論 文 の 内 容 の 要 旨

論文題目　Study of Electromagnetic Vibration Energy Harvesting Based on Combined Free / Impact Motion for Low Frequency Operation
(低周波数で駆動するフリー・インパクトモーション混合型電磁気振動環境発電に関する研究)

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This dissertation presents study of an electromagnetic vibration energy harvesting configuration that can work effectively at low frequencies. Unlike the conventional form of vibration energy harvesters in which the mass is directly connected to a vibrating frame with spring suspension, the mass in the configuration under study is allowed to move freely within a certain distance (stroke) inside a frame – carrying an electrical coil and make impacts with two frame end stops. The way of end stops impact largely affects the oscillator dynamic behavior and consequently the harvesting performance. Thus, two ways of impacts are introduced in this work leading to two different harvesting architectures: The first includes impact with elastic end stops (FEH), and the second includes impact with hard end stops (FHH). Theoretical modeling on the non-linear behavior and numerical simulation of both architectures are vigorously conducted with some experiments results.

Unlike linear spring – mass harvester, FEH can give an increase in the resonant relative amplitude when matching lower frequencies using larger allowed free motion distance (Stroke). Higher resonant relative amplitude gives higher relative velocity and consequently higher voltage and power output. Thus, it would be preferred for low frequency applications that are seeking for resonant amplification. However, FHH shows a non-resonant behavior in which the output power increases with both input amplitude and/or frequency. In addition, it has a simple construction that allow fabrication with small size, which can makes it suitable for important kinds of applications such as human powered devices. The detailed summary of each harvester study is stated below.

(1) Free / elastic end stops impact harvester (FEH).

In the free / elastic end stops impact harvester (FEH), the magnet is allowed to freely move within a certain distance inside the frame and makes impacts with two spring end stops. The presence of spring mass separation with elastic end stops impact allows matching low frequencies with high resonant relative amplitude compare to similar linear spring-mass system (CH) with the same mass. As a result, higher relative velocity could be obtained and consequently higher power could be generated when matching low frequencies. Therefore, FEH is preferred to be used over CH in some cases; when matching low frequencies with a sufficient allowable internal mass displacement while there is a restriction on the maximum utilized Q-factor. In fact, CH has a better performance in high Q-factor systems and the critical Q-factor below which FEH is preferred to be used depends on the design configuration. For example, simulation case study shows that FEH is preferred to be used over CH with 0.03 Kg oscillation mass at 14 Hz when the Q-factor cannot increase over 5.28.

FEH shows an uncommon resonant dynamic behavior, in which the magnet/frame relative oscillation can take four different ways of response over the range of input frequencies. Unlike the linear spring – mass system, the resonant frequency of FEH can be shifted to lower frequency ranges using larger strokes without a decrease in the resonant relative amplitude. Simulation comparisons between FEH and optimum linear spring – mass harvester with zero coulomb's friction and Q=2.64 (Q is determined based on experimental value of *C)* at the same resonant frequency are carried out as well as an experimental comparison with similar CH. Simulation results show FEH's power magnification of more than 3 and 7 times at a frequency of 14 Hz and 11 Hz respectively. The power magnification generally increases by matching lower frequencies. The effectiveness of an experimental prototype can reach 8.6% at 10 Hz and 10 mm input amplitude.

Due to the resonant natural of FEH as well as the significant resonant magnification at low frequencies, it could be well suited for quite steady-low frequency applications that are seeking for resonant amplification. This vibration condition could be observed in some machine mediums or associated with some engine vibrations.

(2) Free / hard stops impact harvester (FHH).

The free / hard stops impact harvester simply consists of a permanent magnet mass allowed to move freely inside a frame – carrying an electrical coil and make impacts with two hard end stops. Simulation of a case study shows a unique behavior of FHH, in which four different ways of response appear over the range input amplitudes and frequencies. FHH shows a non-resonant behavior. The output power increases with input amplitude and / or frequency. The allowed free motion enables efficient harvesting at low frequencies. In addition, FHH has a simple construction which allows harvester fabrication with small sizes. Therefore, FHH could be well suited for the application that deem small size harvesters and involved unsteady large amplitude – low frequency vibrations such as human body associated devices.

Two different experiments are conducted. The first is to show the effect of magnet shape on the system performance, and the second is to investigate the power and power density of different size prototypes with the input amplitude. The first experiment shows the superior performance of a ball magnet prototype at low input frequencies due to low associated coulomb's friction. It can generate 30.95 μW at an input vibration of (5 Hz and 10 mm Amp.), while cylindrical and double-ball magnets can generate 15.18 μW and 23.05 μW respectively at the same input vibration. However, cylindrical magnet and double-ball magnet prototypes have better performance at higher frequencies due to the large magnetic flux component normal to the area bounded by the coil turns during oscillation. They can generate 500 μW and 407 μW respectively at an input vibration of (10 Hz and 10 mm Amp.) while ball magnet can generate only 205.6 μW at the same input vibration. The second experiment shows that the output power can be increased with the number of coil turns. For example, a prototype of D9×L12 mm cylindrical total size and 300 coil turns can generate RMS power of 71.8 μW at (2.5 Hz and 5.2 ms^{-2}), and 113.3 μW at (3.33 Hz, and 12.38 ms^{-2}). Another of D7×L12 mm total size and 200 coil turns can generate RMS power of 28.4 μW at (2.5 Hz and 5.2 ms^{-2}), and 82.9 μW at (3.33 Hz, and 12.38 ms^{-2}). However, the power density in some cases decreases with the number of coil turns due to the increase of the harvester size without a corresponding significant increase in the output power. The effectiveness of D9L12 prototype can reach 7.34% at 2.5 Hz and 30 mm input amplitude.

The advantages of FHH can make it more suitable for an important kind of applications, which are the human body associated devices. However, in order to correctly evaluate the performance of FHH with such important applications, FHH has been tested with actual human body motion. FHH is selected to be tested at three body locations which are ankle, pocket place (upper leg), and wrist during three natural gaits which are walking with 76 m/min, walking with 105 m/min, and jogging with 150 m/min. Two similar prototype of different magnet shapes (ball and cylindrical) are tested. FHH generally shows an effective performance with human induce vibration, in which the RMS output power could reach 445 μW. Ball magnet prototype shows a better performance over cylindrical magnet one. The output power of FHH generally increases with the body moving speed as well as the power harvesting from ankle is higher that from pocket place than that from wrist. Finally, a way of parameters selection of FHH for a certain body application with a size constraint is discussed.