Design and simulation of a novel ancient Chinese bow-type piezoelectric actuator

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Abstract. Piezoelectric materials are increasingly researched and used because of their ability to convert electrical energy and mechanical energy. Piezoelectric patches are usually applied with other structures to form piezoelectric actuators to expand the capability and use of piezoelectric patches. In this paper, a new piezoelectric actuator based on the ancient Chinese arch structure is proposed. The piezoelectric actuator is mainly composed of a bow device and several piezoelectric plates. Firstly, the electromechanical coupling model of the cantilever beam structure is established based on the finite element method. The action characteristics of the bow-type piezoelectric actuator are studied. Then static analysis of the cantilever beam with the bow-type piezoelectric actuator is applied. The effect of the bow-type piezoelectric actuator on the cantilever beam under different parameters is analysed and compared, including actuation voltages, locations and physical dimensions of the bow-type structure. Especially, the thickness of the device and the span of the bow device are optimized to better capability. The simulation results show that the thickness and the span of the bow-type device in the bow-type piezoelectric actuator affect the action of the piezoelectric actuator on the cantilever beam remarkably. Additionally, the bow-type piezoelectric actuator is easy to install, simple to manufacture, and can be reused. The research in this paper will provide a reference for the active control or energy harvesting of structural vibration.

1. Introduction
Piezoelectricity naturally occurs in many single crystal materials such as quartz, tourmaline, topaz and Rochelle salts. Piezoelectric material is relatively easy to produce and exhibit strong coupling between mechanical and electrical domains. However, these materials are easily damaged, and usually used with auxiliary base structures for in vibration control or energy harvesting. The auxiliary base structures greatly improve the capability of the piezoelectric materials.

To improve the capability of actuators, many investigations have been carried out for optimal design of piezoelectric actuators. Wang et al. [1] studied the optimal position and size of a pair of piezoelectric blade actuators arranged on a beam based on the controllability point of view. The optimized operation of the piezoelectric patched driver was optimized by maximizing the controllability index. K Ramesh Kumar and S Narayanan [2] investigated the optimal position of a piezoelectric actuator on a flexible beam, using the finite element method based on Euler-Bernoulli beam theory to model piezoelectric sensor and piezoelectric actuator in the high-mode strain energy region. Zhijun Zhang et al. [3] introduced a new inchworm-type piezoelectric actuator, and designed
an experimental system with high-voltage drive and closed-loop control system. The dynamic model was established and simulated. The simulation results showed that the closed-loop controller designed could be precisely controlled. Wang Wei and Yang Zhichun [4] developed a new piezoelectric stack driver (PISA) that assembles a piezoelectric stack and a metal base of a shape by screws to construct a PISA and derives a formula for calculating the PISA drive torque output. The simulation results show that PISA was an effective actuator for structural active vibration control. In addition, due to its compact configuration design, manufacturing costs will be reduced. Yajun Luo et al. [5] designed a new piezoelectric actuator for vibration control and achieved good results. Isabelle Bruant et al. [6] studied the optimal position and orientation of piezoelectric actuators and sensor locations for active vibration control, using genetic algorithms to find optimal configurations, and genetic algorithms are well suited to solve these easily derivable optimization problems. Simulation results showed the effectiveness of genetic algorithm in these optimization problems. Tarapada Roy and Debabrata Chakraborty [7] carried out simulation control for the shell structure of intelligent fiber reinforced polymer (FRP) composites based on improved genetic algorithm (GA). The results show that the improved genetic algorithm-based combined optimization configuration and (LQR) control scheme not only improves the closed-loop damping ratio, but also greatly reduces the input/drive voltage. Ali Reza Mehrabian and Aghil Yousefi-Koma [8] proposed a new method to optimize the position of piezoelectric actuators by recording the frequency response function (FRF) of the system. The optimal arrangement of the piezoelectric actuator on the intelligent fin was obtained, and the three-layer perceptron neural network was used to perform surface fitting on the discrete data generated by the finite element method, and then the actuator position was optimized by the IWO algorithm. The results showed that the FRF peak data surface fit was accurate for the optimal position of the piezoelectric actuator. The method they propose can be used to solve any actuator-sensor-optimized positioning problem on complex flexible smart structures. Georgia A. Foutsiti et al. [9] conducted numerical studies on the optimal voltage and optimum position of piezoelectric actuators for shape control of beam structures, and established piezoelectric fabrication based on Timoshenko beam theory. The finite element model of actuator performance is proposed based on the hybrid scheme of fluid and genetic algorithm, and the proposed hybrid genetic algorithm has the ability to determine the optimal voltage and position for controlling the actuator in a possible position.

Based on previous investigations, this paper studies a new type of ancient Chinese bow-type piezoelectric actuator. The ancient Chinese bow adopts such a shape to transmit the force well, which makes the bow and arrow more powerful. The bow is used as the piezoelectric actuator. The use of the bow-type transmission force can make the force transfer better, so that the piezoelectric actuator can fully exert its function. Section 2 gives a description of the Bow-type actuator, containing geometric design and constitutive relations of the piezoelectric material and the auxiliary structures. Numerical simulations of the actuation are displayed in Section 3. Finally, some conclusions are presented in Section 4.

2. Actuator configuration

Figure 1 displays the bow-type piezoelectric actuator bonded on a cantilever beam. The actuator is composed of two piezoelectric patches attached to a bow-shaped base. The base is attached to a cantilever beam imitates the shape of ancient Chinese bow. The curved arch base is bent and deformed to have an effect on the attached beam. As the arch base and the beam are connected with glue, the bow-type piezoelectric actuator is easy to install, simple to manufacture, and can be reused. The geometrical parameters of the piezoelectric actuator are shown in Figure 2, where $h_1$ is the thickness of the arch base and $h_2$ is the total length of the actuator, $h_3$ is the height of the actuator.
The linear electrical behavior of the piezoelectric material is [10]:
\[ D = \varepsilon E \]  
where \( D \) is the electric charge density displacement (electric displacement), \( \varepsilon \) is permittivity (free-body dielectric constant), \( E \) is electric field strength, and \( \nabla \cdot D = 0, \nabla \times E = 0 \).

The linear elastic materials satisfies the Hooke’s Law:
\[ S = sT \]  
where \( S \) is strain, \( s \) is compliance under short-circuit conditions, \( T \) is stress, and
\[ \nabla \cdot T = 0, \quad S = \frac{\nabla u + \nabla u^T}{2} \]

Hence the constitutive relation of piezoelectric materials in the strain-charge form is [11]:
\[ S = s^E T + d^E E \]
\[ D = dT + \varepsilon E \]
where \( d \) is the matrix for the direct piezoelectric effect and \( d^t \) is the matrix for the converse piezoelectric effect. The superscript \( E \) indicates a zero, or constant, electric field; the superscript \( T \) indicates a zero, or constant, stress field; and the superscript \( t \) stands for transposition of a matrix.

3. Finite element model
This paper uses ANSYS software to model and analyse this ancient Chinese bow-type piezoelectric actuator. The basic structure used to test the piezoelectric actuator is a cantilever beam. The size of the cantilever beam is 500×50×5mm\(^3\), and the left end of the beam is completely constrained. The density of the cantilever beam \( \rho = 2790\text{kg/m}^3 \) and the Young's modulus \( E = 7.15 \times 10^9\text{N/m}^2 \), Poisson's ratio \( \nu = 0.34 \). The width of the bow-type piezoelectric actuator is 30mm, height \( h_3 = 16\text{mm} \), and the entire device needs to be attached to the cantilever beam through two feet on the base plane to achieve its corresponding function.
**The density of the Piezoelectric patches used in ANSYS is 7750kg/m³. The width of the piezoelectric patches is the same as the width of the bow-type piezoelectric actuator. The stiffness matrix $C^E$ is shown below [12-13]:**

$$C^E = \begin{bmatrix}
12.1 & 7.54 & 7.52 & 0 & 0 & 0 \\
7.54 & 12.1 & 7.52 & 0 & 0 & 0 \\
7.52 & 7.52 & 11.1 & 0 & 0 & 0 \\
0 & 0 & 0 & 2.26 & 0 & 0 \\
0 & 0 & 0 & 0 & 2.11 & 0 \\
0 & 0 & 0 & 0 & 0 & 2.11
\end{bmatrix} \times 10^{10} \text{ N/m}^2 \quad (6)$$

Piezoelectric stress constant matrix is:

$$e = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 12.3 \\
0 & 0 & 0 & 12.3 & 0 & 0 \\
-5.4 & -5.4 & 15.8 & 0 & 0 & 0
\end{bmatrix} \text{ c/m}^2 \quad (7)$$

The absolute value of the input dielectric constant in ANSYS is:

$$e^S = \begin{bmatrix}
0.811 & 0 & 0 \\
0 & 0.811 & 0 \\
0 & 0 & 0.735
\end{bmatrix} \times 10^{-8} \text{ F/m} \quad (8)$$

The material properties are set up in Ansys for static analysis of a cantilever beam attached with the Bow-type actuator. Firstly, the finite element model is established in ANSYS, with element type of Solid5 is chosen to describe the piezoelectric material and the structure. The mesh of the total structure is shown in Figure 3. The left hand of the beam is fully constrained, and voltages are applied on the two surfaces of the piezoelectric patches.

![Figure 3. Meshed model in ANSYS](image)

When given electric field, the piezoelectric material deforms as the positive piezoelectric effect, the base arch transfers the deformation from piezoelectric patches to the cantilever beam, resulting the bending deformation of the cantilever beam. From the deformed image of the finite element solution is in Figure 4, one can find the maximum deformation is on the free end of the beam, therefore in the following studies, the maximum displacement represents the displacement of the free end.

![Figure 4. Finite element deformation map](image)
for processing and comparison. The data analysis of the piezoelectric actuator in Figure 5 is to analyse the effect of the piezoelectric actuator by changing the voltage that is supplied to the piezoelectric patches in the case where the size of the bow-type device is constant. Where $h_1=3\text{mm}$, $h_2=135\text{mm}$, $h_3=19\text{mm}$ the voltage of the piezoelectric piece is raised from 50V to 250V and is used as a function voltage demarcation point every 50V. Finally, the displacement values of all the nodes on one line of the cantilever beam are extracted, and the curves of different voltage values on the cantilever beam are shown in Figure 5.

![Figure 5. Effect of piezoelectric actuators under different voltages](image1)

(a) Displacement of beams at different voltages
(b) Maximum displacement of beams at different voltages

It can be seen from Figure 5(a) that the displacement of the cantilever beam increases while the actuation voltages increase from 50V to 250V. From Figure 5(b), one can also find that the actuation force is approximately proportional to the applied voltages. The deformation is very small from $x=0\text{mm}$ to $x=100\text{mm}$, the main reason is that the actuator supplies an additional stiffness to the host beam structure.

Then the influence of the thickness of the piezoelectric actuator $h_1$ is investigated. The thickness of the piezoelectric actuator is chosen from 1mm to the thickness of the cantilever beam. A fixed voltage of 150V is applied to the piezoelectric pieces, and the span of the piezoelectric actuator is kept unchanged at 135mm. Two beams are used in this simulation, one has a thickness of 5mm, and the other has a thickness of 10mm. The deformation of the two is shown in Figure 6.
Figure 6. Effect of piezoelectric actuators under different thicknesses
(a) Displacement of 5mm beams at different bow-type thicknesses
(b) Displacement of 10mm beams at different bow-type thicknesses
(c) Maximum displacement of 5mm beams at different bow-type thicknesses
(d) Maximum displacement of 10mm beams at different bow-type thicknesses

It can be seen from Figure 6(a) that the effect of the piezoelectric actuator on the 5mm thick cantilever beam is continuously enhanced from 1mm to 2mm, and the effect is weakened at 3mm to 5mm; Figure 6(b) shows the piezoelectric actuator the effect on the 10mm cantilever beam is continuously enhanced from 1mm to 4mm, and the effect is weakened at 5mm to 10mm. It is found from Figure 6(c) and Figure 6(d) that the piezoelectric actuator has a thickness of 2/5 of the beam thickness, which is most effective for the maximum displacement of the cantilever beam. This is because the closer the thickness of the bow device is to the thickness of the cantilever beam, the greater the stiffness of the cantilever itself, the smaller the deformation, and the smaller the bending moment transmitted to the cantilever beam, thereby reducing the deformation of the cantilever beam; The thickness of the bow device is too small, and the deformation force generated by the piezoelectric piece is mostly used in the deformation of the bow device itself, which consumes a large number of bending moments, so that the bending moment of the bow device transmitted to the cantilever beam is reduced, thus The deformation of the cantilever beam is reduced.

The effects of arch spans on the piezoelectric actuator is also studied, three cases for different span $h_2$ are provided in Figure 7. The thickness of the fixed piezoelectric actuator is $h_1=3$mm, the height $h_3=16$mm, and the voltage of $V=150$V is applied to the piezoelectric piece, and the effect of the span of the piezoelectric actuator $h_2$ at 110mm, 135mm and 160mm on the cantilever beam is simulated.

Figure 7. Influence of different spans on the effect of piezoelectric actuator
From the plots in Figure 7, it can be seen that the effect of the piezoelectric actuator is enhanced as the span is continuously increased. It is also found that the effect of the span on the cantilever beam after changing from 110mm to 135mm is greater than the change from 135mm to 160mm. In the next work, the parameters are to be analysed qualitatively and experiments will be given to verifying the simulations. In practical applications, the appropriate span of the piezoelectric actuator should be chosen to ensure that the piezoelectric actuator can perform its better performance.

4. Conclusion
This paper introduces a new type of ancient Chinese arcuate piezoelectric actuator and numerically studies the characteristics of the actuator. Through numerical simulation research, it is found that:

(1) The power of the piezoelectric actuator is proportional to the voltage applied to the piezoelectric piece.

(2) The thickness of the piezoelectric actuator has a good effect when the thickness of the base arch is about 2/5 of the beam thickness.

(3) The output torque of the piezoelectric actuator gradually increases as the span increases.

(4) The arcuate piezoelectric actuator is easy to install and can be reused.

This paper considers that this arcuate piezoelectric actuator has certain development potential in collecting vibration and converting it into electric energy. It is also believed that this energy conversion of the piezoelectric actuator can be used for active control of structural vibration.

Acknowledgements
This research received financial support from National Natural Science Foundation of China (Grant No. 11702162) and Natural Science Foundation of Shandong Province (Grant No. ZR2018LE014 and ZR2016EEM12).

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