When considering the concept of the actuator, it must be

*Lead zirconate titanate

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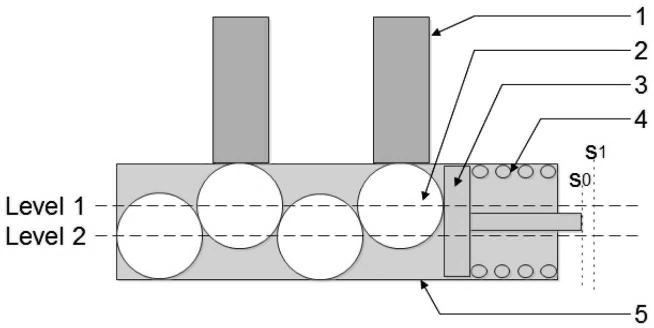

Figure 2 Concept (not actuated)
1*: Piezo stack (not actuated)* 4*: Spring*
2*: Pressure pieces* 5*: Housing*
3*: Piston*

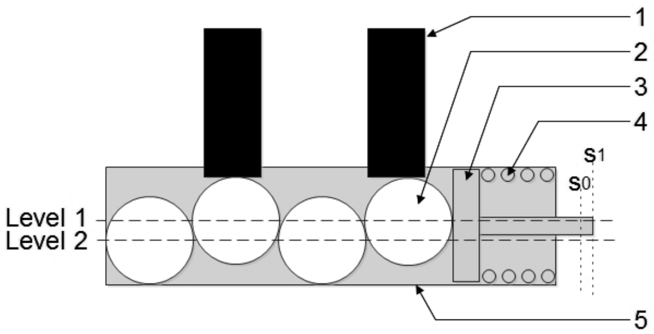

Figure 3 Concept (actuated)
1*: Piezo stack (actuated)* 4*: Spring*
2*: Pressure pieces* 5*: Housing*
3*: Piston*

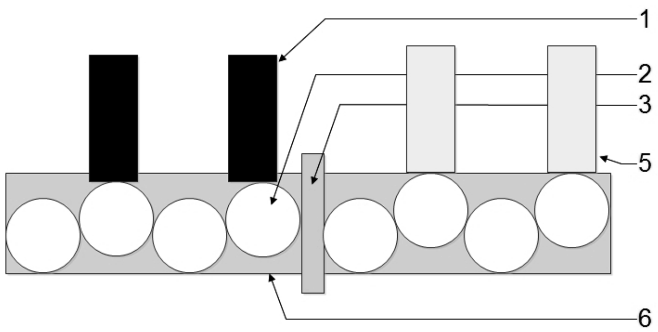

Figure 4 Concept (actuated) without spring
1*: Piezo stack (actuated)* 5*: Piezo stack (not actuated)*
2*: Pressure pieces* 6*: Housing*
3*: Piston*

emphasised that the invention enables a displacement greater than the diameter of the pressure pieces. This is shown by figure 5 and figure 6. The stroke is thus not dependent on the diameter of the bodies. In figure 5, 3 levels are shown. Level 1 represents the basic position of the upper, in this case smaller, pressure pieces, and level 3 represents the position of the pressure pieces when the piezo stacks are activated. Level 2 represents the position of the lower, in this case larger, pressure pieces. Furthermore, the axes of piezo stacks 1 and 2 are shown. When looking at figure 5, it is noticeable that the axis of the left, small pressure pieces intersects with the axis of piezo stack 1. The pressure pieces on piezo stack 2 are slightly shifted to the left of the axis of piezo stack 2 in figure 5. If piezo stack 1 is now energised, as shown in figure 6, the pressure pieces are moved to the right. It is noticeable that the pressure pieces on piezo stack 1 are now to the right of its axis. It is also noticeable that the pressure piece on piezo stack 2 now intersect with its axis. This ensures a permanent positive connection between the elements. This aspect must be considered when designing the actuator. This problem can be easily influenced by the position of the piezo stacks or pistons in the housing. Although shown here with piezo stacks, the problem rather concerns pistons with a large stroke. This is due to the larger stroke of the piston; the distance travelled by the pressure pieces is greater. It would thus be theoretically conceivable for all pistons or piezo stacks to be controlled simultaneously, for a pressure piece to not yet be in contact with a piezo stack or piston. As far as the regulation or control of the actuator is concerned, this means that the piezo stacks or pistons are either actuated in series one after the other or are grouped together. A CAD model has shown at this point that 10 piezo stacks with a stroke of 100 μm can be controlled simultaneously in this application without any pressure pieces having lost contact with the piezo stack. If more piezo stacks are needed, then, for example, the first 10 piezo stacks are first activated and then the remaining ones. Another possibility is to use pressure pieces with a larger diameter or different body types.

4 Piezo System Components Selection

The piezo system, which was selected in order to examine the concept more closely under real conditions, consists of the controller (1) along with the piezo modules (2) and the piezo stacks (3). This system is shown in figure 7.

The controller used is a digital LVPZT† controller. The system was chosen because it meets the technical requirements and is also simple to operate. The system is widely configurable and can be adapted to a very diverse range of requirements. The basic system consists of the housing and the control element with the display. This makes it possible for the developer to manually control the individual piezo stacks during initial tests. The system can, for example, control the static position of the piezo stacks, but also implement first dynamic investigations using an integrated function generator. In addition, the system can be connected to a PC and thus allows the ceramics to be controlled by programs that are generated in, for example, Matlab or Labview. When developing a new

†Low Voltage Lead zirconate titanate ceramics

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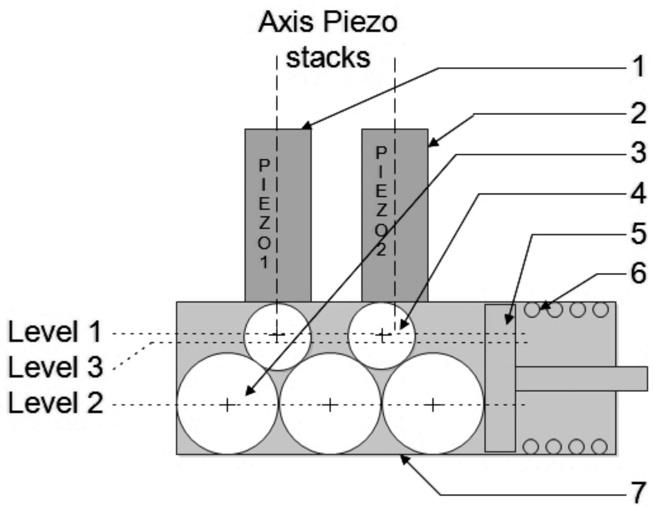

Figure 5 Displacement actuator not limited by the diameter of the pressure pieces No.1

1: *Piezo stack 1 (not actuated)*
2: *Piezo stack 2 (not actuated)*
3: *Pressure pieces (big)*
4: *Pressure pieces (small)*
5: *Piston*
6: *Spring*
7: *Housing*

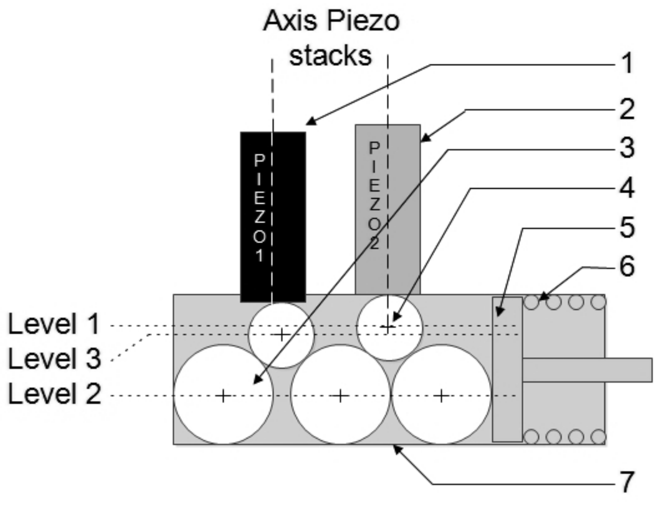

Figure 6 Displacement actuator not limited by the diameter of the pressure pieces No.2

1: *Piezo stack 1 (actuated)*
2: *Piezo stack 2 (not actuated)*
3: *Pressure pieces (big)*
4: *Pressure pieces (small)*
5: *Piston*
6: *Spring*
7: *Housing*

Figure 7 Piezo system

1: *Digital piezo amplifier*
2: *3x LVPZT modules EVD300*
3: *3x piezo actuators PA 70/14 SG*

actuator concept, a digital system simplifies the work, since no signal needs to be generated externally e.g. by an analogue controller.

In addition to the housing and the operating element, the controller consists of the LVPZT plug-in elements. As this is a low-voltage system, all plug-in elements available in the offering deliver a voltage of between -30 V and +145 V. However, the elements differ in respect to the amount of available electric current. Since, when viewed simply, piezoelectric components display the same behaviour as capacitors âĂŞ the larger the ceramic, the higher the capacitance âĂŞ the magnitude of the current determines the working frequency of the ceramics. The envisaged working frequency of the prototype is 66.67 Hz, therefore 60 Hz is selected. In order to select a suitable LVPZT module and a piezo actuator, it is necessary to investigate what current is required by the controller to operate a specific ceramic size with the corresponding operating frequency. To be able to comment on the working frequency of different ceramic sizes and thus capacitances in combination with any arbitrary amplifier module, Equation 3 [6] is introduced. The result is shown in Figure 8 for the use of a maximum voltage of 145 V.

$$f_{max} = \frac{I \cdot 1000}{C \cdot \pi \cdot U} \tag{3}$$

Where:

I = Current in mA
C = Capacitance in μF
U = Voltage in V

It follows from Figure 8 that for the small ceramics PA25, PA35 and PA45, a current of $\leq$250 mA is required to achieve the required operating frequency of 60 Hz. The ceramic PA50 just reaches the required frequency with a current of 300 mA. The PA50 actuator achieves a maximum deflection of 60 μm. The deflection generated in this way is considered sufficient for our usage case when planning the prototype. The piezo module which offers 300 mA, the EVD300, is thus selected. The d-Drive system has capacity for three modules. This is shown in figure 7 by (2). This makes it possible to use three piezo ceramics in the prototype.

A basic rule, particularly in the area of piezo actuator design, suggests that the designer should not strain the ceramics by constantly utilising the entire available stroke. Due to age-

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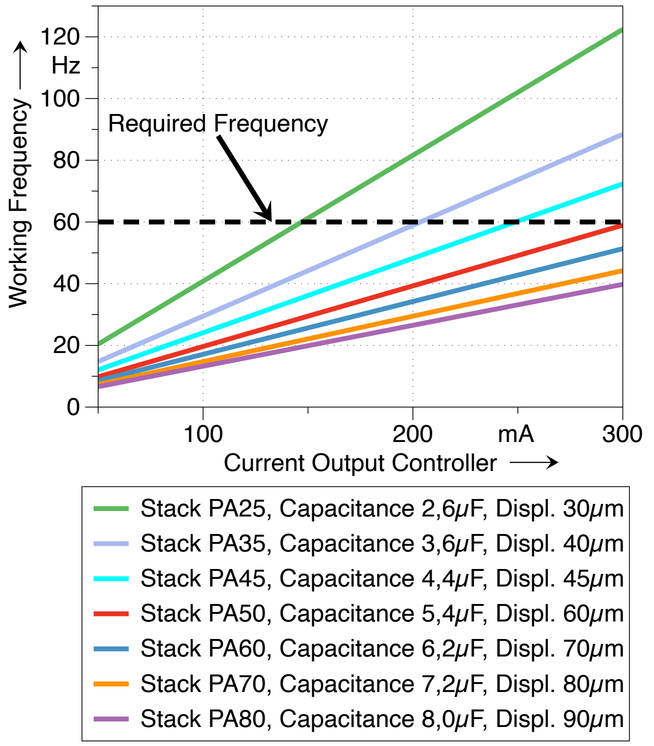

Figure 8 Achievable operating frequency of different capacitances via controller current at U = 100 V, I = 300 mA (const.)

ing effects and to avoid depolarisation coming too close to the Curie temperature, the stroke of the piezo elements should only be exploited up to 80 %, especially in the field of development or when building prototypes. Since figure 8 showed that a maximum stroke of 60 μm can be achieved with the selected piezo module, a corresponding piezo actuator must now be selected. To prevent the actuator from having to cover more than 80 % of its stroke, it must be ensured that the ceramic provides a stroke $> 60\,\mu m \cdot 1.2 = 72\,\mu m$. This is guaranteed by the actuator PA70/14. To achieve the required operating frequency with this actuator, this ceramic is only deflected up to 60 μm. This is easy to achieve by reducing the voltage. The PA70/14 is a biased multilayer actuator with a nominal length of 89 mm.

With the help of the prototype, the aim is for long-term tests, among other things, to be able to provide information about the operational safety of the piezo ceramics and the wear behaviour of the pressure hull. For this reason, it is necessary to assess how the ceramic heats up. This analysis is shown in figure 9. The diagram 'heat generation PA70', figure 9, was provided by the company Piezo Jena, but is not published. As can be seen, the heat generated when operating at a frequency of 60 Hz is approximately 20 °C and is thus far from the maximum operating temperature, which is half the Curie temperature of the ceramic material. The investigation regarding the generated heating of the ceramics was carried out without any obstruction of the ceramics. However, since the expected temperature is by no means within a critical range, the installation of the ceramic in a housing is not expected to exceed half the Curie temperature. From a thermal point of view, the configuration should therefore pose no problems and additional cooling of the ceramics is not required.

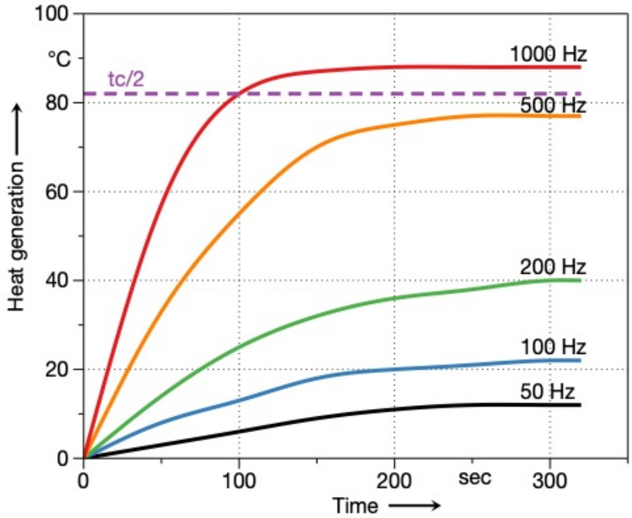

Figure 9 Heat generation PA70/14 piezo ceramic

Since the components of the piezo system have now been selected and parameters such as the maximum operating frequency have also been defined, the expected force of the piezo actuators can be taken into account. On the one hand, piezo actuators are characterised by the fact that they generate their maximum force when the ceramic is firmly clamped and cannot expand. This force is known as blocking force. For the PA70/14, it is 850 N. The other characteristic point is the idle deflection. This is achieved when the ceramic is energised to a maximum without a force acting on the outside of the actuator. The PA70/14 achieves an idle deflection of 94.81 μm. The force diagram is shown in figure 10 and is based on the technical data of the piezo stack [7]. It can be seen from the diagram that the available force continues to decrease as deflection increases. This aspect must be taken into account for the deflection. Because of this, it is also common for the force diagram to define a working range. This is marked in the illustration by the blue area. This range depends on the ceramic used and the requirements set. At a deflection of $76\,\mu m = 80\,\%$, which is also the point of maximum intended deflection, the selected ceramic still supplies a force of 170 N. This is sufficient for the project planned here.

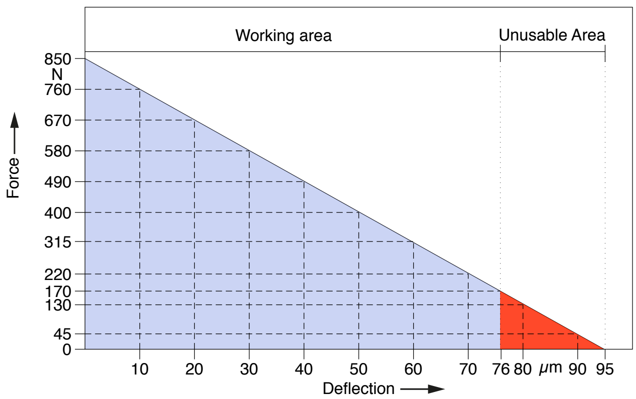

Figure 10 Force/displacement behaviour PA70/14 [7]

Since the aim of this study is to develop a highly dynamic

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actuator, it makes sense to acquire precise knowledge of the stroke of the individual piezo elements in order to be able to draw conclusions about any unexpected behaviour of the prototype piston. In the field of piezo actuators, it is customary to use strain gauges when studying this. These strain gauges are mounted by the manufacturer directly on the ceramics and thus allow targeted control of the stroke generated. The system thus has closed-loop control. Since the d-Drive systems can process the data of the strain gauge sensors and this could be useful for the later tests, the three piezo actuators were fitted with strain gauge sensors.

5 Prototype of the Linear Piezo Actuator

The prototype for the linear piezo actuator is generated based on the concept shown in section 3 and the selected components of the piezo system from section 4. To do this, a model is generated in CAD, which is then simulated and manufactured. The model is shown in figure 11. The housing measures 128.6 × 105 × 25 mm.

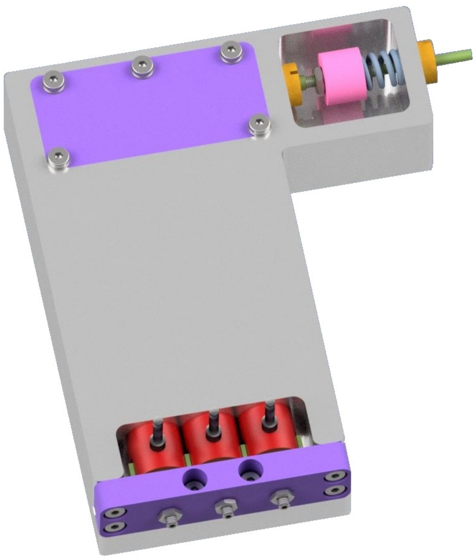

Figure 11 CAD model of the linear actuator for manufacturing

For a better understanding of the design and function, the prototype is illustrated in figure 12 as an exploded view.

According to figure 12, the actuator can be divided into seven assemblies. The definition and design of the assemblies aimed, on the one hand, at lightweight construction of the dynamic components and, on the other, at protection against wear, especially of the more complex assemblies. The more complex assemblies of the tensioner (4), the holder for the piezo stacks (5), and the housing (7) are not in contact with moving components during operation and are therefore not subject to wear. The assemblies of the cover (1), the running surface, pressure pieces and end stops (2), and the pistons, piston guide, spring and spring tensioner (3) are involved in the movement or guidance of the mechanical components and are thus subject to wear. However, one aim for these components was that they should be simple to manufacture. With regard to the weight, the focus was especially on the pressure pieces, piston and spring tensioner, since these components

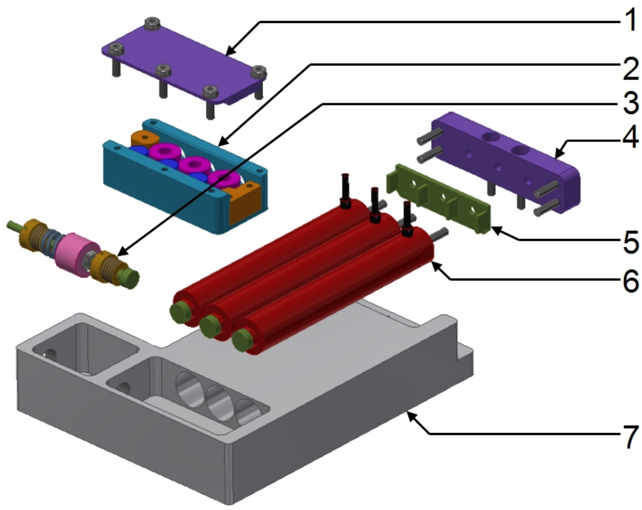

Figure 12 Linear actuator for manufacturing - exploded view

1*: Cover*
2*: Running surface, pressure pieces, end stops*
3*: Piston, piston guide, spring, spring tensioner*
4*: Tensioner*
5*: Holder piezo stacks*
6*: Piezo stacks*
7*: Housing*

move during operation. Although made from 42CrMo4 (density = 7.85 kg/dm^3) for this prototype, the mass of the pressure pieces, the piston and the spring tensioner is 39.17 g. This value is satisfactory for the prototype, but could be reduced to a value of 22.46 g by, for example, using a material such as titanium (density = 4.501 kg/dm^3), whose use is permissible based on calculations.

The expected deflection can now be simulated on the basis of the CAD model generated. The expected deflection and its behaviour is shown in Figure 13. During the simulation, the three piezo actuators were consecutively deflected from 0 % to 100 %. The maximum deflection was defined as 70 μm. The resulting total deflection of the actuator here is 0.452 mm. This value is below the required deflection of 2.5 mm; however, it is necessary here to point out the force of the actuator that is generated. Since the piezo actuators are deflected by 70 μm, as shown in figure 10, each actuator produces a force of 220 N. This results in a total system force of 660 N, generated by the piston. By using a mechanical transmission, with a view to the required force of the actuator system of 100 N, one could achieve a system deflection of 2.983 mm, assuming a mechanical efficiency of 1. This is satisfactory, since the required deflection of 2.5 mm is exceeded.

One possible arrangement of a mechanical transmission is shown schematically in Figure 14. Such an arrangement of the lever transmission would, on the one hand, have the advantage of allowing a more optimal arrangement of the piezo stacks, since the flux of the force is deflected by 180°. This could reduce the dimensions of the housing. Another advantage would be a further reduction in the material used and thus of the weight of the pressure pieces, since the lever reduces the force generated by the piezo stack and causes a larger de-

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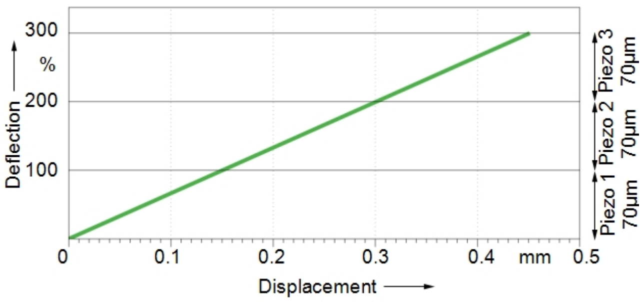

Figure 13 Expected deflection of the piezo actuator

flection. This would result in lower tension for the pressure piece components. However, no transmission was used when defining the prototype of the linear piezo actuator. This has to do with the resulting difference in load acting upon the piezo ceramics. Piezo ceramics react sensitively to lateral forces. Since these is present in this case, the prototype should be used to provide evidence of correct, unimpeded use of the piezo stacks. For this reason, no transmission is used in the prototype created.

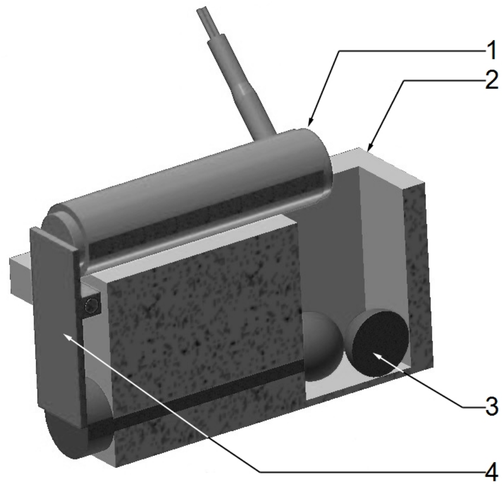

Figure 14 Concept with internal lever transmission

1: *Piezo stack* 3: *Pressure pieces*
2: *Housing* 4: *Lever*

The mechanical components of the prototype are manufactured according to the CAD model of the linear actuator shown in figure 11. The manufactured components are shown in figure 15 and figure 16.

The concept of the linear piezo actuator to be examined here transmits the force through pressure pieces, which generate sliding friction during operation. To reduce the force lost due to friction, the components could be lubricated or coated. In this case, a decision was made to coat the components, since the system could also be used in fields such as laser technology, where no oil circuit system or the like is present. A DLC‡ coating was chosen, since this has a lower coefficient of friction (0.05 - 0.15, dry vs. steel) and, especially in applications such as these, enables the components to run dry without using lubricants. Specifically, the 'axyprotect' coating [8] was used here. The coated components are shown in figure 17.

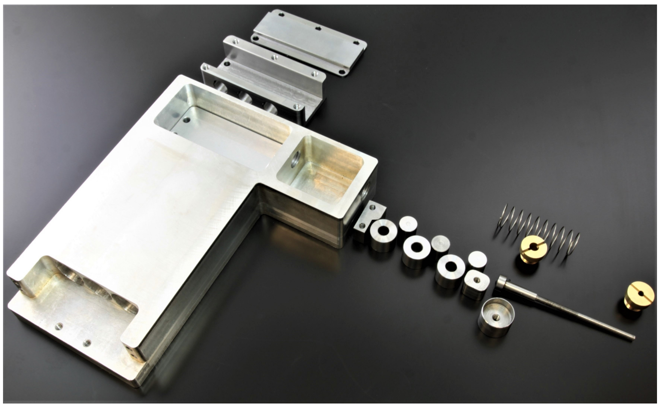

Figure 15 Prototype linear piezo actuator - exploded view

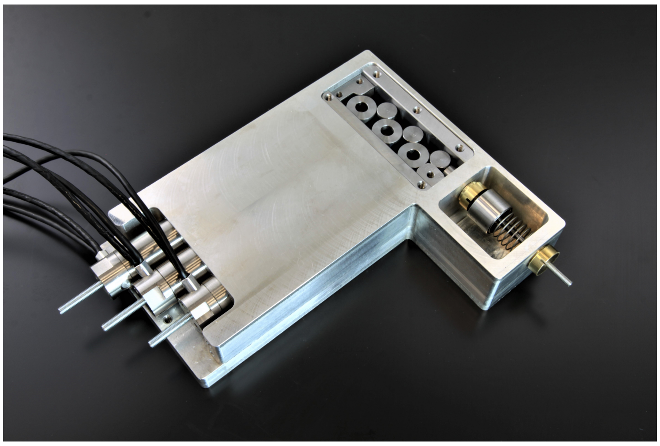

Figure 16 Assembly of linear piezo actuator w/o cover

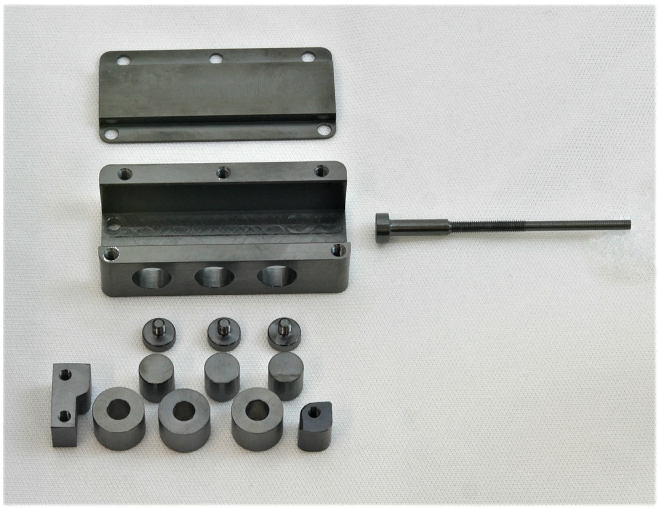

Figure 17 DLC-coated components

‡Diamond like carbon

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6 Measurements

The investigations should provide information about the quasistatic and dynamic behaviour of the linear piezo actuator. This is defined by the behaviour of the prototype's piston. To measure the position of the piston as a function of time, an optical laser measuring system, the optoNCDT ILD1320-10 [9], is used. The experimental setup of the measurements is shown in figure 18. The laser beam of the measuring system is aimed directly onto the tip of the piston of the linear piezo actuator.

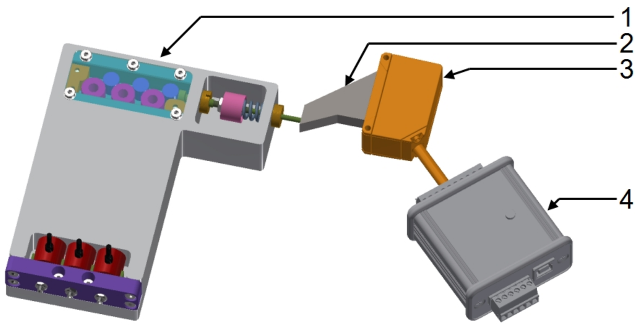

Figure 18 Actuator with measuring system
1: *Actuator*
2: *Measurement area*
3: *Sensor optoNCDT ILD1320-10*
4: *Coupling box - RS422/USB Converter IF2001/USB*

The piezo actuators and the piezo system selected enable the actuators to be operated in open-loop mode (OL) and in closed-loop mode (CL). In OL mode, the piezo amplifier merely generates a voltage and this is passed on to the piezo actuators. The deflection and thus the position of the head pieces screwed into the piezo actuators are unregulated in this mode of operation. In contrast, in CL-mode, there is targeted control of the deflection of the piezo actuators by means of strain gauges mounted on the piezo ceramics. The advantage of this mode is exact control of the deflection down to the nm-range and suppression of hysteresis and drift phenomena, which occur when using piezo actuators. A disadvantage of CL mode, however, is the limitation of the deflection on the part of the system, especially when using higher operating frequencies [10]. This limitation is necessary to give the control system reserves for the control process via PID controller. For this reason, all measurements shown here are carried out in OL mode.

The first measurements address the quasistatic behaviour of the selected piezo actuator and of the linear piezo prototype. These measurements are, on the one hand, intended to obtain the correct function of the mechanism or of the piezo actuator and, on the other hand, a first impression with regard to deflection performance. These measurements are considered in subsection 7.1. In the quasistatic investigations, the required deflection is manually increased by 5 μm every 5 s from 0 % to 100 % (deflection actuator).

The subsequent measurements in subsection 7.2 deal with the dynamic behaviour of the prototype. For these measurements, all three piezo actuators are simultaneously operated by a sinusoidal signal. The measurements differ in the working frequency selected. The frequencies 1 Hz, 30 Hz, 60 Hz and 100 Hz are considered here.

7 Measurement Results

7.1 Quasistatic Investigations

In the first measuring process, the piezo stack is deflected from 0 % to 100 % in CL mode and in OL mode. The deflection is manually increased by 5 μm every 5 s. As the deflection is manually adjusted, slight shifts of 1 s may occur on the abscissa axis for the measured values. The data obtained are shown in figure 19.

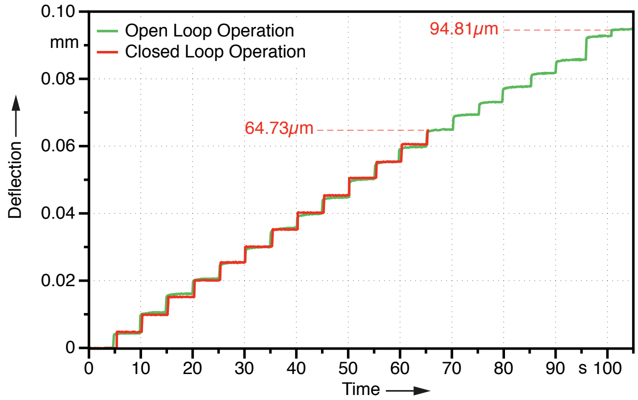

Figure 19 Deflection of piezo actuator from 0 % to 100 % in CL and OL

The most striking finding of this test is that the two operating modes CL and OL allow different deflections. The deflection measured by the sensor in CL mode is 64.73 μm. This is consistent with the value measured by the strain gauge sensor. Due to this finding, the sensor values can be considered as plausible. The deflection in OL mode is 94.81 μm. The deflection in CL mode is lower because the maximum deflection in this mode is limited to 64.5 μm by the system. The limitation in CL mode is due to the control technology used, here a PID controller, and is required in order to maintain necessary reserves for the control system. The value of 94.81 μm is achieved in OL mode as the entire control loop of the PID controller is bypassed in OL mode. This limitation on the system side is not present in OL mode.

The curve of the measurement signal in figure 20 represents the deflection of the piston of the linear prototype under the influence of all three piezo stacks in OL mode. The deflection achieved in OL mode is 445.4 μm. As with the measurements in OL mode, it can be seen that the influence of drift and creep effects are superimposed on the measurement signal. Despite the lower precision of the piezo stacks in OL mode, correct extension of the piston can be observed. It was possible to carry out the quasistatic tests without any errors being detected in the form of play/clearance in the mechanics or clamping. In addition, it was possible to confirm the expected characteristics of the system caused by the simulations. Since the quasistatic analysis confirmed that the mechanics function satisfactorily, the system is now analysed by means of dynamic excitation.

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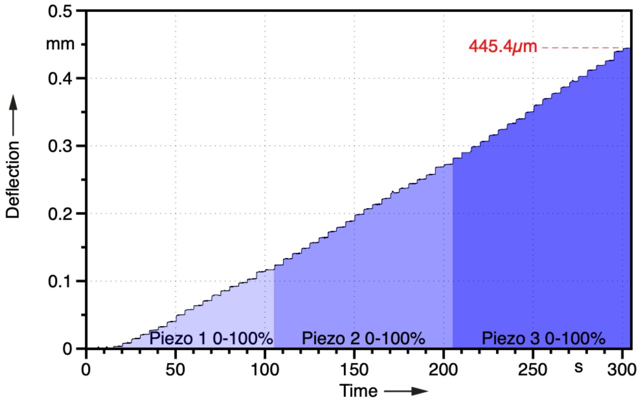

Figure 20 Prototype - all stacks - OL 100 % 0 Hz

7.2 Dynamic Investigations

The curve of the prototype measurement - all stacks - OL SIN (sinus signal) 80 % 1 Hz is shown in figure 21. The set operating frequency here of 1 Hz is the same as the measured frequency. The cycle duration is therefore 1 s. In this measuring process, which is carried out in OL mode, the maximum deflection is 416.5 μm. The offset is 0.005 μm. Due to the precision of the measuring system, the offset can be assumed to be 0 μm. The SIN signal can be identified as such and is free of plateaus and other irregularities that would be noticeable in the form of oscillations on the signal curve.

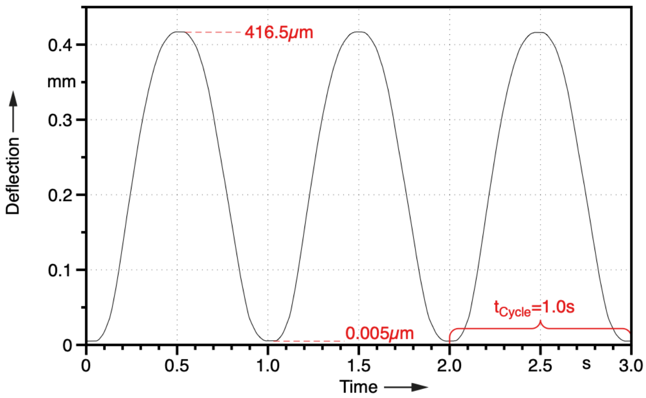

Figure 21 Prototype - all stacks - OL SIN 80 % 1 Hz

The data of the prototype measurement - all stacks - OL SIN 80 % 30 Hz can be seen in figure 22. Even when measuring OL SIN 80 % 30 Hz, the curve of the deflection can be reproduced as desired. In this measurement, a deflection of 384.5 μm can be observed. In the measurement in OL mode at 1 Hz in figure 21, the deflection was 416.5 μm. The deflection was therefore reduced by a value of 416.5 $\mu m - 384.5\,\mu m = 32\,\mu m$ due to limitations of the system. The offset achieves a value of 14 μm. As is typical for the measurements at 30 Hz, the duration of the plateaus is 1.5 ms. The offset and plateaus are specific for dynamic operation with the selected d-Drive system and are due to the integrated electronics.

The curve of the prototype measurement - all stacks - OL SIN 80 % 60 Hz is shown in figure 23. In this measurement, the operating frequency of the piston corresponds with the set operating frequency and is therefore output correctly. In addition, the SIN signal can be identified as such and has no irregularities. The deflection achieved is 417 μm. Since the value of the offset is 34.8 μm, the deflection achieved by the piston results in a value of 382.2 μm. With regard to the plateaus, the behaviour of the operating frequency of 60 Hz can be detected. The duration of the plateaus is 2 ms.

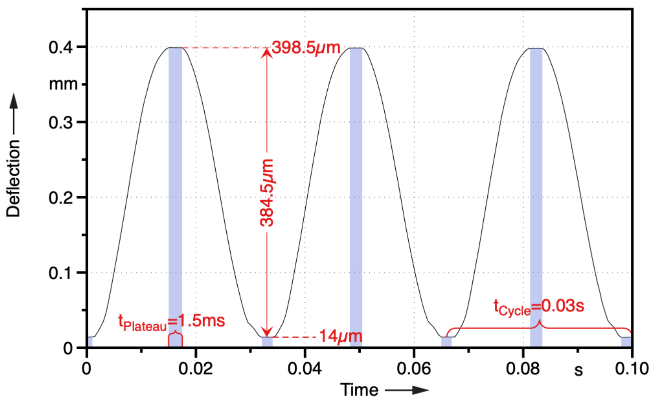

Figure 22 Prototype - all stacks - OL SIN 80 % 30 Hz

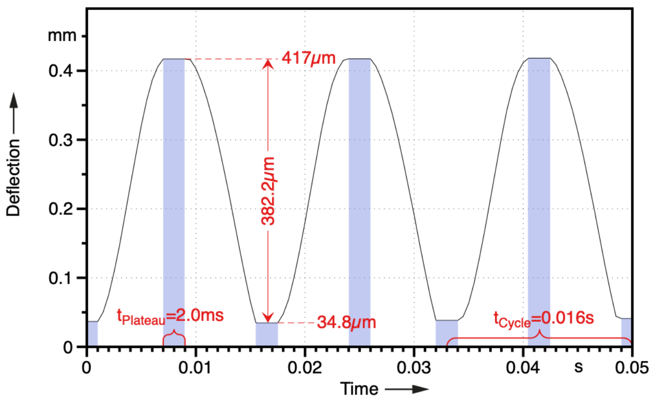

Figure 23 Prototype - all stacks - OL SIN 80 % 60 Hz

Compared to the measurements signal at 30 Hz and 60 Hz, the SIN signal cannot easily be identified as such here under the influence of 100 Hz. Compared to the measurements at frequencies of 30 Hz and 60 Hz, irregularities can be identified when measuring at 100 Hz. When considering the rising and falling slopes of the measuring signal, irregularities can be detected in the form of waves. These fluctuations occur due to the piston spring having too low a preload. To show this error, the measurements are represented with this irregularity. This irregularity is caused by the spring preload being set for the operating frequency of 60 Hz by the spring tensioner. This irregularity can be prevented by adjusting the spring preload to a correct value.

The curve of the prototype measurement - all stacks - OL SIN 80 % 100 Hz is shown in figure 24. In this measurement, the operating frequency of the piston corresponds with the set operating frequency and is therefore output correctly. The deflection achieved is 356.2 μm. Since the value of the offset here is 157 μm, the deflection achieved by the piston results in a value of 199.2 μm. With regards to the plateaus, behaviour typical of the operating frequency of 100 Hz can be detected. The duration of the plateaus is 2 ms.

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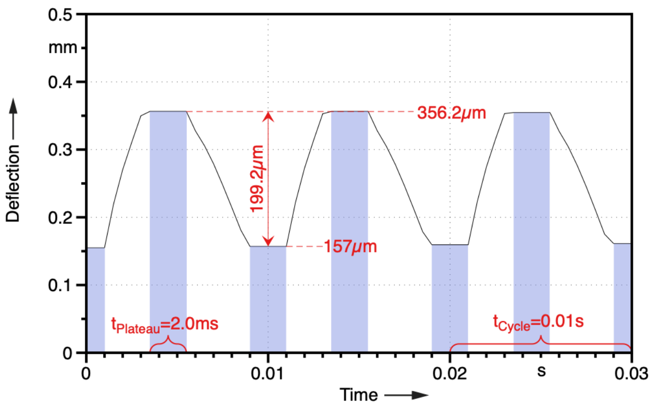

Figure 24 Prototype - all stacks - OL SIN 80 % 100 Hz

8 Summary and Outlook

The aim of the investigation was to examine the behaviour of the linear prototype under the influence of static and dynamic excitation. These tests were successful. The system functions as desired and confirms the behaviour assumed by the simulations in terms of deflection and characteristics.

It is possible to use the prototype to mechanically couple the deflections of any number of actuators, in this case piezo actuators. The strain the piezo actuators were subjected to during the measuring processes was found to have not caused any damage to them. The use of these piezo actuators in the mechanical system generated was therefore found to be permissible.

Although the required deflection of 2.5 mm was not achieved by using three piezo stacks with the concept presented here without the use of a transmission, this concept nevertheless offers numerous possibilities for application not offered by the current state of this technology.

With regard to linear actuators, the function of the concept considered here was demonstrated in the course of this publication. The combination selected here and the application were evaluated up to an operating frequency of 100 Hz. However, this could easily be increased by using another amplifier. Furthermore, it is possible for users of this concept to easily adapt the actuator stroke that can be achieved. The stroke can be adjusted by using other piezo actuators or by adjusting the number of stacks. The concept presented here allows a maximum deflection of $445.4\,\mu m$. If an attempt was made at this point to reproduce this stroke with a single piezo actuator, this would lead to a ceramic length of $\approx 445.4\,\mu m \cdot 1500 = 668100\,\mu m = \underline{66.81\,\text{cm}}$, since the achievable deflection is primarily dependent on the length of the ceramic. In many applications, especially in the field of actuators for valves or laser technology, this would lead to a problematic package. In addition, such a long ceramic of this kind would be a prototype, which would lead to further problems in terms of availability and costs.

In the next step of the investigations, the intention is to design a prototype which converts the linear deflection of the piezoelectric actuators into a rotary movement. In the field of piezo actuators, concepts of this type of movement are only available in the form of systems that transmit their force by means of traction (friction). This means that the torques of the current state of the art are limited to $\leq 10\,\text{Nm}$. However, the concept presented here offers transmission of the force by means of positive locking, which suggests an increase in the maximum achievable torque. The prototype to be investigated in the next steps is shown in Figure 25 and Figure 26. As can be seen from the illustrations, the conversion of the linear movement into a rotary movement is achieved by the curvature of the runway in which the pressure pieces slide.

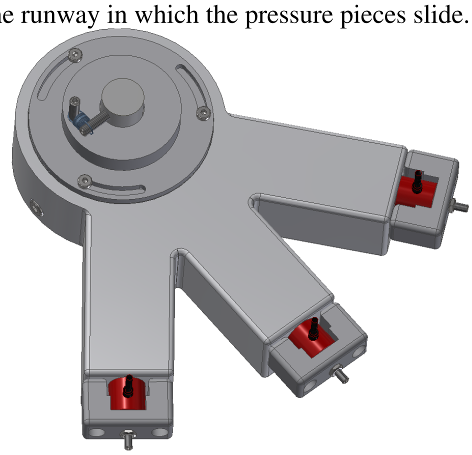

Figure 25 CAD model of rotational prototype

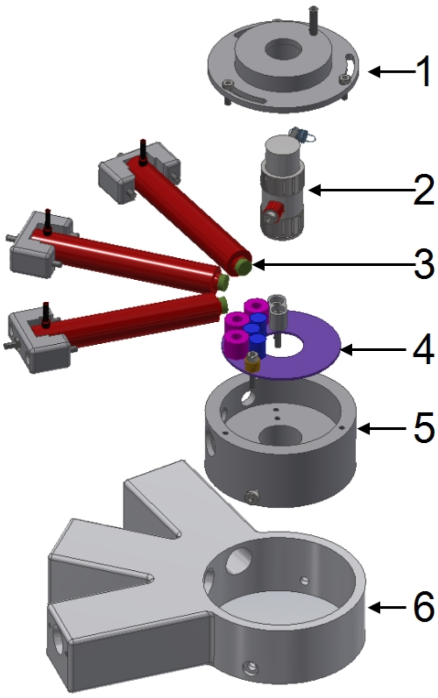

Figure 26 Rotational prototype - exploded view
1: *Cover*
2: *Shaft*
3: *Piezo stacks and tensioners*
4: *Floor, pressure pieces, end stops*
5: *Runway*
6: *Housing*

Following the tests on the rotatory actuator, further investigations could be carried out on the basis of the linear prototype. These investigations would aim to optimise an already existing concept in the field of piezo actuators, the PAD (**P**iezo **A**ctuator **D**rive) converter. The concept of the PAD converter is shown in figure 27.

Figure 27 shows two stack actuators which are spatially shifted by 90° towards each other. They are firmly attached

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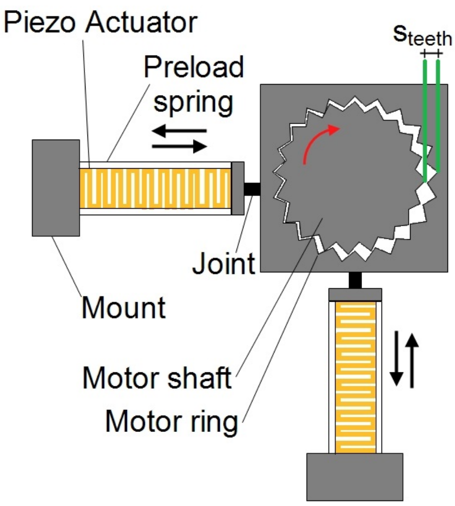

Figure 27 Concept PAD Actor - Height of teeth must be smaller than displacement of piezos [11]

to a metal ring. This configuration is the stator (motor ring) which houses a shaft (motor shaft). If both piezo actuators are activated quasi-statically with two sinusoidal alternating voltages of the same amplitude and frequency and are phase-shifted by 90° this results in a rotating motion of the drive ring. Since steady contact is maintained between the ring and shaft, the shaft can unroll off the inner surface of the ring, causing continuous rotation. The rotational direction is determined by the phase shift, and the speed, by the frequency of the control signal. As can be seen here, the force is transmitted via micro-serration. The height of the teeth is $\approx 10\,\mu m$. Due to the concept, the stroke provided for the piezo stacks s_{teeth} has to be greater than the height of the teeth[11].

To optimize the idea of the PAD actuator a greater displacement of the piezo stacks is needed. As shown in the measurements in subsection 7.2, a greater stroke is now available. Based on the measurements shown here, an actuator system which uses two of the linear prototype presented here could replace the two piezo stacks in Figure 27. This would lead to a system as shown in Figure 28. The advantages of using the prototype developed here in the PAD actuator lie in the higher flanks of the teeth. This results in manufacturing and performance advantages. From a manufacturing point of view, the use of the prototype can avoid the difficult to produce tooth flank height of $10\,\mu m$. From a performance point of view, a higher torque can also be transmitted with the higher tooth flanks. This is 11 Nm for the existing PAD actuator[11]. At this point it is assumed that the transmittable torque is limited by the height of the tooth flanks.

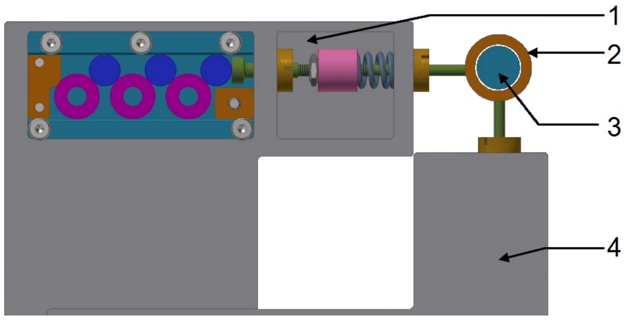

Figure 28 Model for the optimisation of the PAD actuator concept

1: *Actuator with pressure components no. 1*
2: *Stator*
3: *Driveshaft*
4: *Actuator with pressure components no. 2*

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