Design of Two-Stage Force Amplification Frame for Piezoelectric Energy Harvester

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ABSTRACT

This paper describes the design of a two-stage force amplification frame for the piezoelectric energy harvester to capture mechanical energy from walking human footsteps. The frame design optimises the stress distribution to improve the force amplification ratio on the existing footstep energy harvesters. The magnification of the input force exerted on a piezoelectric stack increases the system's power output. A combination of single and compound two-stage frame design with additional linkage support was proposed, which maximise the conversion of tension to compression forces. The proposed frame also significantly reduces the maximum displacement of the frame to ensure walking comfort. The frame is tested with the input force of 85 N to 120 N based on the adult footstep during walking and running. The simulated results show that the proposed frame has a force amplification ratio of 25.3, an 11.85% improvement from the existing frames. The frame

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also limits the maximum displacement to 1.02 mm, 22.14% compared to the existing frames.

Keywords: *Energy Harvester; Compound Two-Stage Frame; Piezoelectric; Force Amplification Mechanism;Force Amplification Ratio*

Introduction

Mechanical energy from various sorts of vibration, motion, or any other source is not being gathered. Therefore, this source of energy is wasted and thus dispersed to the surrounding. To effectively utilise these losses, wasted mechanical energy is absorbed by piezoelectric material and becomes valuable electrical energy [1]. Piezoelectric generation only depends on mechanical factors such as pressure, strain, or vibration. Piezoelectric material will convert these mechanical factors to electrical power [2]. Therefore, if the mechanical energy of human footsteps can be successfully converted into useful electrical energy, it will benefit energy conservation and reduce emissions [3]. Research on piezoelectric energy harvesting has been conducted extensively in various applications, including structural condition monitoring, implanted biomedical devices, rain energy harvesting, vibration-based harvesting, and other electronic devices [4]-[8].

The technology of piezoelectric on floor tiles to harvest energy is relatively new. By utilising human footsteps, useful energy can be harvested and generate electricity [9]. Energy production depends on humans' weight, deflection of piezoelectric material, type, and movement frequency. Piezoelectric floors were applied and tested at Tokyo stations by East Japan Railway Company in 2008, which have more than 400,000 people pass by per day [10]. It was installed around the ticket machines in the station instead of installing all over the station. The station installed 25 square meters of piezoelectric floors, producing approximately 1.4 kWh daily, enough to power the monitors and ticket machines. Besides that, PaveGen installed tiles on a public soccer field in Rio de Janeiro to store electricity for lighting after sunset [11].

Cantilever beams are the most common Piezoelectric Energy Harvester (PEH) as they generate an enormous average strain with external force than plates, diaphragms, and disks. Cantilever beams are well-functioned with input excitations and tip plucking by using a proof mass placed at the end to reduce the resonance frequency and improve the inertial force. However, the cantilever beam cannot work with high compressive force excitation as it has a smaller force-to-displacement ratio [12]. The conventional piezoelectric harvesting module combines a piezoelectric unimorph and a bimorph cantilever arrangement. One or two layers of piezoelectric element are laminated to a single flexible plate and function in bending mode. Typically, typical cantilever-type energy harvesters generate a negligible amount of output power. It is easily broken and cracks near the clamping end under a small amount of pressure.

A variable-geometry cantilever beam was used to enhance the power harvesting process. However, it suffered from overstraining near the clamping area. Calio et al. [13] used a trapezoidal cantilever beam to avoid overstrain. The strain was distributed more evenly along with the beam structure, and it could sustain higher excitation loading, which led to an increase in the harvested energy density. Trapezoidal shape cantilever beam has a more evenly distributed strain throughout the beam than the rectangular beam, consisting of non-uniform strain distribution. Besides, a trapezoidal cantilever produced twice the energy compared to a cantilever beam in a rectangular shape for the same volume of PZT material.

A flex-compressive mode cymbal transducer was designed by Wang et al. to fully utilise the compressive stress in piezoelectric elements as the tensile strength of a piezoelectric material was always lower than the compressive strength [14]. The transducer improved the stiffness of the cymbal mechanism and enhanced the load capacity. The flex-compressive mode piezoelectric energy harvesting cell (F-C PEHC) was assembled from two PZT piezoelectric stacks and four types of steel elements. The cymbal top plate with short limbs was implemented to enhance the load capacity. The structures were mechanically assembled and had no bonding layer, and all the structural parts were replaceable.

A non-linear parametric model was developed by Chen et al. [15] to estimate the deformation of the frame accurately by considering the possible constraints of each frame part. The results of the non-linear parametric model showed an accuracy of at least 95%. The results showed that the force amplification ratio was improved by reducing the thickness of the linkage, and a longer linkage improved the bending deflection of the frame. However, a longer and thinner linkage produced more significant stress on the linkage and the blocks.

As the force amplification frame, various lever mechanisms may be utilised. The bridge-type amplification frame, which has a high amplification ratio and a small size, was one of them. However, the conventional bridge-type amplification frame is limited by its low load capacity, which cannot withstand high loading forces. The force amplification cannot be promised by force applied onto the frame because different humans have different weights when walking on the frame. Hence, Wen et al. [16] developed a compound two-stage (CTS) force amplification frame to increase the frame stability under high loading force conditions. When an input force was exerted vertically downward on the top of the outer frame, the frame produced a horizontal tension force along the x-axis, pulling the outer frame's output ends on both sides away from the centre. As the output ends of the outer frame were attached to the input ends of the inner frame, the outer frame generated a tensile force that pulled the input ends of the inner frame away from the centre. Thus, the output ends of the inner frame generated compressive force along the z-axis, which was connected to both ends of the piezoelectric stack. Consequently, compared to the conventional bridge-type amplification frame, this frame has a greater force amplification ratio, a greater safety factor, and a smaller size.

The force amplification frame consisted of two shapes which were convex and concave frames. Convex and concave frames applied tensile and compressive force to the piezoelectric stack. Generally, the force amplification ratio for a convex frame was higher than the concave frame for a single amplification frame because the input end has a large deformation. High deformation caused a decrease in safety factors when the surface area of bending increased. According to the law of energy conservation, the increase in input force decreased the output displacement of the frame for the two-stage force amplification mechanism. The concave frame's inner frame could not generate a high force amplification ratio due to the outer frame's diminished output displacement. Mechanical deformation consumed the majority of the strain energy stored in the frame, thereby decreasing the total amplification ratio of the frame [16].

A standard bridge-type amplification frame has only single input and output ends, where external force was applied to a small contact area. The structure was not able to sustain tension stress. Besides that, each force amplifier can only support a limited load capacity, and it can damage the structure when the load exceeds the yield strength of the material. Hence, a protective structure was needed to improve the strength of the mechanism. A wedge structure can support a large force, but it has a relatively small safety factor and an enormous size. Wen and Xu [16] designed an integrated multi-stage (IMS) force amplifier that used both force amplifiers in the frame to improve output performance and sustain high input force.

The structural characteristic of the wedge mechanism allowed it to convert and amplify the vertically downward input force into horizontal force. The leverage structure improved the force amplification and reduced the physical size of the frame. However, the limitation of this structure was that the frictional force acting on the contact surface between the two wedges restricted the movement and caused a reduction in the force amplification ratio.

The existing bridge-type force amplification frames have a limited capacity for tolerating the loading force. When different human weights are exerted on the frame, the force amplification cannot be guaranteed by the loading forces exerted on the frame. Researchers have tried to optimise the force amplification frame by balancing the safety factor and force amplification ratio, but improving it is challenging [16]. Hence, factors such as force amplification ratio and force transmission efficiency are still insufficient in the current research. The conversion efficiency reduces with the size of the piezoelectric modules because the coverage of footprints reduces when the module area increases [17]. Besides, a large area of mechanical strain may damage the material due to its brittleness. The output voltage generated from piezoelectric material is also significantly low compared to other energy sources [2]. The level of comfort experienced by humans when stepping on a frame is directly related to its displacement-generally, a smaller displacement results in greater comfort. However, the output energy of a piezoelectric energy harvester depends on the degree of compression of the piezoelectric stack. The amplification frame acts as a converter to maximise the output energy, converting the vertical load from the human step into a horizontal load that compresses the piezoelectric stack. The vertical displacement should be at a minimum, and the horizontal displacement to be at a maximum. Therefore, this paper aims to optimise the force amplification ratio of the piezoelectric energy harvester while minimising the frame displacement to ensure human comfort. This can be achieved by improving the effectiveness of force conversion through the design of the frame.

Mechanical Design

Mechanism description of the amplification frame

The proposed design of the energy harvester's amplification frame is shown in Figure 1. This design is composed of a combination of the single and compound two-stage frame. It consists of two-beam layers at the inner frame to ensure the stress is evenly distributed. The design is supported with a layered beam at the outer frame to avoid high-stress concentration. Besides, a linkage is added at the outer frame to assist in pushing the output end of the inner frame inward to compress the piezoelectric stack attached to the output ends of the inner frame. Figure 1(a) depicts the input force, F_i, acting vertically downward at point *A* onto the outer frame's input end. This force compresses the input ends *A*, pushing the *BC* ends outward and the *DE* ends inward, leading to the compression of the inner frame, as illustrated in Figure 1(b). The *DE* ends apply compression forces to the piezoelectric stack inside the inner frame. Furthermore, the tensile force on *BC* helps to further compress the *DE* ends. Figure 1(c) presents the system's overall design, where the applied force F_i causes the *BC* ends to extend outward and the *DE* ends to compress inward. The detail dimension of the amplification frame is shown in Figure 2.

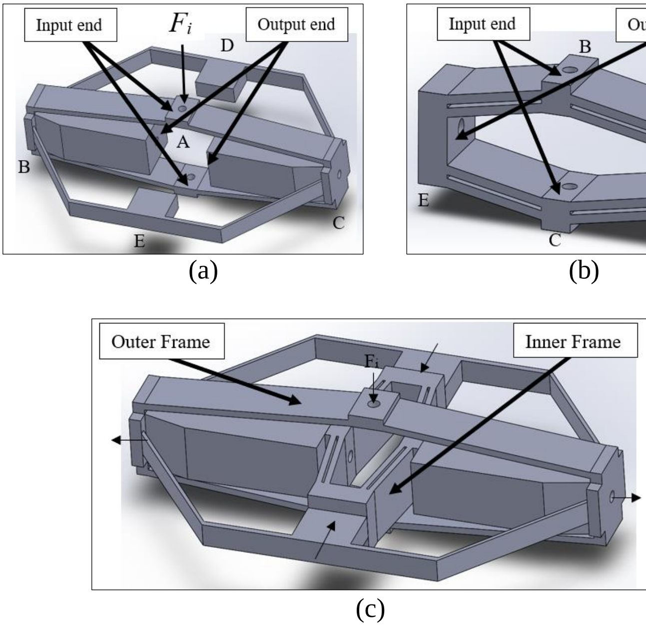

Figure 1: (a) Outer frame; (b) inner frame; and (c) assembly of the outer and inner frame

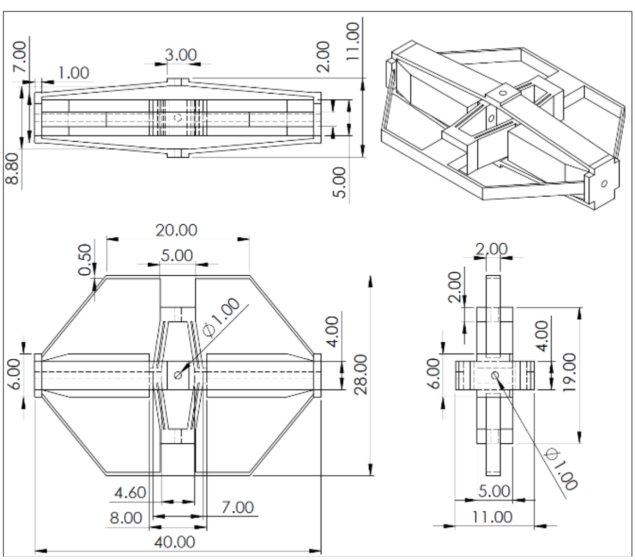

Figure 2: Detail dimension of the amplification frame

Design criteria and constraints

The design of the piezoelectric energy harvester's amplification frame was made with several considerations and constraints, including the selection of material, amplification mechanism, and frame features. Alloy steel 4150 was proposed as the frame material in this design because of its high tensile and yield strength and higher Young's modulus *(E)* to density, ρ ratio. A greater E-ρ ratio allows the frame to have more significant deformation. The material properties of alloy steel 4150 are shown in Table 1.

Table 1: Material properties of alloy steel 4150

Properties	Value
Density	8.03×10^3 kg/m^3
Poisson's ratio	0.27
Young's modulus	190 GPa

The proposed amplification frame is based on the frame designed by Wen et al. [18]. The force amplification frame design by Wen et al. [18] utilised the outer frame for pulling the inner frame and inducing compression on the output ends of the inner frame, thereby compressing the piezoelectric stack. The outer frame itself was pulling on the inner frame. Hence, the compression of the piezoelectric stack is entirely dependent on the outer frame's pulling force. This design lacked a sufficient force amplification ratio because the forces were only transmitted to the inner frame via the connection between the output ends of the outer frame and the input ends of the inner frame, which did not maximise force transmission. When an extra compressive force acts on the inner frame's output ends, the inner frame's output ends experience additional compressive force from the outer frame, which increases the force amplification ratio.

Hence, the proposed design in this paper used a combination of single and compound two-stage frames to maximise the force transmission. This design consists of two layers of the beam at the inner frame to ensure the stress was evenly distributed and to avoid high-stress concentrations occurring in the single-layer outer frame design. Besides that, an additional linkage was added to the outer frame to assist in pushing the output end of the inner frame inward to compress the piezoelectric stack attached to the output ends of the inner frame.

Finite element modelling and simulation

The finite element model was created to estimate the force amplification ratio of the force amplification frame. The numerical analysis of the proposed frame was done in ANSYS simulation software. The results of stress distribution, total deformation, reaction force, Factor of Safety (FOS) and amplification ratio for a range of input forces were analysed. The input force of 100 N was applied vertically on the top and bottom ends of the outer frame, giving a compressive load of 100 N. The detailed location of the constraints and force inputs on the model are shown in Figure 3. Both output ends of the inner frame were fixed to determine the reaction force from the applied input force through the outer and inner force amplification frame. Mesh refinements were used on the beam's surface, and the outer frame's input ends to obtain accurate stress distribution and total deformation results along the beam. The mesh size of 1 mm was used in the simulation based on the result obtained from the mesh convergence test. The model validation was made by comparing the total deformation and maximum stress of the model published by Wen et al. [18] before modification was made to the Wen et al. [18] model.

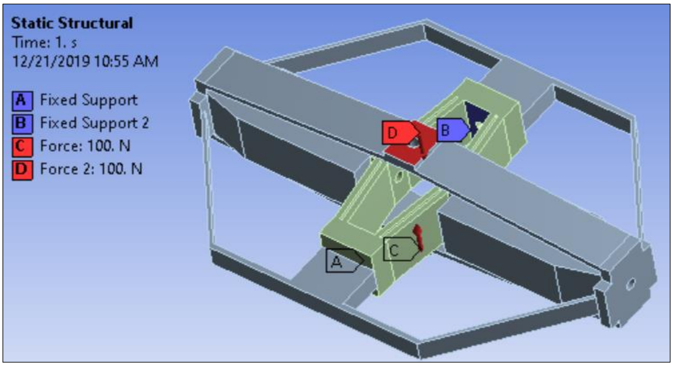

Figure 3: Location of the constraints and force inputs in the ANSYS simulation model

Results and Discussion

The effect of input force on the force amplification ratio

After validating the model with an input force of 100 N, the model was analysed with input forces ranging from 5 N to 160 N with a 5 N increment. Figure 4 displays the ratio of force amplification for input forces ranging from 5 N to 160 N. Based on clinical data from Keller et al., the range of input force from 85 N to 120 N was equivalent to the force input from average human footsteps [19]. However, the model was analysed from 5 N to show the full range of energy input, including the input force from children's steps. Furthermore, the input force is tested until the safety limit of the model, which is 160 N, to cover the extreme case.

The results with an input force of 100 N were compared with the existing literature models. Figure 4 shows that the force amplification ratio fluctuated from 25.299 to 25.300 when the input force increased from 5 N to 50 N. The 0.004% fluctuation here is insignificant to explain the effect of input force on the amplification ratio. Still, it is due to the deviation from Discrete Element Modeling. With the input range from 55 N to 160 N, the amplification ratio increase gradually from 25.2982 to 25.2994 with the rise in the input force. The trend is comparable with peer results [20]. This design's amplification ratio was relatively higher than existing models, with an amplification ratio between 17.90 and 22.62. The improvement in the force amplification ratio will contribute to the larger power output.

Deriving from the result in Figure 4, the factor of safety of the proposed design is 1.35 to 1.85 with an input force of 85 N to 120 N. At the input force of 160 N, the factor of safety will reach unity, and this is the maximum allowable input force for this design. Based on the size of the proposed amplification frame, each floor tile can fit in 16 units of the frames. Thus, the maximum weight a floor tile can support is up to 260 kg, sufficient for typical human steps.

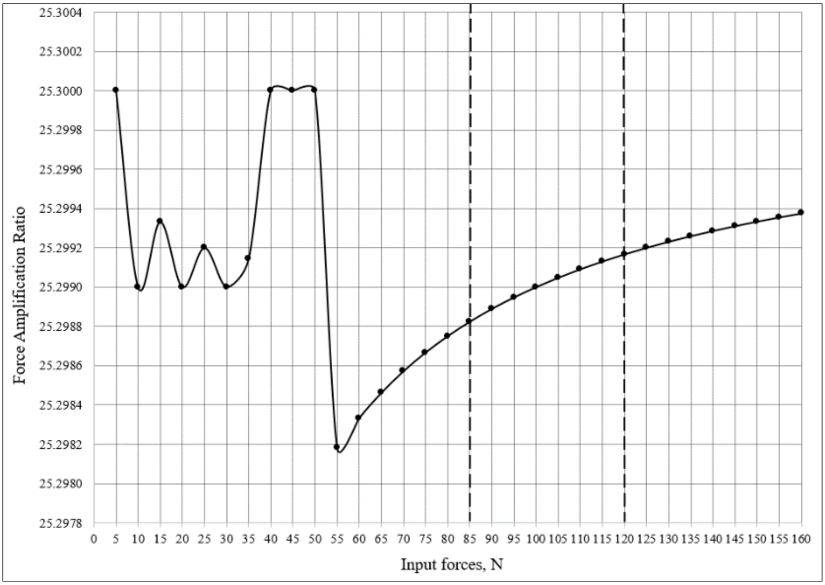

Figure 4: Graph of force amplification ratio against input forces, N

Stress distribution of the proposed frame when subjected to 100N input force.

Figure 5 showed the stress distribution of the model when a compressive force of 100 N was applied. The results showed that the maximum stress on the frame was 1075.90 MPa. The stress was concentrated on the outer frame, where the maximum stress occurred near the outer frame's input end, as shown in Figure 6. Besides, there was also a high-stress concentration at both ends of the outer frame. The stress was evenly distributed on the inner frame along the compound beams, reducing the stress concentrated at a particular location.

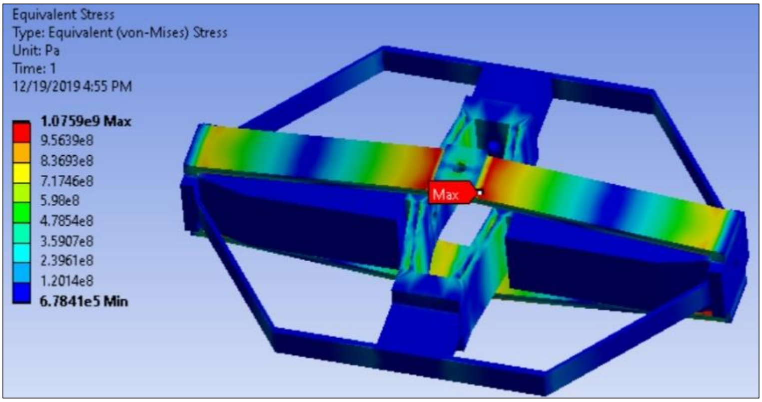

Figure 5: Maximum equivalent (Von-Mises) stress for input force of 100 N

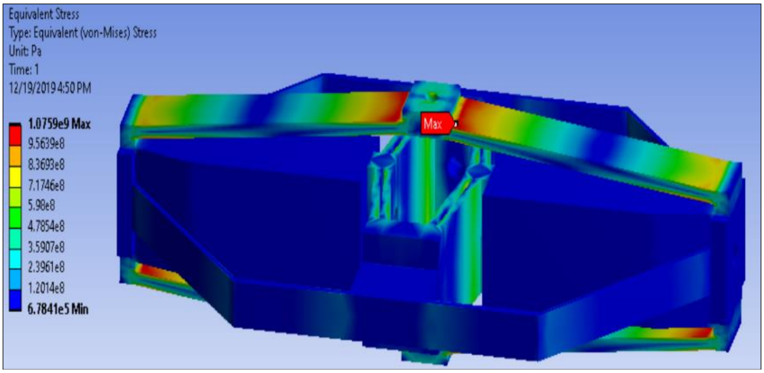

Figure 6: Location of maximum stress on the beam of the outer frame

Total deformation of the proposed frame based on input force of 100 N

Figure 7 showed the frame's total deformation and the maximum deformation location when 100 N compressive force was applied to the model. The results showed that the maximum deflection was 1.0186 mm, located at the outer frame's centre. The deflection was lower than the peers' models, which was

1.31 mm to 4.21 mm. The reduction in the frame's deflection ensures human comfort while stepping on it.

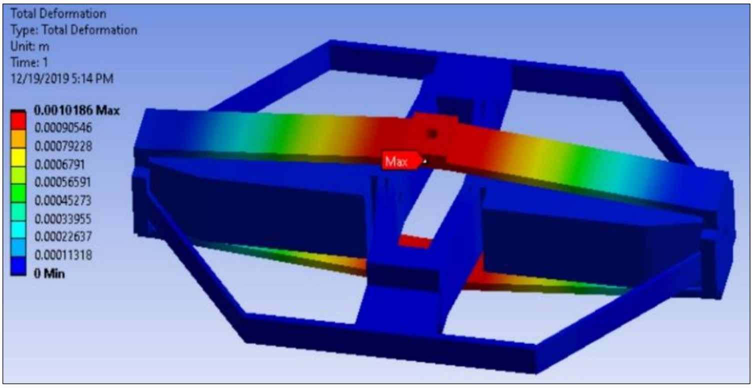

Figure 7: Total deformation when input force of 100 N was applied

Performance comparison with existing frames

The performance of this newly proposed frame showed improvement in most aspects compared to existing designs. The comparison table was constructed as shown in Table 2. The model had the highest force amplification ratio among other current designs. The force amplification ratio obtained for this proposed design was 25.30 compared to 22.62 on the existing designs, with an 11.85% improvement. Besides, the FOS of the proposed design was also higher than the single two-stage harvester design, which was 1.60 compared to 1.23 but lower than the compound two-stage harvester design and IMS harvester design. Moreover, the total deformation for the proposed design was the lowest among all existing designs. Lower deformation of the frame ensured human comfort while stepping on it.

Table 2: Performance comparison of various designs of the energy harvester's frames

Indicator	Proposed design	Single two-stage harvester [18]	Compound two-stage harvester [18]	IMS harvester [16]
Input force (N)	100	100	100	67.73
Maximum	1.02	4.21	1.31	3
Minimum factor	1.6	1.23	2.94	1.98
Force	25.3	22.62	17.9	18.83

Conclusion

This paper presents the design and modelling of a piezoelectric energy harvester's amplification frame based on a multi-stage force amplification mechanism. The main design variables of the models are optimised to achieve the best force amplification ratio with a more prominent safety factor. The proposed model has a force amplification ratio of 25.30, and 11.85% improvement compared to existing designs. A minimum Factor of Safety (FOS) of 1.6 was obtained for the proposed design, supporting the application. The model also showed a deformation of 1.02 mm, which is the lowest compared to existing designs. The reduction in the deformation improves human comfort while stepping on it.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest

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