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Simulation Study on Material Property of Cantilever Piezoelectric Vibration Generator

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Abstract: For increasing generating capacity of cantilever piezoelectric vibration generator with limited volume, relation between output voltage, inherent frequency and material parameter of unimorph, bimorph in series type and bimorph in parallel type piezoelectric vibration generator is analyzed respectively by mechanical model and finite element modeling. The results indicate PZT-4, PZT-5A and PZT-5H piezoelectric materials and stainless steel, nickel alloy substrate material should be firstly chosen. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Wireless sensor network, Vibration energy harvesting, Micro piezoelectric vibration generator, Finite element modeling.

1. Introduction

Piezoelectric vibration generator made in MEMS can infinite and continue to supply energy for low power electric device, which effectively solves the energy supply problem in rugged working condition of wireless sensor network [1-7]. However, output power of piezoelectric harvesting is still limited at present, which hinder seriously widespread use of the technology, and how to enhance effectively generating capacity of generating set is key problems needed to be solved currently. In recent years, research has shown that piezoelectric generating capacity mainly depends on material property, structure parameter, base frequency and incentive method. Ericka [8] design piezoelectric vibration generator bearing big load and its material is unimorph film. Wang [9] design drum type piezoelectric vibration generator which has high output energy density, but resonant frequency of drum type generator general is beyond 200 Hz, and output power is low because it's difficult to resonant in low-frequency environment. Hu Hongping [10] adopt heliciform double piezoelectric ceramic piece as generating component, and its characteristic is small volume, micromation and good stability, and it can reduce effectively structure inherent frequency. But its area is small, so quantity of electric charge of collecting and output power is respectively few. Generating area of rectangle piezoelectric plate of cantilever piezoelectric vibration generator is big relative to heliciform piezoelectric piece, so quantity of electric charge of collecting and output power are enhanced, and it already become research hotspot of many countries all around the world. He Qing [11], Shad Roundy [12], Du Xiaozhen [13], Cheng Guangming [14] et al. respectively have researched structure optimization, mechanical model, workmanship and experimental measurement system of cantilever piezoelectric generator, few researcher, however, have addressed the question of optimization research of cantilever piezoelectric generator's materials. So, in this article fem simulative analysis is apply to verify mechanical model precision based on electromechanical coupling distribution parameter, and influence rule of material parameter of cantilever piezoelectric generator to inherent frequency and output voltage respectively is studied, then material parameter is optimized analysis, and research foundation for enhancing generating capacity of cantilever piezoelectric generator with limited volume in working environment is laid.

2. Structure and Modeling

Cantilever piezoelectric generator form by piezoelectric ceramics, electrode, elastic substrate and fixed support. Piezoelectric ceramics cover and tightly integrated with substrate, and electrode cover on piezoelectric ceramics. One end of generator is fastened to support, another end vibrates freely with vibration source. Because generator's length and width are far greater than thickness, which belongs to thin walled beam structure and meets theoretical assumption of composite Euler–Bernoulli beam, so influence of shear deformation and rotational inertia can be neglected, and transformation regard as linear treatment under small amplitude condition.

When suffering persistent excitation, piezoelectric ceramics generate charge which move and deform with vibration source, and continuous load resistance current output is generated at load resistance, consequently, Mechanical vibration energy translate into electric energy. Structural representation of three essential cantilever piezoelectric generators are shown in Fig. 1. Fig. 1(a) is shown unimorph piezoelectric beam structure, and Fig. 1(b) is shown bimorph in series type beam structure, and Fig. 1(c) is shown bimorph in parallel type beam structure. Piezoelectric beam's length is indicated by l, width is indicated by b, thickness is indicated by h, superscript (or subscript) s and p respectively present substrate and piezoelectric layer, subscript u, bs, bp respectively present unimorph, bimorph in series type and bimorph in parallel type beam.

According to piezoelectrics theory, surface of piezoelectric beam which suffer continuous bending deformation will generate free charge. The stress and electric field of piezoelectrics obey piezoelectric equation:

$$\begin{cases} \{D\} = [d]\{T\} + [\varepsilon^T]\{E\} \\ \{S\} = [s^E]\{T\} + [d]^t\{E\} \end{cases}, \tag{1}$$

where $\{D\}$ express electric displacement, $\{E\}$ express electric field intensity, $[d]$ express piezoelectric constant matrix, $\{S\}$ and $\{T\}$ respectively express strain and stress, $[\varepsilon^T]$ express free dielectric constant matrix at stress constant, $[s^E]$ express short circuit elastic compliance ratio matrix at electric field constant.

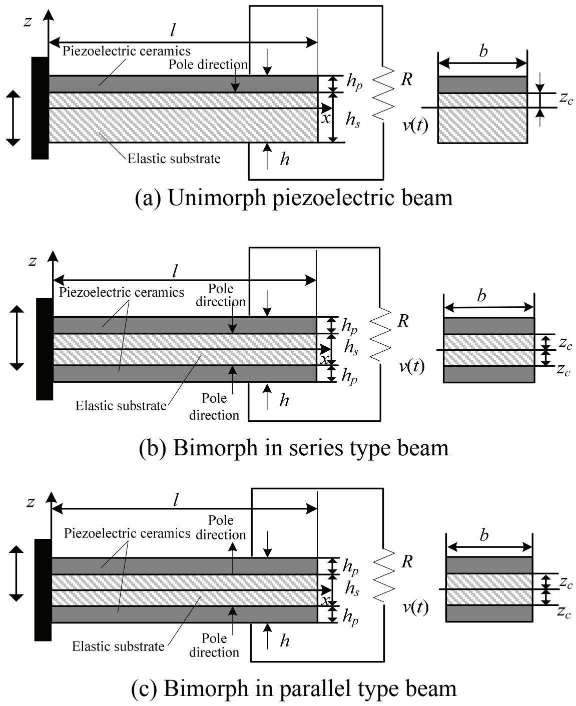


Fig. 1. Unimorph beam and bimorph beam.

Under piezoelectric beam suffer harmonic excitation, when excitation frequency is close by r-order inherent frequency, voltage response of unimorph, bimorph in series type and bimorph in parallel type respectively is [15, 16]:

$$\hat{v}_u(t) = \frac{j\omega R k_r^u F_r e^{j\omega t}}{\left(1 + j\omega R C_p^u\right)\left(\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega\right) + j\omega R k_r^u \chi_r^u}, \tag{2}$$

$$\hat{v}_{bs}(t) = \frac{j2\omega R k_r^{bs} F_r e^{j\omega t}}{\left(2 + j\omega R C_p^{bs}\right)\left(\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega\right) + j2\omega R k_r^{bs} \chi_r^{bs}}, \tag{3}$$

$$\hat{v}_{bp}(t) = \frac{j2\omega R k_r^{bp} F_r e^{j\omega t}}{\left(1 + j2\omega R C_p^{bp}\right)\left(\omega_r^2 - \omega^2 + j2\zeta_r\omega_r\omega\right) + j2\omega R k_r^{bp} \chi_r^{bp}}, \tag{4}$$

where R indicates load resistance, k_r indicates modal coupling item, F_r indicates amplitude excitation function, C_p indicates piezoelectric capacitance, ζ_r indicates mechanical damping ratio, χ_r indicates electromechanical coupling item.

R-order inherent frequency ω_{rd} is expressed as [14, 15]:

$$\omega_{rd} = \lambda_r^2 \sqrt{\frac{YI}{ml^4}} \sqrt{1 - \zeta_r^2}, \tag{5}$$

where λ_r indicates nondimensional frequency, Y indicates elastic module, I indicates moment of inertia, m indicates mass of per unit length.

3. Performance Simulation Analysis

Software of finite element analysis ANSYS is applied to model and simulate for cantilever piezoelectric generator, and computed result of mechanical model is further validated. For bearing more deformation, phosphor bronze with larger elasticity modulus is selected as substrate material, and PZT-5H is selected as piezoelectric ceramics material, and performance parameter of unimorph beam is shown in Table 1. For comparing generating capacity of unimorph with bimorph in series type and bimorph in parallel type in same volume, thickness of each of bimorph is same which is half with unimorph.

Table 1. Structural and material parameters of unimorph piezoelectric beam.

Parameter	Piezoelectric layer (PZT-5H)	Phosphor bronze substrate
Density ρ (kg/m^3)	7600	8860
Elastic module E(GP$_a$)	60.6	110.0
Poisson's ratio μ	0.289	0.330
piezoelectric constant $d31$ (10^{-12} m/V)	-274	—
dielectric constant ε_{33}^{s} (F/m)	$1470\varepsilon_0$	—
Length l (mm)	50	50
Width w (mm)	15	15
Thickness h (mm)	0.4	0.4

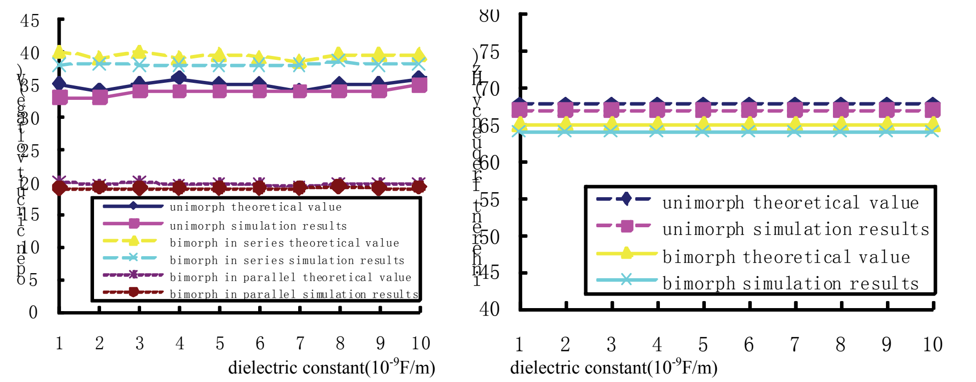
Influence of dielectric constant, density, elasticity modulus and piezoelectric constant of piezoelectric layer to open circuit voltage and inherent frequency respectively is shown from Fig. 2 to Fig. 5.

Sees from the Fig. 2, open circuit voltage and first order inherent frequency aren't basic influenced by dielectric constant.

Sees from the Fig. 3, influence of density to open circuit voltage is small too, but first order inherent frequency of unimorph and bimorph beam are slightly lower with increasing of density.

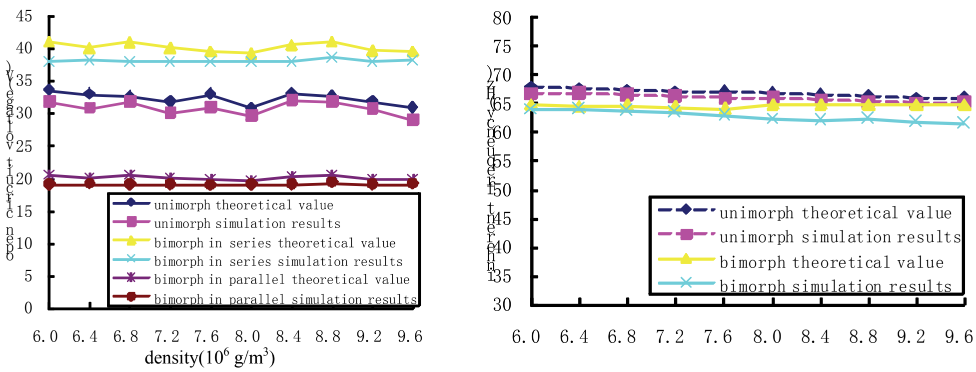
From Fig. 4, influence of elastic module to generating capacity is larger, open circuit voltage and first order inherence frequency of unimorph and bimorph beam increase with increasing piezoelectric elasticity modulus.

From Fig. 5(a), influence of piezoelectric constant to open circuit voltage is larger too, and open circuit voltage increases first, and then decreases with increasing piezoelectric constant, and open circuit voltage of bimorph beam is the largest when piezoelectric constant is about -180 pm/V, so the best piezoelectric constant of bimorph beam is about -180 pm/V; open circuit voltage of unimorph beam is the largest when piezoelectric constant is about -210 pm/V, so the best piezoelectric constant of unimorph beam is about -210 pm/V. From Fig. 5(b), first order inherent frequency isn't basic influenced by piezoelectric constant.



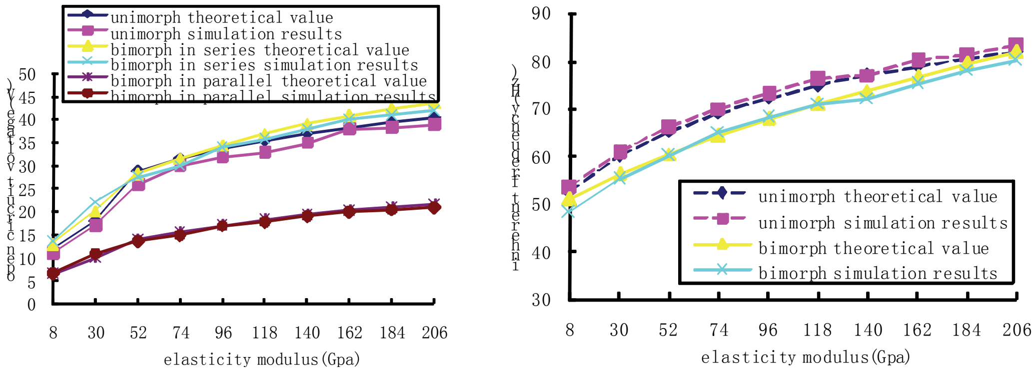
(a) Open circuit voltage vs. dielectric constant (b) Inherent frequency vs. dielectric constant

Fig. 2. Generating performance vs. dielectric constant of piezoelectric layer.



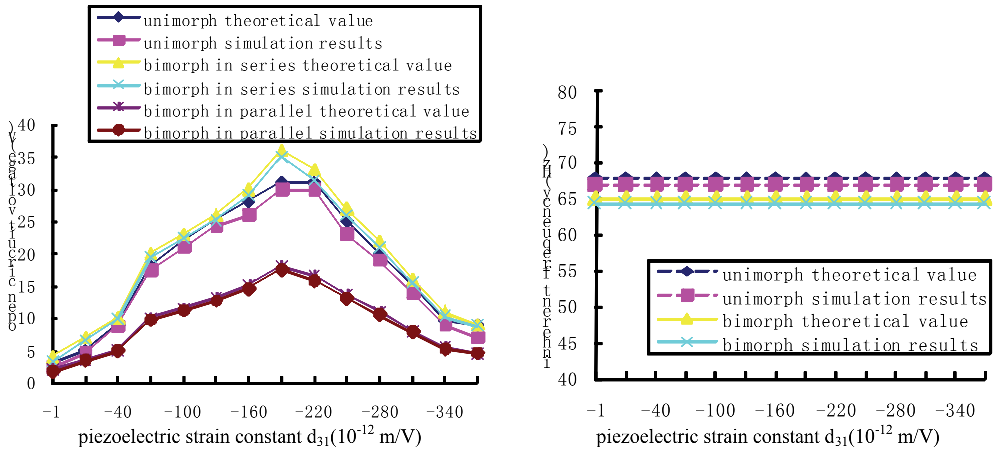
(a) Open circuit voltage vs. density (b) Inherent frequency vs. density

Fig. 3. Generating performance vs. density of piezoelectric layer.



(a) Open-circuit voltage vs. elastic modulus (b) Inherent frequency vs. elastic modulus

Fig. 4. Generating performance vs. elastic modulus of piezoelectric layer.



(a) Open-circuit voltage vs. piezoelectric constant (b) Inherent frequency vs. piezoelectric constant

Fig. 5. Generating performance vs. piezoelectric constant of piezoelectric layer.

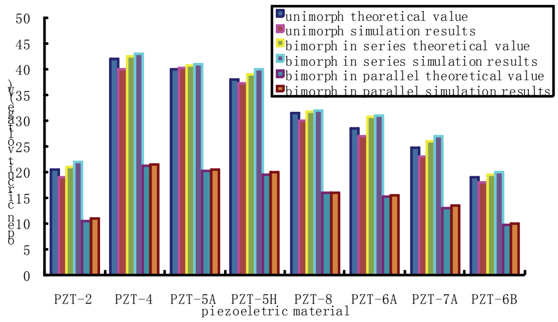
It can be seen from the above analysis that for obtaining larger open circuit voltage and lower first order inherent frequency, larger density and piezoelectric constant between -180 to -210 pm/V should be selected, and elasticity modulus should be overall consideration according to requisite output voltage and environmental vibration frequency. But material parameter of specific piezoelectric materials is inherent attribute which don't random match, and material performance parameter of common PZT piezoelectric material is shown in Table 2. Influencing characteristic of common PZT piezoelectric material to open circuit voltage and inherent frequency are analyzed to find that open circuit voltage of piezoelectric ceramics PZT-4, PZT-5A and PZT-5H is larger, the result is shown in Fig. 6. So cantilever piezoelectric generator is made to select firstly above three piezoelectric materials.

Influence of substrate material parameter to generating performance is analyzed to discover that open circuit voltage and first order inherent frequency is increase with the increasing substrate elasticity modulus, and result is shown in Fig. 7. So, substrate elasticity modulus is selected which take into account demands of vibration source frequency and output voltage value.

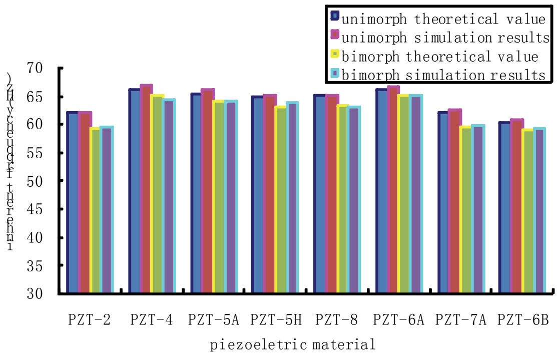
Influence of substrate density to open circuit voltage and first order inherent frequency are shown in Fig. 8. From Fig. 8, influence of substrate density to open circuit voltage is little, but first order inherent frequency is reducing with increasing substrate density. So, substrate material should be larger density for obtaining high generating performance.

Table 2. Common PZT piezoelectric material parameters.

Material parameter / Piezoelectric material	ε_{33}^{s} / ε_0	d_{31}(10^{-12} m/V)	s_{11}^{E}(10^{-12} m^2/N)	ρ(10^3 kg/m^3)
PZT-2	260	-60	11.6	7.50
PZT-4	635	-123	12.3	7.50
PZT-5A	830	-171	16.4	7.75
PZT-5H	1470	-274	16.5	7.50
PAT-6A	730	-80	10.7	7.45
PZT-6B	386	-27	9.0	7.55
PZT-7A	235	-60	10.7	7.60
PZT-8	600	-93	12.0	7.60

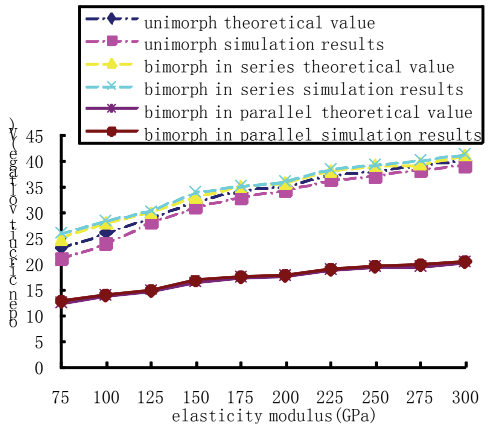


(a) Open circuit voltage vs. piezoelectric material

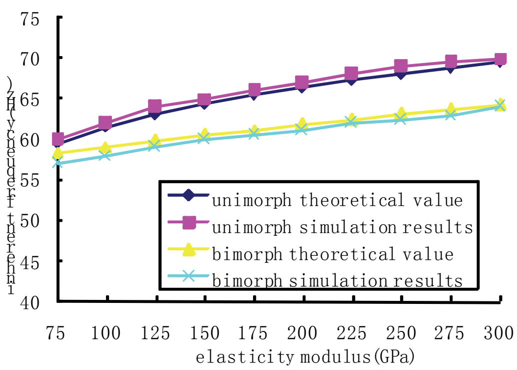


(b) Inherent frequency vs. piezoelectric material

Fig. 6. Generating performance vs. common piezoelectric material.

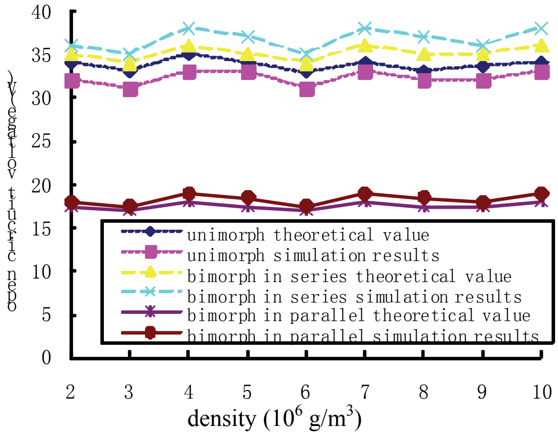


(a) Open-circuit voltage vs. elasticity modulus

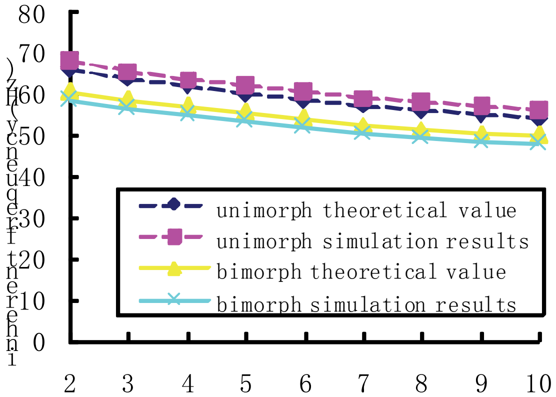


(b) Inherent frequency vs. elasticity modulus

Fig. 7. Generating performance vs. elasticity modulus of substrate.



(a) Open circuit voltage vs. density



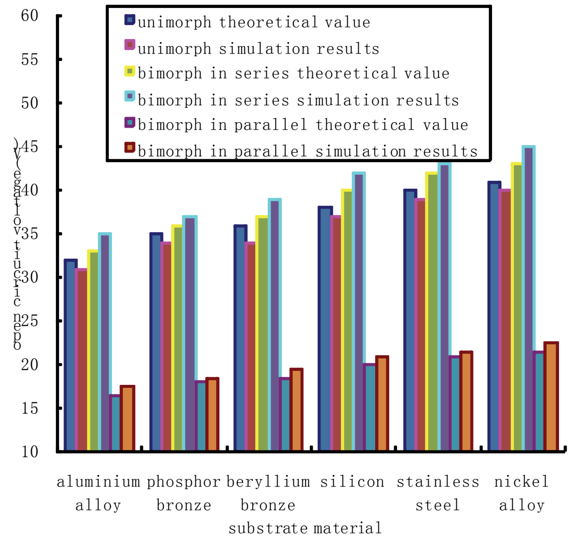
(b) Inherent frequency vs. density

Fig. 8. Generating performance vs. density of substrate.

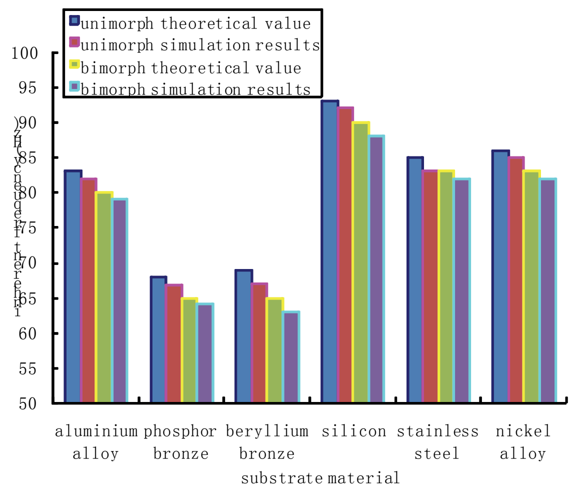
Based on substrate material of beryllium bronze, stainless steel, nickel alloy and phosphor bronze, which parameters are shown in Table 3, and influence of substrate material to open circuit voltage and first order inherent frequency are analyzed which is similar to analytical method of piezoelectric layer above, and results are shown in Fig. 9. From Fig. 9, output voltage of unimorph and bimorph beam with stainless steel and nickel alloy substrate material are larger, and first order inherent frequency of unimorph and bimorph beam with phosphor bronze and beryllium bronze substrate material are lower, which work well with low frequency incentive environment.

Table 3. Common substrate material parameters.

Material parameter / Substrate material	elasticity modulus Y_s(GPa)	Poisson's ratio γ	Density ρ(kg/m^3)
Beryllium bronze	118	0.35	8920
Stainless steel	197	0.28	7800
Aluminium alloy	75	0.33	2700
Nickel alloy	210	0.32	8800
Silicon	170	0.28	2328
Phosphor bronze	110	0.33	8860



(a) Open-circuit voltage vs. substrate material



(b) Inherent frequency vs. substrate material

Fig. 9. Generating performance vs. common substrate material.

4. Conclusions

Mechanical model accuracy is verified which apply ANSYS finite element simulation, and influence rule of material parameter of cantilever piezoelectric generator to inherent frequency and output voltage are studied, and material parameter is optimized analysis aiming maximum output electric energy with minimum volume. The results indicate PZT-4, PZT-5A and PZT-5H piezoelectric materials and stainless steel, nickel alloy substrate material should be firstly chosen.

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