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Improvement of micro-jitter energy harvesting efficiency of piezoelectric-based surge-inducing optimal switching strategy

Seong-Cheol Kwon[a], Junjiro Onoda[b], Hyun-Ung Oh[a,*]

[a] Space Technology Synthesis Laboratory, Department of Aerospace Engineering, Chosun University, 375 Seosuk-dong, Dong-gu, Gwangju 501-759, South Korea

[b] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa, 252-5210, Japan

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ABSTRACT

Micro-jitter is regarded as a primary source of image-quality degradation for high-resolution observation satellites. To comply with the strict mission requirements of high-quality image acquisitions, most technical efforts have been directed toward isolating the micro-jitter disturbances. However, in this study, we focused on the feasibility of utilizing the micro-jitter as a piezoelectric-based energy-harvesting target. To harvest the micro-scale jitter effectively, a switching strategy that intentionally induces a surge phenomenon was applied. The surge phenomenon was induced by a sudden current transition in the inductor, right after the switching action, such that the piezo-induced voltage can be significantly boosted. This switching strategy was suitable for the micro-jitter energy harvesting and was further enhanced by adopting an optimal switching duration. The effectiveness of the proposed piezoelectric-based surge-inducing optimal switching strategy was demonstrated through incorporating numerical simulation and experiments.

1. Introduction

The line-of-sight (LOS) jitter on an imaging sensor of a high-resolution observation satellite is defined as time-varying motion on the focal plane during image acquisition, which is caused by internal and external disturbances acting on the optical payloads [1]. To comply with the strict mission requirements, the jitter level should be predicted accurately through numerical or experimental approaches to determine whether it meets the given specifications. If the jitter level exceeds the given requirements, a technical mitigation plan has to be implemented to manage the jitter properly.

The internal jitter contributors of the satellite commonly have mechanical moving parts such as the reaction wheel assembly (RWA), the control moment gyroscope (CMG) for altitude control, the gimbal-type data link antenna for transmitting massive image data to a ground station, and the spaceborne cryocooler to cool the focal plane of an infrared imaging sensor. Micro-jitter is a term generally used in the spacecraft community to describe low amplitude vibrations, which are a main source of image quality degradations [2,3].

To manage the micro-jitter induced by the aforementioned internal contributors, passive-type isolators are generally employed in space applications owing to their simplicity and reliability [4–7]. However, efforts to positively utilize the micro-jitter energy as a source of renewable energy have not been made in space applications but only forwarded to reducing the micro-jitter to obtain high-quality images from the observation satellite. At this point, we focus on the feasibility of positively utilizing the micro-jitter as a renewable power source by employing energy harvesting technology.

In this study, the mechanical micro-jitter induced by spaceborne cooler operations is selected as a renewable energy source because of the following advantages. First, the spaceborne cooler operates continuously during the entire service life of the satellite except for the safe-hold mode when the cooler is turned off, thus the harvester can continuously harvest the mechanical energy. Second, the cooler operates mainly at a singular frequency; hence, it is easy to identify the excitation characteristics of the cooler, therefore simplifying the design of the harvester.

Previously, basic research studies reported on the conversion of the mechanical jitter energy of the cooler into useable electrical energy. For example, Kwon et al. [8] proposed a complex system that can guarantee dual strategies in energy harvesting and micro-vibration isolation from the cooler. This system is mainly composed of a spaceborne cooler that generates mechanical vibration dis-

* Corresponding author.
E-mail addresses: mine1147@hanmail.net (S.-C. Kwon), onoda@isas.jaxa.jp (J. Onoda), ohu129@chosun.ac.kr (H.-U. Oh).

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turbances, a tuned mass damper (TMD)-type electromagnetic energy harvester, and a passive vibration isolator that supports a cooler with a low stiffness. The effectiveness of the proposed system was verified through numerical simulation and experimental approaches. The feasibility of using the harvested recycling energy was then confirmed by operating a low power consumption accelerometer that measures the cooler-induced vibration level without a provision of external power. However, to assure the desired performance of the complex system, the mass ratio of the TMD harvester to the cooler should exceed a target value as much as possible, thus the mass and volume of the TMD harvester inevitably increased. From the satellite system point of view, the increase of mass and size is not desirable owing to its significant effect on the launch cost.

To overcome the above-mentioned drawbacks of the electromagnetic energy harvester [8], in this study we focused on the use of piezoelectric material as an energy harvester. In practice, over the last decade, a great deal of research has been directed toward developing a piezoelectric energy harvesting system for various applications owing to its compact and simple implementation potential. In line with this increased attention, various technical efforts to enhance further their energy harvesting capability have been followed by improved specifications [9–16]. For example, Ottman et al. [9] proposed a maximum power point tracking technique (MPPT) as an adaptive piezoelectric energy harvesting circuit. This technique uses a DC-DC converter between the rectifier output and the battery; thus, the output voltage of the rectifier is optimally adjusted to achieve maximum power transfer into the battery. Their experimental results revealed that the use of an adaptive DC-DC converter increased the power transfer capability by over 400% compared to the condition in which the DC-DC converter was not employed. Guyomar et al. [10] proposed a non-linear harvesting technique, the so-called synchronized switch harvesting on inductor (SSHI) technique. The proposed SSHI technique intentionally synchronizes the control switching signal with the periodic input signal so that the voltage across the piezoelectric element becomes largely inverted as much as the quality factor of the switching $R-L-C$ circuit. Because of its practical applicability and superiority in harvesting performance, many researchers have assessed the SSHI technique from various points of view [11,12]. Moreover, to further increase the harvesting efficiency of the SSHI technique, Makihara et al. [13] proposed a low energy dissipation SSHI circuit. The proposed circuit has only two diodes, thus reducing the voltage drop during the harvesting process. Their experimental results indicated that the low energy dissipation circuit increased the harvested energy output by as much as 120% compared to the original SSHI. In addition to the listed papers, the SSHI technique has spawned various interesting studies, i.e., 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 [17,18]. 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 various techniques were efficient in boosting the voltage signal produced by the piezoelectric harvester.

In the present study, a modified synchronized switching strategy has been applied to effectively harvest the micro-scale jitter energy from the cooler. This switching strategy locates the synchronous switch on a different position compared to the conventional SSHI, such that the inductor employed in the modified switching strategy acts as a charge-pump unlike its role in the conventional SSHI in which the inductor only executes voltage-inverting actions at the switching instant. In the modified switching scheme, the current from the piezoelectric material instantly flows through the inductor at the switching instant and is suddenly discharged right after the switching off, inducing a surge phenomenon that significantly boosts the voltage out of the inductor. Thus, the highly boosted voltage can easily exceed the threshold voltage accompanied by the forward voltage drop of the diode, even if the jitter level is regarded to be on the micro-scale in which its value is too small to charge the storage device when using the conventional SSHI technique. The energy harvesting capability of the surge-inducing switching strategy can be further enhanced by employing an optimal switching duration as well as by supporting the cooler on a low-stiffness passive vibration isolator. The combination of the vibration isolator with the cooler assures the micro-jitter isolation performance as well, which is one of the important technical concerns in image quality of the high-resolution observation satellite. In this study, the effectiveness of the surge-inducing switching strategy has been demonstrated through a numerical simulation and the functional performance of the surge-inducing switching strategy was then experimentally assessed by implementing a cantilever type piezoelectric harvester with a switching circuit.

2. Piezoelectric-based surge-inducing optimal switching strategy

2.1. Numerical simulation model

To investigate the feasibility of the piezoelectric-based surge-inducing switching strategy, we established a numerical simulation model, as shown in Fig. 1. This simulation model is mainly composed of a cooler that induces mechanical micro-jitter, a conventional passive vibration isolator to support the cooler with low stiffness [7], a piezoelectric energy harvester (PEH), and an interface circuit to manage the harvested electrical energy. Hereafter, the whole assembly shown in Fig. 1 is called a PEH system. In this model, m_1 indicates the mass of the cooler (3.8 kg), and the dashpot element c_1 and spring element k_1 indicate the damping coefficient and stiffness of the passive vibration isolator [7], respectively. The reason why the passive vibration isolator is employed in the PEH system will be discussed in the next simulation results section. In the piezoelectric harvester model, m_2 and k_2 indicate the mass and the stiffness of the piezoelectric harvester tuned to have a frequency coupling effect with the main excitation frequency of the cooler; the dashpot element c_2 depicts the mechanical damping coefficient of the piezoelectric harvester. In addition, the piezoelectric energy harvester includes a mechanical-electrical transformer α that converts the mechanical displacement into an electrical potential. This electrical potential is then instantaneously accumulated in the capacitance C_p of the piezoelectric element, such that the piezoelectric voltage V_p is induced across the piezoelec-