



Article A Novel Non-Intrusive Vibration Energy Harvesting Method for Air Conditioning Compressor Unit

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Abstract: The purpose of harvesting vibration energy is to obtain clean and sustainable energy by converting vibration energy from ambient sources into a voltage output. In this work, a piezoelectric sensor, PZT-5H is attached to a 3D printed and custom-made mounting to be placed at an air conditioning condenser unit, to harvest vibration energy. The configuration of the harvester is non-intrusive, in which the harvester did not intrude into compressor unit operation. Temperature (20 °C, 22 °C, and 24 °C) and air volume flow rates (3 levels of air volume flow rate at 245 L/second, 274 L/second, and 297 L/second) were taken into consideration in this investigation. An accelerometer was first used to investigate the optimum vibration frequency in Hertz, and six locations were identified. Next, the piezoelectric sensor was mounted at these six locations, and the output rootmean-square (RMS) voltage from the piezoelectric sensor was obtained. The analysis of variance (ANOVA) indicated that temperature and air volume flow rates factors were significant. It was found that the location identified with the highest amount of vibration at 830.2 Hz from accelerometer measurement, was also the highest amount of RMS voltage, at 510.82 mV, harvested by the piezoelectric, from the temperature of 20 °C and air volume flow rates at high level (air flow volume flow rate at 297 L/second). From this work, it is feasible to utilize this novel method of harvesting waste vibration energy from the air conditioning compressor unit.

Keywords: energy harvesting; vibration energy; piezoelectric sensor; sustainable energy; air conditioning compressor

1. Introduction

One of the renewable and sustainable energies which is potential to be harvested by end users is from harvesting vibration energy [1–3]. Currently, most vibration-based energy harvesting is to convert mechanical energy from the ambient to electrical energy [4]. This vibration energy harvesting offers potential to researchers to perform further research since the technology maturity is still not achieved for this energy generation technology [5,6]. The few advantages of the vibration energy harvesting are the energy generated is clean, minimal maintenance cost, and non-intrusive to the existing state [6].

A non-intrusive energy harvesting ensures that the existing system's operation are uninterrupted or non-contact to the internal components during the energy harvesting process. Non-intrusive energy harvesting had been performed on air-conditioning compressor unit by attaching piezoelectric sensors at the air conditioning outdoor unit [7,8]. From the authors work [7], there is a lack of dedicated custom-made mounting to place



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the piezoelectric sensor for optimized energy harvesting. In the authors work [8], the placement of the piezoelectric sensor was at the evaporator fan outlet and the vibration was from the exhaust air from evaporator fan. Various researchers [9,10] had utilized non-intrusive energy harvesting for power meter devices and wireless sensors in the field of electric power system. It was found that there are various potentials for researchers to explore the field of non-intrusive energy harvesting.

In this work, the vibration source is from the air conditioning compressor unit located at the outdoor unit. In an air conditioning system, the refrigerant enters the compressor as a vapor and is compressed to the condenser pressure. When the refrigerant leaves the compressor, it is at a relatively high temperature and cools down and condenses as it flows through the coils of the condenser by removing heat to the ambient. Next, the refrigerant enters a capillary tube and subsequently the low-temperature refrigerant then enters the evaporator, where it evaporates by absorbing heat from the refrigerated area. This vapor-compression refrigeration cycle is completed as the refrigerant leaves the evaporator and reenters the compressor again [11]. Due to this repeating cycle, the work of the compressor causes vibration in the air conditioning outdoor unit [12,13]. Previous research work has been done to determine the most dominant vibration power flow transmission path on a compressor system mounted in an air conditioning out-door unit [14]. On top of that, the air conditioning indoor unit's air volume flow rates also has effect on the work of the compressor due to results of the indoor air flow heat transfer coefficients and the refrigerant heat transfer correlations from experimental results from researchers [15].

Therefore, to harvest energy from compressor vibration, one of the methods is through piezoelectric sensor [7,8]. Piezoelectricity is the electric charge that come from applied mechanical stress on certain solid material such as crystals and certain ceramics. The word piezoelectric is comes from Greek which means electrical energy that resulting from pressure [16]. Piezoelectricity is commonly used to convert ambient vibration into electricity. Piezoelectric effect generates voltage when certain types of materials experience mechanical stress or strain [4,17]. Examples of material that exhibit piezoelectric effect are aluminum nitride, gallium arsenide, lead zirconate titanate (PZT), quartz, and polymer polyvinylidene fluoride [4,17]. These piezoelectric materials are fabricated as thin layers or membranes to allow ambient vibration to easily induce mechanical stress and strain and therefore generate voltages. PZT is still the most popular piezoelectric material in energy harvesters [18]. Researchers have worked on a specially fabricated rotational piezoelectric energy harvester, PZT-5H, that consists of a 40 mm piezoelectric bimorph beam and the setup generated a maximum of 0.024 voltage output from a simulated input frequency of 18 Hz [2]. Previous research work done on PZT-5H concludes that this piezoelectric was an optimal road energy harvester due to the adaptable nature of the material [19]. One of the methodologies to implement the piezoelectric harvester was to structure it as a cantilever beam type that requires a fixed support in one end and the other free end with a tip mass [19]. In another research work, a rectangular shape piezoelectric, PZT-5A at a constant load of 20 N was able to harvest maximum 4.24 V experimentally at a frequency of 40 Hz [20].

Advantages and popularity of PZT piezoelectric material in energy harvesting have enabled many researchers to utilize and mount it inside the shoe heel and on the tire or rim of cars [18,21–23]. However, stiff piezoceramics are not able to capture much mechanical energy if they are directly attached to a vibration host [18]. Therefore, researchers harvesting energy from vibration of the tire or rim of car have utilized various design mountings for optimum harvesting output [21–23]. One effective piezoelectric mounting is to attach one end of the piezoelectric sensor to a fixed support and the other free end is to attach a tip mass to reduce the resonant frequency and enhance the vibration induced stress toward the piezoelectric sensor [18]. The tip mass varies from 5.5 g to 16.4 g, resulting in a range of the first resonant frequency of 20–150 Hz [18].

The main contribution of this paper is a novel non-intrusive vibration energy harvesting method for air conditioning compressor unit. To demonstrate the feasibility, a piezoelectric sensor, PZT-5H is attached to a 3D printed and custom-made mounting to be placed on an enclosure location directly adjacent to air conditioning condenser unit, to harvest vibration energy. The configuration of the harvester is non-intrusive, in which the harvester did not intrude into compressor unit operation. The influences of air conditioning indoor unit of temperature (20 °C, 22 °C, and 24 °C) and air volume flow rates (3 levels of air volume flow rate at level 1 (245 L/second), level 2 (274 L/second), and level 3 (297 L/second) were taken into consideration in this investigation.

2. Materials and Methods

A schematic diagram of the experimental setup to obtain the vibration data and RMS voltage data are shown in Figure 1. The details of materials and methods used are discussed in Sections 2.1–2.10.



Figure 1. Schematic diagram of the experimental setup to obtain the vibration data and RMS volt-age data.

2.1. Air Conditioning Outdoor Unit

The compressor unit is located at the air conditioning outdoor unit. This air conditioning unit is located at a lab in Faculty of Engineering, International Islamic University Malaysia. Figure 2 shows the compressor unit (circled in red) used in this work [24]. The air conditioning compressor unit is the component labeled 8 in Figure 2. The placement of the piezoelectric sensor, attached to a 3D printed and custom-made mounting, is at the service panel, Figure 2, (circled in blue, labelled 10) which is the enclosure directly adjacent to the compressor unit.

Two experiments were done to verify the optimum placement for the energy harvesting on the enclosure directly adjacent to the compressor unit. The first experiment was to investigate vibration data using accelerometer while the second experiment was to obtain data for the root mean square (RMS) voltage utilizing one the piezoelectric sensor beam. Both experiments were executed on 6 placement points (A, B, C, D, E, and F) on the service panel enclosure directly adjacent to the compressor unit, as shown in Figure 3a. In Figure 3b, it shows the air conditioning outdoor unit being anchored to the wall using "L" shaped wall support mounting with no anti-vibration support. This is illustrated by the red circle in Figure 3b. During operation, the system makes a buzzing sound. This air conditioning system is more than 5 years old.



Figure 2. Compressor unit (labeled 8) and service panel (labeled 10) locations at the air conditioning outdoor unit.

Vibration and noise are inherent in an air conditioning outdoor unit due to the compressor system [14]. Compressor system will generate vibration and transmit it to the chassis structure of the air conditioning outdoor unit causing noise. Figure 3c shows the vibration and noise generated from the compressor system of the air conditioning outdoor unit in this experiment based on the work of researchers [14].

2.2. Air Conditioning Indoor Unit

The air conditioning indoor unit is shown in Figure 4 [25]. The temperature settings parameters investigated in this work were at 20 °C, 22 °C, and 24 °C, which are typical temperature settings in Malaysia [26]. About 92% of Malaysia households prefer to set their air conditioning temperature below the recommended Malaysia's air conditioning setting at 24 °C [26]. The Malaysian Government has also advised the setting of air conditioning temperature setting in government offices at 24 °C or 25 °C [27]. In the commercial sector, the Malaysian Association for Shopping and Highrise Complex Management advised around 400 members to set their air conditioning temperature at 23 °C or 24 °C [28]. There are 3 levels of air volume flow rates which indicate the air volume flow rate at level 1 (245 L/second), level 2 (274 L/second), and level 3 (297 L/second) [25].

2.3. Accelerometer

In this project, an accelerometer (ICP Accelerometers (352C33) by PCB Piezotronics) will be used to measure vibrations at the 6 placement points indicated in Figure 3a.

2.4. Piezoelectric Sensor

The piezoelectric sensor that will be used Piezo Ceramic Bimorph which is a lead zirconate titanate, or PZT material. This material is chosen for energy harvesting because it has the high piezoelectric effect and low dielectric loss [17]. The dimension of this piezoelectric sensor is 45 mm length, 10 mm width, and thickness of 0.5 mm with a 40 mm ceramic layer length. This piezoelectric also has a resonant frequency of 2 kHz with a tolerance of $\pm 5\%$ [29].



(a)



Figure 3. (**a**). 6 placement points (A, B, C, D, E, and F) on the service panel enclosure directly adjacent to the compressor unit. (**b**). Air conditioning outdoor unit being anchored to the wall using "L" shaped wall support mounting with no anti-vibration support. (**c**). Vibration and Noise generated from the compressor system of the air conditioning outdoor unit in this experiment.



Figure 4. Air Conditioning Indoor Unit.

2.5. 3D Printed and Custom-Made Mounting for Piezoelectric Sensor

The mounting for piezoelectric sensor is needed to enhance the deformation of the material. This is because when higher deformation occurs, the sensor will generate more electrical energy due to greater piezo effect. Therefore, the energy harvesting will be optimized by the piezoelectric sensor. Based on previous research works [18], one end of the piezoelectric sensor to be attached to a fixed support and the other free end is to attach a tip mass. Therefore, a weight of 6 g was used for the tip mass. According to previous research work [18], the tip mass can vary from 5.5 g to 16.4 g to optimize the deformation of the piezoelectric sensor beam. Figure 5 shows the output of 3D printed and custom-made mounting for piezoelectric sensor.



Figure 5. 3D printed and custom-made mounting for piezoelectric sensor.

For this experimental work, the orientation of the mounting was orientated to the 9 o' clock position as shown in Figure 6. This orientation was used to validate the hypothesis for the experiment to obtain the RMS voltage utilizing the piezoelectric sensor from the non-intrusive energy harvesting methodology.



Figure 6. Piezoelectric mounting at 9 o'clock orientation on the outdoor unit panel.

2.6. Experimental Setup to Obtain Vibration Data

A signal conditioner and oscilloscope were required to obtain the vibration data from the accelerometer. The signal from accelerometer went through a signal conditioner and then an oscilloscope displayed the results of the vibration frequency. The configuration of the setup is shown in Figure 7.



Figure 7. Experimental setup to obtain vibration data.

Next, the accelerometer will be placed on air conditioning unit using adhesive which is Petro wax which comes with the accelerometer. Based on the General Operating Guide of the ICP Accelerometers Model 352C33, the adhesive mounting delivered best performance for temporary installation. Then, the accelerometer was placed on 6 placement points (A, B, C, D, E, and F) on the service panel enclosure directly adjacent to the compressor unit, as shown in Figure 3a.

2.7. Experimental Setup for Piezoelectric Sensor

In this experimental setup, the 3D printed and custom-made mounting with the attached piezoelectric sensor was placed on 6 placement points (A, B, C, D, E, and F) on the service panel enclosure directly adjacent to the compressor unit, as shown in Figure 8. For this experiment, piezoelectric sensor was connected to oscilloscope using dual alligator clip Y splice oscilloscope cable. The piezoelectric sensor was attached to a 3D printed and custom-made mounting. Then, the mounting was placed on the air conditioning unit using double sided tissue tape. This adhesive is suitable to attach on the service panel enclosure directly adjacent to the compressor unit. Figure 8 shows the setup for piezoelectric sensor. The mounting with attached piezoelectric sensor is placed at one placement point at a time to obtain the required readings. The experiments are repeated until all readings were obtained from the 6 placement points (A, B, C, D, E, and F).



Figure 8. Experimental setup for piezoelectric sensor.

2.8. RMS Voltage Calculation

From the experiment using piezoelectric sensor, the readings that were displayed on the oscilloscope is the voltage in alternate current (AC) waveform. Therefore, the calculation of root mean square (RMS) voltage is needed because it used to express an AC quantity of voltage in terms of functionally equivalent to DC. The readings that were being collected from the oscilloscope are the mean voltage. Hence, the formula that that was used is shown in Equation (1).

$$V_{RMS} = \frac{\pi}{2\sqrt{2}} \times V_{mean} = 1.11 \times V_{mean} \tag{1}$$

2.9. Data Analysis Using the One Factor Analysis of Variance (ANOVA)

One factor analysis of variance (ANOVA) is used to differentiate the means of more than two independent groups. This data analysis was used to verify the data are statistically significant. To get the significant data, *p*-value need to be less than alpha(α) value. For the experiment, the α value is 0.05 because of it commonly used in statistical calculation. The result of this analysis is tabulated as shown in Table 1.

Source	Sum of Squares	Degree of Freedom	Mean Square	F	<i>p</i> -Value	F Crit
Between Groups (Factor)	SS _F	$V_{\rm F}$	MS _F	F		
Within Groups (Error)	SSE	V _E	MS _E			
Total	SST					

Table 1. Data of the analysis tabulation.

All formula in the results are shown in Equations (2)–(9).

$$SS_F = \sum_k n_k (\overline{x}_k - \overline{x})^2 \tag{2}$$

$$SS_E = \sum_k \sum_i (x_{ik} - \overline{x}_k)^2 \tag{3}$$

$$SS_T = SS_F + SS_E \tag{4}$$

$$v_F = k - 1 \tag{5}$$

$$v_E = n - k \tag{6}$$

$$MS_F = \frac{SS_F}{v_F} \tag{7}$$

$$MS_E = \frac{SS_E}{v_E} \tag{8}$$

$$F = \frac{MS_F}{MS_F} \tag{9}$$

where;

k = Number of groups;

- *n* = Total sample size (all groups combined);
- n_k = Sample size of group k;

 \overline{x}_k = Sample mean of group *k*;

 \overline{x} = Grand mean.

To find *p* value, F distribution table is needed to locate the *p* value. A statistical software, such as Microsoft Excel, is used to obtain the exact number of *p* value. To identify the data is significant, *p* value need to be less than the alpha value. Critical value, F α need to be find in critical values table for alpha value, α equals 0.05. Figure 9 shows the result of one factor ANOVA analysis.

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7074.6	2	3537.3	7.89041	0.002002	3.354131
Within Groups	12104.2	27	448.3037			
Total	19178.8	29				

Figure 9. Result of one factor ANOVA.

2.10. Data Analysis Using the Two Factor Analysis of Variance (ANOVA)

To analyze the data from the experiments, two factor ANOVA technique were being used because there are two independent factors in the experiment. The experiment was performed with two factors which were temperature (Factor A) and air volume flow rates (Factor B) which was indicated by the air volume flow rate. The collected data were tabulated according to Table 2.

Table 2. Data for two factor experimental design.

	Air V	olume Flow Rates (Fac	ctor B)
Temperature (Factor A)	1 (Low)	2 (Medium)	3 (High)
20 °C	y111,, y11n	y121, , y12n	y131, , y13n
22 °C	Y_{211},\ldots, y_{21n}	y221, , y22n	y231, , y23n
24 °C	y311,, y31n	y321,, y32n	y331, , y33n

These observations can be written in a mathematical model as in Equation (10).

$$y_{ijk} = \mu + (f_A)i + (f_B)j + (f_{AB})ij + \in ijk$$
(10)

The total number of observations, N,

$$N = abn \tag{11}$$

where,

a = number of levels in factor A;

b = number of levels in factor B;

c = total number of trials.

$$A_{ij} = \sum_{k=1}^{n} y_{ijk} \tag{12}$$

$$A_{Ai} = \sum_{j=1}^{b} A_{ij} \tag{13}$$

$$A_{Bj} = \sum_{i=1}^{a} A_{ij} \tag{14}$$

$$T = \sum_{i=1}^{a} A_{Ai} = \sum_{j=1}^{b} A_{Bj}$$
(15)

The total variability in the data can be expressed as Sum if Squares Total (SS_T) as shown in Equation (16).

$$SS_T = SS_A + SS_B + SS_{AB} + SS_E \tag{16}$$

where the total sum of squares, sum of squares due to factor A (SS_A), sum of squares due to factor B (SS_B), sum of squares due to the interaction between factor A and B (SS_{AB}), and sum of squares to the error (SS_E) are shown in Equations (17)–(21).

$$SS_T = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} y^2_{ijk} - \frac{T^2}{N}$$
(17)

$$SS_A = \sum_{i=1}^{a} \frac{A^2_{Ai}}{bn} - \frac{T^2}{N}$$
(18)

$$SS_B = \sum_{j=1}^{b} \frac{A^2{}_{Bj}}{an} - \frac{T^2}{N}$$
(19)

$$SS_{AB} = \sum_{i=1}^{a} \sum_{j=1}^{b} \frac{A^{2}_{ij}}{n} - \frac{T^{2}}{N} - SS_{A} - SS_{B}$$
(20)

$$SS_E = SS_T - SS_A - SS_B - SS_{AB}$$
⁽²¹⁾

Then, the Mean Square (*MS*) are calculated by dividing the sum of square with to the number of degrees of freedom. The mean square for factor A (*MS*_A) and B (*MS*_B), interaction between factors (*MS*_{AB}) and error (*MS*_E) are shown in Equations (22)–(25).

$$MS_A = \frac{SS_A}{v_A} \tag{22}$$

$$MS_B = \frac{SS_B}{v_B} \tag{23}$$

$$MS_{AB} = \frac{SS_{AB}}{v_{AB}} \tag{24}$$

$$MS_E = \frac{SS_E}{v_E} \tag{25}$$

For degree of freedom for the factor A (v_A) and B (v_B), interaction between factors (v_{AB}) and error (v_E) are shown in Equations (26)–(29).

$$v_A = a - 1 \tag{26}$$

$$v_B = b - 1 \tag{27}$$

$$v_{AB} = (a-1) (b-1)$$
(28)

$$v_E = N - ab \tag{29}$$

Next, the ratio of variance in factor A (F_A) and factor B (F_B), interaction between factors (F_{AB}) are calculated using Equations (30)–(32).

$$F_A = \frac{MS_A}{MS_E} \tag{30}$$

$$F_B = \frac{MS_B}{MS_E} \tag{31}$$

$$F_{AB} = \frac{MS_{AB}}{MS_E} \tag{32}$$

Next, critical value, F_{α} need to be find in critical values table for alpha value, α equals 0.05. The critical value was chosen based on numerator (v₁) and the denominator (v₂). For factor A, v₁ = v_A and v₂ = v_E while factor B, v₁ = v_B and v₂ = v_E. For the interaction between factor A and B, v₁ = v_{AB} and v₂ = v_E.

The results of all the calculations are tabulated in Table 3. To identify the significant of the factor, ratio of variance (F) value needs to be more than critical value (F_{α}).

Source	Sum of Squares	Degree of Freedom	Mean Square	F	$F_{\alpha,v1,v2}$	Significant (Yes/No)
Factor A	SSA	vA	MS_A	F_A	$F_{\alpha,vA,vE}$	
Factor B	SSB	v_B	MS _B	F _B	$F_{\alpha,vB,vE}$	
Factor AB	SS _{AB}	V _{AB}	MS _{AB}	F _{AB}	$F_{\alpha,vAB,vE}$	
Error	SSE	$v_{\rm E}$	MS _E			
Total	SST					

Table 3. Result for a two-factor experimental design.

To determine the factor is significant, the value of 'F' needs to be more than the value of 'F critical'. Figure 10 show the result of two factor ANOVA analysis.

ANOVA					
Source of Variation	SS	df	MS	F	F crit
Factor A	1988.144	2	994.072	3.010586	3.109311
Factor B	18270.67	2	9135.337	27.66673	3.109311
Factor AB	14.26498	4	3.566245	0.010801	2.484441
Error	26745.56	81	330.1922		
Total	47018.65	89			

Figure 10. Results of two factor ANOVA.

3. Results and Discussion

3.1. Vibration Frequency Data

In this experiment, the vibration frequency has been collected using accelerometer that was placed on 6 placement points (A, B, C, D, E, and F) on the service panel enclosure directly adjacent to the compressor unit. Supplementary Materials, Figure S1 shows the data collected. The experiment was performed with two factor which were temperature (Factor A) which were at 20 °C, 22 °C, and 24 °C and air volume flow rates (Factor B) which were at level low, medium, and high. There were six placements around the compressor that were being tested. The frequencies generated from each spot was recorded every 5 s of run and this step was repeated for 10 times to obtain the average value. The result of each point is varied with range from 102.8 Hz to 830.2 Hz. To test the data that have been recorded are statistically significant, one factor analysis of variance (ANOVA) was being used to find the *p*-value. To verify the data are significant, *p*- value need to be less than the α -value which is 0.05. This analysis is needed due to the vibration frequency data range was large under the same conditions. Table 4 shows the summary of the analysis. All the details for the analysis are shown in Supplementary Materials, Figure S2.

		Significant?	
Temperature	20 °C	22 °C	24 °C
Point A	Yes	Yes	Yes
Point B	Yes	Yes	Yes
Point C	Yes	Yes	Yes
Point D	Yes	Yes	No
Point E	Yes	Yes	Yes
Point F	Yes	Yes	Yes

Table 4. Summary of the one factor analysis of variance (ANOVA) for vibration frequency data.

To summarize result in Table 4, data at all locations are statistically significant except at Point D with temperature 24 °C. This may be due to error while collecting the data for that location.

Then, all the vibration data for each placement were analyzed using two factor ANOVA. Supplementary Materials, Figure S3 shows the two-way ANOVA for vibration frequency. This is to determine the significant factor that will be used in comparing the data to identify the highest vibration point on the air conditioner. The summary of the two-way ANOVA analysis is shown in Table 5.

Table 5. Summary of the two-way ANOVA analysis for vibration frequency.

		Significant (Yes/No)	
Placement	Factor A (Temperature)	Factor B (Air Volume Flow Rates)	Factor AB
А	Yes	Yes	No
В	Yes	Yes	No
С	Yes	Yes	No
D	Yes	Yes	No
E	Yes	Yes	No
F	Yes	Yes	No

To sum up based on all result of the two-factor ANOVA analysis for each placement, the effect of temperature and air volume flow rates on the vibration data is significant for

all placements. Therefore, all the data will be used to compare which placement is the best for the piezoelectric harvester.

Figures 11–16 shows the average vibration frequency for the six placement locations at the 3 temperatures settings (Factor A) and 3 air volume flow rates settings (Factor B).



Figure 11. Average vibration frequency (Hz) for point A, B, C at 20 $^\circ$ C.



Figure 12. Average vibration frequency (Hz) for point D, E, F at 20 °C.



Figure 13. Average vibration frequency (Hz) for point A, B, C at 22 °C.



Figure 14. Average vibration frequency (Hz) for point D, E, F at 22 °C.



Figure 15. Average vibration frequency (Hz) for point A, B, C at 24 °C.



Figure 16. Average vibration frequency (Hz) for point D, E, F at 24 °C.

To summarize those charts, the maximum value of vibration frequency for each placement is being extracted. This is for comparing the highest vibration point that was produced by each placement A, B, C, D, E, and F. Figure 17 shows the summary of the chart.



Figure 17. Summary of highest average frequency of each placement.

From the result, it can be inferred that point F produces the highest frequency as compared to other placements. However, data from accelerometer need to be confirmed by one more experiment where the piezoelectric sensor being used to collect data. This experiment is used to validate the data that were collected by the accelerometer.

3.2. Voltage Data

In this experiment, RMS voltage data were collected to compare the results from previous experiment. Supplementary Materials, Figure S4 shows the result of RMS voltage utilizing piezoelectric sensor collected at the 6 placement points (A, B, C, D, E, and F) on the service panel enclosure directly adjacent to the compressor unit. This is for proving the optimum point on the air conditioning system for piezoelectric energy harvester. The piezoelectric sensor is being connected to an oscilloscope to get the reading of RMS voltage. The way to run this experiment was same as the experiment using accelerometer. The placements to put the piezoelectric sensor also the same with previous experiment. The result of each point is varied with range from 22.42 mV to 510.82 mV.

The piezoelectric produced high amount of voltage when there was high amount of exerted force. The formula to find the electrical charge produce by the piezoelectric sensor are shown in Equation (33) [30].

$$q = d33 \times F \tag{33}$$

where:

q = electrical charge; d33 = piezoelectric constant; F = exerted force.

Based on Equation (1), electrical charge, q is corresponding to the exerted force, F. When vibration force increase, the electrical charge produce is high. The equation in Equation (25) can be replaced in terms of voltage as shown in Equation (34) [30].

$$u = \frac{F \times d \times d33}{A \times e33} \tag{34}$$

where:

u = voltage; *F* = the exerted force;

- *d* = the thickness of the piezoelectric material;
- A = the area of the piezoelectric material;
- *d*33 = piezoelectric constant;
- *e*33 = piezoelectric constant.

Based on Equation (34), the voltage produces is depends on the exerted force toward the sensors. From the experiment that have been conducted, force is from the compressor vibration located at the air conditioning outdoor unit that applied to the piezoelectric sensor.

Then, two-factor ANOVA analysis needed for this experiment to determine the significant factor that will be used for comparing the data for each placement. The process to analyze the data is the same as previous two-factor ANOVA analysis. Supplementary Materials, Figure S5 shows the two-factor ANOVA data for RMS voltage. The summarization of the two-factor ANOVA analysis for RMS voltage data are shown in Table 6.

Factor B Yes	Factor AB No
Yes	No
Yes	No
	Yes Yes Yes Yes

Table 6. Summary of the two-way ANOVA analysis for RMS voltage data.

Based on Table 6, all factor B is significant at all placements while all factor A are significant at all placements except at placement A. This may be due to error while conducting the experiment. Probably, the piezoelectric mounting was not attached properly to the service panel enclosure directly adjacent to the compressor unit at location A. Based on previous analysis, temperature factor, and air volume flow rates factor were used to summarize RMS voltage data. Therefore, charts of RMS voltage data are being constructed using different air volume flow rates factor with three temperature factors. All the charts of average RMS Voltage (mV) for each point at different temperature are shown in Figures 18–23.



Figure 18. Average RMS voltage (mV) for point A, B, C at 20 °C.



Figure 19. Average RMS voltage (mV) for point D, E, F at 20 °C.



Figure 20. Average RMS voltage (mV) for point A, B, C at 22 °C.



Figure 21. Average RMS voltage (mV) for point D, E, F at 22 °C.



Figure 22. Average RMS voltage (mV) for point A, B, C at 24 °C.



Figure 23. Average RMS voltage (mV) for point D, E, F at 24 °C.

To summarize the charts, the maximum value of RMS voltage for each placement were extracted. Figure 24 shows the summary of the chart.



Figure 24. Summary of highest RMS voltage (mV) for each placement.

From the result, it concluded that placement at point F generates the highest amount of RMS voltage followed by point D, E, C, A, and B. Therefore, the optimum placement for the piezoelectric energy harvester has been confirmed at point F. This is due to the results from both experiments which are shown in Figures 19 and 24 conclude that location F produce high vibration frequency (830.2 Hz) and RMS voltage (510.82 mV). The reason location F produced high vibration is because the location was the nearest place to the bracket that hold the compressor.

Furthermore, the optimum air conditioning indoor unit settings are the lowest temperature which is at 20 °C and the highest air flow volume flow at level 3 (air flow volume flow rate at 297 L/second). This is because when the temperature setting is low, the compressor needs to increase work output to supply the cool fluid to the evaporator. In addition, when high air flow volume flow setting was used, the temperature of the cool fluid at the evaporator will increase faster and increase the workload of the compressor.

4. Conclusions

In conclusion, the optimum placement that produces high amount of vibration was determined. Based on the experiment, the highest vibration output is 830.2 Hz which is at location F. This is due to point F is the nearest location to the part of compressor which produce optimum amount of vibration.

Furthermore, point F was being verified as the best location to mount the piezoelectric energy harvester. This is because RMS voltage produced at the location F was highest at 510.82 mV. Therefore, this proves that the highest vibration source will harvest high amount of electrical energy through piezoelectric sensor.

In summary, the lowest temperature which is at 20 °C and highest air flow volume flow which is at level 3 (air flow volume flow rate at 297 L/second), are the best air conditioning indoor unit setting to harvest electrical energy. This is due to the high compression workload of the air conditioning compressor unit which results in high amount of vibration produced. From this work, it is feasible to utilize this novel method of harvesting waste vibration energy from the air conditioning compressor unit. In future work, it was proposed to further perform experiments to investigate the relationship between the orientation of the mounting and the voltage produce by the piezoelectric sensor.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10 .3390/su131810300/s1, Figure S1: Result of vibration frequency using accelerometer, Figure S2: One way ANOVA analysis for vibration frequency, Figure S3: Two way ANOVA analysis for vibration frequency, Figure S4: Result of RMS voltage utilizing piezoelectric sensor, Figure S5: Two factors ANOVA analysis for RMS voltage.

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