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ABSTRACT

This paper has proposed a vibration energy harvester (VEH) with double frequency-up conversion (FUC) mechanism which can be applied to harvest energy from vibrations at ultra-low frequency. The device can initially up-convert the external vibrations with sub-Hertz into tens of Hertz, and further convert to hundreds of Hertz by the second FUC mechanism, which gives a high conversion ratio of 8400. A comprehensive dynamic model has been proposed and verified both from the theoretical analysis and COMSOL simulation to analyze the frequency conversion process and output voltage. When excited by a frequency of 0.2 Hz, an average output power of 75 μW could be obtained with a compact size. Benefiting from the non-contact design, the device could be applied in some sealed scenarios for smart city construction. Herein, a wireless humid-temperature sensor node in the pipeline was successfully powered by harvesting energy from humans walking with the proposed VEH, showing promising application prospects.

1. Introduction

Due to the fast-growing population and rapid development of urbanization, cities are getting much more enormous and complex than ever. To guarantee people’s daily routines and productions, even the underground space is fully utilized for pipeline and metro construction. Equipping wireless sensor networks to monitor their operating conditions has been proposed as an effective method to construct the smart city [1–4]. However, the energy source is still one of the major limitations preventing its large-scale application. Cell batteries as the standard choice for power supply are hard to satisfy in the underground environment for the requirement of periodic maintenance. Also, solar and wind energy are infeasible under this circumstance. On the other hand, the city has numerous vibration sources due to human activities, such as human motion and vibrations of buildings and vehicles. Therefore, the power supply problem could be solved once the kinetic energy from the vibrations can be efficiently harnessed.

Vibration energy harvesting (VEH) technology is such kind of technology that can harvest energy from vibrations from the ambient environment and convert it into electricity with electromagnetic [5–9], electrostatic [10–15], triboelectric [16–21], and piezoelectric [22–27] transduction mechanisms. With the application of VEH, more sensor nodes could be applied in the smart city for environment monitoring; for example, the health condition of infrastructure, the air quality indoor or outdoor could be detected efficiently with self-powered systems. Furthermore, the VEH could also provide power for the sensors in the underground pipes and sealed scenarios in the city, where regular maintenance is hard to access.

However, most previous-reported VEH were designed and fabricated based on the resonant structure, which can only operate within a specific frequency. Moreover, the theoretical maximum output power of the VEH with a resonant structure is proportional to the $\omega^3$, where $\omega$ is the

Abbreviations: VEH, Vibration Energy Harvester; FUC, Frequency-up Conversion; PZT, Pb-based Lanthanum doped Zirconate Titanates.

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resonant frequency and n is generally assumed to be 3 according to either the CDRG model or the VDRG model [28,29]. Most of the vibration sources in the city, however, exhibit distributed frequencies at a low frequency [29]. The mismatch between the vibration sources in the city and the resonant VEHs would lead to a poor energy conversion efficiency, which is not qualified to provide enough power for a wireless sensor network.

To address this issue, increased research efforts have contributed to developing possible approaches. Among VEHs, there are mainly two kinds of strategies. For energy harvesters with resonant structures, frequency-up conversion technology based on two oscillators is widely used. A low-frequency oscillator is applied to absorb the energy from external vibration at low frequency and then stimulate the high-frequency oscillator, either by mechanical or magnetic coupling. Afterward, the high-frequency oscillator can vibrate at its resonant frequency and generate electricity. For example, Dhakar et al. [30] reported a piezoelectric energy harvester comprised of a pure piezoelectric bimorph with a high resonant frequency and a piezoelectric beam with a polyvinylidene fluoride (PVDF) film with a low resonant frequency. The composite cantilever design enables the device to convert the input frequency from 36 Hz to 275 Hz with a bandwidth of 16.4 Hz. Halim et al. [31] presented an impact frequency up-converted piezoelectric energy harvester in which two high-frequency piezoelectric beams are plucked simultaneously by a low-frequency oscillating beam. The energy conversion efficiency was increased to approximately 85%. Fan et al. [32] fabricated a piezoelectric energy harvester based on the magnetic coupling between the beam and a roller which can scavenge energy from sway and vibration. The external vibration could be up-converted from 0.6 Hz to 32 Hz, and a maximum voltage of 13 V could be achieved with this approach.

Apart from the resonant structure, a few energy harvesters with the non-resonant structure were recently adopted to harvest energy from vibrations at low frequencies. Some of them used the eccentric wheel [33,34] or the moving mass structure [35,36] to directly couple with the swing motion at low frequency. Wang et al. [37] have demonstrated a fully enclosed TENG which generates electricity by the surface contact electrification effect between the inside rolling Nylon ball and the spherical shell with Kapton film. It could provide a peak current of 1 μA and instantaneous output power of 10 mW. Some of them applied the gear-driving [38,39], twist-driving [40], string-driving [41], and cantilever-driving [42] methods to achieve both the FUC and the conversion from vibration to rotation. Fan et al. [43] have designed a string-driven rotor consisting of a rotor with a shaft, an inelastic string to drive the rotor, and an elastic string as the restoring system. When the string-driven rotor was driven by human pulling motion at approximately 4 Hz, the energy harvester could provide up to 6.5 mW power. Besides, there are also some approaches based on the origami-based structure [44–46] and the drop-lip structure [17,47].

However, the frequency conversion rate is still low for all of the above-mentioned approaches which limits the output power and application scenarios. In addition, most of the reported energy harvesters, their kinetic energy harvesting part and electricity generation part are embedded together, which may not be suitable for some sealed scenarios in the city, such as the sealed pipeline. This paper proposes a double frequency-up conversion mechanism that combines the twist-driving method for non-resonant structure and the magnetic plucking method for resonant structure. With the combination of these two methods, the vertical linear motion at sub-Hertz in an ambient environment is firstly up-converted to tens of Hertz and further driven to hundreds of Hertz, which is suitable for vibrations at ultra-low frequency. Besides, benefiting from the non-contact design, the device can be divided into the kinetic energy gathering part at the first FUC and the electrical energy generation part at the second part, which could hopefully be applied in some sealed scenarios for smart city construction as demonstrated in Fig. 1A.

Following the introduction, we have initially introduced the schematic of the proposed device. The working principle of the double FUC is also illustrated. Secondly, to better analyze the frequency conversion process of this mechanism, a comprehensive dynamic model has been proposed and verified both from the theoretical calculation and the COMSOL simulation, where the calculation results and the simulation results show good agreement with each other. The output voltage of the device has also been predicted based on the dynamic model. Subsequently, the effectiveness of the double FUC mechanism is verified both from the video taken by the high-speed camera and the output voltage waveform of the device. Afterward, a series of energy harvesters based on the proposed double FUC mechanism with different design parameters have been designed and fabricated. The effects of design parameters and vibration properties have been investigated and discussed in detail. Finally, potential applications of this energy harvester on wireless sensor nodes in the pipeline have been demonstrated, showing promising application prospects in the smart city with sealed scenarios.

2. Schematic and working principle of the proposed device

The proposed energy harvester with a double frequency-up conversion mechanism is demonstrated in Fig. 1B, where the system is composed mainly of two components, including the inertial rotary structure as the first frequency-up conversion (FUC) part and a Pb-based Lanthanum doped Zirconate Titanates (PZT) beam as the second FUC component.

The first FUC part is used to directly collect vibrations from human motion, consisting of two sub-structures: twist-driving structure and inertial rotor structure. The twist-driving structure could scavenge the kinetic energy and convert the linear motion to high-speed rotation during human compression, achieving the first FUC. Among this structure, a lid is applied to bear and collect the compression into the system. The movement direction of the lid is constrained by four guide rails and restored by the tower-shaped spring. A rotating disk is held in the bearing and fits together with the twist-rod.

The inertial rotor structure works as an energy storage component. It can store the kinetic energy as the high-speed rotation of the rotor and release it gradually, which could further decrease the requirement of the input frequency. This structure mainly includes a rotor held by another bearing with ratchet construction. A chock is fixed together with the circular disk mentioned in the twist-driving structure, and two paddles are symmetrically mounted on the chock, which can swing flexibly. The pair of ratchet and pawl act as a very flexible one-way bearing. It can drive the rotor upon external impact applied to the device but keep it rotating inertially during the interval between two impacts. Besides, several magnets are evenly distributed on the circumference of the rotor for magnetic coupling.

The second FUC component behaves much more straightforwardly than the first FUC part. It only consists of a PZT beam with a small magnet as the proof mass mounted at its free end. The resonant frequency of the PZT beam could be influenced by the mass of magnet [28,48]. A thick PZT-S layer is deposited on the stainless-steel substrate (bottom electrode), and the silver paste is coated on the PZT as another electrode. The PZT beam is clamped in a holder and vertically aligned to the rotor, exhibiting the resonant frequency at hundreds of Hertz. The photograph of a typical fabricated device is also illustrated in Fig. 1B. It should be noted that only one PZT was applied in this design to illustrate this mechanism and investigate different influences. However, multi PZT beams could be adopted in the actual application and compose the PZT array circumferentially to promote the output power and energy conversion efficiency. Except for the component manufactured of steel which should endure a large impact, the frame structures of the device are fabricated with Acrylic and UV curable resin by laser cutting and 3D printing technology for a fast prototype. The detailed design parameters of the device are listed in Table 1.

The working principle of the proposed double FUC mechanism is illustrated in Fig. 1C. When applying low-frequency vibrations, the twist-rod can be driven downwards, which would further rotate the
Fig. 1. Smart city with proposed VEH and double frequency-up conversion mechanism. (A) Harvesting energy from vibrations in the city can be a possible method for providing stable power resources for wireless sensor nodes in an underground environment. (B) 3D schematic of the proposed double frequency-up conversion energy harvester, where the device is composed of the first FUC inertial rotary structure and a PZT beam. (C) The principle of the double frequency-up conversion process.
pawls due to the double helix structure. Afterward, the two pawls mesh with the ratchet on the rotor and expedite the rotor and magnets on it up to a high-speed rotation according to the Catch-driving model [29]. Besides, when the external compression is released from the device, the twist-rod would be lifted by the spring and restored to its initial position while the two pawls rotate reversely without obstructing the rotation of the rotor. With this process, the vibrations in the ambient environment at sub-Hertz could be firstly up-converted to the rotation of the rotor with tens of Hertz, and the conversion ratio is mainly dependent on the angle of the twist-rod. Next, the rotation of magnets on the rotor would periodically pluck the magnet on PZT due to the magnetically coupling, which stimulates the vibration of PZT at its natural frequency. Meanwhile, the PZT would vibrate as damped oscillation due to the electrical and mechanical damping. Consequently, the rotation of the rotor with tens of Hertz is again up-converted to the natural frequency of PZT with hundreds of Hertz, whereas the kinetic energy could be harvested to electricity due to the piezoelectric effect.

3. Theoretical analysis and modeling

To further analyze the dynamical model and the output performance of the VEH with the double FUC mechanism, the magnetic coupling force between magnets should be firstly calculated. Akoun and Yonnet [49] have proposed a theoretical model to calculate the magnetic coupling force between two cuboidal magnets with parallel magnetization directions. However, the model does not apply in our case because the magnetization directions of the magnets fixed on the inertial rotor change continuously during rotation. Therefore, this work proposes a novel theoretical model to calculate the magnetic coupling force in the VEH.

In the theoretical model, as illustrated in Fig. 2A, the cuboidal magnet is approximately modeled as a square loop current. Fig. 2B is the cross-section of the square loop current, in which the point and cross represent the outward and inward current perpendicular to the paper surface, respectively. Through integrating the Biot-Savart law, which is introduced in Supplementary Text S1, the magnetic flux density \( |B_c| \) at any point \( P \) in space produced by a section of current, as demonstrated in Fig. 2C, can be given as

\[
|B| = \frac{\mu_0 I}{4\pi r'} \left( \cos \theta_1 - \cos \theta_2 \right)
\]  

(1)

Therefore, the magnetic flux density \( |B_c| \) on the center of the square loop current can be calculated below.

\[
|B_c| = \frac{4\mu_0 I_s}{4\pi (l_m/2)} \left( \cos \frac{\pi}{4} - \cos \frac{3\pi}{4} \right) = 2\sqrt{2}\mu_0 I_s \frac{l_m}{\pi}
\]

(2)

Typically, the relationship between magnetization \( M \) and magnetic flux density \( B \) is given as \( B = \mu_0 (H + M) \), in which \( H \) is the magnetic field intensity. Here, \( H = 0 \) and the equation can be written as \( B = \mu_0 M \). Then, substituting \( \mu_0 \) into it, the current magnitude \( I_s \) of the square loop

Fig. 2. The analysis of magnetic coupling force between magnets in the proposed energy harvester. (A) Model the cuboidal permanent magnet as a square loop current. (B) The cross-section of the square loop current. (C) Magnetic flux density is produced by a section of current. (D) Magnetic coupling force between two sections of current with each other. (E) The 3D view and the top view of the double FUC structure after replacing magnets with corresponding equivalent square loop currents. (F) The theoretical and simulation results of magnetic coupling forces applied to the magnet \( M_1 \) in the \( x \) direction. (G) The theoretical and simulation results of magnetic coupling forces applied to the magnet \( M_1 \) in the \( y \) direction.
current can be obtained as
\[ I_s = \frac{\xi \mu_0 M_0}{\sqrt{2}} \]  
(3)

where \( M_0 \) is the magnetization of the cuboidal permanent magnet. In this model, the cuboidal permanent magnet is considered as a square loop current. However, this approximate modeling is not perfectly accurate and an empirical coefficient needs to be introduced to correct the calculation results. Therefore, \( \xi \) as an empirical coefficient is introduced in the Eq. (3), which takes the value of 0.34.

According to the ampere force law, the magnetic force on a unit current element in the magnetic field can be obtained by substitution Eq. (1) into it and integrating it. The magnetic current element in the magnetic field can be obtained by calculation results. Therefore, \( I_s \) as an empirical coefficient is introduced in the Eq. (3), which takes the value of 0.34.

Then, Substituting Eq. (1) into it and integrating it, the magnetic coupling force in the x direction achieves two opposite maximum values at the rotation angle \( \theta \) of about 80° and 100°. Fig. 2G displays the theoretical and simulation results of magnetic coupling forces applied to the magnet \( M_1 \) in the y direction. There is a sudden change of the magnetic coupling force in the y direction in the range from 70° to 110° of rotation angle \( \theta \) and the peak value can be obtained at the rotation angle \( \theta \) of 90°. Under different distances between magnets on the rotor and PZT cantilever, the theoretical calculation results and the COMSOL simulation results of the magnetic coupling force applied to the magnet \( M_1 \) in the y direction are exhibited in Supplementary Fig. S1A.

Furthermore, supplementary Fig. S1B shows the relationship between magnetic coupling force and magnet spacing. As the figure shows, the magnetic coupling force decreases with the distance between magnets. Through comparison, we can see that calculation results from our theoretical model are in good agreement with simulation results, which confirms that our theoretical model has excellent accuracy. What’s more, the magnetic flux density of magnet \( M_2 \) under the different distances is also measured, as illustrated in Supplementary Fig. S1C. With the gap distance increased from 3 mm to 5 mm, the magnetic flux density generated by the magnet \( M_2 \) was decreased from 330 Gs to 210 Gs, which indicates that the magnetic plucking force to PZT cantilever would decrease with the magnet spacing. As the magnetic plucking force decreases, the deformation of the PZT cantilever also decreases, which further diminishes the output performance of the device.

To further characterize the dynamical behavior and output performance, the cantilever deformation and the voltage output of the PZT material under periodic plucking of magnetic coupling force also need to be analyzed. An accurate theoretical model using a distributed-parameter method proposed by Erturk and Inman [50] could be applied to analyze dynamical behaviors and electromechanical characteristics of a piezoelectric cantilever. In our paper, adaptation has been made for the VEH with the double FUC mechanism. The magnetic coupling force \( F_c \) applied to the magnet \( M_1 \) in the y direction is regarded as an external force applied at the free end of the PZT piezoelectric cantilever. In addition, the magnet on the PZT piezoelectric cantilever is considered a proof mass. Fig. 3A illustrates the schematic diagram of the PZT piezoelectric cantilever with a series connection of PZT layers, and Fig. 3B exhibits its cross-sectional view.

Then, the coupled electromechanical equation of the PZT piezoelectric cantilever under external excitation of magnetic coupling force can be expressed as

\[
\begin{align*}
Y_1 & \frac{\partial^2 w(x,t)}{\partial x^2} + c_f I \frac{\partial w(x,t)}{\partial t} + c_c \frac{\partial w(x,t)}{\partial t} + [m + \rho \delta(x - L)] \frac{\partial^2 w(x,t)}{\partial t^2} \\
\frac{\partial V(t)}{\partial t} & \text{with} \quad V(t) = \frac{1}{2} \frac{\partial^2 w(x,t)}{\partial x^2} dx = 0
\end{align*}
\]  
(6)

where \( Y_1 \) is the modulus of the cantilever, \( c_f \) is the damping coefficient, \( c_c \) is the internal damping coefficient, \( c_c \) is the air damping coefficient, \( m \) is the mass per unit length of the piezoelectric cantilever, \( M \) is the mass of magnet \( M_1 \), \( \delta \) is the piezoelectric coupling term, \( V(t) \) is the voltage across an external resistive load \( R_0 \). \( \delta(x) \) is Dirac delta function, \( H(x) \) is Heaviside function, \( F_c(t) \) is the magnetic coupling force applied to the magnet \( M_1 \) in the y direction. \( C_p \) is the inherent capacitance of a PZT layer, \( c_{31} \) is the piezoelectric constant of PZT, \( L \) is the length of the cantilever, \( W \) is the width of the cantilever, and \( \theta \) is the rotation angle of the inertial rotor, the magnetic coupling force will continuously and periodically pluck the PZT piezoelectric cantilever.
When the number of magnets on the inertial rotor is one, according to our proposed theoretical model, Fig. 3C exhibits the waveform of the external excitation and the magnetic coupling force $F_y(t)$ under a periodic ultra-low frequency external excitation, which displays the whole process of double FUC. In the first FUC, the external excitation in sub-Hertz is up-converted into the periodic magnetic plucking force with tens of Hertz. Then, the magnetic plucking force is up-converted into the free vibration of the PZT cantilever with hundreds of Hertz to complete the second FUC.

3.1. Experimental validation

The double FUC mechanism corresponding to Fig. 3C could be verified through experimental tests, as shown in Fig. 3D. In this experiment, an external excitation with the ultra-low frequency of 0.1 Hz was applied to the device, and its open-circuit voltage was measured by a voltmeter. The detailed measurement setup is depicted in Supplementary Text S2. From the test results, we can see that the envelope of the curve witnessed a gradual diminution within one period. This phenomenon could be explained as the decayed vibration amplitude of PZT when stimulated by a slower inertial rotation speed of the magnet and rotor. Meanwhile, when we zoom in on this figure, it could also be noticed that the macroscopical attenuation curve is composed of many small curves. The interval of 0.042 s of two small curves means the rotation frequency of the rotor was firstly up-converted to 24 Hz after the acceleration (when there is only 1 magnet on the rotor). Moreover, the free vibration of PZT after the second frequency-up conversion could be observed when we further zoom in on this curve. Herein, the device maintained energy conversion and damping oscillated at its natural frequency of 420 Hz.

Furthermore, with the aid of a high-speed camera, the double FUC mechanism could also be visually observed. Fig. 4A and Supplementary Video S1 demonstrate the vibration of the PZT beam at one period. It could be noticed that the PZT was attracted and disengaged from its free position with the approach of a magnet on the rotor. After the rotor turns away to another side, the PZT beam would keep vibrating freely due to the diminished electromagnetic force until the next magnet rotates and approaches.

To further exhibit the effectiveness of the proposed double FUC mechanism, we have also compared the open-circuit output voltage of PZT after 0, 1, and 2 times FUC when driven by excitation with ultra-low frequency as depicted in Fig. 4B where the x-axis shows the frequency-up conversion modes. When the PZT was mounted on the shaker with 0.1 Hz sinusoidal wave excitation (0-time FUC), we can hardly harvest energy from the vibration. While when the PZT was magnetically plucked by an up-down reciprocated magnet with 0.1 Hz, namely, the regular frequency-up conversion scheme (1-time FUC), the output voltage witnessed a sharp curve which means only a few power could be harvested. However, with the proposed double FUC approach, the energy harvester can still generate decent power even driven by vibration at ultra-low frequency. The output energy through these methods are almost 0 J (0 time), $2.25 \times 10^{-9}$ J (1 time), and $3 \times 10^{-6}$ J (2 times), respectively. The effectiveness of the proposed double FUC mechanism could be proved through this experiment. Readers could refer to the detailed output voltage waveform with different FUC mechanisms in Supplementary Fig. S2.

In addition, a series of energy harvesters were fabricated to investigate the influence of device design parameters. We have first
investigated the optimal load resistance of the individual PZT and its resonant resistance on a shaker, as shown in Supplementary Fig. S3. In this design, the resonant frequency of PZT in this device varies from 400 to 600 Hz depending on the clamped position. It could be noticed that, for a typical PZT, with an optimal load of about 0.065 MΩ, maximum RMS power of about 6.5 μW was harvested at the resonant frequency of 545 Hz from the vibration with the RMS amplitude of 5 m/s². Therefore, unless otherwise noted, the external load resistance was fixed to 0.065 MΩ in the following experiments.

Besides, in this design, the PZT beam is vertically aligned to the rotor while other installation methods were also discussed in Supplementary Fig. S4. Due to the circular shape of the pipe, minimum gap distances could be achieved when the PZT beam is vertically installed. Experimental results prove that the vertical-aligned device exhibits a better magnetic coupling effect than other methods.

Fig. 4C illustrates the effect of magnet number on the rotor. The output power and voltage were measured with the number of the magnets increased from 1, 2, 4, and 8 while keeping the excitation frequency unchanged at 0.1 Hz. The odd number of magnets was avoided to prevent the rotor’s eccentric rotation. When the number of the magnets on the rotor increased from 1 to 4, it should be observed that the output voltage was increased, as more frequent second FUC plucking could cause a larger deformation of the PZT cantilever beam. Meanwhile, the average output power of the device was also increased. It is because the increase of the magnet number can contribute to more energy converted from the kinetic energy of the rotor to electrical power in each cycle. Consequently, less energy was lost on friction, leading to larger output power.

However, the output power cannot be unlimitedly promoted. The output voltage and the output power curves show a sudden drop when the number of magnets on the rotor increases to 8. This could be explained from two aspects. On the one hand, the magnetic coupling force is influenced. Supplementary Fig. S5 exhibits the effect of the number of magnets on magnetic coupling force. When the number of magnets is 2 or 4, the peak value of the overall magnetic coupling force is hardly affected and is close to the number of magnets of 1. However, when the number of magnets increases to 8, due to the interaction of multiple magnetic coupling forces from densely distributed magnets, the overall magnetic coupling force will have two opposite peaks with similar magnitude, and the magnitude of the peak will also be diminished. On the other hand, with the increase in the number of magnets, the time interval between peaks decreases rapidly, which causes the PZT...
cantilever to be plucked by the next peak of magnetic coupling force in the opposite direction before the end of free vibration. As demonstrated in Fig. 4D-F. When the magnets are increased from 1 to 2, the vibration of PZT would gradually stop with the decreased interval of plucking. Meanwhile, the vibration of PZT could still stop when the magnet is 4, although the plucking interval becomes insignificant. However, when the magnets are increased to 8, the output voltage waveform exhibits chaos due to the interference, which would also weaken the output power.

Hence, considering the output power and demand of a more clearly plucking interval for experimental analysis, 2 magnets are installed on the device for later evaluation.

3.2. Effects of vibration properties

Based on the above-mentioned design, two components of the device were installed individually to mimic the potential applications in the sealed scenario. As demonstrated in Fig. 5A, the first FUC inertial rotation part was applied to collect energy from motions at an ultra-low frequency, such as human walking, while the second PZT component was fixed inside the pipeline for energy conversion. During the measurement, the device was mounted on a creak-slider measurement, and a periodic compression was applied on the first FUC part to mimic the vibrations. By varying the distance of magnets between rotor and PZT, and compression profiles (velocity and frequency) of the slider, the working performance of the proposed energy harvester under different working environments could be precisely evaluated. Detailed

Fig. 5. Measurement results of the proposed device. (A) Effect of the magnet distance between the rotor and the PZT. (B) The output voltage waveform of PZT with various magnet distances and different excitation frequencies. (C) Effect of the externally driven frequency at different distances. (D) Effect of external compressing velocity. (E), (F) the output voltage waveform of the device when driven by different compressing velocities in (D).
description on the measurement method is described in Supplementary Test S2.

Fig. 5A illustrates the effect of the gap distance between the rotor and the PZT beam, which could be precisely controlled by an X-Y moving stage at the excitation frequency of 0.2 Hz. With the increase of gap distance, the energy converted to PZT in each plucking cycle would decrease due to a weaker magnetic coupling force as analyzed above. Hence, the maximum output voltage and peak output power also decreased.

The output voltage waveform of the device is listed in Fig. 5B with different excitation frequencies at a gap distance of 3 mm and 5 mm, respectively. With the increase in gap distance, the rotor can rotate longer because of the smaller magnetic coupling force, which means more energy is wasted on the friction. Moreover, when we zoom in on the voltage waveform at a distance of 3 mm in Supplementary Fig. S6, it should also be noticed that the output voltage would almost not be affected by the varying external excitation frequency. This phenomenon proves that the proposed device could keep harvesting energy from 0.05 Hz to 0.5 Hz. Although the proposed device exhibits a good energy harvesting performance for the random frequency spectrum, the increase of excitation frequency could affect the maximum output voltage of the device in some circumstances. According to Fig. 5B, the maximum output voltage at 0.2 Hz is clearly smaller than the other two curves, and it is particularly apparent at the gap distance of 5 mm. To explain this phenomenon, a catch-driving model for a ratchet-pawl clutching system should be introduced in Supplementary Text S3, which was proposed by Luo et al. [29]. Based on this model, the whole acceleration time is fixed with a certain compressing velocity. If the rotor retains a rotation speed before the acceleration, the pawl should first spend some acceleration time to catch up with the rotor and then accelerate it, as demonstrated in Supplementary Fig. S7A. This would lead to a lower rotation speed of the rotor after acceleration. Therefore, the maximum output voltage would decrease with the increase of excitation frequency, as described in Supplementary Fig. S7B-C.

Fig. 5C reported the effect of gap distance and excitation frequency for RMS output power. The experiment results exhibit a totally country conclusion. With the gap distance D=3 mm, the strong magnetic coupling force can immediately stop the rotor rotation, as shown in Supplementary Fig. S8. An increased excitation frequency could contribute to the greater output power due to more frequent input energy. A maximum RMS output power of 75 μW could be acquired when driven by the vibration frequency of 0.2 Hz. However, when the gap distance is increased to D=5 mm, it is very interesting that the output power of the device is almost getting close. This could be explained based on the rivalry between the decreased output voltage and the increased energy input frequency. Because of the small magnetic coupling force, the rotor could rotate for a relatively long time more than 15 s. Although a more frequent excitation may increase the energy harvester system’s input kinetic energy frequency, it would also rather decrease the maximum rotation speed of the rotor (output voltage) due to the catch-driving model. It could also be noticed that under a fixed excitation frequency, the average output power is decrease with the increase of gap distance. This phenomenon could be explained as weaker magnetic coupling effect on the PZT beam and more energy lost on the friction of the device. The maximum output voltage of the device is described in Supplementary Fig. S9. Conversely, with the increase in excitation frequency, the harvester system could not fully scavenge the kinetic energy, which leads to a non-growth of average output power under this circumstance.

We have also studied the effect of external compressing velocity in Fig. 5D. It could be noticed that the output power could be positively influenced by the increase of compressing velocity due to the increased plucking speed, which could be observed in Fig. 5E-F, where the interval between two peaks gradually becomes smaller with the increase of compressing velocity. The RMS output power and maximum output voltage are illustrated in Supplementary Fig. S10. A maximum RMS output power of 54 μW could be harvested when the device with a gap distance of 4 mm was driven by the average compression velocity of 197.5 mm/s at an ultra-low frequency of 0.5 Hz. As a consequence, the decent output power of the device guarantees promising application in self-powered electronic devices.

3.3. Application demonstrations

The possible applications of the proposed energy harvester with the double FUC mechanism have also been demonstrated in Fig. 6. As depicted in Fig. 6A, the device was firstly applied to harvest energy from human walking and provide power for a LED lamp. Supplementary Text S4 and Supplementary Video S2 demonstrate this application experiment. Initially, because of the mismatched frequency, the LED lamp could not be lighted up when driven by a continuous compression directly on the pipeline (0-time FUC). However, when we used the proposed double FUC mechanism, the LED lamp could be powered after 38 s charging with 4 footsteps, as shown in Fig. 6B. It should also be noticed that the light was still visible during the interval of vibration, which proves the continuous energy output ability of the device.

Furthermore, benefiting from the decent output power of the energy harvester, the energy harvester could also be applied to provide power for the wireless sensor node in the pipeline to avoid its battery maintenance. Herein, as schemed in Fig. 6C, a humid&temperature sensor was adopted to monitor the environmental conditions in the pipeline. A power management system and an MCU with a wireless transmitter were used to manage the energy and transmit the wireless signal. Upon collecting enough energy, the power management system would release it to the sensor and MCU. Afterward, the sensing information was acquired and uploaded to the cloud, which could be remotely monitored on the mobile phone. Fig. 6D and Supplementary Video S3 show the function algorithm for the event-driven wireless sensing system. It could be observed from Fig. 6F that the system can gather the environment information every 3 min with tens-of footsteps.

4. Discussion

This paper presented a double FUC mechanism that could be adopted in VEH for ultra-low frequency vibrations energy harvesting. The device comprises an inertial rotary structure as the first FUC mechanism and a PZT beam as the second FUC component. With a twist-driving and ratchet-clutch structure, the vertical linear motion at sub-Hertz in an ambient environment is firstly up-converted to the rotor’s rotation at tens of Hertz and keeps rotating inertially during the interval of two excitations. Afterward, owing to the magnetic coupling between the magnets on the rotor and the PZT beam, the PZT beam could be further driven to vibrate at its natural frequency of hundreds of Hertz. A comparison between the proposed device and the state-of-the-art energy harvester with frequency-up conversion mechanism is given in Tables 1 and 2. Thanks to the high frequency conversion ratio of 8400, the device could harvest kinetic energy efficiently and generate decent power even for the vibration scenarios at sub-Hertz. The frequency conversion process was successfully verified from the experiment. Besides, a comprehensive dynamic model has also been proposed to analyze this process both from the theoretical calculation and the COMSOL simulation, where the calculation results and the simulation results show good agreement. Moreover, the output voltage of the proposed device could also be predicted based on the theoretical analysis. The effects of the number of magnets on the rotor, gap distance of magnets between rotor and PZT, excitation frequency, and compressing velocity have been investigated in detail. When excited by a continuous compression at an ultra-low frequency of 0.2 Hz, an average output power of 75 μW could be obtained with a compact size. Finally, benefit from the non-contact design, the proposed energy harvester could harvest energy from nearby human walking and provide power for wireless humid-
Teaser

A vibration energy harvester with double frequency-up conversion mechanism for kinetic energy harvesting at ultra-low frequency.

CRediT authorship contribution statement

**Anxin Luo**: Conceptualization, Methodology, Formal analysis, Writing – original draft, Funding acquisition, **Weihan Xu**: Methodology, Software, Formal analysis, Writing – original draft, **Jiangyong Sun**: Investigation, Data curation, **Kunling Xi**: Investigation, Data curation, **Siya Tang**: Visualization, **Xinge Guo**: Writing – review & editing, **Chengkuo Lee**: Writing – review & editing, Supervision, **Fei Wang**: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

**Table 1** Parameters. Parameters of the energy harvester with double frequency-up conversion mechanism.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$ (cm$^3$)</td>
<td>Volume of the first FUC structure</td>
<td>3.5 × 3.5 × 3.5</td>
</tr>
<tr>
<td>$V_2$ (mm$^3$)</td>
<td>Volume of the PZT beam without magnet</td>
<td>14.5 × 3.5 × 0.25</td>
</tr>
<tr>
<td>$M_{Mag1}$ (g)</td>
<td>Mass of the magnet on rotor</td>
<td>0.37</td>
</tr>
<tr>
<td>$V_{Mag1}$ (mm$^3$)</td>
<td>Volume of the magnet on PZT</td>
<td>3 × 3 × 2</td>
</tr>
<tr>
<td>$M_{Mag2}$ (g)</td>
<td>Mass of the magnet on PZT</td>
<td>0.13</td>
</tr>
<tr>
<td>$R_{Load}$ (MΩ)</td>
<td>Matched resistance of the PZT</td>
<td>0.065</td>
</tr>
<tr>
<td>$V$ (mm/s)</td>
<td>Average compressing velocity of slider</td>
<td>158</td>
</tr>
</tbody>
</table>

temperature sensor node in the pipeline, showing broad application scenarios in smart city construction.
Table 2
Comparison. Performance comparison among the state-of-the-art energy harvester with frequency-up conversion mechanism and this work.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Input Freq. (Hz)</th>
<th>Accel. (g)</th>
<th>Resonant Freq. (Hz)</th>
<th>Freq. conversion ratio</th>
<th>$\text{Av}$ (g·P(W))</th>
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<tbody>
<tr>
<td>[51]</td>
<td>36</td>
<td>0.6</td>
<td>618</td>
<td>17.2</td>
<td>0.094</td>
</tr>
<tr>
<td>[30]</td>
<td>36</td>
<td>0.2</td>
<td>275</td>
<td>7.6</td>
<td>90</td>
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<tr>
<td>[52]</td>
<td>40</td>
<td>0.3</td>
<td>1012</td>
<td>25.3</td>
<td>0.2</td>
</tr>
<tr>
<td>[53]</td>
<td>16</td>
<td>1</td>
<td>28</td>
<td>1.9</td>
<td>0.25</td>
</tr>
<tr>
<td>[31]</td>
<td>14.5</td>
<td>0.6</td>
<td>606</td>
<td>41.8</td>
<td>377</td>
</tr>
<tr>
<td>[54]</td>
<td>10</td>
<td>1</td>
<td>926</td>
<td>92.6</td>
<td>3.25</td>
</tr>
<tr>
<td>[55]</td>
<td>10</td>
<td>–</td>
<td>394</td>
<td>39.4</td>
<td>544.7</td>
</tr>
<tr>
<td>[56]</td>
<td>5.8</td>
<td>2</td>
<td>315</td>
<td>54.3</td>
<td>103.55</td>
</tr>
<tr>
<td>[57]</td>
<td>50</td>
<td>2</td>
<td>428</td>
<td>8.6</td>
<td>1</td>
</tr>
<tr>
<td>[58]</td>
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<td>1</td>
<td>384.6</td>
<td>38.5</td>
<td>1800</td>
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<tr>
<td>[59]</td>
<td>64</td>
<td>1</td>
<td>215</td>
<td>3.4</td>
<td>970</td>
</tr>
<tr>
<td>[60]</td>
<td>2</td>
<td>–</td>
<td>29</td>
<td>14.5</td>
<td>7380(peak)</td>
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<tr>
<td>[61]</td>
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<td>1333</td>
<td>16.5</td>
<td>48</td>
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<tr>
<td>[62]</td>
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<td>0.03</td>
<td>130</td>
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<td>9.8</td>
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<tr>
<td>[63]</td>
<td>30</td>
<td>3</td>
<td>143</td>
<td>4.8</td>
<td>2.9</td>
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<tr>
<td>[64]</td>
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<td>77</td>
<td>5.1</td>
<td>10</td>
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<tr>
<td>[65]</td>
<td>24</td>
<td>1</td>
<td>340</td>
<td>14.2</td>
<td>800</td>
</tr>
<tr>
<td>[66]</td>
<td>4.96</td>
<td>2</td>
<td>50</td>
<td>10.1</td>
<td>96</td>
</tr>
<tr>
<td>[67]</td>
<td>40</td>
<td>1</td>
<td>85</td>
<td>2.1</td>
<td>300</td>
</tr>
<tr>
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<td>15</td>
<td>1</td>
<td>240</td>
<td>16</td>
<td>22</td>
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<tr>
<td>[69]</td>
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<td>1.5</td>
<td>33.4</td>
<td>16.7</td>
<td>1500</td>
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<tr>
<td>[70]</td>
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<td>0.8</td>
<td>42</td>
<td>8.8</td>
<td>1310</td>
</tr>
<tr>
<td>[71]</td>
<td>5</td>
<td>2</td>
<td>26.67</td>
<td>13.3</td>
<td>1000</td>
</tr>
<tr>
<td>This work</td>
<td>0.05</td>
<td>197.5(mm/s Compressing V)</td>
<td>420</td>
<td>8400</td>
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<tr>
<td>This work</td>
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<td>158(mm/s Compressing V)</td>
<td>420</td>
<td>2100</td>
<td>75</td>
</tr>
</tbody>
</table>

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

Data Availability
Data will be made available on request.

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Author contributions
Conceptualization: FW, Methodology: AL, FW, Investigation: AL, WX, JS, KX, Visualization: AL, WX, ST, Supervision: FW, CL, Writing—original draft: AL, WX, Writing—review & editing: AL, WX, FW, XG, CL.

Appendix A. Supporting information
Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2022.108030.

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A. Luo et al.
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