

PIEZOELECTRIC POWER CONVERSION WITH SELF-INDUCED OSCILLATION

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Abstract: This paper reports the simulation, design, fabrication, and testing of piezoelectric cantilever generators as electrical power sources for autonomous sensors and sensor nodes. Three...nine cantilevers are arranged in rows one beside each other. All of them are operating in a streaming flow. Bluff bodies in front of the cantilevers lead to vortices in the streaming. These vortices are connected with a pressure lower as the surrounding area. Hence, cantilevers will be forced to deflect into the low pressure region. Due to noticeable resetting spring forces cantilevers starts to oscillate. Some tests have been carried out in air, others were done in water. Cantilevers oscillate in air with their first Eigenfrequency. A synchronized oscillation was found for cantilevers in a water stream. Electric power generated in the cantilevers was processed in an electric circuitry. This circuitry is supplied with energy by the cantilevers and it is used to feed an external electric load.

INTRODUCTION

Piezoelectric power converters require for continuous energy conversion a continuous movement of an active piezoelectric element. Therefore, most research groups have focused their harvesting strategies to sources which deliver continuous mechanical vibration [1]. Power conversion is only efficient if the frequency of the source is well adapted to the resonance frequency of the vibration converters. Unfortunately, vibrations can be observed often in a very wide frequency range. These basic thoughts have driven us to find other solutions independent from the frequency of an external source. We have focused our investigations to possibilities of converting kinetic energy of a streaming medium into electrical energy. Basic condition of the conversion should be a simple

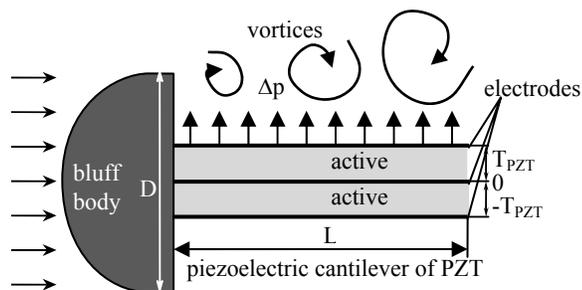


Fig. 1: Scheme of a piezoelectric cantilever in a streaming medium

mechanical movement without any rotation since rotational movement requires normally a lot of maintenance. First we thought about devices like "Mouth Blown Free Reed Instruments". Reeds oscillate in these instruments when a gas flow exists. Unfortunately, these systems are not fault tolerant against particles in the streaming. This becomes more

important the smaller the reeds are. Therefore, we have pursued a way which should overcome all described disadvantages above. In our mind we had extremely miniaturized flags fluttering in the wind with the first basic oscillation. Fluttering of a flag is caused by the flagpole due to the development of so called von Kármán's vortex streets. If it succeeds to generate vortices in much smaller dimensions, one could work with oscillating reeds without any limitations. Instead of the flagpole we have introduced a bluff body. Hereby, the bluff body supports the flag and serves as a flow disturbance. As flag acts a piezoelectric cantilever connected with one end onto the bluff body. While the bluff body stays fix an oscillation of the free end of the cantilever can take place in a media flow caused by von Kármán's vortex streets. An example of this thought is shown in Figure 1. Each single cantilever consists of minimum two piezoelectric plates including their electrode layers bonded together (Bimorph). Upward deflection leads to compressive stress in the top plate and simultaneously to tensile stress in the bottom layer. Since stresses polarize piezoelectric materials charge separation will occur and a voltage will be built up between the electrodes (top-middle or bottom-middle). A suited circuitry allows for taking off a voltage two times higher as produced by one piezoelectric layer.

Bending forces perpendicular to the streaming direction are not available in regular flows. The flow is laminar and cantilever oscillations as reason for the energy conversion will not occur. Behind a flow disturbing body vortices will emerge and one can observe a "von Kármán's Vortex Street". Pressure drops Δp emerges close to the whirls since their

streaming velocity is higher as the surrounding flow. These low pressure regions induce deflection forces across the piezoelectric cantilever. Von Kármán's vortex streets are stable at Reynolds-Numbers between $Re=50 \dots 10\,000$. Vortices become more and more stochastically and the flow turns to fully turbulent when a critical Reynolds number is reached. Best energy transfer conditions can be found with microscopic vortices existing in turbulent flows as in von Kármán's Vortex Streets. Therefore, an increase of energy conversion efficiency can be achieved with reduced dimensions of the cantilevers. It is obvious that only a combination of a multitude of piezoelectric cantilevers, each with small dimensions can lead to a noticeable power generation.

FINITE ELEMENTS ANALYSIS

Piezoelectric harvesters have been considered by means of a FEM analysis (COMSOL). Goal of the simulation was to get information about the optimal shape of the bluff body. Furthermore, the simulation should deliver parameters for an optimally arrangement of several cantilevers in a closed surrounding.

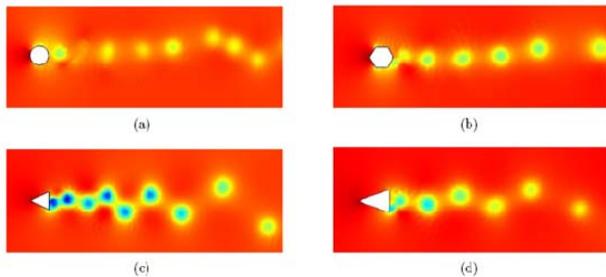


Fig. 2: Pressure development of different bluff bodies @ an air streaming velocity of 10m/s

Figure 2 shows the development of the pressure in a streaming media behind a bluff body. One can see different shapes and low pressure regions developing behind the bluff body. While the pressure in the streaming medium is colored red one can see yellow to blue colored low pressure regions, too. Best results in terms of periodicity and value of the low pressure can be found with solution c). Circular shaped cross sections a) of the bluff body show a not calculable behavior. In general it was found that best results can be achieved if the bluff bodies possess a very sharp tear-off-edge similar to c) and d). Transient simulations have also shown, that vortices generated from bluff bodies arranged behind each other can amplify the development of vortices of following bluff bodies.

DESIGN CONSIDERATIONS

Important for energy conversion are the dimensions of

the cantilevers in combination with the dimensions of the bluff body. Both dimensional values are not independent.

The characteristic dimension D of the bluff body can be calculated with the Reynolds-Number Re and physical properties of the medium (η - dynamic viscosity, v_e -velocity, ρ -density)

$$D = \frac{Re \cdot \eta}{v_e \cdot \rho} \quad (1)$$

Applying this equation for water with a flow velocity of 2 m/s one can achieve for D a value-range of

$$D = 25 \mu\text{m} \dots 5 \text{ mm}.$$

Cantilevers would oscillate not only in the first harmonic mode if they are long enough. Higher oscillation modes could lead to a balancing in charges in one layer and thus no electric voltage at the corresponding electrodes [2]. Therefore, it is essential to reduce the length of the cantilever L to half of the vortex-tear-off-wavelength. Under these circumstances one can find an expression for the optimal L to D ratio[3].

$$\frac{L}{D} = 2.125 \quad (2)$$

Cantilevers with a shorter Length L would not deflect with sufficient amplitude. Longer cantilevers would not deliver a voltage due to the neutralization of charges.

EXPERIMENTAL SETUP

In our experiments we have used different types of harvesters. In a first series three cantilevers were arranged in a row and fixed on a mechanical construction that acts as bluff body, too (Figure 3). Electrical connections inside the bluff body have been realized before a molding procedure was carried out. PDMS was used as mold material. This enables also examinations in fluidic solutions. Piezoelectric plates used were available on market. These plates have not

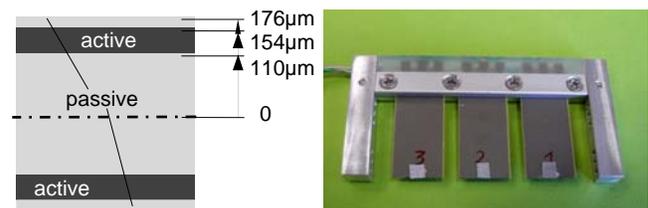


Fig. 3: Plates of the first series; active thickness: 88µm; arrangement in a row

fulfilled the requirements for harvesting purpose. The internal structure of the plates is shown in figure 3. Each plate consists of 5 ceramic layers and 4 metal layers as electrodes. Active piezoelectric material

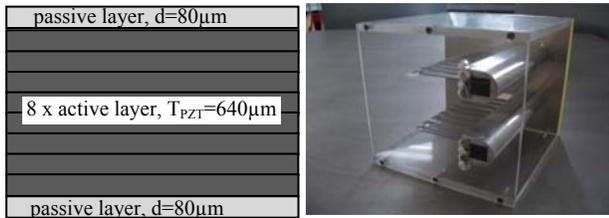


Fig. 4: Piezoelectric cantilevers of the third series and their arrangement in 2 rows

exists in two small layers only. The rest of the material possesses no piezoelectric properties. The relation between active material and passive material is about 1:3. Three of these combinations were arranged behind each other at the same height in flow direction. A carrier construction was used that allows also an arrangement of the rows in different heights. We have reduced in a second series the length of the piezoplate by increasing the overlapping zone of the bluff body. This is possible since the tear off edge is responsible for the development of vortices. In a third series other cantilevers were used. Their internal structure consists of 10 layers (Fig. 4). Two of them are not piezoelectric active. However, bluff bodies have been designed in two cases in agreement with equation (2). Different experimental setups are shown in the table.

	Series 1	Series 2	Series 3
L/mm	22	22	38
D/mm	10.35	4.35	18
W/mm	11.8	11.8	6
T_{PZT} /mm	0.088	0.088	0.64

Bluff bodies in the second series were not in agreement with equation (2). This mismatching was considered to verify the theoretical assumptions. Measurements have been carried out in artificial air and water channels. Cantilevers of series 1 and 2 were used in both media. Cantilevers of the third series were used in air stream only. Voltage and oscillation frequency generated by each cantilever were



Fig. 5: Measurement set up in air (left) and water (right)

measured simultaneously. Typical measurement arrangements are shown in Figure 5. Left hand side is a top view of the harvesting unit positioned in an

channel. Right is shown a side view of the cantilever carrier in a water channel during an experiment.

RESULTS

Main results of our considerations are described in the following. Differences in power conversion can be found comparing series 1 and 2. For the case of power adjustment one can find a better conversion in series 1. This verifies the model assumptions and especially equation (2). It indicates furthermore that shrinking of the characteristic dimension D requires a shrink of the length L too for optimized power conversion. Voltage

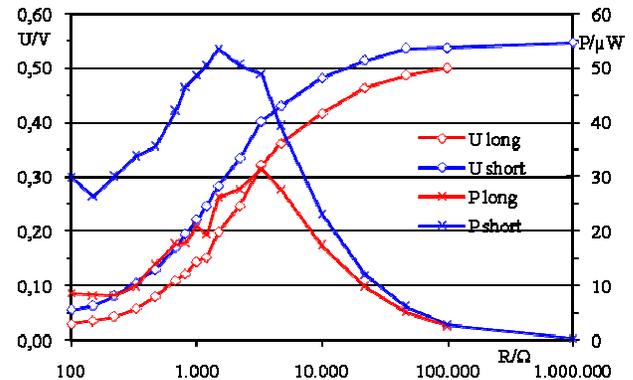


Fig. 6: Voltage and Power conversion depending on the external load with cantilevers of series 1 and 2; air, $v=40\text{m/s}$

and power generated in a single piezoelectric layer are shown for different values of an external load (Figure 6). The index “long” stands for series 2 and index “short” represents series 1. The first piezoelectric

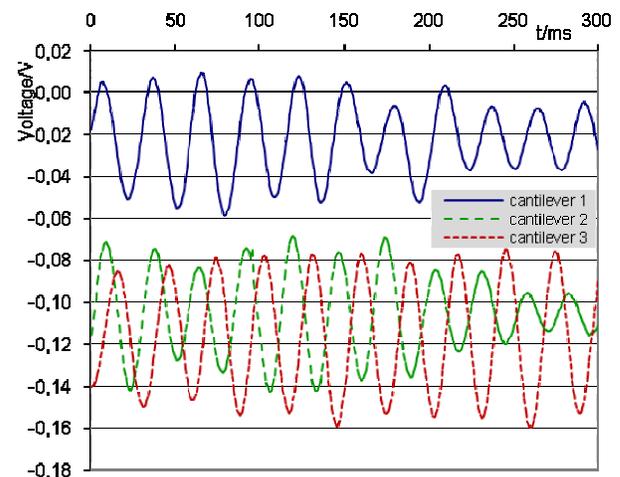


Fig. 7: Oscillation of 3 cantilevers in a row @30m/s in air

layers of cantilevers of series 3 deliver about the double voltage of series 1 under same streaming conditions. This makes stapled piezoelectric plates for power conversion more attractive. One of our main interests was the oscillation behavior of different

cantilevers. Synchronized oscillation would lead to a comfortable and very simple electric circuitry. Figure 7 shows this behavior for series 1 in air at a velocity of 10m/s. First one can observe a sinusoidal oscillation of all cantilevers. All wavelengths appear to be a little bit different. This slight difference results from differences in the Eigenfrequency of the cantilevers. A synchronized oscillation seems to be not easy to achieve. One can see furthermore, that cantilever 1 shows much lower output voltages as the other cantilevers. Reason for that was an internal break of on electrode layer. After exchanging the behavior of all cantilevers was comparable. Testing the same cantilevers in water led to a surprising behavior. As shown in Figure 8 we have observed a completely synchronous oscillation behavior of all

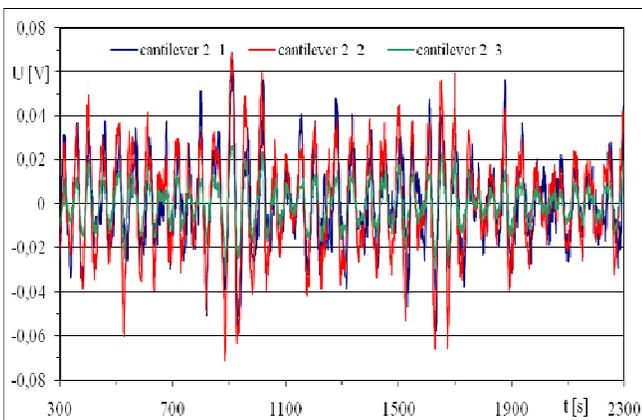


Fig. 8: Oscillation of 3 cantilevers in a row @0.8m/s in water

cantilevers considered. Water as a coupling medium leads obviously to a mechanical coupling of the cantilevers in a row. The time scale indicates, that the frequency is reduced in water noticeable. Reasons for that behavior can be found in damping effects. However, the results in water show the possibility of a synchronized oscillation of cantilevers in streaming

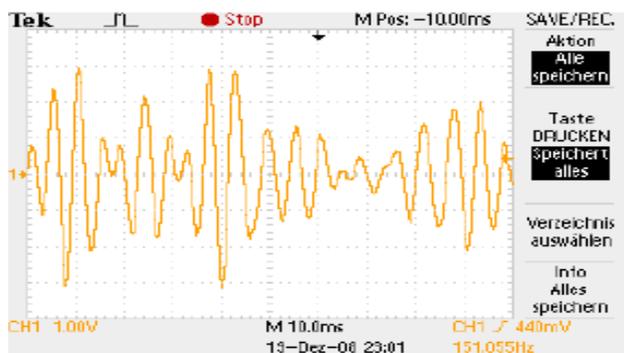


Fig. 9: Snap shot of voltage generation of 9 cantilevers in serial @8m/s in air; Scaling: horizontal $1\text{square}=1\text{ms}$ vertical $1\text{square}=1\text{V}$

media. This is very important as it allows the built up

of harvesters with a simple electronic circuitry. It is very interesting that the voltage generated in water show nearby the same value as it was found in air although the streaming velocity differ massively in both experiments. Liquids with much higher densities as gases are therefore very promising in terms of power conversion using the principle described.

Power Generation with the third series of cantilevers is more effective as with cantilevers of the other series. More active piezoelectric material can be used for converting. Voltage values of up to $U_{pp}=0.6\text{V}$ (peak to peak) have been achieved at comparable low streaming velocities. Cantilevers of the first series have shown first noticeable voltage values ($>10\text{mV}$) at streaming velocities above 15m/s. Figure 9 shows a snap shot print of the Voltage generated from 9 cantilevers connected in serial at a streaming velocity of about 8m/s. The oscillation frequency in this figure is an average of the oscillation of all cantilevers. Nevertheless, we have found during these experiments very long periods of synchronized oscillation of all cantilevers. Sometimes the synchronized oscillation was interrupted but the system itself went back into the synchronized mode. Power generated in this system was stored in a capacitor. The energy of the capacitor was used for supplying an external load and a circuitry connecting the capacitor with the load with energy. Energy converted by this system is sufficient for supplying sensors logical circuits and wireless data transmission circuits, too.

CONCLUSION

Piezoelectric harvesters can convert the energy of streaming media due to self induced oscillation. The smaller the converters are the better is the efficiency of power conversion. The internal structure of the cantilever and their geometrical dimensions in relation to the bluff are important for the amount of power to be converted. Cantilevers arranged in a row oscillate synchronous in water and under defined conditions in gases, too.

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