Frequency up conversion approach to scavenge mechanical energy from an electromagnetic digital actuator

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Abstract. This paper reports the practical design and experimental testing of a piezoelectric energy reclamation system. The presented system aims at scavenging energy from a miniaturized electromagnetic digital actuator for additional function such as obtains the discrete position information for enhanced reliability. Based on frequency up conversion technique, and the considered actuator dynamical responses, a piezoelectric energy harvester has been experimentally evaluated. In plane integration is the next step.

1. Introduction

The integration of several actuators to realize a smart surface is a potential route to develop flexible conveyors. Compared to analog actuators, the digital ones have the features of relatively simple control loop, low cost and low energy consumption. Although feedback sensor is not mandatory in multi-stable digital actuators design, the implementation of sensors can improve the reliabilities of such actuators. In order to prevent extra energy supply and wires for this additional sensing function, energy harvesting design for powering sensing system is a promising approach.

The final target of this study is a fully integrated miniaturized self-powered position-sensing device for multi-stable digital actuators. Vibration energy harvesting strategy to scavenge energy from the actuation movement is investigated. The concept is demonstrated on an electromagnetic (EM) digital actuator proposed by Petit et al [1-2] (figure 1). The electromagnetic digital actuator is capable of achieving two-dimensional movement in plane by switching a mobile permanent magnet (MPM) among four discrete positions by generating electromechanical force from related fixed wires carrying proper currents.

Since the position switching movement of the EM digital actuator is a low frequency motion (less than a few hertz) and it could be intermittent due to the practical applications and tasks, the conventional natural frequency matched resonator is not suitable for the VEH design. Therefore, an alternative adaptive harvester design based on frequency up-conversion strategy is investigated. In order to avoid modifying the magnetization distribution of the EM digital actuator, piezoelectric transduction is chosen due to its compactness, lightness and ease of implementation features.

In the literature, several piezoelectric harvesters, which implement a frequency up-conversion strategy, have been reported. It aims at decoupling the excitation frequency and the structural frequency of the VEH, allowing scavenging energy by a high resonance frequency harvester in a low frequency excitation scenario. The frequency up-conversion effect is usually enabled either by contact mechanisms [3-4] or by non-contact interactions [5-6].
2. Energy harvesting concept

Position switch movement of the MPM between two stable positions is used to initiate the deformation of a high frequency VEH device. The proposed approach is similar to the magnetic latching principle introduced in [4]. However, instead of magnet, a small piece of ferromagnetic material is attached on the tip of the VEH to achieve mechanical deformation and to avoid changing the magnetization distribution. Once the restoring force of the VEH is greater than the magnetic force interaction between the MPM and the tip end of the VEH, it is released. Then part of the obtained mechanical energy can be converted to electrical energy by the piezoelectric material and stored in the dedicated circuit.

From the energy transfer point of view (from energy supply to the mechanical energy of the system consisting of the MPM and the VEH, part of the mechanical energy of the VEH to electrical energy), the harvested energy is linked to the energy supplied to drive the EM actuator. The amount of the obtained mechanical energy in the VEH is designed to be much lower than the supplied energy so that negligible supplementary power for actuation is required. From the piezovoltage waveforms of the VEHs system, the position of the MPM can be detected. Although the feature of position detection is theoretically dispensable for the operation of a digital actuator, it allows to improve the reliability and to monitor the actuators array, which is a requested feature for practical implementation.

![Figure 1. Illustration of the electromagnetic digital actuator: a) side view and b) top view](image)

3. Experimental results

In order to validate the design concept, preliminary experiments are carried out. Simple cantilever beams equipped with a piezoelectric patch are arranged over the EM digital actuator (figure 2) and the tip of each beam connects to the MPM when the latter is at the \((x, y)=(-d_{\text{stroke}}/2, d_{\text{stroke}}/2)\) discrete position. To control the magnetic attraction between the tip end of the cantilever and the MPM, a media plastic layer is added on the iron piece at the tip of the cantilever beam. By tuning the thickness of this layer, the magnetic force between the MPM and the tip of the cantilever beam can be controlled.

dSPACE real-time solution and a voltage/current converter \([-10V, 10V]\)) implement the pulse signal of the driving current. A 250 ms current pulse signal is supplied to generate the electromagnetic force for the position switch of the MPM. It should be noted that the out of plane cantilever harvester is only used in this study for the concept validation. In-plane integration will be accomplished in future work. Dynamical waveforms of the VEH in open-circuit are plotted in figure 3.
Figure 2. a) Illustration of the VEH; b) picture of the system at the discrete position (-d_{stroke}/2, d_{stroke}/2).

The experimental results illustrate the release and the contact of the VEH cantilever with the MPM. It is shown that the VEH can successfully separate from the MPM and transfer the potential energy stored in the cantilever beam during its free oscillation. It is also shown that when the MPM goes back and impacts the VEH, a voltage signal can be observed.
By connecting the piezoelectric element to a dedicated circuit, part of the stored potential energy of the cantilever beam can be harvested. A voltage doubler circuit (figure 4) which is one of the simplest yet effective circuits for energy harvesting [7] is taken for this first step of feasibility proof.

![Voltage doubler circuit](image)

The dynamical response for the piezovoltage and the voltage on the storage capacitor (1 µF) are plotted in figure 5. It can be found that around 4.7 µJ (more than 30% of the VEH stored potential energy) is harvested at each release. The small stiffness of the cantilever \((k = 9 \text{ N/m})\) is chosen to maintain the proper function of the EM digital actuator. Moreover, the position information of the MPM can clearly be inferred from the waveforms.

![Energy harvesting experimental waveform](image)
4. Conclusion

In this paper, a piezoelectric vibration energy harvester system is designed based on the frequency up conversion principle aiming at harvesting energy from an electromechanical digital actuator and obtaining position information. In order to implement the frequency up conversion technique, a small piece of ferromagnetic material is used for generating the magnetic attraction between the harvester and the mobile permanent magnet, taking advantage of the characteristics of the EM digital actuator.

When the MPM is experiencing an electromagnetic force for position switch, the harvester will move with the MPM towards the aimed discrete position. After reaching a critical position where the restoring force equals the magnetic attraction, the harvester and the MPM separate and the VEH oscillates freely. Thus, mechanical energy can be converted by the piezoelectric materials and further stored on a capacitor. 4.7 µJ harvested energy is obtained in the preliminary experiment with a 16 mN magnetic attraction between the tip end of the harvester and the MPM. When the MPM is close to the aimed discrete position, another harvester is attracted by the MPM and comes into contact. Then they move together until the rest position. Thus, based on the dynamical responses of the energy harvesting system, the position information of the EM digital actuator is obtained from the piezoelectric voltages.

By integrating the proposed VEH system, additional functions such as sensing capability of the electromagnetic digital actuator smart surface will be achieved and its reliability can be eventually improved without adding supplementary power supply and extra wires.

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