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Various Aspects of the Placement of a Piezoelectric Material in Composite Actuators, Motors, and Transducers

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Piezoelectric materials have found wide applications in technical systems. Most often, a combination of piezoelectric and other materials is advantageous. The position and the amount of the piezoelectric material within the overall system depends on various aspects, such as the maximum mechanical output to the load, the maximum electromechanical efficiency of the system, the maximum utilization of the piezoelectric material, the minimum self-heating of the piezoelectric material, and the controllability of the system, which might be key aspects for the optimization of the system design. For a composite longitudinal vibrator (bolted Langevin transducer), which is a base for many technical applications, this contribution shows in detail, how the above-mentioned aspects depend on the position and the volume of the piezoelectric material related to the mode shape.

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I. INTRODUCTION

Since the scientific description of piezoelectric effects by Jacques and Pierre Curie in 1880/1881, many kind of piezoelectric materials have been developed and are now used in sensors, actuators, transformers and generators. Today, most often, PZT ceramics are used to fulfill different tasks, *e.g.* generation of micro-displacements at high forces for precise positioning, dynamical actuation of valve systems for fuel injection, and the generation of ultrasonic vibrations. Within ultrasonic motors, these microscopic vibrations are converted to useful macroscopic translatory or rotatory movement. Within processes like cleaning, sieving, bonding, welding, drilling or cutting the microscopic vibrations directly cause, or at least enhance, the desired processes.

As PZT ceramics are brittle and cannot withstand wear, high humidity, aggressive media *etc.* for a long time, the system design has to be done carefully. Additionally, as piezoelectric materials are most often much more expensive than conventional design materials, there is a strong desire to use as little piezoelectric material as needed. Thus, two main questions arise, which are constrained by the field of application: 1) How much piezoelectric material is needed to fulfill the desired task? 2) Where should the piezoelectric material be placed within the overall system?

The placement of the piezoelectric material for vibration damping has already been discussed intensively in the literature, *e.g.* Ref. 1 or Ref. 2, but there is little information about placing piezoelectric material within composite actuators, motors and transducers. This paper will first give a survey of different devices using piezocomposite structures. The placement of the piezoelectric materials within these structures will be analyzed in detail. The advantages and the disadvantages of the given designs in various applications will be discussed. Then, we will have a look at various aspects such as the maximum mechanical output to the load, the maximum electromechanical efficiency of the system, the maximum uti-

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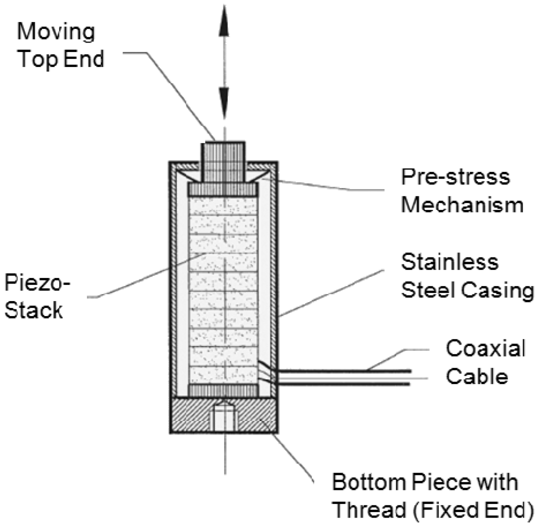

Fig. 1. Piezoelectric stack actuator with an output-plunger, a pre-stressing spring, and a housing [5].

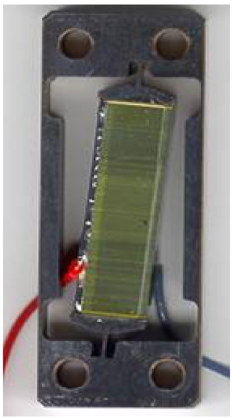

Fig. 2. (Color online) Piezoelectric multilayer actuator with a stroke-amplifying mechanism using flexural hinges [6].

lization of the piezoelectric material, the minimum self-heating of the piezoelectric material, and the controllability of the system, which might be key aspects for the optimization of the system design. For a composite longitudinal vibrator (bolted Langevin transducer), which is a base for many technical applications, we will show in detail, how the above-mentioned aspects depend on the position and the volume of the piezoelectric material related to the mode shape.

II. COMPOSITE ACTUATORS, MOTORS AND TRANSDUCERS

In most actuator applications, the piezoelectric material is pre-stressed. This avoids tensile stresses in the ceramics, which would lead to early failure due to crack building. Figure 1 shows a typical set-up of a piezoelectric stack actuator that is pre-stressed by using a spring and that is covered by a housing to prevent detrimental effects by outside influences, such as high humidity, mechanical impact, *etc.* The piezoelectric actuator is attached to a plunger. Thus, undue loads, like bending moments or torques are not directly given to the piezoelectric actuator. However, the pre-stress mechanism, the plunger and the housing need some construction volume. The effective stroke of the piezoelectric material (typically up to 0.2% of the active materials' length, see Ref. 3) can be lowered to about 0.1% of the overall systems' length, see Ref. 4. In almost the same manner, the total weight of the system is about twice the weight of the piezoelectric actuator itself. If the construction volume and the weight are to be reduced, the housing itself can be used as the pre-stressing spring, but in this case, a tradeoff between optimum pre-stress stiffness (as low as possible: pre-stress should not vary over the stroke and the force spent in the pre-stress spring cannot be used for the load), protection from outside influence (lateral forces, *etc.*), and cost-effectiveness must be found.

Figure 2 shows a typical setup to increase the stroke of a piezoelectric actuator. If the kinematical transmission in flexural hinge mechanisms is used, the stroke can be amplified by a factor of about 5 to 15. Coincidentally, the actuator force is lowered by at least the same factor. Depending on the design of the flexural hinges, some amount of the actuator force is lost in these hinges. Theoretically, the flexural hinges can be made infinitely small, but practically, machining and lifetime aspects also give rise to limitations.

Both designs, pre-stress mechanism and kinematical transmission, decrease the mechanical resonance frequency, and thus lead to a limitation of the driving frequency for dynamic use. Hence, the non-piezoelectric parts in composite actuator systems should be as small and lightweight as possible, but at the same time, they should provide optimum pre-stress and protect the piezoelectric material.

Within ultrasonic motors, piezoelectrically generated microscopical small vibrations are converted to translational or rotational movement by highly-dynamic friction contact mechanisms. There are many different designs to yield the desired vibration; surveys are given in *e.g.* Refs. 7 and 8. A motor with comparably high power and efficiency was proposed by Kurosawa *et al.* [9]. It is based on two pre-stressed piezoelectric stack actuators, which are combined under an angle of 45 degree by a common driving tip. Driving the two actuators with phase-shifted harmonic signals in resonance yields a complex longitudinal-flexural mode shape that leads to elliptical movement of the driving tip. The piezoelectric actuators are placed close to a vibration node. The amount of piezoelectric material is much lower than the amount of metal parts. This design seems to be advantageous for power generation and efficiency.

Another motor, which delivers small power at (rather) low cost, is commercialized by Elliptec GmbH [10]. It

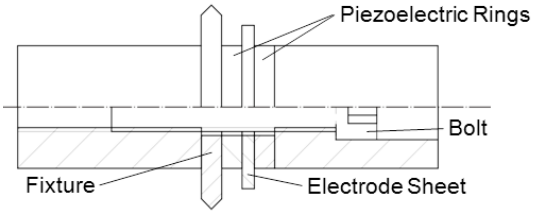

Fig. 3. Bolted Langevin transducer: piezoelectric elements are pre-stressed by a bolt.

is based on a piezoelectric multilayer actuator, which is pre-stressed by a metallic frame. Driven with one single harmonic signal only, an elliptical trajectory of the output tip is generated by mode coupling of longitudinal and flexural modes. By using different frequencies, forward and backward motion is realized. When driven for a longer time, the piezoelectric multilayer actuator suffers from strong heating. Although this design with combined piezoelectric and metal parts is quite similar to Kurosawa's design, the generated power and efficiency are rather low.

In various applications, like cleaning, sieving, bonding, welding, drilling or cutting, piezoelectric elements are used in a similar way: already in the early 20th century, Langevin proposed combining and pre-stressing piezoelectric elements with metal elements (see Fig. 3). This design offers some advantages against *e.g.* bonding by adhesive glue: tensile stresses which could lead to cracks within the brittle ceramics are avoided, there are no insulating gluing layers that might increase the capacitance, the mechanical pre-stress can enhance the piezoelectric coupling, the heat generated by the piezoelectric material due to electrical and mechanical losses is conducted to metal parts easily, and electrodes can be connected easily by using additional inserted electrode sheets.

Most often, bolted Langevin transducers are adapted to their loads by using additional elements: horn structures that amplify the output stroke, cones, and plates or funnels that radiate ultrasonic waves to arbitrary media. The generated power of such systems is mainly defined by their size and is constrained by the application. Efficiency can reach values of more than 90%. The setup of these transducers is basically similar to that of piezoelectric actuators and motors, they all combine piezoelectric materials with other design materials. The bolted Langevin transducer design will be the base for further investigation within this paper.

III. ASPECTS ON THE PLACEMENT OF A PIEZOELECTRIC MATERIAL WITHIN COMPOSITE STRUCTURES

One very common method used during the design of new piezoelectric systems is to adapt existing transducers to new applications. Unfortunately, this most often leads to tradeoff solutions that are cost effective but seldom give optimum results for the wanted application. Iterative experimental fitting is time consuming, as well. Another option is to do sophisticated modeling and analysis, but for many applications, it is still quite impossible to compute the electromechanical coupling of the piezoelectric elements while incorporating driving electronics and application load.

To understand the basic behavior of piezoelectric elements and their coupling to their environment, simplifying models can be helpful. For example, the electromechanical characteristics of a bolted Langevin transducer, which is driven in its longitudinal resonance, can easily be modeled by using a mechanical mass-spring-damper system or an equivalent electronic circuit. If the vibration shape is to be investigated, an off-resonance drive is wanted or higher harmonics should be included, one-dimensional continuum models are still sufficient. The mathematical background for such a kind of modeling is given in *e.g.* Ref. 11.

Depending on the application, different optimization criteria arise:

- plastics welding requires high power and robustness,
- cleaning processes require high power radiated to a fluid, and cavitation is wanted, but hinders ultrasonic radiation; thus, a specific optimum vibration amplitude exists,
- levitation requires strong acoustic pressure; thus, the largest vibration amplitude is wanted. Uniform planar ultrasound offers the possibility to levitate larger objects, and focusing or directive ultrasound can be used for additional movement of small objects.

The amount of power delivered to a load depends on the transducer's power generation capability, as well as the matching to the load. For weak loads, it is sufficient to investigate the free vibration characteristics of the transducer. Strong loads significantly influence the vibration behavior and should be included in the calculation models. Nevertheless, the investigation of a freely vibrating system can give some helpful information.

At the same time, some restrictions resulting from the piezoelectric materials' characteristics have to be taken into account. Tensile stresses must be avoided, as they will lead to chattering of the bolted Langevin structure and/or crack initiation if additional glue is used. Compressive stresses may not exceed a specific limit as they could lead to mechanical depolarization, and strain mustn't exceed a specific limit; otherwise, the mechanical losses of the ceramic will increase drastically, leading to heat-up and resulting in failure.

Figure 4 shows the strain and the displacement distributions within a bolted Langevin transducer that is

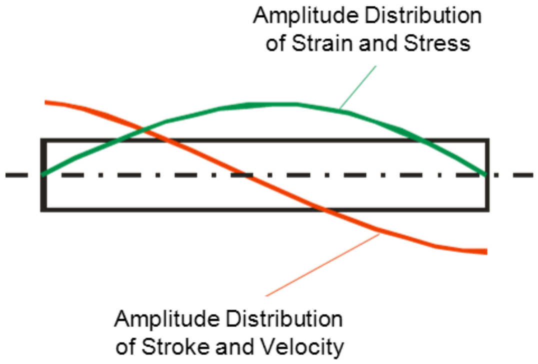

Fig. 4. (Color online) Strain, stress, stroke and velocity amplitude distributions of a transducer freely vibrating at its first longitudinal mode.

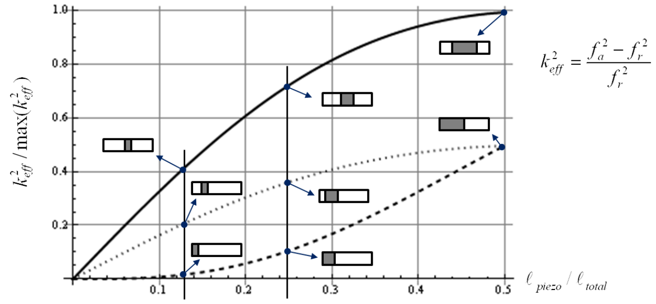

Fig. 5. Dependency of the effective coupling coefficient on the position of the piezoelectric material and its fraction within a Langevin transducer that is freely vibrating in its first longitudinal mode. The fraction of the piezoelectric material is given as the ratio of the length of the piezoelectric material to the total length of the transducer (*e.g.*, the same amounts of piezo and passive material yield a fraction value of 0.5).

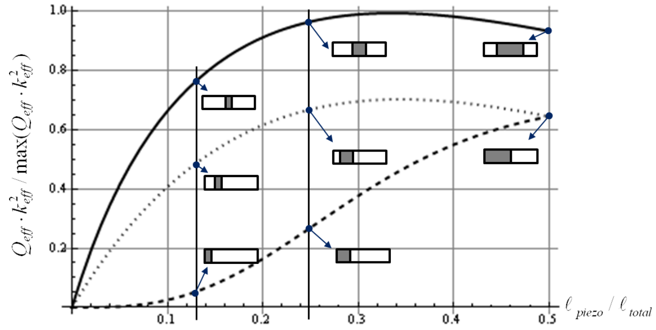

Fig. 6. Dependency of Qk^2_{eff} on the amount and the position of the piezoelectric material within a Langevin transducer that is freely vibrating in its first longitudinal mode.

freely vibrating in its first longitudinal mode. As the transducer is symmetric, the vibration amplitudes at the two ends are the same, and the vibration node is at the middle. The maximum strain and the maximum stress develop in the middle. Thus, the mechanical stored energy is also maximal at the middle position. Taking into account that mechanical losses and the related heat-up are proportional to stored mechanical energy, a conclusion that considers the protection of the piezoelectric elements only is to never place piezoelectric elements in the middle of a freely-vibrating, symmetric, longitudinal transducer. This is also valid for weak loads, such as radiating ultrasound into air.

Another argument to place the piezoelectric material at one end of the transducer is the fact that the vibration amplitude is mainly limited by the maximum strain and stress in the piezoelectric elements, but placing them at an outside position is limited by the needed end-mass and bolt for pre-stressing. Additionally, the needed excitation voltage is higher if the piezoelectric elements are positioned outside the middle position. A good tradeoff solution might be to place the piezoelectric elements - as far as possible - to one end of the transducer. In practical cases, this is a position around one quarter of the transducers length.

The capability of power conversion in piezoelectric elements is mainly related to the effective electromechanical coupling coefficient, which results from the material's coupling coefficient and the placement of the piezoelectric elements in relation to the mode shape. This means, that the effective coupling coefficient will be zero if the piezoelectric elements are positioned in a way that they cannot excite the mode shape, but the effective coupling coefficient can be higher than the material's coupling coefficient if the piezoelectric material is positioned in an optimum manner. For weakly damped systems, the effective coupling coefficient can be calculated from the system's resonance and anti-resonance frequencies. Figure 5 shows the dependency of the effective coupling coefficient on the amount and the position of piezoelectric material within a Langevin transducer that is freely vibrating in its first longitudinal mode. The coupling efficiency is maximal if the piezoelectric material is placed in the middle and if it covers one half of the full transducer length.

Another key-aspect for the evaluation of piezoelectric systems is the mechanical quality factor. This factor describes the amplitude boost caused by resonance effect. Typically, if the exciting voltage is limited, a large quality factor is beneficial for achieving large vibration amplitudes. On the other hand, systems with high quality factors offer a narrow bandwidth only. Thus, control is more challenging, and robustness against load fluctuation and outside influences is reduced.

A better measure for controllability, robustness and capability to transfer power is the product of the mechanical quality factor and the square of the effective coupling coefficient. The dependency of this product on the amount and the position of piezoelectric material within a Langevin tranducer that is freely vibrating in its first longitudinal mode is shown in Fig. 6. The optimum value is reached if the piezoelectric elements are placed in the middle and if they cover one third of the transducer length. Almost the same behavior applies if the transducer acts against medium and strong loads, such as radiating into water or plastics welding.

IV. CONCLUSIONS

In conclusion, the placement and the amount of a piezoelectric material within composite structures have been discussed from various aspects. For the widely-used bolted Langevin transducer, an analytical model has been used to find an optimum setup. The amount of the piezoelectric material that is needed always depends on the amount of power that is needed within the application. If the transducer is used to generate a high acoustic pressure in air, the piezoelectric elements should ideally be placed at the back of the transducer. Due to fabrication needs and the pre-stressing of the piezoelectric ceramics, a trade-off solution could be to place the piezoelectric ceramic elements as close to the transducer's back as possible. For high-power applications, *e.g.* plastics welding, the piezoelectric material should cover one third of the $\lambda/2$-transducer in the middle of the transducer.

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