A sandwiched piezoelectric transducer with flex end-caps for energy harvesting in large force environments

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Abstract
This paper presents a sandwiched piezoelectric transducer (SPT) for energy harvesting in large force environments with increased load capacity and electric power output. The SPT uses (1) flex end-caps to amplify the applied load force so as to increase its power output and (2) a sandwiched piezoelectric-substrate structure to reduce the stress concentration in the piezoelectric material so as to increase the load capacity. A coupled piezoelectric-circuit finite element model (CPC-FEM) was developed, which is able to directly predict the electric power output of the SPT connected to a load resistor. The CPC-FEM was used to study the effects of various parameters of the SPT on the performance to obtain an optimal design. These parameters included the substrate thickness, the end-cap material and thickness, the electrode length, the joint length, the end-cap internal angle and the PZT thickness. A prototype with optimised parameters was tested on a loading machine, and the experimental results were compared with simulation. A good agreement was observed between simulation and experiment. When subjected to a 1 kN 2 Hz sinusoidal force applied by the loading machine, the SPT produced an average power of 4.68 mW. The application of the SPT as a footwear energy harvester was demonstrated by fitting the SPT into a boot and performing the tests on a treadmill, and the SPT generated an average power of 2.5 mW at a walking speed of 4.8 km h⁻¹.

Keywords: piezoelectric energy harvesting, sandwiched piezoelectric transducer, cymbal transducer, wearable energy harvesting, shoe energy harvesting

(Some figures may appear in colour only in the online journal)
resonance frequency and increase the inertial force, cantilever beams work well with input excitations in the form of base acceleration and tip plucking [6]. However, cantilever beams can only take small forces and cannot work under a high compressive force excitation. For applications where the kinetic energy is in the form of large compressive forces, for instance, under shoes, floor tiles, motorways and vehicle/machine suspensions—the force can be up to hundreds or even thousands of Newton, an alternative energy harvesting structure is required.

PZT stack structures are a straightforward solution for energy harvesting in the compressive force environments [7–10]. Xiong et al [8] and Roshani et al [9] separately proposed to use piezoelectric stacks for energy harvesting from roadways. However, because the resonance frequency of the PZT stacks (in the range of kilohertz) is very high compared to the frequency of the applied force (a few hertz), the mechanical energy coupled to the PZT and thus the electric energy output is low. A more efficient way to use PZT stacks is to couple them between two mechanical amplifiers to form a so-called ‘cymbal’ transducer. A typical cymbal transducer for energy harvesting is shown in figure 1. It is of circular shape and composed of a piezoelectric disk sandwiched between two metal end-caps. Owing to the presence of the cavity, the end-cap amplifies and transfers the incident load on the apex to the radius direction of the piezoelectric disk, leading to an improved electric power output.

Cymbal transducers were originally developed for piezoelectric actuation [11]. The first study of cymbal transducers for energy harvesting was reported by Kim et al [12, 13]. When actuated by a 200 Hz 70N cyclic force, a cymbal transducer based on a PZT disk with a diameter of 29 mm produced power around 100 mW. Following that, cymbal transducers with modified dimensions or shapes were explored by other researchers for energy harvesting under modest forces (<25N) [14–16] and achieved power output between 0.66 and 14 mW, which is highly dependent on the excitation frequency. One limitation of these cymbal transducers is that the load capacity is very limited. In large force environments, e.g. under shoes, where the compressive force can be two or three times of the body weight, the stress limit of the piezoelectric material can be reached because of the force amplification effect of the end-caps as well as the stress concentration in the transducer. To increase the load capacity, Mo et al [17] proposed a unimorph piezoelectric cymbal transducer, where a steel substrate was used to reinforce the PZT disk. Although the transducer was demonstrated to work safely under a peak excitation force of 1940N, most of the input mechanical energy was absorbed by the substrate, the thickness of which is 8.38 time of the PZT disk, leading to a low electric power output. Li [18] and Wang [19], respectively modified the conventional flex-tensile cymbal transducer to a flex-compressive transducer so that the PZT stacks were compressed in operation. Because the compressive strength of PZT is much higher than the tensile strength, this method can greatly increase the load capacity of the transducer. However, both transducers required the PZT stacks to be placed outside the end-caps, resulting in a bulky design (length up to 152 mm), and thus might not be suitable for applications with limited space.

The purpose of this paper is to further explore the design of a sandwiched piezoelectric transducer (SPT) with flex end-caps, which was proposed in a previous work [20] by the present authors for energy harvesting in high compressive force environments. The SPT uses the force amplification mechanism of the conventional cymbal transducers, i.e. by using the flex end-caps, but it adopts a sandwiched piezoelectric-substrate structure to reduce the stress concentration in the piezoelectric material, thus increasing its load capacity. Luo et al [21] used sequential quadratic programming on meta-models to optimise the parameters of the SPT. However, the study did not investigate the effects of individual parameters on the power output, and thus cannot provide guidance for similar transducer design. Moreover, some of the optimised parameters reached the limit of the design ranges, suggesting that the actual optimal parameters may be out of the range set by the authors. A transducer design similar to the SPT was also reported by Sharpes et al [22], which fully covered the design, fabrication and application of a floor tile energy harvester. However, the analytic model used in their study and thus the design analysis was limited to the mechanical characteristics of the energy harvester. The power output of the energy harvester can only be analysed qualitatively.

This study develops a coupled piezoelectric-circuit finite element model (CPC-FEM) of the transducer, which is validated by experiment and able to directly predict both the mechanical characteristics and the electric power output of the SPT with different mechanical configurations as well as different load resistors, thus providing a powerful virtual designing tool to optimise the transducer design. The effects of various factors on the performance are investigated and analysed, including the geometric parameters and material properties of the transducer. The simulation results can provide design guidance for both the SPT and similar cymbal transducers. Guided by the simulation results, a prototype is fabricated and tested. The experimental results are compared with the simulation results, analysed and further discussed. Finally, the transducer is retrofitted to a boot to study its feasibility as a footwear energy harvesting.

2. Sandwiched piezoelectric transducer (SPT)

The studied SPT for energy harvesting is shown in figure 2(a). It comprises two flex end-caps and a 31-mode PZT plate sandwiched between two metal substrates. The SPT is different...
from the conventional cymbal transducers in two aspects. Firstly, it uses a rectangular PZT plate instead of a PZT disc to make full use of the optimal orientation of piezoelectric materials [14, 23]. Secondly, the PZT plate is sandwiched between two metal substrates to form a sandwiched piezo-electric-substrate structure (abbreviated as ‘sandwiched structure’ in this paper). As will be demonstrated by the FE modelling in section 3.2.1, the use of the sandwiched structure significantly reduces the stress concentration in the PZT, thus increasing the load capacity.

Like conventional cymbal transducers, the end-caps of the SPT serve as a mechanical transformer with a force amplification effect (figure 2(b)) to transfer the compressive load force $F$ into tensile force $F_{xp}$ along the $x$-axis. The total tensile force exerted on the sandwiched structure is

$$F_{\text{tot}} = 2F_{xp} = 2F_x = F\cot\theta$$  \hspace{1cm} (1)

where $\theta$ is the end-cap internal angle and $\cot\theta$ is usually denoted as the amplification factor. Equation (1) clearly suggests that when the internal angle is less than 45°, the end-caps amplify the incident force and thus increases the tensile stress developed in the piezoelectric material and the generated power output. The apex (BC) and the inclined segments (AB and CD) are in compression due to the force $F_{\text{apex}}$ and $F_{\text{in}}$, respectively. $F_{\text{apex}}$ and $F_{\text{in}}$ can be expressed as

$$F_{\text{apex}} = F\cot\theta/2$$  \hspace{1cm} (2)

$$F_{\text{in}} = F/2\sin\theta.$$  \hspace{1cm} (3)

### 3. Design analyses using finite element modelling

The SPT designed in this study is expected to work under a 1 kN load force for footwear energy harvesting. By applying a safety factor of 2 when considering the stress limit, the SPT can work safely under forces up 2 kN. Within this constraint, the effects of various design parameters on the power output and stress distribution were studied by finite element (FE) modelling in this section in a bid to obtain an optimised design.

#### 3.1. FE modelling approaches

ANSYS 14.5 software package was used to develop the CPC-FEM of the SPT for design analyses. The CPC-FEM comprises a 3D structure of the SPT with a load resistor connected across the electrodes of the piezoelectric plate, as shown in figure 3. It combines the simulation of piezoelectricity and electric circuit in one model. The initial dimensions of the SPT and the variation ranges of the dimensions investigated in this study are listed in table 1.

**Table 1.** The initial dimensions of the SPT and the variation ranges of the dimensions investigated in this study.

| Dimensions | Symbols | Initial value | Lower limit | Upper limit |
|------------|---------|---------------|-------------|-------------|
| Total length (mm) | $L$ | 52 | — | — |
| Width (mm) | $W$ | 30 | — | — |
| Cavity height (mm) | $H$ | 3.5 | 1 | 13 |
| Cavity length (mm) | $L_c$ | 40 | — | — |
| Apex length (mm) | $L_a$ | 14 | — | — |
| Electrode length (mm) | $L_e$ | 40 | 25 | 52 |
| Joint length (mm) | $L_j$ | 6 | 2 | 10 |
| PZT thickness (mm) | $t_p$ | 4 | 0.5 | 9 |
| Substrate thickness (mm) | $t_s$ | 0.6 | 0.2 | 0.9 |
| End-cap thickness (mm) | $t_c$ | 2 | 0.3 | 3 |
| End-cap angle (°) | $\theta$ | 15 | 4.4 | 45 |
The piezoelectric material, the structure materials (the end-caps and the substrates) and the load resistor were modelled using element types of SOLID 226, SOLID 95 and CIRCU94, respectively. DL-53HD PZT (Del Piezo Specialities) was selected as the piezoelectric material (properties listed in table 2) because of its high figure of merit value, as suggested by literature [24]. On the top and bottom surfaces of the PZT plate, electrodes covered fully in the width direction (y-axis) and partially in the length direction (x-axis) by a length $L_e$, as shown in figure 3. The electric potentials of the nodes in the top and bottom electrodes were coupled individually to form two connecting points, which were connected with the load resistor. The load resistance was the optimal resistance that matches the internal impedance of the PZT plate and was calculated as

$$R_{\text{opt}} = \frac{1}{2\pi f C_p}$$

where $f$ is the frequency of the excitation force and $C_p$ is the capacitance of the PZT plate. $C_p$ is

$$C_p = \varepsilon_0 \varepsilon_{33} W L_e \frac{W}{L}$$

where $\varepsilon_0$ and $\varepsilon_{33}$ are the free space permittivity and the relative permittivity constant of PZT, respectively. For the PZT plate with dimensions listed in table 1, the optimal resistance $R_{\text{opt}}$ is 10 MΩ. The mechanical loss was accounted by specifying a mechanical quality factor of 20.

The adhesive layers between the substrates and the PZT plate were ignored, and all the parts of the SPT were bonded together by coupling the degrees of freedom at the bonding areas. The lower end-cap was fixed, while a sinusoidal force with an amplitude of 1 kN and a frequency of 2 Hz was uniformly applied at the apex of the upper end-cap. The harmonic analysis was performed to study the effects of the various parameters on the power output of the SPT. When one parameter was studied, the other parameters were kept the same as table 1 unless specified. The average electric power output of the SPT was obtained by recording the element solutions of the load resistor.

Table 2. The material properties of the piezoelectric material (DL-53 HD PZT).

| Parameters | Values |
|------------|--------|
| Density (kg m$^{-3}$) | 7900 |
| $S_{11}$ ($\times 10^{12}$ m$^2$ N$^{-1}$) | 15.1 |
| $S_{12}$ ($\times 10^{12}$ m$^2$ N$^{-1}$) | -4.5 |
| $S_{33}$ ($\times 10^{12}$ m$^2$ N$^{-1}$) | -9.4 |
| $S_{31}$ ($\times 10^{12}$ m$^2$ N$^{-1}$) | 24.8 |
| $S_{44}$ ($\times 10^{12}$ m$^2$ N$^{-1}$) | 37.1 |
| $S_{66}$ ($\times 10^{12}$ m$^2$ N$^{-1}$) | 39.2 |
| $d_{31}$ ($\times 10^{-12}$ m V$^{-1}$) | -300 |
| $d_{33}$ ($\times 10^{-12}$ m V$^{-1}$) | 680 |
| $\varepsilon_{11}$ | 810 |
| $\varepsilon_{33}$ | 3550 |
| $\varepsilon_{31}$ | 3850 |

The stress in the PZT with the substrate needs to be understood, and so it was first investigated. Simulation was performed on the SPT with and without using substrates. When used, the substrates were 0.6 mm thick and made of stainless steel. The Von Mises stress profiles of the PZT and the substrates along the length direction (x-axis) shown in figure 3) are presented in figure 4. The stress was derived from the major surfaces of the PZT and the substrate. Without the substrates, stress concentration is clearly observed at the edge of the joint, where the PZT plate is bonded to the end-caps. This is understandable because the geometry in the joint is not continuous while geometry discontinuity is the main cause of stress concentration. The peak stress in the PZT is as high as 52 MPa, which is much higher than its stress limit (35 MPa), although the stress of the PZT in the cavity region is only ~17 MPa. This stress concentration can easily result in the mechanical failure of the piezoelectric material, which was reported in [25]. When the substrates are used, stress concentration is only observed on the substrates, which are bonded to the end-caps in this case. The PZT suffers from little stress concentration, as evidenced by the evenly distributed stress. Therefore, by sandwiching the PZT between two substrates, the stress concentration is mainly located on the substrate instead of the PZT. Because the stainless steel substrate has a much higher stress limit (250 MPa) and thus a higher tolerance for stress concentration than PZT, this sandwiched structure is able to increase the load capacity of the SPT.

Figure 5(a) shows the power output of the SPT as a function of the substrate thickness. As the substrate thickness $t_s$ rises from 0.2 mm to 0.9 mm, the average power output declines from 9.1 to 4.2 mW. This can be explained by the variation of the stress in the PZT with $t_s$, as presented in figure 5(b). As $t_s$ increases, the Von Mises stress (mainly due to tensile stress) in the PZT decreases. This is because as $t_s$ increases, the cross-section area of the sandwiched structure increases, resulting in a reduced stress level when the same force is applied. It is
also observed that the substrates’ ability to reduce the stress concentration gradually decreases as the substrate becomes thinner. Considering the tensile stress limit of 35 MPa for the PZT and a safety factor of 2, the maximum stress in the PZT should be 17.5 MPa. Therefore, the minimum applicable thickness is 0.6 mm, which leads to a tensile stress of 17 MPa in the PZT and a power output of 5.7 mW. This substrate thickness will be used when prototyping the SPT in section 4.

3.2.2. Effects of the end-cap material and thickness. To evaluate the effects of the end-cap material and thickness on the power output, four metallic materials with different Young’s modulus and stress limits were used for the end-cap. They are stainless steel, copper alloy, titanium alloy and aluminium alloy. The material properties are listed in table 3.

| Properties of the materials used for the end-caps [26]. | AK stainless steel 304 | Copper alloy C17200 | Titanium alloy Ti–5Al–2.5Sn | Aluminium alloy 1100 |
|--------------------------------------------------------|------------------------|---------------------|----------------------------|---------------------|
| Young’s modulus (GPa)                                 | 193                    | 128                 | 110                        | 69                  |
| Poisson’s ratio                                       | 0.24                   | 0.3                 | 0.34                       | 0.33                |
| Density (kg m\(^{-3}\))                               | 8030                   | 8250                | 4480                       | 2710                |
| Yield strength (MPa)                                  | 205                    | 195                 | 760                        | 117                 |

The power output of the SPT with different end-cap materials and thickness is presented in figure 6. The average power decreases with the increasing end-cap thickness \(t_c\) for all the four materials. This is because as \(t_c\) increases, the end-caps become stiffer and thus deform less under the same load force. This means that the mechanical work made to the SPT becomes less, and so does the mechanical energy absorbed by the SPT. As a result, the electric power output is reduced. At \(t_c = 0.3\) mm, the SPT with the four end-cap materials produces about the same electric power. As \(t_c\) increases, the differences among these materials increase. The SPT with Al alloy end-caps always output the highest power, followed by the Ti alloy and the Cu alloy end-caps. The stainless steel end-caps are associated with the lowest power output. This is attributed to the Young’s modulus of the materials: Al alloy...
obtained at 6 mm, the maximum power output is 6.12 mW, which exists for each joint length. For example, with a joint length \( L = 52 \text{ mm} \), the maximum power output is 15.4 mW. The maximum von Mises stress in the end-caps is always slightly larger than the cavity length, as shown in figure 7. The maximum von Mises stress in these regions increases as the end-cap becomes thinner. To ensure a safe operation, when designing the applicable minimum end-cap thickness, \( t_{c, \text{min}} \), one must make sure that the maximum von Mises stress is within the yield strength of the end-cap material (listed in table 3). Considering a safety factor of 2, the applicable end-cap thickness, the corresponding power output and maximum von Mises stress in the end-caps are presented in table 4. Ti alloy has the highest power output and it can work safely with \( t_{c, \text{min}} = 0.3 \text{ mm} \) and produce \( P_{\text{ave}} = 15.4 \text{ mW} \). This benefits from its high yield strength (760 MPa), which is much higher than other materials. The stainless steel and the Cu alloy perform similarly with \( t_{c, \text{min}} = 2 \text{ mm} \), whereas the Al alloy requires the maximum \( t_{c, \text{min}} \) of 3 mm due to its lowest yield strength. Therefore, among the four materials studied, the Ti alloy is the best material for end-cap. It should be noted that for each end-cap material and thickness, the stress in the PZT should also be evaluated individually. This study selects stainless steel as the end-cap material for the overall consideration of the material strength, power output, and cost availability.

3.2.3. Effects of the electrode length and the joint length. The effects of the electrode length \( L_e \) and joint length \( L_j \) on the power output are presented in figure 8. In the simulation, varying the joint length was achieved by changing the values of the apex length \( L_a \) and the cavity length \( L_c \) but keeping \((L_c - L_a)/2\) and the cavity length \( H \) constant at 13 and 3.5 mm, respectively. This maintains the end-cap angle at 15°. An optimal electrode length \( L_{e, \text{opt}} \), which maximises the power output, exists for each joint length. For example, with a joint length of 6 mm, the maximum power output is 6.12 mW, which is obtained at \( L_e = 42.5 \text{ mm} \) and represents an 18% increase compared to the power output of 5.15 mW when the electrode fully covers the PZT \( (L_e = 52 \text{ mm}) \). It is also found that \( L_{e, \text{opt}} \) is always slightly larger than the cavity length, as shown in table 5.

The presence of the optimal electrode length is related to the clamping effect of the joint on the PZT, which can be revealed by the stress distribution of the PZT previously showed in figure 4. Due to the clamping effect of the joint, a portion of PZT under the joint is hardly stressed along \( x \)-axis and makes little contribution to the charge generation. The highly stressed part of the PZT, which produces most of the charge generation, has a length slightly larger than the cavity length. Therefore, the optimal electrode length \( L_{e, \text{opt}} \) is the length that covers the highly stressed part of the PZT. When the electrode length is smaller than \( L_{e, \text{opt}} \), part of the highly stressed PZT is not covered by the electrode and therefore does not contribute to the charge generation, leading to a reduced power output. When the electrode length is larger than \( L_{e, \text{opt}} \), the hardly stressed part of the PZT, which is covered by the electrode, generates little charge but increases the capacitance of the PZT by increasing the electrode area as suggested by equation (5). The increase of the capacitance gives rise to a reduced energy when the charge \( Q \) is a constant because the relationship between the energy and the capacitance is

\[
E = \frac{1}{2} \frac{Q^2}{C_p}.
\]

The results herein also agree with the observations on piezoelectric cantilever-based energy harvesters [27] that the maximum power can be generated when the electrode only covers the high-stress portion of the piezoelectric material and the

| Table 4. The applicable minimum end-cap thickness, the corresponding average power output and maximum von Mises stress in the end-caps. |
|---------------------------------------------------------------|
| **Applicable** \( t_{c, \text{min}} \) (mm) | **Power** \( P_{\text{ave}} \) (mW) | **Maximum von Mises stress** (MPa) |
| AK stainless steel 304 | 2 | 2 |
| Copper alloy C17200 | 5.7 | 6.39 |
| Titanium alloy Ti–5Al–2.5Sn | 0.3 | 15.4 |
| Aluminium alloy 1100 c | 3 | 4.17 |
| Maximum von Mises stress (MPa) | 94.6 | 88.1 | 378 | 55 |
power generation will be reduced if the electrode coverage expands to the low-stress portion.

It can also be observed from table 5 that the maximum power output decreases as the joint length increases. This can be simply explained by the increase of the clamping portion of the PZT plate. Although a short joint length is beneficial in energy generation, the minimum joint length is limited by the fabrication process and the required joint strength between the end-caps and the substrate. As the joint becomes shorter, the maximum force it can withstand safely decrease. For the SPT prototyped in section 4, a joint length of 6 mm will be selected to allow enough space for the laser welding during fabrication. The electrode covers the full length, instead of the optimal length, for ease of fabrication.

### 3.2.4. Effects of end-cap internal angle

Figure 9 shows the power output of the SPT as a function of the internal angle. The different internal angles in the simulation were achieved by varying the height of the end-cap \( H \) while keeping other parameters listed in table 1 at their initial values. That means the length of the inclined segments in the end-cap has to change with the internal angle. The end-cap height \( H \) was varied from 1 to 13 mm, leading to the internal angle varying from 4.4° to 45°.

As can be seen from figure 9, as the internal angle is reduced, the power output first increases and then decreases. It is worthwhile mentioning that for all the internal angles studies herein, the end-cap displacement along \( z \)-axis increases smoothly as the internal angle decreases. This means end-caps did not buckle since the buckling of the end-caps should be accompanied by an abrupt change in the displacement [28]. The observations from figure 9 disagree with the prediction of equation (1) and the analytic simulation results from [22] that a smaller internal angle results in a larger amplification factor, and thus a larger \( F_{tx} \) and higher electric power output, until the end-caps buckled. This is because equation (1) is only valid when the deformation of the end-cap is small enough, while the [22] does not consider the length change of the end-cap segments.

The effect of the length change of the end-cap segments on the amplification effect is graphically studied in figure 10. A compressive load force is applied on the apex BC of the end-cap with a profile of ABCD. If the end-cap segments do not change its length, the end-cap will deform to \( A_1B_1C_1D_1 \) with \( B_1C_1 = BC \), \( A_1B_1 = AB \) and \( C_1D_1 = CD \). The horizontal displacement of the end-cap at the joint is \( AA_1 \) or \( DD_1 \). In reality, when \( F_{apex} \) and \( F_{in} \), shown in figure 2(b), are large enough in the case of a very small internal angle, the apex (BC) and the inclined segments (AB and CD) will be shortened. As a result, the end-cap is deformed as \( A_2B_2C_2D_2 \) with \( B_2C_2 < B_1C_1 = BC \), \( A_2B_2 < A_1B_1 = AB \) and \( C_2D_2 < C_1D_1 = CD \). In such a case, the horizontal displacement of the end-cap at the joint part with the PZT will be \( AA_2 \) or \( DD_2 \). Because the horizontal displacement of the end-cap is also the displacement of the sandwiched structure, it can be used to evaluate the amplification effect of the end-cap. Figure 10 clearly shows \( DD_2 < DD_1 \).
Therefore, the amplification factor of the end-cap is reduced when the end-cap segments are shortened by the large forces, which is exactly the case when the internal angle of the SPT is too small and the power starts to decrease, shown in figure 9.

3.2.5. Effects of the piezoelectric plate thickness. There exists an optimal PZT thickness, $t_{\text{p, opt}}$, which has the maximum power output from the SPT, as shown in figure 11. The SPT with $t_{e} = 0.5$ mm outputs the maximum power of about 15 mW at $t_{\text{p, opt}} = 2$ mm. This is because as $t_{p}$ increases, the mass of the PZT increases and so does the ratio of the PZT mass to the SPT mass. The ratio of PZT mass to the SPT mass increases monotonously from 0.18 to 0.80 as $t_{p}$ increases from 0.5 to 9 mm. This means a larger portion of the mechanical energy input to the SPT is absorbed by a relatively thicker PZT. Meanwhile, as $t_{p}$ increases, the SPT becomes stiffer. As a result, less displacement is generated in the apex under the same load force, which means that less mechanical energy is input to the SPT. Therefore, as $t_{p}$ increases, the total mechanical energy input to the SPT decreases whereas the portion of the energy distributed in the PZT increases. This leads to an optimal $t_{p}$ at which the mechanical energy absorbed by the PZT reaches the maximum, and so does the electric power output. Since $t_{\text{p, opt}}$ is related to the mass ratio of the PZT to the SPT, it is also related to the thickness of the end-cap as evidenced by the result in figure 11: when $t_{e}$ increases from 0.5 to 2 mm, $t_{\text{p, opt}}$ increases from 2 to 4 mm.

4. Prototype fabrication

A prototype of the SPT (figure 12) was fabricated based on the initial dimensions listed in table 1, except that an electrode length of 52 was used. The end-caps were made by using a metal sheet bending machine. The substrates were bonded to the end-caps by laser welding. The PZT plate (DL-53HD, Del Piezo Specialities) was attached to the substrates by structure adhesive (3M Scotch-Weld™ DP-460).

5. Experimental characterisation of the SPT

5.1. Testing the SPT on a loading machine

5.1.1. Experimental setup and methods. The fabricated SPT was first tested on a loading machine (ElectroPlus™ E1000 Test System, Instron Corporation, UK), as shown in figure 13. The loading machine applied a compressive force on the SPT, which takes the form of

$$ F = F_{\text{pre}} + F_{L}\sin(2\pi ft). \tag{7} $$

$F_{\text{pre}}$ is the pre-load force, which does not affect the power output but ensures that the SPT is always in compression. $F_{L}$ is the amplitude of applied dynamic force and $f$ is the applied frequency. During the test, the SPT was connected to a circuit board with a load resistor. The voltage produced across the load resistor was measured by a data log (NI 9229, National Instrument) to calculate the power generation.

5.1.2. Results and discussions. The experiments were first performed with $F_{L} = 1$ kN, $F_{\text{pre}} = -1.1$ kN and $f = 2$ Hz to validate the FE model. The measured average power output at different load resistors are compared with simulation in
The simulation was performed with parameters being the same as the fabricated prototype. Good agreements are observed between the measured and simulation results. The measured power peaks at 4.68 mW with a 6.6 MΩ load resistor, while the simulated power peaks at 5.15 mW with a 7.8 MΩ resistor. The difference between the measured and simulated peak power output is 9.1% possibly due to the tolerances of the material properties and structural parameters between the FE model and the prototype.

Figure 15 shows the power output of the SPT as a function of the applied frequency \( f \) and the applied force amplitude \( F_L \). The average power increases quadratically with \( F_L \) and linearly with \( f \). As \( F_L \) increases from 0.1 to 1 kN, the power output increases from 0.04 to 4.68 mW; as \( f \) increases from 2 Hz to 50 Hz, the power output increases from 1.2 to 55 mW. This is not surprising because the power output of a piezoelectric material under cyclic excitations is proportional to the applied frequency and the square of the average stress [12]. In Roshani et al [9], four piezoelectric stacks for energy harvesting from asphalt pavement roadways generated an average power of ~2 mW when actuated by a 5 Hz cyclic force with a peak amplitude of 2 kN. When actuated at the same force condition, the SPT generated 11.5 mW, which is more than 5 times of the power generated by the piezoelectric stacks in [9].

5.2. Testing the PTF used as a footwear energy harvester

5.2.1. Experimental setups and methods. To demonstrate the application of the designed SPT, the SPT was retrofitted to a boot as shown in Figure 16. A metal plate was used between the boot and the SPT to increase the contact area. A Nylon strap was used to secure the position of the SPT. During the test, a human subject (weight 76 kg) wearing the boots walked on a treadmill at 4.8 km h\(^{-1}\) to generate energy. The SPT was connected to a variable load resistor. For each load resistor tested, the human subject walked continuously for 2 min, and the voltage generated across the load resistor was recorded to calculate the average power output.

5.2.2. Results and discussions. When the SPT was used as a footwear energy harvester, the typical voltage measured across a 2 MΩ load resistor is shown in Figure 17(a). The step frequency, which can be identified from the voltage, is 1.4 Hz. The average power output of the SPT at different load resistors is presented in Figure 17(b). The optimal load resistor is identified as 2 MΩ, which is lower than the expected value of 9.4 MΩ, calculated by equation (4). This is because although the step frequency is 1.4 Hz, the generated voltage has not only a component at 1.4 Hz but also high-value harmonic components at higher frequencies, leading to a reduced optimal resistor. The SPT generated the maximum average power of 2.5 mW. Although this power is lower than the power consumption of a wireless sensor, which is usually in the range of tens of milliwatts, the SPT together with a proper power management circuit and energy storage, can be used to power the wireless sensors in an intermittent mode, which is required by most real application cases, for example, body or structural health monitoring [29].
6. Conclusions

In this work, a SPT with flex end-caps was designed and characterised for energy harvesting in high compressive force environments. A CPC-FEM was developed to study the effects of various parameters on the performance of the SPT. The modelling results provide the following guidance for optimising the design of the studied SPT:

1. By sandwiching the PZT between two metal substrates, the stress concentration is shifted from the PZT surfaces to the substrate surfaces and therefore, the load capacity is enhanced.
2. Within the stress limit, thinner end-caps made of a more compliant material are always recommended because more mechanical energy is coupled to the transducer when the same load force is applied.
3. The electrode coverage should exclude the clamped portion of the piezoelectric material, which increases the capacitance of the transducer but contributes little energy generation.
4. When the bonding strength is met, the joint area should keep as small as possible to reduce the clamped portion of the piezoelectric material.
5. At small internal angles, the length change of the end-caps’ inclined segments reduces their amplification effect.
6. There is an optimal piezoelectric thickness associated with each end-cap thickness.

An SPT prototype was fabricated and characterised using a loading machine. The experimental results agreed well with simulation. The prototyped SPT produced an average power of 4.68 mW when subjected to a 1 kN 2 Hz sinusoidal force. Average power up to 55 mW was measured when the SPT was excited by a 0.5 kN 50 Hz sinusoidal force. The SPT can be used for energy harvesting in large force environments such as under footwear, floor tiles, and railways. The generated electric energy can be used to supply low-power-consumption wireless sensors. As a case study, the SPT was fit into a boot to work as a footwear energy harvester, which generated an average power of 2.5 mW at a walking speed of 4.8 km h⁻¹.

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