POWER HARVESTING FROM HUMAN WALKING

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Abstract: This paper presents a device for power harvesting from human motion. Piezoelectric disc benders as functional part are sensitive to low frequency mechanical stimuli and aperiodic excitation. A numerical model in ANSYS serves as a design tool to specify the disc benders for different load applications. With the performance of 1.3 mW from 1 Hz stimuli, the generators are powerful to drive small integrated circuits in wearable self-powered systems. The generators allover thickness of 4 mm approves the simple implementation into the base of shoes. Low cost parts and a simple set-up were chosen to facilitate the latter realization as industrial product.

Key Words: energy harvesting, wearable power generator, piezoelectric

1. INTRODUCTION

The ascent of miniaturization and performance enhancement has transformed wearable electronics to our ubiquitous daily attendant. Li-Ion rechargeable batteries are state of the art to power such hand–held devices, e.g. mobile phone, PDAs. However, the growth of battery technology has remained stagnant compared to electronics in the last decade, as stated in [1]. Since the range of our new freedom is limited by the frequent act of recharging a battery a basic question arises: Is there an alternative to storage-based power supply? In fact, the most discussed issue is where to get the power from.

Apparently, power has to be gathered from the users environment or from the user itself to maintain full mobility. For this purpose, energy harvesting from mechanical forces appears as a promising candidate. Among the force transducing materials, PZT and PVDF are the top performers for power harvesting applications [2]. Starner [3] and later Niu [4] investigated the energy available from human body motions. The heel strike was found as the most powerful and most simply accessible source. In the following years shoe-mounted power generators based on piezoelectric materials were presented by Kymissis [5] and Shenck [6]. A different concept was chosen by Prahlad [7] using dielectric elastomers a the heel strike generator. All of them achieved very competitive power outputs of several mW. A closer look evidences, that the expensive parts of theses generators and their complicated set-up makes them to experimental devices. With the spread of self-powered devices in daily life in mind, cost effective parts and a simple and modular design are required. This work presents the design and fabrication of a piezoelectric heel strike generator that can be easily turned into an industrial product.

2. DESIGN

Functional part of our generators are PZT steel composite discs (see Figure 1), which feature a good performance at low costs and are available in numerous sizes. With regard to the working principle of the piezoelectric effect, a high stress in the PZT layer is desirable. Engineering mechanics shows that the highest stresses occur in the plane of a bended composite structure. The output for a clamped and pressure-loaded plate was investigated by Kim [8-9]. In order to avoid such complex treatment and to retrieve the

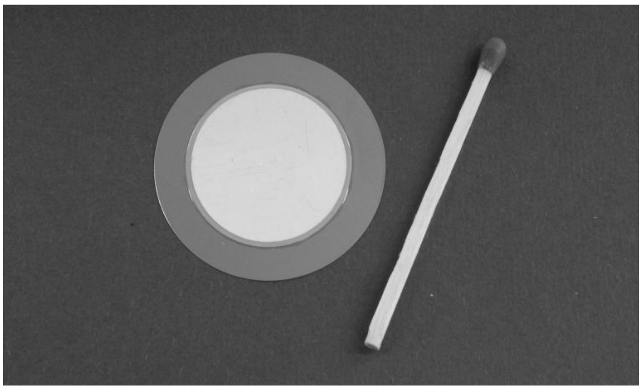

Fig. 1: Photograph of a piezoelectric disc bender.

maximum energy, we have chosen a roller support instead. Through its two degrees of freedom at the circumference (see Figure 2), the piezo discs can uniformly contract under loading and a larger deflection and a uniform curvature are achieved. The second and as well important advantage is the simple mechanical implementation of the support. The disc is placed into a staged cylinder. Under loading, the disc slides over the edge which forms a roller like bearing.

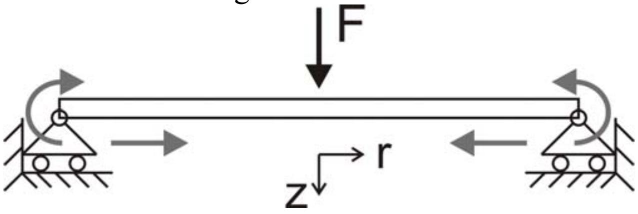

Fig. 2: Degrees of freedom of the roller support.

This design has been verified and optimized with a reliable theoretical model. Although the set-up does not look too different from the simple Kirchhoff plate theory, a major assumption is not satisfied. Through the possible shift in r-direction the diameter remains not constant. For this reason analytical theories can not be adopted to describe the generator. Additionally, the retro action of the generated voltage on the deflection is not considered. Therefore numerical simulation tools were used to model the piezoelectric device. The 3D coupled-field analysis was performed in ANSYS. Solid226 was used for PZT (assuming to be orthotropic) and solid95 for the steel sheet. A 10 degree section was created and meshed with 20 node bricks. For applying the roller support, we have constrained the z-displacement of the discs circumference at the supporting circle.

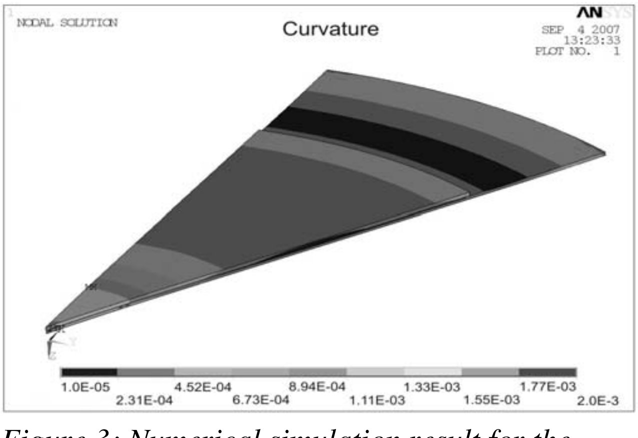

Figure 3: Numerical simulation result for the plate's curvature.

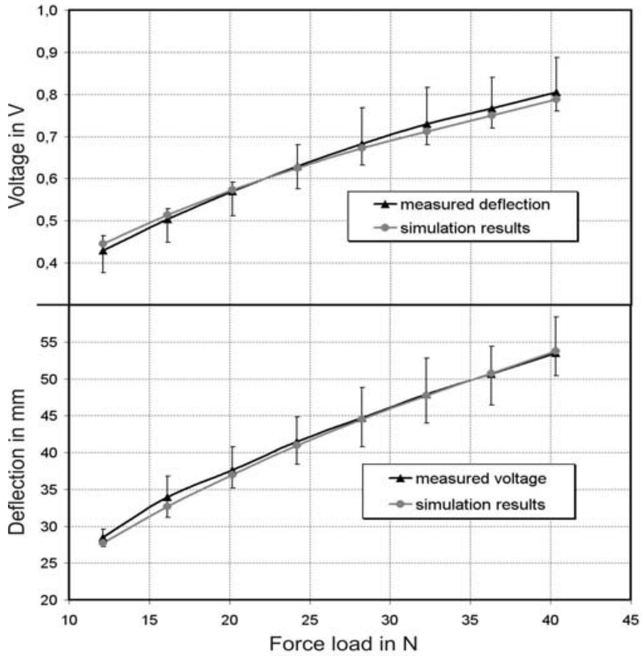

Figure 4: Comparison of the results from the numerical simulation with measured values of deflection and voltage.

Additionally, the center point motion was restricted to the z-direction to prevent the plate of shifting sideways. Figure 3 depicts the curvature results on the modeled disc section. The center displacement and the generated electrode potential were calculated. Figure 4 shows the comparison of the numerical results with measurements. Due to the good coincidence, the numerical model can serve as a tool to specify the disc benders for different load cases, and furthermore to predict the generated charge. In order to ensure a reliable operation the maximum deflection for a maximum strain of 0.35% ([10]) was determined from the numerical analysis, and incorporated into the housing design.

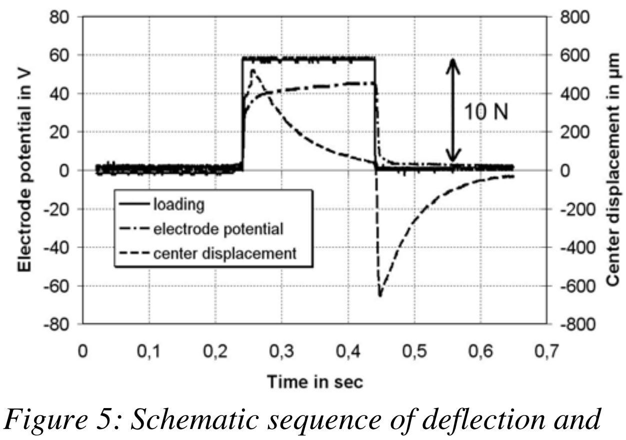

Figure 5: Schematic sequence of deflection and electrode potential for one load pulse.

Since the device forms a power generator, all optimizations are focused on the enhancement of the power output. The “environment” was optimized by the choice of the roller support. However, also the generator has to be treated. Basically the disc bender can be seen as capacitor with a time-dependent charge. The stored charge grows linear with the capacitors surface area. For this reason multilayer disc benders were fabricated by gluing together single discs and intermediate electrodes periodically.

4. EXPERIMENTAL

For the basic investigations discs consisting of a 120 µm PZT layer with 25 mm diameter sintered onto a 100 µm steel shim with 35 mm diameter were used. The loading conditions from the pneumatic actuator are: F = 10 N, on-time = 0.2 sec, frequency = 1 Hz. First, the resulting deflection is detected with a laser distance sensor and second, the generated voltage is monitored on an oscilloscope. The sequence for one load pulse is depicted in Figure 5. It can be seen, that the electrode potential should be relaxated during the constant displacement to retrieve the full backward voltage from the step back into the non-deflected state. Under ideal conditions, both phases will deliver the same amount of energy.

To confirm the performance enhancement of a multilayer set-up, the output power of different layered generators was evaluated. For the reason of comparison, the load was adjusted in such a way that all generators show the same deflection. So the load is averaged to 10 N per layer. From

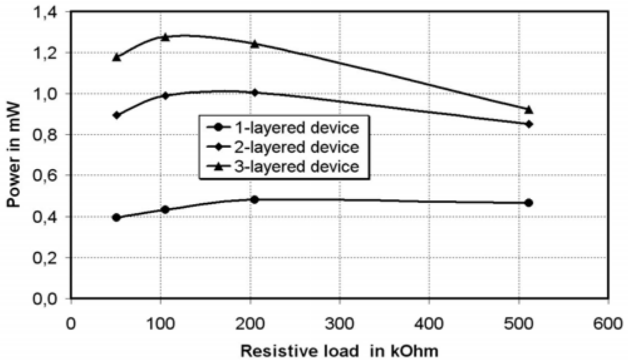

Fig. 6: Comparison of the output power versus resistive load of generators with different number of layers.

Figure 6 which displays the results, it can be seen, that output power increases in accordance to the theory by the layer number. Next, the generators capability to charge a 1000 µF capacitor was determined. A passive full bridge rectifier with 1N5804 diodes was used to demodulate the voltage. Figure 7 shows the charging sequence of the capacitor for different resistive loads. The detail graph shows the rise of the capacitor voltage for the first few steps.

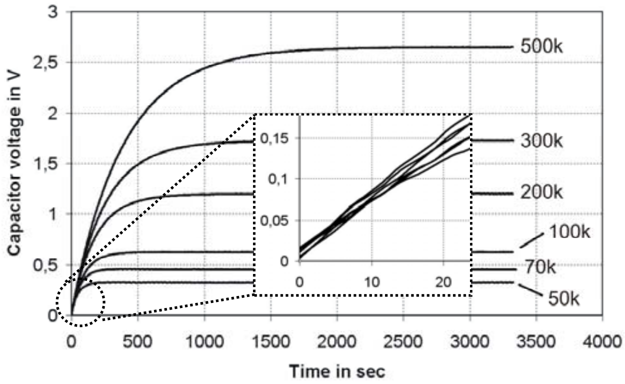

Figure 7: Charging sequence of a 1000µF capacitor with different resistive load.

3. DISCUSSION

During the design, attention was paid to meet the maximum output with a set-up as simple as possible. By the choice of the roller support, the largest possible disc deflection and a uniform curvature are achieved. At the same time the support is easy to fabricate since no complex bearing is necessary. With this functionality our generator overcomes the set-up of [8,9] by multiple. A possibility to further increase the output power is to optimize the area relation between PZT and base. Compared to other shoe-mounted energy harvesting devices, the functional part is commonly available, cost effective and durable. The whole set-up is simple and contains only a few parts.

A numerical model was developed to serve as design tool to predict the generated voltage. As shown in Figure 4, the curvature values have only one sign. This proofs that the curvature is homogeneous as preset by the mechanical design of the generator. Accordingly only charges of one polarity occur on each electrode and internal shortcut currents are avoided. The excellent accordance between the numerical results and the measurements is shown in Figure 3. Furthermore, to specify the disc benders for different load conditions, the limits of load and deflection were determined. The attained values were utilized for the housing design to ensure a durable operation. The deflection is limited by the cavity depth of the support. Figure 8 shows an assembled generator in a lab-housing. Both parts of the housing can be fabricated by injection molding which supports the industrial realization.

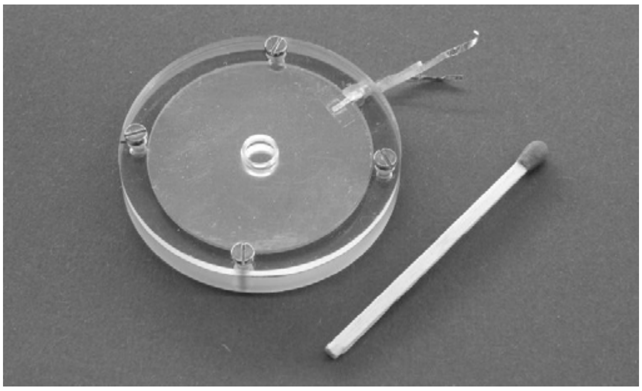

Fig. 8: Assembled generator in a lab-housing.

The measurement results for the output power in Figure 6 indicate the efficiency of our generator. With 1.3 mW at 1 Hz the current performance is slightly below the value of [6-8], but finally, the energy density of our generator overcomes these alternative solutions since we only use one slim generator. The detail in Figure 7 shows that for the first 10 load pulses the capacitor voltage is independent from the resistance load. The average charge per load cycle harvested in this period is calculated to $8*10^{-5}$ As. In the open circuit state, $3*10^{-4}$ As are generated. Improvements can be made by using an active bipolar or CMOS rectifier which reduces the voltage drop at the rectifier to less than 100 mV, thus making the capacitor voltage will faster and higher. To supply an attached circuit a buffer capacitor with not more than 50 µF should be switched between the bridge rectifier and the circuit. In this configuration the buffer voltage will increase to several volts, which is sufficient for low power electronics.

4. CONCLUSION

The introduced generator states above a prototype and the realization as industrial product is facilitated through its smart modular design and the use of low cost parts. Beside the major application as power supply for wearable electronics, the generator can operate as self-sufficient sensor. For instance as an impact messenger for patients wearing orthotics it might ensure a faster healing of injuries of the lower limbs, e.g. fractures and tendon cracks.

REFERENCES

[1] J.A. Paradiso, T. Starner, "Energy scavenging for mobile and wireless electronics", *IEEE Pervasive Computing*, Vol. 4, pp. 18-27, 2005

[2] S.R. Anton, H.A. Sodano, "A Review of power harvesting using piezoelectric materials (2003-2006), *Journal of Smart Materials and Structures*, Vol. 16, pp. R1-R21, 2007

[3] T. Starner, "Human powered wearable computing", *IBM Systems Journal*, Vol. 35, pp. 618-629, 1996.

[4] P. Niu, P. Chapman, R. Riemer, X. Zhang, *Proc. 35th IEEE Power ElectronicsConference*, Aachen, pp. 2100-6, 2004

[5] J. Kymissis, C. Kendall, J. Paradiso, N. Gershenfeld, "Parasitic power harvesting in shoes", *Second IEEE Conf. Wearable Computing*, Los Alamitos, pp. 132-139, 1998.

[6] N. S. Shenck, J.A. Paradiso, "Energy scavenging with shoe-mounted piezoelectrics", *IEEE Micro*, Vol. 21, No. 3, pp. 30-42, 2001.

[7] H. Prahlad, R. Kornbluh, R. Pelrine, S. Stanford, J. Eckerle, S. Oh, "Polymer Power: Dielectric Elastomers and Their Applications in Distributed Actuation and Power Generation", *Proceedings of ISSS 2005*, pp. 100-107, Bangalore, India, 2005

[8] S. Kim, W. Clark, Q-M. Wang, "Piezoelectric Energy Harvesting with a Clamped Circular Plate: Analysis", *Journal of Intelligent Material Systems and Structures*, Vol. 10, No. 10, pp. 847-854, 2005

[9] S. Kim, W. Clark, Q-M. Wang, "Piezoelectric Energy Harvesting with a Clamped Circular Plate: Experimental Study", *Journal of Intelligent Material Systems and Structures*, Vol. 16, No. 10, pp. 855-863, 2005

[10] M. Gall, B. Thielicke, Ch. Poizat, "Experimentelle und numerische Untersuchung zur Lebensdauer von flächigen PZT-Funktionsmodulden", *15. Symposium Verbundwerkstoffe und Werkstoffverbunde*, Kassel, pp. 427-432, 2005