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A switched-mode piezoelectric interface circuit for dynamics sensing, energy harvesting, and vibration excitation multi-functional purpose

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ABSTRACT

Piezoelectric materials are versatile. They were made into various successful engineering products, such as sensors, actuators, and generators. However, almost all of the previous designs were found only capable of one specific function among those three. From a more fundamental physical point of view, a piezoelectric element, as a transducer, provides a bidirectional channel for energy conversion between mechanical and electrical domains. It makes no bias to any of those functions. This paper analyzes the obstacle against developing multi-functional piezoelectric devices, clears that barrier, and further proposes a switched-mode interface circuit towards an unprecedented multi-functional piezoelectric design. It was developed based on a buck-boost switched-mode circuit. By properly controlling the switch actions, this interface circuit can realize all functions of dynamics sensing, energy harvesting (generation), and vibration excitation (actuation) in a time-sharing manner. The dynamics sensing function is realized according to the time ratio between piezoelectric capacitor discharging (through an inductor) and the inductor's freewheeling. The discharging period is set to be as short as possible to avoid much interference to the stored charge of the piezoelectric capacitor, which is related to the dynamic displacement. The energy harvesting function is carried out by discharging the piezoelectric capacitor through an inductor (more drastically than that in sensing mode). The extracted energy in the inductor then freewheels into a storage capacitor. For the vibration excitation function, the control logic reverses. It first pumps energy from the storage capacitor to the inductor, then freewheels the energy to the piezoelectric capacitor. The actual control scheme is more complicated because the piezoelectric voltage is an ac output. The multi-functional design should comprehensively consider the discharging and freewheeling requirements under positive and negative polarities. Under these working principles, a prototyped multi-functional piezoelectric interface circuit is implemented and tested. The three functions are successfully demonstrated. By making a comprehensive collaboration between piezoelectric transducers and power electronics, this design starts a new chapter for the applications of piezoelectric materials toward multi-functional engineering designs.

Keywords: piezoelectric transducer, switched-mode power converter, buck-boost converter, multi-functional device

1. INTRODUCTION

As a kind of smart material connecting mechanical and electrical domains, piezoelectric materials are widely used in many applications. They were made into different engineering products such as sensors, actuators, and nano-generators. From a general physical point of view, a piezoelectric transducer provides an unbiased electromechanical coupling interface. Whether a transducer is used for information acquisition or power conversion is specified according to the later engineering designs. In the energy harvesting application, the interface circuit realizes AC/DC conversion and stores the DC energy in a storage device, such as a super-capacitor. As shown in figure 1(a), in these designs, energy flows from the piezoelectric element to the storage device, while a part of the energy might be dissipated during energy conditioning. Some designs adopt the synchronous switch technology for boosting the harvested power, for example, the synchronous electric charge extraction (SECE),[1,2] synchronized switch harvesting on inductor (SSHI),[3,4] and their derivatives.[5–7] External sensors sense the peak

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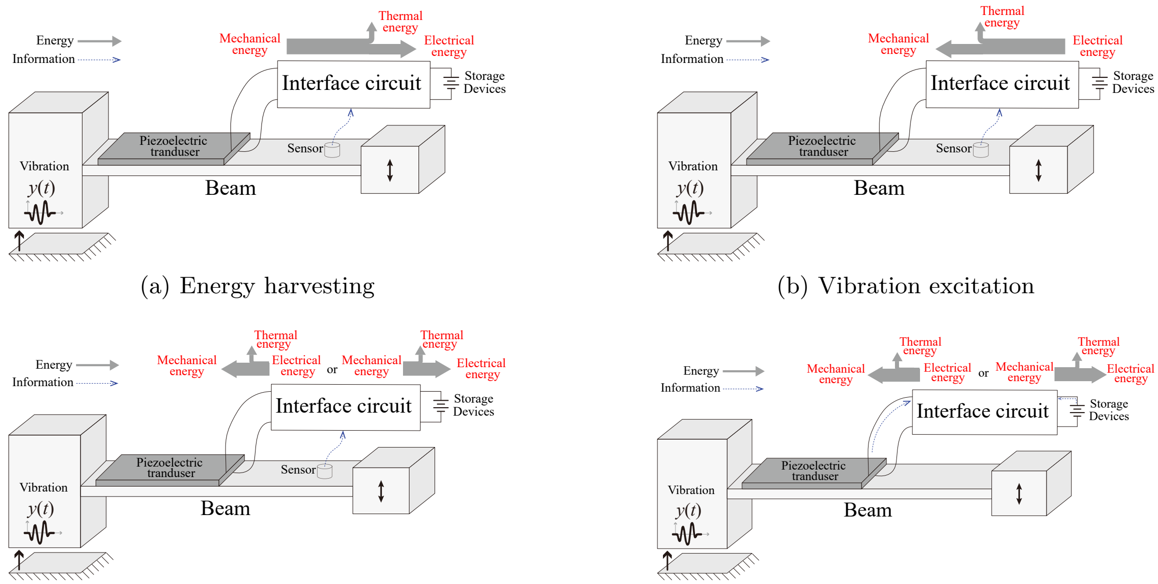


(a) Energy harvesting

(b) Vibration excitation

(c) Bidirectional energy conversion

(d) Multi-functional device

Figure 1. The energy flow pictures within some typical piezoelectric devices.

voltage instants, at which we carry out the synchronized switch actions. In the vibration excitation case, energy is injected from the storage to the transducer to excite the mechanical structure. The corresponding energy flow is shown in figure 1(b). External sensors are also necessary for providing feedback signals toward closed-loop positioning or vibration control.[8–10]

The energy conversion channel of the piezoelectric transducer is inherently bidirectional. The specialization was basically introduced by circuit design under specific application scenarios. Recently, there are some bidirectional energy conversion circuits designed for time-sharing energy harvesting, and vibration excitation purpose.[11] They are utilized to excite the high-energy orbit vibration in nonlinear piezoelectric energy harvesting application.[12] The energy flow picture of a bidirectional piezoelectric device is shown in figure 1(c). In those designs, the sensing function was realized by using external sensors.

It is curious that whether a single piezoelectric interface circuit can help realize all possible functions of a piezoelectric device, say, sensing, actuating, and energy harvesting. Since high-efficiency energy conversion is a prior design criterion for any power conditioning circuit, this circuit should be developed based on the switched-mode power electronics, which has enabled efficient power conversion in many successful applications. The concept of a multi-functional piezoelectric device is shown in figure 1(d). Besides the bidirectional energy conversion capability, this design incorporates the sensing function, which was implemented externally in figure 1(c). Such a self-contained multi-functional convenience was unprecedented in the piezoelectric devices.

2. CIRCUIT DESIGN AND WORKING PRINCIPLE

The topology of the multi-functional piezoelectric circuit (MFPC) is shown in figure 2. The piezoelectric equivalent consists of an equivalent current source i_{eq}, whose value is proportional to the vibration velocity, the piezoelectric capacitance C_p, and the dielectric resistance R_p. As an AC source, the piezoelectric element is connected to the main circuit by a bidirectional switch S_1. There are four shunted paths in the main circuit. The voltage reference path is composed of four diode-connected transistors and the switch S_2. It provides an absolute voltage reference $2v_{be}$ for calibrating the piezoelectric and storage voltage levels during dynamics sensing. Two storage paths composed of S_3, C_{rp} and S_4, C_{rn} offer positive and negative rails for energy conversion, respectively. The inductive path, which is composed of L_i and two oppositely connected diodes, acts as a medium or interchange in every step of energy transfer. It is an extended buck-boost converter, which can handle bidirectional current flow for AC sources. The sensing function is newly added in this design. The ratio

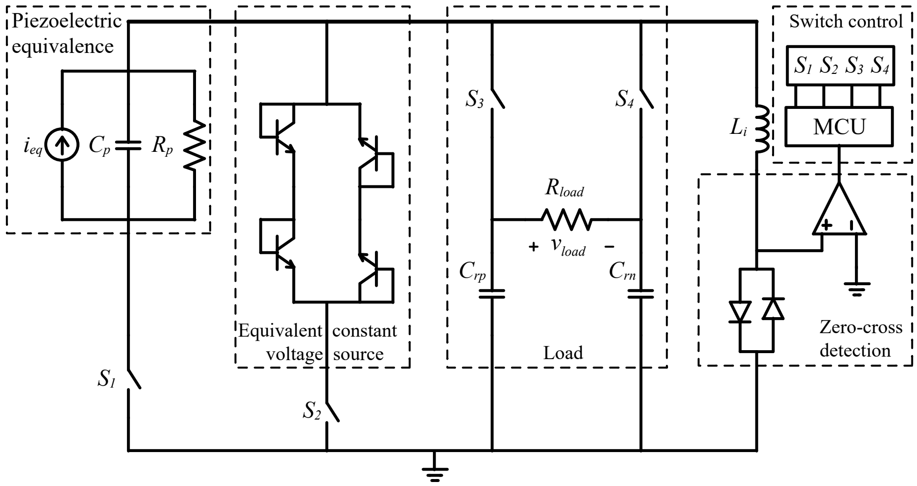


Figure 2. The MFPC circuit.

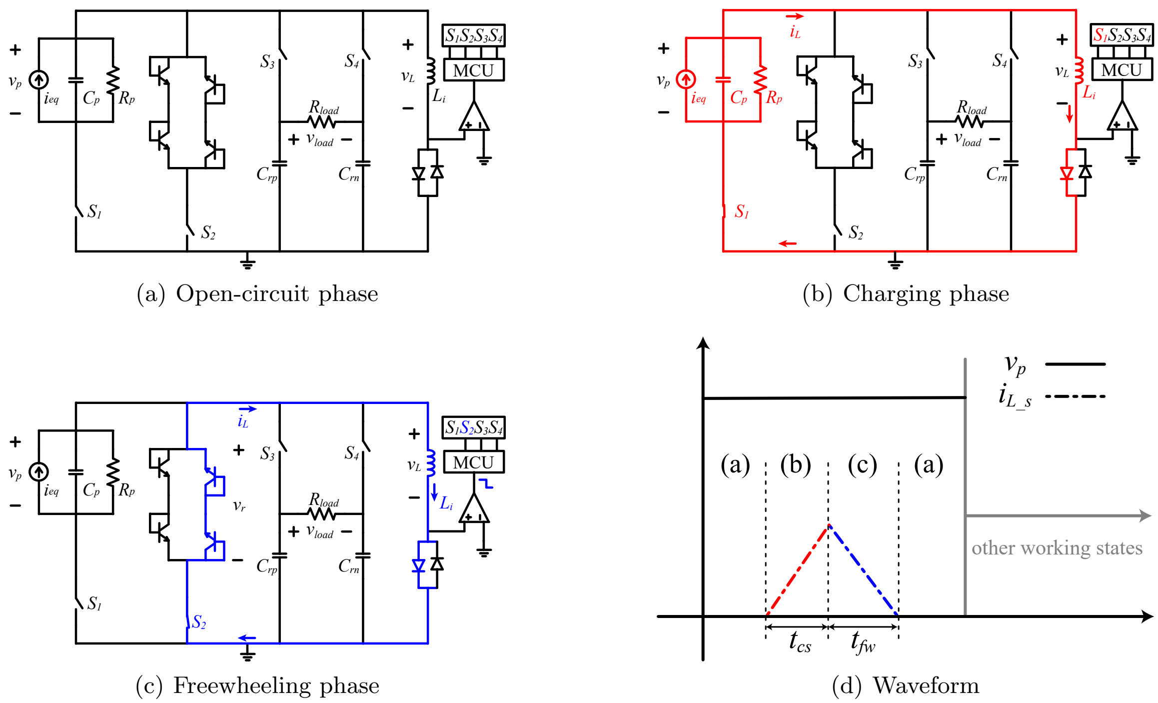
between the inductor charging and freewheeling intervals in discontinuous conduction mode (DCM) contains the relative information between energy source and destination in each switching action in the buck-boost circuit. The zero-crossing detector in figure 2 is used to collect such a relative relation. The relative relation is sufficient to figure out the maximum or minimum piezoelectric voltage points in every cycle. For better knowledge about the absolute value, we need to use the voltage reference path. The switch controls of all functions are carried out by a micro-controller.

2.1 Dynamics Sensing

The dynamics sensing function of the multi-functional interface circuit is realized by switch actions with very small intervals. Dynamics sensing function can be realized by sampling the voltage across the piezoelectric transducer. The working phases include the open-circuit phase, charging phase, and freewheeling phase, as shown in figure 3. When the interface circuit works in voltage sensing state, the micro-controller turns on the switch S_1 for a constant time t_{cs}. The conducting path is shown in figure 3(b). This constant period is set as short as possible to reduce the influence on the charge in the piezoelectric transducer. This stage can be regarded as charging the inductor at a constant voltage, i.e., v_p is almost constant during discharging. Therefore, the slope of the inductor current $\mathrm{d}i_L/\mathrm{d}t = v_p/L_i$. Then the micro-controller turns on switch S_2. The inductor current freewheels through the diode-connected transistors, such that the voltage across the inductor L_i is clamped at a constant voltage v_r, as shown in figure 3(c). During the freewheeling phase, the slope of the inductor current is $\mathrm{d}i_L/\mathrm{d}t = -v_r/L_i$. The freewheeling phase ends when i_L crosses zero. The zero-crossing moment is detected by the comparator, such that the micro-controller can immediately record the freewheeling interval t_{fw} and guess the value of the piezoelectric voltage $\tilde{v}_p = v_r t_{fw}/t_{cs}$. At the end of the freewheeling, the interface circuit returns to the open-circuit phase and waits for the next working state.

2.2 Energy Harvesting

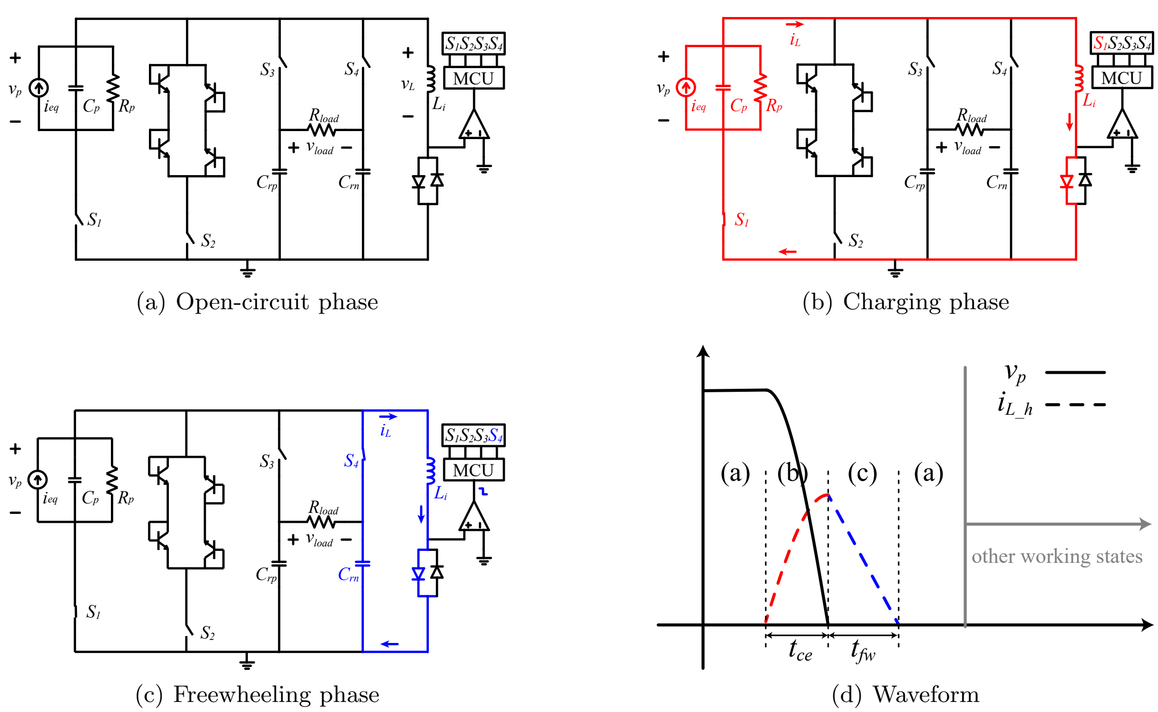
The energy harvesting function is similar to the SECE approach. The working phases and waveform of the energy harvesting function are shown in figure 4. First, the micro-controller turns on switch S_1 for a constant interval, whose duration is $t_{ce} = (8\pi\sqrt{L_i C_p})^{-1}$, a quarter of an LC cycle. At this moment, the voltage across the piezoelectric transducer falls to zero because of the charge extraction, as shown in figure 5(b). After that, S_4 is turned on, the inductor current freewheels into the storage capacitor C_{rp} or C_{rn} respectively for either of the two different current directions, as shown in figure 5(c). The freewheeling phase ends at the falling edge of the zero-crossing detecting comparator. After the charge extraction, the interface circuit returns to the open-circuit phase. To carry out the charge extraction at maximum piezoelectric voltage instants, we have to carry out the synchronization. It is realized through a uniform sampling procedure and peak identification based on the sampled data. The energy harvesting and dynamics sensing functions are carried out in a time-sharing way.



(a) Open-circuit phase (b) Charging phase

(c) Freewheeling phase (d) Waveform

Figure 3. The working phases and waveform of dynamics sensing function.

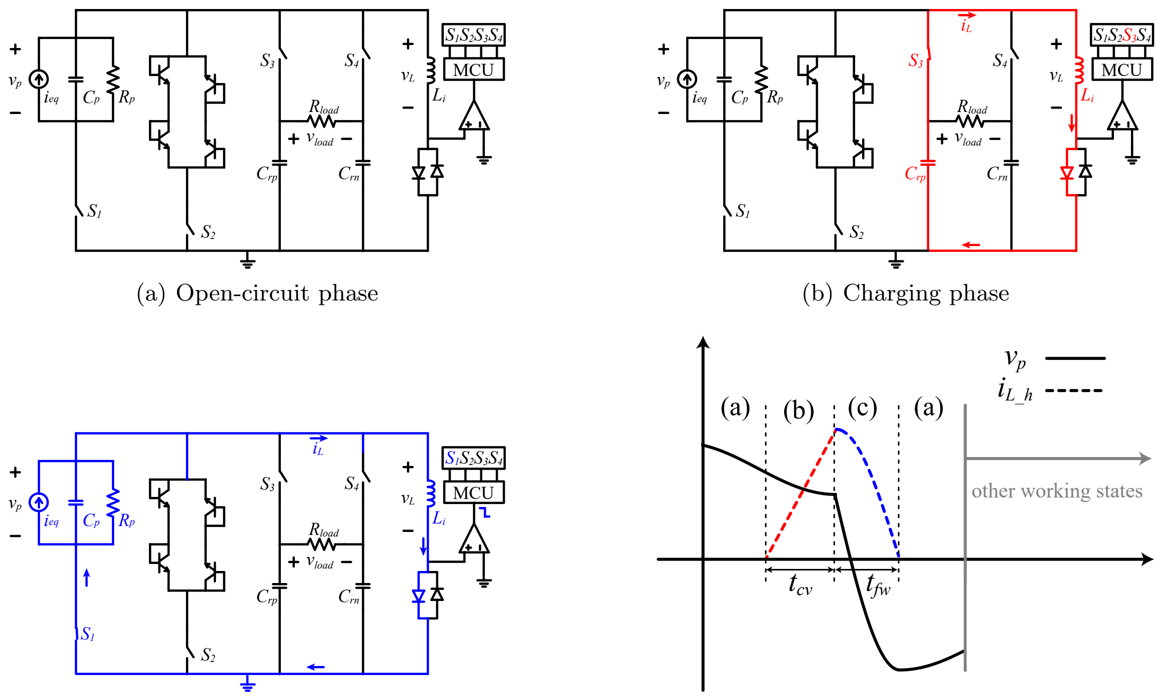


(a) Open-circuit phase (b) Charging phase

(c) Freewheeling phase (d) Waveform

Figure 4. The working phases and waveform of energy harvesting function.

Given the possible delays in uniform sampling and peak identification, the instants of charge extraction might be more or less later than the exact maximum voltage points. A detailed investigation of the effect of such a delay will be discussed in our future work.



(a) Open-circuit phase (b) Charging phase

(c) Freewheeling phase (d) Waveform

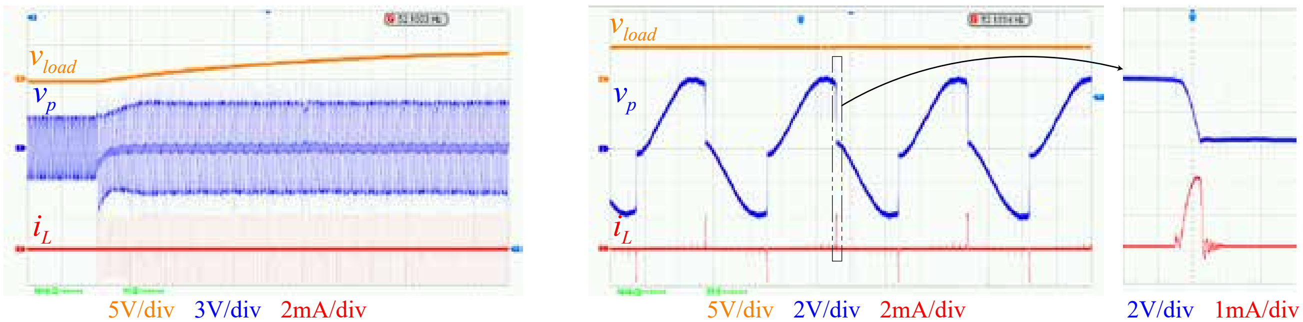
Figure 5. The working phases and waveform of vibration excitation function

(a) (b)

Figure 6. Prototyped PCB and mechanical structure.

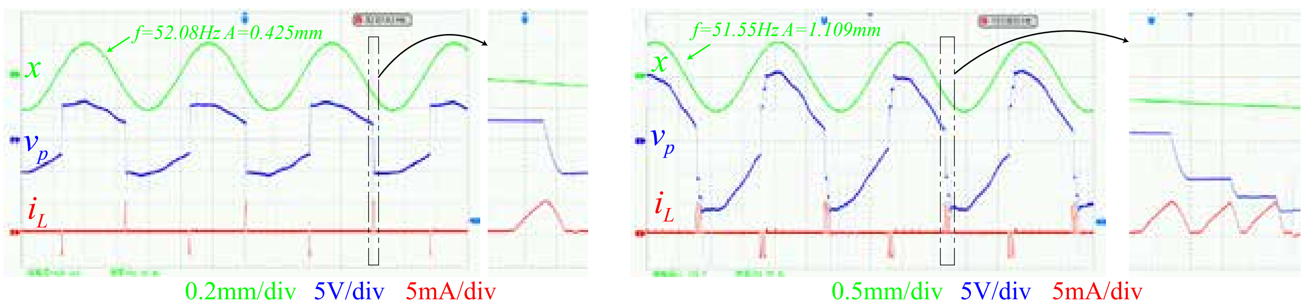
2.3 Vibration Excitation

The vibration excitation function is realized by the charge injection method, a reverse process of charge extraction. During the vibration excitation, the charge is pumped from the energy storage to the piezoelectric transducer for making a rapid change of piezoelectric voltage according to its current polarity, such that to ensure the energy flow direction from electrical to the mechanical domain. The operating phases and waveform are shown in figure 5. First, switch S_3 is turned on for a preset interval. The positive-rail storage capacitor C_{rp} (or negative-rail storage capacitor C_{rn}) charges the inductor L_i with an almost constant current slope $\mathrm{d}i_L/\mathrm{d}t = v_{rp}/L_i$ (or v_{rn}/L_i), as shown in figure 5(b). Then S_3 is off and S_1 is turned on, inductor current freewheels into the piezoelectric capacitor C_p, making v_p an opposite sign to i_{eq}. The freewheeling phase, whose conducting path is shown in figure 5(c), continues until i_L drains out. After that, all switches are turned off. The circuit returns to the open-circuit phase. Synchronization is also necessary for carrying out the energy injection function. It is realized in the same way through uniform sampling as the energy harvesting function does.



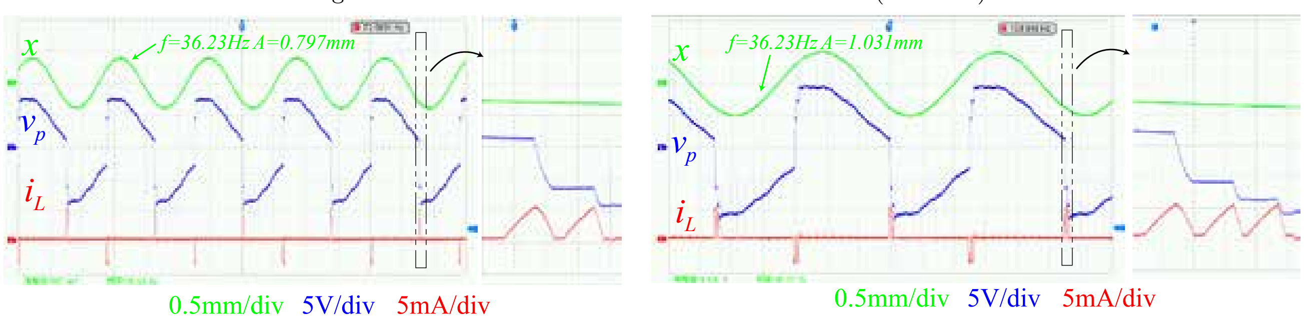
(a) (b)

Figure 7. Waveform in energy harvesting function.



(a) (b)

Figure 8. Waveform in vibration excitation function (52.08 Hz).



(a) (b)

Figure 9. Waveform in vibration excitation function (36.23 Hz).

3. EXPERIMENTS

The printed circuit board (PCB) and mechanical structure used in the experiment are shown in figure 6. The sampling frequency in sensing $f_s = 800$ Hz is preset in the micro-controller program. Adjusting the resonance frequency can be achieved by moving the position of the mass.

In the energy harvesting experiment, the piezoelectric cantilever beam is subjected to a harmonic base excitation, whose frequency is $f_0 = 52.08$ Hz and acceleration magnitude is 1 m/s^2. Figure 7(a) shows the waveform of the piezoelectric voltage v_p and load voltage v_{load} during storage charging. Figure 7(b) shows the enlarged view of several cycles at the end of this charging process. The peak detection and synchronized charge extraction are successfully realized by using the switched-mode voltage sensing function. Due to the delay in peak estimation, the switch instants are somewhat later than the voltage peaks.

In the vibration excitation experiment, there is no external excitation applied to the base. Two lithium

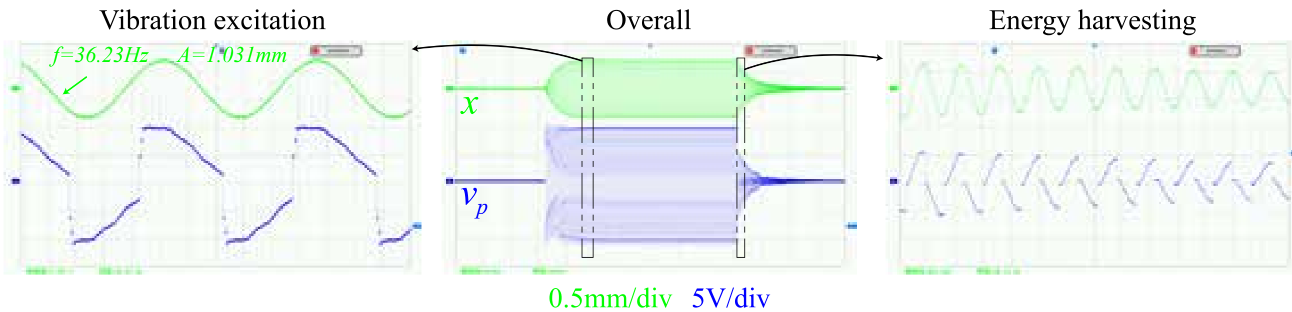


Figure 10. The waveforms of switching between vibration excitation and energy harvesting

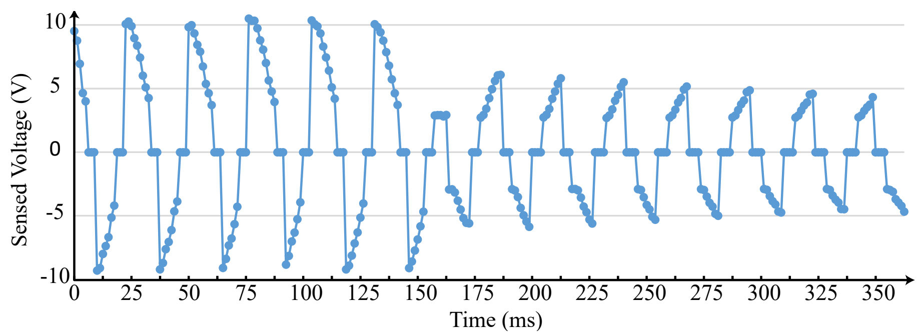


Figure 11. The voltage sensing results

batteries are connected to the load capacitors C_{rp} and C_{rn} as power supplies for vibration excitation. The piezoelectric voltage waveform and displacement information (obtained with a laser vibrometer OFV-552/5000, Polytec GmbH) of the cantilever beam are shown in figure 8(a). By repeating multiple steps of charge injections, the vibration amplitude can be further increased, as shown in the figure 8(b). The optimal switching positions should be the peaks and troughs of the displacement. As we can observe from figure 8, in the current experiment, there is some phase lead between the steep voltage jumps and the corresponding displacement extreme instants. Because when the piezoelectric voltage is small, the slope of the inductor current is small. The charging speed is too low to give a good result instantaneously. Therefore, the u-turns at small voltage levels below a certain voltage threshold are not easy to be identified in the current design. New algorithms will be developed in future designs for more precise synchronization. The synchronization is adaptive to structures with different resonant frequencies according to the sensed information. For example, when the end mass is moved closer to the free end, figure 9 demonstrates the same design can also successfully find the right instants for charge injections under a new resonant frequency.

In operation, the vibration excitation and energy harvesting functions can be switched freely according to the actual demand. One example is shown in figure 10. The cantilever beam starts from standing still, i.e., $x = 0$. It is excited for several periods until the displacement amplitude equals 1.031 mm. It later switched to the harvesting mode, in which the displacement decrease rapidly back to zero. The detailed waveform in vibration excitation and energy harvesting is consistent with the results of single-function cases. We have also extracted the switched-mode sensed result around the transition between vibration excitation and energy harvesting functions. The sensed waveform using the switched-mode technology is shown in figure 11, which shows a good agreement with the measurement results from an oscilloscope. As we can observe, there is a dead zone when the absolute value of v_p is smaller than about 3 volts. The switching phase lead in the excitation function is basically caused by the incompetency under small v_p.

4. CONCLUSION

A switched-mode piezoelectric interface circuit solution for a multi-functional device was proposed in this paper. The three functions of dynamics sensing, energy harvesting, and vibration excitation can be realized with the same circuit in a time-sharing manner. Such an interface circuit is designed based on a double-rail buck-boost converter, which can carry out bidirectional AC power transmission. The switched-mode interface circuit works under strong DCM operation. The piezoelectric transducer stays at the open-circuit phase most of the time. The voltage sensing function is realized based on the proportional relation between charging/freewheeling voltage phase is proportional to the inductor current slope. A zero-crossing detector is used to trigger an interrupt to the microcontroller for determining the freewheeling interval and calculating the piezoelectric voltage. The self-contained voltage sensing function offers convenience for locating the extreme voltage positions, where synchronized switch actions are carried out for performing charge extraction or injection. Compared with the previous single-function circuit solutions, this multi-function interface circuit solution provides unprecedented design freedom and compact topology towards future engineering designs.

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