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Performance Dependence on Initial Free-End Levitation of a Magnetically Levitated Piezoelectric Vibration Energy Harvester With a Composite Cantilever Beam

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ABSTRACT Vibration energy harvesting by using piezoelectric materials provides a promising alternative solution for a wide range of self-powered systems. In this paper, performance dependence on initial free-end levitation position (IFLP) of a magnetically levitated piezoelectric vibration energy harvester (PVEH) with a composite cantilever beam is presented. A prototype consisting of a high-stiffness lead zirconate titanate beam with a proof mass and a flexible brass beam with a tip mass as well as an auxiliary structure adjusting repulsive magnetic force was fabricated to evaluate the IFLP effects. Experimental results showed that the performance of the magnetically levitated PVEH was varied with different IFLPs. With declining of the IFLP, the peak power output at the first resonance frequency decreased monotonically from 1541 to 343.2 μW, meanwhile, the power output initially decreased from 2735.6 to 904.5 μW and then constantly increased from 904.5 to 2220.9 μW at the second resonance frequency. The frequency variation at the first and second resonance points was 1.5 and 4 Hz, respectively. It was found that the IFLP had a stronger impact on the performance when it was above the horizontal orientation than below the horizontal orientation. Moreover, the IFLP brought a more significant influence on the second resonance frequency than the first one. In addition, the IFLP had a larger effect on the power output than the resonance frequency.

INDEX TERMS Energy harvesting, piezoelectric vibration energy harvester, composite cantilever beam, magnetic levitation, initial free-end levitation position, resonance frequency.

I. INTRODUCTION

With recent advances on low-power portable electronics, wireless sensors and communication devices, harvesting energy from the ambient environment has gained considerable interest to replace the conventional electrochemical batteries because of their inherent shortcomings like short lifetime, limited power storage and maintenance issues [1]–[5]. To date, a variety of alternative energy sources are converted into the electricity, such as vibration, solar, ocean wave, rain, sound, wind, rotation, acoustics, and thermal energy [6]–[9]. Among these sources, vibration energy is one of the most omnipresent and potential energy sources [10]–[12]. In general, vibration-based energy harvesting can transform the ambient kinetic energy into useful electrical energy using electromagnetic [13], [14], electrostatic [15], [16], or piezoelectric [17], [18] mechanisms. Although each method is able to harvest a useful amount of energy, piezoelectric mechanism has received significant attention due to simple structure, high power density, high energy conversion efficiency and ease of energy acquisition [19]–[22]. Hence, piezoelectric vibration energy harvesters (PVEHs) have been the most widely studied and applied [23]–[25].

Conventionally, a PVEH is made up of a piezoelectric cantilever beam with a proof mass and it is frequently considered as a single-degree-of-freedom linear vibration resonator [26], [27]. As is well known, one of the shortcomings of the cantilever-type structure is narrow operating bandwidth. The maximum power can be generated only when the resonant frequency closely matches the vibration frequency. Nevertheless, PVEHs will suffer from poor output power out of range near the resonance frequency [28], [29]. Therefore, many efforts have been dedicated to broadening the operational bandwidth to enhance the performance of traditional PVEHs [30]–[32]. Because it is very hard to tune the resonance frequency through adjusting the mass and stiffness of the piezoelectric elements, the frequency tuning is usually realized by changing the proof mass. However, the tunable effectiveness obtained from the change of the proof mass is still limited. Therefore, an additional flexible beam was introduced and combined with the piezoelectric beam to construct a composite cantilever beam, where the resonance frequency of the piezoelectric elements could be indirectly tuned and two resonance frequencies would be achieved. Furthermore, the magnetic coupling was introduced to change the stiffness of the piezoelectric plates and further realize the frequency tunability. The techniques of multimodal harvesting and nonlinear magnetic coupling were thus presented [27], [33], [34]. In general, the early multimodal configuration was a cantilever beam array and most beams remained inactive at a given frequency [35]. To overcome the issue, various combination forms of flexible beams and piezoelectric beams were developed. Wu *et al.* [27], [36] proposed a novel compact piezoelectric energy harvester using two vibration modes to achieve two close resonances and then the operating bandwidth was further broadened through incorporating magnetic nonlinearity into the energy harvester. Tang and Yang [26] presented a multiple-degree-of-freedom (multiple-DOF) piezoelectric energy harvesting model to overcome the bandwidth issue. Xiao *et al.* [37] validated that the harvesting performance could be significantly enhanced by introducing one or multiple additional piezoelectric elements placed between every two nearby oscillators. To extend the operation frequency bandwidth, Liu *et al.* [38] proposed a novel two-degree-of-freedom (2-DOF) piecewise-linear PVEH which consisted of a piezoelectric cantilever composite beam serving as energy conversion component and a cantilever driven beam acting as stopper. It verified that wider operation frequency bandwidth was achieved in two resonances.

Apart from the multimodal technique, magnetic interaction as a nonlinear technique has also been frequently employed to broaden the bandwidth of PVEHs. Using the magnetic interaction, bistable vibration energy harvesters were developed to transform low-frequency broadband mechanical vibrations into electrical power [39]. Challa *et al.* [40] introduced a magnetic force at cantilever tip to tune the natural frequency of a PVEH by modifying the overall stiffness of the beam. It showed that the technique enabled resonance tuning to $\pm 20\%$ of the untuned resonant frequency by using either attractive or repulsive magnetic force. Lin *et al.* [41] utilized non-linear magnetic coupling to tune the resonant frequency and bandwidth of PVEHs to enhance the power conversion efficiency and alter the frequency spectrum. Tang and Yang [42] reported a nonlinear PVEH with a magnetic oscillator, where the introduction of the magnetic oscillator broadened the operating bandwidth and at the same time substantially enhanced the achievable power. Al-Ashtari *et al.* [43] presented a natural frequency tuning technique of PVEHs using magnetic force. The natural frequency of PVEHs could be adjusted without directly touching the vibrating structure. Afterwards, Al-Ashtari *et al.* [44] used the attractive force between two permanent magnets to add stiffness to the PVEH. It showed this magnetic stiffening countered the effect of a tip mass on the efficient operation frequency. Shih *et al.* [45] proposed a magnetic pair to serve as the stoppers for piezoelectric beam to enlarge the bandwidth using perturbation. Fan *et al.* developed a nonlinear PVEH via introducing the magnetic coupling between a ferromagnetic ball and four piezoelectric cantilever beams. Therefore, the PVEH was capable of harvesting energy from various directions of vibrations [28].

In fact, the magnetic coupling was often applied in the multimodal technique as well. Yang *et al.* [46] presented a broadband PVEH by combining magnetic forces and multi-cantilever beams with different natural frequencies to increase the power. Wu *et al.* [36] tuned two resonant response peaks of a PVEH with a composite beam to be close enough by adjusting the distance between two repulsive permanent magnets. Zhao *et al.* [34] proposed a piezoelectric aeroelastic energy harvester with a cut-out cantilever and two magnets in order to improve the power efficiency in the low wind speed. The aforementioned research works demonstrated that the combination of multimodal technique and nonlinear method was capable of tuning multiple response peaks to be close enough so that PVEH could achieve wider frequency bandwidth. Furthermore, the influence of structures and parameters like the excitation level, proof mass and magnetic force on the harvesting performance was also obtained for multiple-DOF cantilever-type PVEHs. Some intriguing progress and advancement have been made in the combination technique of multimodal and nonlinear energy harvesting.

Generally, a conventional PVEH with a composite cantilever beam was composed of a primary beam and a secondary beam with their respective proof mass [27]. In order to harvest low-frequency vibration and achieve two close resonant frequencies, the beam structure and additional mass were usually adjustable, especially the proof mass. Besides, the magnetic coupling method was frequently incorporated into the composite cantilever PVEH to obtain the desired frequency bandwidth. Apparently, the free end of the PVEH with a composite cantilever beam was under the suspension condition after the PVEH was fabricated and assembled. Due to the different stiffness and length of the piezoelectric beam and flexible beam as well as the proof mass and magnetic mass, the initial free-end levitation position (IFLP) could be more or less random before the PVEH operated. Various

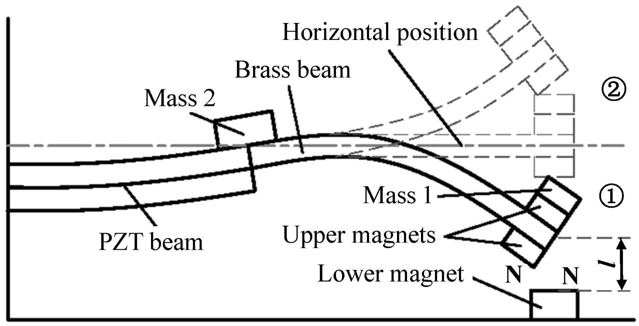

FIGURE 1. Design of the magnetically levitated PVEH with a composite cantilever beam under different IFLPs.

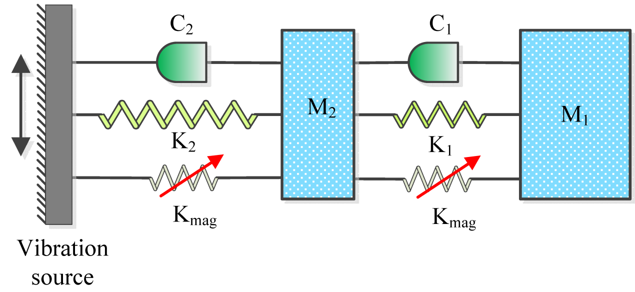

FIGURE 2. Lumped parameter model of the system.

pre-strain of piezoelectric elements was caused by different IFLPs. The initial working status of the PVEH was thus varied. So it was necessary to figure out that how the IFLP affected the harvesting characteristics of a PVEH with a composite cantilever beam. To the authors' best knowledge, so far no reports emphasize the effect of the IFLP on the PVEH performance.

In this paper, the attention is focused on the effect of the IFLP on the performance of a magnetically levitated PVEH with a composite cantilever beam. A composite cantilever PVEH consisting of a preflex lead zirconate titanate (PZT) beam (primary beam) and a flexible brass beam (secondary beam) was designed and fabricated, meanwhile, the repulsive permanent magnets were adopted. Not only the magnets could act as a part of the tip mass to lower the resonance frequency, but also the adjustment of the IFLP would be readily realized through the magnetic interaction. In order to explore the influence of the IFLP, the frequency characteristics of the magnetically levitated PVEH with a composite cantilever beam under different IFLPs were tested and compared via adjusting the repulsive magnetic force. The paper is structured as follows: Section II describes the system design and model analysis; section III depicts the fabricated prototype of the composite cantilever PVEH; and section IV presents experimental process, testing results and a further discussion on the results. Conclusions are in section V.

II. SYSTEM DESIGN AND MODEL ANALYSIS

The schematic diagram of the magnetically levitated PVEH with a composite cantilever beam under different IFLPs is shown in Fig. 1, where two kinds of IFLPs are graphically depicted. The harvester was mainly composed of a higher-stiffness primary beam with a proof mass and a lower-stiffness secondary beam with a tip mass. One end of the primary beam was fixed while the other end was connected to one end of the secondary beam. The other end of the secondary beam was free and a tip mass was attached to the free end. The positions ① and ② in Fig. 1 represent the IFLP of below and above the horizontal orientation, respectively. The different initial positons of the free end were adjustable through the repulsive magnetic force between the upper magnets attached at the tip mass and the movable lower magnet.

To analyze the dynamic characteristics of the magnetically levitated PVEH with a composite cantilever beam, it is simplified as a 2-DOF lumped parameter mass-spring-damping model, as illustrated in Fig. 2. The primary beam was modelled as an equivalent mass M_2, spring constant K_2 and a damping coefficient C_2, meanwhile, the secondary beam was modelled as a mass M_1, spring constant K_1 and a damping coefficient C_1. The application of the repulsive magnetic force resulted in an additional stiffness. The resulting equivalent stiffness of the secondary and primary beams were the sum of the stiffness K_1 and K_2 of the secondary and primary beams and the additional magnetic stiffness K_{mag} introduced by the magnetic force, respectively. Moreover, the magnetic stiffness acted as a variable spring, whose stiffness was dependent on the change in magnetic force over the separation distance.

When the piezoelectric cantilever beam is considered as a composite Euler-Bernoulli beam, the governing equation of the system can be derived by using the extended Hamilton's principle [47], [48]

$$M_1\ddot{x}_1 + C_1\dot{x}_1 + (K_1 + K_{mag})x_1 = F_e + F_m \tag{1}$$

$$M_2\ddot{x}_2 + C_2\dot{x}_2 + (K_2 + K_{mag})x_2 = F_e + F_m \tag{2}$$

where F_{e} is the excitation force from ambient vibration, F_{m} is the magnetic force between the permanent magnets, x_1 and x_2 are the tip displacements of the secondary and primary beams, respectively. For the piezoelectric beam, the equivalent mass M_{eq}, the equivalent damping coefficient C_{eq}, and the equivalent stiffness K_{eq} are defined as [49]

$$M_{eq} = A_b \int \rho\,(x) r\,(x)^2 dx \tag{3}$$

$$C_{eq} = \Gamma I \int r\,(x) \frac{\partial^4 r\,(x)}{\partial x^4} dx \tag{4}$$

$$K_{eq} = YI \int r\,(x) \frac{\partial^4 r\,(x)}{\partial x^4} dx \tag{5}$$

where A_b, Γ, Y, and I are the cross-sectional area, the Kelvin-Voigt viscosity, the Young's modulus, and the moment of inertia of area, respectively. It should be noted that not only the above four parameters and the integral interval is different for the primary and secondary beams. $\rho(\mathrm{x})$ and $r(\mathrm{x})$ are the density function and the mode shape function, respectively. The shape function $r(\mathrm{x})$ can be obtained according to the reference [33], [50]. Moreover, using the Raleigh-Ritz method, the vibration displacement in single mode approximation of the piezoelectric beam can be represented by the shape function $r(\mathrm{x})$, as expressed in the following equation.

$$w(x,t) = r(x)\,\eta(t) \tag{6}$$

where $\eta(t)$ is the modal mechanical coordinate.

Based on equations (1) and (2), the two fundamental resonance frequencies of the composite cantilever PVEH can be given as follows:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{K_1 + K_{mag}}{M_1}} \tag{7}$$

$$f_2 = \frac{1}{2\pi}\sqrt{\frac{K_2 + K_{mag}}{M_2}} \tag{8}$$

According to the literature [40], the magnetic force of F_m can be expressed as

$$F_m = -\frac{3\mu_0 m_1 m_2}{2\pi(l \pm x_1)^4} \tag{9}$$

where m_1 and m_2 are the moments of the magnetic dipoles, μ_0 is the vacuum permeability, l is the initial distance between the magnetic dipoles. As can be seen from Fig. 1, the parameter l in the equation (9) reflects the IFLP indirectly. Different IFLPs can be realized through changing the value of l. Actually, various IFLPs or values of l lead to the change of the pre-deformation of the composite cantilever beam. Thus, the pre-strain/pre-stress on the PZT of the PVEH varies with the IFLP. It means that the initial working condition and operating range of the piezoelectric element are totally different under various IFLPs. Therefore, the IFLP must bring an influence on the performance of the PVEH with the composite cantilever beam.

When the PVEH is subjected to a sinusoidal vibration excitation of $y(t) = A\sin\omega t$, the governing equations (1) and (2) become

$$M_1\ddot{x}_1 + \mathrm{C}_1\dot{x}_1 + (K_1 + K_{mag})x_1 = M_1 A\omega^2 \sin\omega \mathrm{t} + F_m \tag{10}$$

$$M_2\ddot{x}_2 + C_2\dot{x}_2 + (K_2 + K_{mag})x_2 = M_2 A\omega^2 \sin\omega \mathrm{t} + F_m \tag{11}$$

Substituting equation (9) into equations (10) and (11), equations (1) and (2) are given as follows:

$$M_1\ddot{x}_1 + \mathrm{C}_1\dot{x}_1 + (K_1 + K_{mag})x_1 = M_1 A\omega^2 \sin\omega \mathrm{t} - \frac{3\mu_0 m_1 m_2}{2\pi(l \pm x_1)^4} \tag{12}$$

$$M_2\ddot{x}_2 + C_2\dot{x}_2 + (K_2 + K_{mag})x_2 = M_2 A\omega^2 \sin\omega \mathrm{t} - \frac{3\mu_0 m_1 m_2}{2\pi(l \pm x_1)^4} \tag{13}$$

As expressed by [40], the magnitude of the equivalent magnetic stiffness K_mag is a function of both the magnetic force and the magnet distance.

$$\bar{K}_{mag} = \left|\frac{\delta F_m}{\delta(l \pm x_1)}\right| = \left|\frac{\partial F_m}{\partial(l \pm x_1)}\right| = \left|\frac{6\mu_0 m_1 m_2}{\pi(l \pm x_1)^5}\right| \tag{14}$$

where the sign of K_mag is positive for the repulsive magnetic force.

According to the Euler-Bernoulli beam theory, the open-circuit output voltage of a cantilever-type PVEH under an external excitation force F from ambient vibration is given by [51]

$$V_g = -\frac{3\alpha(1-\alpha)\beta g_{31} l_p}{\gamma t w_p} F \tag{15}$$

where

$$\alpha = \frac{t_m}{t}$$

$$\beta = \frac{E_m}{E_p}$$

$$\gamma = \alpha^4(1-\beta)^2 - 2\alpha\,(2\alpha^2 - 3\alpha + 2)(1-\beta) + 1$$

g_{31}	piezoelectric voltage coefficient
t_m	thickness of the substrate plate
t	thickness of the piezo-cantilever
E_m	the Young's modulus of the substrate plate
E_p	the Young's modulus of the PZT
l_p	length the PZT beam
w_p	width of the PZT beam
F	applied force

Here, the applied force F is from the combination of sinusoidal vibration and the repulsive magnetic force. Therefore, the output power P_{out} can be calculated as a function of the open-circuit voltage V_g and the equivalent impedance R_s of the PZT beam [40]. The output power P_{out} is given as

$$P_{out} = \frac{V_g^2}{4R_s} \tag{16}$$

where the equivalent impedance R_s is defined as

$$R_s = \frac{1}{\omega C_p} \tag{17}$$

where C_p is the equivalent capacitance of PZT beam, and ω is the angular frequency. Since the PZT is a dielectric material, the equivalent capacitance of C_p can be calculated as

$$C_p = \frac{\varepsilon_r \varepsilon_0 l_p w_p}{t_p} \tag{18}$$

where ε_r is the relative dielectric coefficient of the piezoelectric element, ε_0 is vacuum dielectric constant and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, l_p, w_p and t_p are the length, width and thickness of PZT beam, respectively.

III. FABRICATION

Based on the design specification, a magnetically levitated PVEH with a composite cantilever beam is fabricated, as shown in Fig. 3. The magnetically levitated PVEH consisted of PZT beam, brass beam, two proof masses, permanent magnets and adjusting screw. Because the primary beam was required to generate the relatively high output voltage as well as hold the whole structure, a commercial piezoelectric plate with the size of $45 \times 39 \times 0.5$ mm^3 was adopted as

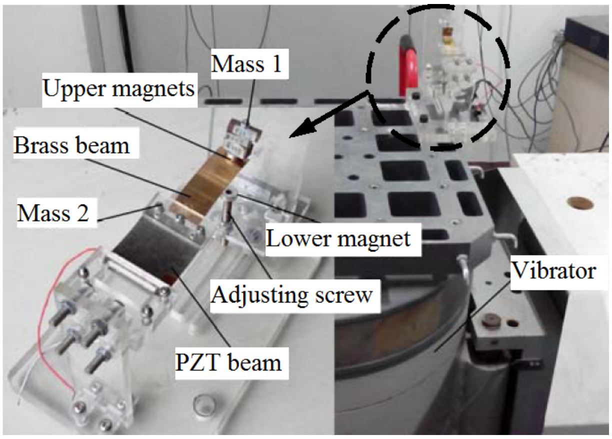

FIGURE 3. Schematic diagram of a magnetically levitated PVEH with a composite cantilever beam.

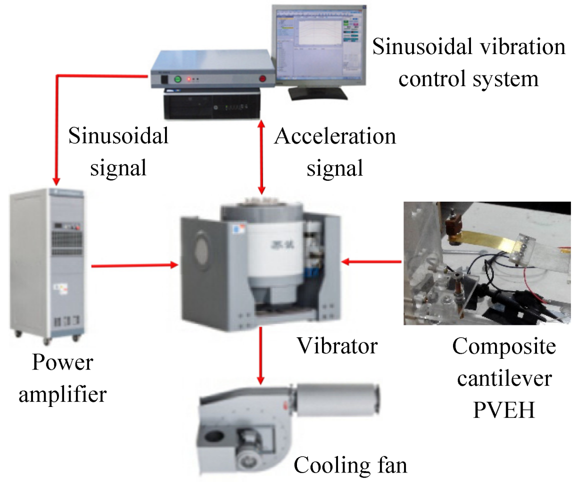

FIGURE 4. Experimental setup.

the primary beam. Nevertheless, this piezoelectric patch was not flat but curved and the calculated curvature radius of the PZT beam was 106 mm. The Young's modulus of the PZT and substrate plate were around 75 GPa and 206 GPa, respectively. The thicknesses of PZT plate and substrate plate were 0.3 mm and 0.2 mm, respectively. A clamping fixture with the weight of 7.20 g was regarded as the proof mass attached to the PZT beam. A brass beam with size of $62 \times 20 \times 0.2$ mm^3, as the secondary beam, was connected to the primary beam via the clamping fixture. The Young's modulus of the brass beam was around 80 GPa. In order to lower the resonance frequency, a tip mass was attached at the free end of the brass beam, namely the free end of the composite cantilever PVEH. The adjustment of the IFLP was accomplished by the repulsive magnetic force. Three same permanent magnets with the size and weight of Ø12×4 mm^3 and 2.37 g were used and arranged as follows: two upper magnets were respectively placed on the top and bottom of free end of brass beam, while another lower magnet was vertically aligned with the upper magnets and mounted on the adjustable screw. The poles of the upper and lower permanent magnets were oriented in the same direction to generate repulsive magnetic force. The total tip mass (including small metal plates on the tip, two permanent magnets and an additional fixture that held the magnets) of the brass beam was 19.66 g.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

To evaluate the influence of the IFLP on the performance of the magnetically levitated PVEH, the testing was performed to compare the dynamic characteristics of the PVEH prototype under different IFLPs. The experimental setup is schematically illustrated in Fig. 4.

The fabricated prototype was mounted on an electrodynamic vibration generator (Type DC-1000-15, Suzhou SUSHI test instrument co., LTD of China). It could achieve a maximum acceleration of 980 m/s^2, a maximum displacement of 51 mm$_{p-p}$, and a maximum velocity of 2.0 m/s with a frequency range of 5-3500 Hz. The sinusoidal excitation signal was generated using a digital sinusoidal/random vibration control system (Type RC-3000-4, SUSHI) and amplified by a switching power amplifier including an excitation power (Type SA-15, SUSHI). In the experiments, the vibration excitation was held constant at a displacement amplitude of 0.5 mm to examine the dynamic response of the magnetically levitated PVEH with a composite cantilever beam.

In fact, the different IFLPs referred roughly to two kinds of conditions, i.e. above and below the horizontal orientation. To distinguish between position ① and ② definitely, the horizontal position of the PVEH cantilever tip needed to be determined firstly. It was observed that when the distance between the lower magnet and upper magnet approached 33 mm through adjusting the screw, the IFLP was in the horizontal position via the repulsive interaction. Then the effect of the IFLP on the performance of the magnetically levitated PVEH in the positions ① and ② was experimentally investigated one after the other. Starting from the horizontal orientation of the IFLP, when the distance was gradually increased from 33 mm to infinite using the adjustable screw, the magnetically levitated PVEH with various IFLPs that were lower than the horizontal orientation was obtained as well as the dynamic characteristics of the magnetically levitated PVEH were tested and compared.

Fig. 5 shows the energy harvesting performance in terms of the output power as a function of the excitation frequency when the IFLP was lower than the horizontal orientation (position ①). In Fig. 5, the symbol of ∞ denotes that the distance of l between the upper magnet and lower magnet is infinite, i.e. the lower magnet is removed. In this situation, the IFLP is only subjected to the gravity and the cantilever tip hangs down freely. As expected, two power peaks were observed for all the response curves. Because the fabricated prototype could be simplified as a 2-DOF system, there would be two natural frequencies for the frequency response. Nevertheless, the effect of the IFLP on two resonance frequencies was different. As seen in Fig. 5, the IFLP had no influence

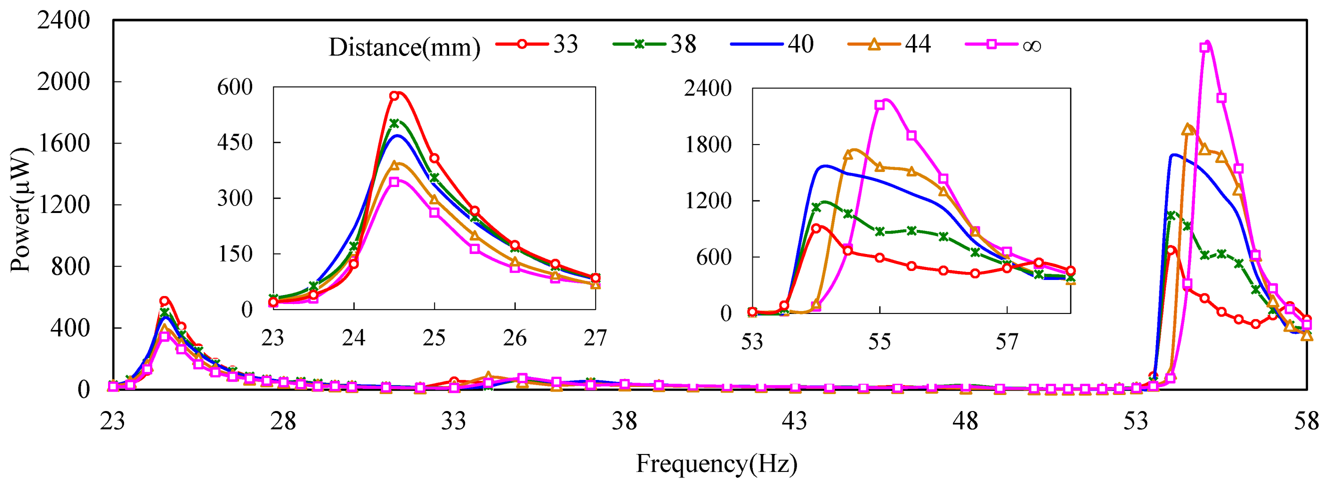

FIGURE 5. The relationship between the power output and excitation frequency when the initial free-end levitation position is lower than the horizontal orientation (position ①).

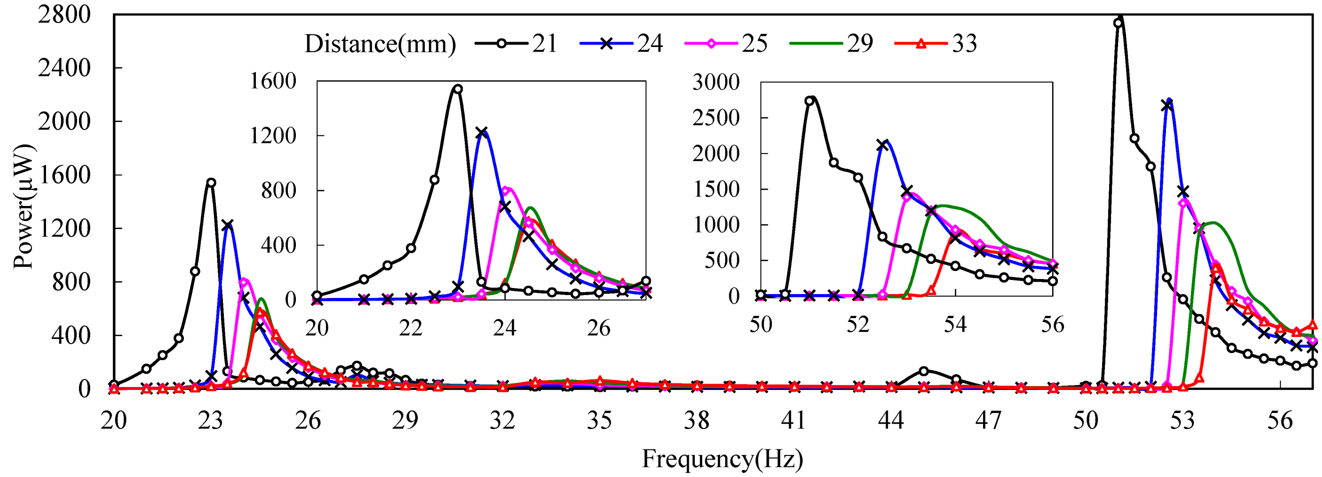

FIGURE 6. The relationship between the power output and excitation frequency when the initial free-end levitation position is higher than the horizontal orientation (position ②).

on the first resonance frequency, where the first resonance frequency was almost not affected and the value of 24.5 Hz stayed constant for all the curves. On the contrary, the IFLP brought a slight influence on the second natural frequency, where it was shifted from 54 to 55 Hz when the IFLP was changed from horizontal orientation to free-hanging state. In addition, Fig. 5 shows that the IFLP has a relatively strong influence on both the peak powers. With the gradual declining of the IFLP, the peak power output decreased from 575.5 to 343.2 μW and was reduced by 40.1% at the first resonance frequency, while the peak power increased from 904.5 to 2220.9 μW and was improved by 145.5% at the second resonance frequency.

Similarly, the magnetically levitated PVEH with various IFLPs that were higher than the horizontal orientation was realized though decreasing the distance between the upper and lower magnets after the IFLP was adjusted to the horizontal orientation using the repulsive magnetic force. Fig. 6 depicts the relationship between the output power and the excitation frequency under different IFLPs for the position ②. On one hand, unlike the IFLP in position ①, not only the second resonance frequency but also the first resonance frequency was affected by the IFLP. With the rising of the IFLP, the first resonance frequency was slightly decreased from 24.5 to 23 Hz, while the second resonance frequency decreased from 54 to 51 Hz. On the other hand, the peak power output was increased with the rising of the IFLP, regardless of the first or second resonance frequency. Specifically, the peak power at the first resonance frequency was increased from 575.5 to 1541 μW and was enhanced by 167.8% when a distance change of 12 mm occurred for the IFLP, while the peak power at the second resonance frequency was increased from 904.5 to 2735.6 μW and was improved by 202.4%. Compared with the second resonance frequency

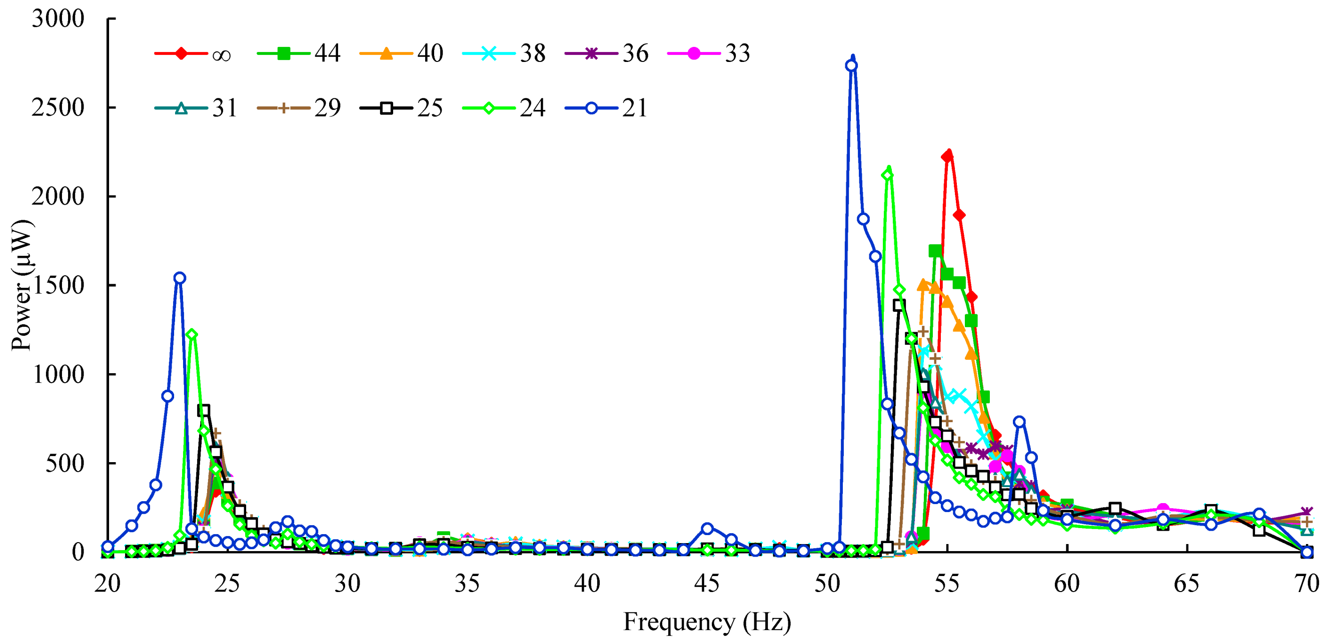

FIGURE 7. **The relationship between the power output and excitation frequency under different initial free-end levitation positions.**

for the position ①, the IFLP in the position ② brought a bit stronger influence on the resonance frequency as well as the power output. Besides, it should be noted that the dynamic characteristics of the fabricated harvester were almost the same after the IFLP was 12 mm higher than the horizontal orientation. It meant there was a limit of the IFLP for the position ②, where a much higher IFLP could not alter the resonance frequency or achieve greater power output.

Roughly, the effect of the IFLP on dynamic characteristics of the magnetically levitated PVEH with a composite cantilever beam could be observed through the frequency response curves in Figs. 5 and 6. To further depict and compare the IFLP effect more clearly, the power output as a function of excitation frequency is demonstrated to figure out the influence trend under various positions ① and ②, as illustrated in Fig. 7. Here, two groups of additional measured data under different positions were also added to exhibit a continuous change of the IFLP, where the data were omitted in Figs. 5 and 6 because their dynamic responses were comparatively similar with those in other positions.

It could obviously be seen from Fig. 7 that the dynamic characteristics of the composite cantilever PVEH were impacted by the IFLP, especially the second resonance frequency. To figure out the performance dependence of a magnetically levitated PVEH with a composite cantilever beam on the IFLP, the relationship between the IFLP and the resonance frequency/power output is directly illustrated based on the testing results of Figs. 5 and 6, as shown in Fig. 8. Here, the distance of l between the lower magnet and upper magnet represents the IFLP as an independent variable, meanwhile, P_{out1}/f_1 and P_{out2}/f_2 denote peak values of the output power and the resonance frequency values at the first and second resonance points, respectively.

Fig. 8 demonstrates the IFLP brings a larger influence on the second resonance point than the first one, regardless of the resonance frequency or the peak power output. Furthermore, no matter which resonance point it was, the resonance frequency was not as influential as the peak power output by the IFLP. As illustrated in Fig. 8, at the first resonance frequency, the peak power output decreases monotonically from 1541 to 343.2 μW with reducing the height of the IFLP. A variation of 1197.8 μW was caused and the rate of change was approximately 349%. The peak power output at highest IFLP became 4.5 times greater than the counterpart at lowest IFLP. At the second resonance frequency, however, the power output showed a quasi-quadratic variation, where the second peak power initially decreased and then constantly increased. Specifically, the power output decreased rapidly from 2735.6 to 904.5 μW until the IFLP approached the horizontal orientation and then started to increase from 904.5 to 2220.9 μW with reducing the height of the IFLP. The maximum power output variation reached 1831.1 μW and the rate of change was approximately 202%. The reason why the power output at the first resonance frequency was monotonically decreased could be that the repulsive magnetic force decreased with reducing the height of the IFLP, as shown in equation (9). As for the power output at the second resonance frequency, when the IFLP was in horizontal orientation, it could be assumed that there was little pre-strain or preloading applied on the PZT beam and the deformation of the PZT beam was minimum. Furthermore, it was found that the frequency variation at the first and second resonance points was 1.5 Hz and 4 Hz as well as the corresponding rate of change approached 6.5% and 7.8%, respectively. It presented a good agreement with the theoretical analysis, as shown in equations (7) and (8). In fact, the stiffness of the PZT beam

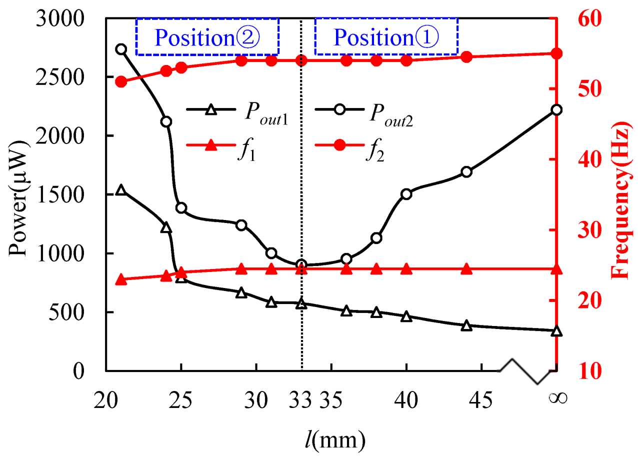

FIGURE 8. The power output and resonance frequency as a function of the initial free-end levitation position.

was impacted by not only the variable magnetic stiffness but also the stiffness tuning of the brass beam. Accordingly, the influence of the IFLP on the second resonance frequency was relatively big. Moreover, since there was a slight fluctuation of the resonance frequency, it indicated that the IFLP had a minor influence on the equivalent stiffness of both primary and secondary beams, compared with the IFLP effect on the power output. In addition, the distance between the first and second resonance frequencies was varied from 30.5 to 28 Hz with the rising of the IFLP. It meant it was beneficial to gain two closer resonance frequencies when the IFLP influence was effectively utilized.

V. CONCLUSIONS

In this paper, the effect of the IFLP on the performance of a magnetically levitated PVEH with a composite cantilever beam is presented. It demonstrated a strong dependence of the dynamic characteristics on the initial free-end levitation for the composite cantilever PVEH. Three principal conclusions were drawn through the theoretical analysis and experimental results. Firstly, the IFLP had a stronger impact on the performance when it was above the horizontal orientation than below the horizontal orientation. Specifically, the first and second resonance frequencies were respectively varied from 24.5 to 23 Hz and from 54 to 51 Hz for the former, while it was kept constant and shifted from 54 to 55 Hz for the latter, respectively. The peak power output at the first and second resonance points was respectively varied from 575.5 to 1541 μW and from 904.5 to 2735.6 μW for the former, while it was varied from 575.5 to 343.2 μW and from 904.5 to 2220.9 μW for the latter, respectively. Secondly, the IFLP brought a more significant influence on the second resonance frequency than the first one. The frequency fluctuation at second resonance point was 4 Hz, while it was only 1.5 Hz at the first resonance point. The peak power output at second resonance point presented a quadratic variation and a maximum power difference of 1831.1 μW was achieved, while it decreased monotonically and a power variation of 1197.8 μW occurred at the first resonance point. Thirdly, the IFLP had a larger effect on the power output than the resonance frequency. At the first and second resonance points, the change rate of the power output respectively reached 349% and 202%, while the change rate of the resonance frequency was approximately 6.5% and 7.8%, respectively. In a word, it is evident that the performance of the composite cantilever PVEH is varied with different IFLPs. The IFLP impact should be taken into consideration when some researches are related to a magnetically levitated PVEH with one and even multiple composite cantilever beams.

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