Improvement on output torque and deformation of the rotary joint actuated by dielectric elastomer

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Abstract. The rotary joint actuated by dielectric elastomer has advantages to fabricate a biomimetic soft robot because of the large output torque, deformation and light weight. Conventional rotary joint actuated by dielectric elastomer is difficult to meet the requirements due to its small output torque. This paper proposes improved fabrication process and structure which can increase comprehensive performance. From experiments, the improved design had a maximum output moment of 14.21mNm which was almost 2 times that of the conventional design, its voltage-induced deformation angle was improved 5 degrees and weight was decreased too. The improved rotary joint will benefit load capacity of the soft robot actuated by dielectric elastomers.

1. Introduction
Compared with other smart materials actuators, dielectric elastomers (DE) actuator [1, 2] demonstrates high strain response [3], high energy density (70 times higher than the conventional electromagnetic actuators) [4], high energy conversion efficiency (peak theoretical value is 60% - 90%). The dielectric elastomer minimum energy structure (DEMES) was first proposed by Kofod et al. [5] as a kind of dielectric elastomer actuator, and had attracted wide attention [6]. After a pre-stretched dielectric elastomers film adhering on a thin elastic framework such as polyethylene terephthalate (PET) [7], polyvinyl chloride (PVC) [8] and acrylonitrile butadiene styrene (ABS) [9] the restoring force of the film bends the elastic framework into a minimum energy state. The DE film will be thinned by the Maxwell stress in electric field when kilovolts of low-current electricity are applied across the dielectric elastomer, contributing to the decrease of the bending angle of the framework [10]. Experimental results illustrate that the actuator will continue to generate rotational motions when an alternating voltage is applied, demonstrating its great potential in soft robotic systems [11, 12], bionic aquatic organisms [13, 14] and microsatellite grippers [15].

Nevertheless, the output torque, strain and lifetime were the limiting factors for the application of DE. Although the actuator structure had been improved to make the output torque of the joint increased based on DEMES, the lifetime of the structure had not been significantly improved. Thus we present a latest structure design and material improvement solutions based on conventional actuators [16]. By means of experimental measurements, the improved structure showed larger output torque, longer lifetime and better voltage-induced deformation compared with the conventional structure.
2. Structure of the rotary joint actuated by dielectric elastomer (RJ-DE)

2.1. Structure of the conventional RJ-DE
The structure of the RJ-DE was designed by Autodesk Computer Aided Design and it can be divided into four parts: primary frame, electrodes, pre-stretched DE film and stiffening frames. The three-dimensional model and the parameters of the conventional RJ-DE are shown in figure 1.

![Three-dimensional model (shown in (a)) and parameters (shown in (b)) of the conventional RJ-DE.](image)

Figure 1. Three-dimensional model (shown in (a)) and parameters (shown in (b)) of the conventional RJ-DE.

where \( l \) and \( w \) are the total length and width, \( t \) is the thickness of primary frame, \( p \) and \( q \) are the thickness and width of stiffening frame, \( s \) is the spacing between two stiffening frames and \( r \) is the radius of each semicircle. \( t \) and \( p \) are exaggerated for clarity.

The fabrication process and the picture of a conventional RJ-DE are shown in figure 2. After the materials well prepared, pre-stretched the VHB film (3M VHB4910) biaxially to 400%*400% and coated with carbon grease (NYE NYOGEL 756G) on both sides as electrodes. Then, bonded stiffening frames (made of acrylic) to primary frame (made by laser cutter with PET), mounted them to pre-stretched film and finally cut them from the holding frame.

![Fabrication process (shown in (a)) and the picture (shown in (b)) of the conventional RJ-DE.](image)

Figure 2. Fabrication process (shown in (a)) and the picture (shown in (b)) of the conventional RJ-DE.

2.2. Structure of the improved RJ-DE
The performance of conventional RJ-DE cannot meet the requirements from our experiments. The DE film was affected by voltage-induced deformation due to the pre-stretching force processing. The bonding area between the film and stiffening frame was so small that a hollow area existed, which led to adhesion loose and resulted in actuator breakdown after periodical motions. Besides, the conventional stiffening frame thickness cannot be more than 3mm and that of improved one can be more than 6mm which provided a larger output torque to satisfy our demands. The conventional and improved RJ-DEs are shown in figure 3 (the thickness of each part of the actuator is exaggerated for clarity).
In order to increase the lifetime and reduce the weight of RJ-DE, we made changes to structure and processing method. The section of the conventional frame is a rectangle while that of the improved frame is a trapezium which offered close fit to DE film and stiffening frame. The stiffening frames were fabricated by 3D printer with an internal filling density setting at 15%. Comparisons of the stiffening frames which have the same thickness of 3mm are shown in figure 4 and table 1.

![Figure 3](image-url)

**Figure 3.** The structures of conventional (shown in (a)) and the improved (shown in (b)) RJ-DEs.

![Figure 4](image-url)

**Figure 4.** Structures of two stiffening frames. (a) is the conventional and (b) is the improved.

| Stiffening frame | Material | Weight (g) | Adhering area (mm²) | Processing |
|------------------|----------|------------|---------------------|------------|
| Conventional     | Acrylic  | 0.84       | 184.18              | Purchasing |
| Improved         | ABS      | 0.63       | 323.53              | 3D printing|

We found the weight of the improved structure is reduced by 25% and the adhesion area is increased by 75.6%, which helps avoid hollow areas formation and improves RJ-DE lifetime significantly. Thus, adopting this new stiffening frame to RJ-DE fabrication is necessary.

### 3. Improvement on output torque of the RJ-DE

The RJ-DE force analysis with an initial angle of 90° is shown in figure 5. Based on beam bending analysis and ignoring any deformation of film and frames, the relationship between restoring torque $T_{frame}$ and bending angle $\theta$ could be demonstrated as Equation (1), which is based on beam bending analysis [17]. Relationship between bending torque $T_{film}$ and stiffening frame thickness $p$ could be demonstrated as Equation (2). When the power was turned off, the actuator output torque can be calculated as Equation (3). Combined with Equation (2), the greater the stiffening frame thickness $p$ is, the greater the actuator output torque $T_{out}$ will be. However, in the conventional RJ-DE, the thickness $p$ cannot be too large (because the adhesion area is too small to keep stable, the increase of the thickness $p$ will lead to an adhesion failure and easier RJ-DE breakdown). In the improved RJ-DE, the stiffening frame thickness $p$ can be larger because of a better structure and a better adhesion between ABS material and the DE film.
Figure 5. Force analysis in cross section of the conventional (shown in (a)) and improved RJ-DE (shown in (b)).

\[ T_{frame} = \frac{E(w-2r)r^3}{12s} \theta \]  
\[ T_{film} = F\left(\frac{r}{2} + p\right)\cos\alpha + Fr\sin\alpha \]  

where \( E \) is the Young’s modulus of the frame, \( \theta \) is the bending angle, \( \alpha \) is the angle between the DE film and stiffening frame, \( T_{film} \) is the bending torque of force \( F \) on the frame, \( T_{frame} \) is the restoring torque of the frame.

Based on static equilibrium,

\[ T_{out} = T_{film} - T_{frame} \]  

where \( T_{out} \) is the output torque.

An experimental setup to measure the output torque of RJ-DEs is shown in figure 6.

Figure 6. The schematic (shown in (a)) and the picture (shown in (b)) of output torque test platform.

The output torque \( T \) can be approximately calculated by:

\[ T = Fr \]  

We designed nine experiments on conventional and improved RJ-DEs with a same actuated area of 738.9mm². We investigated the changes in output torque with the changes in bending angle from 90 to 180 degrees at a given stiffening frame thickness from 1mm to 6mm. The bending angle and the corresponding output torque data were recorded and plotted in figure 7. Because of the influence of hollow area of conventional structure, the maximum thickness we can set is 3mm so as to there is no curve of conventional RJ-DE in figure 7(d).
Figure 7. Output torque-bending angle curves with different thickness of the both RJ-DEs. (a), (b), (c) and (d) show the comparison of output torque appearances with a given thickness of stiffening frame. (e) is the relationship between output torque and thickness.

From these experimental data, the output torque increased as the bending angle increased, and the output torque of improved RJ-DE was larger than that of conventional RJ-DE in any of the contrast experiments. For conventional RJ-DE, when the thickness of stiffening frames reached more than 3mm, the hollow area was damaged and unable to complete data record due to the small adhesive area. However, the improved RJ-DE still motioned with a thickness of 6mm and output larger torque. With the thickness of 3mm, the conventional RJ-DE only had a maximum torque of 7.25mNm while the improved RJ-DE had a maximum torque of 8.05mNm and it can achieve a larger torque of 14.21mNm with a thickness of 6mm.
4. Improvement on deformation of the RJ-DE
To investigate the voltage-induce deformation angle appearance and obtain the relationship between bending angle and driving voltage and the relationship between bending angle and thickness of stiffening frame, we designed multiple experiments whose procedure was shown in figure 8. The voltage is applied by a voltage amplifier (10/10B-HS); although the voltage is so high, the output current is less than 10mA.

![Figure 8. Experimental procedure of the voltage-induced deformation ability of the joint.](image)

In the experiments, the thickness $p$ of stiffening frame was set from 1mm to 4mm. At different thickness value, we observed the changes in bending angle with changes in given driving voltage from 3KV to 6KV and measured every 0.1KV. Because of the influence of hollow area of conventional structure, the maximum thickness we can set is 3mm so as to there is no curve of conventional RJ-DE in figure 9(d). In contrast to the conventional RJ-DE, the improved RJ-DE has better ability of voltage-induced deformation which is shown as figure 9.

From the comparison above, when the thickness of stiffening frame keeps constant, the higher the driving voltage is, the larger the bending angle will be. When the driving voltage keeps constant, the thicker the thickness of stiffening frame is, the smaller the bending angle will be. The bending angle reaches the maximum value while the thickness is 1mm and the driving voltage is 6KV; the maximum bending angle of the conventional RJ-DE is 71degrees and that of the improved RJ-DE is 76degrees.

5. Comparison of comprehensive performance of conventional and improved RJ-DE
The comprehensive performance of the conventional and the improved RJ-DE was compared based on experimental measurements and shown in table 2. The maximum output torque of conventional RJ-DE was 7.25mNm obtained at a stiffening frame thickness of 3mm while the maximum output torque of improved RJ-DE was 14.21mNm obtained at a stiffening frame thickness of 6mm; if needed, the thickness can be greater and output larger torque. The maximum voltage-induced deformation angle was obtained at a stiffening frame thickness of 1mm and a driving voltage of 6KV; the maximum value of conventional RJ-DE was 71degrees and that of improved RJ-DE was 76degrees.

A larger thickness will lead to a larger output torque and a smaller voltage-induced deformation. Thus, the choice of thickness depends entirely on the needs of the application. Choose a large thickness if a large output torque is required; choose a small thickness if a large deformation is required.

The lighter stiffening frames of improved RJ-DE were used and we can get a lighter one if we change the material or the value of internal filling density. The relationship between the structure, mass and comprehensive performance we will still discuss in future works. In joint output torque and voltage-induced deformation measurements, the accuracy of the experimental instruments had affected the results, so we conducted multiple experiments to reduce the error. In future research, we will acquire more accurate results with precise instruments.
Figure 9. Voltage-induce deformation angle appearance of the both RJ-DEs. (a), (b), (c) and (d) show the comparison of voltage-induced deformation appearances at a given thickness of stiffening frame. (e) is the relationship between bending angle and thickness at a same driving voltage.
Table 2. Comparison of comprehensive performance of the conventional and the improved RJ-DEs.

| RJ-DE      | Thickness of stiffening frames (mm) | Maximum output torque (mNm) | Voltage-induced deformation angle (deg) | Mass (g) |
|------------|-------------------------------------|-----------------------------|----------------------------------------|----------|
| Conventional 1 | 4.29                               | 71                          |                                        | 3.08     |
| Improved 1 | 4.40                                | 76                          |                                        | 2.84     |
| Conventional 2 | 5.90                               | 70                          |                                        | 3.71     |
| Improved 2 | 6.07                                | 75                          |                                        | 3.26     |
| Conventional 3 | 7.25                               | 65                          |                                        | 4.34     |
| Improved 3 | 8.05                                | 70                          |                                        | 4.09     |
| Improved 4 | 9.52                                | 63                          |                                        | 4.60     |
| Improved 5 | 11.57                               | 61                          |                                        | 4.93     |
| Improved 6 | 14.21                               | 59                          |                                        | 5.25     |

6. Conclusions
We found that the conventional RJ-DE structure although can realize the larger output torque of the joint in theory, it is difficult to achieve in practical application. That is a little significant to the application of the joint. Thus in this paper we improved the fabrication process and structure and realized the larger output torque of the joint in experiments. The principle of increasing output torque is given and the statics of the joint is analyzed. Based on experimental measurements we find that the improved joint has some advantages. Compared to conventional joint, the improved joint has a larger output torque, larger voltage-induced deformation and lighter weight. In the future, the improved joint can be applied to drive a soft robot actuated by dielectric elastomer which can increase the mechanical performance and lifetime of the robot.

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