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# The effect of housing volume of a converting loudspeaker on the output electric power of a loudspeaker-based acoustic energy harvester

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**Abstract:** Acoustic energy harvester is a device that converts sound or acoustic energy into electrical energy. Generally, the main components of this instrument are an acoustic transducer and an acoustic resonator. In this study, the transducer used was a 4-inch woofer loudspeaker, without acoustic resonator but equipped with a cylindrical housing with a fixed cross-sectional area and a length that can be varied from 6 cm until 25 cm by using a piston. Experimental results for various housing volumes showed a similar pattern of the dependence of the generated electric power on the incoming sound frequencies. In addition, it was found that (within the range of the volume variations) the output electric power increased significantly when the volume of the housing was increased. The highest root-mean-square (rms) electric power obtained was 1.72 mW resulting from sound with a sound pressure level (SPL) of 105 dB and a frequency of 84 Hz and by using a length of the housing cylinder of 25 cm (housing volume of 3243.7 cm$^3$).

**Keyword:** loudspeaker, housing volume, acoustic energy, energy harvester, electric power

## 1. Introduction

Research themes on energy harvesting have generated great interest among researchers in recent years (Yuan et al., 2019). One of the energies that can be harvested (captured) from the environment is acoustic energy (sound waves). This harvested acoustic energy can enable the application of new technologies such as wireless sensor networks (Pillai & Deenadayalan, 2014). Technological developments in the realization of autonomous small mechanical-electronic devices and energy storage have made acoustic energy harvesting a technology that is increasingly being developed.

Acoustic energy harvesting can be described as the process of converting strong and continuous acoustic waves from the environment into electrical energy using an acoustic transducer and a resonator (Sherrit, 2008; Dornfeld, 2013). Acoustic energy harvesting is usually carried out in a fairly noisy environment (Pillai & Deenadayalan, 2014). In Indonesia, especially in big cities, there are various sources of acoustic energy, which are usually noise in environments with high sound pressure level (SPL). The various ambient acoustic energy sources include road noise (80-90 dB), factory machines and music concerts (120 dB), as well as aircraft jet engines at airports (140 dB) (Pillai & Deenadayalan, 2014; Serway & Jawwet, 2014).

In previous studies, the acoustic transducers used (such as loudspeakers and piezoelectric plates) are not equipped with a housing so that the back side of the acoustic transducer is directly facing the open free air (while the front side is connected to the resonator cavity (Smoker et al., 2012; Setiawan, 2019; Santosa et al., 2019). In fact, the additional housing on the back side of the loudspeaker can provide an additional resonant effect on loudspeaker (Tijani, 2002). This is thought to be able to improve the performance of the acoustic energy harvester so that it generates a relatively large enough electric power.

In this study, the acoustic transducer used was a 4-inch woofer loudspeaker, while the housing was cylindrical with a fixed diameter and variable length. An important variable of the housing is its volume which is commonly referred to as the back volume (Tijani, 2002) because it is located behind the loudspeaker. Therefore, this research will examine the effect of back volume (namely the volume of the loudspeaker housing) on the performance of the acoustic energy harvester in the sense of the electrical power generated.

## 2. Theoretical Basis

The resonant frequency of a loudspeaker ($f_l$) depends on the stiffness ($s_l$) of the loudspeaker suspension and the mass ($m$) of the oscillating component which can be expressed by

$$f_l = \frac{1}{2\pi}\sqrt{\frac{s_l}{m}} \tag{1}$$

When the loudspeaker is installed in a housing as illustrated in Figure 1, the gas behind the loudspeaker will behave like a spring which will compress and stretch following the oscillating motion of the loudspeaker diaphragm. The stiffness of the loudspeaker and housing system is given by the stiffness of the loudspeaker plus that of the gas spring ($s_g$). Therefore, the resonant frequency of this system ($f_s$) can be described by the equation

$$f_s = \frac{1}{2\pi}\sqrt{\frac{s_l + s_g}{m}} \tag{2}$$

In this case, the gas in the housing is atmospheric air and the stiffness of the air in the housing is (Tijani, 2002)

$$s_g = \frac{\gamma p A_{ld}^2}{V_h} \tag{3}$$

where $\gamma$ is the Laplace constant for air, $p$ is the air pressure (1 atm), $A_{ld}^2$ is the cross-sectional area of the loudspeaker diaphragm, and $V_h$ is the volume of the housing cavity (behind the loudspeaker).

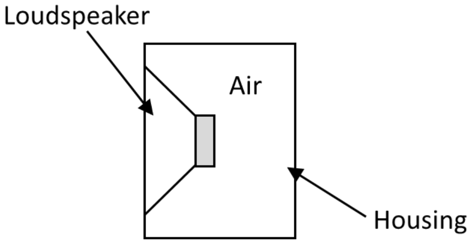

**Figure 1.** Schematic diagram of the loudspeaker and its housing.

Thus, the presence of a housing cavity behind the loudspeaker causes the resonance frequency of the loudspeaker and housing system to be greater than that of the loudspeaker alone without a housing equipped. However, the larger the housing volume the smaller the resonant frequency. For very large to infinite housing volumes, the gas stiffness behind the loudspeaker disappears and the resonant frequency returns to that of the loudspeaker only (without housing).

## 3. Experimental Method

The acoustic energy harvester examined in this study used a loudspeaker as an acoustic transducer that converted sound waves into alternating electric current. The loudspeaker used was a 4-inch woofer type as shown in Figure 2, and was referred to as a converting loudspeaker.

To determine the influence of using (adding) a housing to the converting loudspeaker and the effect of the housing volume on the electric power generated by this acoustic energy harvester, this research was carried out in two experimental stages. The first stage was an experiment on the converting loudspeaker alone without a housing, while the second stage was an experiment on the converting loudspeaker equipped with a housing whose volume varied. In each experiment, the output electrical power generated by the acoustic energy harvester which was subjected to sound with varying frequencies and sound pressure level (SPL) were measured on a load resistor.

**Figure 2.** The 4-inch woofer loudspeaker used as the acoustic transducer in the acoustic energy harvester in this study.

### 3.1. Experiment on the converting loudspeaker only

The schematic arrangement of the equipment used in this first experiment stage is shown in Figure 3. The sound source system consisted of a GW Instek digital function generator model GFG-8216a, an audio amplifier, and a 15-inch loudspeaker (called source loudspeaker) mounted on a loudspeaker box. The function generator produced sinusoidal electrical signals with a frequency that can be chosen and varied. The electrical signals were then amplified using an audio amplifier before being fed into the source loudspeaker to produce intense sound waves. The sound pressure level (SPL) at a distance of about 18 cm in front of the source loudspeaker was measured using a Lutron sound level meter (SLM) model SL-4012.

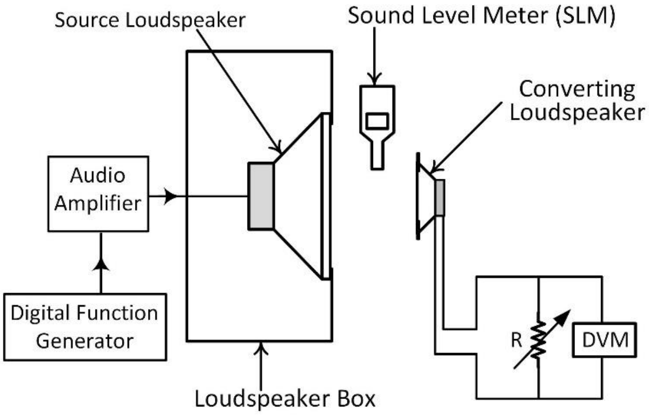

**Figure 3.** The schematic diagram of experimental setup for the experiment with a converting loudspeaker only.

A converting loudspeaker (see Figure 1) was positioned facing the source loudspeaker at a distance of 20 cm. The terminals of the converting loudspeaker were connected to a load resistor which had a resistance ($R$) of 4.6 ohms (that was a variable resistor which was set at a resistance of 4.6 ohms). The converting loudspeaker transformed sound waves it received into an alternating electric current that passed through the load resistor. The root-mean-square (rms) voltage ($V_{rms}$) across the load resistor was measured using a digital volt-meter. The rms electric power ($P_{rms}$) was calculated using the equation

$$P_{rms} = \frac{V_{rms}^2}{R} \tag{3}$$

The measurement of $V_{rms}$ the was carried out first with variation in sound frequencies ($f$) and a fixed SPL, and second with variation in SPL and a fixed sound frequency.

### 3.2. Experiment on the converting loudspeaker equipped with a housing

Figure 4 shows a schematic diagram of the experimental setup for the experiment with a converting loudspeaker which was equipped with a housing whose volume can be varied. In this case, the converting loudspeaker was mounted on a cylindrical housing made of 5-inchies polyvinyl chloride (PVC) pipe with an inner diameter ($D_c$) of

13.4 cm. The housing was equipped with a piston which can be slid so that the volume of the housing cavity behind the converting loudspeaker can be varied. Two rubber O-rings were installed on the piston to make the contact between the piston and housing wall quite tight. Figure 5 shows the face of the converting loudspeaker located inside the housing, while Figure 6 shows the housing, piston shaft, and some other apparatus.

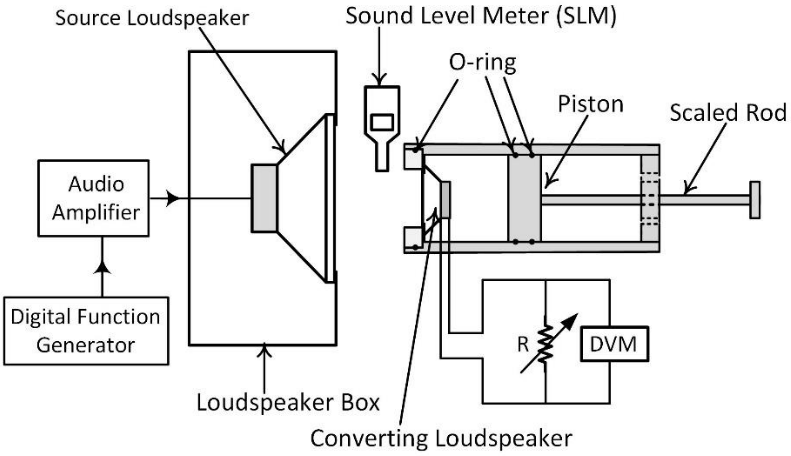

**Figure 4.** The schematic diagram of experimental setup for the experiment with a converting loudspeaker which is equipped with a housing.

**Figure 5.** Front view of the 4-inch converting loudspeaker inside the housing.

**Figure 6.** The arrangement of some experimental apparatus (signal generator unit and audio amplifier unit not shown) for the experiment on the converting loudspeaker equipped with a loudspeaker housing.

The working principle of this second experiment stage was generally similar to that of in the first experiment stage described above. However, in this case, the measurement of $V_{rms}$ for various sound frequency at a constant SPL, and at a constant frequency and various SPL, were carried out for several different housing volumes. The housing volume was varied by sliding the piston, that was, by pushing or pulling the piston shaft (rod).

There was a length scale on the piston rod which indicates the length $(L_c)$ of the housing cylinder. Since the diameter of the housing cylinder was constant, the variation in the volume of the housing was proportional to the variation in the length of the cylinder. However, since there was a converting loudspeaker in the housing cylinder, the housing volume behind the converting loudspeaker (i.e., the back volume) was the cylinder volume minus the volume of space occupied by the converting loudspeaker, say it $V_l$. Therefore, the housing volume in the equation (3) can be written as

$$V_h = \frac{1}{4}\pi D_c^2 L_c - V_l \tag{5}$$

In this study, $D_c$ was 13.4 cm and $V_l$ was approximately 282 cm$^3$, so that the relation between the housing (back) volume $(V_h)$ and the length of the housing cylinder $(L_c)$ is

$$V_h = (141.03\ \mathrm{cm}^2)L_c - 282\ \mathrm{cm}^3 \tag{5}$$

where $L_c$ was in cm unit and varied from 6 cm until 25 cm. Table 1 shows various $L_c$ values and the corresponding housing volumes used in this experiment.

**Table 1.** The housing cylinder length $(L_c)$ and the approximate housing volume $(V_h)$.

| No. | $L_c$ (cm) | $V_h$ (cm$^3$) |
|---|---|---|
| 1 | 6 | 564.2 |
| 2 | 10 | 1128.3 |
| 3 | 15 | 1833.4 |
| 4 | 20 | 2538.5 |
| 5 | 25 | 3243.7 |

## 4. Results and Discussion

### *4.1. Experiment on the converting loudspeaker only*

The experimental results with sound frequency variations in the experiment on the converting loudspeaker only is depicted in Figure 7 which shows the rms output electrical power $(P_{rms})$ generated in a frequency $(f)$ range from 28 Hz to 300 Hz at a constant SPL of 100 dB. It can be seen that there are three peaks in the frequency spectrum, called peak 1, peak 2, and peak 3, respectively appearing at the frequencies of $f_1 = 32$ Hz, $f_2 = 53$ Hz, and $f_3 = 96$ Hz. The three peaks of the spectrum are likely related to the first, second, and third harmonic resonances that the loudspeaker has. The visible pattern could be written as $f_n \approx (n-1)(3/2)f_1$ where $n = 2, 3$. In addition, it can be seen in Figure 7 that the third peak is higher than the second peak, and the second peak is higher than the first peak, where the peak height represents the amount of rms electric power generated. In this case, the heights of the first, second, and third peaks are 0.055 mW, 0.091 mW, and 0.13 mW, respectively. Moreover, the spectrum in Figure 7 provides information that the electric power produced is relatively very small, that is, below 20% of the maximum electric power, when the sound frequency is higher than 128 Hz. Therefore, it can be said that the converting loudspeaker used in this study has an operating frequency width of about 100 Hz, that is, in the frequency range of 28 Hz -128 Hz.

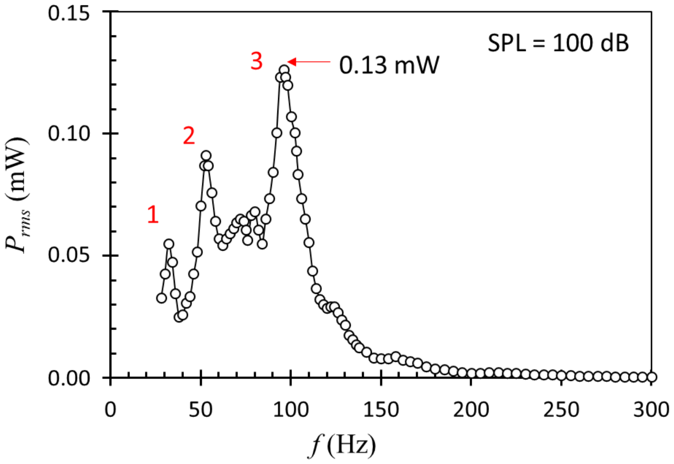

**Figure 7.** The rms electric power ($P_{rms}$) generated by the converting loudspeaker from the sound with an SPL of 100 dB and frequencies ($f$) in the range of 28 Hz - 300 Hz.

The next experiment on the converting loudspeakers only was the measurement of the output electric power (by measuring the rms voltage across the load resistor) with various SPL. In this case, the sound frequency was chosen at the third peak frequency ($f_3$ = 96 Hz) which in the previous experiment provided the highest rms output power (see Figure 7). The results are shown in Figure 8 with SPL variation from 78 dB to 105 dB. It can be seen that the output electrical power increases almost exponentially when the SPL is getting larger. The output power increases significantly when the SPL increases above 95 dB. At 100 dB SPL, the rms electric power obtained is around 0.13 mW. This is in accordance with the results in the previous experiment shown in Figure 7. In addition, the largest rms electric power obtained was 0.18 mW when the SPL was 105 dB.

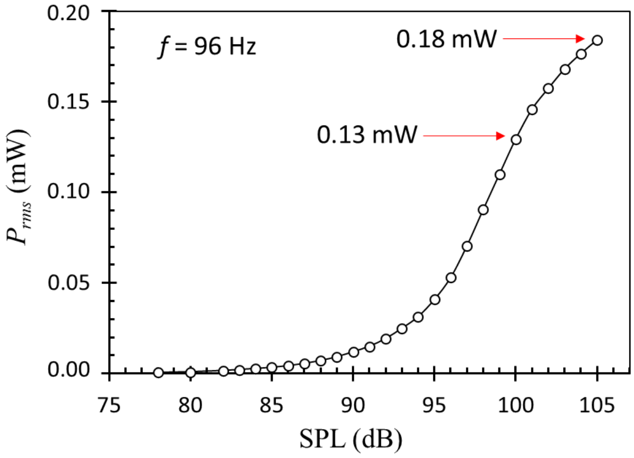

**Figure 8.** The rms electric power ($P_{rms}$) generated by the converting loudspeaker from sound at a frequency of 96 Hz ($f_3$) with SPL variation in the range of 78 dB - 105 dB.

The results above are the characterization of the conversion loudspeaker used in the acoustic energy harvester in this study. These results will be used as a comparison for the results of subsequent experiments on the converting loudspeaker equipped with a housing cylinder with various volume.

### *4.2. Experiment on the converting loudspeaker equipped with a housing*

In this experiment stage, the variation in the housing volume was done by varying the length of housing cylinder ($L_c$) as indicated by the scale printed on the piston rod. The housing volumes for several different cylinder lengths used in this study have been listed in the Table 1. For each different housing volume, the output electrical power was measured for various sound frequencies from 28 Hz to 300 Hz at a constant SPL of 100 dB.

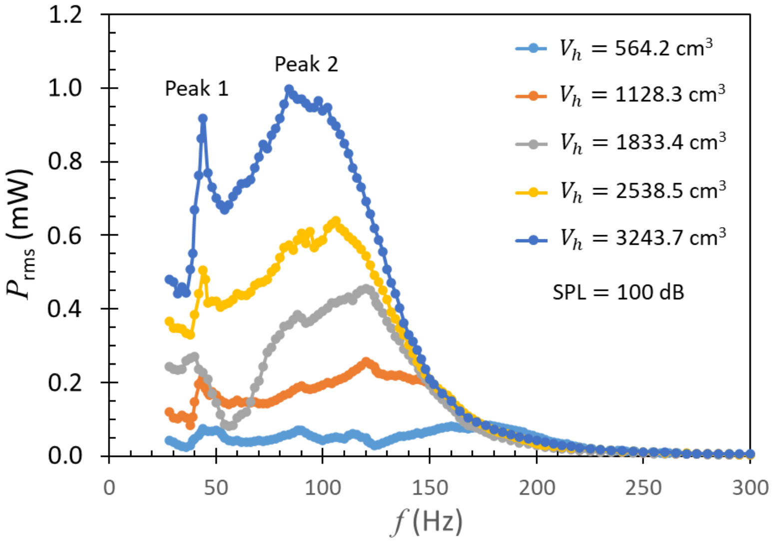

**Figure 9.** The rms electric power ($P_{rms}$) generated by the converting loudspeaker equipped with a housing cylinder with various volumes ($V_h$), resulting from incoming sound with 100 dB SPL and in a frequency ($f$) range of 28 Hz - 300 Hz.

The results of this experiment are shown in Figure 9 which generally shows the similarity of the obtained frequency spectrum patterns, and it can be said that 2 spectrum peaks always appear (peak 1 and peak 2). It can be roughly seen that the frequency of peak 1 does not change, while that of peak 2 tends to shift to a lower frequency value as the housing volume increases, as shown more clearly in Figure 10. When we look in more detail, it is found that the frequency of peak 1 is always the same at 44 Hz, except when using housing volume $V_h$ of 1883.4 cm$^3$ (with $L_c$ = 15 cm) which resulted in a peak frequency 1 of 40 Hz. Presumably, the frequency of the peak 1 could be interpreted as the characteristic frequency of the converting loudspeaker when it is combined with the housing cylinder. In addition, by comparing the spectrums in Figure 7 and Figure 9, it is found that the spectrum patterns are very different. It means that the combination of the converting loudspeaker and the housing cylinder has its own characteristic frequency spectrum which is different from that of the loudspeaker only.

On the other hand, Figure 9 also reveals that the peak frequency 2 tends to shift to a lower frequency value as the housing volume increases, as is also shown in Figure 10.

This peak frequency 2 can be interpreted as the resonance frequency of the combined system of the converting loudspeaker and its housing, as stated by the equation (2). In this case, the larger the housing volume, the lower the peak frequency 2. It will be interesting to learn more experimentally of using a larger volume of the housing, because based on the equations (2) and (3), peak frequency 2 tends towards the value of peak frequency 1 when the housing volume increases further.

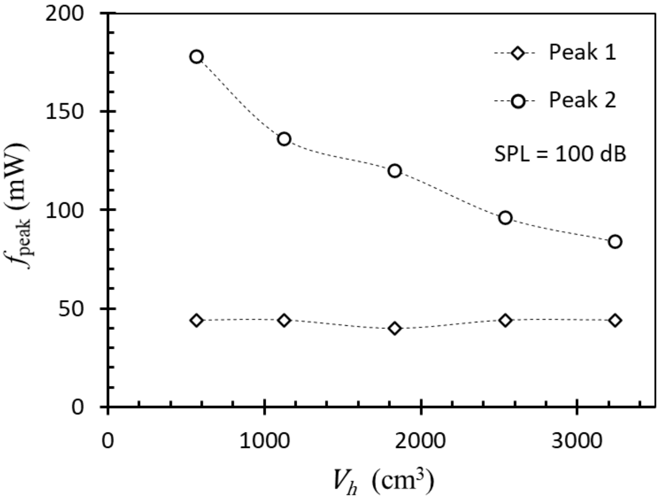

**Figure 10.** Frequencies variation of peak 1 and peak 2 of the spectrums in Figure 9 for various housing volumes ($V_h$).

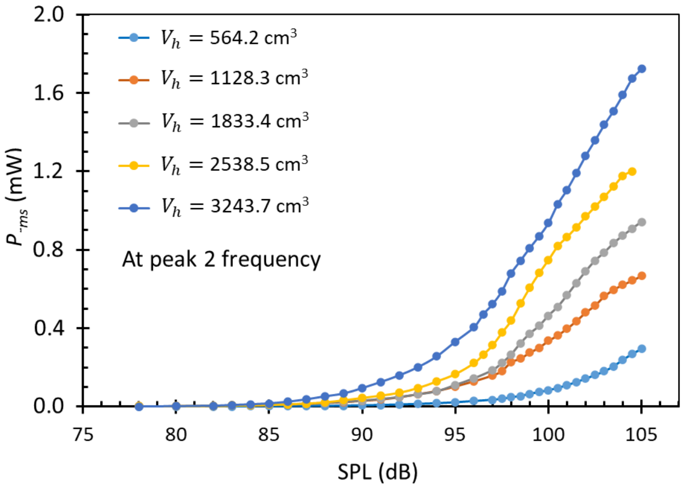

**Figure 11.** The dependence of rms electric power ($P_{rms}$) on the SPL of the incoming sound for various housing volumes.

Figure 11 shows the experimental results of the influence of SPL variation from 78 dB to 105 dB on the electric power generated by the acoustic energy harvester for various housing volumes. It is found that the output electric power ($P_{rms}$) increases significantly as the SPL started to increase from about 95 dB with an increment tended to be exponential. The largest rms electric power in this case is 1.72 mW resulting from the sound with an SPL of 105 dB and the housing volume of 3243.7 cm$^3$ (with $L_c = 25$ cm).

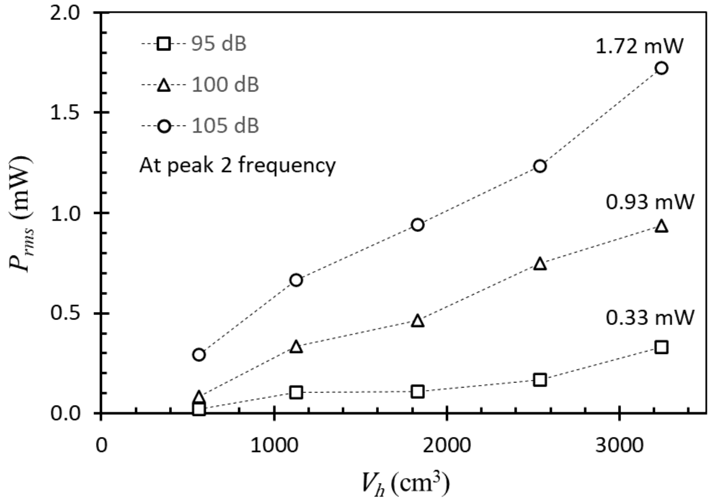

**Figure 12.** The dependence of rms electric power ($P_{rms}$) on housing volume ($V_h$) for three different SPL of the incoming sounds.

Some of the data in Figure 11 is reproduced in another way in Figure 12 which shows more clearly the dependence of the output electric power on the housing volume. It can be seen that the output electric power tends to linearly increase along with the increase in housing volume. This is understandable because as the housing volume increases, the peak frequency 2 (i.e., the frequency of the combined system of the converting loudspeaker system and housing) got closer to the peak frequency 1 (the converting loudspeaker resonance frequency). As a result, the resonance effect becomes larger so did the amplitude of the loudspeaker diaphragm vibrations, and in turn produce a greater output electric power.

Based on results described above, it is necessary in further research to try using a larger housing volume so that the second peak frequency can get closer to or even coincide with the first peak frequency. If this happens, it is expected that the maximum output power will be obtained.

## 5. Conclusion

The study on the effect of housing volume of a converting loudspeaker in an acoustic energy harvester on the output electric power has been carried out. The following results were obtained. First, the combined system of the converting loudspeaker and the housing provides a frequency spectrum having two spectrum peaks. The first peak frequency is understood to be closely related to the self-frequency of the converting loudspeaker mounted to the housing cylinder, so that it is less affected by the variation of housing volume used. The second peak frequency tends to shift to a lower frequency value as the housing volume increases. This second frequency is understood to be the resonance frequency of the combined system of the converting loudspeaker and its housing. This is because there is a tendency that the second peak frequency shifts towards the self-frequency of the converting loudspeaker when the volume of the housing becomes very large (i.e. as if there were no housing). Second, in the range of volume variation used, it is found that the larger the housing volume produces the greater the electric power. This is happened because the greater the housing volume provided the second peak frequency closer to the first peak frequency so that the resonance effect was greater and resulted in a larger vibration amplitude of the converting loudspeaker diaphragm which yielded in a higher output electric power.

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