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Performance evaluation of a novel piezoelectric-based high-frequency surge-inducing synchronized switching strategy for micro-scale energy harvesting

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ABSTRACT

Energy harvesting technology has recently received remarkable attention in line with progressive developments in low-power-consuming microsystems used in daily applications. In particular, piezoelectric elements have received considerable attention for promising energy harvesting systems because of their applicability and simplicity. In this study, a high-frequency surge-inducing synchronized switching (H-S^3HI) strategy that exploits the full potential of the surge phenomenon is proposed to effectively improve the energy harvesting efficiency of piezoelectric harvesters. Moreover, this strategy can guarantee the useable energy harvesting performance even for micro-scale vibrations. The effectiveness of the proposed switching strategy was demonstrated by performing numerical simulations and experiments with a cantilever-type piezoelectric harvester under sinusoidal and random-vibration conditions.

1. Introduction

High-resolution images obtained from observation satellites can be degraded by undesirable micro-vibration disturbances induced by on-board appendages that have mechanical moving parts, such as reaction-wheel assemblies, control moment gyroscopes, gimbal-type antennas, and spaceborne cryocoolers [1–5]. Thereby, micro-vibration disturbances from on-board appendages have always been subjected to isolation objective in order to acquire high-quality images from observation satellites. However, in this study, we focus on the feasibility of positively utilizing such micro-vibrations as renewable energy sources.

From the abovementioned on-board appendages, we selected spaceborne coolers for renewable energy sources, because they have several advantages for energy harvesting systems. For example, the harvester can continuously produce recycled energy because the cooler is continuously operating over the entire orbit, except during safe-hold mode, in which the cooler is turned off. In addition, the single operating frequency of the cooler is easy to characterize, which is advantageous for designing the energy harvester.

However, efforts to positively utilize such mechanical vibrations as a renewable energy source have never been exerted in the space research field. Moreover, efforts have shifted only toward reducing mechanical vibrations to comply with strict

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micro-vibration requirements [6], because the micro-vibrations induced by such payloads heavily affect the image quality of high-resolution observation satellites. Besides, the low vibration amplitudes, regarded as micro-scale, have so far acted as an entry barrier for harvesting technology. In previous researches, there were only a few basic studies that dealt with using cooler-induced micro-vibrations as a renewable energy source. For example, Kwon et al. [7] proposed a tuned-mass-damper-type electromagnetic energy harvester for spaceborne coolers. They verified the feasibility of using the harvested energy by driving a low-power-consuming accelerometer to measure the cooler-induced vibration level itself. As a result, a self-powered standalone vibration sensor system was implemented by using recycled energy from cooler-induced micro-vibrations.

On the other hand, the technological progress in sensor applications has triggered the development of nanowatt-powered sensor systems. These advancements allow for overcoming critical obstacles that have prevented the realization of energy harvesting systems, especially on micro-vibration fields. Among the various examples of the nanowatt-powered sensors, Shimamura et al. [8] developed a nanowatt-powered vibration sensor for ambient intelligence applications. This sensor system barely dissipates power, operating at a rate of 0.7 nW/h while in vibration-sensing mode, and its feasibility was verified via an experimental approach. Additionally, micro-electromechanical systems (MEMS)-based sensors are being increasingly evaluated as an attractive technology, because the use of such MEMS-based sensors has resulted in drastic reductions in power consumption, enabled by the miniaturization of components [9]. As a result, the power requirements of MEMS-based devices can be substantially minimized such that energy harvesting technologies become a high-potential alternative, contributing to increasing the power budget and reducing the overall mass of the system. Moreover, such low power-consuming MEMS-based sensor systems have triggered research in the use of energy harvesting technology in space applications. For example, a cube satellite named as piezoelectric assisted smart satellite structure (PEASSS) [10] had a piezoelectric-based smart structure as a means of generating power from the pyroelectric effect, capable of generating >1 W/m^2. This cube satellite was launched in February 2017, and successfully demonstrated the functionality of the pyroelectric effect for harvesting power in an on-orbit environment as a result of the temperature changes in the piezoelectric power generator itself.

In particular, piezoelectric elements have received considerable attention because of their high-power density and promising integration potential, and because of the widely available vibratory energy sources in various fields [11,12], to the extent that several researchers have dealt with piezoelectric elements as promising potential components in energy harvesting applications. In line with the increased attention on piezoelectric elements, various technical efforts to enhance their energy harvesting capabilities have been made as well. For example, Guyomar et al. [13] proposed a non-linear harvesting technique, called synchronized switch harvesting on inductor (SSHI). The proposed SSHI technique has garnered considerable attention on account of its practical applicability and superior harvesting performance, and it has sparked various researches that have been reported, e.g., self-powered SSHI (SP-SSHI) [14], velocity control SSHI (V-SSHI) [15], and synchronous electric charge extraction (SECE) [16]. Based on SSHI technique, an inductor less synchronized switch harvesting strategy was also reported [17]. A unique point of such a reference, called synchronized switching harvesting on capacitor (SSHC), is that it inverts the piezo-induced voltage by using capacitors rather than an inductor. This strategy allowed to miniaturize the circuit due to relatively small volume (less than 0.5 mm^3) of the capacitor compared with the inductor (generally $\sim$100's mm^3), while guaranteeing promising energy harvesting capability as much as the conventional inductor based SSH strategy. Such a SSHC strategy, thereby, shows a great technical advancement especially for applications that require small volume of the circuit but promising harvesting performance, e.g. miniaturized MEMS energy harvesting systems. However, to obtain such a substantial performance from the SSHC, multiple capacitors and switches are required to flip or invert the voltage, inevitably increasing the energy dissipations in the switch or peripheral resistances. Moreover, if the voltage inversion factor (or bias-flip factor) of the SSHC strategy is the same with the standard SSHI; and the forward voltage drop of diodes in the rectifier bridge is the same, performance of SSHC will be the same as that of the standard SSHI although the SSHC strategy still has an advantage in terms of circuit size due to small volume of the capacitor. These varied techniques were efficient in boosting the voltage produced by the piezoelectric harvesters. Aside from above listed researches, Kwon et al. [18] numerically investigated the feasibility of using a surge-inducing synchronized switching harvesting strategy (S^{3}HI) on a piezoelectric energy harvester. The main feature of the surge-inducing strategy was inducing sudden current transits in an inductor by intentionally shortening the switching duration compared with the optimal switching duration of conventional SSHI [13]. Thereby, the piezoelectric voltage could be substantially boosted over the threshold voltage, accompanied by a diode forward voltage drop and the existing stored voltage in a battery. As a result, the surge-inducing switching strategy can guarantee effective harvesting capabilities even under micro-scale vibration amplitudes because of the surge phenomenon. However, such a strategy inevitably suffers from a series of energy losses in the inductor at every instance of switching, due to its relatively shorter switching duration compared with conventional SSHI.

To overcome the abovementioned drawbacks of the conventional surge-inducing switching strategy while still striving to induce surge phenomena to exploit their full potential from the point of view of energy harvesting capability, a novel strategy that combines high-frequency switching with conventional surge-inducing switching is proposed in this study. The basic concept of the proposed strategy is to make the switching duration relatively longer than the conventional one, while finely splitting it up to realize high-frequency switching. Thereby, both the demands of maximizing the incoming energy in the inductor and maintaining the surge-inducing mechanism can be satisfied by the proposed switching strategy, which we called the high-frequency-included surge-inducing synchronized-switch harvesting (H-S^{3}HI) strategy. To investigate the feasibility of the proposed switching strategy, numerical simulations were performed based on the output of basic characteristic tests. The effectiveness of the H-S^{3}HI strategy was then demonstrated via performance evaluation tests with a simple