Multi-frequency vibration-driven electret generator for wireless sensor applications

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Abstract. We had reported the power output enhancement of an electret harvester and the operation of wireless sensor modules only on electricity from our electret harvester[1]. Since vibration is random and irregular in actual fields, there is the issue that power output of vibration harvesters can’t be obtained outside the range of frequencies designed to resonate the inner mass. As a way to solve, we fabricated four electret harvesters tuned to different resonant frequencies only by assembling different springs and weights, and developed voltage conversion circuits with 73% efficiency from 70V AC to 3.6V DC. We demonstrated to obtain stable DC power output at a broad range of frequencies from 27.6Hz to 30.6Hz by combining the four electret harvesters and voltage conversion circuits.

1. Introduction
It is expected that Internet of Things (IoT) described as a network of devices to sense and collect data around physical objects expands further. In order to expand IoT, almost IoT devices need to connect wirelessly to form networks. It depends on IoT devices with wireless interfaces capable of operating for years without battery replacement. Unfortunately, it is difficult to deploy many more IoT devices for a reason of power source. Replacing the batteries in each IoT devices is very difficult to implement with the expansion of these devices. For sustainability of wireless network operations, energy harvesting techniques have obtained much attention recently.

For example, IoT applications include the structural health monitoring for bridges and railway. There is a growing need to enhance safety and useful life-span of these society’s infrastructures. In the actual fields of bridges or railway, vibration is random and irregular. Many naturally occurring vibrations don’t have fixed frequency spectrums and vibrate over a broad range of frequencies. It is important for vibration energy harvesters to generate electricity from random vibrations. In this paper, we present mainly following two aspects.
1. High efficiency voltage converting circuits techniques
2. Multi-frequency electret harvester combined four harvesters tuned to different vibration frequencies respectively

2. Electret harvester
There are three kinds of vibration-driven microgenerators: electromagnetic, piezoelectric and electrostatic/electret types have been reported. Compared to electromagnetic or piezoelectric generators, electrostatics/electret is thought to have advantages in the viewpoint of compatibility to
microfabrication, adaptability to low frequency vibration. In addition, vibrating stress doesn’t apply to the electricity-generating parts in electrostatics/electret generators.

Suzuki found out CYTOP (Asahi Glass Co., Ltd) as an electret material and his group proposed MEMS electret harvesters fabricated everything by MEMS process. However, power output of fully-MEMS harvester using electret was under 10µW despite high frequency (>100Hz) vibrations in some previous reports. For fully-MEMS harvesters, reduced size necessarily means reduced mass, meaning reduced output power in an inertially-driven device. Furthermore, the smaller harvesters have smaller space available for proof mass motion. We thought that power output need to enhance more as a generator for IoT devices and developed partially using high precision processing technology.

As a basic design of our electret harvester, there are mainly three points. To obtain the large power output from vibration, 1) giving high surface potential (-700V) to electret electrodes using CYTOP, 2) amplifying the amplitude (2mm_{0,p}) of inner mass by coil springs, and 3) narrowing the separation gap (70µm) between electret and collector electrodes, make advantage. As ambient vibrations are generally low in amplitude, the use of a mass-spring system generates a resonance phenomenon and amplifies the relative movement amplitude of the inner mass compared to the vibrations amplitude to enhance the harvested power. Thanks to coil springs, it is easy to obtain large amplitude and to design the resonance frequency of inner mass as shown in Fig.1. Our electret harvester is a very compact and lightweight generator. As shown in Fig.1, its size and weight are respectively 20×20×4 mm^3 and 3.7g, and similar in size to coin battery. This is aimed at extending the range of applications.

Fig.2 shows the output voltage trace at 30Hz and 1.47ms^{-2} (0.15G) acceleration. We prepared the electret harvester tuned to this vibration frequency and acceleration as an example of ambient vibration. AC outputs with peak-to-peak voltage over 70V were obtained. Fig.3 shows the load voltage and power output to different loads at resonant frequency of 30Hz. As we expected, output voltage increased with the increase in load $R$. Maximum power output was obtained at $R=15M\Omega$ and its value was over 100µW. We designed the power output over 100µW when the amplitude of inner mass is 2mm_{0,p} at resonant frequency of 30Hz.

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**Figure 1.** Schematic and photo of the electret harvester. Electret harvester in picture is assembled from a glass lid to view the inside.

**Figure 2.** Time trace of the output voltage at 30Hz and 0.15G.

**Figure 3.** Power output and load voltage versus loads at 30Hz and 0.15G.
3. Experiment

3.1. High efficiency voltage conversion circuits

Since an output impedance of the electret harvester is very large, it is necessary to step down the output voltage from 70V AC. A required voltage after converting depends on the driving voltage of IoT devices and it is usually between the voltage of about 1.2V and 3.6V. There is a gap between the voltage of electret harvester and the required voltage. In addition, power output of 100μW is not enough. It is important to reflect these characteristics into the circuits.

In this time, we present voltage conversion techniques. Fig.4 shows the schematic of our circuits. First capacitors $C_1$ are connected in series. This $C_1$ group divides high voltage of the electret harvester to close the voltage gap. AC output voltage of the electret harvester charges once multiple capacitors $C_1$ connected in series and simultaneously supplies to a load circuit connected in parallel to each second capacitor $C_2$. Charging efficiency $E_{C1}$ between the electret harvester and the $C_1$ group is represented by the following equation. Charging efficiency $E_{C1}$ is a big part of conversion efficiency of our circuits.

$$E_{C1} = \frac{\text{amount of energy accumulated in } C_1 \text{ group per unit time}}{\text{amount of electric power generated by electret harvester with match resistance}}$$

Fig.5 shows theoretical correlations between the charging efficiency $E_{C1}$ defined as described above and the voltage of $C_1$ group. Maximum efficiency is obtained when the voltage of $C_1$ group is equal to half of the output voltage of electret harvester. In the actual circuits, the number of $C_1$ we designed is ten. We achieved to convert with high efficiency of 73% as shown in Table 1.

![Figure 4. Schematic of our voltage conversion circuits.](image)

![Figure 5. Theoretical Correlations between the charging efficiency and the voltage of $C_1$ group.](image)
Table 1. Experimental results on our circuits. Measuring points at (a), (b) and (c) are plotted respectively on Fig. 2.

|                   | (a) Generator 70V | (b) Rectified & Smoothed 3.6V | (c) Down Convert 3.6V |
|-------------------|-------------------|-------------------------------|-----------------------|
| Power output      | 71 μW AC          | 60 μW DC                      | 52 μW DC              |
| Efficiency        | -                 | 85%                           | 73%                   |

3.2. Multi-frequency electret harvester

There are three methods to widen the range of frequency adaptable to random vibrations in the actual fields. 1) Multi-frequency\cite{9}\cite{10}, 2) nonlinear springs\cite{11}\cite{12}, and 3) dual mass-spring systems\cite{13}\cite{14} were reported. From the aspects of design and structure, we thought that the multi-frequency method has many advantage over another methods.

As a demonstration, we fabricated four electret harvesters tuned to different resonant frequency by assembling springs and weight as a specification of Table 2. Spring constant can be changed easily by coil designs such as wire diameter, outside dimension and coil tunes. As shown in Fig.6 and Fig.7, we demonstrated to obtain stable DC power outputs by combining four harvesters and high efficiency AC/DC conversion circuit described above.

Table 2. Resonant frequencies designed by spring constant and weight

| Electret harvester | Design resonant frequency (Hz) | Spring constant (N/mm) | Weights (g) |
|--------------------|--------------------------------|------------------------|-------------|
| # EH 1             | 27.6                           | 0.0261                 | 1.73        |
| # EH 2             | 28.4                           | 0.0276                 | 1.73        |
| # EH 3             | 29.7                           | 0.0302                 | 1.73        |
| # EH 4             | 30.6                           | 0.0320                 | 1.73        |

![Figure 6](image)

**Figure 6.** Experimental results of DC power outputs of four electret harvesters tuned to the frequency shown in Table 2.

![Figure 7](image)

**Figure 7.** Photo of our wireless sensor module. External size is 65×45×25mm³.

4. Conclusion

We developed high efficiency voltage conversion circuits and achieved to convert the voltage over 70V AC into that of 3.6V DC with high efficiency of 73%.
We fabricated four electret harvesters tuned to different resonant frequencies only by assembling springs and weights. We demonstrated to obtain stable DC power output by combining four electret harvesters and AC/DC conversion circuits at a broad range of frequencies from 27.6Hz to 30.6Hz.

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