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A Broadband Circular Arc Array Piezoelectric VEH with Absorbing Multi-Directional Vibration

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Abstract
A circular arc array piezoelectric VEH based on nonlinear structure is proposed in this work. This array piezoelectric VEH can absorb multi-directional vibrational energy at the broadband frequency. It is composed of four circular arc piezoelectric VEHs, where each circular arc piezoelectric VEH can still effectively absorb multi-direction energy at the same frequency. The deformation displacement of single circular arc piezoelectric VEH and the traditional piezoelectric VEH are compared. The stress distribution of the array piezoelectric VEH is analyzed based on the finite element method, and its models of output voltage and output power are established. This circular arc array piezoelectric VEH is designed using a CNC technology. The multi-directional energy harvesting and the broad frequency band energy harvesting of this array piezoelectric VEH are measured. The measured results show that (No.2 and No.3) circular arc piezoelectric VEHs have higher output performance, and the highest absorption efficiency is from the Z-direction vibration. Therefore, this array piezoelectric VEH provides an effective solution for multi-directional energy harvesting in the broad frequency band.

Key words: multi-directional, broadband, VEH, same resonance frequency, output voltage, output power.

1. Introduction

In recent years, energy harvesting from ambient vibration has aroused substantial interest [1-3]. For example, extending battery life is the use of miniature renewable self-contained power supply units, which can convert ambient vibration in the environment into electrical form [4, 5]. There are three mechanisms that can be utilized to convert vibration energy into electrical energy, i.e., electromagnetic, electrostatic, and piezoelectric.

The electromagnetic generators are generally based on the relative velocity or the mechanical strain within the system for electricity generation, but the electromagnetic systems have the limitations that the wafer and submillimeter scale are difficult to be implemented [6-8]. The electrostatic generators can be miniaturized using MEMS technology [9-11], but they can't transfer the polarizing charge quickly and suffer from parasitic capacitances [12]. Therefore, the electrostatic harvester usually has the limitations for being used in high frequency environment. Compared to the mentioned VEH type above, the piezoelectric harvester is more suitable in broadband environment, with other merits such as miniaturization and high performance [13-15]. Piezoelectric materials are perfect candidates for harvesting power from the multi-frequency ambient vibration.

However, a single conventional piezoelectric harvester usually absorbs vibration at only one resonant frequency in environment. It just absorbs the vertical force vector at the top surface of mass block, and the absorption efficiency of this single traditional VEH at multi-directional vibration is usually low. Therefore, to design harvesting structures with multi-directional vibration and broad frequency band are highly demanded [16-18].

A circular arc array piezoelectric VEH based on nonlinear structure is designed in this work. It can effectively absorb energy with broad and/or multi-frequency spectra, and the operation frequency can be widened and shifted to the dominant frequency band of its ambient environments for more effective energy harvesting. Besides, the advantages of each single circular arc VEH are retained by this array system, which can still absorb multi-directional vibration at one resonant frequency. In Section 2, the principle of circular arc array piezoelectric VEH is given. Then the deformation displacement of single circular arc piezoelectric VEH is compared with that of the traditional piezoelectric VEH. The stress distribution of the array piezoelectric VEH is analyzed based on the finite element method. The theoretical models of the output voltage and the output power are established. In Section 3, the output voltage and the output power of circular arc array piezoelectric VEH are measured in broadband multi-directional vibration energy and the measured results are discussed with the theoretical results. Finally, some conclusions are drawn in Section 4.

2. Design and Theory

The circular arc array piezoelectric VEH is shown in Fig.1 (a). The structure is composed of two fixed ends, two rectangular main beams, and four circular arc piezoelectric VEHs. These circular arcs piezoelectric VEHs are labeled as No.1, No.2, No.3 and No.4, where the No.1 and No.3 circular arc beams are fixed on one main beam, and the No.2 and No.4 circular arc beams are fixed on the other main beam. Each single circular arc piezoelectric VEH is composed of a 90-degree circular arc beam, a 30-degree circular arc piezoelectric layer and a mass block as shown in Fig.1(b).

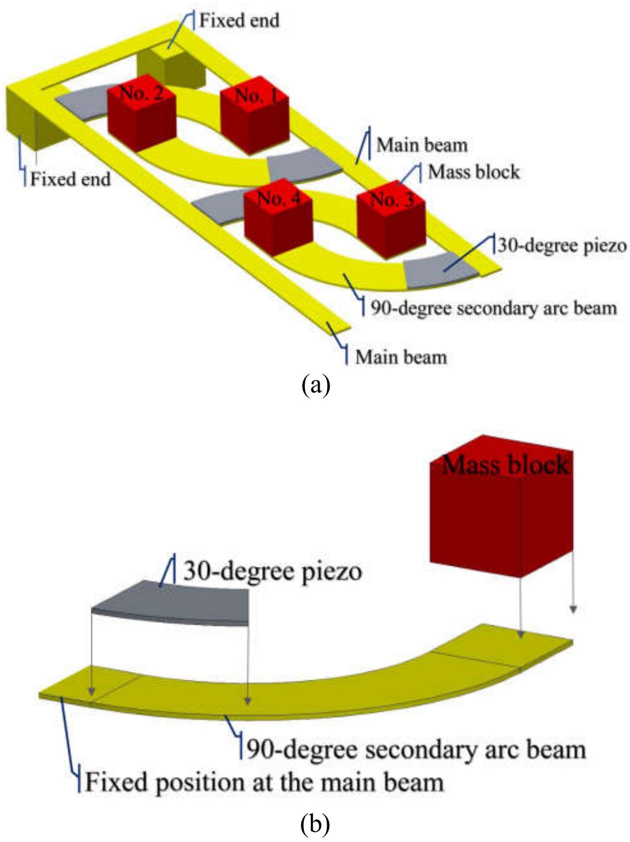


Figure 1. (a) The circular arc array piezoelectric VEH, (b) Single circular arc piezoelectric VEH

In order to have a broad frequency band, each circular arc piezoelectric VEH is fixed at different position of the main beams. Meanwhile, the advantages of each circular arc piezoelectric VEH are preserved in this array mode, which can absorb the multi-directional vibration energy at the one resonance frequency. The piezoelectric layer is made of a PZT-5H material. The cantilever beam and the mass block are made of the copper material. The surface of the piezoelectric material is contacted with the silver as output electrode (+). The fixed end is connected with the GND (-). The structure parameters of this circular arc array VEH are shown in Table.1. The material parameters are given in Table.2.

Table 1. Structure parameters of this VEH

	Main beam	Secondary beam	Piezoelectric material	Proof mass
Size				10x10 mm^2
Length	100 mm			
Width	5 mm			
Outer radius		30 mm	30 mm	
Inner radius		20 mm	20 mm	
Thickness	0.5 mm	0.5 mm	0.5 mm	10 mm

Table 2. Material parameters of this VEH

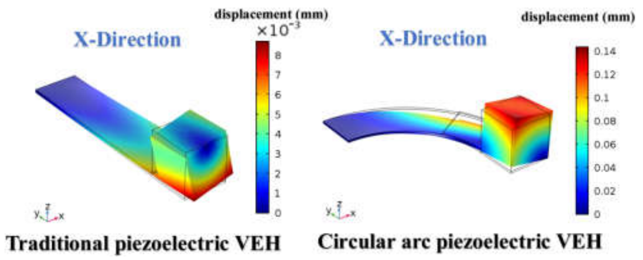
	Cantilever beam	PZT-5H
Mass density	8900 Kg/m^3	7500 Kg/m^3
Young's modulus	130 GPa	76 GPa
Poisson's ratio	0.35	0.33

2.1. Multi-Directional Energy Harvesting

The traditional piezoelectric VEH based on linear geometry only has a bending moment deformation mode when the vibration energy acts on the mass block. While the circular arc piezoelectric VEH based on nonlinear geometry has both a bending moment deformation mode and a torque deformation mode. As shown in Fig.2, the deformation displacement of single circular arc piezoelectric VEH and the traditional piezoelectric VEH are compared. The piezoelectric layer is used with the same area and same thickness, and the same material parameters and the same area force (10 Pa) as excitation are used in the both structures.

When the vibration is perpendicular to the side surface of the mass block, the bending moment deformation and the torque deformation for the circular arc piezoelectric VEH will produce in X-direction and Y-direction, while the bending moment deformation for the traditional piezoelectric VEH will not produce as shown in Fig.2 (a) and (b). The maximum deformation displacement of this circular arc piezoelectric VEH can achieve 0.14 mm in X-direction and 0.5 mm in Y-direction, while the maximum deformation displacement of the traditional VEH only achieves 8×10^{-3} mm in X-direction and 1.1×10^{-3} mm in Y-direction.

When the vibration is perpendicular to the top surface of the mass block, the bending moment deformation will produce in Z-direction as shown in Fig.2 (c). The maximum deformation displacement of the circular arc piezoelectric VEH (0.6 mm) is a little larger than that of the traditional VEH (0.5 mm). Therefore, the single circular arc piezoelectric VEH can harvest the multi-directional energy.



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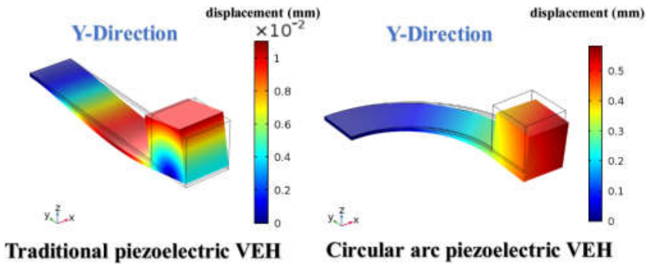

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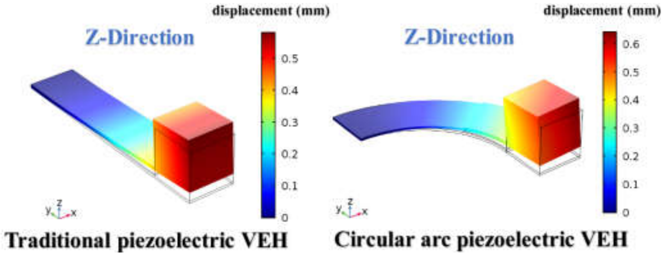
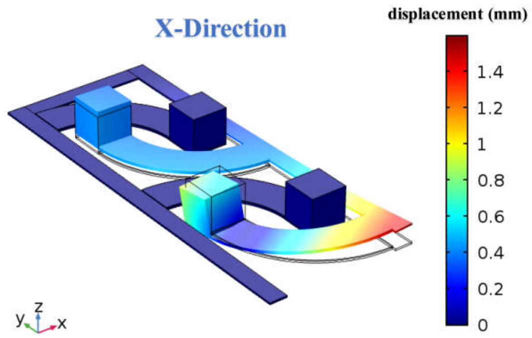


(c)

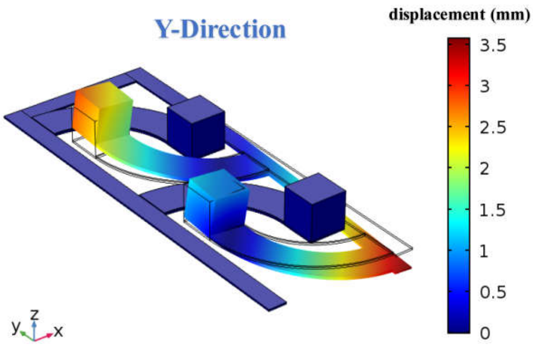
Figure 2. The different deformation mode (a) X-direction (b) Y-direction (c) Z-direction.

The multi-directional energy harvesting of each circular arc piezoelectric VEH is preserved in this array piezoelectric VEH as shown in Fig.3. When the vibration is perpendicular to the side surface of the mass blocks, the bending moment deformation and the torque deformation will produce in X-direction and Y-direction as shown in Fig.3 (a) and (b). The maximum deformation displacement can achieve 1.4 mm in X-direction and 3.5 mm in Y-direction. When the vibration is perpendicular to the top surface of the mass blocks, the bending moment deformation will produce in Z-direction as shown in Fig.3 (c). The maximum deformation displacement can achieve 7 mm in Z-direction.

The (No.1 and No.3) or (No.2 and No.4) of their deformation displacements are affected by each other in the same main beam. The deformation displacement of the No. 4 circular arc beam is the largest in the multi-directional vibration. The deformation displacement of the No. 2 circular arc beam is the relatively large, which is affected by No. 4. The deformation displacement of the (No.1 and No.3) circular arc beam is relatively small. The main reason is that the distance of (the No. 2 and No. 4) away from the fixed end is longer than that of (No. 1 and No. 3). Therefore, the torque and the bending moment of the (No. 2 and No. 4) beams are smaller than the (No. 1 and No. 3) beams.



(a)



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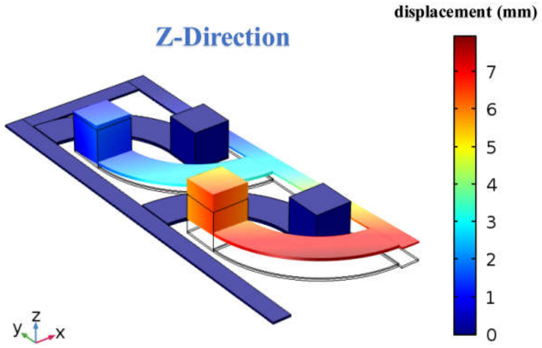


(c)

Figure 3. The deformation mode of circular arc array piezoelectric VEH (a)X-direction (b)Y-direction (c) Z-direction.

2.2. Broad Frequency Band Energy Harvesting

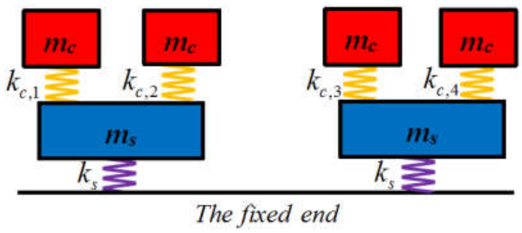


Figure 4. The "spring-mass" model of the circular arc array piezoelectric VEH.

The "spring-mass" model of the circular arc array piezoelectric VEH is shown in Fig. 4, where k_s is the spring stiffness of a rectangle main beam, k_c is the spring stiffness of the circular arc secondary beam, m_s is the equivalent mass of a rectangle main beam, and m_c is the equivalent mass of the mass block.

According to the theory of energy conservation, the relationship of the kinetic energy with the potential energy can be expressed as [19]:

$$\frac{d\left(E_k+E_p\right)}{dt}=0 \tag{1}$$

Where E_k is the kinetic energy, and E_p is the potential energy.

In a multi-degree of freedom system, the equation (1) can be expressed as:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial x_i}\right)-\left(\frac{\partial E_k}{\partial x_i}\right)+\left(\frac{\partial E_p}{\partial x_i}\right)=0 \tag{2}$$

Where x_i is independent generalized coordinates.

Ignoring the effect of external force and damping [20-21], the kinetic energy and the potential energy of the circular arc array piezoelectric VEH are expressed as follows:

$$\begin{cases} E_k=2m_s\left(\dot{S}_s\right)^2+\frac{1}{2}m_c\sum_{i=1}^{4}\left(\dot{S}_{c,i}\right)^2 \\ E_p=2k_sS_s^{\,2}+\frac{1}{2}k_c\cdot\sum_{i=1}^{4}\left(S_{c,i}-S_s\right)^2 \end{cases} \tag{3}$$

Where S_s the relative displacement equation of the main is beam, and $S_{c,i}$ is the relative displacement equation of each circular arc secondary beam.

When the radian θ of the circular arc structure is very small, the unit length Δl of traditional beam is approximately equivalent to $r \cdot \Delta\theta$. The spring stiffness of circular arc piezoelectric VEH can be approximately solved by the sum of much different elastic stiffness of the same length traditional beams. Therefore, when the boundary radian $\theta_{\max} = \pi/2$, the spring stiffness of the quarter-circular piezoelectric VEH can be obtained as:

$$k_c = \frac{3E_{arc} \cdot \left(t_m + t_p\right) b_m}{2\left(\pi r\right)^2} \tag{4}$$

Where E_{arc} is the equivalent elastic modulus, I_{arc} is the inertia moment, *r* is the arc radius, b_m is the width of cantilever metal layer, respectively, t_p is the thickness of piezoelectric layer, and t_m is the thickness of cantilever metal layer.

By substituting equation (3) into equation (2), the vibration equation of the circular arc array piezoelectric VEH can be expressed as:

$$\begin{bmatrix} 4m_s & & & & \\ & m_c & & & \\ & & m_c & & \\ & & & m_c & \\ & & & & m_c \end{bmatrix} \begin{bmatrix} \ddot{S}_s \\ \ddot{S}_{c,1} \\ \ddot{S}_{c,2} \\ \ddot{S}_{c,3} \\ \ddot{S}_{c,4} \end{bmatrix} + \begin{bmatrix} 4\left(k_s + k_c\right) & k_c & k_c & k_c & k_c \\ -k_c & k_c & & & \\ -k_c & & k_c & & \\ -k_c & & & k_c & \\ -k_c & & & & k_c \end{bmatrix} \begin{bmatrix} S_s \\ S_{c,1} \\ S_{c,2} \\ S_{c,3} \\ S_{c,4} \end{bmatrix} = 0 \tag{5}$$

According to equations (1) ~ (3), equation (5) can calculate as:

$$\begin{bmatrix} 4\left(k_s + k_c - \omega^2 m_s\right) & -k_c & -k_c & -k_c & -k_c \\ -k_c & k_c - \omega^2 m_c & & & \\ -k_c & & k_c - \omega^2 m_c & & \\ -k_c & & & k_c - \omega^2 m_c & \\ -k_c & & & & k_c - \omega^2 m_c \end{bmatrix} \begin{bmatrix} S_s \\ S_{c,1} \\ S_{c,2} \\ S_{c,3} \\ S_{c,4} \end{bmatrix} = 0 \tag{6}$$

Where ω is the resonance frequency?

In order to obtain a non-zero solution of the equation, equation (6) can be simplified as:

$$\begin{vmatrix} 4\left(k_s + k_c - \omega^2 m_s\right) & -k_c & -k_c & -k_c & -k_c \\ -k_c & k_c - \omega^2 m_c & & & \\ -k_c & & k_c - \omega^2 m_c & & \\ -k_c & & & k_c - \omega^2 m_c & \\ -k_c & & & & k_c - \omega^2 m_c \end{vmatrix} = 0 \tag{7}$$

The equivalent elastic modulus of each circular arc piezoelectric VEH is obtained as

$$E_{arc} = \frac{2E_P b_P (4t_p^3 + 3t_m^2 + 6t_m t_p^2) + E_m b_m t_m^3}{2b_p (4t_p^3 + 3t_m^2 + 6t_m t_p^2) + b_m t_m^3} \tag{8}$$

Where b_p is the width of piezoelectric layer, E_p is the elastic modulus of piezoelectric layer, and E_m is the elastic modulus of the cantilever metal layer.

The inertia moment of each circular arc piezoelectric VEH can be expressed as

$$I_{arc} = \frac{\pi}{3} r\left(4t_p^3 + 3t_m^2 t_p + 6t_m t_p^2 + 2t_m^3\right) \tag{9}$$

Above all, the fourth-order resonance frequencies of the circular arc array piezoelectric VEH can be obtained according to equation (7):

$$\begin{cases} \omega_1 = 0.77\sqrt{\dfrac{k_c}{m_c}} \\ \omega_2 = 0.83\sqrt{\dfrac{k_c}{m_c}} \\ \omega_3 = 0.89\sqrt{\dfrac{k_c}{m_c}} \\ \omega_4 = 0.95\sqrt{\dfrac{k_c}{m_c}} \end{cases} \tag{10}$$

Where ω_1, ω_2, ω_3, ω_4 is the resonance frequencies of the No.1, No.2, No.3 and No.4 circular arc piezoelectric VEH. The fourth-order resonant frequencies are 4.08 Hz, 4.38 Hz, 4.5 Hz, and 4.74 Hz. Equation (10) shows that the fourth-order resonance frequencies of the circular arc array piezoelectric VEH is lower than that of the single circular arc piezoelectric VEH. The longer the distance of No.1, No.2, No.3 and No.4 circular arc piezoelectric VEHs away from the fixed end, the smaller the resonance frequency. Therefore, the resonance frequency of No.4 circular arc piezoelectric VEH is largest, and the resonance frequency of No.1 circular arc piezoelectric VEH is smallest. The operation frequency band can be widened and shifted to the dominant frequency band of its ambient environments by adjusting the difference resonance frequency of No.1, No.2, No.3 and No.4 circular arc piezoelectric VEHs.

2.3. The Output Voltage and the Output Power

Since the main beam based on linear geometry, which vibration equation can be expressed as:

$$S_s = Acos(\omega t + \varphi) \tag{11}$$

$$A = \frac{\omega_n{}^2 F_{ou} e^{j\omega_{ou}t}}{\sqrt{\left(\omega_n^2 - \omega_{ou}^2\right)^2 + 4\xi_n^2\omega_n^2\omega_{ou}^2}} \tag{12}$$

$$\varphi = \arctan\left(\frac{2\xi_n\omega_n\omega_{ou}}{\omega_n^2 - \omega_{ou}^2}\right) \tag{13}$$

Where ξ_n the damping ratio is in the equivalent model, ω_{ou} is the external excitation frequency, F_{ou} is the sum of external force phasor, and ω_n is the n-order resonance frequency of VEH.

The circular arc beam based on non-linear geometry, which solution of the relative displacement equation can be expressed as [22]:

$$S_i = \frac{\left(1 + j\omega_n R_l C_{arc}\right)\psi_{r1}\left(x\right)F_{ou}e^{j\omega_{ou}t}}{\left(1 + j\omega_{ou}R_l C_{acr}\right)\left(\omega_n^2 + \omega_{ou}{}^2 - j2\xi_n\omega_{ou}\omega_n\right) - j\omega_{ou}R_l\gamma^2} \tag{14}$$

Where $\psi_{r1}(x)$ the mode of nonlinear structure is, C_{arc} is the capacitance of PZT layer, R_l is the load resistance, and γ is the effective coupling coefficient.

According to the squeeze film damping theory [23], the damping ratio equation can be expressed as:

$$\xi_n = \frac{S_{in}}{|S|}\cdot\frac{\mu b_m}{2\vartheta^3\rho\left(t_p + t_m\right)\omega_n} \tag{15}$$

where μ is the air viscosity, ρ is the density of the cantilever, ϑ is the initial spacing between the cantilever and the fixed end, S is the displacement of the mass block, and S_{in} is the displacement of the shaker.

Four piezo layers are connected in parallel. According to the principle of equivalent capacitance, the equivalent capacitance of the piezoelectric layer is defined as

$$C_{arc}=\frac{b_p^4 e_p^3 k_c\left(\left(\frac{E_m t_m^3 t_p}{12E_p}+\left(\frac{t_m^2 t_p^{\ 2}}{2}+t_p^3 t_m+\frac{2t_p^4}{3}\right)\right)(3t_m^2+6t_m t_p+4t_p^2)+\frac{4}{b_p^2}\right)(t_m+t_p)^2}{12\left(\frac{E_m b_p t_m^3}{12}+E_p b_p\left(\frac{t_m^2 t_p}{2}+t_p^2 t_m+\frac{2t_p^3}{3}\right)\right)^2}+\frac{\varepsilon_p t_p}{b_p k_c} \tag{16}$$

Where e_p and ε_p is the strain constant and the dielectric constant of the piezoelectric layer, respectively. According to equation (11) and (14), the open circuit voltage is obtained as

$$V_{oc}=\frac{j\omega_{ou}\gamma R_l F e^{j\omega_{ou}t}}{(1+j\omega_{ou}R_l C_{arc})\left(\omega_n^2+\omega_{ou}^{\ 2}-j2\xi_n\omega_n\omega_{ou}\right)-j\omega_{ou}R_l\gamma^2} \tag{17}$$

The output power can be expressed as

$$P=\frac{|V_{oc}|^2}{2R_l} \tag{18}$$

3. Measurements and Discusses

This circular arc array piezoelectric VEH is designed using a CNC (Computer Numerical Control) technology. The mass block is soldered on the metal beam, and the piezoelectric layer on the metal beam is connected with the conductive glue. As shown in Fig. 5, the PCB is fixed on the shaker by a nut and is very close to the fixed end of the circular arc array piezoelectric VEH. In addition, the stiffness of the PCB is much greater than the stiffness of this piezoelectric VEH. Therefore, the effect of the PCB on the circular arc array piezoelectric VEH is negligible. Each piezoelectric layer is connected in parallel.

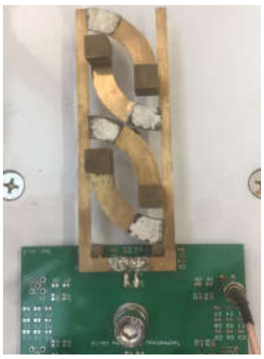


Figure 5. The measured structures of circular arc array piezoelectric VEH.

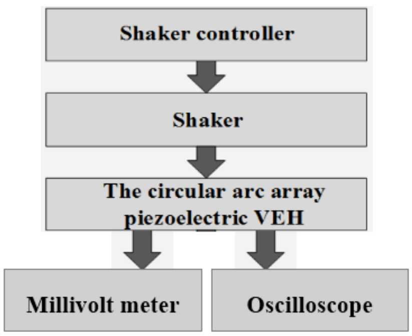


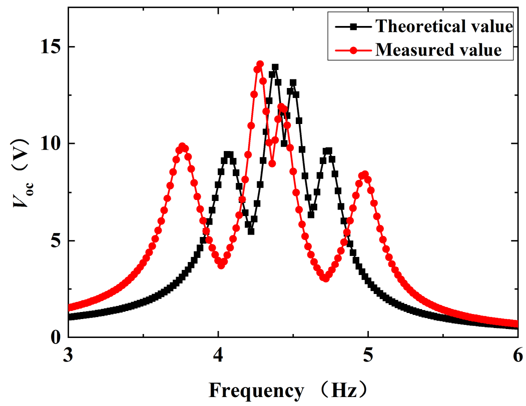
Figure 6. The schematic diagram of measurement.

The schematic diagram of measurement is shown in Fig. 6. The vibration excitation is provided by a multiparameter electromagnetic shaker (YBF YDC-100). The shaker can provide the vibration in two directions (horizontal direction and vertical direction) at the same time. The frequency of multi-parameters electromagnetic shaker varies from 0 Hz to 600 Hz and the precision is 0.1 Hz. The output waveform is detected by the oscilloscope (MSO-X 2002A). The output voltage is obtained by the precise millivolt meter (Fluke 8808A 5-1/2).

3.1. Output Voltage Measurement

One important measurement of the circular arc array piezoelectric VEH is the output voltage measurement. The frequency and amplitude of the shaker are controlled by a signal generator. The frequency of multi-parameters electromagnetic shaker varies from 2 Hz to 20 Hz. The vibration acceleration is measured by an accelerometer mounted on the shaker, which value is around 1.08 G. The voltages are recorded by millivolt meter.

In order to research the bandwidth of this circular arc array piezoelectric VEH, the relationship of the voltage with the frequency in the multi-direction vibration is shown in Fig.7. The theoretical bandwidth of circular arc piezoelectric array VEH is shorter than that of measured bandwidth. The main reason is that the theoretical frequency model is based on energy conservation with ignoring the effect of external force and damping, but it exists in the experiment. The vibration coupling of circular arc beams on the same main beam will reduce the difference of damping ratios ($|\xi_1 - \xi_3|$ or $|\xi_2 - \xi_4|$) between the circular arc beams， according to equation (15), the smaller difference of damping ratio lead to the wider resonant frequency band ($|\omega_1 - \omega_3|$ or $|\omega_2 - \omega_4|$). Therefore, the interaction coupling between the circular arc beams in experiment causes that the measured broadband is wider than theoretical broadband. Meanwhile, the measured voltage is lower than the theoretical voltage, because the energy is lost by coupling vibration.



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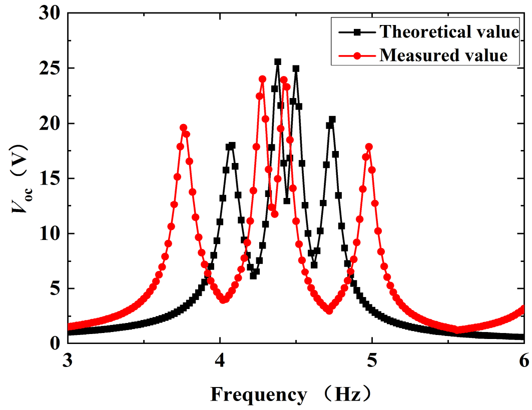

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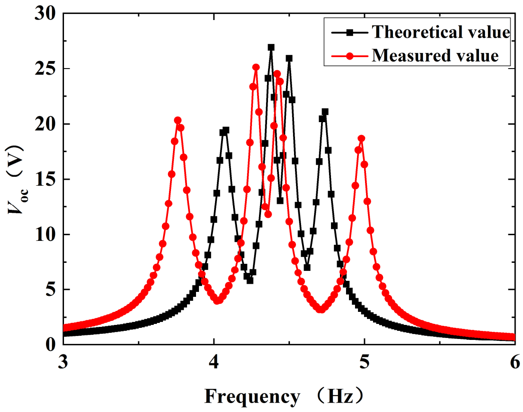


(c)

Figure 7. The measured voltage and theoretical voltage at (a) X-direction, (b) Y-direction, (c) Z-direction

In order to research the multi-directional energy harvesting of this circular arc array piezoelectric VEH, the measured voltage of multi-direction is shown in Table. 3. The first-order voltage of X-direction is 10.93 V, the second-order voltage is 15.74 V, the third-order voltage is 12.66 V and the fourth-order voltage is 9.11 V. The first-order voltage of Y-direction is 20.34 V, the second-order voltage is 25.17 V, the third-order voltage is 24.13 V and the fourth-order voltage is 19.08 V. The first-order voltage of Z-direction is 20.45 V, the second-order voltage is 26.83 V, the third-order voltage is 25.93 V and the fourth-order voltage is 21.09 V. The fourth order resonance frequencies of the circular arc array VEH are 3.76 Hz, 4.28 Hz, 4.42 Hz and 4.98 Hz.

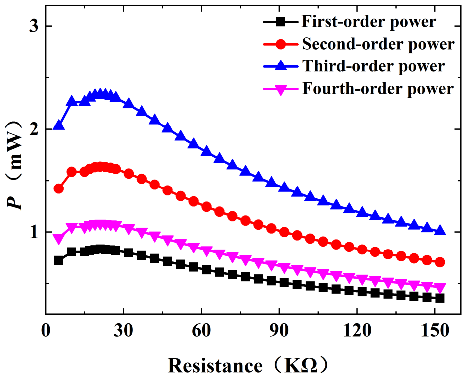
Table 3. Measured voltage of multi-directions

Direction	X	Y	Z
First-order voltage	10.93 V	20.34 V	20.45 V
First-order frequency		3.76 Hz	
Second-order voltage	15.74 V	25.17 V	26.83 V
Second-order frequency		4.28 Hz	
Third- order voltage	12.66 V	24.13 V	25.93 V
Third-order frequency		4.42 Hz	
Fourth-order voltage	9.11 V	19.08 V	21.09 V
Fourth-order frequency		4.98 Hz	

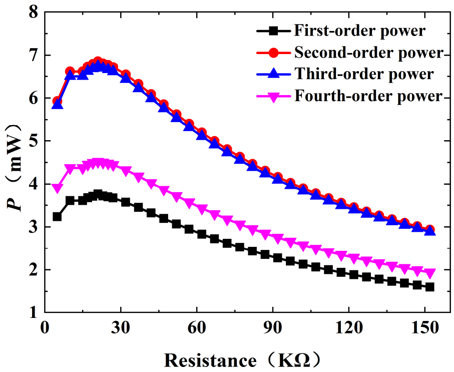
The longer the distance of No.1, No.2, No.3 and No.4 circular arc beams away from the fixed end, the smaller the resonance frequency. Each single circular arc VEH can absorb multi-directional vibration at one resonant frequency. The reason for absorbing vibration in multi-direction is that each circular arc beam can be deformed at multi-directional vibration, and the reason for absorbing vibration at the same frequency is that the resonance frequency is also related to mass block and stiffness by $\sqrt{k_c/m_c}$, while the stiffness is unchanged at the multi-directional vibration in equation (4). Therefore, the circular arc array VEH has a good broadband performance with absorbing multi-direction vibration energy.

3.2. Output Power Measurement

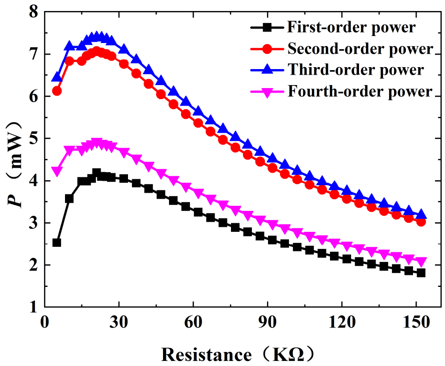
Another important measurement of this circular arc array piezoelectric VEH is the output power measurement. The external load is equipped in circuit which measures output power. The matching resistance of each single circular arc array piezoelectric VEH is around 21 KΩ. The power measurement at the multi-direction is shown in Fig.8. The higher output performance of the（No.2 and No.3） circular arc piezoelectric VEHs indicate the better positions in the middle of main beam. The main reason is that the damping ratio of the （No.2 and No.3） circular arc piezoelectric VEHs is smaller in equation (15), and the output performance is higher in equation (17) and (18).



(a)



(b)



(c)

Figure 8. Output power of circular arc array piezoelectric VEH at (a) X-direction, (b) Y-direction, (c) Z-direction

Table 4. Measured power of the circular arc array piezoelectric VEH

Direction	X	Y	Z
First-order power	1.07 mW	3.92 mW	4.19 mW
Second-order power	1.86 mW	6.81 mW	7.07 mW
Third-order power	1.97 mW	7.04 mW	7.39 mW
Fourth-order power	0.96 mW	4.41 mW	4.92 mW

The measured maximum power of the multi-direction is shown in Table. 4. The maximum power at X-direction is 1.07 mW, 1.86 mW, 1.97 mW and 0.96 mW for first-order, second-order, third-order and fourth-order. The maximum power at Y-direction is 3.92 mW, 6.81 mW, 7.04 mW and 4.41 mW for first-order, second-order, third-order and fourth-order. The maximum power at Z-direction is 4.19 mW, 7.07 mW, 7.39 mW and 4.92 mW for first-order, second-order, third-order and fourth-order. The output power in the Z-direction is greater than that in the X-direction and Y-direction. The higher output performance is due to the larger average stress of the piezoelectric layer. The stress distribution of the circular arc array piezoelectric VEH is analyzed in Fig.9. When the excitation is applied on different side surface of the mass blocks, the stress distribution in the X-direction or the Y-direction as shown in Fig.9 (a) and (b). When the excitation is applied on the top surface of the mass blocks, the stress distribution in the Z-direction as shown in Fig.9 (c). The average stress of this array circular arc piezoelectric VEH can achieve 1.0×10^{6} N/m^2 at X-direction， 2.7×10^{6} N/m^2 at Y-direction and 2.9×10^{6}

N/m^2 at Z-direction. When the vibration is in the X-direction, the stress distribution is mainly distributed on the No. 3 circular arc beam. When the vibration is in the Y-direction and Z-direction, the stress distribution is mainly distributed on the (No. 2 and No. 3) circular arc beams. Therefore, the（No.2 and No.3） circular arc piezoelectric VEHs have higher output performance, and the highest absorption efficiency is from the Z-direction vibration.

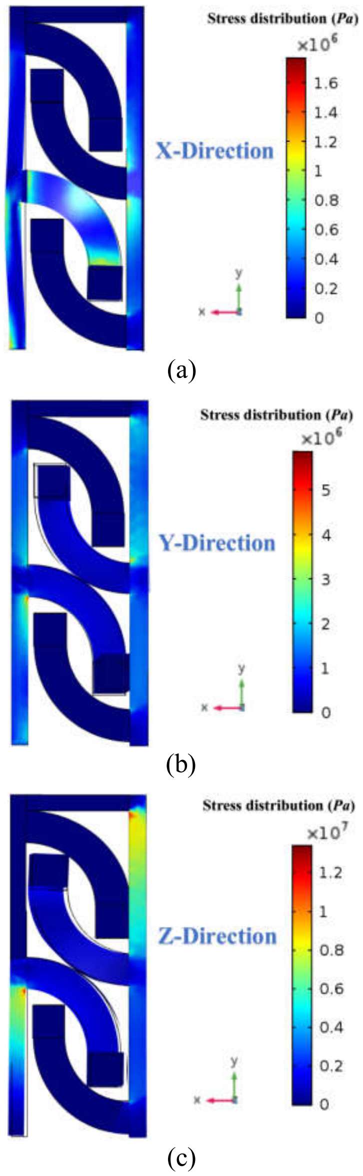


Figure 9. The stress distribution (a) X-direction (b) Y-direction (c) Z-direction

4. Conclusions

In summary, this novel circular arc array piezoelectric VEH can absorb multi-directional vibrational energy at the broadband frequency, where each circular arc piezoelectric VEH can still effectively absorb multi-directional vibration energy at one resonant frequency. The measurement results reveal that an agreement between the theoretical model and experiment is obtained. This circular arc array piezoelectric VEH will be widely used in more fields in the future.

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