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Performance analysis and test of magnetic coupling excitation piezoelectric rotating generator

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Abstract

In order to meet the self-power demand of wireless monitoring system and network in agricultural remote sensing monitoring system, and avoid the environmental pollution and water waste caused by battery production and waste battery, a magnetically coupled piezoelectric rotary generator was proposed. The piezoelectric vibrator of the piezoelectric rotating generator is excited by the rotating magnetic force to produce bending deformation to generate electricity. The exciting magnet arc length influence on output performance of piezoelectric rotating generator is studied theoretically and experimentally. The results show that the arc length of the exciting magnet has an effect on the output voltage peak and waveform curve. When the rotating speed is 834 r/min as well as the exciting magnet number is 3 and 5, there are 3 and 5 oscillating waves in a single waveform. The exciting magnet number has an effect on the rotating speed- voltage characteristic curve of the piezoelectric rotating generator. There are several obvious optimal speeds make the output voltage peak.

With the increase of the exciting magnet number, the amplitude of oscillating waves increases and the number of oscillating waves decreases.

Keywords: Exciting magnet; Piezoelectric rotating generator; Arc length of moving magnet; output voltage

1 Introduction

In order to meet the self-power supply requirements of micro-power electronic products, wireless monitoring systems and networks, and avoid the environmental pollution caused by battery production and waste battery disposal, the research of generators based on electromagnetic, triboelectric, piezoelectric and other principles has become a research hotspots at home and abroad [1-3] . Each type of micro-miniature generator has its own characteristics and applications. The advantages of piezoelectric generators are: simple structure, miniaturization and integration, especially low-frequency excitation can generate higher voltage. Existing piezoelectric generators have been gradually used in communication/internet of things [4-5], medical/biomedical engineering [6-7], aerospace [8-9], buildings/bridges [10-11], railway transportation [12-13] and other fields.

Piezoelectric rotary generator is one of the important methods to recover the kinetic energy of rotating body. Because gyromagnetic excitation has no impact, low noise, and relatively high safety, it has attracted much attention in recent years. Fu [14] proposed a miniature radial flow turbine piezoelectric generator in 2015, and by changing the magnet polarity configuration , it was found that the generator has a higher output power when the magnets are installed to repel. In 2018, Yang [15] designed a low wind speed turbine piezoelectric generator suitable for wireless sensors in order to overcome the disadvantage of low power generation efficiency of traditional horizontal axis piezoelectric wind generators at low wind speeds. Zhao [16] studied a piezoelectric-electromagnetic hybrid turbogenerator in 2019. The magnets are installed symmetrically and with opposite polarities, which can reduce the torque, and similarly enhance the effective magnetic force and improve the power , and reliability are high . Tang Wei [17] established a parameter model of nonlinear distribution which can be used to describe the dynamic behavior of the system , and used the harmonic balance method to give the analytical solution of the harmonic response .

In this work, for improving the environmental adaptability, reliability and power generation capability of the piezoelectric rotary generator, a magnetic coupling excitation piezoelectric rotary generator is proposed, which uses the moving magnet to excite the piezoelectric vibrator to bend and deform to generate electricity, and has the advantages of high reliability and environmental adaptability. Sexual strength and other advantages.

2 The structure and working principle of the generator

The structural principle of the magnetically coupled excitation piezoelectric rotary generator is shown in Fig.1. It mainly includes components such as a fixed magnet, a moving magnet, a turntable, a fixed rod and a piezoelectric vibrator. The piezoelectric vibrator is bonded by a metal substrate and a piezoelectric ceramic. The fixed magnet is fixed and installed on the center of the piezoelectric vibrator by bolts. The turntable and its moving magnets are installed on the rotating shaft through bearings, and the moving and fixed magnets are installed facing each other. During the working process, the turntable drives the moving magnet to rotate. When the moving magnet is close to the fixed magnet on the piezoelectric vibrator, the interaction force between the moving magnet and the fixed magnet increases, causing the piezoelectric vibrator to deform axially; when the moving magnet is far away from the fixed magnet, the interaction force between the moving and stationary magnets decreases, and the piezoelectric beam returns to its original state due to its own elastic effect. The piezoelectric vibrator converts mechanical energy into electrical energy through reciprocating bending deformation.

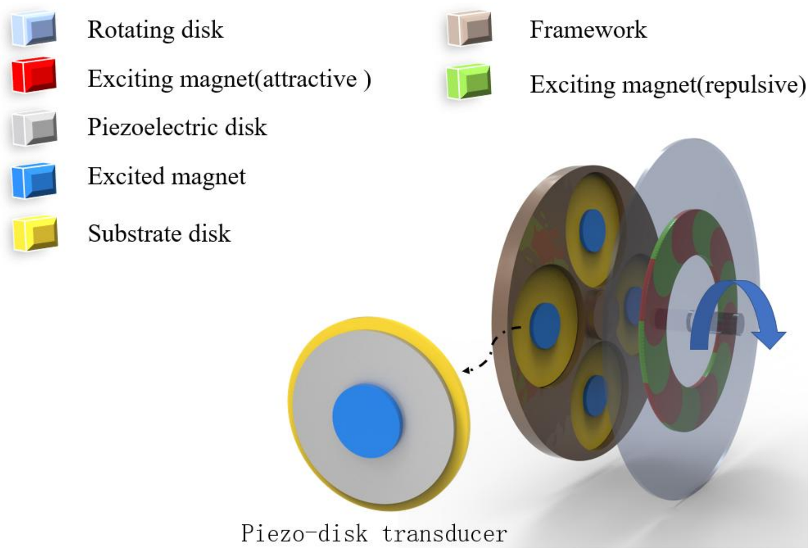


Fig.1. The schematic diagram of the structure of the rotary piezoelectric generator

3. Establishment of generator dynamic model

The magnetic coupling excitation piezoelectric rotary generator proposed in this paper is to excite the fixed magnet on the piezoelectric vibrator through the moving magnet, so that the piezoelectric vibrator is bent and deformed to generate electricity. According to previous research, when the piezoelectric vibrator is subjected to external force, the relationship between the deformation at the center and the generated open circuit voltage is [18]

$$V_g = \lambda_0 x(t) \tag{1}$$

Among them, λ_0 is the coefficient related to the structure size and material parameters of the piezoelectric vibrator, $x(t)$ is the deformation amount at the center of the piezoelectric vibrator, and its magnitude depends on the response characteristics of the piezoelectric vibrator when it is subjected to magnetic force. According to the vibration theory, the differential equation of motion of the system is

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{2}$$

Where m , c and k are the total equivalent mass, damping coefficient, and total equivalent stiffness of the system, respectively, and $F(t)$ is the exciting force.

In order to obtain the expression of the vibration response function of the piezoelectric vibrator when it is excited by the moving magnet, the relationship between the fixed magnet and the moving magnet during the rotation process is firstly studied, as shown in Fig.2.

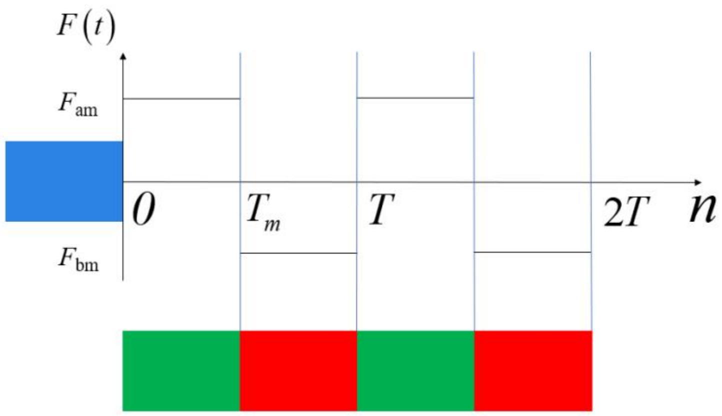


Fig.2. Schematic diagram of excitation force analysis

Assuming that the moving magnet is in contact with the fixed magnet to generate a stable axial force (the attraction of the two magnets is F_{am} , and the repulsion of the two magnets is F_{bm}), the exciting force of the piezoelectric vibrator is [19]:

$$F(t)=\begin{cases}F_{am}, & 0<t<T_m \\ F_{bm}, & T_m<t<T\end{cases} \tag{3}$$

Among them, $T_m=\dfrac{2RN_a}{n}\arctan(\dfrac{r}{R})$ is the action time of the attractive excitation force, is the action time $T=\dfrac{2R(N_a+N_b)}{n}\arctan(\dfrac{r}{R})$ of the total excitation force, is the number N_a of attracting moving magnets , is the number N_b of repelling moving magnets , is the rotating speed of the turntable, r is n the magnet radius, and R is the magnet gyration radius.

Pull transformation of formula (2) , we get

$$L\ \{F(t)\}=\frac{F_{am}[1-(F_{am}-F_{bm})\ e^{-T_m s}]}{s} \tag{4}$$

Combining formula (2) and formula (4) , the vibration response function of the piezoelectric vibrator can be obtained as

$$\begin{aligned}x(t)=[&-\frac{F_{am}}{k\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_d t+\phi_1)+\frac{F_{am}-F_{bm}}{k\sqrt{1-\zeta^2}}e^{-\zeta\omega_n(t-T_m)}\sin\{\omega_d(t-T_m)+\phi_1\}]\\&-\frac{x_0}{\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_d t+\phi_1)+\frac{2\zeta\omega_n x_0+\dot{x}_0}{\omega_n\sqrt{1-\zeta^2}}e^{-\zeta\omega_n t}\sin(\omega_d t)+\frac{F_{bm}}{k}\end{aligned} \tag{5}$$

Among them, $\phi_1=\cos^{-1}\zeta$, $\zeta=c/(2\sqrt{km})$ is the damping ratio, x_0 is the zero initial displacement of $\dot{x}_0$ the center position of the piezoelectric vibrator , is its initial velocity, $\omega_{\mathrm{n}}=\sqrt{k/\mathrm{m}}$ and $\omega_{\mathrm{d}}=\omega_{\mathrm{n}}\sqrt{1-\zeta^2}$ is the natural frequency of the piezoelectric vibrator without damping and damping, respectively.

According to formula (5) , the amplitude amplification ratio of the piezoelectric vibrator is obtained as

$$\beta=\frac{x(t)*k}{F_{am}} \tag{6}$$

Equations (5) and (6) show that when the other conditions of the system remain unchanged, the deformation of the piezoelectric vibrator is mainly determined by the excitation force and the excitation method. The amplitude amplification ratio β is the ratio of the vibration amplitude of the piezoelectric vibrator to its static displacement , which can be used to represent the output voltage.

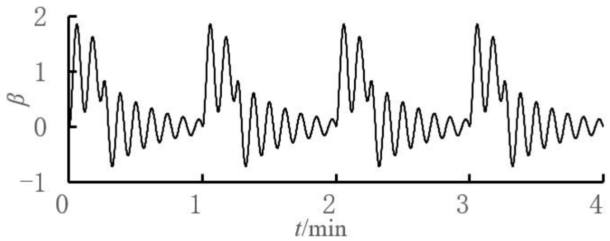
4 Simulation analysis model of the generator

Some influencing factors (such as the magnetic coupling force between the magnets) are ignored in the dynamic model of the system , so the analysis model only shows the influence trend of the relevant parameters on the dynamic response of the generator. At present, it is difficult or impossible to establish an accurate analytical model for accurate calculation. In order to obtain the influence of the relevant parameters on the vibration response characteristics of the system, the maple software program is used to carry out visual simulation calculation of the established theoretical model. The physical parameters of the system involved in the simulation are shown in Table 1.

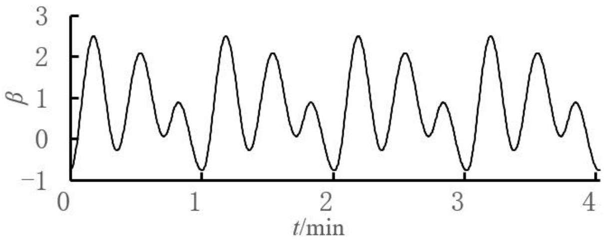
Table 1 Physical parameter values

physical parameters	Physical parameter value
Magnet radius r	3 mm
Magnet gyration radius R	60mm
Damping ratio ζ	0.015
Piezoelectric vibrator total mass m	3.75g
Piezoelectric vibrator relative stiffness k	100N / mm
Magnet force F_{am}	1 N

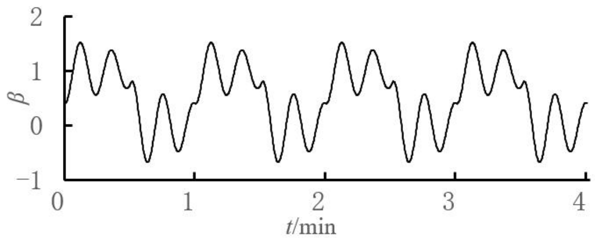
Figure 3 shows the time domain waveform diagram of the amplitude amplification ratio of the piezoelectric vibrator when the rotating speed is 650 r/min and the arc length of the moving magnet is different. It can be seen from the figure that the waveform of the arc length of the moving magnet to the amplitude amplification ratio and the unit time The number of waveforms has a greater impact: when the arc length of the moving magnet is s = 24 mm , the piezoelectric vibrator is excited by pulses, and the waveform in a single cycle is composed of the previous vibration waveform and the next free vibration waveform, and the free vibration waveform produces peaks The number decreases with the increase of the arc length of the moving magnet; when the arc length of the moving magnet is long (s = 72 mm), only one non-simple harmonic vibration voltage waveform appears in a single cycle due to the short free vibration time of the piezoelectric vibrator. It can be seen from the figure that the arc length of the moving magnet has a great influence on the number of peaks and the symmetry of the waveform in the time domain waveform diagram . Basically unchanged. The amplitude amplification ratio of the piezoelectric vibrator can directly characterize the output voltage, so the arc length of the moving magnet has a significant impact on the output performance of the piezoelectric generator.



s = 24 mm



s = 48mm



s = 72 mm

Fig.3. Time-domain waveforms of piezoelectric vibrator amplitude amplification ratios with different arc lengths of moving magnets

5 Fabrication and experiments

In order to verify the relationship between the output characteristics of the piezoelectric rotary generator and the arc length of the moving magnet, a prototype of the generator was made and a test system was built, as shown in Figure 4. The main test instruments include motor (rated speed 2850 r/min), frequency converter (frequency conversion range 50 Hz, frequency modulation step size 0.5 Hz), DS5024M digital storage oscilloscope, etc. In the test, the moving magnet and the fixed magnet are installed facing each other, and the axial distance is 3.5 mm.

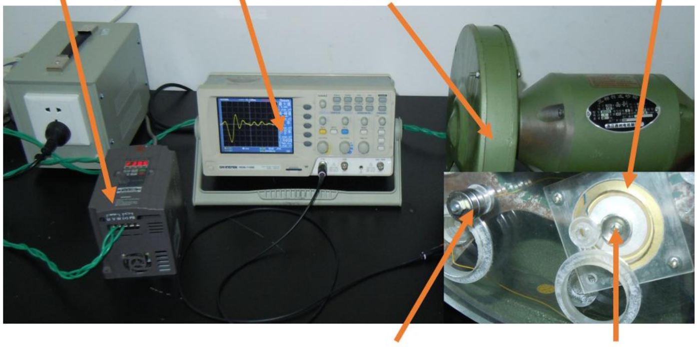
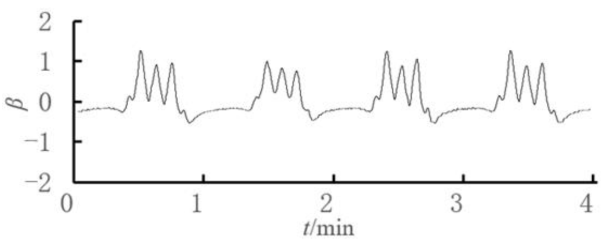
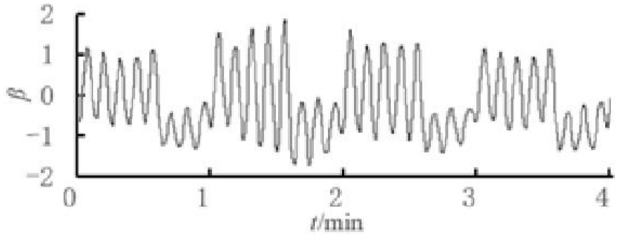


Fig.4. Magnetic coupling excitation piezoelectric rotary generator test system and prototype

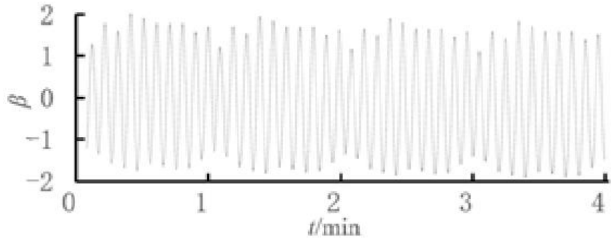
The peak-to-peak voltage of the piezoelectric vibrator at the natural frequency is the largest [20], that is, the frequency corresponding to the maximum voltage can be considered to be equal to the natural frequency of the generator. For the convenience of adjusting the parameters required for the test, the moving magnets are arranged in series to obtain the arc length of the moving magnets (arc length=number×diameter). Because the moving magnet arc length is different and the excitation force acting time is different, the bending deformation of the piezoelectric vibrator under a single excitation is different. Figure 5 shows the voltage waveforms when the motor speed is 8 34 r / min, the repulsive force between the moving and stationary magnets, and the arc lengths of the moving magnets are different. Analysis of the waveform shows that the arc length of the moving magnet has an influence on the peak voltage and the number of peaks. When other parameters are the same, as the arc length of the moving magnet increases, the voltage value and quantity of the peak voltage in the waveform diagram increase. When the arc length of the moving magnet is 48 mm, its response waveform is approximately a sine wave , and there is no oscillation waveform, which improves the power generation efficiency of the generator, but the peak voltage value is small. In practical applications, factors such as voltage requirements, operating speed and reliability should be considered to reasonably select the arc length of the moving magnet.



(a) s = 18 mm



(a) s = 30 mm



(a) s = 48 mm

Fig.5. Voltage waveforms of moving magnets with different arc lengths

Figure 6 shows the relationship between the output voltage and the rotational speed when the moving magnet and the fixed magnet are repulsive, and the arc length of the moving magnet is different . It can be seen from the figure that when other parameters are the same, there are multiple optimal rotational speeds that make the output voltage reach the peak value within the rated rotational speed range, and as the arc length of the moving magnet increases, the natural frequency and each optimal rotational speed increase. Each magnet arc length has an optimal rotation speed to maximize the output voltage. As the number of magnets increases, the output voltage increases. When the arc length of the moving magnet is 12 mm, 24 mm and 36 mm, the maximum voltage and its corresponding maximum voltage increase. The optimal speed is 2 451 r / min , 2,479 r / min and 2 565 r / min and 35.2 V , 37.6 V and 42 V , when the moving magnet arc length is longer (s = 36 mm), the output voltage is higher. The optimal speed and output performance of the generator can be adjusted by adjusting the arc length of the moving magnet. In the relationship curve, there is an obvious peak point of the output voltage changing with the rotation speed, which will cause problems such as unstable working performance of the generator and energy waste. Therefore, from the perspective of the amplitude of the output energy and the stability of the generator, the generator with the smallest vibration amplitude Best performance.

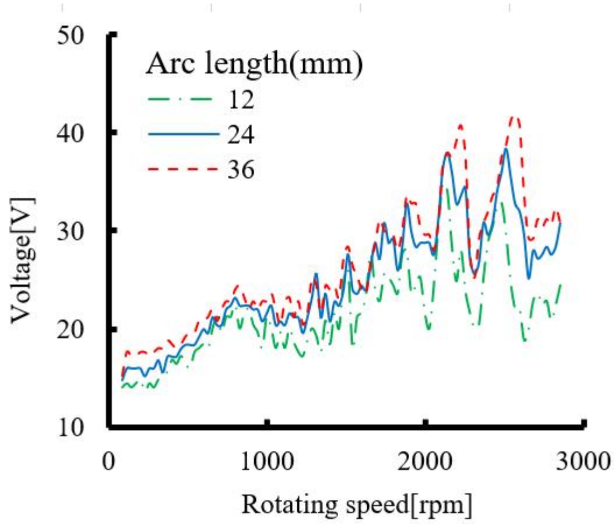


Fig.6. The relationship between output voltage and rotational speed when the arc length of the moving magnet is different

Figure 7 shows the relationship between the output voltage and the rotational speed when the number of moving magnets is 6 and the excitation methods are different (attraction, suction-discharge phase-to-phase, repulsion). It can be seen that there are multiple optimal rotational speeds to make the output voltage *U* reach the peak value, and the maximum output voltage increases with the increase of rotational speed. Among them, when the excitation modes are 6 rows, 3 rows and 3 suctions, and 6 suctions, respectively, the maximum output voltages are $U_{6\ rows}$ = 2 2 V , $U_{3\ rows\ and\ 3\ suction}$ = 2 2 V , and $U_{6\ suction}$ = 16.8 V. Therefore, changing the excitation mode of the moving magnet has an impact on the output voltage of the generator, and a reasonable configuration of the magnet can increase the output voltage of the generator.

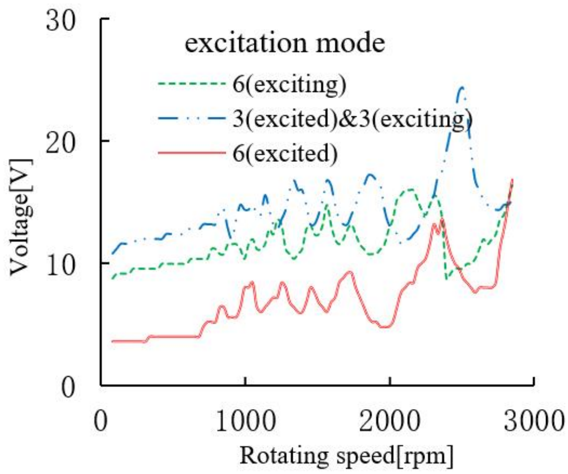


Fig.7. Relationship between maximum voltage and rotational speed with different excitation modes

6 Conclusion

this paper , the magnetic coupling excitation piezoelectric rotary generator is studied through simulation and experiment , the steady-state waveform response expression of the system at different speeds is given, and the response of the moving magnet arc length and excitation mode to the piezoelectric rotary generator is analyzed. characteristics and power generation capacity. The conclusion is (1) The arc length of the moving magnet has an influence on the voltage waveform curve. When other parameters are the same, with the increase of the arc length of the moving magnet, the voltage value and quantity of the peak voltage in the waveform diagram increase. In practical applications, factors such as voltage requirements, operating speed and reliability should be considered to reasonably select the arc length of the moving magnet; (2) When other parameters are the same, there are multiple optimal rotational speeds that make the output voltage reach the peak value within the rated rotational speed range, and as the arc length of the moving magnet increases, the natural frequency and each optimal rotational speed increase. The optimal speed and output performance of the generator can be adjusted by adjusting the arc length of the moving magnet; (3) The test results show that changing the excitation mode of the moving magnet has an effect on the output voltage of the generator, and a reasonable configuration of the moving magnet can increase the output voltage of the generator.

CRediT authorship contribution statement

Shengjie Li: Conceptualization, Methodology, Software, Formal analysis, Writing-original draft, Writing-review & editing. **Junwu Kan:** Conceptualization, Investigation, Writing-original draft, Writing-review & editing, Validation, Visualization. **Xuyuan Shen:** Conceptualization, Methodology, Software, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CRediT authorship contribution statement

Shengjie Li: Conceptualization, Methodology, Software, Formal analysis, Writing-original draft, Writing-review & editing. **Junwu Kan:** Conceptualization, Investigation, Writing-original draft, Writing-review & editing, Validation, Visualization. **Xuyuan Shen:** Conceptualization, Methodology, Software, Formal analysis.

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