An Efficient Energy Absorbing Structure Inspired by Energy Harvesting Device

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Abstract. An auxetic structure, exhibiting Negative Poisson's Ratio (NPR) effect, is different from a conventional structure due to its special properties, including indentation resistance, shear resistance, and sound absorption. The auxetic structure gets expanded when it is stretched, or becomes shrunk when it is compressed. Inspired by authors' previous research on design optimization of energy harvesting device (Piezoelectric Flex Transducer) scavenging biokinetic energy from human walking, a novel NPR structure is further developed, which has demonstrated potential ability to absorb impact energy as well as increase structural strength. The research into this NPR structure provides useful guidance on practical applications in various engineering subjects, particularly in tissue, aerospace, automobile and structural engineering.

Introduction

With rapid development of low power consuming devices, demands for mobile energy harvesters are increased and this will finally lead to the reduction of the use of battery. There are many energy harvesters designed to harvest energy from ambient environment and to power mobile devices, such as the wearable thermoelectric generator and the cantilevered bimorphs piezoelectric vibration harvester. As one of the micro-scale energy harvesters, piezoelectric energy harvesting has received great attentions since piezoelectric materials have good electrical–mechanical coupling effects. There have been a number of reviews that are specifically on piezoelectric energy harvesters and piezoelectric materials (Siddique et al. 2015), which evidenced the recent and rapid development of this special form of energy harvesters.

To improve the efficiency of mobile piezoelectric harvesting devices, design optimization has been carried out to maximize the power output. Silva and Kikuchi (1999) applied topology optimization method (TOM) to obtain the efficient layout of piezoelectric materials. They found an optimal distribution of the materials and void phases using finite element model and then generated the optimal design of the piezoelectric transducer. Kögl and Silva (2005) proposed a new material model that was based on the SIMP (solid isotropic material with penalization) to improve the design of piezoelectric actuators using topology optimization. Lu et al. (2011) proposed a maximum power point tracking scheme based on a time-multiplexing mechanism for general piezoelectric energy harvesters to improve the efficiency of energy harvesting from the circuit. Deng et al. (2015) maximized the output of a piezoelectric vibration energy harvester by finding the optimal damping ratio and electromechanical coefficient. Zhao et al. (2016) employed the synchronized charged extraction circuit to enhance the galloping piezoelectric energy harvesting. Luo et al. (2017) applied a metamodel assisted optimization strategy to achieve the maximal bio-kinetic energy conversion from the bio-kinetic energy of human body movement.

Negative Poisson's Ratio (NPR) structure has very fine applications in various engineering subjects, such as aerospace, automotive, biomedicine and defense sectors. NPR structures can improve mechanical properties, including shear resistance, indentation resistance and fracture toughness, compared to conventional materials from which they are made. Lakes (Lakes, 1987) first developed the NPR polyurethane foam with re-entrant structure, which had a Poisson's ratio of -0.7. In contrast to conventional materials (like rubber, glass, metals, etc.), NPR structures expand transversely when pulled longitudinally and contract transversely when pushed longitudinally. A set of materials possessing the NPR property, such as synthetic polymer-polytetrafluorothylene (PTFE), microporous ultra high molecular weight polyethylene (UHMWPE) and polypropylene (PP), have been successfully investigated by many researchers. To achieve unusual and improved mechanical performance, NPR materials have been utilized to offer a new direction for the enhanced structural properties. Scarpa (2004) demonstrated that the NPR foam also showed an overall superiority regarding damping and acoustic properties compared to the original conventional foam. Recently, the energy absorption capacity of NPR structures has been focused on to absorb the collision energy and improve the impact crashworthiness (Yoon et al. 2016).

In this work, an energy harvesting device (Piezoelectric Flex Transducer, PFT) scavenging biokinetic energy from human walking has been briefly introduced based on authors' previous research (Luo et al. 2017). A coupled piezoelectric-circuit finite element model (CPC-FEM) to study the responses of the PFT is developed. Then, metamodels are constructed using Genetic Programming from a 140-point optimal Latin hypercube design of experiments to replace the time-consuming computation of the responses functions. Finally, an optimal design of piezoelectric flex transducer to achieve the maximal bio-kinetic energy conversion is achieved. Inspired by this optimal PFT device, a novel Negative Poisson's Ratio (NPR) structure is proposed, which has demonstrated its ability to absorb impact energy as well as increase structural strength. The research into this NPR structure provides useful guidance on practical applications in various engineering subjects, particularly in tissue, aerospace, automobile and structural engineering.

Brief Review of Optimal Piezoelectric Flex Transducer Design

Piezoelectric Flex Transducer (PFT) that was developed base on the Cymbal device, was optimized to achieve the higher bio-kinetic energy conversion by Luo et al. (2017). The numerical simulations in ANSYS were performed using a coupled piezoelectric-circuit finite element model (CPC-FEM) shown in Fig. 1.

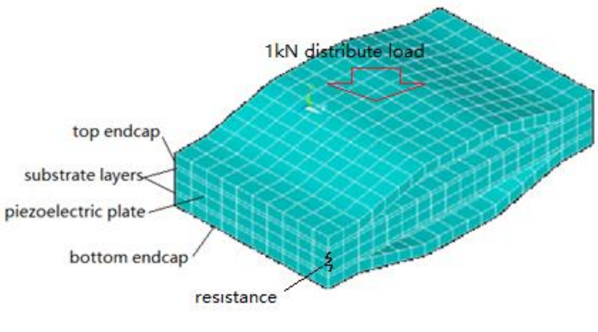

Fig. 1 FE modelling of piezoelectric flex transducer

To determine the optimal geometric parameters of the PFT device for the best design configuration in terms of the maximal power generation subject to stress and displacement requirements, parametric optimization of the PFT device is performed based on the metamodels, which are built by Genetic Programming from a 140-point optimal Latin hypercube design of experiments. This entire optimization process will be described in the following paragraphs and for more details, see Luo et al. (2017).

Design of Experiments (DOE) is a powerful statistical technique to study the effect of multiple variables simultaneously and this technique can also strongly influence the quality of a metamodel. To construct high accurate and efficient metamodels, a uniform Latin hypercube DOE based on the use of the Audze-Eglais optimality criterion (Audze and Eglais, 1977), is used in this paper. Then, the FE analyses of the proposed DOE are performed at the 140 uniformly distributed design points to optimise the PFT. The bar chart of the minimum distances between the sampling points is shown in Fig.2 with the indication of a good uniformity of the DOE.

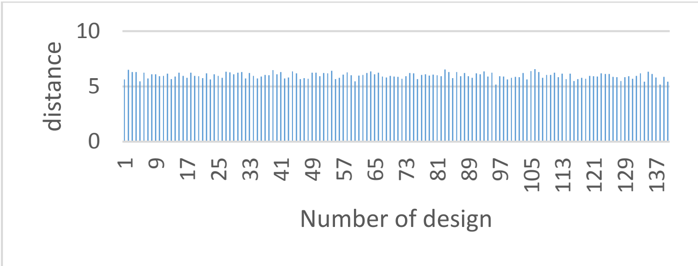

Fig. 2 Minimum distances between points in 140–point optimal Latin hypercube DOE.

Once the sampling points are determined by the above DOE technique, Genetic Programming (GP) is applied to build the metamodels, which will be used to replace the time-consuming FE simulations of the responses functions. GP (Koza, 1992) is a systematic way of selecting a structure of high quality global approximations. Selection of the structure of an analytical approximation function is a problem of empirical model building. The genetic programming code was first developed according to the guidelines provided by Koza (1992), then implemented by Armani et al. (2014). The common genetic operations used in genetic programming are reproduction, mutation and crossover, which are performed on mathematical expressions stripped of their corresponding numerical values. More details about genetic programming used in this paper can be found in Armani (2014).

The PFT device consists of a piezoelectric plate sandwiched between two metal endcaps with shallow cavities as shown in Fig. 3. Two geometric parameters, i.e., the total length (D_p=52mm) and the width (W=30mm), are kept constant in the optimization process. Clearly, the effective design should amplify and redirect the downward applied mechanical force to a horizontal force so that the majority of the applied force acts to stretch piezo-plate horizontally. The design should also allow a certain amount of space between the piezo-plate and the endcaps so that the piezo-plate can actuate more freely for a higher elastic deformation or elastic strain, which will correspond to a higher generation of electricity.

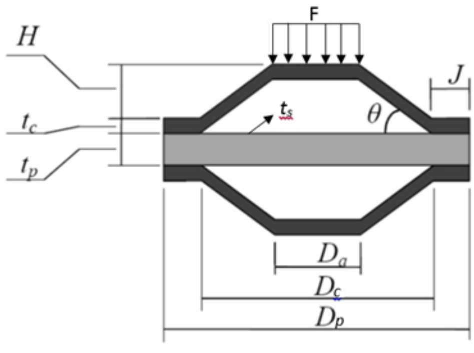

Fig. 3 Geometrical parameters describing the PFT configuration

Taking into account all the above, the design variables chosen to vary the geometry of the PTF include the cavity length (*Dc*), the apex length (D_a), the endcap internal angle (θ) and the respective thicknesses of the piezoelectric plate (t_p), the substrate layer (t_s), and the cap (t_c). By altering the cavity length, the internal angle, and the apex length, the overall height of the cap (*H*) will be changed. The joint length (*J*) can be defined as a function of the cavity length. . Thus, the optimization problem is formulated as shown below:

Max *P*

Subject to:

$$\frac{D_{disp}}{H} < 1 \qquad (1)$$

$$\frac{\sigma}{\sigma_y} \leq 0.5 \quad (2)$$

where P means the non-dimensional electrical power. H is the height of endcap and J is the joint length, D_{disp} is the displacement of the apex, σ_y is the yield stress of the endcap material, σ is the maximum principal stress in the cap component. The material properties of the device, bounds for design variable, and the detailed parametric optimization are given in (Luo et al. 2017).

A Novel Negative Poisson's Ratio Structure and Its Application in Tissue Engineering

Inspired by the above PFT design configuration shown in Fig. 3, a novel Negative Poisson's Ratio (NPR) structure is proposed and depicted in Fig. 4. NPR materials (Lakes, 1987) get fatter when they are stretched, or become smaller when compressed, in contrast to conventional materials. One of distinct features possessed by NPR materials/structures is the excellent energy absorption capacity and resistance to impacts (Evans & Alderson, 2000) because when an object hits NPR materials, it compresses the material flowing in one direction to as well as laterally contracts towards the vicinity of the impact, as shown in Figure 5. In light of authors' research interests in muscle tissue engineering (Dong et al. 2016), the potentials of NPR structures and optimization techniques will be further explored for biomedical applications, such as design of vascular network and artificial blood vessels rupture, in future study.

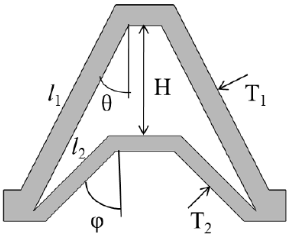

Fig. 4 Deformations of conventional (left) and NPR structures (right) subject to impact loads

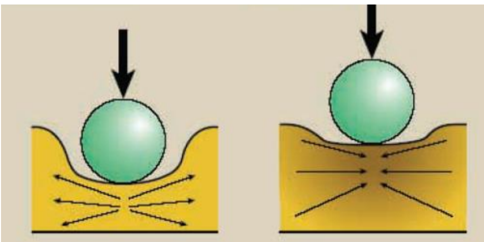

Fig. 5 NPR structure developed from Piezoelectric Flex Transducer device

The above NPR structure has an upper and a lower endcaps, which will generate the horizontal force components with different magnitudes due to the inclined angles φ and θ in the free body diagram analysis. This feature will lead to the axial compression deformation (highlighted with gray color at the legs in Fig.6) when forces are applied on the top (downwards) and bottom endcaps (upwards) to induct the vertical compression deformation (highlighted with gray color at the endcaps), which is in line with the definition of a NPR structure. The potential application of this NPR structure in tissue engineering will be employed to fabricate the micro-/nano-scale blood vessels to prevent the rupture and improve the strength capacity when subject to a pulse of blood. With the development of 3D printing technology, other promising applications of NPR structures suitable to biomedical engineering can be demonstrated as pressure sensors, the replacement of bones, etc.

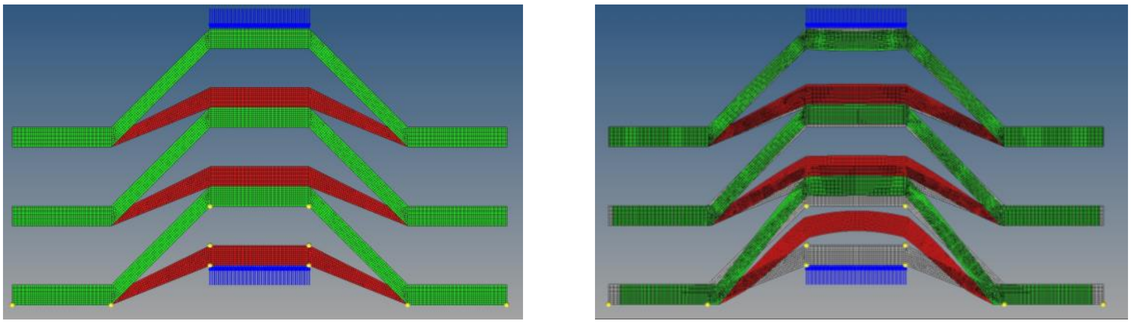

Fig. 6 Deformations of the NPR structure subject to compressive loads, left: undeformed, right: deformed

Conclusions

In this paper, a novel Negative Poisson's Ratio (NPR) structure is proposed based on previous research on energy harvesting device (Piezoelectric Flex Transducer, PFT), which is used to scavenge biokinetic energy from human walking. Through design optimization of the PFT for the maximal electrical power output, the optimal configuration is obtained by Genetic Algorithm on the metamodels. The entire optimization process of the PFT lays the foundation for the innovative design of the developed NPR structure. Then, this NPR structure is conceptually validated by finite element simulations for its correctness. It is noted that better ability to absorb impact energy as well as increase structural strength makes NPR structures outperform the conventional structures in the various engineering applications when integrated with 3D printing technology. In conclusion, the research into NPR structures provides useful guidance on potential applications in biomedical engineering, especially in tissue, aerospace, automobile and structural engineering.

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