A new micro hydro power device

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ABSTRACT

Two possible designs are presented for the generation of electrical energy using the kinetic energy of flowing rivers. Both designs are connected with a turbulent flow or other hydrodynamic instabilities like a von Kármán's vortex street. The first is a fluttering flag made of a piezoelectric material, which follows the turbulence hence, bending periodically. Electrodes on the surface collect the generated charges.
Secondly a microstructured piezo-bimorph is presented. It is connected with a paddle that also bends in a turbulent flow.

Keywords: piezoelectric generator, PVDF, Kynar, PZT, bimorph, kinetic energy, turbulent, von Kármán's vortex street

1 INTRODUCTION

The use of renewable instead of fossil energy resources becomes more and more important in the next future. A lot of investigations have been done in the past to use the natural energy of wind. Unfortunately, windmills can deliver energy only when the wind is blowing and not when energy is really needed. Therefore, wind energy always has to be buffered by a power distribution network and/or wind power plants in other regions. Waterpower has an advantage because of its ability to produce energy continuously. Usable recourses are limited with common technologies [1]. Furthermore, these resources are not sufficient in several regions.
We have focused our research to new principles of converting energy by means of microstructured components. It is possible to extend the usable water power recourses by converting the kinetic energy directly, similar to wind turbines, instead of using the potential energy as known from common water power stations.

2 AVAILABLE ENERGY

The kinetic energy of flowing water depends in a huge manner on the flow velocity v_∞ and is continuously available in almost every flowing water. It can be estimated using the following Formula [2]:

$$E_{max} = \frac{\rho}{2} \cdot A \cdot v_\infty^3 \cdot c_B \qquad (1)$$

Where ρ is the density of water, A the cross section of the generator, v_∞ the flow velocity of the river. The Betz-Number c_B introduces the flow velocity before (v_1) and after (v_2) the generator:

$$c_B = \frac{1}{2} \cdot \left(1 - \frac{v_2^2}{v_1^2}\right) \cdot \left(1 + \frac{v_2}{v_1}\right) \qquad (2)$$

With a velocity relation of 3 to 1 the theoretical maximum value of the Betz-Number of 0.592 is achieved. Practical values are in the range of 0.35 – 0.45. Thus the usable kinetic energy of a river with a flow velocity of 2m/s can be calculated to about 1.6kW per cross sectional square meter.
The maximum theoretical Power conversion factor of a piezo ceramic transducer in transversal configuration is given by [3]:

$$\eta_{max} = \frac{k_{31}^2}{2\sqrt{1 - k_{31}^2}} \qquad (3)$$

For available PZT material (PSI-5A-S3, Piezo Systems, Inc. [4]) this would be 6.1%. Using this piezo ceramic material a Power of about 90W/m^2 could be achieved theoretically.
We have designed and modelled two types of power converters. Deviating from turbines or propellers the developed designs have no rotating parts that need maintenance. They consist only of elastically deformable parts without any sliding or rolling friction.

3 FLUTTERING FLAG DESIGN

The first design is a fluttering flag made of a piezoelectric polymer material. These flag flutters because of the turbulence caused by the bar where the flag is fixed. Under certain circumstances this turbulence can form a von Kármán's vortex street in which the flag is moving (see Figure 1). Vortexes separate alternating from both sides of the bar and travel downstream resulting in different flow velocities on both sides of the flag thus a pressure difference occurs. Driven by this pressure difference the flag moves towards the lower pressure resulting in bending. With the downstream travelling of the vortexes the bend areas moves downstream too causing reverse bending.

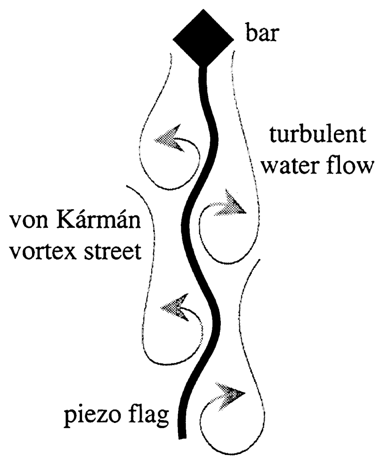

Figure 1: moving flag in turbulent flow regime

The flag consist of two layers of the piezoelectric polymer PVDF with an electrode in-between. During bending one side is stretched while the other one is compressed. These mechanical deformations lead to a charge separation inside the piezoelectric material. Striped electrodes that are applied at the foil surface collect the charges (Figure 2). Opposite electrodes are connected electrically. The d_{31}-coefficient of PVDF is very low (18-20pC/N) [5] compared to piezo ceramic materials (180pC/N). Assuming electromechanical coupling constants between 0.12 and 0.2 [6] the maximum power conversion factor (Eq. 3) for PVDF varies from 0.7% to 2%.
This type of generator could be produced easily and cost effective.

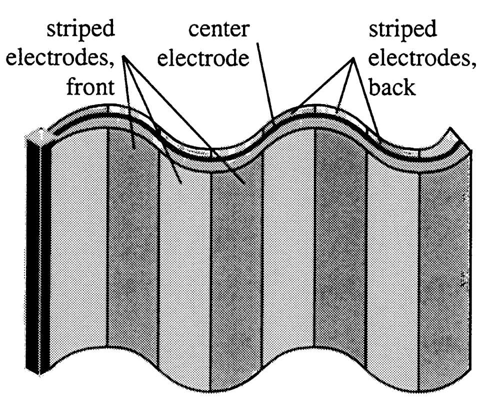

Figure 2: electrodes on the flag surface

4 BIMORPH PADDLE DESIGN

The second design is a generator, which consists of a piezoelectric bimorph membrane connected with a paddle.

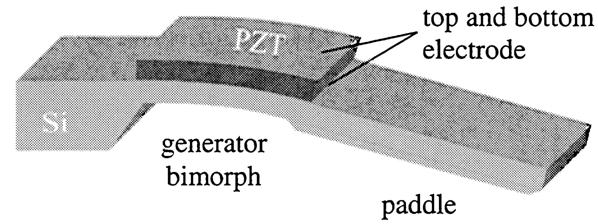

Figure 3: 3D view of the bend micro generator.

The bimorph and the paddle are located inside the water flow that the water flows over the surface of the paddle. For proper function of the device the flow must be turbulent again. This is possible with the natural turbulence of the river or better with turbulence inducing arrangements like a bar in front of the generator. Flow velocity components perpendicular to the mean flow direction, as usual in turbulent flow regimes or different flow velocities on top and bottom of the paddle, produce forces on the paddle in vertical direction as shown in Figure 5. These forces bend the bimorph and a charge separation occurs. The design is shown in figures 3 and 4.

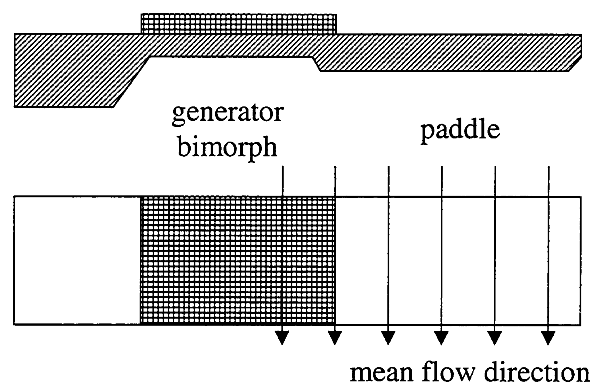

Figure 4: cross sectional and plan view

Following assumption have been made to calculate the electrical energy generated in a piezo material in bimorph configuration deflected by an external force:

- The neutral plane of the bimorph is at the interface between the support material and the piezo ceramic thus giving the maximum efficiency.
- Bending is limited by the tensile strength of the ceramic.

So the maximum electrical energy E_{el} of a rectangular piezo bimorph for the maximum deflection in one direction can be calculated by the following equation [7]:

$$E_{el} = \frac{1}{8} \cdot K_3^T \cdot \varepsilon_0 \cdot \sigma_{max}^2 \cdot g_{31}^2 \cdot w \cdot l \cdot t \quad (4)$$

Where K_3^T is the permittivity ratio of the material, ε_0 the permittivity of free space, σ_{max} the maximum tensile strength, g_{31} the piezoelectric voltage coefficient and the dimensions w - width, l – length and t – thickness of the piezo ceramic. To achieve the maximum value of the electrical energy E_{el} a force of

$$F_{max} = \frac{2}{3} \cdot \sigma_{max} \cdot \frac{w \cdot t^2}{l} \quad (5)$$

has to be applied at the end of the bimorph section.
Using these equation for a bimorph made of the previously mentioned materials (k_3=1800, σ_{max}=21Mpa, g_{31}=-11.5mVm/N) with the dimensions of l_{PZT}=6mm, w_{PZT}=3mm and t_{PZT}=50μm an electrical energy E_{el} of 0.1μJ can be achieved with a force of 18mN neglecting dielectric losses. The force can be produced either by a different flow velocities (Eq. 6) on (v_1) and below (v_2) the paddle or by flow components perpendicular to the paddle (Eq. 7) and can be roughly calculated for both cases as follows

$$F_{P1} = A_P \cdot \frac{\rho}{2} \cdot \left(v_1^2 - v_2^2\right) \quad (6)$$

$$F_{P2} = c_d \cdot A_P \cdot \frac{\rho}{2} \cdot v_\perp^2 \quad (7)$$

Where A_P is the area of the Paddle and c_d the drag coefficient which varies with the shape of the paddle in the desired region between 1.0 and 1.2 and $v_\perp$ the velocity component perpendicular to the paddle surface. With the force of 0.18mN and a flow velocity relation 1 to 2 at a mean flow velocity of 2m/s a paddle area of 12mm^2 is necessary to achieve the desired force. At a given width of the paddle of 3mm the length have to be 4mm. Setting this area in Eq. 7 give a force of 2.7mN at a flow velocity $v_\perp$ of 2m/s.

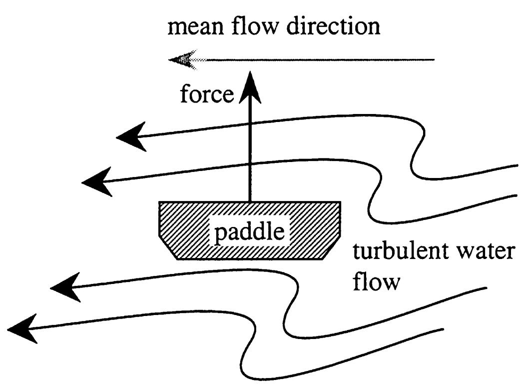

Figure 5: water flow and force

The energy of 0.1μJ is generated during the movement from the neutral to the maximum deflection. Twice the amount is generated between the positive and negative maximum deflection as usual during oscillation.
In order to take as much as possible power out of the piezoelectric material, high deformation rates are necessary. Therefore, small structures with low inertia's and high resonant frequencies are necessary which are preferably made using micro technologies. Assuming an oscillation frequency of 25Hz a power rating of 5μW excluding the dielectric losses and power dissipation in the rectifier can be realised with one structure.

5 SYSTEM DESIGN

Collecting these charges and rectifying with a high efficiency rectifier the output voltage must be converted to a usable value. The overall efficiency depends on the rectifier and voltage converter too. The development of these electronic devices will be done soon.
To create a micro power plant with usable power rating a lot of these small micro generators have to work in parallel. Due to this parallelisation the reliability can be strongly increased in comparison to a single device. The micro power plant can be installed in a ship like vessel that is anchored in flowing water whereby the water passes the power plant. Thus expensive construction works as usual with common hydropower plants that also effects the environment can be saved and the micro power plant stays mobile.
Up to now the designs are on a theoretical base and will be verified by experiments in the next step.

6 CONCLUSIONS

The presented ideas showing a new approach for broaden the usable hydropower recourses with micro generators using the piezoelectric principle. The advantage of both designs is the absence of rotating elements thus maintenance free devices are possible. Some simplified calculations have been made to estimate the power range. For the bimorph-paddle design with over all dimensions of height=2mm width=4mm length=10mm a power rating of about 5μW can be achieved theoretically in a volume of 80mm^3. With other dimensions or preferably multiple elements the power can be increased. The calculated power density using these converters is in a range of about 62W/m^3. Although this value seems to be very low one has to take into account, that these kinds of power converters without any maintenance could be very attractive in combination with other alternative power sources
The results will be proved by experiments in the near future.

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