INCREASED POWER OUTPUT FROM PIEZOELECTRIC ENERGY HARVESTERS BY PRE-BIASING

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Abstract: This paper presents, for the first time, experimental results demonstrating a new approach to increasing the power output of piezoelectric energy harvesters by applying a bias charge at the beginning of each half cycle of motion. Ultimate power limits of inertial energy harvesters depend only on the device size and nature of the excitation, rather than on the transduction mechanism. However, practical devices generally perform well below the theoretical limit, often because a sufficiently high transducer damping force cannot be achieved. For such cases, we show that the generator effectiveness is improved by a pre-biasing technique, and present simulation results with experimental verification. These results show that the effectiveness of the piezoelectric generator is improved by more than 10 times compared to an optimised purely resistive load. In practice our gains were limited by the voltage breakdown of the components used.

Keywords: Energy harvesting, pre-biasing, piezoelectric

INTRODUCTION

Piezoelectric transduction is very popular for inertial energy harvesters [1], but due to low electromechanical coupling the achievable electrical damping forces are low. When a microgenerator must operate with a low ratio of Z_l/Y_0 the electrical damping must be high in order that the proof mass does not hit the generator end-stops so that the maximum possible power density can be achieved [2]. Piezoelectric transducers operated with a resistive load are generally unable to provide sufficient damping force under such circumstances [3]; this limitation is primarily caused by the intrinsic shunt capacitance, which limits the real power transfer capability of the transducer into a resistive load. Several techniques have been proposed to overcome this limitation, such as the SSH techniques described by Guyomar [4]. In this paper we present a generalised solution to previously presented work and show that by using a combination of pre-biasing and synchronous charge extraction a significant improvement can be made to the output power of piezoelectric harvesters operating at low Z_l/Y_0 ratios where large electrical damping is required. As the electrical damping force in a piezoelectric generator is equal to the cell voltage times the piezoelectric force factor α, it is possible to increase the damping force presented by the piezoelectric material and to increase output power, by placing a bias charge on the piezoelectric when the mass is at its maximum displacement in either direction. In this paper we demonstrate our method for improving the power output of such a device by simulation and the construction of a prototype that improves the power output of the generator by a factor of 10 over an optimal resistive load.

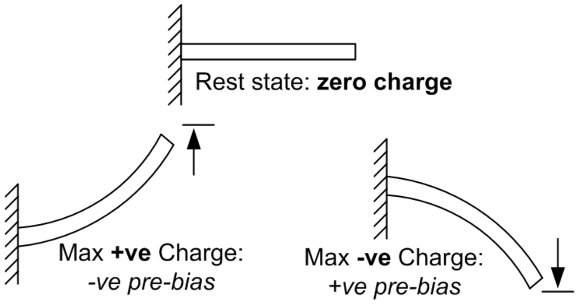

Fig. 1. Pre-bias of piezo to increase damping force

PRE-BIASING

When a piezoelectric material is strained in one direction in open circuit, the resulting charge displacement causes a force which tries to move the material back to an unstrained state, and some work is done in straining the material. If a charge is placed onto the material forcing it to become strained in one direction before the material is forced to move in the other direction by an external force, more mechanical work can be done as the force presented by the piezoelectric material is increased. Therefore more electrical energy can be be generated. This is illustrated graphically in Fig. 1. When the piezo cantilever is strained upward at maximum displacement such that a positive charge would be generated by the deflection of the material if in open circuit, a negative pre-bias voltage is applied to the material allowing increased mechanical work to

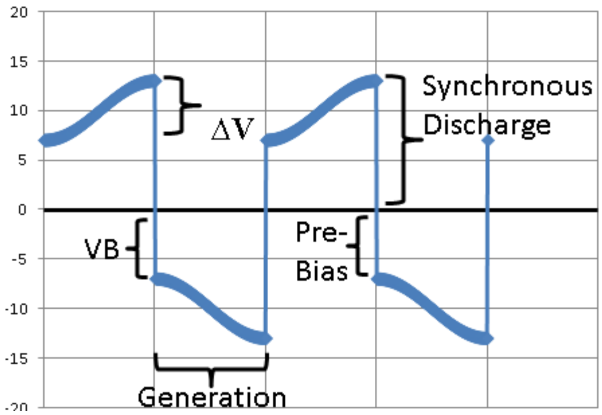

Fig. 2. Ideal waveform with synchronous charge extraction and pre-biasing

be done as the cantilever free end moves downwards. The opposite applies when the free end of the piezo cantilever is at the maximum downwards position.

If the applied bias V_B is large compared to the piezoelectrically induced voltage change ΔV_p, the force magnitude will now be constant at $\approx \alpha V_B$, rather than oscillating in the range $\pm\alpha\Delta V_p$. The output voltage waveform will be as sketched in Fig. 2. This can be seen as a generalisation of the method developed by Guyomar et al. [3] in which the cell voltage is inverted synchronously. In that case the explanation of improved power output is given in terms of the nonlinear functioning of the circuit, but it is the increased mechanical force due to the resultant cell biasing that is the essential origin of the increased output power. Therefore this bias can be implimented in any way, but must be delivered efficiently to give a net power benefit.

Use of the dedicated biasing circuit presented here in Fig. 4 allows the damping force to be adapted dynamically to the source amplitude, providing maximum power point tracking. The output stage shown in Fig. 4 allows the piezo capacitor to be synchronously discharged to the load at the end of a generation cycle just before pre-biasing occurs as illustrated in Fig. 2.

ANALYSIS

Energy stored on the capacitance of the piezoelectric cell is proportional to the square of the voltage. Therefore, if there already exists a charge on the material before charge is added due to mechanical strain, more work is done to charge the piezoelectric internal capacitance because that charge is driven into a higher voltage than in the case where no initial charge was present. Therefore, after synchronously discharging the energy generated in the previous half cycle, the piezoelectric cell should be pre-charged at each extremmity of position before movement occurs in the opposite direction.

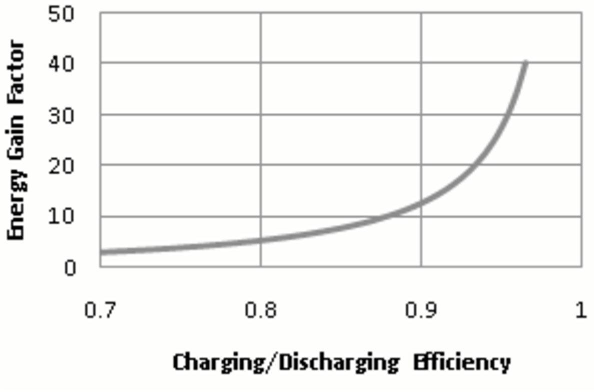

Fig. 3. Theoretical power enhancement relative to conventional piezoelectric cell vs. efficiency of pre-biasing

The gain in energy by applying the pre-bias can now be readily calculated. If we define efficiencies for the charging and discharging process as η_c and η_d respectively, then the energy that must be supplied to charge the piezo to a voltage V_B is $CV_B{}^2/2\eta_c$, while the energy that is usefully obtained at discharge is $1/2 \times C[\eta_d(V_B+\Delta V)^2]$. This gives a net energy output of:

$$E = \frac{1}{2}C[\eta_d(V_B+\Delta V)^2 - V^2/\eta_c] \qquad (1)$$

The optimum value for V_B in terms of ΔV is found by setting $dE/dV_B = 0$:

$$V_B = \frac{\eta_c\eta_d}{1-\eta_c\eta_d}\Delta V \qquad (2)$$

From this we can derive an expression for the optimum energy gain vs. efficiency. Taking the case where $\eta_c = \eta_d = \eta$ and combining (1) and (2), we obtain an energy gain factor (the ratio of energy generated for synchronous extraction with zero pre-bias to energy generated with the optimal pre-bias for a given efficiency) of:

$$f_E = \frac{E(\eta)}{E(V_B=0)} = \frac{3\eta^3}{(1-\eta^2)} + \eta \qquad (3)$$

This function is plotted in Fig. 3, and shows that high output gain is obtained for efficiencies above 90%.

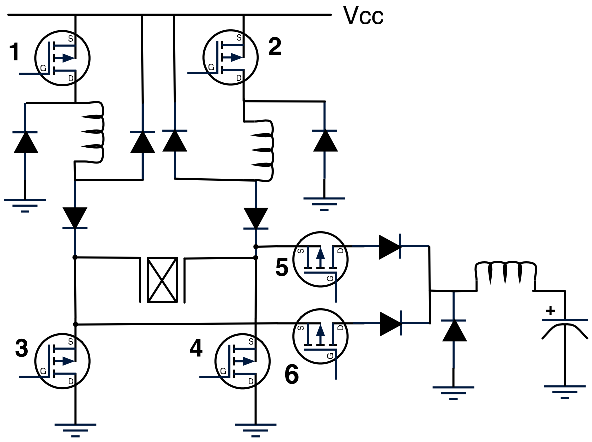

Fig. 4. Piezo Pre-Bias H-Bridge Circuit

CIRCUITRY

The charging circuit shown in Fig. 4 comprises an H-bridge with an inductor after the collector of the top two FETs. The inductor enables near-lossles charging of the piezo capacitor, with current allowed to freewheel between VCC and ground via two diodes. The gates are controlled as per a normal H-Bridge configuration with FETs 1 and 4 allowing per-charging in one direction and 2 and 3 in the reverse direction. FETs 5 and 6 are used for synchronous discharge of the piezoelectric capacitance in an interlieved buck configuration.

The circuit as described was simulated using *PSpice* using inductors of 15 mH with a 350 $m\Omega$ series resistance and the capacitors were modelled as ideal. Real semicondictor models were used.

SIMULATION RESULTS

The piezoelectric device used for experimentation was a *Kingsgate KPSG-100 Loudspeaker* as used Guyomar et. al. in [4]. The data-sheet states a piezoelectric capacitance of 65 nF, although our sample was measured as 50 nF. Our simulation was set up so that the device, being excited so it produces a current of magnitude 122 μA at 105 Hz was connected to an optimal load resistance of 30.3 kΩ [3]. In simulation, this resistor dissipates 0.1 mW. The was taken as a base case.

In order to test the likely practical effectiveness of our pre-biasing technique a simulation was run with the piezo excited with the same mechanical motion. The circuit of Fig. 4 was implemented in PSpice using 2N7000 MOSFETS and ZC5800 Schottky diodes. In the simulation the pre-bias technique was shown to generate up to 6.25 mW net power, a factor of 62.5 more than the optimised resistive load. In a second simulation (this time with an 80 Hz excitation and a piezo current magnitude of 500 μA) the ideal load (30.6 $k\Omega$) developed 0.6 mW. Synchronous extraction with an 18 V pre-bias voltage developed 7 mW net power output.

It was noted that the system is particularly sensitive to the relative values of the charge extraction pulse length and the output inductor size due to the resonant nature of the charging circuit. The system is surprisingly insensitive to the series resistance of the inductor and the system still performed within 50% of the stated power gain values with a series resistance as high as 2 Ω - although better practical components can be sourced.

EXPERIMENTATION

A PCB of Fig. 4 was manufactured and the Kingsgate piezo element mounted on a shaker. The vibration level was increased at a set freqency until the piezo voltage under open-circuit matched that of the simulation. In practice the position measurements for the synchronisation of the pre-bias and discharge gate pulses were difficult to generate directly from the measured piezo voltage since as soon as a charge is placed on the piezo the voltage changes. Therefore the position was sensed by measuring the voltage of the shaker coil and a suitable phase shift added. This waveform was fed into a DSP chip and a peak rate-of-change detection algorithm determined the frequency and amplitude and hence the appropriate charge/discharge instants. The DSP then drove the MOSFET gate drivers. Scope traces are shown in Fig. 6.

RESULTS & VERIFICATION OF MODEL

The open-circuit output voltage was 5 V_{p-p}, which given an ideal 50 nF shunt capacitor equates to an optimal load resistor of $(2\pi fC)^{-1} = 30.3\ k\Omega$. This resistive load gave an output power (P_R) of 0.103 mW (calculated by measuring the voltage across the resistor). This agrees with the value for the same test found in PSpice. The power into the pre-biasing system was calculated using a sense resistor. A measurement was taken for each pre-charge voltage and the energy extracted per cycle was calculated from $\frac{1}{2}CV_{PEAK}^2$ at the peak of the cycle. The results are promising: the power gain increases as a function of pre-bias voltage as predicted, suggesting the limit of the method is the voltage the piezo can support. Figure 7 shows the output power improvement ratio (when compared

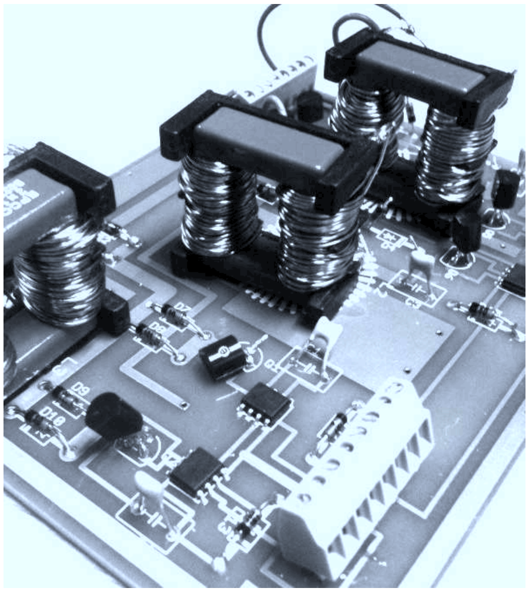

Fig. 5. Circuit Implementation

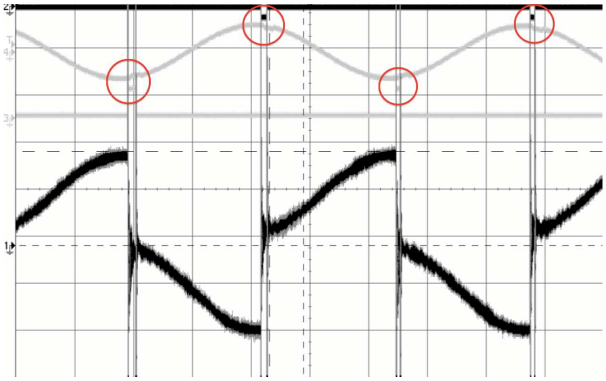

Fig. 6. Experimental waveform with positive and negative pre-bias firing angles highlighted

to the optimal shunt resistor case) for different pre-bias voltages. It can be seen that in the case where the pre-bias voltage is zero (synchronous extraction alone) the power output doubles. In our experiment the MOSFETs broke down at around 35 V causing the efficiency to drop sharply as the piezo capacitor began to discharge directly through ground and pre-biasing was no longer achieved.

CONCLUSIONS

We have shown that greater electro-mechanical coupling can be achieved by pre-biasing the internal capacitance of a piezo-electric device, and that doing so improves the overall power output of the system by an order of magnitude compared to an ideal resistive load on the same device. It was demonstrated that the method works in practice and effectively extracts more energy from a source of excitation than the optimal shunt load resistor. The method is primarily suitable for applications where the source excitation is un-dampable (e.g engines, foot-traffic etc.), and for low-frequency but high source amplitude operation since the efficacy is heavily dependent on the amplitude of the excitation.

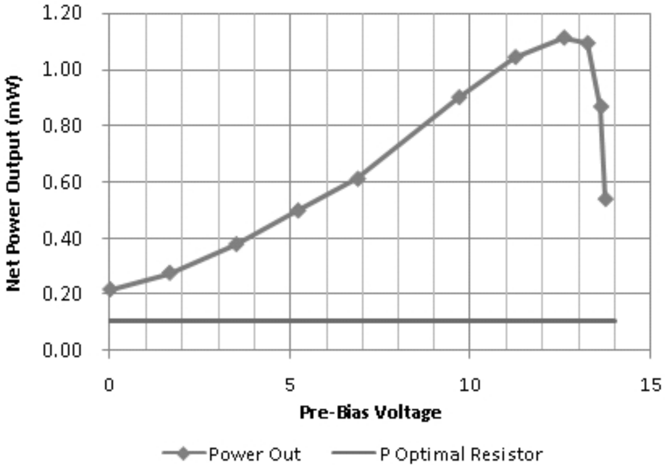

Fig. 7. Output power improvement compared to ideal resistive load

FURTHER WORK

The next stage is to develop a standalone circuit that derives the pre-bias voltage from the output. Self-start circuitry will be needed, as it may be the case that the piezo alone will not charge the reservoir capacitor sufficiently to power the gate drives. The amount by which the pre-bias method increases power output will depend on the load placed upon the system by signal processing and pre-charging and discharging circuitry. This means the system may be unsuitable for operation at very low power although this is a matter for further investigation.

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