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Research Article

An Experimental Study of a Multi-Axis Generator

Min Chie Chiu[1]*, Ying Chun Chang[1], Ho Chih Cheng[2] and Tan Cheng Tsao[1]

[1]*Department of Mechanical and Materials Engineering, Tatung University, Taiwan, ROC.*

[2]*Department of Intelligent Automation Engineering, Chung Chou University of Science and Technolog, Taiwan, ROC.*

***Corresponding author:** Min Chie Chiu, Department of Mechanical and Materials Engineering, Tatung University, Taiwan , ROC

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Abstract

In daily life, many devices, including U-bike bicycle and flying wheel in gym, can convert vibrational mechanical energy into electrical energy. The electrical generation power generations are generally classified into the electromagnetic induction type and the piezoelectric type. The electromagnetic induction type is found to have a best power generation voltage in a low frequency environment. Therefore, based on the electromagnetic induction type, a multi-axis power generator used in a low-speed environment has been introduced and assessed in this paper. In this study, according to Faraday's law and Lenz's law, the characteristics of the magnetic attraction between the magnets are used and instead of the springs, so that the magnets will move in the way of pistons between the pipes. The electromagnetic induction power generation device has a simple structure which is capable of generating a high voltage at a low rotation speed and is easy to obtain. In this study, there are three kinds of power generation devices invented, including a two-axis, a three-axis, and a four-axis electricity generation device. The voltages generated at the respective rotation speeds of each type has been compared and evaluated. Consequently, a four-axis power generation device is found to be capable of generating a high voltage at a low speed. The maximum peak voltage of 21.2 volts and the electric power of 71.54 watts are obtained at a speed of 160 RPM. The four-axis power generation device is the most excellent power generation capability among the three power generation devices.

Keywords: Electromechanical Generator; Multi-Axis; Magnet; Rotation

Nomenclature

This paper is constructed on the basis of the following notations:

T: time period (s)

N: number of coilers turn

ε: induced electrical voltage (Volt)

Φ: the magnetic flux (Wb)

ΔΦ: variation of the magnetic flux (Wb

Introduction

Many energy extraction methods such as the piezoelectric, electromagnetic, magneto-strictive, and electrostatic transducer types have been developed [1,2]. Recently, a vibration-based generator using electromagnetic principle has been widely explored [3-7]. In addition, because of the huge progress in the semiconductor field, MEMS [8] were widely developed. Huang et al. [9] developed a MEMS-based generator using the sea wave in 2017. Their study indicated that an electrical power of 68.9μW will be produced via the sea wave with the actuating frequencies of 0.6 Hz~1 Hz. According to Santosh Kulkarnir [10], the electrical power of an electromagnetic type generator reached 0.59 μW. In order to improve the electricity, Serre et al. [11] increased the number of the induction coiler. And El-Hami et al. [12] enhanced the electricity by enlarging the reciprocating displacement of the generator. Some electromagnetic generators [13,14] using multi-layer coiler were proposed. In addition, a generator with multiple magnetic poles was proposed by Pan and Wu [15]. Because of no need of specific frequency actuated at the generator, the multi-pole generator will be more convenient in practical application [16]. Even though the electromagnetic generators do not require to run at a specific frequency, the research of generator always focus on the situation of high-speed rotation. As the generator design by Raisigel et al. [17], the rotation speed of the generator was at 400 RPM. Also, from the research of generator design by Arnold et al. [18], the rotation speed of the generator was at 350 RPM. However, for most of rotating machine, the low frequencies are almost located within 40 RPM~ 200 RPM. Because some of the exercise, such as the bike or the flying wheel, have a system's frequency of 40 RPM~ 200 RPM, how to transform the kinetic energy to the electrical energy by using the electromagnetic generators is the main issue in the paper. In order to develop a low-frequency generator, three kinds of power generation devices, including two-axis, three-axis and four-axis, are proposed and experimentally assessed in this study.

Design of the Vibration-based Mechanism for Electromagnetic Generators

The mechanism of multi-axis generator is shown in Figure 1. The allocation of the magnet is also illustrated in Figure 2. According to Faraday's law of electromagnetic induction, the electrical voltage will be induced when the magnetic flux (Φ) varies. The induced electrical voltage (ε) is

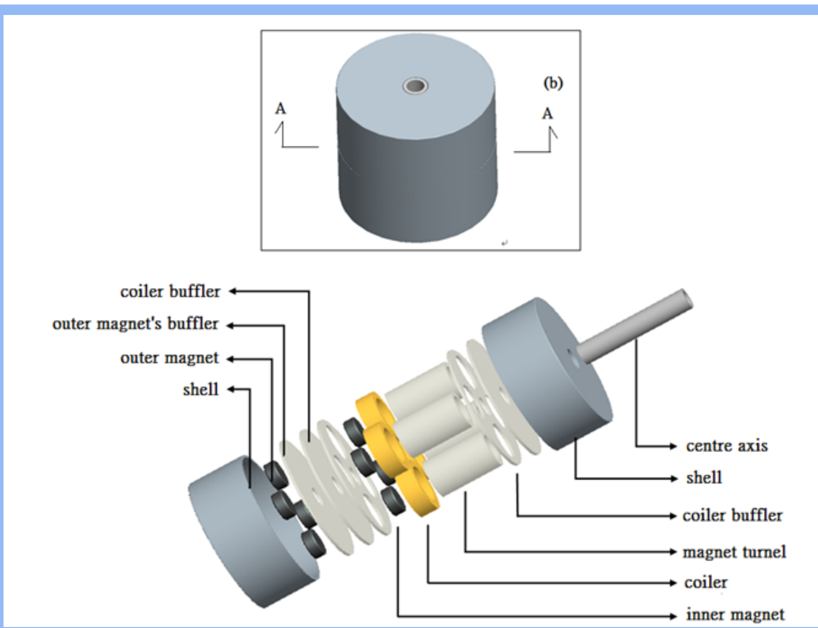

Figure 1: The mechanism of multi-axis generator.

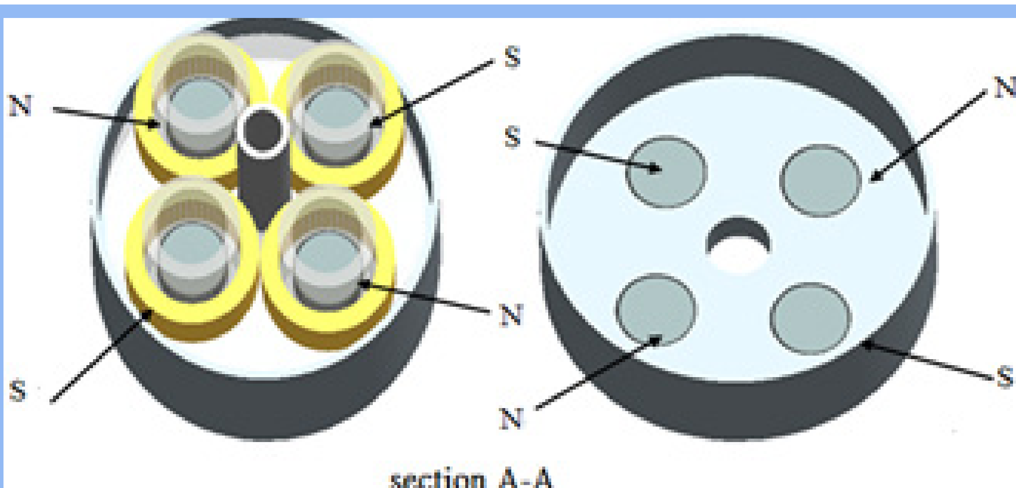

Figure 2: The allocation of magnet array.

$$\varepsilon=-N\,\Delta\Phi/\Delta t \quad (1)$$

where $\Delta\Phi$ is the variation of the magnetic flux and N is the number of coilers.

As indicated in Figure 2 in order to generate continuous electricity, the N pole and the S pole of the magnets are crossbedding. In order to sum up the current from different flowing direction, a current filtering device shown in Figure 3 is adopted. In addition, an experimental instrument of actuating the generator and measuring the induced electrical voltage is set up and depicted in Figure 4. The flow diagram in electricity generation and measuring process is demonstrated in Figure 5.

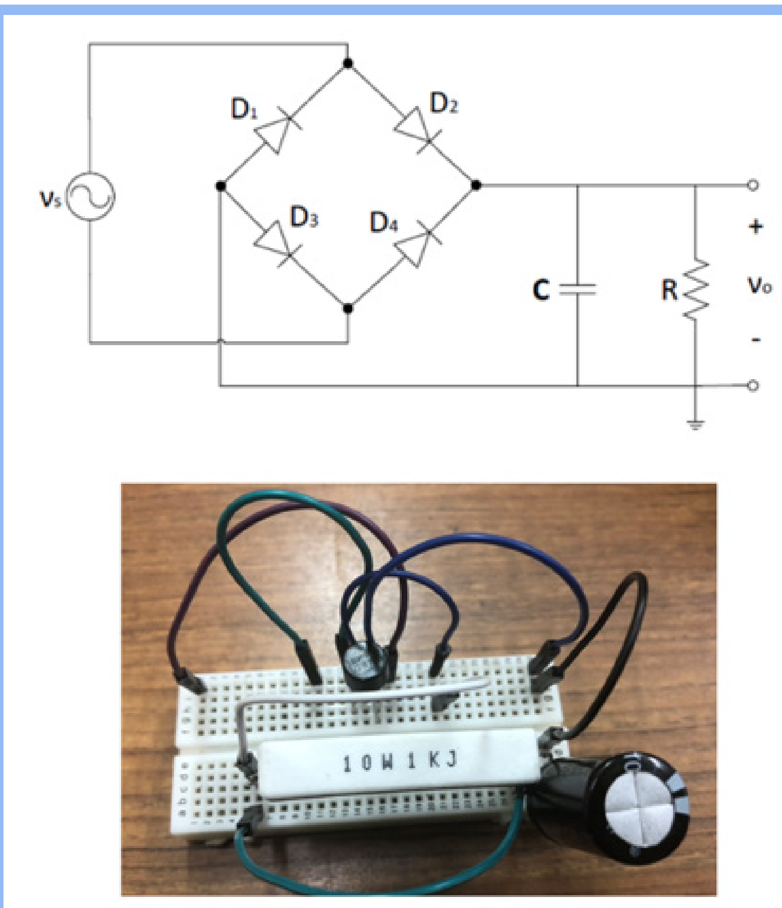

Figure 3: Electrical filtering circuit.

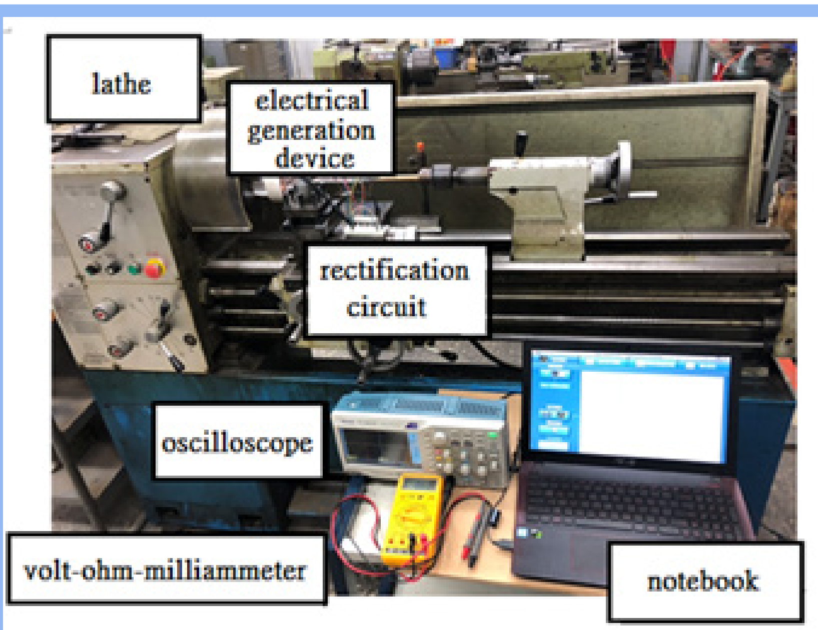

Figure 4: Experimental instrument set up.

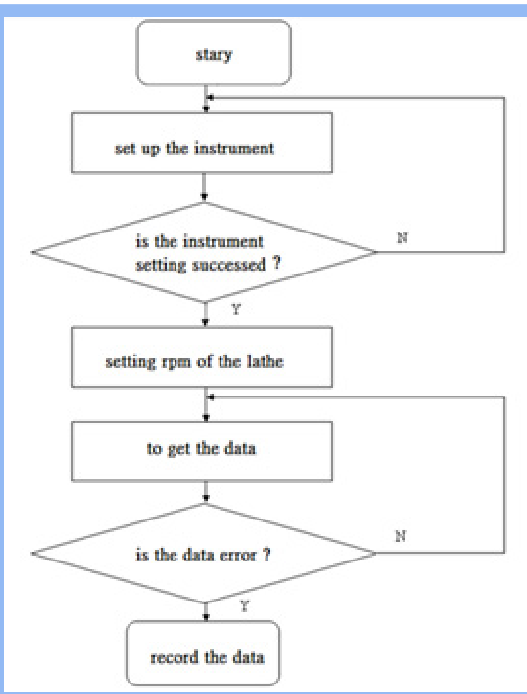

Figure 5: The flow diagram in electricity generation and measuring process.

Two-axis Generator

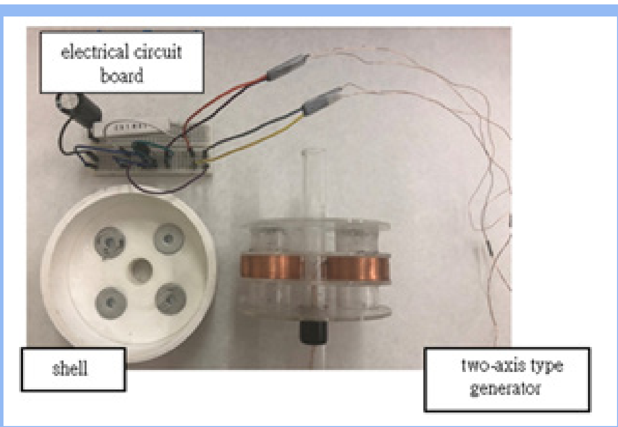

Figure 6: The mechanism of a two-axis generator.

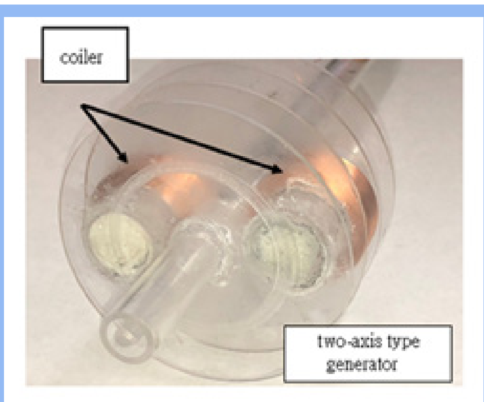

Figure 7: The two sets of coilers surrounding around two tubes.

Table 1: The specification of the two-axis generator.

Shell	
Magnet	20× 6.1×8 (mm)
Number of magnet	4 set
Central axis	
Coiler specification	38× 27×12 (mm)
N (number of coiler set)	2 sets
N (turn number of coiler)	680 turns
middle tube specification	25× 21×45 (mm)

The mechanism of the two-axis generator using one N pole and one S pole is shown in Figure 6. As indicated in Figure 7, two sets of coilers surrounding around two tubes are fixed on the central port of the generator. The specification of the two-axis generator is depicted in Table 1. Two free magnets (with different poles) at one end of the generator will be triggered to move forward and backward via the magnetic attraction force and repelling force when on set of magnets (one N pole and one S pole) fixed at the other end of the generator rotates. First, the two-axis generator is triggered by using a rotation speed of 40 RPM via a lathe. The induced electrical voltage is shown in Figure 8. Similarly, the induced electrical voltage is shown in Figures 9-12 when using a rotation speed of 80 RPM, 120 RPM, 160 RPM, and 200 RPM, respectively. In addition, the induced electrical voltage of the two-axis generator at various operating speeds is illustrated in Table 2. And, the induced electrical current of the two-axis generator at various operating speeds is also shown in Table 3.

Table 2: The induced electrical voltage of the two-axis generator at various operating speeds.

Electrical voltage	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Peak value of the electrical voltage (V)	4	5.4	6.8	6.8	3.8
The averaged electrical voltage (V)	0.243	0.316	0.608	0.594	0.435
The electrical voltage in RMS (V)	0.491	0.709	1.19	1.07	0.888
The time Period (ms)	714.8	376.2	241.8	186	143.4

Table 3: The induced electrical current of the two-axis generator at various operating speeds.

	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Electrical current (mA)	4.81	6.5	6.6	4.22	3.94

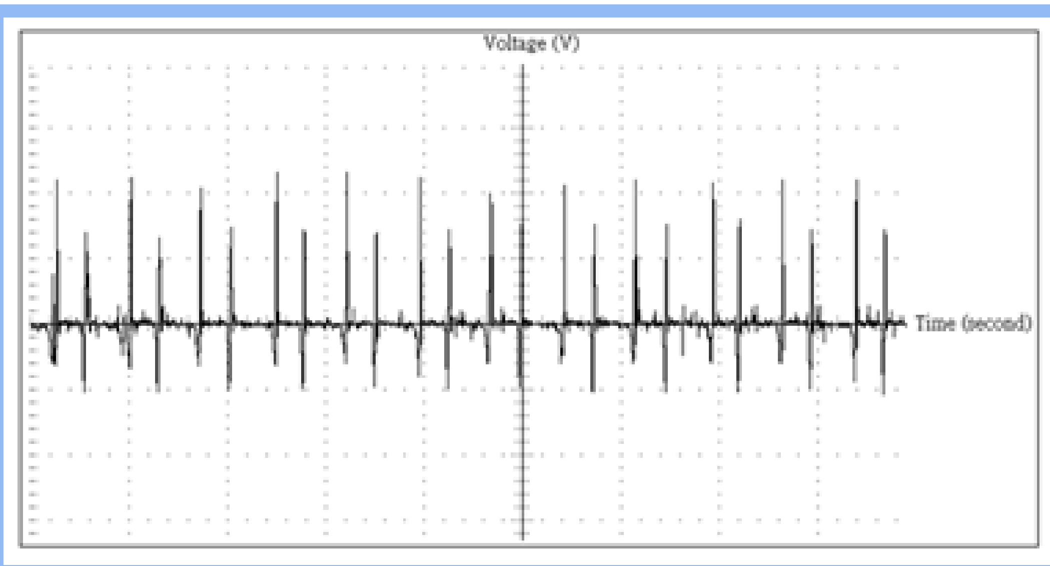

Figure 8: The response of voltage for a two-axis generator operating at 40 rpm.

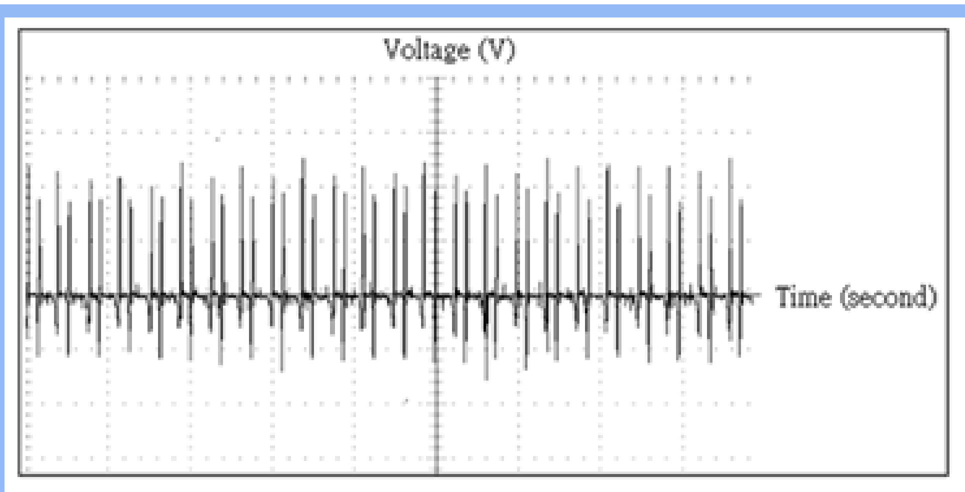

Figure 9: The response of voltage of a two-axis generator operating at 80 rpm.

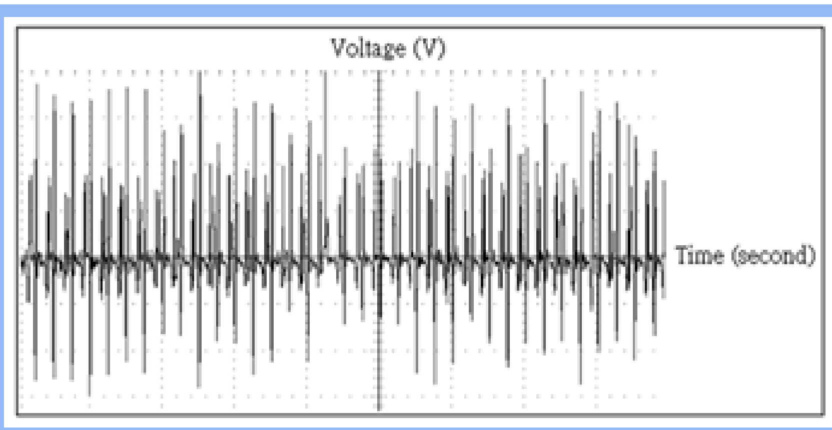

Figure 10: The response of voltage of a two-axis generator operating at 120 rpm.

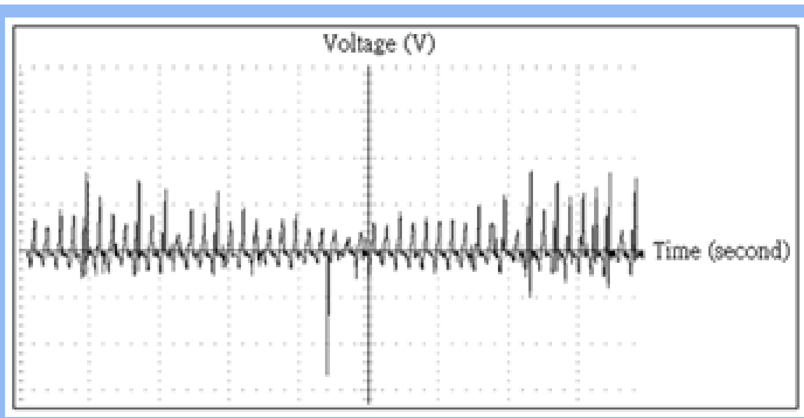

Figure 11: The response of voltage of a two-axis generator operating at 160 rpm.

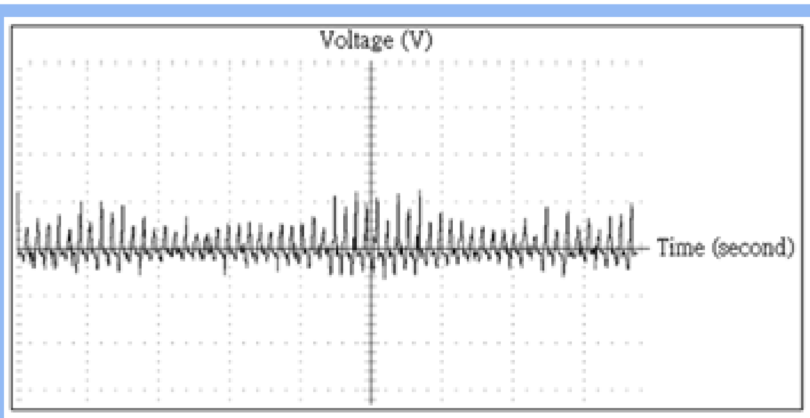

Figure 12: The response of voltage of a two-axis generator operating at 200 rpm.

Three-axis Generator

The mechanism of the three-axis generator using two N poles and one S pole is shown in Figure 13. Similarly, as can be seen in Figure 14, three sets of coilers surrounding around three tubes are fixed on the central port of the generator. The specification of the three-axis generator is depicted in Table 4. Three free magnets (two N pole and one S pole) at one end of the generator will be triggered to move forward and backward via the magnetic attraction force and repelling force when one set of magnets (one N pole and two S poles) fixed at the other end of the generator rotates. First, the three-axis generator is triggered by using a rotation speed of 40 RPM via a lathe. The induced electrical voltage is shown in Figure 15. Similarly, the induced electrical voltage is shown in Figures 16-19 when using a rotation speed of 80 RPM, 120 RPM, 160 RPM, and 200 RPM, respectively. In addition, the induced electrical voltage of the three-axis generator at various operating speeds is illustrated in Table 5. And, the induced electrical current of the three-axis generator at various operating speeds is also shown in Table 6.

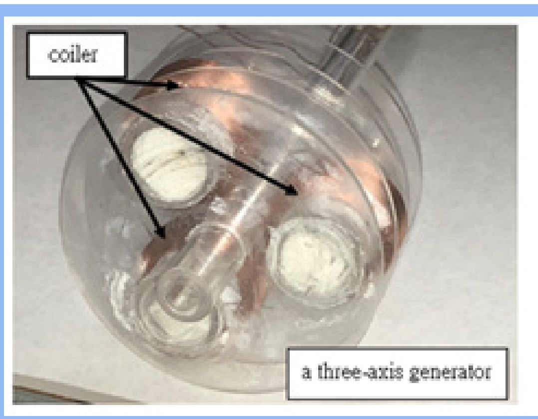

Figure 13: The mechanism of a three-axis generator.

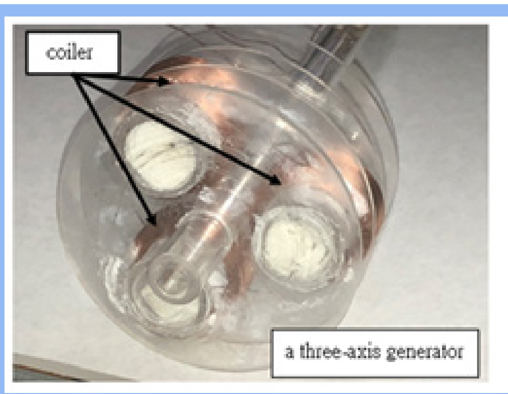

Figure 14: The three sets of coilers surrounding around three tubes.

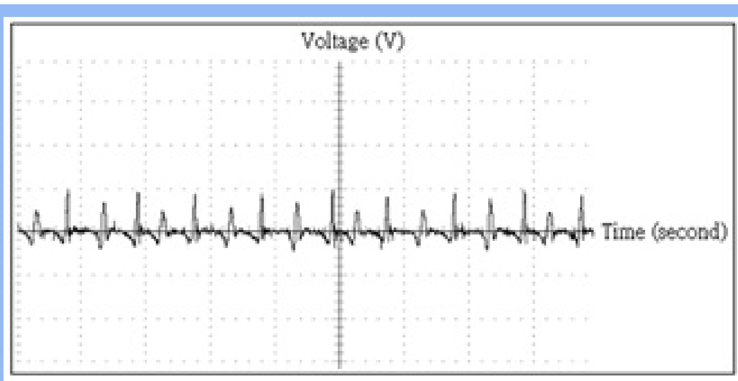

Figure 15: The response of voltage for a three-axis generator operating at 40 rpm.

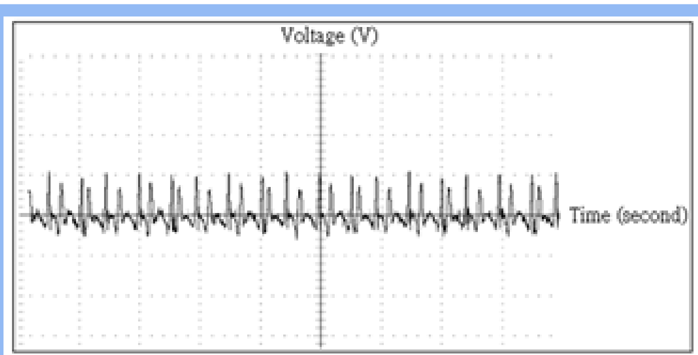

Figure 16: The response of voltage for a three-axis generator operating at 80 rpm.

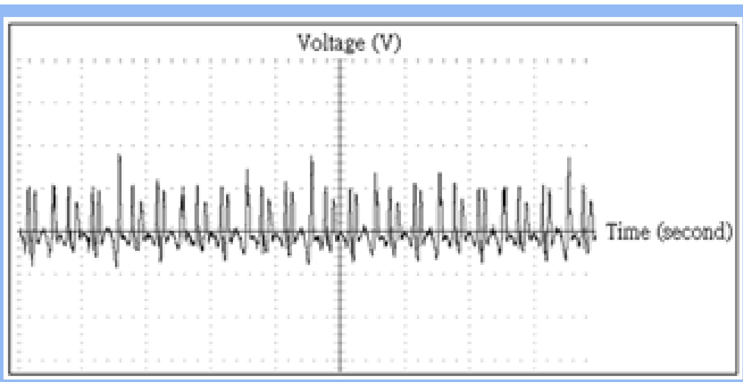

Figure 17: The response of voltage for a three-axis generator operating at 120 rpm.

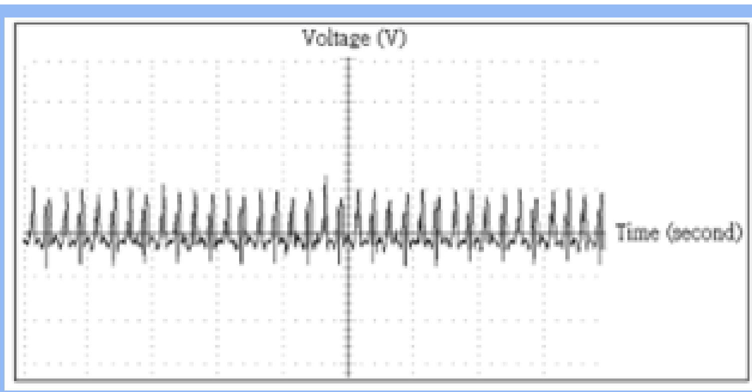

Figure 18: The response of voltage for a three-axis generator operating at 160 rpm.

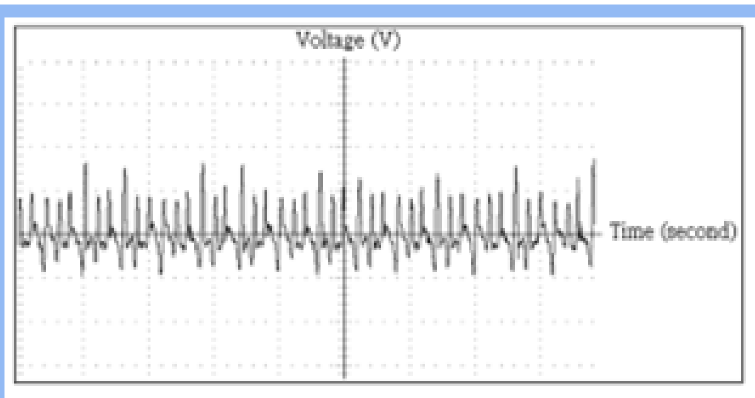

Figure 19: The response of voltage for a three-axis generator operating at 200 rpm.

Table 4: The specification of the three-axis generator.

Shell	
Magnet	20× 6.1×8 (mm)
Number of magnet	4 set
Central axis	
Coiler specification	38× 27×12 (mm)
N (number of coiler set)	3 sets
N (turn number of coiler)	680 turns
middle tube specification	25× 21×45 (mm)

Table 5: The induced electrical voltage of the three-axis generator at various operating speed.

Electrical voltage	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Peak value of the electrical voltage (V)	4	5	4.6	7.6	4
The averaged electrical voltage (V)	0.24	0.439	0.624	0.937	0.645
The electrical voltage in RMS (V)	0.639	1.2	1.94	1.77	1.41
The time period (ms)	250	123	81	60	88

Table 6: The induced electrical current of the three-axis generator at various operating speed.

	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Electrical current (mA)	1.42	1.78	4.52	4.63	4.62

Four-axis Generator

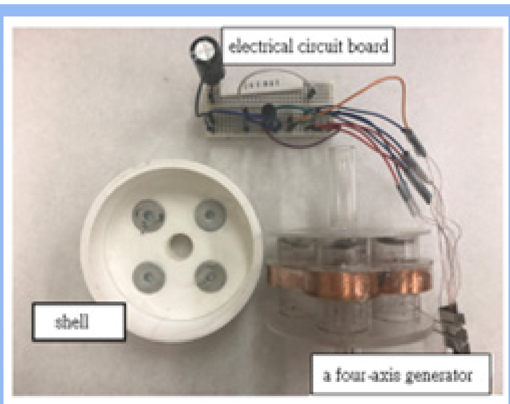

Figure 20: **The mechanism of a four-axis generator.**

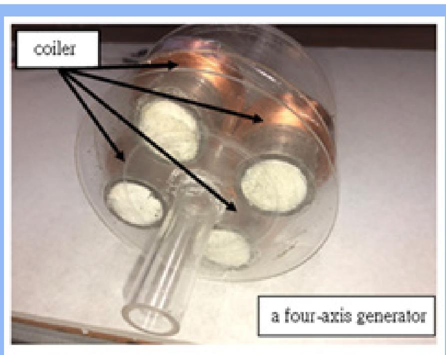

Figure 21: The four sets of coilers surrounding around four tubes.

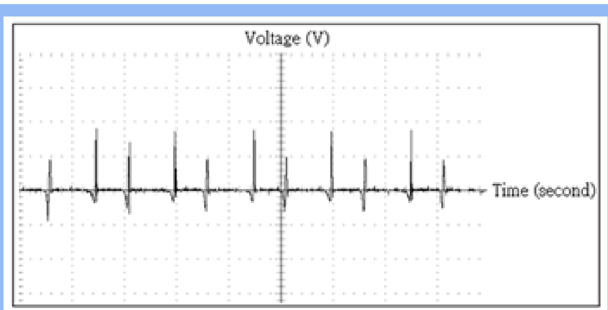

Figure 22: The response of voltage for a four-axis generator operating at 40 rpm.

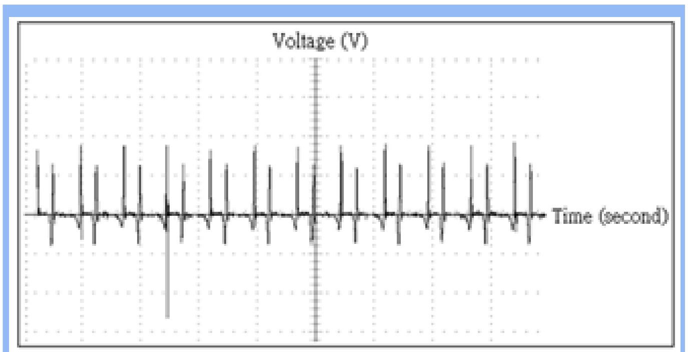

Figure 23: The response of voltage for a four-axis generator operating at 80 rpm.

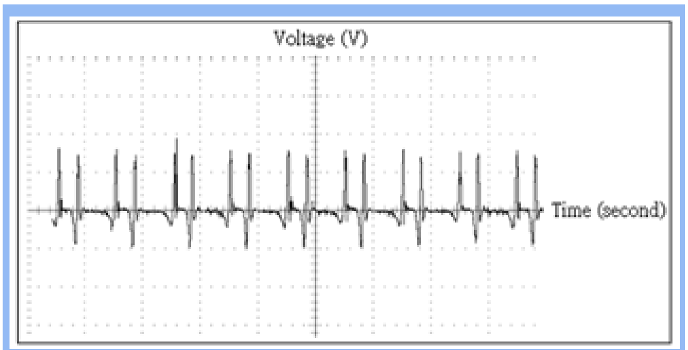

Figure 24: The response of voltage for a four-axis generator operating at 120 rpm.

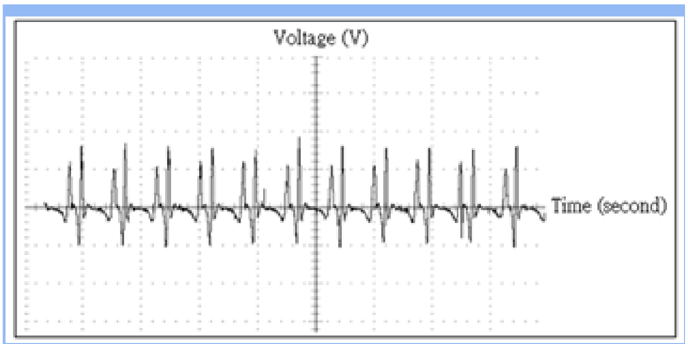

Figure 25: The response of voltage for a four-axis generator operating at 160 rpm.

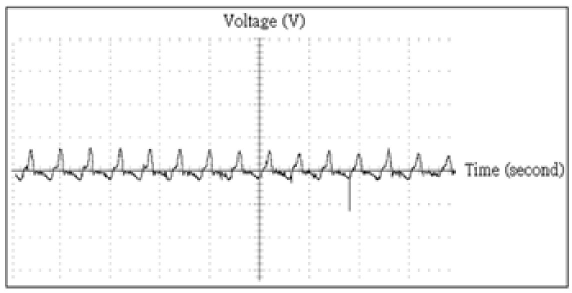

Figure 26: The response of voltage for a four-axis generator operating at 200 rpm.

The mechanism of the four-axis generator using two N poles and two S poles is shown in Figure 20. The N pole and S pole will be located in a crisscross form. Similarly, as can be seen in Figure 21, four sets of coilers surrounding around four tubes are fixed on the central port of the generator. The specification of the four-axis generator is depicted in Table 7. Four free magnets (an interlacing of two N poles and two S poles) at one end of the generator will be triggered to move forward and backward via the magnetic attraction force and repelling force when one set of magnets (two N poles interlocked with two S poles) fixed at the other end of the generator rotates. First, the four-axis generator is triggered by using a rotation speed of 40 RPM via a lathe. The induced electrical voltage is shown in Figure 22. Similarly, the induced electrical voltage is shown in Figures 23-26 when using a rotation speed of 80 RPM, 120 RPM, 160 RPM, and 200 RPM, respectively. In addition, the induced electrical voltage of the four-axis generator at various operating speeds is illustrated in Table 8. And, the induced electrical current of the four-axis generator at various operating speeds is also shown in Table 9.

Table 7: The specification of the four-axis generator.

Shell	
Magnet	20× 6.1×8 (mm)
Number of magnet	4 set
Central axis	
Coiler specification	38× 27×12 (mm)
N (number of coiler set)	4 sets
N (turn number of coiler)	680 turns
middle tube specification	25× 21×45 (mm)

Table 8: The induced electrical voltage of the four-axis generator at various operating speeds.

Electrical voltage	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Peak value of the electrical voltage (V)	20	20	20	21.2	10.4
The averaged electrical voltage (V)	1.01	1.14	1.97	2.57	1.39
The electrical voltage in RMS (V)	3.08	3.01	4.88	4.38	2.16
The time period (ms)	740	376	248	189.8	144

Table 9: The induced electrical current of the four-axis generator at various operating speeds.

	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Electrical current (mA)	8.24	9.94	8.87	10.22	3.05

Results and Discussion

Results

Two-axis Generator

To investigate the influence of generated electrical voltage with respect to various rotation speeds, five kinds of rotation speeds (40 RPM, 80 RPM, 120 RPM, 160 RPM, and 200 RPM) are selected as the parameter. The experimental results are depicted in Figures 8-12 and Tables 2-3. Figures 8-12 and Tables 2-3 show that based on the same magnetic field of a two-axis generator, the induced electrical voltage will change if the rotation speed varies. As can be seen above, the value of electrical voltage will be the largest one when the rotation speed is tuned to 120 RPM-160 RPM.

Three-axis Generator

Similarly, to investigate the influence of generated electrical voltage with respect to the rotation speed, five kinds of rotation speeds (40 RPM, 80 RPM, 120 RPM, 160 RPM, and 200 RPM) are also chosen as the parameter. The experimental results are obtained and plotted in Figures 15-19 and Tables 5-6. Figures 15-19 and Tables 5-6 reveal that the induced electrical voltage of the two-axis generator will reach the maximum when the rotation speed is adjusted to 120 RPM-160 RPM.

Four-axis Generator

Similarly, to investigate the influence of a four-axis generator's generated electrical voltage with respect to various rotation speeds, five kinds of rotation speeds (40 RPM, 80 RPM, 120 RPM, 160 RPM, and 200 RPM) are also chosen as the parameter. Experimental results show in Figures 22-26 and Tables 8 & 9 reveal that the induced electrical voltage of the four-axis generator will reach the maximal value when the rotation speed is adjusted at 120 RPM-160 RPM.

Discussion

As discussed above, for three kinds of multi-axis generators (a two-axis generator, a three-axis generator, and a four-axis generator), the value of the induced electrical voltage will be the largest one when the operating speed reaches 120 RPM. Also, the time period with respect to the rotating speed at various types of generators is investigated and shown in Figure 27 and Table 10. As indicated in Figure 27 and Table 10, the time period is inversely proportional to the rotation speed. In addition, both the two-axis generator and the four-axis generator have the same T & rotation-speed curves. Moreover, the comparison of the peak electrical voltage with respect to the rotating speed at various types of generators has been performed and shown in Figure 28 and Table 11. As can be seen in Figure 28 and Table 11, the peak electrical voltage of the four-axis generator is superior to that of other generators. Similarly, the comparison of the electrical current with respect to the rotating speed at various types of generators is performed experimentally. Results in Figure 29 and Table 12 indicate that the four-axis generator has the largest electrical current than others. In addition, the maximum peak voltage of 21.2 volts and the electric power of 71.54 watts are obtained at a speed of 160 RPM. Furthermore, a comparison of the electrical power with respect to the rotating speed at various types of generators is also experimentally assessed and shown in Figure 30 and Table 13. Figure 30 and Table 13 indicate that the four-axis has the largest induced electrical power than others two generators.

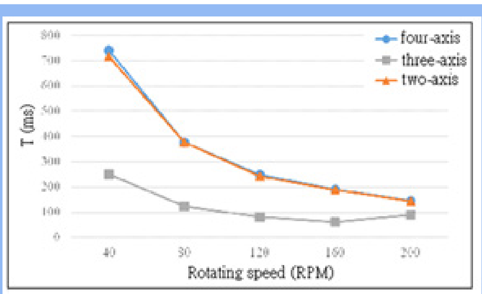

Figure 27: The comparison of the time period with respect to the rotating speed at various type of generators.

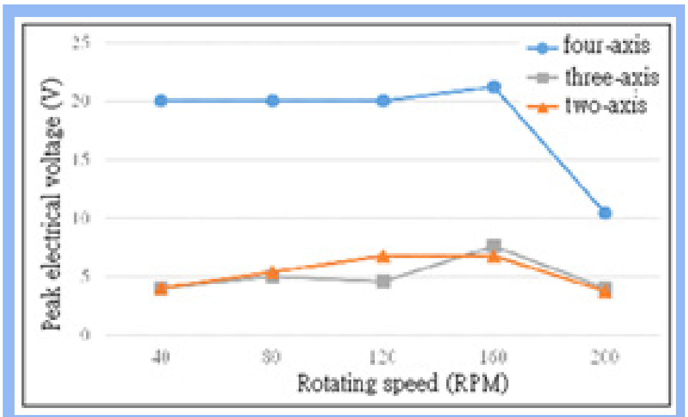

Figure 28: The comparison of the peak electrical voltage with respect to the rotating speed at various types of generators.

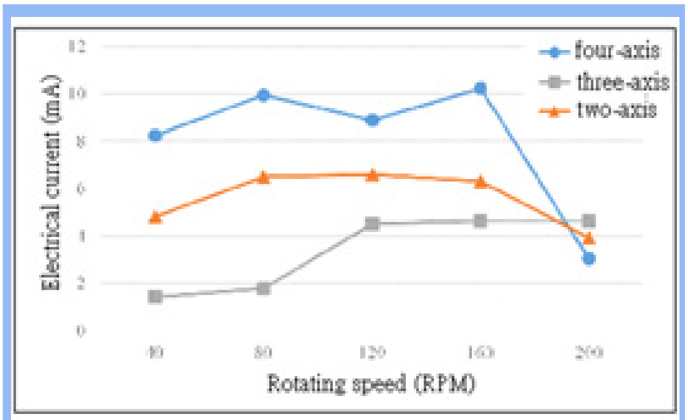

Figure 29: The comparison of the electrical current with respect to the rotating speed at various types of generators.

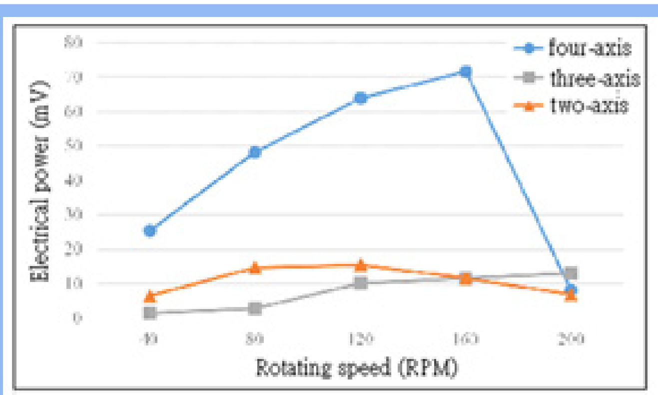

Figure 30: The comparison of the electrical power with respect to the rotating speed at various types of generators.

Table 10: The time period with respect to the rotation speed at three kinds of generators.

Time period of the electrical voltage (ms)	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Two-axis generator	714.8	376.2	241.8	186	143.4
Three-axis generator	250	123	81	60	88
Four-axis generator	740	376	248	189.8	144

Table 11: The peak value of electrical voltage with respect to the rotation speed at three kinds of generators.

The peak value of the electrical voltage (V)	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Two-axis generator	4	5.4	6.8	6.8	3.8
Three-axis generator	4	5	4.6	7.6	4
Four-axis generator	20	20	20	21.2	10.4

Table 12: The electrical current with respect to the rotation speed at three kinds of generators.

Electrical current (mA)	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Two-axis generator	4.81	6.5	6.6	6.3	3.94
Three-axis generator	1.42	1.78	4.52	4.63	4.62
Four-axis generator	8.24	9.94	8.87	10.22	3.05

Table 13: The electrical power with respect to the rotation speed at three kinds of generators.

Electrical power (mW)	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Two-axis generator	6.5416	14.56	15.312	11.592	6.8556
Three-axis generator	1.42	2.848	10.1248	11.575	12.936
Four-axis generator	25.2968	48.209	63.864	71.54	8.0825

Considering a commercial product of electrical generator (a xero dynamo brand) shown in Figure 31, the mechanism of the xero dynamo wheel set generator is illustrated in Figure 32. The comparison of the electrical voltage between the four-axis generator and the current commercial generator (xero dynamo wheel type) is also experimentally assessed and shown in Figure 33 and Table 14. As indicated in Figure 33 and Table 14, the induced electrical voltage of the four-axis generator is higher than that of the xero dynamo wheel set generator when the operating speed is within 40 RMP – 160 RPM. However, the induced electrical voltage of the four-axis generator is lower than that of the xero dynamo wheel set generator when the operating speed is at 200 RPM and above. Moreover, as can be seen in the Figure 33 and Table 14, the efficiency of electricity performance for a four-axis generator is obvious when the operating is getting lower.

Figure 31: The outline of a xero dynamo wheel set generator.

Figure 32: Mechanism of a xero dynamo wheel set generator.

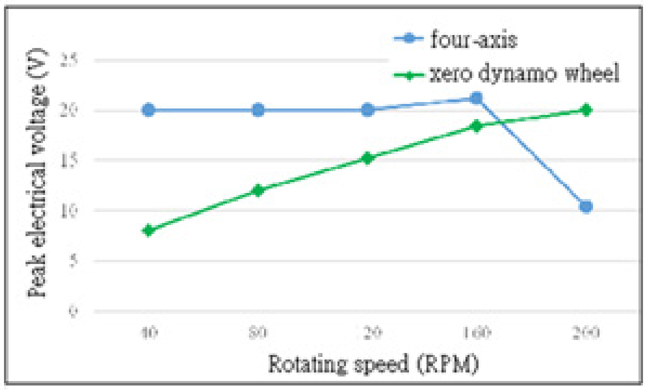

Figure 33: The comparison of the electrical voltage between the four-axis generator and the current commercial generator (xero dynamo wheel type).t generator.

Table 14: The comparison of peak electrical voltage between the four-axis generator and the xero dynamo wheel set generator at various rotation speeds.

Peak value of the electrical voltage (V)	40RPM	80RPM	120 RPM	160 RPM	200 RPM
Four-axis generator	20	20	20	21.2	10.4
The Xero Dynamo Wheel Set Generator	8	12	15.2	18.4	20

Conclusion

The goal of this paper is to develop a multi-axis electromagnetic generator. The free magnets have been attracted and repelled to move forward and backward along the tubes when an array of the magnets fixed on the other end of the generator is rotated. The magnetic flux will change, and the induced electrical voltage is then occurred. On the vibration basis, three kinds of the multi-axis generators, including a two-axis generator, a three-axis generator, and a four-axis generator, are experimentally explored. Experimental result reveals that a four-axis generator has the best electrical power. Also, the induced electrical power will be the largest when the rotation speed reaches 120 RPM to 160 RPH. The four-axis generator is also compared to the commercial generator, a xero dynamo wheel set generator. As can be seen in the result, the induce electricity of the xero dynamo wheel set generator is proportional to the operating speed. However, the value of the electrical voltage is smaller than that of the four-axis generator when the operating speed is below 160 RPM. Result also indicates that the related induced electrical voltage with respect to the four-axis generator and the xero dynamo wheel set generator is 20 (V) and 8 (V) when the rotation speed is at 40 RPM. And the related induced electrical voltage with respect to the four-axis generator and the xero dynamo wheel set generator is 21 (V) and 18 (V) when the rotation speed is at 160 RPM. It is obvious that the four-axis generator has higher electricity efficiency than the xero dynamo wheel set generator when the frequency of the triggering force is in lower status. Consequently, the four-axis generator can be suitable for the energy regeneration of the vibrational device which has the low frequency.

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