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Design and optimization of an Electromagnetic-Piezoelectric Composite Vibration Generator

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Abstract: *Piezoelectric power generations refer to the piezoelectric integrated structure which realize the transformation of conversion from environmental vibration based mechanical energy to electric energy. A new type of vibration energy generator with cantilever beam structure is designed in this paper. In order to reveal the underlying of piezoelectric transducer mechanism, the vibration mechanics analysis is carried out by establishing a mathematical model, namely, the vibration mechanism of cantilever beam caused by external vibration excitation is described by using spring mass block damping single degree of freedom system model. In order to get the vibration generator with reasonable structure and excellent performance, frequency response and transient, the relationship between the cantilever thickness, cantilever width, cantilever length and vibration characteristics are optimazed by using COMSOL-Multiphysics FEM simulation software to model and analyze the generator body. To evaluate the output performance of the piezoelectric module, finite element modeling and analysis is conducted. According to the evaluation, the design of electromagnetic and -piezoelectric composite vibration generator presented in this paper is proising for environmental vibration based energy harvest.*

Keywords: *cantilever beam, power generation, piezoelectric, electromagnetic, piezoelectric-electromagnetic, finite element simulation*

1. Introduction

With the distribution and portability of electronic products, environmental energy collection has attracted more and more attention. Nowadays, the research and application of solar energy, wind energy and thermal energy in the environment have become more and more mature.However, the vibration energy which also exists in the environment has not been effectively developed and applied. In the environment of mechanical motion, the form of motion such as vibration is very common, and the vibration energy collected in the environment is often enough to drive some electronic equipment to work. Using the piezoelectric effect of functional material [1], a piezoelectric integrated structure is designed to convert mechanical energy into electrical energy. By converting and collecting the generated electrical energy, it can provide power for various low-power electronic systems. The general ways to convert vibration energy into electrical energy are electromagnetic, electrostatic, piezoelectric, magnetostrictive and composite energy acquisition technology [2]. Nowadays, the main form of energy conversion is piezoelectric. Piezoelectric vibration generator has the advantages of high output voltage, simple structure, less heating, easy integration with microelectronic sensor containing silicon body and less peripheral energy controller. In this paper, the COMSOL-Multiphysics FEM simulation software is used to analyze the finite element modeling of the generator body[3,4], and the relationship between the cantilever thickness, cantilever width, cantilever length and vibration characteristics is obtained. Through the establishment of vibration model [5] and finite element simulation optimization, a piezoelectric vibration device is designed to highlight its advantages and improve the output performance of the generator.

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

2. System Structure and Mathematical Model

2.1. System Structure and Principle

The vibration based piezoelectric device can be described by the structure shown in Figure 1 (a). The device consists of a piezoelectric cantilever beam with a mass at the end. The mass is used to excite vibration and adjust resonance frequency. The vibration of the cantilever is caused by external vibration[6]. The piezoelectric sheet is under the action of stress to generate charge, and the total output energy is increased by integrating these two parts of energy.

2.2. Mathematical model

The piezoelectric cantilever structure is most sensitive to environmental excitation and is easy to produce forced vibration. When analyzing the vibration mechanics, the spring mass block damping single degree of freedom system model can be used to describe the vibration model of cantilever beam under external vibration excitation, as shown in Figure 1(b). The model of vibration system is:

$$\ddot{z}(\mathrm{t})+2\xi\omega_{\mathrm{n}}\dot{z}(\mathrm{t})+\omega_{\mathrm{n}}{}^{2}\mathrm{z}(\mathrm{t})=-\ddot{y}(\mathrm{t}) \tag{1}$$

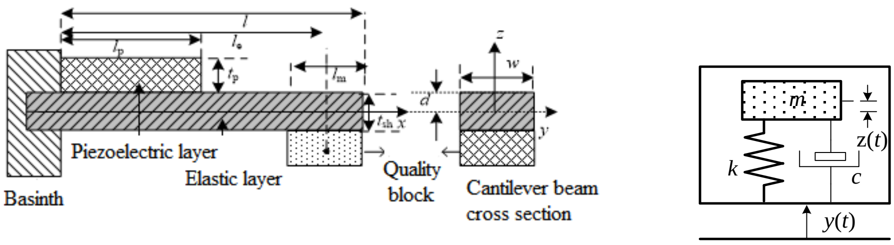
In the Formula (1)

y (t)——Vibration displacement of the external environment foundation;

z(t)——Relative vibration displacement of the mass block;

ξ——Damping ratio, $\xi = c/2\sqrt{km}$, c is damping;

ω_{n} ——System fundamental frequency angular frequency, $\omega_{\mathrm{n}}=\sqrt{K/m}$, K is the system efficient elastic coefficient, m = Δm +0.236 M [7], Δm is the mass of mass blocks, M is the cantilever beam mass.



(a).Structural model of the cantilever beam (b). Spring mass block damping model

Figure 1: Model of unequal length single crystal CVPG

According to the cross section transformation method[7] and the parallel axis theorem of moment of inertia[8], the equivalent section moment of inertia of cantilever beam in x = 0 ~ LP and x = LP ~ Le sections is:

$$\begin{cases} I_1=\eta[\frac{wt_{\mathrm{sh}}{}^3}{12}+wt_{\mathrm{sh}}(\frac{t_{\mathrm{sh}}}{2}-d)^2]+[\frac{wt_{\mathrm{p}}{}^3}{12}+wt_{\mathrm{p}}(\frac{t_{\mathrm{p}}}{2}+d)^2] \\ I_2=\frac{\eta wt_{\mathrm{sh}}{}^3}{12} \end{cases} \tag{2}$$

In the Formula (2)

d——Distance of the lower surface of the piezoelectric layer from the neutral axis,d = (*η*tsh2 - tp2) /2(tp +ηtsh),the tp and tsh are the thickness of the piezoelectric layer and the elastic layer, respectively;

w——Width of the cantilever beam;

η——*η* = Ysh/Yp,The Ysh, Yp is the elastic modulus of the elastic layer and the piezoelectric layer, respectively;

According to the of structural mechanics[7], the effective elastic coefficient of the cantilever beam is:

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

$$K = \frac{3Y_p I_1 I_2}{({l_e}^3 - (l_e - l_p)^3) I_2 + (l_e - l_p)^3 I_1} \tag{3}$$

Using the vibration angle frequency formula of the system base frequency:

$$\omega_n = K_1 \sqrt{\frac{K}{m}} = K_1 \sqrt{\frac{3Y_p I_1 I_2}{[({l_e}^3 - (l_e - l_p)^3) I_2 + (l_e - l_p)^3 I_1](\Delta m + 0.236M)}} \tag{4}$$

K_1——For the frequency correction factor.

It is remarkably seen from the piezoelectric equation[7]that when the cantilever beam receives the inertial force in the z direction, the piezoelectric layer produces tension and compression in the x direction and forms a coupled electric field in the z direction. For the piezoelectric strain δ = –d31E3, it can be equivalent to a concentrated force FE, at the end of the cantilever beam after adding an electric field force in formula (1):

$$m\ddot{z}(t) + c\dot{z}(t) + Kz(t) = -m\ddot{y}(t) - F_E(t) \tag{5}$$

$F_E = k_1 U$ according to the equation and relation of strain and bending moment, $k_1 = 4\frac{d_{31} Y_p I_1}{(2l_b - l_p)(t_p + 2d)t_p}$. Substitute the F_E into the formula (4),obtain the（6):

$$z = \frac{\omega^2 y - k_1 U / m}{-\omega^2 + j2\xi\omega\omega_n + {\omega_n}^2} \tag{6}$$

According to the principle of thermal equilibrium, the internal energy [9] generated in the infinitesimal unit is represented as the total energy of the piezoelectric layer. Using the relationship[10,11] of the cantilever beam, the relationship between the open circuit voltage and vibration excitation acceleration of the vibration generator is:

$$V_o = \left(\frac{K_2 \frac{Kk_2}{C_p} A_{in}}{-\omega^2 + j2\xi\omega\omega_n + {\omega_n}^2 (1 + k_p)} \right) \tag{7}$$

A_{in}——Indicates the acceleration of the external excitation vibration,$A_{in} = \omega^2 y$.

K_2——For the voltage correction factor.

In the formula, Ki is the correction coefficient, the multiple experimental data of resonance angle frequency and the average of the corresponding theoretical calculated value, Ki= $\frac{\omega_1'/\omega_{n0} + \omega_2'/\omega_{n0} + \cdots + \omega_n'/\omega_{n0}}{n}$, ω_n' has measured data for the experiment of resonance angular frequency and n is the number of experiments. The modified formula can be directly applied to the COMSOL simulation virtual experiment, greatly improving the time efficiency and design accuracy of the cantilever beam device design.

3. Finite Element Simulation and Optimization Analysis of Piezoelectric Cantilever Vibration Device

3.1. Simulation Analysis of the Characteristic Frequency

The structural analysis of the vibration device shall first simulate the characteristic frequency of the structure itself. The natural characteristic frequency and the characteristic diagram of the vibration mechanism can be determined by the characteristic frequency solver. The first sixth orders characteristic frequency of the vibration mechanism model is 12.029Hz, 51.189Hz, 94.202Hz, 427.28Hz, 572.5Hz, 1082.3Hz.

Figures 2, 3 and 4are the three-dimensional vibration patterns of the first third order of the vibration mechanism model respectively:

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

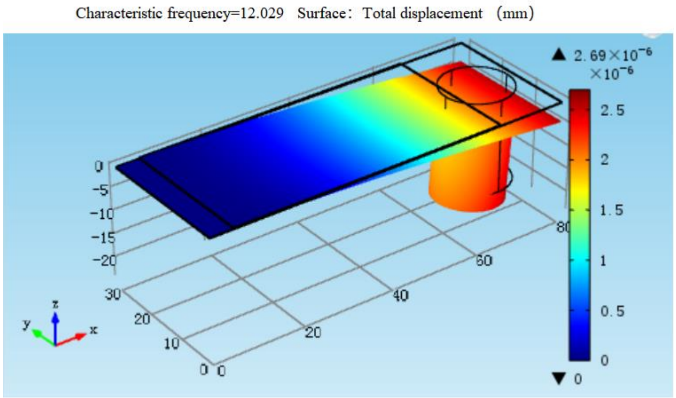


Figure 2: First-order vibration type diagram

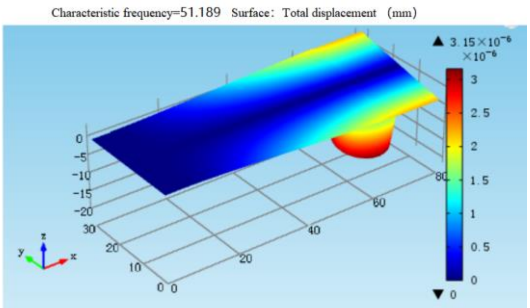


Figure 3: Second-order vibration type diagram

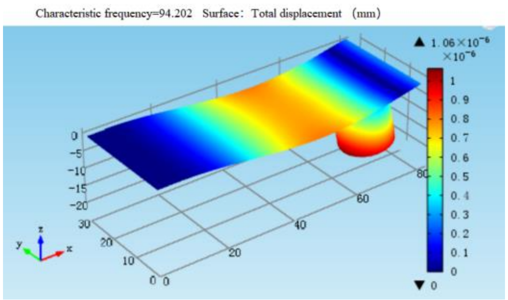


Figure 4: Third-order vibration type diagram

During the vibration mechanism in the process of vibration, the mass blocks the end of the cantilever beam under the non-z direction. However, the vibration typed characteristic frequencies above the second order are far away from the low-frequency vibrations produced in real mechanical motion, so the focus of this paper is on the response in the first-order characteristic frequency range. Increase the difference between first order and higher order vibration type frequency as much as possible to ensure the stable operation of the vibration mechanism under excitation.

2.2. Simulation Analysis of Frequency Domain Response

Frequency domain response analysis mainly analyzes the mass block amplitude and mass block amplitude within a certain frequency range. From the response curve, the peak frequency, which is the resonant frequency. Figures 5 and 6 give mass block amplitude and amplitude response curves:

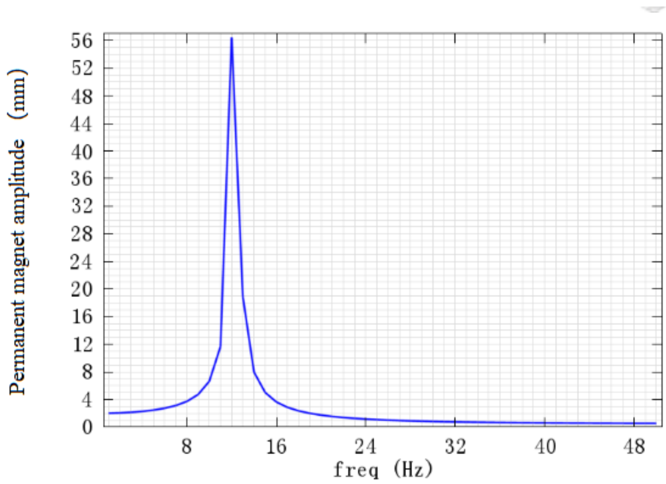


Figure 5: The 1-50Hz mass block amplitude response curve

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

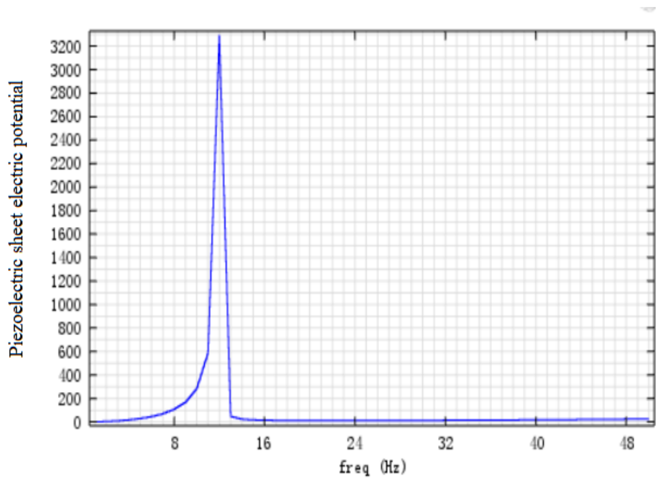


Figure 6: Potential response curve of 1-50Hz piezoelectric sheet

Through FIGS. 2-4 and 2-5, it is clearly observed that the peak frequency in the response curve is near the first order characteristic frequency obtained by 12Hz, and 2.1 analysis, and the amplitude of the mass block and the potential of the piezoelectric sheet near the characteristic frequency reach the maximum. When the frequency is one but deviates from this frequency, the amplitude of the mass block and the potential response of the piezoelectric sheet decrease rapidly.

2.3. Transient Simulation Analysis

This section performs a dynamic analysis of a frequency range near the characteristic frequency based on the above two sections. The method is to apply a discrete frequency to the vibration mechanism, and to analyze the specific displacement value of the cantilever arm end mass block and the specific potential value of the piezoelectric plate within a specified frequency.

Figure 7 and Figure 8show the maximum potential of the piezoelectric sheet and the maximum displacement of the mass block at 10, 11, 12,13,13,14, and 15Hz, respectively.

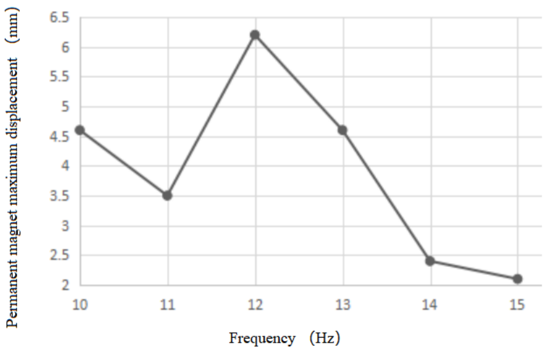


Figure 7: Frequency-displacement relation diagram

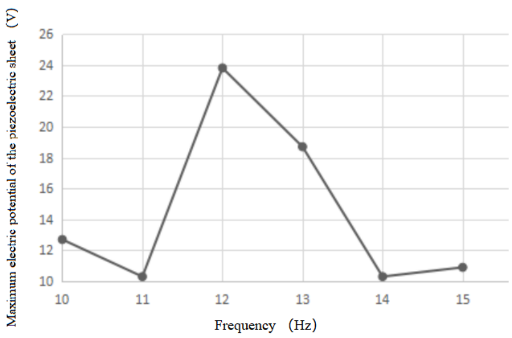


Figure 8: Frequency-potential relationship diagram

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

Figure 9 and figure 10 show the three-dimensional model diagram and stress diagram of the maximum displacement produced by the vibration mechanism when the applied displacement load is 2*sin(2*pi*12*t)[mm].

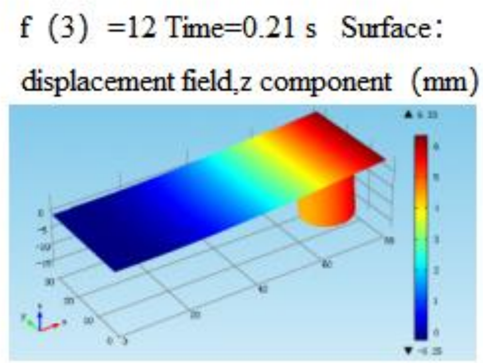


Figure 9: Maximum displacement 3 D model diagram

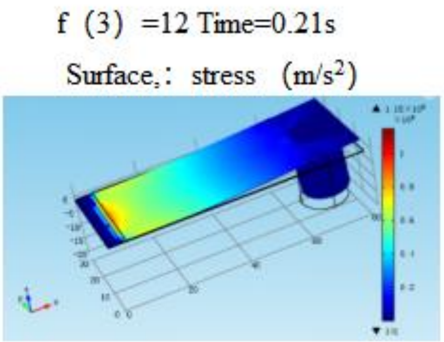


Figure 10: Stress map

The transient analysis shows that the resonant frequency should be near 12Hz. Meanwhile, the time domain analysis shows that the maximum displacement of the mass block can reach the maximum potential of the 6.202mm, piezoelectric sheet up to 23.854v when the resonant frequency is applied.

Based on the above conclusions, we further analyze the application of the resonant frequency. Figure 11 shows the relationship between the mass block displacement at the end when the cantilever beam is stable. When the displacement load applied by the vibration base end of the cantilever beam is 2*sin(2*pi*12*t)[mm], the displacement function of the end mass block is consistent with its frequency, only the amplitude becomes 6.2mm, and lags a certain phase. Figure 12 gives the piezoelectric sheet stabilization potential of the cantilever arm with an amplitude of 10.5V.

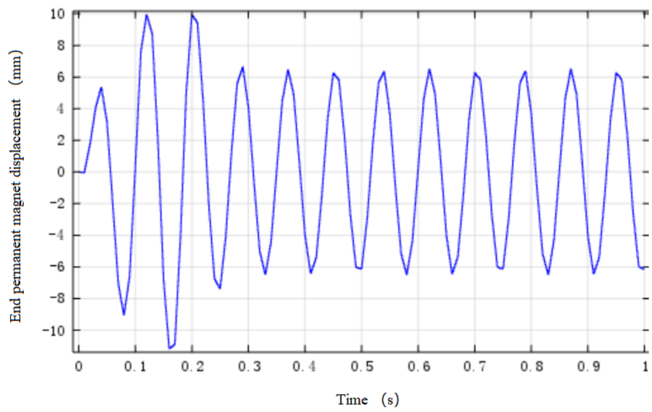


Figure11: Stability displacement diagram

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

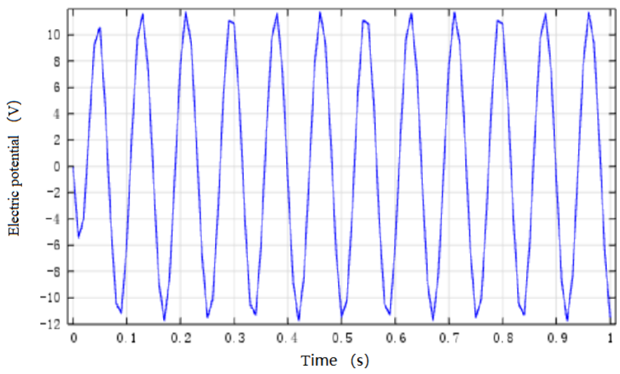


Figure12: Stable piezoelectric potential diagram

2.4. Optimization of Piezoelectric Sheet Size

Through the COMSOL parametric scanning method, the characteristic frequency of different piezoelectric beam sizes can be calculated. In the optimization process, considering the actual significance, the piezoelectric plate adheres to the cantilever beam base plate, so the length of the substrate is longer than the piezoelectric plate, and such a parameter setting is meaningful.

A premise is provided that the substrate has an equal width of 20mm, longer than the piezoelectric sheet. Set a piezoelectric sheet length change range of 50-100mm (10mm) and a width change range of 20-40mm (5mm). Set each set of parameters and record the frequency of the results.

The combination of dimensions close to the characteristic frequency 12Hz screened from the results is shown in Table 1 below:

Table 1: Baseline-Piezoelectric sheet size combination

Combination	Basplate thickness (mm)	Piezoelectric sheet thickness(mm)	Piezoelectric beam length(mm)	Piezoelectric beam width(mm)
1	0.2	0.2	70	20
2	0.2	0.2	80	30
3	0.2	0.2	90	40
4	0.2	0.3	100	35
5	0.3	0.2	90	25
6	0.3	0.3	100	20

Conduct the above combination for transient simulation analysis, obtain the piezoelectric sheet potential, record the data, and analyze the potential changes of the piezoelectric sheet, as shown in Figure 13:

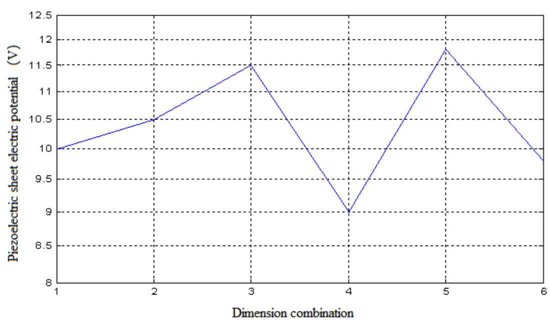


Figure 13: Amplitude diagram of each combined piezoelectric sheet

The above simulation is performed at 12Hz characteristic frequency, comparing the changes of the stability potential of the piezoelectric wafer of each combination, where the amplitude of the

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

combination 5 is maximum. From the comparison of combined dimensions, the analysis shows that when the piezoelectric sheet thickness is relatively thin, long length and narrow width, the piezoelectric sheet generated potential is large.

The steady-state potential diagram of the combination 5 is shown in Figure14:

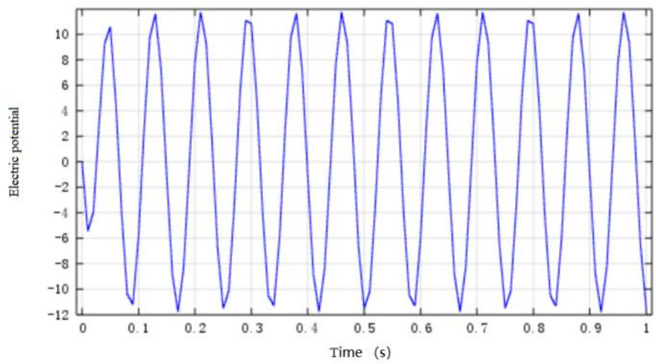


Figure 14: Stability voltage potential diagram

It can be seen from the diagram that the steady-state potential of combination 5 is about 11.5V.

3. Experimental Setting and Analysis

The simulation analysis shows that the device resonance frequency is associated with the structural parameters of the cantilever arm. The resonance frequency of the system can be adjusted by changing parameters such as length, width and thickness of the piezoelectric sheet and substrate plates. The resonance frequency of the system is designed as 12 Hz, combined with the simulation analysis to finally determine the piezoelectric cantilever beam dimension parameters, as shown in Table 2 below:

Table 2: Parameters of the piezoelectric vibration device

Parameter Name	Numerical value	Parameter Name	Numerical value
cantilever beam length (mm)	55	cantilever beam width (mm)	30
Piezoelectric sheet length (mm)	40	Piezoelectric sheet width (mm)	30
Piezoelectric layer thickness (mm)	0.1	Mass block quality (g)	18
Basstrate thickness (mm)	0.08	Mass block height（mm）	15

The experiment is a piezoelectric vibration device split experiment, by testing the output voltage of the piezoelectric beam under the resonance state, to verify the correctness of the analytical model.

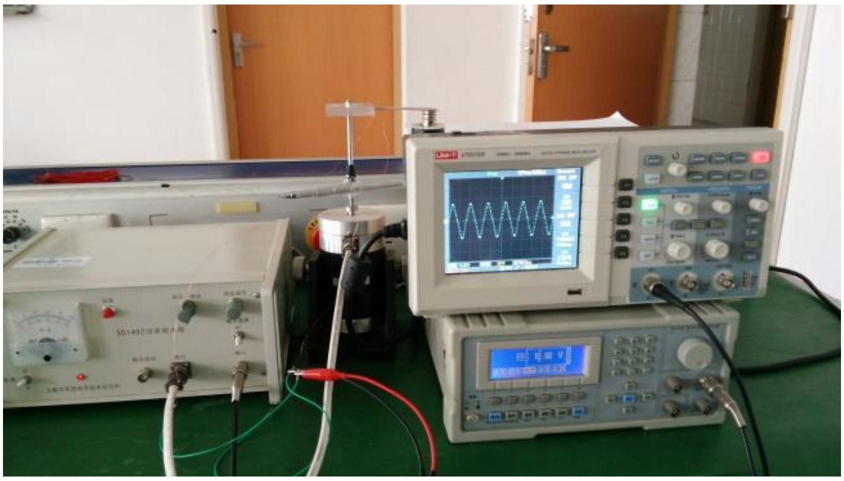


Figure 15: Vibrating generator experimental system

ISSN 2706-6827 Vol. 3, Issue 17: 112-120, DOI: 10.25236/IJFS.2021.031717

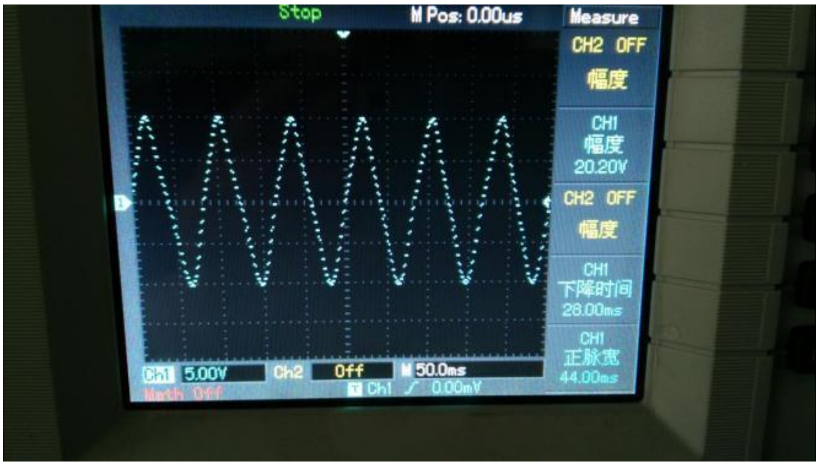


Figure16: Open-circuit voltage waveform diagram of the piezoelectric plate

In the piezoelectric vibration mechanism division experiment, the open circuit voltage of the piezoelectric sheet is shown in Figure15, 16: the open circuit voltage in the experiment is 10.1V, similar to the simulation data in section 2.

In the characteristic frequency simulation, the resonance frequency is 12.029Hz, close to the theoretical value of the resonance frequency of 12Hz.

4. Conclusion

A piezoelectric electromagnetic composite vibration energy generator is designed using COMSOL-Multiphysics FEM simulation software. Key simulation of the vibration mechanism of the generator includes its characteristic frequency, frequency domain response, time domain analysis, and obtained its piezoelectric potential and motion characteristics.

It is concluded from the simulation that the amplitude near the resonance frequency 12Hz and the potential of the mass block and of the piezoelectric sheet reach the maximum, and the maximum displacement of the mass block reaches the maximum potential of the 6.202 mm, 23.854 V.

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