Design and characterisation of a piezoelectric knee-joint energy harvester with frequency up-conversion through magnetic plucking

Yang Kuang, Zhihao Yang and Meiling Zhu
College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK EX4 4QF
E-mail: m.zhu@exeter.ac.uk
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Abstract
Piezoelectric energy harvesting from human motion is challenging because of the low energy conversion efficiency at a low-frequency excitation. Previous studies by the present authors showed that mechanical plucking of a piezoelectric bimorph cantilever was able to provide frequency up-conversion from a few hertz to the resonance frequency of the cantilever, and that a piezoelectric knee-joint energy harvester (KEH) based on this mechanism was able to generate sufficient energy to power a wireless sensor node. However, the direct contact between the bimorph and the plectra leads to reduced longevity and considerable noise. To address these limitations, this paper introduces a magnetic plucking mechanism to replace the mechanical plucking in the KEH, where primary magnets (PM) actuated by knee-joint motion excite the bimorphs through a secondary magnet (SM) fixed on the bimorphs tip and so achieve frequency up-conversion. The key parameters of the new KEH that affect the energy output of a plucked bimorph were investigated. It was found that the bimorph plucked by a repulsive magnetic force produced a higher energy output than an attractive force. The energy output peaked at 32 PMs and increased with a decreasing gap between PM and SM as well as an increasing rotation speed of the PMs. Based on these investigations, a KEH with high energy output was prototyped, which featured 8 piezoelectric bimorphs plucked by 32 PMs through repulsive magnetic forces. The gap between PM and SM was set to 1.5 mm with a consideration on both the energy output and longevity of the bimorphs. When actuated by knee-joint motion of 0.9 Hz, the KEH produced an average power output of 5.8 mW with a life time >7.3 h (about $3.8 \times 10^5$ plucking excitations).

Keywords: piezoelectric energy harvester, human motion, wearable energy harvester, frequency up-conversion, magnetic plucking

(Some figures may appear in colour only in the online journal)

1. Introduction
Implantable and wearable body sensors with wireless communication abilities are increasingly widening their use for applications in athletics, medicine, emergency response and consumer entertainment [1]. These sensors—all of which require power sources—are currently powered by batteries, which have a limited energy storage capacity and thus a limited lifetime. With the batteries being a critical bottleneck for body sensors, wearable energy harvesting has been, in recent years, the subject of a scientific and technological effort worldwide [2], which harvests energy from human activities, such as kinetic and thermal energies, to provide...
sustainable power supplies for these sensors and so establish a
fit-and-forget body sensor technology. Due to the high kinetic
cal energy available in human activities, a significant effort has
been devoted to converting kinetic energy into electric power
by exploiting various mechanisms for operation, including
electromagnetic [3, 4], electrostatic [5, 6] and piezoelectric
[7, 8]. Among these operation mechanisms, piezoelectric
energy harvesting has attracted considerable interest due to its
simple structure, self-contained power generation capability
and high energy density [9, 10].

The main challenge in piezoelectric wearable energy
harvesting is the low frequency of human motion, which is
usually much lower than the resonance frequency of a
piezoelectric energy harvester (PEH). This frequency mismatch
between the excitation and the harvester results in a
low energy transduction efficiency. To address this challenge,
one of the methods, frequency up-conversion strategy has
been recently investigated, which uses low frequency vibra-
tions from ambient environment to excite the resonance of a
PEH at higher frequency. As a result, the PEH always vibrates
at its resonance frequency, regardless of the input excitation.
The most common approach to achieve frequency up-con-
version is to induce an initial deflection in the PEH and then
let it vibrate freely at its resonance frequency. The initial
deflection can be induced by direct impact [11, 12],
mechanical plucking [13] or magnetic plucking [8, 14, 15].

In the previous work, frequency-up conversion based on
mechanical plucking has been extensively studied by the
present authors through finite element modelling [13] and
experimental characterisation [16], which used plastic plectra
to pluck piezoelectric bimorphs. This mechanism was suc-
cessfully applied on a knee-joint energy harvester (KEH),
which used knee-joint motions to generate the relative
movement between the plectra and the bimorphs [17]. The
KEH, which generated an average power of 3.5 mW when
actuated at knee-joint motions of 0.9 Hz and terminated with
an optimal load resistor of 80 kΩ, was able to power a cus-
tom-built wireless sensor node for a period of 46 ms period
every 1.25 s after an initial charging time of 28.4 s [18]. The
KEH could, therefore, be used to power wireless sensors to
sense and transmit data at low sampling frequencies. How-
ever, limitations were also observed on the KEH: the direct
contact during the mechanical plucking decreased the long-
evity of the piezoelectric bimorph and plectra, and produced
considerable noise. This paper will address these limitations
by replacing the mechanical plucking with a non-contact
magnetic plucking since the direct contact between the
piezoelectric bimorph and the plectra can be avoided.

Frequency up-conversion through non-contact magnetic
plucking has been previously reported in several studies for
different applications. For example, Pillatsch et al. [15]
developed a simulation model to study the dynamic perfor-
mance of a piezoelectric beam subject to non-contact mag-
netic plucking, and later proposed a miniaturised energy
harvester for human body applications, where the human
body movements actuated an eccentric proof mass to oscillate
and a magnet on the proof mass plucked a piezoelectric
bimorph through a magnetic force [8]. Tang et al. [19] used a
nonlinear oscillator carrying a driving magnet and actuated by
inertial force to bend a pair of piezoelectric micro-cantilevers
through a magnetic force. Both devices generated power
output in the range of tens of microwatts. The application of
inertial force in both devices to actuate the magnets ensured a
simple device structure; however, it was also found that with
input excitations being at low accelerations and low fre-
frequencies, the driving magnet might get stuck and does not
pluck the piezoelectric element effectively. Luong et al. [14]
used a magnetic force to excite a piezocomposite generating
element in a small-scale windmill, which generated an aver-
age power output up to 2 mW. However, the power density
was much smaller than that in many other windmills using
electromagnetic generators.

This work introduces non-contact magnetic plucking for
wearable knee-joint energy harvesting application to achieve
high electric power output, long life time and low noise level.
The KEH features an optimised number of primary magnets
(PMs) positioned on an outer ring, which is actuated by the
direct force from knee-joint motion to rotate relatively to a
central hub with eight piezoelectric bimorphs fixed. Com-
pared with the literature [15, 19], the use of an optimised
number of PMs can fully exploit the potential of magnetic
plucking, thus increasing the power output, while the direct
force excitation avoids the sticking of the PMs, which might
happen with inertial force excitation. This paper first inves-
tigates effects of the design parameters on the energy output
of a bimorph subject to magnetic plucking and then reports
the performance of a prototyped piezoelectric KEH with
optimised parameters. Based on the design parameters study
and analysis, the KEH with 8 piezoelectric bimorphs gen-
erates an average power as high as 5.8 mW (0.7 mW per
bimorph) when actuated by knee-joint motion at 0.9 Hz. The
KEH has operated continuously for 7.3 h without any sign of
performance decreasing.

2. Description of the piezoelectric KEH

A schematic of the KEH based on magnetic plucking is
shown in figure 1. PMs, which are referred to as PMs here,
are equally positioned along the inner side of the outer ring.
Eight piezoelectric bimorphs are mounted in the inner hub to
form cantilevers, the free ends of which are glued with a
secondary magnet (SM). For the knee-joint wearable application, the inner hub is fixed to the shank, while the outer ring is fixed to the thigh. During walking, the thigh and the shank rotate around the knee joint, causing the inner hub and the outer ring to rotate relatively to each other. As a result, the PMs pass by the SMs and pluck the bimorphs through the magnetic forces.

Figure 2 illustrates the magnetic plucking action when the interactive force between the PM and SM is repulsive: as the PM rotates from P0 to P1 and then P2, the bimorph moves from R0 to R1 and then R2; (b) the bimorph tip displacement during magnetic plucking.

The magnetic forces experienced by a SM on a bimorph are illustrated in Figure 3, where, for simplification, two PMs and one SM are used to analyse the magnetic plucking force acted on the bimorph, and the situation that PM1 passes by the SM and PM2 is away from the SM is considered. PM1 and PM2 apply a repulsive magnetic force, \( F_1 \) and \( F_2 \) to the SM, respectively. The direction of the forces can be changed to be attractive by altering the polarisation direction of the magnets. Each magnet can be regarded as a magnetic dipole, and the magnetic forces between the PMs and SM can be expressed as [20]

\[
F_i = \frac{q_{PM} q_{SM}}{\mu d_i^2},
\]

where the subscript \( i = 1 \) and \( 2 \); \( q_{SM} \) and \( q_{PM} \) are the magnitudes of magnetic poles; \( \mu \) is the permeability and approximately equal to 1 in air; \( d_i \) is the gap between the SM and the corresponding PM, and has a minimum value of \( d \).

Figure 3. The magnetic forces experienced by the bimorph as PM1 passes by the SM.

The resultant force in the y-axis (magnetic compressive force) compresses the bimorph, and thus induces a compressive stress in the bimorph

\[
F_y = F_{iy} + F_{2y}.
\]

The resultant force in the x-axis (magnetic plucking force) plucks the bimorph to generate energy output and therefore is of interest in this study. Because \( F_{ix} \) and \( F_{2x} \) always opposes each, the plucking force takes the form of

\[
F_i = F_{ix} - F_{2x}.
\]

Equation (2) suggests that \( F_{ix} \) is related to the PM/SM gap, and diminishes to zero when the gap is large enough. Therefore, when the number of the PMs positioned on the outer ring is small, i.e. the distance between PM1 and PM2 is...
large, the bimorph only experiences $F_{1a}$ and $F_{2a}$ is negligible. In the extreme case, it represents only one PM installed in the outer ring, which will be studied in sections 3.2.1–3.2.3. When the number of the PMs positioned on the outer ring is large, i.e., the distance between the PM$_1$ and PM$_2$ is small, $F_{2a}$ cannot be neglected and it reduces the total plucking force, as suggested by equation (4). Therefore, the plucking force is affected by the PM/SM gap and the number of PMs, and so is the energy output of the bimorph. The effects of both parameters on the energy output will be studied experimentally in section 3 to maximise energy output.

3. Experimental design and evaluations for one bimorph energy harvester

3.1. Experimental setups and methods

In order to investigate the energy output by a one-off magnetic plucking force and by a continuous magnetic plucking force, two setups were used in the different configurations of the design evaluation, as shown in figure 4. In figure 4(a), there is only one PM installed, allowing the alternation of the polarisation orientation and the gap $d$. The alternation of the polarisation orientation leads to two operation configurations: (1) repelling configuration, where the PM and SM repels each other; and (2) attracting configuration, where the two magnets attract each other. In figure 4(b), there are 64 slots equally positioned along the inner edge of the outer ring (inner diameter 88 mm), and each slot allows one PM to be fixed. Tests were performed with 1, 4, 8, 16, 32 and 64 PMs equally positioned, respectively.

In both setups, a $3 \times 3 \times 3$ mm$^3$ magnet (F316-N35, Magnet Exert Ltd, Tuxford, UK) was glued to the tip of a PZT-5H bimorph (T215-H4-303X, dimension $38.1 \times 12.7 \times 0.38$ mm$^3$, Piezo Systems INC, Woburn, US) and served as a SM. The bimorph was mounted with a free length of 26 mm in the inner hub, which was held steady by a bracket. The outer ring, where the PMs (the same as SMs) were fixed, was actuated by a stepping motor to rotate at an adjustable speed. Furthermore, the PZT-5H bimorph was terminated with a load resistor $R_m$, which was chosen at maximising the energy output. The outer ring was actuated to rotate for a full revolution with an angular velocity, $\omega$, ranging from 0.1 to 2 revolutions per second (rev s$^{-1}$), which is the variation range of the angular velocity of the knee-joint during normal gait [16]. The voltage $V(t)$ across $R_m$ was measured by a NI 9229 data acquisition card (National Instruments, Newbury, UK) to calculate the energy output by equation (5), whereas the displacement at the bimorph tip was monitored by a laser Doppler vibrometer (CLV-2534, Polytec Ltd, Harpenden Hertfordshire, UK).

\[
E(t) = \frac{1}{2} \sum_{k=1}^{N} \frac{V^2(t_k)}{R_m} \Delta t, \tag{6}
\]

where $\Delta t$ is the sampling interval.

3.2. Results and discussions

The results in section 3.2.1–3.2.3 were obtained from the setup, shown in figure 3(a), whereas the results presented in section 3.2.4 were measured on the setup, shown in figure 3(b).

3.2.1. Effects of repelling and attracting configurations on energy output. Initial tests found that the energy output of both repelling and attracting configurations was maximised at $R_m = 40$ kΩ. Therefore, this load resistor was used for the design evaluations. Figure 5 shows the bimorph tip displacement (a), velocity (b), voltage (c), and energy output (d) of the bimorph in both repelling and attracting configurations at $\omega = 2$ rev s$^{-1}$ with $d = 1$ mm.

In the repelling configuration, from the beginning to $R_1$, the bimorph was deflected away from its origin position by the repelling plucking force from the approaching PM (figure 5(a)). The deflection of the bimorph reached a limit of $-0.8$ mm at $R_1$, where the bimorph started to snap through to the opposite side of the origin because of the elastic force.

![Figure 4](image-url) Two experimental setups used in the design evaluation, (a) a single PM installed with an adjustable PM/SM gap $d$; (b) multiple PMs evenly positioned along the outer ring.
developed in the bimorph. After \( R_2 \), the bimorph oscillated around its equilibrium position at its resonance frequency. It is noted that the equilibrium position of the bimorph was shifted upward by the repelling magnetic force, as indicated in figure 5(a), and returned back to the origin as the PM moved away.

During snapping through from \( R_1 \) to \( R_2 \) and with a maximum displacement of 1.6 mm, the repelling configuration generated a voltage up to 60 V (figure 5(c)) and an energy output of 0.2 mJ (figure 5(d)), which accounts for 56% of the total energy generated (0.36 mJ). The resonant vibration stage (\( R_2 \) onwards) produced an energy output of 0.14 mJ, accounting for 39% of the total energy generated.

In the attracting configuration, the bimorph moved towards the PM because of the attracting plucking force from the approaching PM. Then, from \( A_1 \) to \( A_2 \), the bimorph stayed together and oscillated around the travelling PM. At \( A_2 \), the bimorph was released to resonant vibration around its origin position and with decaying amplitude.

During the combined travel stage (\( A_1 \)–\( A_2 \)) and with a maximum displacement of 1.6 mm, the attracting configuration generated a voltage up to 20 V and an energy output of 0.028 mJ, accounting for 28% of the total energy produced (0.1 mJ). The energy produced in the free vibration stage (\( A_2 \) onwards) was 0.062 mJ, accounting for 62% of the total energy produced.

The results suggest that both repelling and attracting configurations are able to provide frequency up-conversion to the resonance frequency of the bimorph. However, the repelling configuration produced 3.6 times more energy output than the attracting configuration, even though the maximum displacement with both configurations was about the same (1.6 mm). This can be explained by the higher vibration velocity of the bimorph in the repelling configuration.
configuration caused by the snapping-through stage. A higher vibration velocity leads to a higher strain rate and consequently a higher generated current in the bimorph, since the generated current is analogous to the strain rate \[21\].

Because the repelling configuration is more efficient in energy generation, it was used for the rest of the studies in this paper.

3.2.2. Effects of the gap between the PM and the SM on the energy output. Figure 6 compares the performance of the repelling configuration with different values of \(d\). As \(d\) increases, decreases are observed in the bimorph displacement, velocity, voltage and energy output. This is mainly because with an increasing \(d\), the plucking force decreases as indicated by equation (5). The decreasing plucking force first of all resulted in a smaller initial deflection and a more gradual release of the bimorph at \(R_1\). With \(d = 3\) mm and displacement being too small at \(R_2\), there was no resonant oscillation at all. Although the energy output increases with a decreasing \(d\), it should be noted that a higher

Figure 6. Bimorph tip displacement (a), velocity (b), voltage (c) and energy output (d) verse time for the repelling configuration actuated at \(\omega = 2\) res s\(^{-1}\) and with \(d = 1.5, 2\) and 3 mm, respectively.

Figure 7. Energy output of the repelling configuration at different rotation speeds with \(d = 1\) mm.
Figure 8. Bimorph tip displacement (a), velocity (b), voltage (c) and energy output for the repelling configuration at different rotation speed $\omega$ with $d = 1$ mm.

Figure 9. Dependence of the energy output on the number of the PMs and the rotation speed with $d = 1.5$ mm, (a) total energy output in a full revolution and (b) the average energy output per PM.
energy output is obtained at a higher displacement and thus a higher stress level, which might decrease the longevity of the bimorph, considering the low strength of the piezoelectric materials. The value of $d$ used for the KEH will be determined by taking account of the longevity and will be discussed in section 4.

3.2.3. Effects of rotation speed $\omega$ on energy output. An increase in the energy output is observed with the rotation speed, as shown in figure 7. The energy output increases from 0.08 to 0.42 mJ as the rotation speed increases from 0.2 to 2 rev s$^{-1}$. Figure 8 compares the performance of the repelling configuration with $\omega = 0.5, 1$ and 2 rev s$^{-1}$.

With the three rotation speeds compared in figure 8, the three stages associated with the repelling configuration, described in section 2, can be clearly identified: (1) a deflection stage to $R_1$ when PM is approaching SM, (2) a snapping-through stage from $R_1$ to $R_2$, and (3) a free vibration.

Figure 10. Bimorph tip displacement (a) and voltage output (b) verse time with different number of PMs ($\omega = 2$ rev s$^{-1}$ and $d = 1.5$ mm).
stage from R₂ onwards; and in each stage, a higher rotation speed generated a higher energy output. In the deflection stage, the higher energy output can be simply explained by the higher displacement amplitude at R₁. Although the displacement at R₂ with different ω is about the same, this displacement was achieved in a shorter time when ω is higher, i.e. the vibration velocity is higher. Consequently, a higher voltage and energy output was produced in the snapping-through stage with a higher ω.

It is noticeable that even though the bimorph was released from about the same position (1.6 mm) at R₂, a higher ω still generated a higher energy output in the resonant vibration stage (0.03, 0.08 and 0.14 mJ corresponding to ω = 0.5, 1 and 2 rev s⁻¹, respectively). With a higher ω the PM travelled away from the bimorph more quickly, consequently allowing the bimorph to have more time for free vibration at the resonance frequency as little or no magnetic plucking force was acted on the bimorph; and therefore, higher vibration velocity and voltage output were observed.

3.2.4. Effects of the number of PMs on the energy output.
The total energy outputs of the bimorph with different number of PMs, N, are presented in figure 9(a), where the outer ring was actuated to rotate for a full revolution at different speeds. At each rotation speed, the total energy output increases and then decreases with N, with a maximum value at N = 32. With each N, a higher energy output is always observed at a higher rotation speed, which agrees with the results in section 3.2.3.

By dividing the total energy output via the corresponding N, the energy output per PM, $E_{PM}$ can be calculated, shown in figure 9(b), which describes the average energy output of one magnetic plucking, or in other words, the efficiency of energy conversion. With N = 1, 4 and 8, $E_{PM}$ stays constant for all the rotation speeds. Following that, $E_{PM}$ decreases with N, that is, the efficiency of the energy conversion from mechanical to electric energy decreases with N. With N = 16 and 32, the decrease in $E_{PM}$ is slow, and hence the total energy output still increases with N. With N = 64, a sharp decrease in $E_{PM}$ is observed and consequently, the total energy output decreases significantly.

To investigate the reason behind the dependence of the energy output on N, the displacement and voltage of the bimorph in the first 0.2 s of a full revolution (0.5 s at ω = 2 rev s⁻¹) are presented in figure 10. With N = 4 and 8, the aforementioned three stages during one magnetic excitation can be clearly identified: a deflection stage (R₁) followed by a snapping-through stage (R₁–R₂) and then a resonant vibration stage (R₂ onward). The resonant vibration of the bimorph had fully rung down before a subsequent approaching PM deflected the bimorph again. Therefore, the subsequent PM did not affect the vibration and thus the voltage induced by the previous PM. Consequently, $E_{PM}$ is the same with N = 4 and 8, as shown figure 9(b). The variations in the initial deflection are caused by the small difference in the positions of the PMs, which lead to variations in PM/SM gap.

With N = 16 and 32, the subsequent PM started to deflect the bimorph before the resonant vibration induced by the previous PM had fully rung down, and as a result, the superposition of the oscillation onto the deflection is observed. Because the bimorph had more time to vibrate at resonance with N = 16 than N = 32, it produced a higher $E_{PM}$ with N = 16. Although the bimorph did not finish the resonant vibration stage, the snapping-through stage was not affected by the subsequent PM, during which the bimorph generated 56% of the energy output as discussed in section 3.2.1; therefore, the decrease in $E_{PM}$ with N is slow (figure 9(b)) and the total energy output still increases with N. It is also noted that by increasing N from 1 to 32, the initial deflection remained at about the same level, suggesting that the plucking force keeps constant with these numbers of PMs.

With N = 64, a significant drop in displacement was observed in both the initial deflection and snapping-through stages, and there was hardly any resonant vibration. This is because with the distance between the PMs being too small, the plucking force was reduced as discussed in section 2, and also the subsequent PM started to deflect the bimorph even when the latter was still in its snapping-through stage. Because of the low vibration amplitude, the bimorph generated very low voltage, and consequently low $E_{PM}$. The sharp drop in $E_{PM}$ leads to a significant decrease in the total energy output.

In light of the results, it can be concluded that to maintain the optimal energy conversion efficiency of the bimorph, the maximum number of PMs is 8. However, the energy output with N = 8 is not the highest. To get the highest energy output, 32 PMs should be used, although the energy conversion is optimal.
Figure 12. Knee-joint motion during human gaits (a) illustration of the angle between the thigh and the shank, reproduced from, and (b) the angular displacement of the knee-joint during one gait cycle.

Figure 13. Bimorph tip displacement (a), voltage output (c), energy output (d) of the KEH with one bimorph installed and \( d = 1.5 \) mm. The four bursts of displacement peaks are highlighted by the dashed circles in (a).
Based on the above evaluation results, a KEH based on magnetic plucking has been prototyped as shown in figure 11. The same 8 piezoelectric bimorphs with a SM glued at the tip of each were mounted in the inner hub, which was held static by a bracket. 32 PMs were equally positioned and fixed on the outer ring, since with this number of the PMs, the bimorph was found to produce the highest energy output although the conversion efficiency per PM was not optimal. The polarisation directions of the magnets were arranged to form a repelling configuration, as it generated a higher energy output than the attracting counterpart. The PM/SM gap between can be adjusted between 1 and 2.5 mm by varying the clamping length of the bimorphs.

The prototype was mounted on a stepping motor, which actuated the outer ring to reproduce the knee-joint motion taken from [17] and presented in figure 12. The knee-joint motion was measured from a human subject during normal walking by a marker-based motion capture system. The angle between the thigh and the shank covers up to 57° during one gait cycle, and the cycle takes 1.1 s, corresponding to a walking frequency of 0.9 Hz.

The characterisation was performed with two steps. In the first step, only one piezoelectric bimorph was installed in the inner hub. The output of the bimorph was connected to a 40 kΩ resistor. This step was performed to examine the dynamic responses of the bimorph and determine a suitable distance \( d \) based on the longevity of the bimorph. In the second step, 8 bimorphs were installed, the outputs of which were connected to 8 full-wave rectifiers. The DC outputs from the rectifiers were individually connected in parallel and then terminated with a load resistor. In both steps, the voltage generated across the load resistor was measured by the NI 9229 data acquisition card to calculate the energy output.

### 4.2. Characterisation results and discussion

#### 4.2.1. Energy output of the KEH with one bimorph

Initially, the gap \( d \) was set to 1 mm. The KEH generated 2.42 ± 0.4 mJ in one step, corresponding to an average power of 2.2 ± 0.36 mW. However, a crack was developed at the root of the bimorph after operating the KEH continuously for 0.5 h, resulting in a sharp drop of the average power to 0.5 mW. With \( d = 1.5 \) mm, the KEH generated an energy output of 0.8 ± 0.22 mJ in one step, corresponding to an average power of 0.72 ± 0.2 mW. In this case, the KEH has been able to be operated continuously for 7.3 h (about \( 2.4 \times 10^5 \) gait cycles) without any signs of performance decreasing. Therefore, \( d = 1.5 \) mm was chosen for the KEH, and the responses of the bimorph in one gait cycle are presented in figure 13.

The knee-joint angle is plotted in each figure. Four bursts of displacement peaks (highlighted by dashed circles) are observed in figure 13(a). They all occurred at the time when large knee angles were covered in a short time, i.e. the rotation speed of the outer ring was high. Figure 13(b) shows the details of the tip displacement in the third burst of peaks. The three stages aforementioned can be clearly identified in each excitation cycle with superimposition of the oscillation onto the deflection, which is similar to what has been discussed in 3.2.4 with \( N = 32 \). Between these bursts of peaks, the outer ring was reversing the rotation directions at low speed, and the bimorph was not effectively deflected by the PM. Four bursts of voltage peaks are observed in figure 13(c), which corresponds to the locations of the displacement peaks. Whenever there is a burst of voltage peaks, a jump in the energy output occurs, as shown in figure 13(d). In one step (1.1 s), the bimorph generated an energy output of 0.59 mJ, corresponding to an average power output of 0.53 mW.

It is worthwhile pointing out that with \( d = 1.5 \) mm, the bimorph worked at a much higher displacement (about ±0.9–1 mm) than the rated one (±0.51 mm) provided by the supplier. With a displacement of 0.9–1 mm, the maximum bending stress in the piezoelectric material is about 50–56 MPa, calculated by equation (6) [22]

\[
\sigma_{\text{max}} = \frac{3Y_p}{t} \left( \frac{l_t}{2} + t_p \right) D_{\text{max}},
\]

where \( Y_p \) (66 GPa) is the Young’s modulus; \( l \) (26 mm) is the free length of the bimorph; \( t_s \) (0.126 mm) is the thickness of the substrate; \( t_p \) (0.127 mm) is the thickness of the piezoelectric layer; \( D_{\text{max}} \) (0.9–1 mm) is the maximum tip deflection of the bimorph. It is generally accepted that under a cyclic bending stress of 50–55 MPa, PZT can operate for about \( 10^5 \) cycles before final fracture [23]. In the case of the KEH, the bimorph experienced 16 plucks in one gait cycle and therefore in the total \( 2.4 \times 10^5 \) gait cycles of the longevity test, it was plucked by 3.8 \( \times 10^5 \) times without any signs of performance decreasing, which suggests a life time higher than the theoretical value of \( 10^5 \) cycles. This may be because the magnetic compressive force (described in section 2) induced an additional compressive stress in the bimorph, which was
superimposed to the bending stress. The additional compressive stress decreased the tensile stress and increased the compressive stress in the bending operation. Because the compressive strength of PZT (>517 MPa) is much higher than its tensile strength (~75.8 MPa) [24], the reduction in tensile stress increased the life time of the bimorphs.

4.2.2. Energy and power output of the KEH with 8 bimorphs.

Figure 14 shows the average output of the KEH across different load resistance with 8 bimorphs installed. At the optimal load resistance of 15 kΩ, the EH generated an average power output of 5.8 mW.

The total voltage and energy output with the optimal load resistance (15 kΩ) are presented in figure 15. The voltage measured across the load resistor is unipolar because of the presence of the rectifiers. Four bursts of voltage peaks are observed, which occurred when the knee-joint rotation speed was high, as discussed in section 4.3.1. At each burst of voltage peaks, a sharp increase in the energy output was observed. In one gait cycle, the EH generated an energy output of 6.4 mJ, corresponding to an average power of 5.8 mW.

5. Conclusions

A piezoelectric KEH was designed and characterised in this paper, which used non-contact magnetic plucking to achieve frequency up-conversion. The magnetic forces between permanent magnets deflected the piezoelectric bimorphs, which were then released to resonant vibration and thus generated a high energy output. The parameters that affected the energy output of a magnetically plucked piezoelectric bimorph were investigated. While both repelling and attracting configurations were able to provide frequency up-conversion to the resonance frequency of the bimorph, the repelling configuration generated 3.6 times higher energy output than the attracting configuration because of the presence of a snapping-through stage, and therefore was used for the KEH. Reducing the gap between the primary and SMs was found to increase the energy output because of the increasing magnetic plucking force. However, the higher energy output was achieved at a higher stress in the piezoelectric material, which could decrease the longevity of the bimorph. There is certainly a trade-off between the energy output and the life time. The energy output can also be increased by increasing the rotation speed of the PMs. This is partly because at a higher rotation speed, the PM caused a higher initial deflection in the bimorph, and also because the PM moved away from the bimorph more quickly and thus allowing the bimorph to have more time for free vibration at the resonant frequency. The bimorph generated the maximum energy output when 32 PMs were positioned in the outer ring, even though the energy conversion efficiency per PM was not optimal.

A KEH with 8 piezoelectric bimorphs and 32 PMs was prototyped and characterised. With a gap of 1.5 mm between the primary and SMs, the KEH, actuated at knee-joint motion of 0.9 Hz, was able to generate an average power output of 5.8 mW for more than 7.3 h (about \(3.85 \times 10^5\) plucks) without any signs of performance decreasing possibly due to the compressive stress introduced by the magnetic force. With this magnitude of power level and longevity, the KEH can be used to power body sensors for real applications. Further practical work will develop a wearable prototype with ergonomic design and test its capability to power wireless sensors.

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References

[1] Jurik A D and Weaver A C 2009 Body sensors: wireless access to physiological data IEEE Softw. 26 71–3
[2] Hannan M A, Mutashar S, Samad S A and Hussain A 2014 Energy harvesting for the implantable biomedical devices: issues and challenges Biomed. Eng. Online 13 79
[3] Donelan J, Li Q, Naing V, Hoffer J, Weber D and Kuo A 2008 Biomechanical energy harvesting: generating electricity during walking with minimal user effort Science 319 807–10
[4] Rome L C, Flynn L, Goldman E M and Yoo T D 2005 Generating electricity while walking with loads Science 309 1725–8
[5] Eun Y et al 2014 A flexible hybrid strain energy harvester using piezoelectric and electrostatic conversion Smart Mater. Struct. 23 045040
[6] Naruse Y, Matsubara N, Mabuchi K, Izumi M and Suzuki S 2009 Electrostatic micro power generation from low-frequency vibration such as human motion J. Micromech. Microeng. 19 094002
[7] Kymissis J, Kendall C, Paradiso J and Gershenfeld N 1998 Parasitic power harvesting in shoes 2nd Int. Symp. on Wearable Computers, 1998. Digest of Papers pp 132–9
[8] Pillatsch P, Yeatman E M and Holmes A S 2014 A piezoelectric frequency up-converting energy harvester with rotating proof mass for human body applications Sensors Actuators A 206 178–85
[9] Cook-Chennault K, Thambi N and Sastry A 2008 Powering MEMS portable devices—a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems Smart Mater. Struct. 17 043001
[10] Shu Y and Lien I 2006 Analysis of power output for piezoelectric energy harvesting systems Smart Mater. Struct. 15 1499
[11] Renaud M, Fiorini P, van Schaijk R and Van Hoof C 2009 Harvesting energy from the motion of human limbs: the design and analysis of an impact-based piezoelectric generator Smart Mater. Struct. 18 035001
[12] Lei G and Carol L 2011 Impact-driven, frequency up-converting coupled vibration energy harvesting device for low frequency operation Smart Mater. Struct. 20 045004
[13] Pozzi M and Zhu M 2011 Plucked piezoelectric bimorphs for knee-joint energy harvesting: modelling and experimental validation Smart Mater. Struct. 20 055007
[14] Luong H T and Goo N S 2012 Use of a magnetic force exciter to vibrate a piezocomposite generating element in a small-scale windmill Smart Mater. Struct. 21 025017
[15] Pillatsch P, Yeatman E and Holmes A 2014 Magnetic plucking of piezoelectric beams for frequency up-converting energy harvesters Smart Mater. Struct. 23 25009–20
[16] Pozzi M and Zhu M 2012 Characterization of a rotary piezoelectric energy harvester based on plucking excitation for knee-joint wearable applications Smart Mater. Struct. 21 055004
[17] Pozzi M, Aung M S, Zhu M, Jones R K and Goulernas J Y 2012 The pizzicato knee-joint energy harvester: characterization with biomechanical data and the effect of backpack load Smart Mater. Struct. 21 075023
[18] Kuang Y and Zhu M 2016 Characterisation of a knee-joint energy harvester powering a wireless communication sensing node Smart Mater. Struct. 25 055013
[19] Tang Q, Yang Y and Li X 2011 Bi-stable frequency up-conversion piezoelectric energy harvester driven by non-contact magnetic repulsion Smart Mater. Struct. 20 125011
[20] Spaldin N A 2010 Magnetic Materials: Fundamentals and Applications (Cambridge: Cambridge University Press)
[21] Roundy S and Wright P K 2004 A piezoelectric vibration based generator for wireless electronics Smart Mater. Struct. 13 1131
[22] Moro L and Benasciutti D 2010 Harvested power and sensitivity analysis of vibrating shoe-mounted piezoelectric cantilevers Smart Mater. Struct. 19 115011
[23] Okayasu M, Ozeki G and Mizuno M 2010 Fatigue failure characteristics of lead zirconate titanate piezoelectric ceramics J. Eur. Ceram. Soc. 30 713–25
[24] Fett T, Munz D and Thun G 1999 Tensile and bending strength of piezoelectric ceramics J. Mater. Sci. Lett. 18 1899–902