Research on the Effect of the Friction on an Inchworm-type Piezoelectric-driven Rotary Actuator via Finite Element Method

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Abstract: The effect of the friction coefficient at the stator-rotor interface on the working performance of the actuator was investigated by using FEA. In this paper, a piezoelectric-driven stepping rotary actuator based on the inchworm motion is designed. Simulation results showed that the stepping rotary angle decreases from 264 μrad to 64 μrad and output torque of the rotor increases 29.6 N·mm to 315.5 N·mm when the friction coefficient increases from 0.1 to 0.5. Therefore, this factor must be taken into consideration in the design and machining of this kind of actuators.

Keywords: Rotary actuator, Inchworm, Finite Element Analysis, Friction.

1. Introduction

With the development of science and technology, the precision positioning system is more and more important in the fields of precision and ultra-precision manufacture, nanotechnology, semiconductor, MEMS and so on. Up to now, piezoelectric driven actuators have caused much attention due to its advantages: high resolution, low energy consumption and accurate positioning capability [1-4]. At present, several typical piezoelectric-driven actuators mainly include inchworm type [5-8], inertial drive type [9-11], and dual-stage type [12, 13]. A typical inchworm-type rotary motor is usually divided to a stator, a rotor and piezoelectric actuators. The piezoelectric actuators are assembled in the stator and drive the inchworm-type rotary motor to achieve unlimited motion range and the holding torque.

The stator usually has complicated structures connected by flexure hinges and high precision requirements. Therefore, the stator should be processed by forging, heat treatment, milling and grinding before wire electrical discharge machining to obtain good elasticity performance of the flexure hinges [2]. Furthermore, friction coefficient at the rotor-stator contact interface can affect the working performance of the actuator further in an indirect way. Moreover, friction is a complex physical phenomenon, and the coefficient of friction has a big relationship with the actual surface roughness after machining, lubricating condition of work, the clamping force, temperature, normal stress, and relative velocity, etc [14, 15]. Therefore, it is of great importance to understand the relationship between the coefficient of friction and the output characteristics inchworm-type piezoelectric-driven rotary actuator.

With the development of computer technology and calculation method, finite element method (FEM) gets more and more widely attention and application in engineering design and scientific research, and it
has become an effective way to improve product quality, shorten the design cycle and enhance the competitiveness of products. Therefore, in this paper, the quasi-static contact analyses of the designed inchworm-type rotary actuator were carried out by using 3-D Finite Element Analysis (FEA). The effect of friction coefficient between the stator and rotor on the performance of the actuator was investigated using FEA.

2. Structure Analysis

2.1. Structure Analysis

The structure of the PZT-driven rotary actuator, Fig. 1, is described in detail in our previous paper [2]. The stator includes two layers which are connected by flexure hinges, nine PZT stacks are assembled in the stator. According to the function, the actuator can be divided into three kinds of units: the clamping unit, the adjusting unit and the driving unit. Detailed structure will not be explained here.

2.2. Driving Principle

Fig. 2 shows the input signals for the PZT stacks in the designed actuator. $V_1$ is the input voltage for the clamping PZT stacks in the upper layer, $V_2$ is the input voltage for the clamping PZT stacks in the under layer, and $V_e$ is the input voltage for the PZT stacks in the driving units. All the input voltages must be given in strict order when the actuator works. As shown in Fig. 2, every working cycle can be further divided into six sub-steps equally. The working principle can be expounded by Fig. 2 and Fig. 3. The detailed driving process is as follows:

a) During the time $t_1$, $V_1$ and $V_2$ get high voltages, so the clamping PZT stacks in the upper and under layer will expend to push the clamping flexure hinges to clamp the rotor tightly, Fig. 3(a).

b) In the period of $t_2$, the input voltage $V_2$ is in low voltage, but $V_1$ is still in high voltage. Thus the clamping flexure hinges of the under layer will be loosened, and the clamping flexure hinges of the upper layer is still clamping the rotor, Fig. 3(b).

c) When the time comes to $t_3$, $V_e$ becomes in high voltage, so the PZT stacks in the driving units get charged, they will push the upper layer. Because the upper layer is connected with the under layer by flexure hinges which work as torsion springs and the under layer is fixed on the base, so the upper layer will turn an angel relative to the under layer. At the same time, $V_1$ is still in high voltage, the rotor is still clamped by the upper layer, so the rotor will turn an angle as well, Fig. 3(c).

d) During the time $t_4$, the clamping units of the under layer will hold the rotor too, as $V_2$ is in high voltage.
e) During the time $t_5$, $V_1$ is in low voltage, the clamping units in the upper layer will loosen up the rotor.

f) In the time $t_6$, $V_2$ is still in high voltage, but $V_e$ changes into low voltage, and under the action of the connected flexure hinges between the upper and the under layer which work as the torsion spring, the upper layer will turn back to the original location.

After the six sub-steps, one working circle is completed, the rotor will turn an angle, and large angles can be achieved when repeating this operation. If the input signals $V_1$ and $V_2$ are exchanged, the rotor will rotate in the opposite direction.

3. Results and Discussion

FEM simulations were carried out by using the implicit commercial software MSC.Marc (MSC Software, 2010), which uses an updated Lagrangian formulation. Inchworm-type actuators are quasi-static motors, hence quasi-static analyses were used in this model, which means that the mechanical analysis is static with inertia forces neglected. The inertia forces can be ignored as they are small compared with the deformation forces [16].

3.1. Mesh and Material

Fig. 4 shows the FE model of the actuator, the stator was constructed by 126,490 ten-node isoparametric 3-D tetrahedron elements (Element 127), with four nodes at the corners of the element and a further six nodes at the middle of each edge. This element type allows for an accurate representation of the strain field in elastic analyses and can be used for all constitutive relations [17]. The mesh around flexure hinges was refined to guarantee the accuracy. The materials of the stator and rotor are both 65 Mn fabricated by heat treatment to improve the elastic properties of the flexure hinges, the mechanical properties of 65 Mn was as shown in Table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s Ratio</th>
<th>Yield Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 Mn</td>
<td>211000</td>
<td>0.288</td>
<td>784.27</td>
</tr>
</tbody>
</table>

3.2. Boundary Conditions

In view of the small deformation, the rotor was set to a rigid body and the load controlled way was selected. When the load controlled way was selected, two additional nodes, called the control nodes, should be defined to associate with the rotor. The first one controls the location of the center of rotation and has three translational degrees of freedom, and the second one controls the rotational degrees of freedom. In this way, both external forces and moments can be applied to the rotor and drive it to rotate. The second control node must be specified in this model, otherwise the rotation of the rotor is prescribed to be zero.

In addition, nine PZT stacks used in the actuator were also set as rigid bodies, including six PZT stacks in clamping units and three PZT stacks in driving units, as shown in Fig. 5.

![Fig. 4. The finite element model used in the simulation.](image)

![Fig. 5. Distribution of equivalent Von Mises stress of the critical sub-steps.](image)
Considering that the displacement of PZT stacks is directly proportional to the driving voltage, displacement controlled way was selected for nine rigid PZT stacks. Three time-dependent curves were defined to control the displacement of PZT stacks, where \( d_1 \) is the displacements of the clamping PZT stacks in the upper layer, \( d_2 \) is the displacements of the clamping PZT stacks in under layer, and \( d_e \) is the displacement of the PZT stacks in the driving units. All the input displacements must be given in strict order as shown in Fig. 4 when the actuator works.

Fig. 5 shows Distribution of equivalent Von Mises stress of the critical four sub-steps. PZT stacks AE0505D08 from Tokin Company were used in the clamping units and driving units, the corresponding elongation value increases from 1 \( \mu \)m to 10 \( \mu \)m while the driving voltage changes from 10 V to 100 V. Besides, the bottom of the stator was fixed in the vertical direction.

### 3.3. Friction Model

In the FEM package MSC.MARC, several friction models are available for users. The Coulomb friction model is the most popular friction model and used for most applications. Here, the Coulomb friction model was adopted at the stator/rotor interface, which states that the friction force is proportional to the normal force through a friction coefficient, \( \mu \), as shown in Eq. (2).

\[
[f_t] = \mu [f_n] \quad \text{(stick)} \quad \text{and} \quad f_t = -\mu f_n \quad \text{t (slip)}
\]

where \( f_t \) is the tangential (friction) force, \( f_n \) is the normal force; \( \vec{t} \) is the tangential vector in the direction of the relative velocity, defined as:

\[
\vec{t} = \frac{\vec{v}_r}{\|\vec{v}_r\|}
\]

in which \( \vec{v}_r \) is the relative sliding velocity. For a given normal force, the friction force has a step function behavior based upon the value of the relative sliding velocity. Since this discontinuity in the friction value may easily cause numerical difficulties, different approximations of the step function have been implemented in MSC.MARC. One of the most basic approximations is the arctangent model, which can be characterized as:

\[
f_t \leq -\mu f_n \cdot 2\alpha \arctan \left( \frac{\|\vec{v}_r\|}{\delta} \right) \cdot t
\]

Physically, \( \delta \) is interpreted as the value of the relative velocity below which sticking occurs. Typically, a value of 1–10% of the applied sliding velocity is recommended and realistic simulation data can be obtained. Based on the friction model discussed above, the effect of friction coefficient on the working performance of the actuator was also investigated.

### 3.4. Effect of the Friction Coefficient at the Rotor-stator Contact Interface

The output torque is another key performance parameter of the actuator because it influences the carrying ability of the actuator. Fig. 6 shows the variation of accumulated rotary angle and corresponding output torque of the rotor with driving time. The chosen frequency \( f \) is 1 Hz, and the displacement of clamping PZT stacks \( d_1 \), \( d_2 \) and driving PZT stacks \( d_e \) are all 10 \( \mu \)m. It can be seen that the rotary angle increases to a new stage at the end of one working circle and corresponding output torque of the rotor will increase to a peak value.

![Fig. 6. Variation of accumulated rotary angle and output torque of the rotor with driving time.](image)

Then, the effects of the friction coefficient at the rotor-stator contact interface on the output stepping rotary angle and torque were investigated by changing the friction coefficient from 0.1 to 0.5. Fig. 7 shows the variation of the stepping rotary angle \( \Delta \theta \) and output torque of the rotor with friction coefficient, \( \mu \). Here, the output torque of the rotor was the peak value of the torque as shown in Fig. 6.

![Fig. 7. Variation of the stepping rotary angle and output torque of the rotor with the friction coefficient.](image)
It is evident that the stepping rotary angle decreases and the output torque of the rotor increases when the friction coefficient increases. The stepping rotary angle changes from 264 μrad to 64 μrad, and the maximum output torque of the rotor changes from 29.6 N·mm to 315.5 N·mm when the friction coefficient increases from 0.1 to 0.5. The results obtained implied that the influence of the friction coefficient at the rotor-stator contact interface on the working performance of the actuator is remarkable.

4. Conclusions

FEM was used for the quasi-static contact analyses of a PZT-driven rotary actuator by means of inchworm motion. FEA results showed that a relatively small change in both the friction coefficient between the stator and the rotor could make a huge difference to the working performance of the actuator. Further, the stepping rotary angle decreases from 264 μrad to 64 μrad and output torque of the rotor increases 29.6 N·mm to 315.5 N·mm when the friction coefficient increases from 0.1 to 0.5. Therefore, the factor must be taken into consideration in the design and machining of this kind of actuators.

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