CHARACTERIZATION OF A HYBRID AMBIENT LOW FREQUENCY, LOW INTENSITY VIBRATION ENERGY SCAVENGER SYSTEM

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Abstract: This paper identifies prior limitations, essential modifications, and effective change in system performance of a hybrid energy scavenger system, coupling both piezoelectric and electrostatic energy conversion using a lead zirconate titanate (PZT) cantilever. Based on energy survey, the system is targeting sinusoidal acceleration of 2.5m/s^2 at 120Hz in a volume of <0.25cm^3. The primary goal of the system is to maximize energy density within the volume, dominated by the proof mass for low frequency resonant operation, by using the mass as a variable capacitor (C_{VAR}) electrode for electrostatic scavenging on a shared platform. Implemented changes enable the observation of a 19.8 percent voltage gain beyond the DC rails provided by the PZT.

Keywords: energy scavenging, harvesting, piezoelectric, electrostatic, synchronous charge control

INTRODUCTION

While vibration scavengers have been widely reported, cantilever-based piezoelectric scavengers require large masses to resonate at the low frequencies that are dominant in the ambient environment. Furthermore, charge-based electrostatic scavengers require storage of a pre-charge and synchronization with the mechanical oscillation to operate properly [2]. Both scenarios result in lower power densities due to the volume occupied by non-transducing components and power consumption by control electronics. To mitigate this, a system-based approach to couple both piezoelectric and electrostatic energy scavenging mechanisms simultaneously in a shared volume has been previously described at the design and simulation level; however, in-plane configurations are limited by tradeoffs between piezoelectric coupling and material compliance as well as complexity of fabrication [3].

Using 2.5m/s^2 at 120Hz excitation, a simplified out-of-plane hybrid vibration scavenger system, depicted in Fig. 1, integrating commercial-off-the-shelf (COTS) components and materials demonstrates primary energy conversion from composite PZT beams with power densities up to 2.8mW/cm^3 while supplying 3.3V DC and synchronous electrostatic charge control based on PZT voltage (V_{PZT}). Despite this, further modifications in design and implementation within electrical and mechanical domains are required for proper operation of the electrostatic converter [1].

This paper describes recent modifications to the hybrid scavenger system and the effective impact on performance, enabling the observation of electrostatic energy conversion as a secondary source of energy.
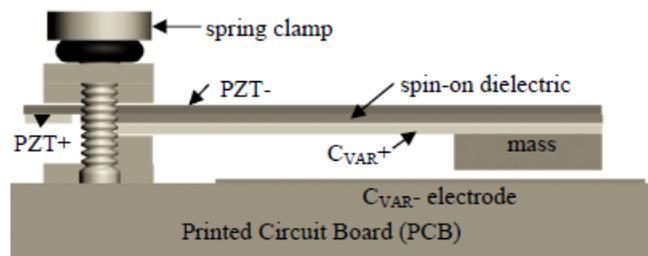

Fig.1: Diagram of simple hybrid scavenger cross-section. The piezoelectric beam (PZT) forms the resonant beam simultaneously creating an AC voltage that provides displacement feedback signal and a rectified DC rail for control and load circuits [1].

ELECTRICAL MODIFICATIONS

In order to facilitate rapid prototyping, the hybrid scavenger diagnostic circuits are comprised of COTS components on a custom PCB that provides: input excitation monitoring via a 3-axis accelerometer, feedback signal conditioning, electrostatic charge control, and measurement circuits. For the energy scavenger circuit, V_{PZT} is rectified to provide positive and negative DC rails. Furthermore, V_{PZT} is used as a displacement feedback signal that is the input to a peak detection circuit that indicates the displacement extrema of the electrostatic electrode / mass.

COTS operational amplifiers used in the diagnostic board consume significantly more energy than an ASIC and could not be solely powered by the system. For these analog devices, power is provided by an external DC power supply through a voltage follower that tracks the DC rail values that are generated by PZT actuation. Care is taken to ensure that external energy from COTS components is not injected into the energy scavenging circuit.
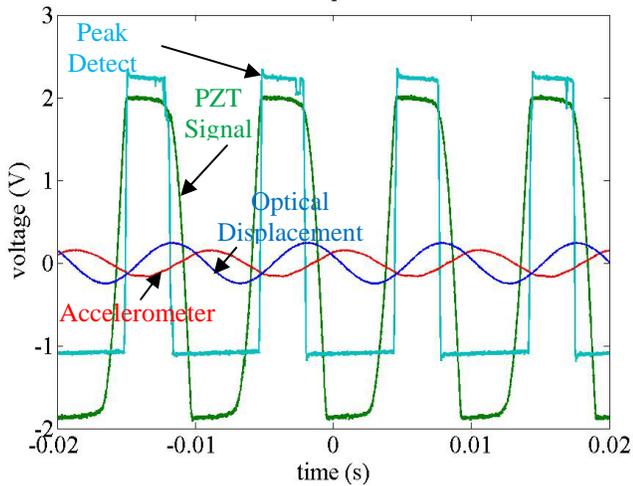
Fig. 2: Performance of peak detection circuit that tracks the piezoelectric voltage to infer tip displacement. Note that DC rail charging causes clipping and wide peak detection pulses; however, the trailing edge corresponds to maximum tip displacement as measured by optical probe [1].
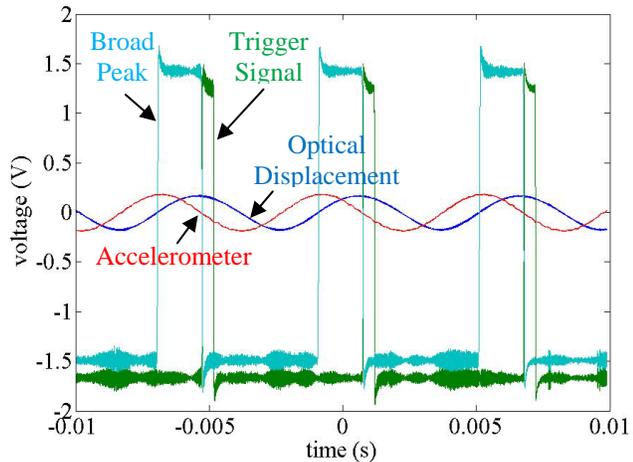

Fig. 3: Use of retriggerable mulitvibrators facilitates edge detection with control over pulse width, to ensure full charge of variable capacitor, as well as logic polarity for triggering solid state switches that control charge transfer for the electrostatic energy scavenger.
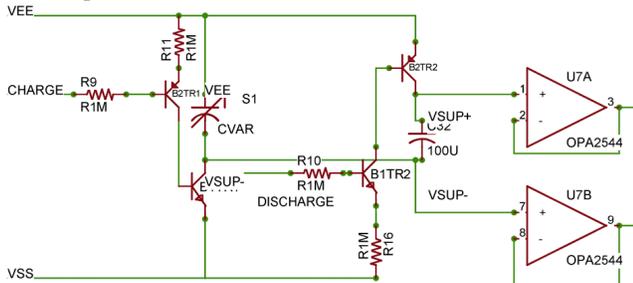

Fig. 4: Bipolar junction transistors used for charge control switching to obtain proper operation beyond the DC rails. Instrumentation amplifiers used for monitoring C_{VAR} behavior without applying a load.
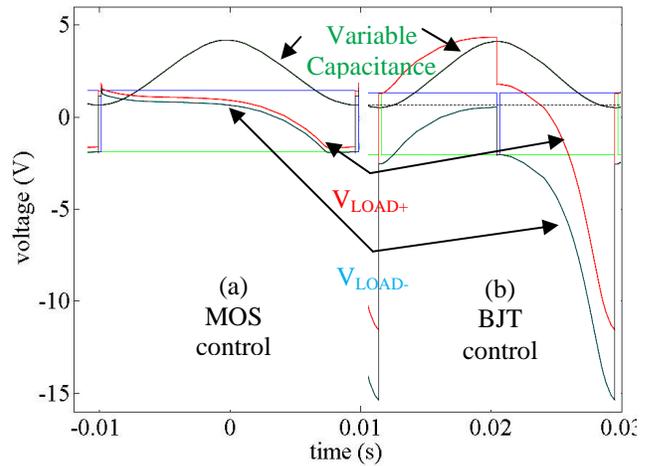

Fig. 5: While charging, the variable capacitor will exceed one of the power rails. (a) Under control of complementary MOSFETS, this will switch the source and drain, turning on the transistor and discharging the capacitor. (b) Under the control of BJTs, the transistors will remain off so long as the base current is zero, allowing proper function.

Peak Displacement Tracking

As previously reported and shown in Fig 2, the system uses the piezoelectric voltage signal to track displacement; however, the voltage clips when charging DC rails resulting in wide peak detection signals [1]. This results in poor electrostatic energy conversion as the displacement and resulting change in capacitance is limited to the narrow regions between positive and negative peaks of V_{PZT}.

This limitation is addressed by introduction of retriggerable multivibrators (LV123A) that provide controllable pulses based on the peak detector edges that are in phase with displacement extrema as illustrated in Fig 3. For diagnostics, a convenient feature of the LV123A is the ability to selectively trigger on rising or falling edges and the ability to tune the trigger pulse width by using a potentiometer. This permits the tailoring of the control pulse to ensure enough time to sufficiently charge/discharge the variable capacitor (C_{VAR}) while capturing as much of the capacitance change as possible.

Charge Control Switches

In the charge control circuit, MOS gates that were used as charge control switches in the original system have been replaced by bipolar junction transistors (BJTs) as shown in Fig. 4. Utilization of MOS switches has been demonstrated to cause uncontrolled switching due to source-drain inversion when the electrostatic scavenger voltage drops below the negative DC rail as measured experimentally and recreated in PSPCIE simulation, shown in Fig 5a.

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Since BJTs are current dependent devices, conduction only occurs when a base current is applied, irrespective of large voltage swings between collector and emitter. As simulated in Fig. 5b, this architecture allows the C_{VAR} voltage to swing below the DC rail. Despite this favorable outcome, the utilization of BJTs increases the current loading of the charge switching and can cause large voltage drops on the DC rails if unchecked. As shown in Fig. 4, current limiting resistors are used to reduce drain on the DC rails through the emitter of biasing transistors. This requires balancing of the reduced C_{VAR} charging current with wider control pulses to ensure that maximum charge is applied.

Instrumentation Amplifiers

The current design of the proof mass/variable capacitor electrode is a simple parallel plate to reduce the need for complicated alignment during the development phase of testing. As a result, the effective capacitance of C_{VAR} is fairly small. Assuming a 100 nm gap, the effective maximum capacitance is 4.4nF. Realistically, the minimum gap will likely be greater than 5 microns, resulting in maximum capacitance of less than 88pF. The limitation of an electrically small C_{VAR} limits the charge availability and precludes direct measurement of charge cycle behavior. Shown in Fig. 4, instrumentation amplifiers (OPA2544) are used, in voltage follower configuration, to facilitate observation of the charge cycle without adversely impacting circuit behavior.

MECHANICAL MODIFICATIONS

Mechanically, the system is constrained by the material properties of PZT and input excitation specifications. Using a 0.05cm^3 tungsten proof mass and composite shim bimorph with 2.5m/s^2 at 120Hz excitation, the displacement of beam tip is measured optically to be 4.54µm relative to the test platform. As discussed in the prior section, the performance of the electrostatic scavenger is dramatically limited by the electrically small capacitance. This is compounded by small displacement that limits the effective change in capacitance and thus energy production.

Variable Capacitor Electrode Gap

As shown in Fig 6a, the counter electrode of the variable capacitor was originally mounted to the PCB via a tripod-style connection using fine-pitch screws. This limits the precision of gap adjustment, resulting in negligible change in capacitance.

The limitation was temporarily mitigated by incorporating an off-platform 3-axis micrometer with the base (C_{VAR-}) electrode connected to it. This configuration yielded precision height control, resulting in measurable capacitance change; however, could not be used as the total displacement between the top (C_{VAR+}) electrode and static C_{VAR-} electrode was exaggerated.

Shown in Fig. 6b, the new tripod configuration, using 20nm resolution differential micrometers is used to provide precision height control. The tripod is mechanically clamped to the PCB via two springs. While the differential micrometers are fine resolution, the effective displacement of the electrode tip is limited by the electrode geometry and design. Adjustments to maintain parallelism and minimum gap without inducing striking of the proof mass using this configuration are still non-trivial. Furthermore, the additional mass of electrode and micrometers as well as clamping springs impact the system by introducing higher order modes, as measured by the on-board accelerometer. Despite these existing limitations, the modifications facilitate measurable capacitance change.
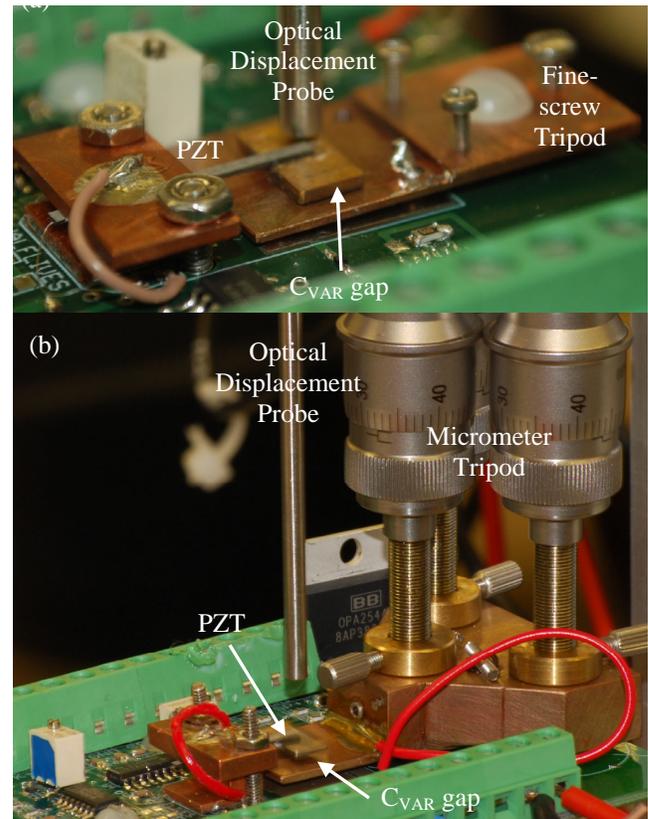

Fig. 6: (a) Photograph of original hybrid scavenger test platform with fine screw tripod that precludes fine tuning of gap [1]. *(b) Photograph of new platform incorporating 20nm resolution micrometers.*
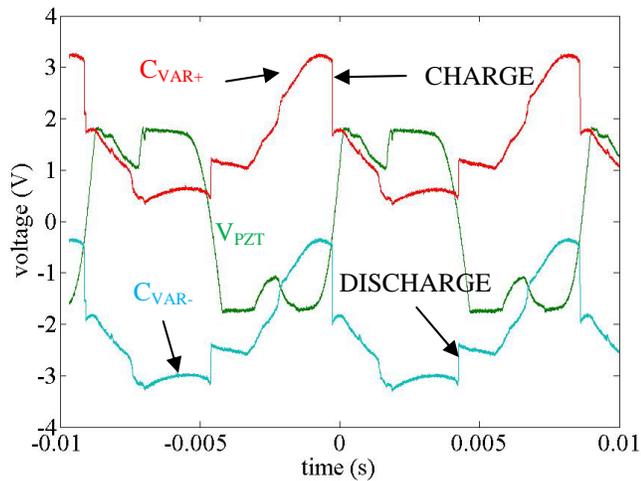
Fig. 7: Measured operation of electrostatic charge control using PZT signal as displacement feedback to obtain proper timing.

ELECTROSTATIC CONVERSION

Implementation of the changes in both the electrical circuits and mechanical electrode assembly facilitate the measurement of electrostatic conversion in the hybrid energy scavenger, show in Fig. 7. Analogous to the simulation in Fig. 5b, charge is applied at the time when displacement is minimized effectively pulling the voltage to the negative DC rail. C_{VAR} is discharged to the storage capacitor when the voltage is at the most negative value.

Measurements differ from the simulation as the negative peak is inverted at the minimum. This inversion is attributed to second order harmonics of the mechanical system. Furthermore, the amplitude of the negative peak is far less than simulated and is attributed to not being able to achieve the estimated 180pF change in capacitance due to sub-optimal positioning and higher mode vibration of the C_{VAR-} electrode platform.

Despite these limitations, the measured increase in voltage output is 664mV over the 3.35V rail or an increase of 19.82 percent at $2.5m/s^2$ at 111Hz. Initial power measurements show less than 1µW additional power is generated and is attributed to low change in capacitance and charge capacity. Despite this, at high vibration amplitudes ($5-7.5m/s^2$), more power is scavenged due to a larger capacitance change without adverse effects and is currently being evaluated.

DISCUSSION

While the basic theory of hybrid piezoelectric and electrostatic energy conversion on a shared mechanical platform is demonstrated, there is substantial room for optimization.

Electrically, to minimize control circuit power consumption, it is imperative to move toward a monolithic ASIC that incorporates the required functionality with a focus on low power operation.

Mechanically, the ability to dynamically and precisely control the electrostatic gap, without significantly increasing volume and introduction of higher order modes, is paramount to obtaining efficient operation of the hybrid system. Additionally, the inclusion of features to enhance surface area at the minimum displacement would increase the maximum change in capacitance, but imposes additional alignment requirements. Furthermore, it is imperative that the input excitation match the resonance of the scavenger structure for maximal voltage generation and change in capacitance. Finally, while the beam has been characterized to operate in a stable regime for millions of cycles, striking on the C_{VAR-} electrode can quickly degrade the performance as micro-scale fractures are induced in the PZT material.

Toward these goals, electrostatic spring architecture is being pursued for integration on the C_{VAR-} electrode. The system will use a parallel set of electrodes to apply electrostatic force to: adjust electrode gap, change resonance of the structure to seek maximum displacement, and detune the system if striking is detected.

CONCLUSION

For the first time, a successful demonstration of a hybrid energy scavenger system that simultaneously couples both piezoelectric and electrostatic energy on a shared MEMS platform is reported. Voltage amplification beyond PZT generated DC rails of 19.8 percent at $2.5m/s^2$ excitation is shown; however, energy production from electrostatics is lower than the generation from the piezoelectric. This is attributed to poor alignment tolerances and limited surface area, resulting in an electrically small variable capacitance.

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