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A novel method of Peak Detecting for Self-Powered Synchronized Switch Harvesting on Inductance Using Reed Switch

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Abstract

Synchronized switch harvesting on inductance (SSHI) has long been studied so as to enhance the power gain of piezoelectric energy harvesting. The idea of the SSHI is to launch an inductance to the circuit on the peak of the waveform so that the inductance resonates with the clamped capacitance of the piezoelectric patch. The resonance causes a rapid inversion of the voltage, which then the switch is turned off, halting the voltage on its inverted state. This technique enhances the power output when appropriate parameters are met. It is notable that detecting the optimal switching time is inevitable in this technique. In spite of the several simple ways already in use, such as voltage peak detection using bipolar transistor or zero velocity crossing detection, these methods requires a considerable amount of energy in respect to the harvested energy. On account of the harvesting efficiency, which the total harvested amount is from the scale of nano-watts to micro-watts, it is mostly impractical to introduce techniques or elements that requires external power sources or extra power consumptions when it comes to a high portion of energy loss considering the limited amount of energy harvested. Thereby, researchers have endeavored to realize the peak detecting in various mechanical and electrical methods so that little or few energies are required. In this work, we propose a new hybrid peak detecting technique utilizing reed switch, which is a non-contact mechanical method that requires little energy consumption. Using a pair of magnets as the proof mass, not only the resonance frequency can be easily tuned, it could also serve as the non-contact control of the reed switch. However, mechanical chattering, a phenomena which exists in all the mechanical switches, is yet to be solved. The phenomena of chattering is the contact bounce when the two metal parts of the switch strike together. In attribution to the elasticity and momentum, the two parts bounces off and on in the transient state for a short moment until settling down to stable. Experiments were conducted to find the losses due to the chatter, and to also find the performance of the new structure. Results showed a promising outcome of 88.9% in comparison to the external powered SSHI. The following sections are divided in to 5 parts: introduction to SSHI and some switching techniques, experiment setup, experiment results, discussion, and conclusion along with some plans of future work.

1. Introduction

Synchronized switching on inductance (SSHI) is a technique to improve the harvested power of the piezoelectric energy harvester, proposed by Lefeuvre et al during 2004 [1-3] originally introduced as synchronized switch damping (SSD) for vibration control [4]. With low electro-mechanical coupling systems, it was discovered that this approach could increase the harvested power by 400% in comparison to the standard circuit of a rectifier consisting four diodes. By applying a non-linear processing electronic circuit of a switch and an inductor to the standard rectifier, the switch was turned on and off on the maximum and the minimum of the mechanical displacement. On the triggering moment, the LC resonance of the inductance and the parasitic capacitance of the piezoelectric patch, was launched. This quick

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resonance was switched off after half the period, causing an inversion of the piezoelectric voltage. Since then, self-powered switching on inductance has long been studied on synchronized switching techniques. Some other techniques of synchronized switch harvesting (SSH) were afterwards proposed after the SSHI parallel and SSHI series (figure 1): DSSH[5], SSDCI [6], SECE [7], ESSH[8]... etc. [9]. However, using a complex circuit also remains and create new issues within the design, such as power efficiency, threshold voltage, frequency selectivity and also parasitic bandwidth filters.

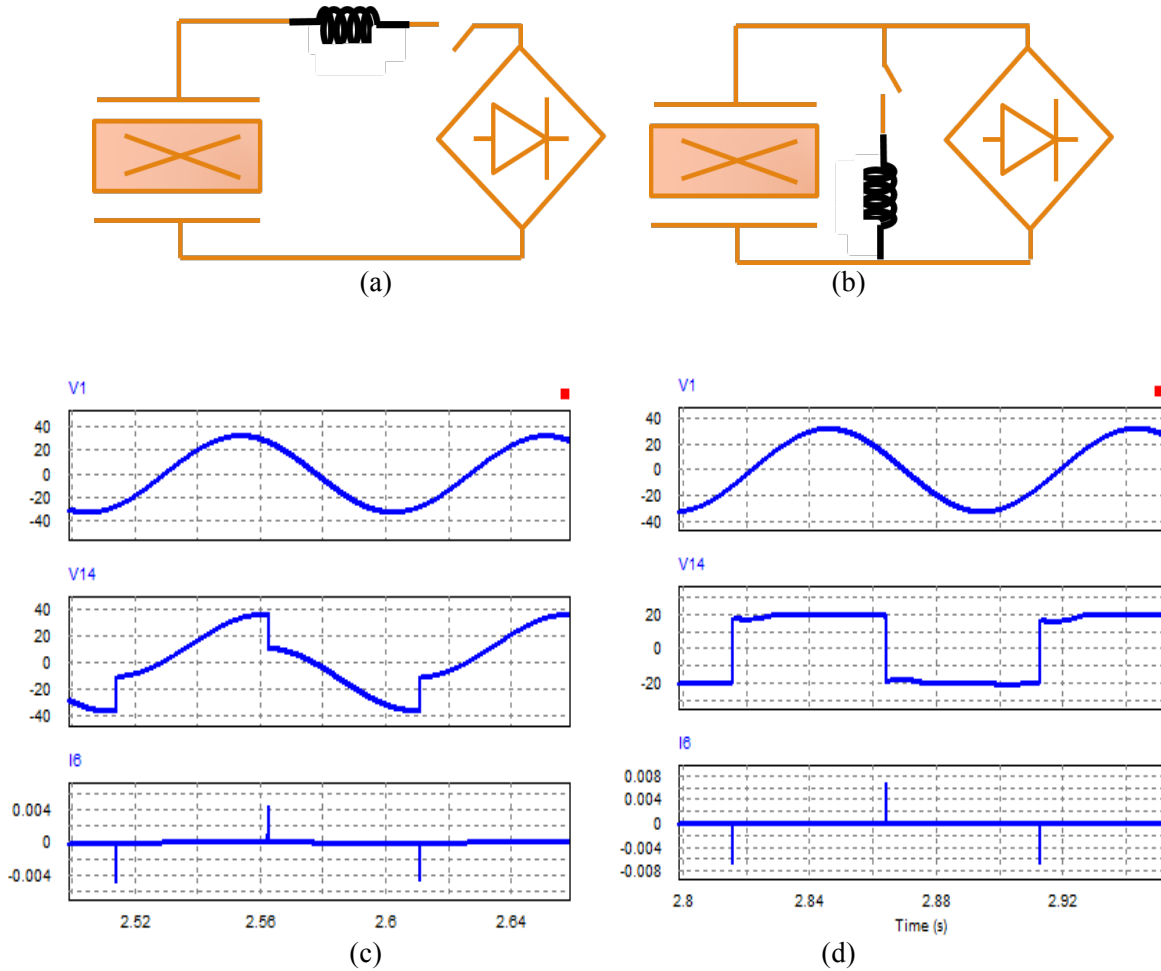


Figure 1. SSHI circuit (a) in the series form (b) in the parallel form (c) waveforms showing from top to low: neutral piezoelectric output, rectified voltage over the load of $2M\Omega$, and the correspondent current of a series SSHI connection (d) waveforms showing from top to low: neutral piezoelectric output, rectified voltage over the load of $2M\Omega$, and the correspondent current of a parallel SSHI connection.

One of the critical issues is to drive the switch on the correct instant. It would make no sense to use externally powered switches, while we aim to harvest power from the vibration. Therefore, a self-powered “smart switch” was developed for this task [2, 10]. The stand-alone smart switch utilizes a comparator and a voltage follower, acting as the energy source in the same time (figure 2.a) [11, 12]. The smart switch should be designed that the exerted energy itself is as little energy as possible. Other approaches of smart switches such as velocity controlled techniques were also introduced by Chen et al [13]. With the velocity control technique, the piezoelectric patch was divided in to three patches: a main patch, and two sub patches (figure 2.b). The main patch is for the main energy harvesting. As for the sub patches, one is for the velocity sensing and the other for supplying a comparator. The velocity sensor was

composed of a current sensing resistor, and a low pass filter to filter the high frequency noise. This sensor outputs the current trace as the form of voltage. Thence, with the comparator connected to the ground, the zero crossing point of the current, which is identical to the waveform maximum or minimum, can be defined. The comparator were provided its power supply of $+V_{cc}$ and $-V_{cc}$ by the other sub patch. By this mean, the maximum and minimum of the voltage signal could be detected and switched.

Comparing the two methods, we find that the smart switch requires one single patch, which is easier to fabricate and apply. Moreover, the transistors and the MOSFETs that were applied in the smart switch may require less power than the comparator. Yet the velocity control has a finer switching instant, attributing to that the threshold voltage of the transistors which are used for voltage comparisons. The differences between the voltage buffer and the piezoelectric voltage has to reach the threshold to trigger the switch, therefore there exists a small time lag in the self-powered switch.

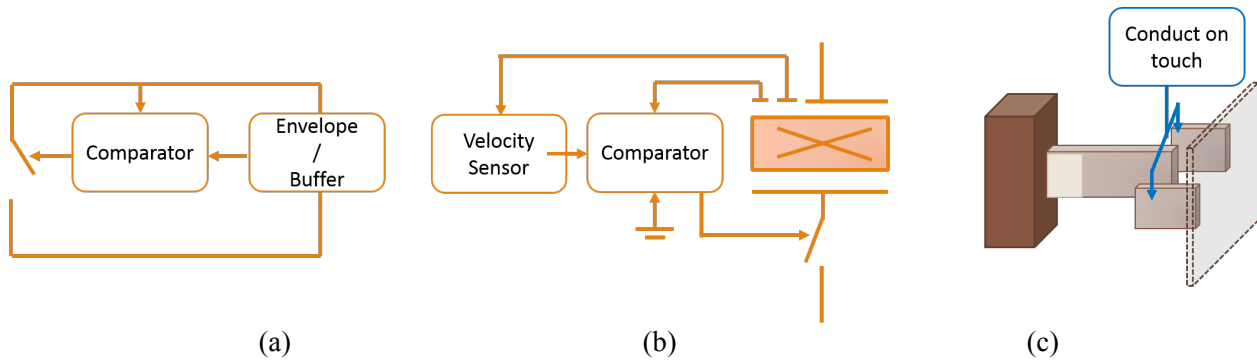


Figure 2. Schematic diagram showing the switching method of (a) electrical self-powered switch (b) electrical velocity sensing switch and (c) mechanical stopper switch.

Yet another method was the mechanical method. Wu et al had integrated stoppers, a method to increase bandwidth, with the mechanical switch [14] (figure 2.c). In their work, introducing the optimized synchronous electric charge extraction (OSECE) [15], as an improved version of SECE proposed by Lefeuvre et al [7]. By taking advantage of the stopper, the switch was switched on as the vibrating part impacts with the stopper. In this way, the components which may establish loss are merely two diodes and no extra energy was required. The outcome was superb, with a wide bandwidth, and enhanced power. Still, the impact of the beam may damage the piezoelectric patch itself, speeding up the fatigue time, and reducing the lifespan of the device.

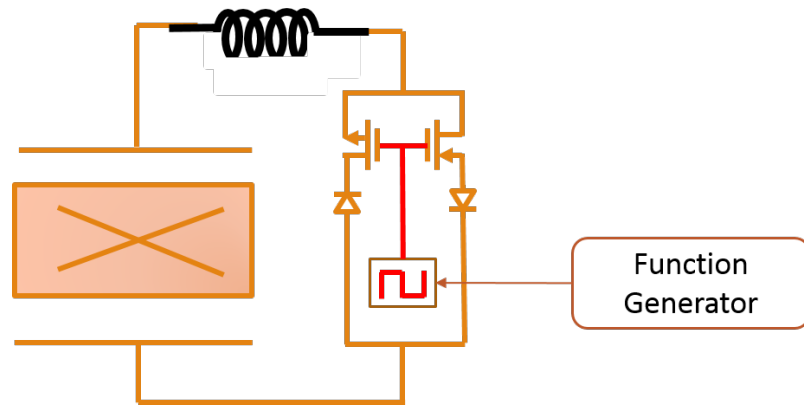


Figure 3. External driven switch demonstration.

Although externally powered switching is not practical in application, it is herein used for a standard, representing a loss-less switching. The method utilizes an extra set of signal from the function

generator, to provide an in-phase square wave for the driving of the NMOS and PMOS set (figure 3). The NMOS and PMOS were each connected to one diode to limit the current flow in single direction. Thereby, the two sets of switches forms a bidirectional switch. The driving power of the NMOS and PMOS are provided by the function generator, so as to consider zero power consumption. It is, however noted, that the cross voltage of the MOSFETs and the inductor resistive loss still do take up a small portion of energy.

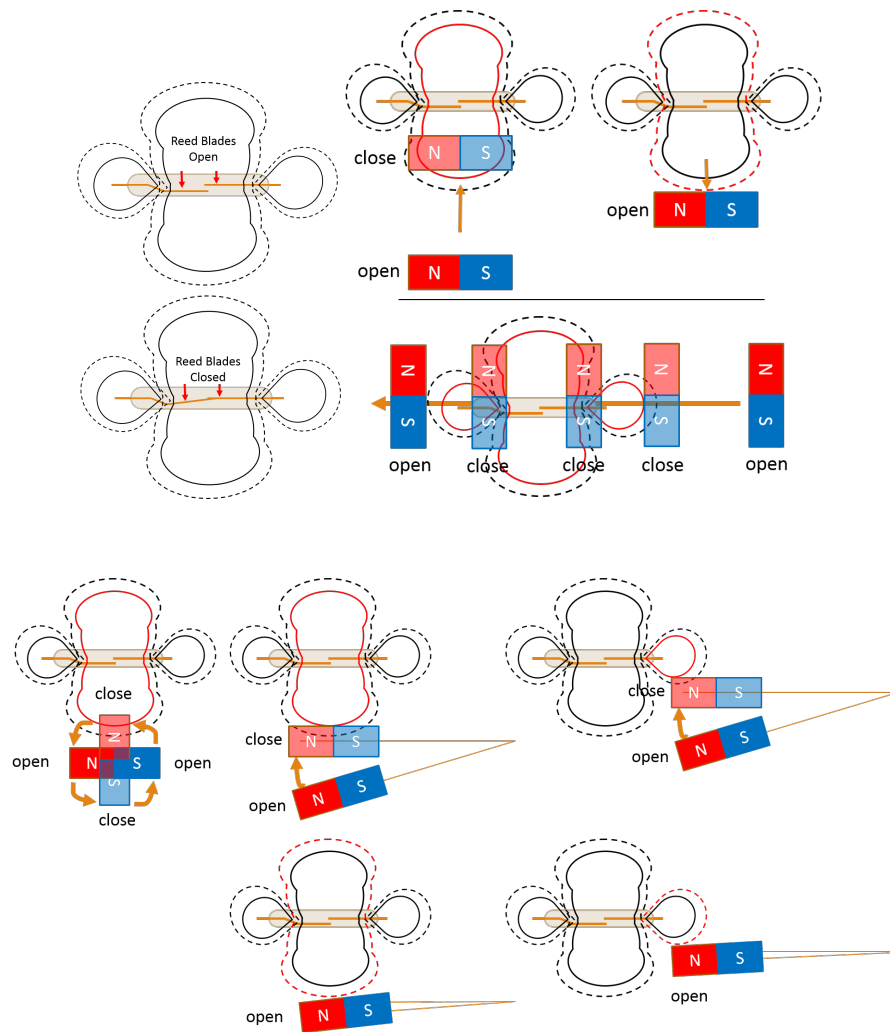


Figure 4. Various ways of triggering the reed switch via permanent magnets

2. Design Concepts and Setup

Reed switches are electrical switches, which can be driven and operated with magnetic fields. With the tiny reed blades enclosed within the glass casing, a normally open switch can be switched on when a

magnetic field approaches the reacting area (depicted as the solid line) (figure 4). The size of this area can be determined by the quantity of the magnetic field. As the magnetic field is removed from the hysteresis area that is a bit larger than the active area (as the dashed line in the plot), the switch would be re-opened. For the normally closed switch, it works vice versa. Opening when applied with magnetic field; reclosing when magnetic fields removed. The altering of the magnetic fields can be performed by different movements of magnets. The magnets can generate field changes with orthogonal, parallel, or rotary movements. Here in the case of cantilever beam, a pivoted motion is applied, using the wings of the active area. It has to be noticed that the fields are actually in three dimensional, therefore, choosing a smaller area, such as the wing, can reduce trouble of overlapping fields. Hence, by installing two reed switches in a solid place nearby the upper and lower tip of the beam, they can be used as mechanical detectors, detecting whether the magnet has reached the location.

Not only driving the reed switch, the magnets used in this work can also serve as the proof mass to tune the resonance frequency. The design concept is rather simple, that is, to use reed switch as a mechanical switch. As the beam wavers to the top, the switch is turned on and LC resonance is launched (figure 5). Unlike electrical switches, mechanical switches do not require extra power, nor does it need a threshold voltage. Therefore an ultra-low voltage operating SSHI can be realized. However, all mechanical switches are subjected to contact bouncing, cutting off the resonance and causing unwanted losses. Therefore an N-channel MOSFET was introduced as the circuit switch, making the reed switch to serve as the peak detector. With the parasitic capacitance of the MOSFET, the ringing was eliminated but nevertheless not sufficient. Thereby, a de-bouncer, such as a low pass filter, is inevitable to filter the chattering signals. Capacitances are required in low pass filters, and its quantity in our case, is decided by two rules: first, the capacitance should be able to provide the required power to drive the N-MOS switch; second, it should also be small enough to eliminate the chattering frequency of the mechanical switch. Hence, it is independent of the driving frequency, and can be used in different low resonance frequency occasions.

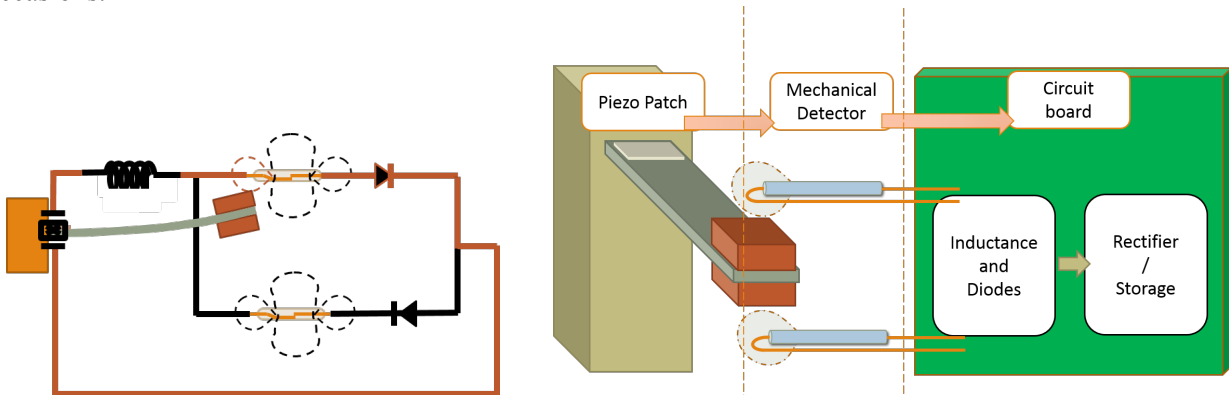


Figure 5. The design of the reed switching technique (a) circuit plot, brown lines indicating the active loop (b) system schematic diagram

3. Experimental Results

In the experiment, a National Instrument Data Acquisition Card© (NI-DAQ card) was used as the analogue-digital interface for driving and obtaining the signals (figure 6). To support with, a LabVIEW© program was created to operate the DAQ card. Attributing to the limited power of the DAQ card output, a power amplifier was set in between the shaker and the DAQ card, so that the shaker can be driven with

enough power. The output signal of the beam was connected to the parallel SSHI with the reed switches (figure 5.a), whilst the overall result could be sent back to the oscillator and, in the same time, the DAQ card while the shaker is at work. It is then the DAQ card which converts the signal, and offers the created interface program the collected signal so that we could perform analysis and information storage.

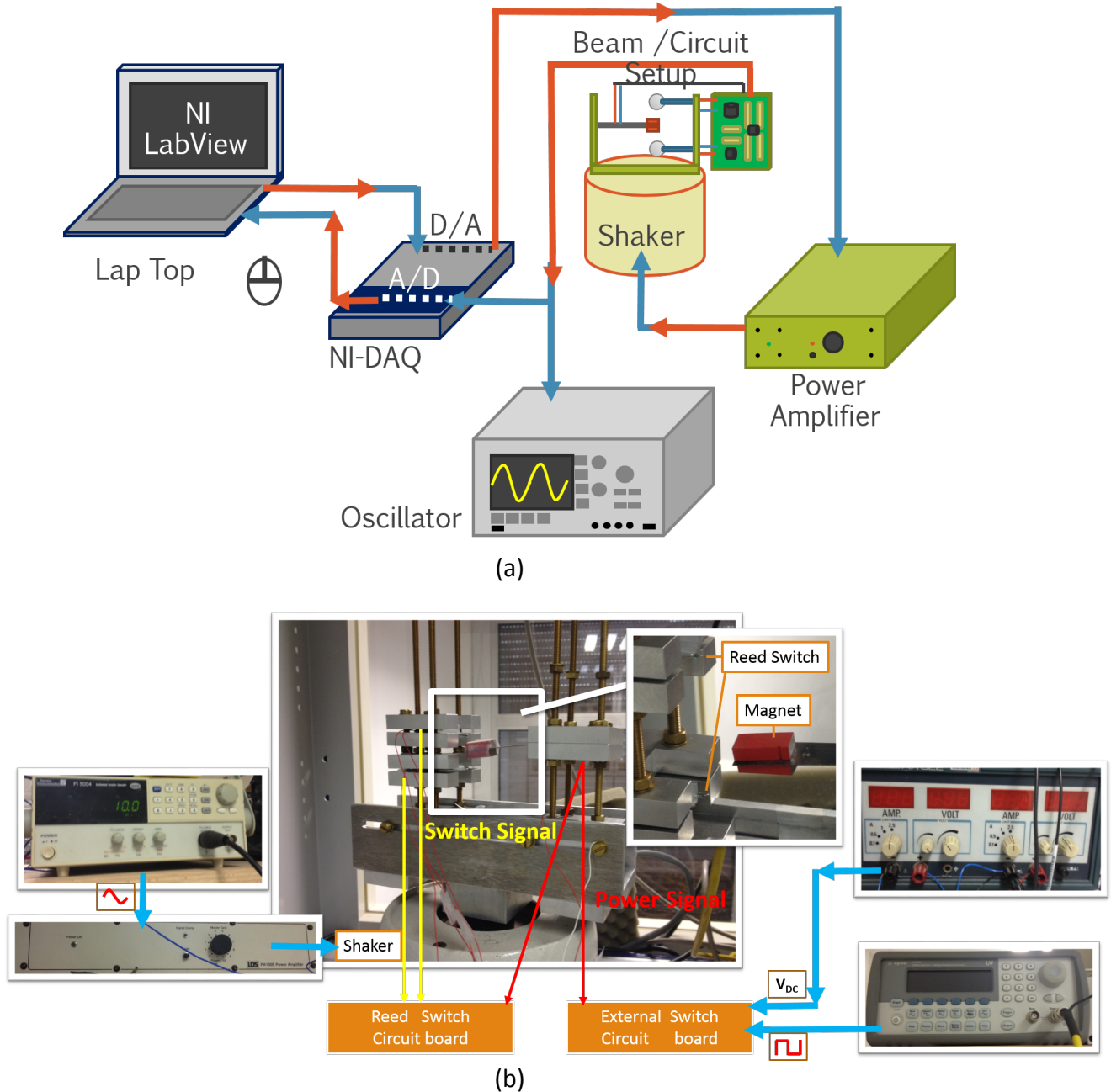


Figure 6. (a) Schematic diagram of experiment setup (b) realizing the experiment.

The experimental piezoelectric output voltage with reed switches is shown as waveform 1 in the figure 7(a). This voltage is preliminarily correct, with some time differences before the optimal switching time, indicated as wave form 3. However, there are considerable oscillations, which are also happening in the

switching instance. This phenomenon, called bouncing or chattering, decreases the inversion voltage in comparison to externally powered SSHI, as shown in the figure 7.b. Waveform 3 in both plots are the driving signal of the externally powered SSHI from a function generator, as a reference of the optimal SSHI, externally powered SSHI does not use any power from the piezoelectric beam to drive the switches. In the following section, we will look closer into the inversion moment, and inspect the chattering which occurs within.

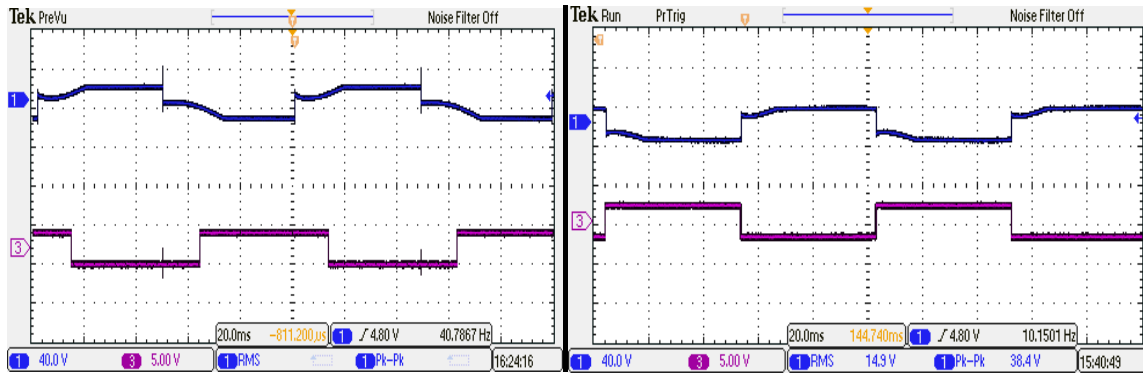


Figure 7. SSHI waveforms using (a) reed switch (b) externally powered switch. Waveform 1 indicating the piezoelectric voltage (rectified), and 2 indicating the function generator signal of optimal switching time.

Chattering

The chattering, or bouncing, as mentioned before, is a parasitic phenomenon of continuous on-off switching due to the elastic contact movement of the mechanical switch. This phenomenon, however, will cause unwanted LC oscillations and excessive load resistances within the inversion period, which lasts approximately one to a few milliseconds. There exist a one to two perfectly detachments, and several wavering contacts with lower contact resistances. The on and off switching and also the change between high and low resistances results in the redundant peaking oscillations, as shown in the figure 8.a. These oscillations which are attributed to the redundant closures causes power losses, exceeding currents and short drags in the inversion. The parasitic capacitance strikes on a LC resonance of a natural period in the scale of nano-seconds. This phenomenon occurs twice to three times each inversion, as shown in the figure 8.b.

Experiment was performed to observe how the reed switch works and also to examine the loss chattering causes. Parallel and series SSHI were introduced as the two standards to test the efficiency of the switch. Figure 9b shows the switching time of the external SSHI (on peak). Figure 9.c, shows the switching instant of the reed switch in comparison to the optimal time of the external SSHI. It is worth to note that, the reed switch, due to the mechanical hinder, can only be pre-switched in time rather than belated. It could be tuned in a more ideal location, however, it takes precision and the displacement is altered as the switching is launched. In figure 9.a, there were two overlapping curves both identified as classical rectifier, they were performed to ensure that the parallel and series SSHI were conducted in identical driving forces, with frequency of 10 Hz.

Result turn out that in series SSHI, the reed driven series SSHI has an efficiency of 88.9%, considering the external powered SSHI to be 100% as the reference. The externally powered enhancing effect of series SSHI in comparison to the classic was 2.42 folds. On the other side, the parallel connections show similar output, where the efficiency was nearly 100%. This result can be related to the topology of the circuit: for the parallel circuit, the piezoelectric patch was normally on. On closure, is the only moment that the switch loss take place. For this reason, the switch loss could have been less dominant in parallel SSHIs. One reason for the equally output can be that the reed switch possesses nearly

zero voltage drop, however the MOSFETs which were used as the electrical switches still requires small cross voltages. On the other hand, the circuit of series SSHI is normally open, and the current flows through the circuit only on the instant of switch closure. The bouncing would have lowered the transmitted current, which also pulls down the power output. Also all the current would pass by the switch, which had wavering loads. Hence with larger currents, the loss over the reed switch is more severe in comparison to the constant cross-voltage of the MOSFET switch.

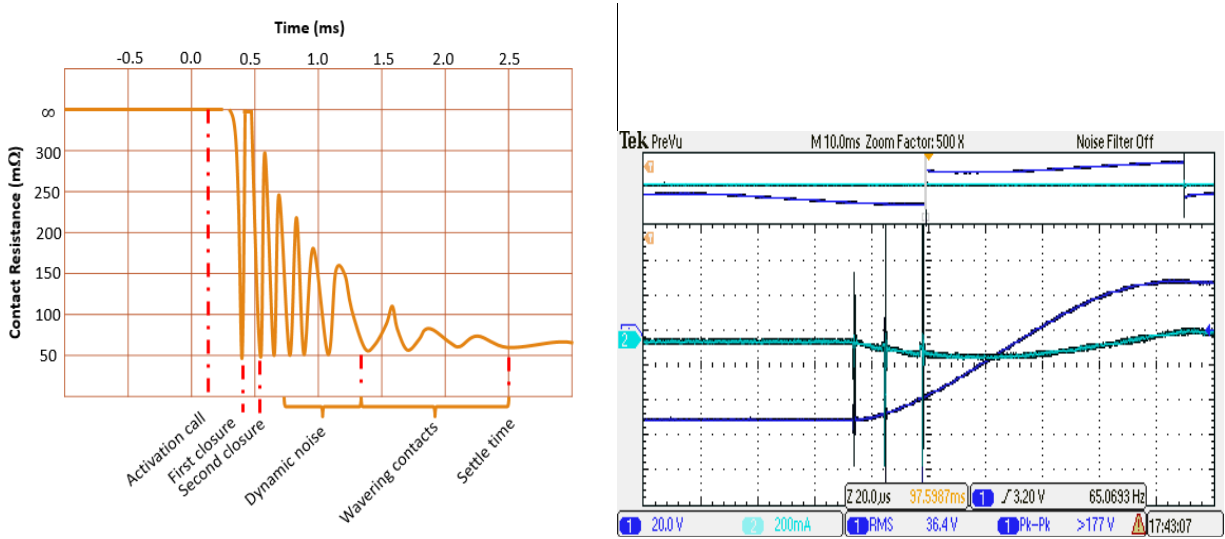


Figure 8. (a) the chattering response of reed switches (b) a inverting instance of reed switched SSHI with the presence of chattering

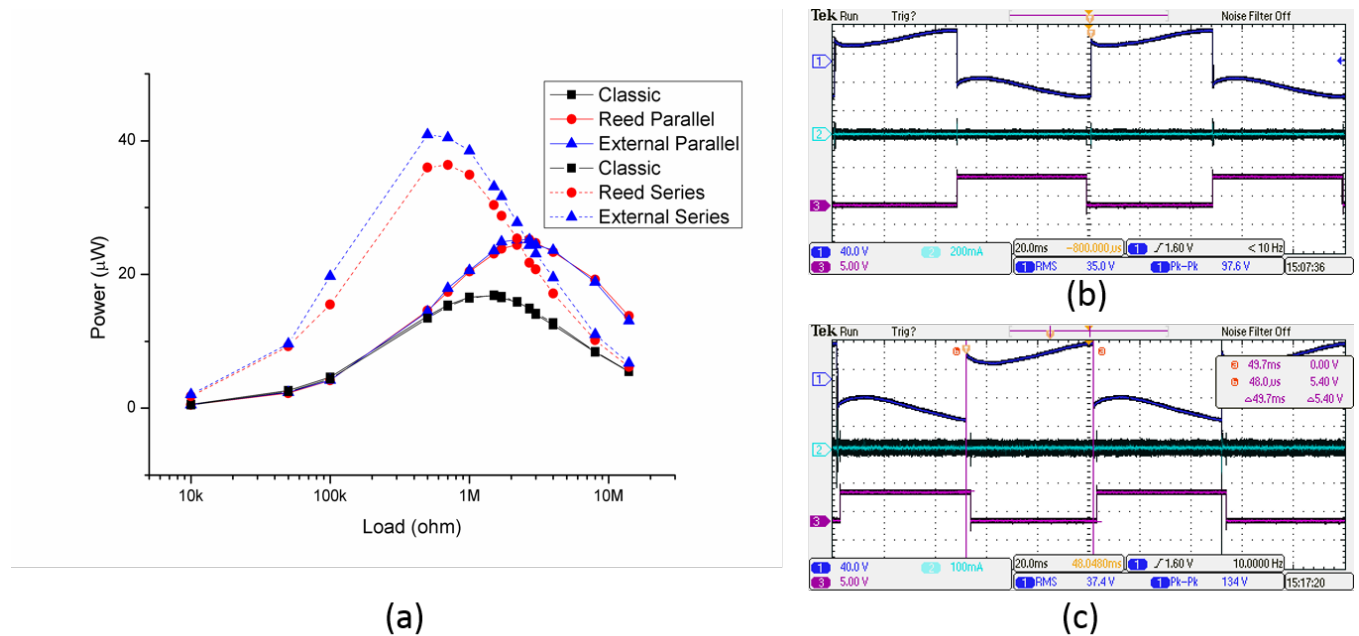


Figure 9. Experiment results showing open loop SSHI (a) comparing series and parallel SSHI with classical circuit, externally powered switch, and reed switches. (b) Switching instant of the externally powered SSHI, waveform 3, which is on the peak of the piezoelectric output waveform 1, (c) Switching instant of the reed switch (1), in

comparison to the waveform 3, the switching signal of externally powered switch. Waveform 2 are the overall current flow, flowing out from the piezoelectric patch.

Another experiment was conducted to inspect how the distance between the tip of the beam and the reed switch will affect the power output. That is, the relationship between the power enhancement and switching instant of the switch. The circuit was connected to parallel SSHI. Experiment results show that, after the ideal switching point, the enhancing effect is greatly reduced. Moreover, switching too early even creates losses. However, this result shows a broader bandwidth (figure 10.a), with a smoother output within the bandwidth. The figure 10.b shows a depiction of ideal and non-ideal positions. When the tip displacement is too large, the switch meets its closure before the maximum point of the waveform. During this period, a portion of the rectified signal showed to be zero, at this moment, no power was harvested, but only energy consumed.

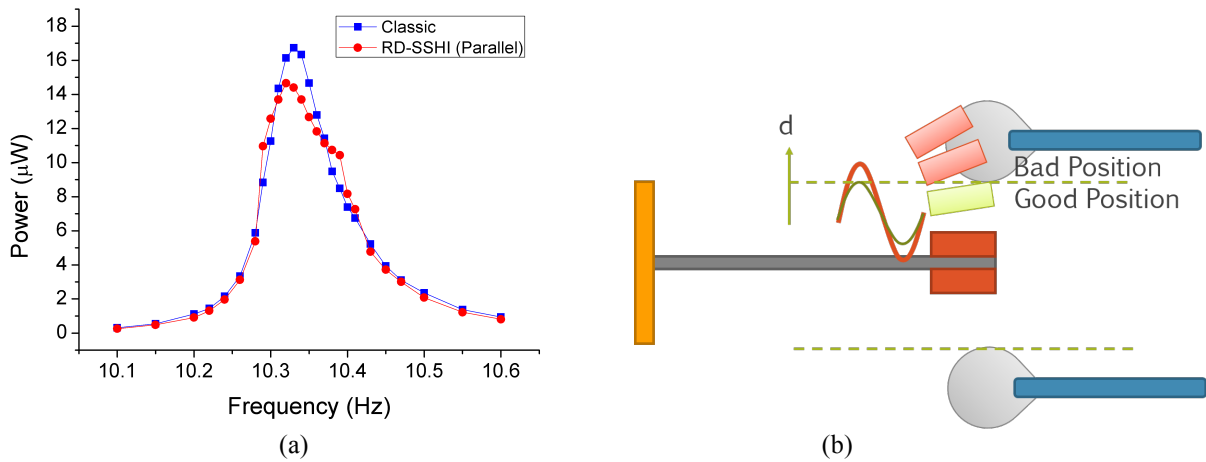


Figure 10. (a) Frequency scan of the reed switched parallel SSHI (b) demonstration of ideal position and non-ideal positions of the beam displacement

Discussions

There are several merits and cons with reed switches. First of all, in comparison to electrical methods of self-powered SSHI, the reed switch can provide zero threshold driving conditions. The chattering, however, drags down some of the harvested power. A solving method can be found in embedded systems, de-bouncers, which were often applied for mechanical switches to avoid multiple signals caused by the chattering. Since experimental results show a fair efficiency of 88.9% of series SSHI in comparison to the externally powered series SSHI, we should carefully design that the power consumption of the de-bouncer is less than the lost power from chattering. Another problem in the reed method is the displacement of the beam is restricted to enable optimal output. A stopper, can be applied to eliminate the over-deflection, and a bi-stable magnet, can be used to keep the displacement large enough. The optimal distance between the beam tip and the reed is however a tradeoff. Reducing the distance may be able to broaden the bandwidth, but in the same time lowering the optimal output. It could be predicted that with distance high enough would narrow the bandwidth, however enlarging the optimal power.

Conclusion and Future work

We have presented a new mechanical structure as a zero-voltage drop switch and a peak detector for synchronized switching on inductance techniques. The structure can be self-powered, with only two diodes required. Despite the chattering of the reed switch, a well-tuned situation of the structure showed a good efficiency in parallel SSHIs, and fair efficiency of 88.9% in series SSHIs in comparison to externally powered cases, which we consider as 100%. The loss of the series SSHI was due to the only path and the large current flow which has to go through the switch. In the spec of bandwidth, by tuning the distance a broader bandwidth response with smooth power output can also be obtained, however, there is a trade-off between the optimal power and the bandwidth. This design is simple to set up, and requires few components. It is also frequency independent, since reed switches can work up till kilo hertz. However it is restricted to the displacement of the beam.

De-bouncers are to be designed in order to reduce the loss of the switch. It is noted that the loss of the de-bouncer should also be carefully taken care of. Structural designs to restrict the displacement such as stoppers and bi-stable techniques can be applied. Bi-stable techniques can be trivial since that the set up itself contains magnets in before hands.

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