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Transient Analysis of Self-Powered Energy-Harvesting using Bond-Graph

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Abstract : The transient phenomenon of self-powered energy-harvesting is assessed using a bond-graph method. The bond-graph is an energy-based approach to describing physical-dynamic systems. It shows power flow graphically, which helps us understand the behavior of complicated systems in simple terms. Because energy-harvesting involves conversion of power in mechanical form to the electrical one, the bond-graph is a good tool to analyze this power flow. Although the bond-graph method can be used to calculate the dynamics of the combining mechanical and electrical systems simultaneously, it has not been used for harvesting analysis. We demonstrate the usability and versatility of bond-graph for not only steady analysis but also transient analysis of harvesting.

Key Words : Energy-Harvesting, Piezoelectric, Bond-Graph, Transient Analysis

1. Introduction

Energy harvesting extracts electrical energy from different forms of energy in the environment such as solar energy, wind energy, heat energy, and vibration energy. Since there are many structures that display mechanical vibrations, vibration-based energy harvesting is of interest for many researchers [1]. Many studies on vibration-based harvesting utilize piezoelectric-material to harvest the vibration energy. One method of effective vibration-based harvesting is based on electrical tuned-mass-damper mechanism [2, 3]. Especially, the synchronized switch harvesting on inductor (SSHI) technique [4, 5] draws much attention because SSHI technique efficiently harvests vibration energy by using an inductor and an on/off switch. SSHI was improved by reducing the power-consumption of device [6]. However, SSHI needs a controller for switching-action, which is a disadvantage of the technique. The control device is power intensive and requires an external power supply. In order to solve the power-supply problem, a novel self-powered system employing a digital processor was invented [7]. The digital unit enabled the harvesting

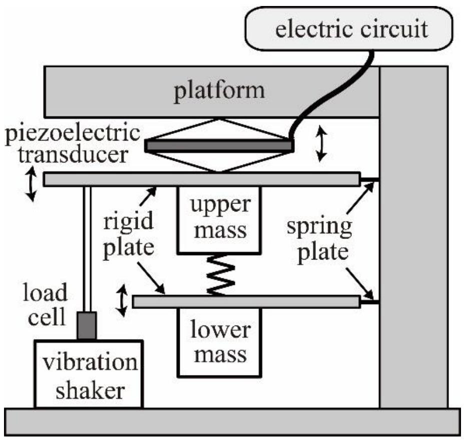

Fig. 1 Experimental Setup for Harvesting

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system to implement complex calculations and to harvest energy from complex vibrations. The digital processor can be driven by harvested energy, leading to a self-powered system that does not need an external power supply. Figure 1 shows an experimental mechanical system for energy harvesting, which consists two masses, two rigid plates, two spring plates, a vibration shaker, and a piezoelectric transducer. The transducer is connected to a harvesting circuit and a storage capacitor. When the structure is vibrated by the vibration shaker, a piezoelectric transducer generates electric voltage. The voltage gradually increases owing to the structural vibration. Figure 2 shows an essence of our self-powered energy harvester. The energy is transferred to the digital processor through a DC/DC converter, and the processor can be driven by the energy harvested from structural vibration. The digital processor calculates the state of vibration to regulate the switches in the harvesting circuit. The digital processor intermittently outputs a control signal to the switches. Then, the harvester achieves efficient harvesting completely without any power supply and control management from the outside. Consequently, this energy harvesting system with the digital unit can be considered a self-powered device.

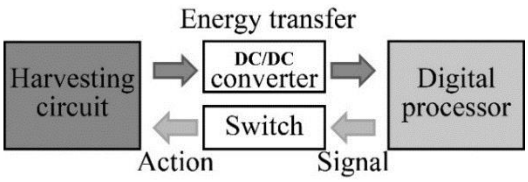

Fig. 2 Essence of Self-Powered Circuit

Although the self-powered system works well for various applications [8, 9], the harvesting circuits are very complicated. It is difficult to analyze its performance using conventional methods of computational simulation. In particular, the self-powered harvester has a multi-bifurcated and looped power flow that requires a flexible and sophisticated simulation method for the power analysis. To develop high-efficiency harvesters, performance analysis of the harvesters is inevitable.

2. Bond-Graph Model Creation of Harvesting Components

We feature the bond-graph [10] that is a power-based approach for describing physical-dynamic systems. It shows power flow graphically, which helps us analyze the behavior of complicated systems in simple terms. A bond-graph model of the self-powered energy harvester is needed to evaluate the performance of the harvester from a power viewpoint. To the best of our knowledge, there have not been power analyses of energy harvesters using the bond-graph calculation. Some bond-graph models of the harvester’s components need to be created. We consider three models: the piezoelectric-transducer model, the diode-bridge model, and the harvesting controller model. These models are used in bond-graph simulations for the self-powered energy-harvester. Since the bond-graph model of the self-powered energy-harvester is very complex to build as a whole, we create the bond-graph models for individual elements. By assembling the individual models, we build the bond-graph model of the self-powered energy-harvester.

The bond graph describes a physical system in terms of “effort” and “flow”. In the mechanical behavior, force is the effort, and velocity is the flow. In the electrical behavior, voltage is the effort, and current is the flow. Table 1 shows the different variables in the physical field.

There are three basic components of the bond graph: C, I, and R. The C and I elements are used to model the phenomenon that relates the effort to the displacement and the flow to the momentum. The C element acts as a spring or a capacitor (energy storage described by a generalized displacement variable), and the I element acts as a mass or an inductor (energy storage described by a generalized momentum variable). The R element is a power dissipative element that acts as a damper or resistor. These elements are tied by a 0-bond or 1-bond. The 0-bond is the constant-effort point such as two elements associated with the same velocity or current. The 1-bond is the constant-flow point such as two elements associated with the same force or voltage. Table 2 lists the components of a bond-graph.

The greatest advantage of the bond graph is that it can be applied to systems in which their electrical components change (*e.g.*, by inserting, removing, or swapping the components). Further, the bond graph solves algebraic equations instead of differential equations. Simulations that solve differential equations are not as effective in simulating these systems because the differential equations have to be reconstructed to adjust for the change when the components change. For more details on bond graphs, see Karnopp et al. [10]

Table 1 Power and Energy Variables in Mechanical and Electrical Fields

	Mechanical rotation	Mechanical translation	Electricity
Effort (e)	Force F [N]	Torque τ [N·m]	Voltage V [V]
Flow (f)	Velocity $\dot{x}$ [m/s]	Angular velocity ω [rad/s]	Current i [A]
Momentum (p)	Momentum P [N·s]	Angular momentum p [N·m·s]	Magnetic flux φ [Wb]
Displacement (q)	Displacement x [m]	Angle θ [rad]	Charge Q [C]

Table 2 Basic Components of Bond-Graph

Component	Exposition	Relation
I	Mass or inductor	$f = f_{\mathrm{I}}(p)$
C	Spring or capacitor	$q = f_{\mathrm{C}}(e)$
R	Damper or resistor	$e = f_{\mathrm{R}}(f)$
0	Constant effort point	$e = \text{const.and} \sum f = 0$
1	Constant flow point	$f = \text{const.and} \sum e = 0$

3. Simulation of Self-Powered Energy Harvester

The overall bond-graph representation of the self-powered energy-harvester is illustrated in Fig. 3. Figure 4 shows the harvested voltage as a result of conventional harvesting and provides comparison between bond-graph simulations and experiments. Three capacitances of the storage capacitor were applied to the harvesting systems. The conventional harvesting was achieved with a diode-bridge and a storage capacitor. Both results agree very well, which leads to the validity of the bond-graph simulation. The converged voltage was 14.5 V, regardless of capacitance value. Figure 5 shows the voltage transition for self-powered harvesting, displaying comparison between bond-graph simulation and experiment results. This figure also demonstrates the high fidelity of the bond-graph to simulate experiments. The converged voltage of the self-powered harvester was 21.5 V, which was much higher than that of the conventional harvester (14.5 V). The superiority of the self-powered harvesting to the conventional one was clearly demonstrated in Figs. 4 and 5. Next, we will check whether the bong-graph can simulate the non-linear transition. Figure 6 is the magnified view of Fig. 5 around a voltage of 5 V. This figure shows that the bond-graph can simulate the non-linear transition beautifully. The 4.7 V is the threshold voltage value where the digital processor systems starts to function. Below this threshold, the processor kept the sleep mode. When the charged voltage becomes greater than the threshold, the processor enters the wake-up mode and starts to work.

4. Conclusions

In this paper, the harvesting performance was assessed using the bond-graph method that was a graphical analysis technique. The switching action increased the harvested energy, which was active harvesting. The active harvesting involving a digital processor leads to higher harvested-energy than passive harvesting. The self-powered harvester was controlled by the digital processor that was in turn powered by the harvested energy. Because the transient of harvesting was too complicated to evaluate using conventional calculation methods, this paper featured the bond-graph method to handle the transient state of energy-harvesting. We confirmed that the self-powered harvester produced higher harvested voltage than the conventional one did. The nonlinear phenomenon of harvesting was simulated precisely with the bond-graph method. The bond-graph simulation agreed with the experimental results even at the transient state. We hope that the bond-graph method will be utilized extensively for energy-harvesting analyses.

Acknowledgement

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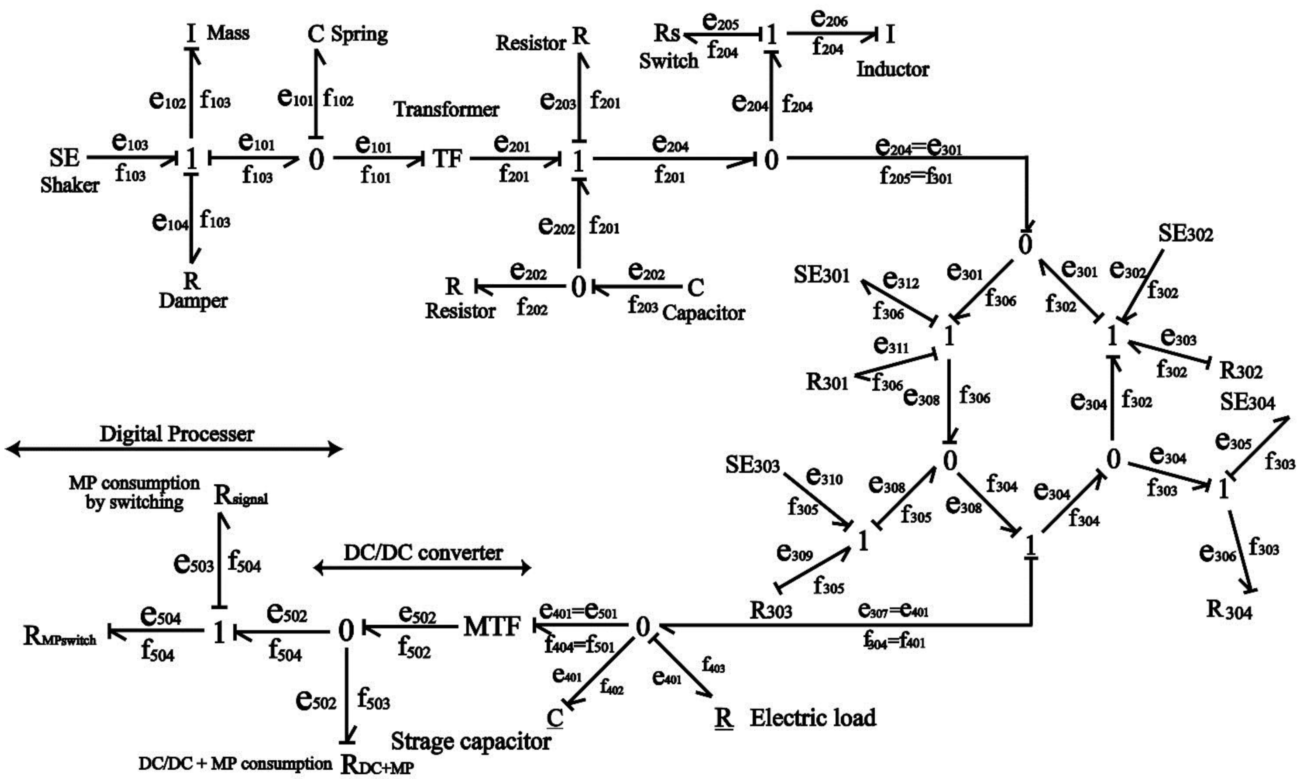
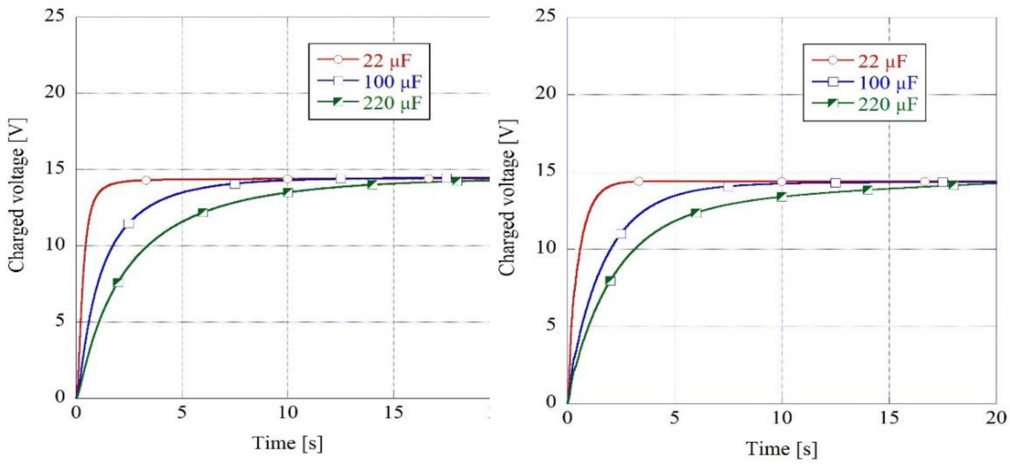
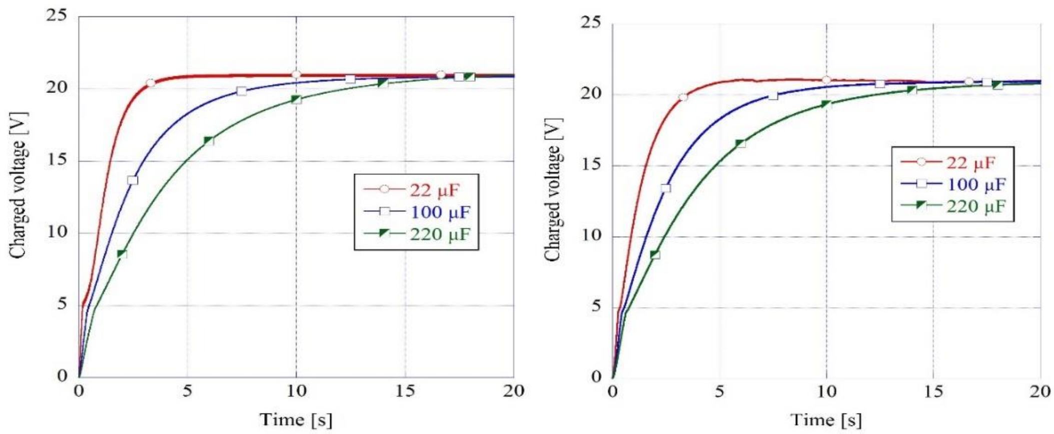


Fig. 3 Overall Bond-Graph Representation of Self-Powered Energy-Harvester



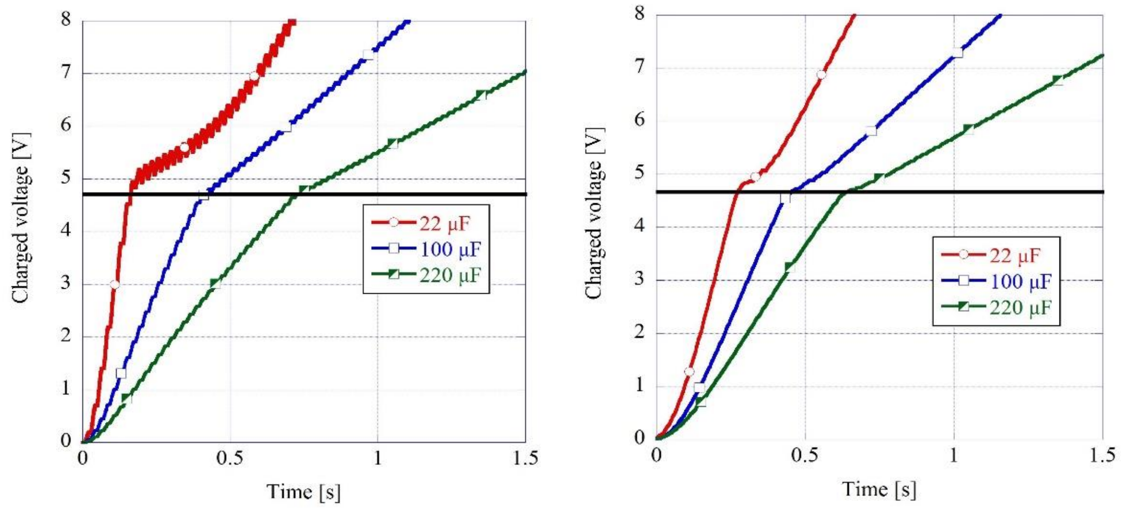
(a) Bond-Graph Simulation (b) Experiment

Fig. 4 History of Harvested Voltage for Conventional Harvesting



(a) Bond-Graph Simulation (b) Experiment

Fig. 5 History of Harvested Voltage for Self-Powered Harvesting



(a) Bond-Graph Simulation (b) Experiment

Fig. 6 Magnified View of Fig. 5