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Realistic Circuit Model of an Impact-Based Piezoelectric Energy Harvester

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***Abstract*—A vibration-based energy harvester and its equivalent circuit models have been reported. Most models predict voltage signals at harmonic excitation. However, vibrations in a natural environment are unpredictable in frequency and amplitude. In this paper, we propose a realistic equivalent circuit model of a frequency-up-converting impact-based piezoelectric energy harvester. It can describe the behavior of the harvester in a real environment where the frequency and the amplitude of the excitation vary arbitrarily. The simulation results of the model were compared with experimental data and showed good agreement. The proposed model can predict both the impact response and long term response in a non-harmonic excitation. The model is also very useful to analyze the performance of energy conversion circuitry with the harvester.**

***Index Terms*—Circuit modeling, energy harvester, impact-based harvester, piezoelectric, vibration**

I. INTRODUCTION

Recently, energy harvesters to convert mechanical energy into electrical energy have been studied as a power source for small and low power electronic devices such as wireless sensing nodes and implantable medical devices [1, 2]. Most vibration-based harvesters have been implemented using electrostatic, electromagnetic and piezoelectric transduction mechanisms. Among them, piezoelectric structures have been widely utilized because they are easier to use and have higher power density [3, 4].

Vibrations occurred at a natural environment, unlike an industrial environment, are distributed in low frequency bands and vary unpredictably from time to time [2]. Therefore various harvesters, which can work at low frequency random vibrations, have been researched to improve energy conversion efficiency [1, 2].

To extract the maximum power from the harvester and to supply stable power to load devices are two main concerns for an energy harvesting system. Equivalent circuit models of a harvester present a harvester, which operates in both mechanical and electric energy domain, as one electrical equivalent, and allow system analysis by using circuit simulation. Piezoelectric harvesters are often represented as an equivalent circuit which consists of two sub-circuits for mechanical and electrical behavior and a transformer to describe piezoelectric coupling between them [3, 5]. They can be further simplified to a current source with a capacitor [6, 7]. These conventional models usually use a sinusoidal power source to describe steady state response to harmonic excitation. Therefore they cannot explain the behavior of harvesters at unpredictable natural vibration. Frequency-up-conversion harvesters also have problems with conventional models because they generate signals with different frequency from an external force applied at regular interval.

We have previously reported an equivalent circuit model of a frequency-up-converting impact-based piezoelectric energy harvester [8, 9]. In this work, we propose an improved circuit model that reflects the behavior of the harvester in a natural environment, i.e.

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unpredictable, non-periodic, and slow movements with varying amplitude.

Section II describes the structure and characteristics of the targeted harvester and proposes an equivalent circuit model. Section III shows test results with the proposed conversion circuit. Next section draws conclusion.

II. CIRCUIT MODELING

1. Targeted Harvester

Fig. 1 shows a schematic of the targeted frequency-up-converting impact-based piezoelectric energy harvester [10]. It consists of an aluminum housing including a freely movable spherical ball and a cantilever-type beam. The beam is made of a piezoceramic fiber-based Macro Fiber Composite (MFC) and a proof mass is attached at the free end. There are two electrical output ports for a reference signal and a generated voltage.

When the harvester vibrates up and down, the freely movable ball impacts the aluminum housing to enable the flexible MFC beam to be expanded and contracted. The MFC converts this mechanical energy into electrical energy, which has higher frequency than the force applied to the harvester. It significantly increases the energy utilization by converting low frequency vibrations into high frequency electrical signals through the impact.

Fig. 2 shows measured open-circuit output voltage of the harvester at 20 Hz excitation with 3 g acceleration. This excitation gives regular impacts on the harvester. As shown in Fig. 2(a), the voltage was generated at double the shaking frequency because the ball moved upwards and downwards in one cycle of its movement. The force of a collision was larger at the bottom than at the top. In addition, expansion and contraction coefficients of the MFC had different magnitudes and opposite signs. The asymmetry in the impacts and the coefficients generates two different waveforms alternately as shown in Fig. 2(b) and (c). Each impact generated oscillating signal around 8.5 KHz, which got exponentially attenuated after the second peak and returned to zero.

Fig. 3 shows generated open-circuit response when the harvester was shaken by hand. The frequency and acceleration of the handshaking excitation were maintained between 1-20 Hz and within 4 g, respectively [11]. The amplitude ranged between 0.1V and 10V. Signal groupings were observed and they were irregularly repeated, which is unlike the response signals to a regular force. One group consisted of a large signal and following decreased signals separated by a short time interval. We presume this signal group is generated when the ball is bounced at the same end repeatedly until kinetic energy of the ball got dissipated.

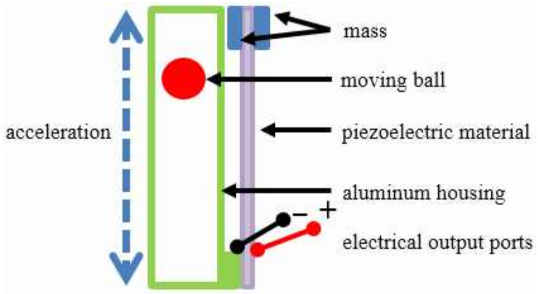


Fig. 1. Schematic of the targeted frequency-up-converting impact-based piezoelectric energy harvester

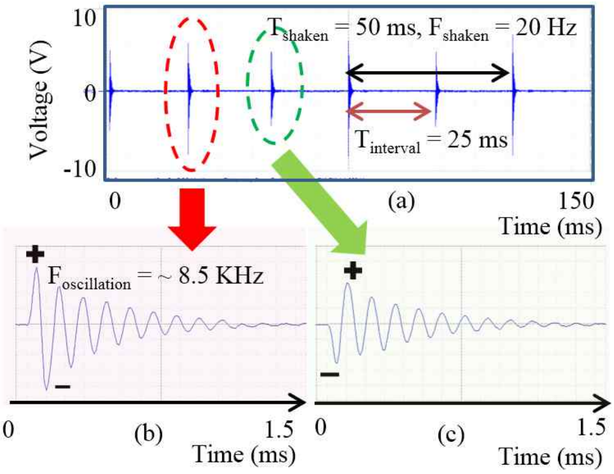


Fig. 2. Measured open-circuit voltage at regular force: 20 Hz excitation with 3 g acceleration (a) during 300 ms, (b) zoomed bottom-collision voltage during 1.5 ms, (c) zoomed up-collision voltage during 1.5 ms

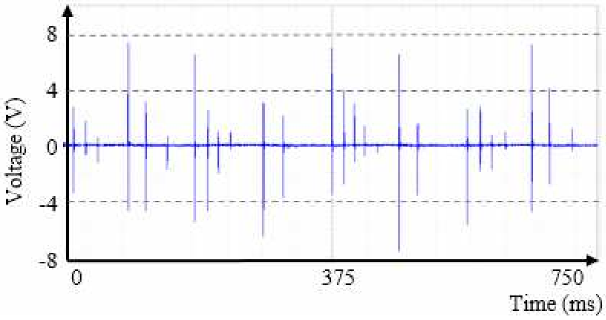


Fig. 3. Measured open-circuit voltage at irregular force: hand shaking

2. Equivalent Circuit Model

Analytical solutions to describe the mechanical behavior of the vibration harvester can be classified into two major techniques: a lumped-parameter system and a distributed-parameter system. The basic difference between them is the number of degrees of freedom [12]. The distributed-parameter system is usually limited to a specific situation: steady state at harmonic excitation [1, 12, 13]. The targeted impact-based harvester generates signals at different frequencies other than a driven frequency. Thus, the lumped-parameter model was used for the proposed model.

Fig. 4 shows a commonly used lumped-parameter model [4, 6, 14], at which *m* represents a rigid mass that is suspended by a lumped spring with a constant *k* and damped by a mechanical damping c_m and an external air damping c_a. A force F makes the mass moved along a displacement *z(t)*. The behavior of the damping mass from the dynamic forces results in the following differential equation.

$$m\frac{d^2z(t)}{dt^2}+(c_m+c_a)\frac{dz(t)}{dt}+kz(t)=F \qquad (1)$$

Because of the analogy with the differential equations for mechanical and electrical systems, the equivalent circuit for the mechanical part can be represented in terms of L_m, C_m and R_m as shown in Fig. 5.

Piezoelectric coupling between the mechanical and electrical parts was modeled as a transformer. The electrical part of the equivalent circuit represents the properties of the piezoelectric material including built-in capacitance C_p and leakage loss R_p. Most of the equivalent circuits [3, 5-7], which were suitable for a resistive load, neglects the leakage resistance. According to our test, however, it could not be ignored in the case of an inductive load.

Because conventional analytical solutions assumed the piezoelectric harvesters generated steady-state response to harmonic excitation [4], their equivalent circuits included a sinusoidal voltage or current source to represent mechanical force. As described in a previous subsection, however, the targeted impact-based harvester generated voltages with two sharp peaks followed by decreased sinusoidal oscillations. To portray these behavioral characteristics, the equivalent circuits have four independent voltage sources, which were modeled by a VPWL source in Spice, as shown in Fig. 5 [8].

Voltage sources of V_{bot-1} and V_{u-1} represented collision impacts at the bottom and the upper end, respectively. They made pulses with different amplitude and opposite phase because expansion and contraction coefficients of the MFC were different and magnitude of the collision were also different even in the case of a regular force. Voltage source V_{bot-2} and V_{u-2} each described the second peak, which was larger than the first peak and was opposite polarity. Four voltage sources generated each pulse at intervals of an applied vibration as shown in Fig. 6.

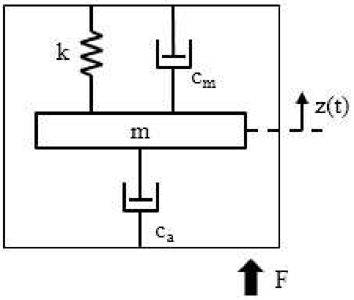


Fig. 4. Commonly used lumped-parameter model

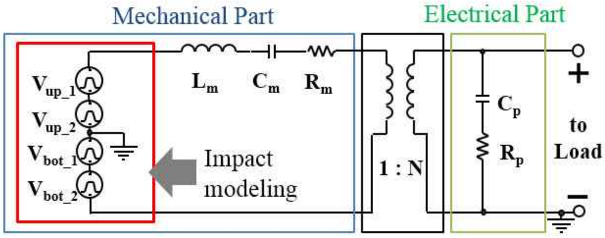


Fig. 5. Equivalent circuit model for a regular force

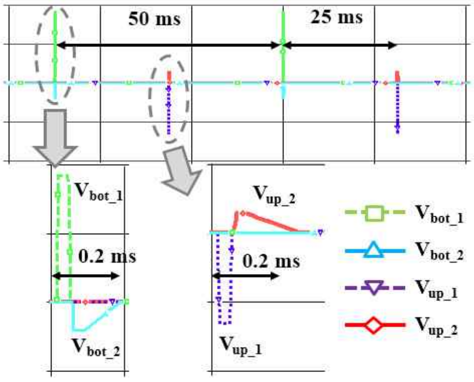
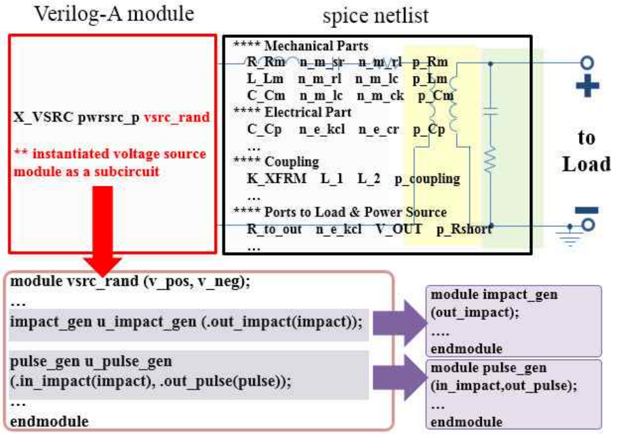


Fig. 6. Pulses generated by four voltage sources: V_{bot-1}, V_{bot-2}, V_{up-1} and V_{up-2}



```
X_VSRC pwrsrc_p vsrc_rand

** instantiated voltage source
module as a subcircuit
```

```
**** Mechanical Parts
  R_Rm   n_m_sr   n_m_rl   p_Rm
  L_Lm   n_m_rl   n_m_lc   p_Lm
  C_Cm   n_m_lc   n_m_ck   p_Cm
**** Electrical Part
  C_Cp   n_e_kcl   n_e_cr   p_Cp
  ...
**** Coupling
  K_XFRM   L_1   L_2   p_coupling
  ...
**** Ports to Load & Power Source
  R_to_out   n_e_kcl   V_OUT   p_Rshort
  ...
```

```
module vsrc_rand (v_pos, v_neg);
...
impact_gen u_impact_gen (.out_impact(impact));
pulse_gen u_pulse_gen
(.in_impact(impact), .out_pulse(pulse));
...
endmodule
```

```
module impact_gen
(out_impact);
....
endmodule
```

```
module pulse_gen
(in_impact,out_pulse);
...
endmodule
```

Fig. 7. Proposed equivalent circuit model using Verilog-A and spice netlists

The equivalent circuit model was further fortified as shown in Fig. 7 to reflect realistic vibration environments where the movements are unpredictable with varying strength. Four VPWL voltage sources, which repeat a user-defined pulse regularly, were redesigned as one module described in Verilog-A, and the others were replaced with equivalent spice models. Verilog-A is a hardware-description language for modeling and simulation of analog circuits at behavioral level. Verilog-A module is instantiated as a sub-circuit in a Spice netlist.

The voltage source module implemented in Verilog-A consists of two submodules: an impact_gen module and a pulse_gen module. A flow chart of the voltage source model is shown in Fig. 8. First, the impact_gen decides when an external force is applied including both amplitude and direction of the force. The pulse_gen module generates pulse voltages according to the given force. Then, the impact_gen sets the next collision parameters such as amplitude and event time depending on the four following cases:

- when the collision occurs at the upper end, the next collision occurs at the bottom.
- if the collision occurs at the bottom and the amplitude is larger than a threshold $V_{th\_bounce\_to\_up}$, the next collision does at the up end.
- if the amplitude is smaller than $V_{th\_bounce\_to\_up}$ and larger than V_{th_bounce}, a collision occurs at the bottom again.
- otherwise the impact_gen waits until a new external force.

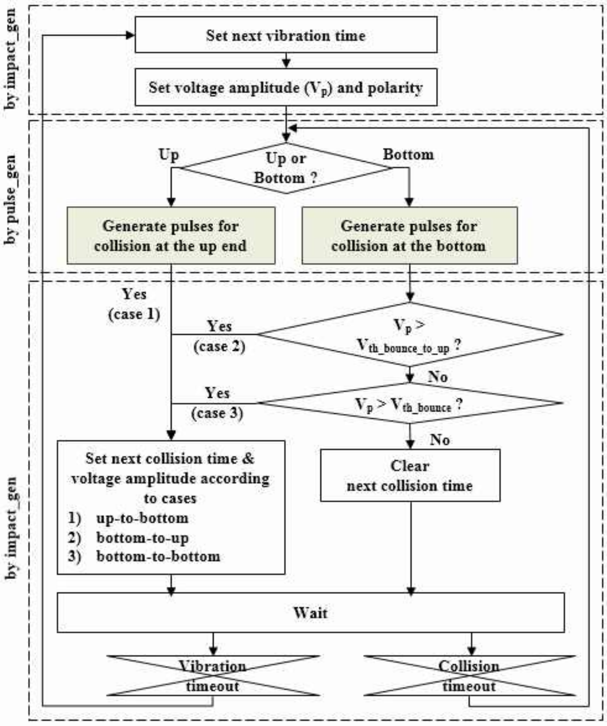


Fig. 8. Flow chart of the voltage source module in Verilog-A

When it is time to collide, the voltage source restarts from pulse generation. The external vibration event has higher priority than the collision event, and makes the procedure restart from the beginning. Regular forces are modeled as the case in which a vibration event has a shorter interval than collision events and the amplitude at the bottom collision is larger than $V_{th\_bounce\_to\_up}$.

III. MEASUREMENT RESULTS

Fig. 9 shows the test setup. A vibration exciter was used to shake the harvester regularly. The harvester was attached to the exciter and shaken vertically as shown in Fig. 1 and 9. The output voltage was measured and stored with an oscilloscope.

To determine parameters of the circuit model, the open and the loaded circuit responses were measured at 20 Hz and 3 g and compared with simulation results. The optimal matching impedance, an inductor of 27 mH, was also determined by changing resistors, capacitors and inductors in steps. Fig. 10 compares measured and simulated voltage signals both at open-circuit and across an optimal load. The peak to peak voltage and waveform obtained experimentally were very close with those

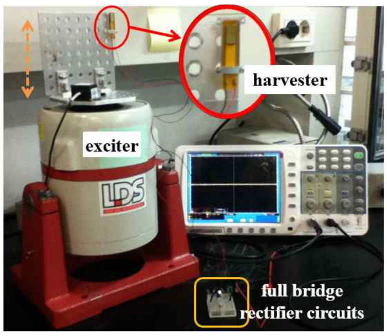


Fig. 9. Test setup

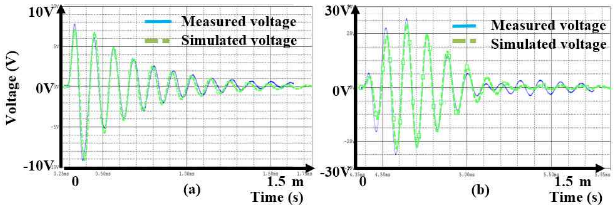


Fig. 10. Measured and simulated voltage (a) at open circuit, (b) across an inductor 27 mL

predicted by modeling. The circuit model can be used to analyze the transient response of the harvester.

Fig. 11 compares the open circuit voltage predicted by the circuit model and that by measured experimentally in the two cases: shaken by a vibration exciter and by hand. As noted in the previous section, the harvester generated two waveforms alternately when it was shaken at 20 Hz and 3 g by the exciter as shown in Fig. 11(a). When shaken by hand, however, it generated irregular voltage signals of different amplitudes. Although the hand-shaking frequency was lower than 20 Hz, some voltage signals were generated at a shorter interval due to a freely movable ball. Simulation shows similar results in Fig. 11(b) and (d). It can be concluded that the realistic equivalent circuit model gives a very good estimation of the harvester behavior in both harmonic excitation and a natural environment.

Figs. 12 and 13 show a full-bridge rectifier circuit and corresponding output voltages respectively. To extract the maximum power, an inductor $L_{matching}$ 27 mH was used between the harvester and a full-bridge circuit. SB140 diodes from VISHAY were used as rectifiers. The output voltage was measured across a capacitor C_{out} of 3.3 μF.

Fig. 13(a) shows a measured output voltage at 20 Hz and 3 g. It took 1.5 s for the exciter to make stable vibration. A rectifier output voltage obtained by hand-shaking in Fig. 13(c) had larger variance in amplitude than that by the exciter. A simulation result at a regular force in Fig. 13(b) had a more stable voltage like a test result in Fig. 13(a). As shown in Fig. 13(d), a voltage simulated in case of a natural environment shows large variance as is shown in Fig. 13(c).

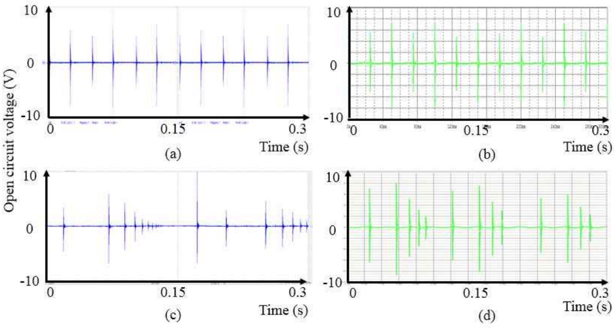


Fig. 11. Open-circuit voltages (a) measured voltage when the harvester was shaken by the exciter, (b) simulation results in case of a regular force, (c) measured voltage when the harvester was shaken by hand, (d) simulation results in case of natural vibration

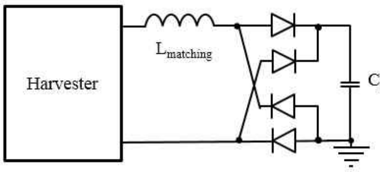


Fig. 12. Full-bridge rectifier circuit

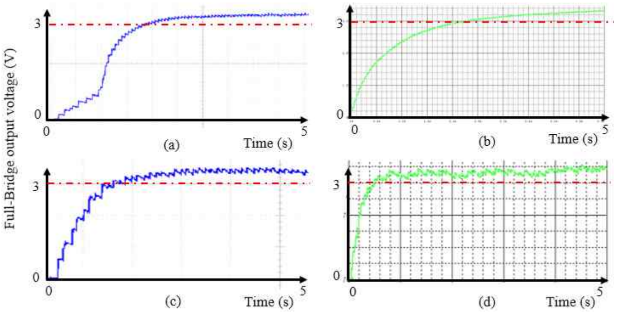


Fig. 13. Output voltage of a full-bridge rectifier (a) measured voltage when the harvester was shaken by the exciter, (b) simulation results in case of a regular force, (c) measured voltage when the harvester was shaken by hand, (d) simulation results in case of natural vibration

In summary, a vibration-based energy harvester in a natural environment shows rather unpredictable behavior such that the efficiency of the harvester tends to degrade compared with that obtained from harmonic excitation.

Our proposed circuit model can be used to accurately analyze system performance of a harvester in various situations.

IV. CONCLUSIONS

In this paper, a realistic equivalent circuit of a frequency-up-converting impact-based piezoelectric energy harvester has been presented. The harvester generated damped-oscillating signals with a higher frequency by an impact than the frequency of the applied force. A harmonic excitation made regular collisions at the up end and the bottom, which generated two asymmetric waveforms alternately at a regular interval. In a natural environment, the frequency and strength of vibrations varied from time to time. It generated voltage signals of various amplitudes, which were separated randomly and grouped with shorter intervals due to a freely movable ball. To describe these behavioral characteristics, the proposed circuit model used a voltage source described in Verilog-A. The model produces pulses timely according to the situation, and the pulse gets oscillated and decreased by other components of the model. This model was proven to give a good estimation of the harvester behaviors by comparing the experimental and simulated results. It can be used not only to predict one impact response and long term response of the harvester in a non-harmonic excitation but also to analyze the system performance in various situations.

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