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EXPERIMENTAL STUDY OF STORING ELECTRICAL ENERGY GENERATED BY AN ACOUSTIC ENERGY HARVESTER INTO A SUPERCAPACITOR

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ABSTRACT

Acoustic energy harvester is a device used to convert environmental noise into electrical energy. Many researches on acoustic energy harvesting have been carried out, but most of them have not yet reached the stage of storing the electrical energy produced. This paper presents an experimental study of storing electrical energy generated by an acoustic energy harvester into a supercapacitor. The acoustic energy harvester in this study used a 4-inch woofer loudspeaker as a noise converter into electricity, equipped with a straight cylindrical resonator, a cylindrical housing, and an electric current rectifier unit. The supercapacitor used has a specification of 100F/2.7V. Experiments were carried out by using several variations of the sound frequency with three variations of sound pressure level (SPL) namely 90 dB, 95 dB, and 100 dB, and by measuring the supercapacitor voltage in a charging time of 60 minutes. It was found that the supercapacitor voltage reached 368 mV which was obtained from noise sound with an SPL of 100 dB and a frequency of 54 Hz which gave an initial charging electric current of about 12 mA. In the last five minutes of charging, the increase in supercapacitor voltage was still linear with time at a rate of about 5.2 mV/min. Therefore, the supercapacitor voltage can still significantly increase if the charging continues.

Keywords: energy harvester; acoustic energy; energy conversion; electrical energy; supercapacitor

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INTRODUCTION

The theme of acoustic energy harvesting has aroused great interest among researchers for many years, as summarized by Yuan et al. [1], Patil & Mandale [2], and Khan & Izhar [3] in their review papers. It is about harnessing noise from the environment to produce electricity. So, it is interesting because it not only reduces environmental noise but also generates electrical energy. Sources of noise that are commonly found in the environment are such as vehicle engines on the highways of big cities, factory machinery, and some industrial and construction process equipment. Potential applications of acoustic energy harvesting are for powering wireless sensors network with low energy consumption [4-5], noise barrier, road lighting, and monitoring [6-7].

A device that harvests noise is called an acoustic energy harvester which usually consists of an acoustic resonator, an acoustic transducer, and an electrical energy storage unit. The research presented here is a continuation of the development of an acoustic energy harvesting device that we carried out, which is the one that uses a loudspeaker as the acoustic transducer [8-11]. The advantage of using a loudspeaker is that the electrical energy produced is quite large when compared to that is using a piezoelectric [11-13]. On the other hand, the results of research on acoustic energy harvesting that have been reported are mostly only up to the measurement of the electrical power generated [1-4], while research on storing it into electrical energy storage units is still lacking. In this research, it would like to develop an acoustic energy harvester that is able to store the generated electrical energy into the supercapacitor. Moreover, this research aims to know the influence of sound pressure level (SPL) and sound frequency that is received by the acoustic energy harvester on the charging rate to the supercapacitor. In other research, supercapacitors were used by Zhang et al [14] in a vibration electromagnetic energy harvesting system for rapid capturing and rectifying the input energy, and for supplying steady power to external loads. Zhang et al [15] also used supercapacitors in an energy regenerative shock absorber for renewable energy applications in extended range electric vehicles.

METHOD

The schematic diagram of the experimental setup is shown in Figure 1. The sound source system consisted of an audio signal generator, an audio amplifier, and an 18-in. loudspeaker (Black Spider BS 201-18) with its box, called the source loudspeaker. The sound frequency was adjusted through the audio signal generator (GW Instek GFG-8250A model), while the sound pressure level (SPL) was regulated through the audio amplifier (Black Spider BA-4 AB Model), and was measured by using a sound level meter (SLM) (Benetech GM1356 model). The sound was then received by an acoustic energy harvester (AEH) consisting of a straight acoustic resonator, a converting loudspeaker (which converts sound energy into electrical energy), and a loudspeaker housing. The resonator had a length of 136 cm and an inside diameter of 10 cm. The converting loudspeaker used was a 4-in. woofer loudspeaker (ACR Curve W8347 B/H model). The loudspeaker housing was a cylindrical tube with an inner diameter of 12.5 cm and a length that could be adjusted using a piston. In this study, the length of the housing was fixed at 16 cm, so it has a volume of about 1974 cm^3. The selection of housing length and resonator length was based on the results of previous research [10] which was the optimum condition that provides maximum output electrical power from the AEH used. The AEH used in this study was the same as that used by Harindra et al [10].

Sound waves entering the resonator vibrated the diaphragm and loudspeaker coil. The vibration of the coil occurred within the magnetic field of the loudspeaker's permanent magnet to generate an alternating induced voltage between the ends of the coil (i.e. loudspeaker output terminals). It was observed in the preliminary experiment that the root-mean-square (RMS) voltage between the two terminals (i.e. loudspeaker output voltage) only can reach a maximum value of about 0.60 volts and was unable to charge the supercapacitor. Therefore, this output voltage was then amplified using a 3A step-up transformer (see Figure 2) and the RMS value of the output voltage of the transformer (V_{ac}) was measured using a digital voltmeter (Sanwa RD700 model).

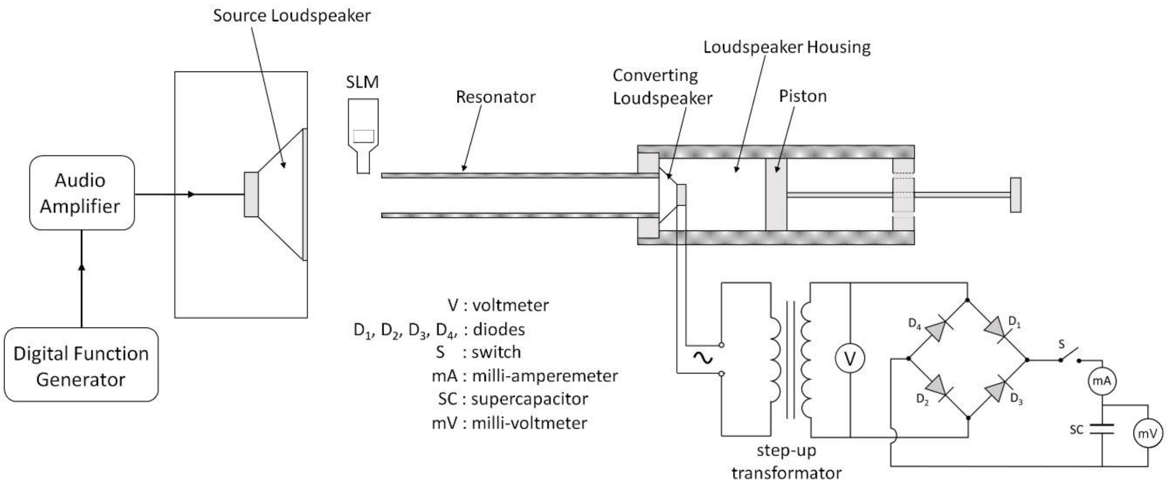

Figure 1. The schematic diagram of the experimental setup.

The resulting alternating current (a.c.) is then converted into direct current (d.c.) using a diode bridge rectifier which used four diodes D1, D2, D3, and D4 as shown in Figure 1. The direct current varied half-wave because the rectifier unit did not use a filter capacitor. The rms value of the direct current (i_{dc}) was measured by using a digital milliampere meter. The direct current then charged the supercapacitor as a medium for storing electrical energy. The supercapacitor was Green-Cap EDLC type with a specification of 100F/2.7 V and is shown in Figure 3. The supercapacitor voltage (V_{SC}) which increased during the charging process was measured using a digital mV-meter. (Note that a very small portion of the electric current that was read on the mA-meter did not completely enter the supercapacitor, but instead flowed through the mV-meter.)

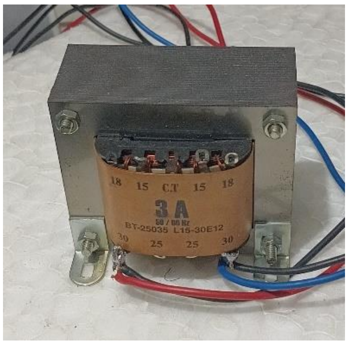

Figure 2. The step-up transformator

Figure 3. The 100F/2.7V supercapacitor

Experiments were carried out using several variations of the sound frequencies in a frequency range of 51 Hz – 60 Hz and three variations of SPL, namely 90 dB, 95 dB, and 100 dB. Switch S was in the open position during setting up the frequency and SPL so that the supercapacitor was not charged before data recording. The switch position is then closed when the recording of the supercapacitor charging time and measuring its voltage begins. In this study, the measurement of the supercapacitor voltage was carried out every minute for one hour of charging time.

RESULTS AND DISCUSSION

The Alternating Current Voltage

The alternating-current (a.c.) voltage (V_{ac}) was the output voltage of the step-up transformator which was measured by a digital voltmeter (DVM) (see Figure 1). It was observed that there was a significant change in the a.c. voltage when the switch is in the open and closed positions. This was because the circuit was connected to the load when the switch was closed which resulted in a decrease in the a.c. voltage. We denoted the RMS values of the voltage of the open circuit as V_{rms}, while those of the closed circuit as V'_{rms}. Figure 4(a) shows the dependence of V_{rms} on the frequency of sound received by AEH in the range of 51 Hz – 60 Hz for the three different SPLs of 90 dB, 95 dB, and 100 dB. It can be seen that the frequency of 54 Hz was the optimum frequency which gave the maximum V_{rms}. This optimum frequency arose from the combined effect of the resonant frequencies of the converting loudspeaker, resonator, and loudspeaker housing, as has been studied in our previous work [10]. In addition, Figure 4(a) shows that the increase in SPL from 90 dB to 95 dB and then 100 dB resulted in a significant increase in V_{rms}. At a frequency of 54 Hz, an SPL of 90 dB produced a V_{rms} of 2.1 V, while SPLs of 95 dB and 100 dB produced V_{rms} of 2.6 V and 4.1 V, respectively. This means that there was an increase in V_{rms} of about 24% when the SPL increased from 90 dB to 95 dB, and the V_{rms} increased of about 58% when the SPL increased from 95 dB to 100 dB. These results indicated the potential that the V_{rms} could increase remarkably if the AEH received greater SPL of noise from environment.

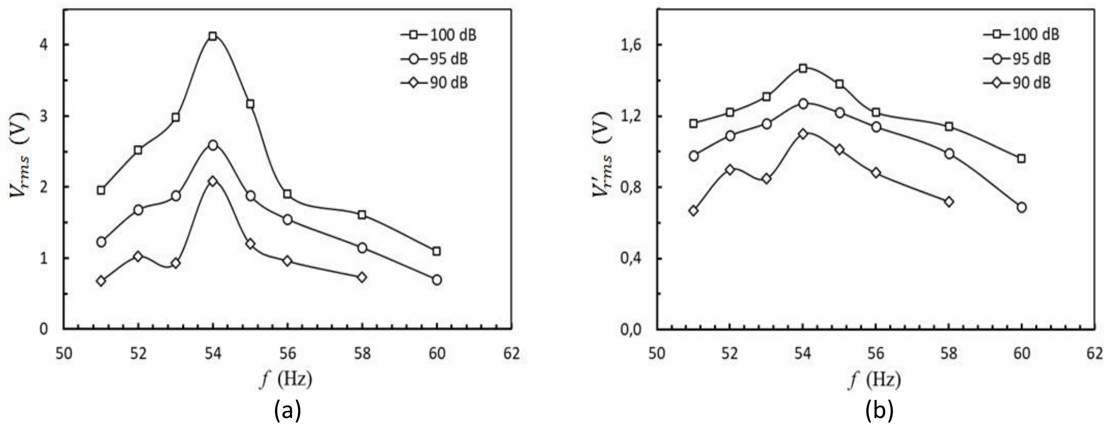

Figure 4. The dependence of V_{rms} (a) and V'_{rms} (b) on the frequency of sound received by AEH in the range of 51 Hz – 60 Hz for the three different SPLs of 90 dB, 95 dB, and 100 dB.

Figure 4(b) depicts the V'_{rms} for various sound frequencies in the range of 51 Hz – 60 Hz for the three different SPLs of 90 dB, 95 dB, and 100 dB. It can be seen that the pattern of V'_{rms} frequency dependence was similar to that of V_{rms} frequency dependence, especially that the V'_{rms} was maximum at 54 Hz. However, when compared to V_{rms}, it appears that there was a relatively large voltage decrease after the switch closed, especially at a frequency of 54 Hz. At that frequency with 100 dB SPL, the voltage decrease was 63% (from 4.1 V to 1.5 V), while with 95 dB and 90 dB, the decrease of voltages were 50% and 52% (from 2.6 V to 1.3 V, and from 2.1 V to 1.1), respectively.

The Charging Current

The rms values of the direct current (i_{dc}) which measured by the milliampere-meter (mA) (see Figure 1) was assumed as the rms charging current for the supercapacitor. In fact, a very small amount of current flowed through the milivolt-meter (mV) besides through the supercapacitor. The initial rms current $i_{rms,0}$ (that was it when the capacitor started charging) generated by AEH from various sound frequencies in a range of 51 Hz – 60 Hz and three different SPLs of 90 dB, 95 dB, and 100 dB is shown in Figure 5. The patterns of this initial rms current ($i_{rms,0}$) data are almost the same as the patterns of V_{rms} data as a function of sound frequency. This result reveals that the initial charging current was proportional to V_{rms} generated by AEH. In addition, for each SPL, the largest initial currents were obtained at the same frequency, namely at 54 Hz. At that frequency, an SPL of 90 dB gave an initial current 3.6 mA, while SPLs of 95 dB and 100 dB resulted in initial currents of 7.3 mA and 11.7 mA, respectively. These results indicated a drastic increase in d.c. current when the SPL rose, i.e., it increased by about 103% when the SPL rose from 90 dB to 95 dB, and increased by about 60% when the SPL rose from 95 dB to 100 dB.

The electric current that was charging the capacitor decreased along with the charging time. This fact is shown in Figure 6 for a frequency of 54 Hz and three different SPLs of 90 dB, 95 dB, and 100 dB with a charging time of 1 hour. It can also be seen in the figure the fitting curves obtained by using MS-Excel with an exponential trendline mode. These curves correspond to the exponential equation of

$$i_{rms}(t) = i_{rms,0}e^{-t/\tau} \tag{1}$$

where $i_{rms}(t)$ was the rms electric current as a function of charging time t and $i_{rms,0}$ was the initial rms electric current. The results of the curve fitting to all data with different SPLs in Figure 4 gave the average time constant $\tau = (270 \pm 20)$ minutes (around 4.5 hours).

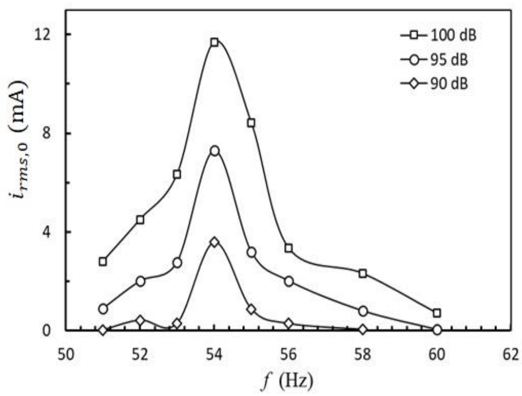

Figure 5. The dependence of the initial rms d.c. currents (the initial charging currents) on the sound frequency. Lines are guides to the eye.

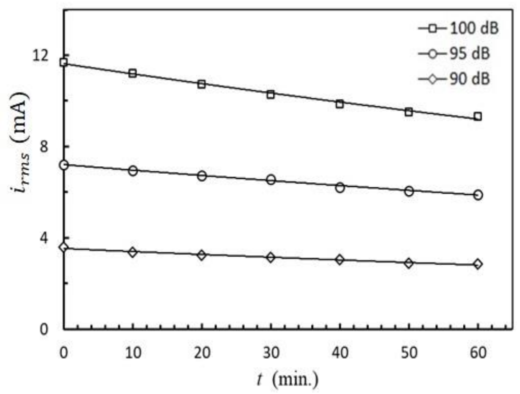

Figure 6. The rms d.c. currents (the charging currents) decreased along with the charging time. Lines are exponential curve fitting.

The Supercapacitor Voltage

Before charging, the supercapacitor was discharged first by short-circuiting the terminals until the voltage was close to zero. The supercapacitor was then charged with electric charges (d.c. current). In the charging process, the supercapacitor voltage (V_{SC}) continued to increase along with the charging time. Figure 7 shows the increasing supercapacitor voltage during one hour of charging time, with a sound frequency of 54 Hz and three different SPLs. After one hour, the supercapacitor voltage reached 166 mV, 240 mV, and 368 mV for 90 dB, 95 dB, and 100 dB SPL, respectively. Judging from the trend (slopes) of the curves, the supercapacitor voltage will still increase with charging time if the charging process continues, especially for charging with an SPL of 100 dB.

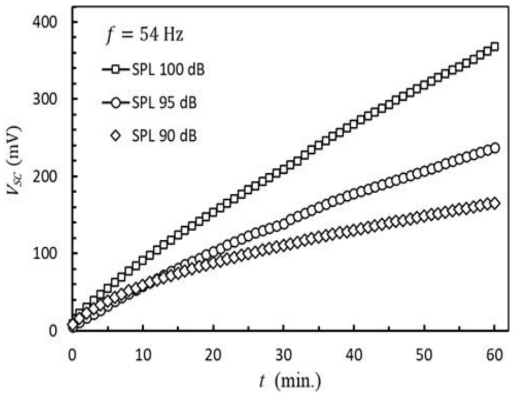

Figure 7. The supercapacitor voltages as a function of time during 60 minutes of charging time. The sound frequency was 54 Hz. Lines are guides to the eye.

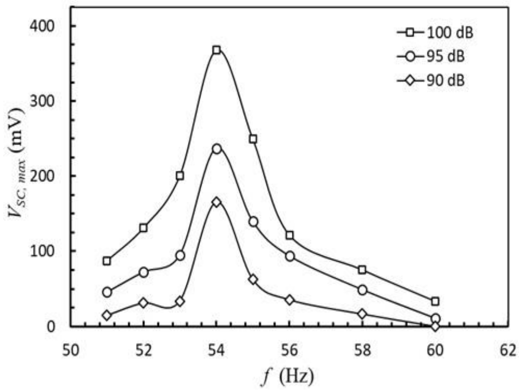

Figure 8. The maximum supercapacitor voltages after 60 minutes charging time with various frequencies. Lines are guides to the eye.

Figure 8 shows the maximum supercapacitor voltage achieved after one hour charging for three different SPLs, namely 90 dB, 95 dB, and 100 dB. For the three values of SPLs, the patterns of the dependence of the supercapacitor voltage on the sound frequency tended to be the same, and all of them had a peak at a frequency of 54 Hz. It also appears that increasing the SPL from 90 dB to 95 dB and then to 100 dB resulted in a significant increase in the supercapacitor voltage. This showed that the SPL of noise was a very important factor in the acoustic energy harvesting process.

The charging process of the supercapacitor by using an acoustic energy harvester from sound with three different SPLs is summarized in Table 1. This table is read by row. For example, the third row provides information that with a 100 dB sound, the rms value of the alternating voltage output of the step-up transformer when the circuit opened (V_{rms}) was 4.1 volts, the rms value of that when the circuit closed (V'_{rms}) was 1.5 volts, the rms value of initial direct electric current (initial charging current, $i_{rms,0}$ was 11.7 milliamperes, and the supercapacitor voltage after charged for 1 hour was 368 millivolts.

Table 1. Summary of supercapacitor charging data charged by using the acoustic energy harvester from sound with three different SPLs.

SPL (dB)	V_{rms} (V)	V'_{rms} (V)	$i_{rms,0}$ (mA)	V_{SC} (mV) after 1 hour
90	2.1	1.1	3.6	166
95	2.6	1.3	7.3	237
100	4.1	1.5	11.7	368

The Influence of Sound Frequency

The effect of sound frequency on the electrical energy produced and the supercapacitor charging process can be seen in Figures 4, 5, and 8. In general, the pattern was similar and there was a peak frequency (optimum frequency) which gave a maximum value for each electric voltage, electric current (charging current), and supercapacitor voltage. In this case, the peak frequency was 54 Hz and was the resonant frequency of the acoustic energy harvesting system used. In addition, for an SPL of 100 dB, it can be seen in Figure 8 that the operating frequency area can be said to be relatively wide, which was around from 51 Hz until 56 Hz (assuming the supercapacitor voltage was around 25% of its maximum value).

CONCLUSION

From the experimental results, it can be concluded that the developed acoustic energy harvester has been able to store the produced electrical energy into a capacitor. In addition, the sound frequency greatly affected the charging rate of the supercapacitor. There was a peak frequency that produced the optimum charging of 54 Hz which was the resonant frequency of the acoustic energy harvester. Moreover, the sound pressure level (SPL) also significantly influenced the charging rate of the supercapacitor. The experimental results of one hour charging showed that an increase in SPL from 90 dB to 100 dB resulted in a 122% increase in the supercapacitor voltage.

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