IMPLEMENTATION OF SINGLE SUPPLY PRE-BIASING WITH SUB-35μW CONTROL OVERHEAD FOR PIEZOELECTRIC ENERGY HARVESTING

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Abstract: Single supply pre-biasing yields a greater power extraction improvement to resonant energy harvesters than any other circuit technique. Power output maximization requires the circuit to perform optimally. This paper exams three methods o maximize power output: minimizing peak detection power consumption whilst maintaining accuracy, applying the optimal pre-bias voltage to the piezo, and optimizing the inductor characteristics. To achieve this, two new peak detection circuits have been designed which either reduce power consumption by a third or double the available piezo material for power generation. Variation in power generated versus pre-bias voltage was experimentally measured and an expression to maximize power through inductor selection was found.

Keywords: single supply pre-biasing, peak detection, Q-factor

INTRODUCTION

Power extraction from a piezo with low coupling factor using single supply pre-biasing (SSPB) is electrically limited by the applied mechanical excitation frequency, f_0, the induced open-circuit voltage across the piezo, V_{po}, the piezo capacitance, C_p and the quality factor of the resonance charging path, Q [1]. For a discussion on the effects of this circuit when coupling is non-negligible, see [2].

$$P_{SSPBmax} = V_{po}^2 f_0 C_p (8Q/\pi) \qquad (1)$$

For a given energy harvester operating at resonance, maximum power extraction requires the SSPB switches to be triggered at the peak and trough of the voltage waveform. Triggering early or late will result in a drop of energy output approximately proportional to the square of the voltage drop. Thus it is necessary to accurately detect when a peak occurs.

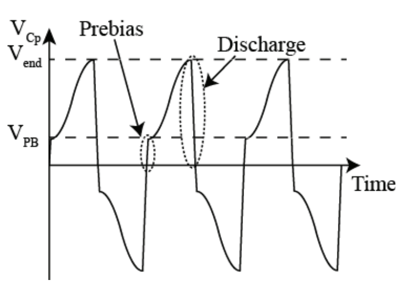

Fig. 1: SSPB piezo voltage waveform [3].

The easiest solution is to mechanically connect but electrically isolate a secondary "sense" piezo to the generating piezo and use an analogue to digital converter with a microprocessor to find the peaks [3]. However this is power intensive and limited in terms of resolution.

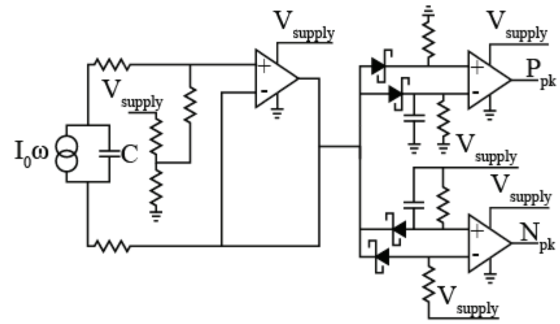

Fig. 2: Peak detector comprising of a differential amplifier and lossy peak-hold circuit (9 μW) [4].

An improved solution measures the output voltage across the piezo with a differential amplifier and compares the instantaneous voltage with a lossy peak-hold circuit (Fig. 2) [4].

This implementation uses considerably less power (9 μW [5]) and can operate over a wide mechanical frequency range by setting the discharge rate of the voltage holding capacitor. However it can only work over a limited range of mechanical excitation amplitudes because the differential amplifier input can exceed the supply rail resulting in clipping.

IMPROVED PEAK DETECTION

Two new approaches to peak detection have been designed to reduce power consumption and increase the operating range.

Level-shifted peak detection

Fig. 3 illustrates the first technique in which a peak detector is made by using a bridge rectifier and capacitor to level shift an electrically isolated sense piezo's output by adding a DC offset. The comparator inputs thus receive a level shifted copy of the piezo voltage where the peak or trough (depending upon the polarity of the piezo) will cross zero.

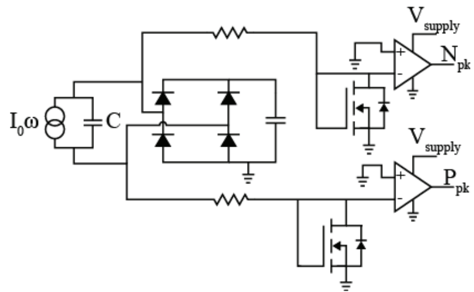

Fig. 3: Peak detection circuit using a bridge rectifier and capacitor to level shift the sense piezo output.

An n-type MOSFET is connected to the comparator input by both its gate and drain terminals. This prevents the input signal from damaging the comparator if the piezo voltage exceeds the comparator's supply rail.

Orcad's PSpice was used to simulate the circuit using models of the chosen components and a physical implementation was constructed to test the generation capability. The voltage protection MOSFETs were Fairchild BSS138s and the comparators were Microchip MCP6542s. Fig. 4 shows the simulated and measured output of the circuit when tested with a Kingsgate KPSG-100 51.2 nF piezo.

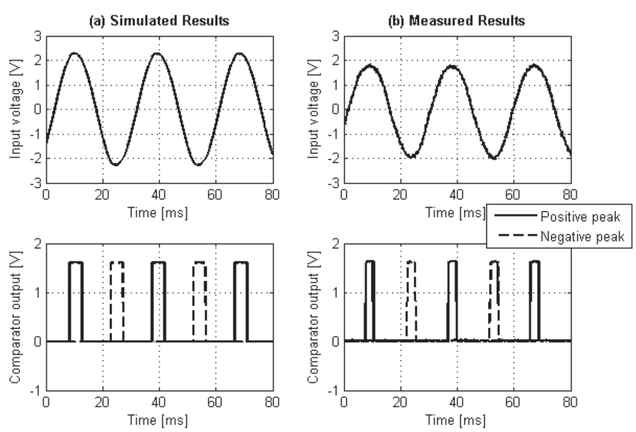

Fig. 4: Peak detection circuit output from (a) Orcad's PSpice simulation (b) experimental measurement.

The zero crossing detector was combined with the controller for an SSPB H-bridge circuit with a Q-factor of 5.5 from [4] and a mechanical excitation force at 30 Hz was applied to the sense and generation piezos inducing a 5V open circuit voltage across the piezo.

The power consumption for the peak detection circuit was 2.72 µW whilst the H-bridge and control circuitry consumed 16.5 µW. The harvester generated 138 µW when V_{cc} = 4.795 V, 5 times more power than a bridge rectifier with optimal output voltage [1].

The level shift peak detection circuit requires a reference signal which is in phase but unaffected by the pre-biasing applied to the generating piezoelectric beam. Peak detection power consumption has been reduced by two-thirds compared with [5] by removing the need for a differential amplifier.

Period measured peak detection

The second peak detection circuit does not require a separate sense piezo. Instead it isolates the generation piezo from the pre-biasing circuit after a given number of cycles and uses a zero crossing detector, low power clock and counter to measure the mechanical excitation period (Fig. 5).

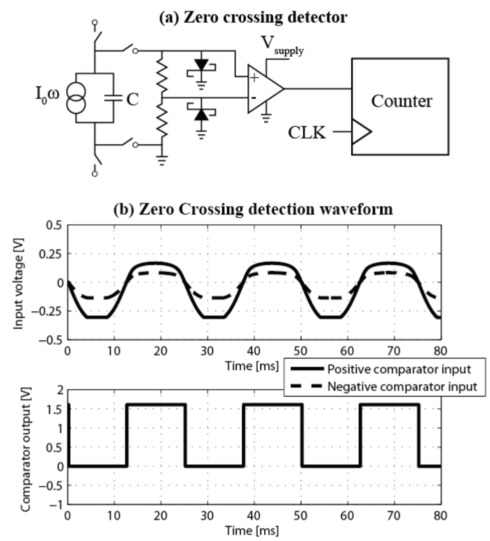

Fig. 5: (a) Zero crossing detector and timer circuit; (b) PSpice simulated waveform output.

After a period has been measured, the detection circuit is isolated and the piezo is re-connected to the SSPB H-bridge circuit. The peaks are then estimated based upon the measured period and used to control the H-bridge's operation.

This circuit has not yet been implemented due to increased complexity in the design of the control algorithm. The control circuit is expected to draw more power than previous implementations, however it is expected that the extra power gained from not requiring a separate sense piezo may offset this deficit.

OPTIMAL PRE-BIAS VOLTAGE

When the peaks of piezo voltage waveform are detected, the degree of electrical damping applied to the piezo is determined by the pre-bias voltage, V_{cc} [2]. For maximum power extraction, an optimal damping needs to be applied. If the voltage is too high or low then the system will be over-damped or under-damped respectively and power extraction output will drop.

This effect can be observed by varying the H-bridge rail voltage and Fig. 6 shows the power extracted when a fixed 50 Hz mechanical excitation force inducing a 5 V open circuit voltage is applied and rail voltage is varied. A 51.1 nF piezo attached to a 5.354 mH with volume 152 cm^3 from Coilcraft were used for testing.

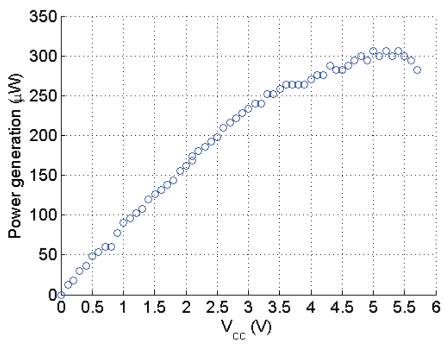

Fig. 6: Measured power generation versus V_{cc} for a 58.9 nF piezo with a fixed excitation force.

Q-FACTOR AND INDUCTOR SELECTION

Theory

Theoretical maximum power extraction by SSPB is given in (1). The transduction method and mechanical excitation amplitude and frequency are determined by the environment it will be utilized in. However, maximizing the quality factor of the resonance charging path, Q, will maximize power extraction.

Q is determined by the inductor, L, piezo's capacitance, C_p, inductor effective series resistance, R_L, and the combined on-state resistance of the switches, R_{sw}. Physical limitations in inductor volume also limit the maximum achievable Q-factor. The Q-factor of the complete resonant path is:

$$Q = 1/(R_L + R_{sw})\sqrt{(L/C_p)} \qquad (2)$$

For an inductor of fixed volume, the inductance increases with the square of the number of turns. However within a fixed volume, to increase the inductance, the wire must be made thinner and longer, hence R_L increases also increases with the square of the number of turns and hence is directly proportional to L.

Fig. 7 shows power generation as a function of inductance (3) for a fixed volume and family of Coilcraft inductors as derived from (1) and (2). Power increases as inductance decreases from 7 mH until such a point (1.4 mH) that the resonance path behavior is dominated by the on-state resistance of the MOSFETs causing the Q-factor and power generation to fall. The expression for the power generated is given in (3) and the optimum inductance can be found by differentiation.

$$P_{SSPBmax} = V_{po}^{\,2} f_0 C_p (8[1/(R_L + R_{sw})\sqrt{(L/C_p)}]/\pi) \qquad (3)$$

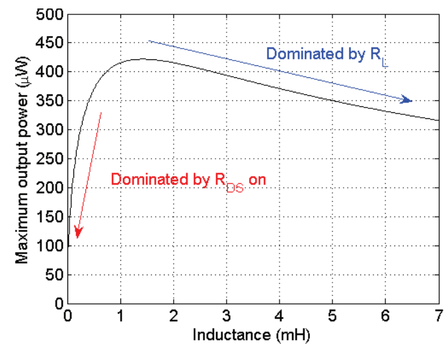

Fig. 7: Inductance versus maximum output power for a 58.9 nF piezo excited at 35Hz, inducing V_{po} = 3 V. The MOSFET R_{sw} = 8.7 Ω with the inductor series resistance empirically found to vary as R_L = 6117.9L.

Experimental results

An investigation into commercially available inductors was conducted with the objective to maximize power extraction for a fixed inductor volume. A series of inductors of 86.4 mm^3 volume were analyzed with respect to Q-factor and power extraction. The Q-factor was calculated by measuring the ring down of the piezo-inductor voltage when a step excitation is applied:

$$Q_{measured} = -\pi/(2\ln(V_2/V_1)) \qquad (4)$$

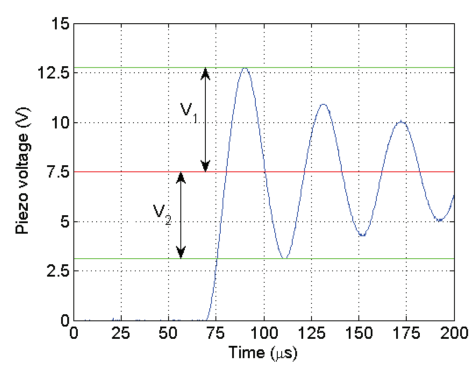

Fig. 8: Calculating Q-factor by Measuring piezo voltage ring down after 7.48 V step function is applied

The Q-factors for the charging path with 15 of Coilcraft's LPS6225 series inductors were measured with a 58.9 nF Kingsgate KPSG-100 piezo and 8.6 Ω resistor in series to represent the on-state resistance of the switches. Fig. 9 shows at low inductances, the R_{sw} causes the Q-factor to fall, however large inductances suffer from high effective series resistance causing the Q-factor to decrease.

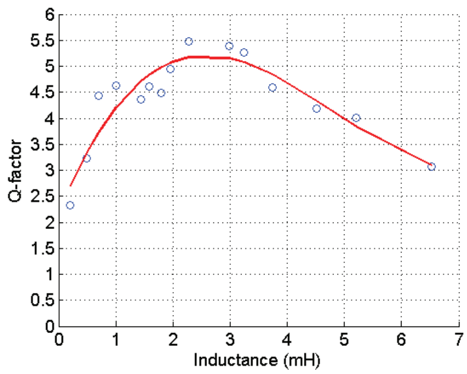

Fig. 9: Measured Q-factor versus inductance of Coilcraft LPS6225 series inductors with a fixed 86.4 mm³ volume, C_p = 58.9 nF and R_{ds} = 8.6 Ω.

Each inductor was inserted into a SSPB circuit [4] with the peak detection circuit shown in Fig. 2. Two Kingsgate KPSG-100 piezos were mechanically connected together to form the sense and generation piezos with 58.9 nF and 46.6 nF capacitance respectively. A mass was added to lower the mechanical resonance frequency to 50 Hz and an excitation force capable of generating 5.0 V open circuit voltage across the piezo was applied.

Fig. 10 shows the power generation by each inductor measured using a Yokogawa WT210 power meter. It can be seen that the peak power occurs close to that predicted by the model in Fig. 9 due to Q-factor being greatest at this point. The generated power is less than expected from (1) due to the peak detection firing early, resulting in a loss of power as described in [5].

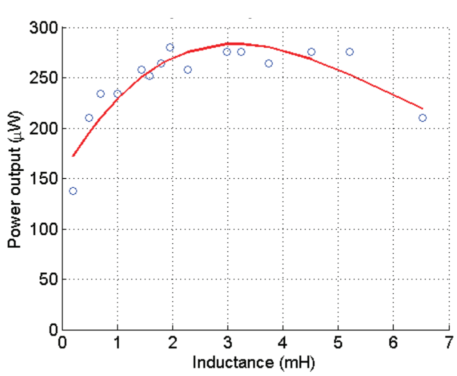

Fig. 10: Power generation versus inductance of Coilcraft LPS6225 series inductors with a fixed 86.4 mm³ volume, C_p = 58.9 nF and R_{ds} = 8.6 Ω.

CONCLUSION

In this paper, two different peak detection circuits have been introduced to either reduce power consumption by the control circuit or remove the need of a sense piezo required in previous techniques. The former has been experimentally demonstrated with the power consumption being reduced by two-thirds. The latter detector has been successfully simulated and work will continue to realize this circuit.

Analysis of the inductor has been performed indicating there is an optimal solution based upon the on-state resistance of the gate switches and the effective series resistance of the inductor. Further work into reducing the on-state switch resistance is required in order to achieve further power gains.

The importance of using the optimal pre-bias voltage to maximize output power has also been shown. Future work into developing a maximum power point tracking function is required to ensure the best performance from the SSPB circuit is achieved.

ACKNOWLEDGEMENTS

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