A New Friction-Type Piezoelectric Motor
Utilizing Mechanism of the Strain Wave Gearing

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Abstract—A new type of motor that utilizes multilayer piezoelectric devices for electromechanical power conversion and mechanism of the strain wave gearing for generation of traveling motive force is proposed in this paper. The construction, basic operation, and torque generation mechanism of the motor are described. The motor can be operated in variable frequency. Experimental results on the prototype motor made of metals are also presented. The feasibility of the proposed motor is verified and the possibility of realizing piezoelectric motors with a larger torque is shown.

I. INTRODUCTION

Electromagnetic actuators are widely used for their high performance in speed control. The mechanical power (torque) per weight (volume) of the actuators is very small, however. A larger power ratio of actuators is strongly desired in such fields as industrial robots. The robots have to lift and support the payloads as well as the deadweights of the robots themselves.

Recently, various types of ultrasonic motors utilizing piezoelectric devices have been developed and they have gained attentions for their compactness and high-power ratios [1]–[3]. The piezodevices generate traveling waves on the surface of the stator by mechanical resonance. The motive force produced by the traveling wave is transmitted to the rotor through friction between the stator and the rotor. Most of the ultrasonic motors are, however, small sized using small piezoelectric devices with a small power and are applied mainly to such small equipment as cameras, plotters, etc. The piezoelectric devices usually operate only in a resonant mode to gain a high efficiency in power conversion.

This paper presents a new type of motor utilizing multilayer piezoelectric devices for electromechanical energy conversion. The piezoelectric devices are relatively large in size with a large power capacity. The new motor also uses a mechanism of strain wave gearing [4] for generation of the traveling wave and the motive force. This motor can be operated in variable speed by exciting the multilayer piezodevices in a nonresonant mode. The devices of the motor can also be excited in a resonant mode by adopting a mechanical resonator. The transmission of torque from the stator to the rotor is made through friction force. We call the new type of motor a friction-type piezoelectric motor.

In this paper, the construction, basic operation, torque generation mechanism, and experimental results of the proposed motor are described. Although the new motor could be made of such nonmetal materials as plastics and ceramics, a prototype of the proposed motor is made of metal and piezoelectric devices just for verifying the feasibility of the motor. The friction-type piezomotor is to be operated in nonresonant mode in this paper.

II. CONSTRUCTION AND BASIC OPERATION OF THE MOTOR

A. Construction

The proposed motor consists of a wave generator (piezoelectric devices), a flexspline, a circular spline (a rotor), and a frame, as shown in Fig. 1. The flexspline is a cylindrical can. The opened orifice of the can is made a little bit flexible and the bottom is fixed on the frame. Hereafter, we mean by the flexspline the opened orifice of the flexspline unless otherwise noted. The circular spline is a solid cylinder with a small taper. It is pressed strongly onto the flexspline. The wave generator consists of \(N\) piezoelectric devices that are radially allocated and are pressed onto the flexspline with the fixing screws. The figure shows the case where there are 16 devices, i.e., \(N = 16\).

B. Basic Operation

When dc voltage is applied to some of the piezoelectric devices, located radially to the central axis of the motor, the devices push the flexspline stronger than the other devices and transform the flexspline into an elliptical shape. Then the flexspline contacts the circular spline at the two portion, as shown in Fig. 1(a). The cross section of the figure is shown in Fig. 1(b). The transformation of the flexspline is exaggerated in the figure. The contact areas may be small and therefore regarded as contact points for simplicity.

When biased multiphase ac voltages are applied to the piezoelectric devices, the ellipsoid rotates and the contact points (\(C\) and \(C'\) of the flexspline also revolve, as shown in Fig. 2. At \(\omega t = 0\), point \(A\) of the flexspline contacts point \(B\) of the circular spline. Because the circumference of the flexspline is a little bit larger than that of the circular spline, point \(A\) moves away from point \(B\) while the ellipsoid...
rotates. The circular spline (the rotor) rotates in an opposite direction to that of the elliptic transformation.

The locus of point $A$ of the flexspline in the period of $\omega t/2 = 0 - \pi$ is approximately elliptic, as shown in Fig. 2. The locus is probably deformed along the surface of the circular spline as shown in Fig. 3. It can, therefore, be considered that the flexspline converts the radial movement of the piezoelectric devices to the tangential movement of the circular spline. We call the conversion directional conversion. The circular spline is rotated by the conversion of the movement through friction.

C. Torque Generation Mechanism

In Section II-B, the rotation mechanism of the circular spline is explained. Here, the generation mechanism of the motor torque to meet the load torque applied to the circular spline is explained.

The torque of the motor is produced by frictional forces (tangential components of the forces) applied to the circular spline at the contact points $C$ and $C'$ as illustrated in Fig. 4(b). If no load torque is applied to the circular spline, the distribution of the forces from the piezoelectric devices is approximately symmetrical with respect to the plane on the contact points $C$ and $C'$ and also on the rotational axis of the circular spline. The force vectors at the contact points are centripetal as shown in Fig. 4(a). When the load torque is applied clockwise, the circular spline pulls the flexspline clockwise. Then the contact points as well as the elliptical transformation of the flexspline are rotated counterclockwise, as shown in Fig. 4(b). As a result, the tangential forces (the
friction forces) are produced at the contact points due to the function of the directional conversion by the flexspline. The generated torque meets the load torque.

III. APPROXIMATE ANALYSIS

For simplicity, approximate analysis is made to obtain expressions for the rotational speed \( n_0 \) and the generated torque \( T_m \) of the motor.

A. Rotational Speed in the Case of No-Load Torque

As shown in Fig. 2, point \( A \) on the flexspline rotates on the elliptic locus once while the contact points \((C \text{ and } C')\) rotate by \( \pi \) rad. The contact points \((C \text{ and } C')\) on the flexspline rotate at the speed \([\text{in } \text{r/s}]\) of a half of the frequency applied to the piezoelectric devices. The rotation of point \( A \) is the same as that of the devices.

The rotational speed \( n_0 \) of the circular spline, in the case of no slip between the flexspline and the circular spline, is obtained from the movement of the contact points \((C \text{ and } C')\) per unit time as follows:

\[
2\pi n_0 + f/2 (X_0 - \Delta X) = 2\pi (f/2) X_0 \tag{2}
\]

where \( f \) is the frequency of the voltages applied to the piezoelectric devices, \( X_0 \) is the radius of the flexspline in the case where it is circular (not transformed), and \( \Delta X \) is the difference between \( X_0 \) and the radius of the circular spline as shown in Fig. 3.

Therefore, the speed \( n_0 \) is given by the following equation:

\[
n_0 = (\Delta X / (X_0 - \Delta X)) f / 2 \tag{3}
\]

B. Generated Torque

An expression for the generated torque \( T_m \) of the motor is derived from the conservation law of energy. We assume that the distributions of the displacements and the forces \( (x_{ak} \text{ and } f_{ak}) \) respectively; \( k = 1, \cdots, N \) produced by the piezoelectric devices are sinusoidal and expressed by the following equations:

\[
x_{ak} = X_0 + \Delta X \cos [\omega t - 2\theta_k] \tag{4}
\]

\[
f_{ak} = F_0 + \Delta F \cos [\omega t - (\theta_k - \phi)] \tag{5}
\]

\[
\theta_k = 2\pi (k - 1)/N \tag{6}
\]

where \( \Delta F \) is the amplitude of force variation, \( \theta_k \) is the angular position of the \( k \)th piezoelectric device and is positive in the clockwise direction, \( \omega \) is the angular frequency \((= 2\pi f)\) applied to the devices, and \( \phi \) is the leading angle of the maximal force point from contact point \( C \).

Assuming no loss in the directional conversion and no slip between the flexspline and the circular spline, the mechanical input power \( P_m \) from the piezoelectric devices is equal to the power to the circular spline as expressed by the following equation:

\[
P_m = \sum_{k=1}^{N} f_{ak} \cdot (dx_{ak} / dt) = T_m \omega_m \tag{7}
\]

Thus

\[
T_m = -NX_0 \Delta F \sin 2 \phi \tag{8}
\]

This equation indicates that the generating torque \( T_m \) is proportional to the product of the amplitude of the force variation \( \Delta F \) produced by the piezoelectric devices and sin \( 2\phi \). The values of \( \Delta F \) and \( \phi \) are determined by the electromechanical characteristics of the piezoelectric devices and the elastic characteristics of the flexspline. In case the elasticity of the circular spline affects the torque characteristics, both \( \Delta F \) and \( \phi \) are expected to be smaller, and consequently torque \( T_m \) becomes smaller.

D. Effect of Friction

There is another factor that limits the generating torque of the friction-type piezoelectric motor. That is the slip that may take place at the contact points between the flexspline and the circular spline and may increase with the larger load torque. The motor may be stalled when the load torque applied to the circular spline is equal to the maximal frictional torque, which is defined as the product of \( X_0 \) and the total of the maximum frictional forces between the flexspline and the circular spline and is denoted as \( T_{fM} \).

When the force \( F_p \) is applied to the circular spline as shown in Fig. 5, the total of the forces \( F_{fs} \) pressing the
circular spline onto the flexspline is given by

$$F_p = \frac{(F_p + W)}{\sin \alpha}$$  \hspace{1cm} (8)

where $\alpha$ is the angle of the taper of the circular spline, and $W$ denotes the dead weight of the circular spline. The maximal frictional torque $T_{FM}$ is given by

$$T_{FM} = \mu F_p X_0 = \frac{\mu (F_p + W) X_0}{\sin \alpha}$$  \hspace{1cm} (9)

where $\mu$ is the friction factor. The maximal frictional torque $T_{FM}$ becomes larger if the larger force of $F_p$ is applied to the circular spline.

According to (1), the motor is also stalled if the variation of displacement of the piezoelectric devices becomes zero due to the extremely large force of $F_p$.

### IV. Experimental Results and Discussion

#### A. Experimental System

The structure of an experimental motor is shown in Fig. 1, and its dimensions are listed in Table I. The circular spline and the flexspline are made of iron, the fixing screws are of stainless steel, and the frame is of brass. Sixteen multilayer piezoelectric devices made of PZT are used to generate a rotating wave of displacement and force. Their rated voltage is 150 V and their capacitance is about 1.5 $\mu$F. The characteristics and dimensions of the piezoelectric devices are shown in Fig. 6. The piezodevices can produce the displacement $x_0$ of about 10 $\mu$m ($f_a = 0$) or a force $F_a$ of about 60 kgf ($x_0 = 0$) when the applied voltage $V_a$ is 106 V.

The driving circuit of the motor is a eight-phase voltage source MOSFET inverter with biased rectangular outputs of 0 and $V_a$ as shown in Fig. 7, where $V_a$ is the dc source voltage of the inverter. Each phase of the inverter drives a pair of piezoelectric devices connected in parallel. In experiments, resistors of 15 $\Omega$ are inserted in series with every pair of piezoelectric devices to avoid excessive currents rushing into the capacitive devices. The rotational speed is obtained by measuring the rotating period of the circular spline. The generating torque is measured by the method shown in Fig. 8. The speed is to be measured while the piezoelectric motor pulls up the weight.

#### B. Experimental Results

Fig. 9 shows characteristics of the rotational speed $n$ versus the applied frequency $f$ of the motor in the case of no-load torque. The parameter in this figure is the force $F_p$ on the circular spline. The rotational speed is approximately proportional to the applied frequency and the speed becomes lower with the larger force of $F_p$. These results coincide well with those from (1). The amplitude $\Delta X$ of the displacement variation is found to be almost constant independent of the applied frequency. From (1), the values of $2 \Delta X$ are about 10 $\mu$m when $F_p = 0$ kgf and about 6 $\mu$m when $F_p = 4.2$ kgf. The maximum value of the rotational speed is about 3 r/min in this experiment.

Although higher speed can be obtained by increasing the applied frequency, the input currents to the piezoelectric devices, which are capacitive and almost reactive, also increase considerably. For example, the input current per device is about 0.51 A rms when $f = 400$ Hz. The large amount of currents generate a considerably large loss produced in the resistors, which are inserted in series with the piezoelectric devices. In practice, the resistors should be replaced with reactors. In addition, from the point of view of efficiency, it is desirable for the motor to be operated in a resonant mode.

Fig. 10 shows characteristics of the rotational speed $n$ versus the load torque $T_L$. Fig. 10(a) shows where the force $F_p$ on the circular spline varies and (b) shows where the applied frequency $f$ is changed. The speed drop with the increase of the load torque is considered mainly due to the reduction of $\Delta X$ or the distortion of the flexspline caused by the tangential forces on the flexspline judging from the fact that there are dead areas where the speed remains zero in certain ranges of the load torque as observed in Fig. 10(a). It is possible for the slip between the flexspline and the circular spline to cause speed reduction. The reverse of the rotation (i.e., the negative rotational speed) is considered mainly due to the slip. The stall torque $T_{SM}$ is defined as the torque where the rotational speed reaches zero from the positive value (in the same direction as that of the generated torque). The torque where the circular spline moves to the opposite direction from the standstill is called maximal stall torque and is denoted by $T_{SM'}$. The stall torque $T_S$ is almost independent of the applied frequency (Fig. 10(b)).

Fig. 11 shows the characteristics of the stall torque $T_S$ and the maximal stall torque $T_{SM'}$ versus the force $F_p$. The solid line in the figure is the numerical result of the maximal frictional torque $T_{FM}$ given by (9) in the case where $\mu = 0.1$ and $X_0 = 17.0$ mm. $T_{FM}$ is almost the same as $T_{SM'}$. The stall torque increases with the force $F_p + W$ as shown in Figs. 10(a) and 11. The increase of the pressure $F_p$ causes the reduction of the displacement $x_0$ (i.e., $\Delta X$). The reduction enlarges the generated force $f_a$ (i.e., $\Delta F$) of the piezoelectric devices. From (7), the stall torque becomes larger.

### Table I

<table>
<thead>
<tr>
<th>Dimensions of the Experimental Motor</th>
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<tbody>
<tr>
<td>Frame</td>
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<td>-------</td>
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<tr>
<td>Dimensions (mm)</td>
</tr>
<tr>
<td>L3 100.0</td>
</tr>
<tr>
<td>L4 40.0</td>
</tr>
<tr>
<td>L7 82.0</td>
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<tr>
<td>L8 7.0</td>
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</table>
with the enlarged $\Delta F$. The stall torque is, however, much smaller than the theoretical maximal frictional torque $T_{FM}$.

The behavior of $\sin 2\phi$ in (7) should also be taken into consideration. But the behavior is very complicated because it is related to the electromechanical characteristics of the piezoelectric devices and the elastic characteristics of both the flex spline and the circular spline. The circular spline is made of iron, whose Young’s modulus is much smaller than that of the piezoelectric devices. The spline is considered to be transformed a little so that $\sin 2\phi$ becomes probably small.
The generated forces of the piezoelectric devices are far more larger than the obtained rotational torque. If the applied force $F_p$ can be made large and the elastic characteristics of the circular spline as well as the friction coefficient and the durability at the contact points are improved, a considerably large torque could be produced.

V. CONCLUSIONS

A new type of motor that utilizes piezoelectric devices and mechanism of the strain wave gearing was proposed. The new motor can be operated in variable frequency. The configuration, basic operation, and torque generation mechanism of the motor were described. Feasibility of the proposed motor was verified by experiments. It was found that the rotational speed of the proposed motor was very low and proportional to the applied frequency. A very large torque could be expected. From the point of view of efficiency, it is desirable that the motor should be operated in a resonant mode.

REFERENCES