

Original Paper

Characteristics of a Friction-Type Piezoelectric Motor Utilizing Mechanism of the Strain Wave Gearing

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A new type of motor which utilizes multi-layer piezoelectric devices for electromechanical power conversion and mechanism of the strain wave gearing for generation of traveling waves and motive force is proposed in this paper. Configuration, basic operation and torque generation mechanism of the motor are described. The motor operates in variable frequency, that is in non-resonant mode. Experimental results on characteristics of rotational speed and generated torque of the experimental motor made of metals except for the piezoelectric devices are also presented, which verifies the feasibility of the proposed motor and indicates the possibility of realizing piezoelectric motors of large torque.

Key Words: strain wave gearing, flexspline, circular spline, piezoelectric device, elliptical transformation, friction force

1. Introduction

Electromagnetic actuators are widely used because they are clean, and they have high performance. However, they produce small mechanical power or torque per weight or volume, which basically gives limitation to performance (force, speed, response, etc.) of the equipment using this type of actuators. In particular, industrial robots require large force or torque per weight to lift and support not only objects to be conveyed but also some of actuators and arms of themselves.

Recently, various types of ultrasonic motors utilizing piezoelectric devices are developed and drawing attention due to their compactness and high power density [1]-[3]. They generate traveling wave on the surface of the stator by mechanical resonance to produce motive force, and transmit the force or torque to their rotor through friction force between the stator and the rotor. However, most of them are small motors using small piezoelectric devices of small power and are applied mainly to small-sized equipment such as

that for OA, AV, etc.. They usually operate only in resonant mode to gain high efficiency power conversion.

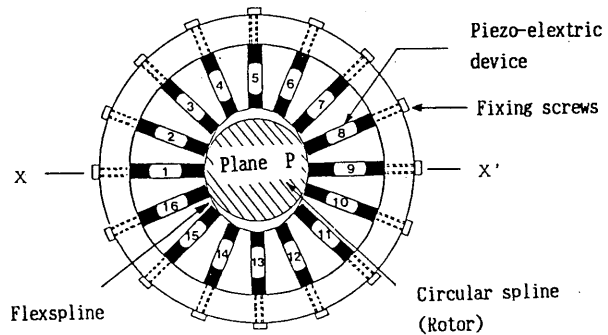
We propose a new type of motor utilizing multi-layer piezoelectric devices, which are of relatively large size and power capacity, for electro-mechanical energy conversion and mechanism of strain wave gearing [4] for generation of the traveling wave and the motive force. This motor operates in variable frequency, that is in non-resonant mode, and can also operate in resonant mode by adopting a mechanical resonator. Transmission of torque from a stator to a rotor is made through friction force as well as in the ultrasonic motors. We call this type of motor friction-type piezoelectric motor.

In this paper, we deal with the friction-type piezoelectric motor which operates in non-resonant mode. Configuration, basic operation, torque generation mechanism and experimental results of the proposed motor are described. Experimental motor is made of metal except the piezoelectric devices to attach importance to feasibility of the proposed motor though it could be made of non-metal materials such as plastics, ceramics and so on.

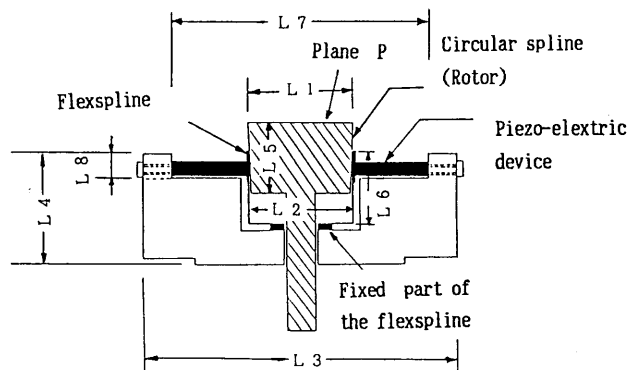
2. Configuration and basic operation of the proposed motor

2. 1 Configuration of the motor

The proposed motor is comprised of a wave generator (piezoelectric devices), a flexspline, a circular spline (a rotor) and a frame, as shown in Fig.1. The flexspline is like a cylindrical can, whose opened orifice is flexible a little and whose bottom is fixed on the frame. We define the flexspline as the opened orifice of the flexspline so long as we do not give any particular notice. The circular spline is a solid cylinder tapered a little to enable it pressed strongly on the flexspline by pushing its plane P. The wave generator is composed of N piezoelectric devices arranged like spokes of a wheel and pressed by fixing screws, where N is the number of the devices and $N = 16$ in Fig.1.



(a) Drawing viewed from the direction of the rotational axis



(b) Drawing of section (A-A' in (a))

Fig. 1. Construction of the friction-type piezoelectric motor

2. 2 Principle of operation

When dc voltage is applied to some of the piezoelectric devices, located symmetrically with respect to the central axis of the motor, the devices push the flexspline stronger than the others and transform it elliptical a little (by several micrometers), so that the flexspline contacts with the circular spline at the two areas where its minor axis crosses it, as shown in Fig.1, where the transformation is exaggerated. 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 elliptical transformation of the flexspline rotates and thus the contact points (C and C') on the flexspline with the circular spline move at the rotational speed of a half of applied frequency, as shown in Fig.2. As a result, the circular spline (the rotor) rotates in an opposite direction to the transformation of the flexspline because a length around the flexspline is a little longer than that around circular spline on its contact line and the bottom of the flexspline is fixed on the frame.

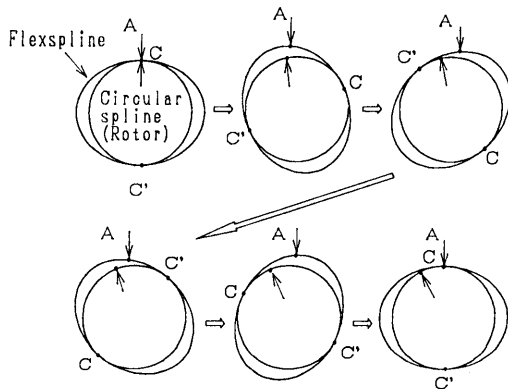


Fig. 2. Movement of the contact points (C and C') between the flexspline and the circular spline

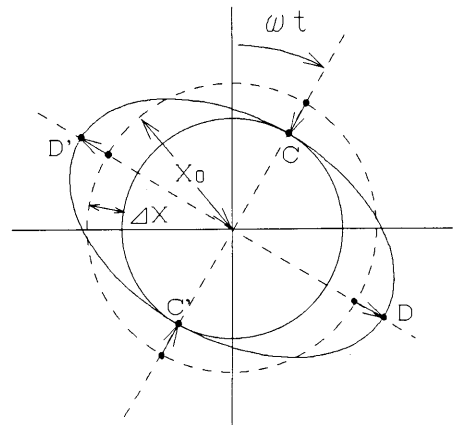


Fig. 3. Variation of the radius of the circular spline by transformation of the flexspline and movement of points on the minor and major axes of the ellipse (flexspline)

It is considered that the contact points (C and C') on the flexspline, which are on the minor axis of the ellipse, and points on the major axis of it are located at the same angular positions as in the case that the flexspline is circular because of the symmetry of the transformation of the flexspline, as shown in Fig.3. As a result, the locus of a point A on the flexspline is approximately described as ellipse, as shown in Fig.4, when the the transformation is rotated. Probably, the locus is a little smoothed along the surface of the circular spline by the force from the piezoelectric devices. It is, therefore, considered that the flexspline has a function that converts the radial movement of the piezoelectric devices to the tangential movement of the

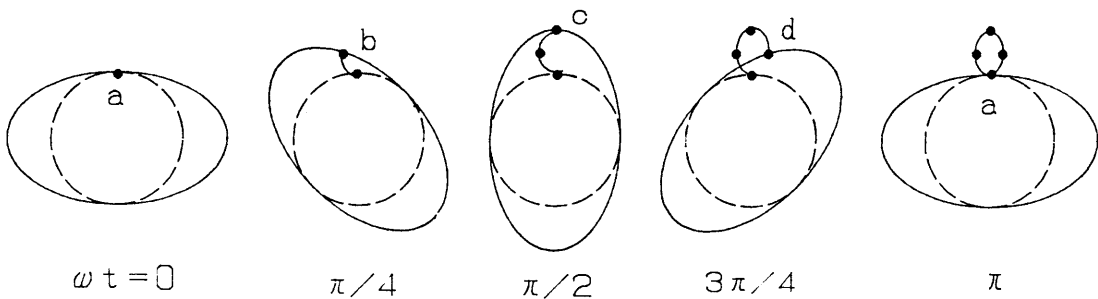
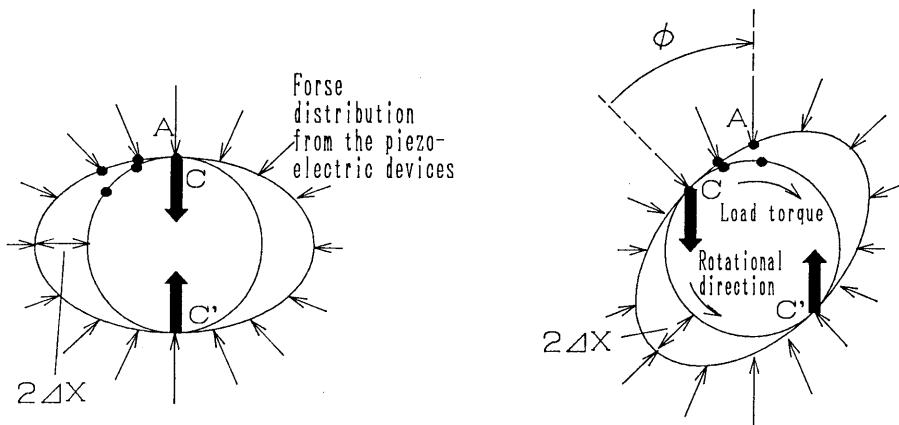


Fig. 4. Locus of a point A on the flexspline



(a) In the case of no load torque

(b) In the case that load torque is applied clockwise

Fig. 5. Distribution of forces applied to the flexspline and the circular spline

contact points on the flexspline with the circular spline, which we call directional conversion, so that the circular spline is rotated by transmission of the movement of the contact points through friction.

2. 3 Torque generation mechanism

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 shown in Fig.5(b). If no load torque is applied to the circular spline, distribution of the forces from the piezoelectric devices is approximately symmetrical with respect to the plane passing the contact points (C and C') and the central axis of the motor, and then the force vectors at the contact points are centripetal, as shown in Fig.5(a). When the load torque is applied clockwise, the contact points are rotated counterclockwise as well as the elliptical transformation of the flexspline because the circular spline pulls the flexspline clockwise, as shown in Fig.5(b). As a result, the tan-

gential forces (the friction forces) are produced at the contacting points due to the function of the directional conversion by the flexspline so that the generated torque meets the load torque.

3. Approximate analysis

3. 1 Rotational speed in the case of no load torque

The rotational speed n_0 of the circular spline, in the case of no slip between the flexspline and the circular spline, is obtained by equating the length where the contact points (C and C') move per unit time. Therefore, n_0 is given by the following equation;

$$\begin{aligned} n_0 &= -(\Delta X / (X_0 - \Delta X)) f / 2 \approx -(\Delta X / X_0) f / 2 \text{ [rps]} \\ &= -30(\Delta X / X_0) f \text{ [rpm]} \end{aligned} \quad (1)$$

where f is a frequency of the applied voltages, X_0 is a radius of the flexspline in the case that it is circular (not transformed) and ΔX is a difference between X_0 and the radius of the circular spline on the contact line with the flexspline, as shown in Fig.3.

When the amplitude of ac voltages applied to the piezoelectric devices, the force applied to the plane P and the load torque applied to the circular spline are constant, the difference ΔX is considered constant and therefore the rotational speed n_0 is expected proportional to the applied frequency f . It is considered that if the plane P is pressed stronger, ΔX becomes smaller and consequently the rotating speed n_0 gets lower.

3. 2 Generated torque

For simplicity, approximate analysis is made to obtain an expression for the generated torque T_m using the relationship of power balance (that is, the conservation law of energy). We assume that the distribution of the displacement and the forces (x_{ak} and f_{ak} , respectively) produced by the piezoelectric devices are expressed as follows,

$$x_{ak} \approx X_0 + \Delta X \cos\{\omega t - 2\theta_k\} \quad (2)$$

$$f_{ak} \approx F_0 + \Delta F \cos\{\omega t - 2(\theta_k - \phi)\} \quad (3)$$

$$\theta_k = 2\pi(k-1)/N \quad (4)$$

where ΔF is an amplitude of force variation, θ_k is an angular position of k -th piezoelectric device and is positive in the clockwise direction, ω is an angular frequency ($=2\pi f$) applied to the devices, and ϕ is a leading angle, where the force distribution takes its maximum value, with respect to the angular position of the contact point C, regarding it as continuous function.

Assuming no loss in the flexspline due to its transformation and no slip at the contact points on it with the circular spline and the piezoelectric devices, the mechanical input power P_m from the piezoelectric devices is equal to the output power to the circular spline as expressed by the following equation;

$$P_m = \sum_{k=1}^N f_{\Delta k} \cdot (dx_{\Delta k} / dt) = T_m \omega_m \quad (5)$$

where ω_m is a rotational angular speed and is obtained from (1) as follows;

$$\omega_m \simeq -(\Delta X / X_0) \omega / 2 \quad [\text{rad/s}] \quad (6)$$

Substituting (2), (3) and (6) into (5) and rearranging (5) yields the following equation;

$$-T_m \cdot (\Delta X / X_0) \omega / 2 \simeq (N \omega \Delta X \Delta F / 2) \sin 2\phi$$

that is,

$$T_m \simeq -N X_0 \Delta F \sin 2\phi \quad (7).$$

This equation indicates that the generating torque T_m is proportional to the product of the amplitude of the force variation ΔF produced by the piezoelectric devices and $\sin 2\phi$. The values of ΔF and ϕ are determined by the electromechanical characteristics of the piezoelectric devices and the elastic characteristics of the flexspline. There is also possibility that the elasticity of the circular spline is concerned in the torque characteristics.

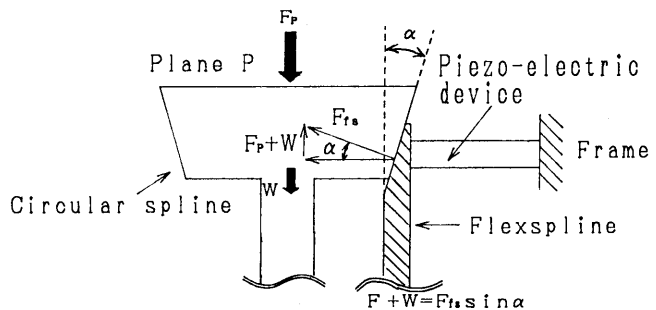
If so, both ΔF and ϕ are expected to be small, and consequently the T_m becomes small.

3. 3 Effect of friction

There is another factor which limits the generating torque of the friction-type piezoelectric motor. That is slip which may take place at the contact points between the flexspline and the circular spline and may increase according as the load torque rises. The motor may be stalled when the load torque applied to the circular spline is equal to the product of X_0 and the maximum 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 denoted as T_{FM} .

When the force F_P is applied to the plane P of the circular spline, as shown in Fig.6, and the dead weight of the circular spline is denoted as W , the total of the forces F_{FS} by which the circular spline pushes the flexspline is given by

$$F_{FS} = (F_P + W) / \sin \alpha$$



(8), Fig. 6. Forces applied to the circular spline

where α is a taper angle by which the circular spline is tapered as shown in Fig.6. Consequently, the maximum frictional torque T_{FM} is given by

$$T_{FM} = \mu F_{PS} X_0 = \mu (F_P + W) X_0 / \sin \alpha \quad (9)$$

where μ is a friction factor. The maximum frictional torque T_{FM} becomes larger if the larger force is applied to the plane P.

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 applied to the plane P.

4. Experimental results and discussion

4.1 Experimental system

The structure of an experimental motor is shown in Fig.1, and its dimensions are shown in Table 1. The circular spline and the flexspline are made of iron, the fixing screws are of stainless steel and the frame is of brass. 16 multilayer piezoelectric devices made of PZT are used to generate rotating wave of displacement and force. Their rated voltage is 150 [V] and their capacitance is about 1.5[μ F]. Their characteristics and dimensions are shown in Fig.7. They can produce the displacement x_a of about 10 [μ m] ($f_a=0$) or the force f_a of about 60[kgf] ($x_a=0$) when the applied voltage V_a is 100[V].

Table 1. Dimensions of the experimental motor

Frame		Circular spline		Flexspline	
	Dimensions[mm]		Dimensions[mm]		Dimensions[mm]
L 3	1 0 0. 0	L 1	3 4. 6	Inside diameter	3 3. 8 5
L 4	4 0. 0	L 2	3 3. 8	Thickness	1. 3 0
L 7	8 2. 0	L 5	1 8. 0	L 6	2 8. 0
L 8	7. 0	$\sin \alpha$	0. 0 2 2		

The driving circuit of the motor is a 8-phase voltage source MOSFET inverter with biased rectangular outputs of 0 and V_a as shown in Fig.8, where V_a is a 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 [Ω] are inserted in series with every pair of piezoelectric devices to avoid excessive currents

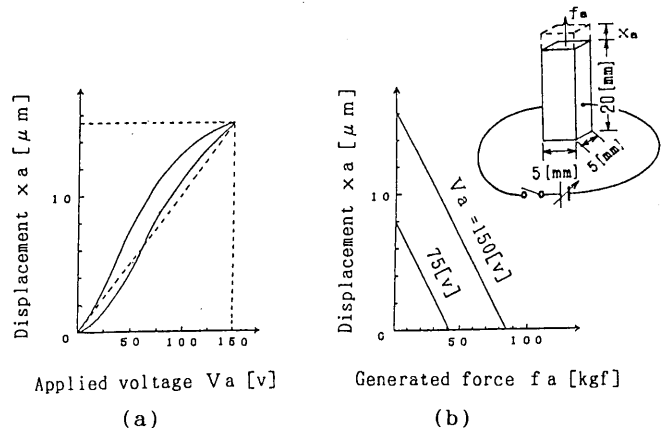


Fig. 7. Characteristics of displacement x_a versus (a) applied voltage V_a and (b) generated force f_a of multilayer piezoelectric device

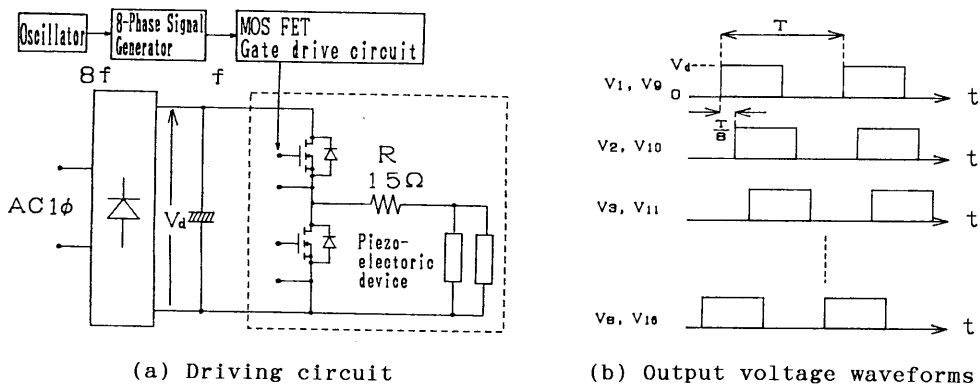


Fig. 8. Simplified diagrams of the driving circuit of the motor and its output voltage waveforms

rushing to the devices because they are capacitive. The rotational speed is obtained by measuring the time for which the circular spline rotates by a turn. The generating torque is measured by the method shown in Fig.9.

4. 2 Experimental results

Fig.10 shows characteristics of the rotational speed n versus applied frequency f of the motor in the case of no load torque. Parameter in this figure is the force F_P applied to the plane P of the circular spline. It is shown that the rotational speed is approximately proportional to the applied frequency and the slope of the line becomes lower as the larger force is applied to the plane P. These results are explained by (1), and indicate that the amplitude ΔX of the displacement variation is almost constant independently of the applied frequency and that the values of $2 \Delta X$ are about $10 [\mu m]$ is 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 $3 [rpm]$ in this experiment.

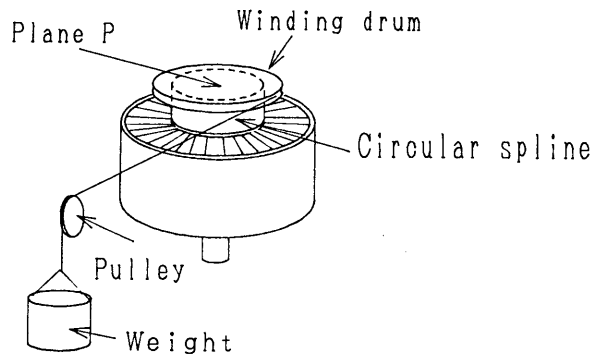


Fig. 9. Method of torque measurement

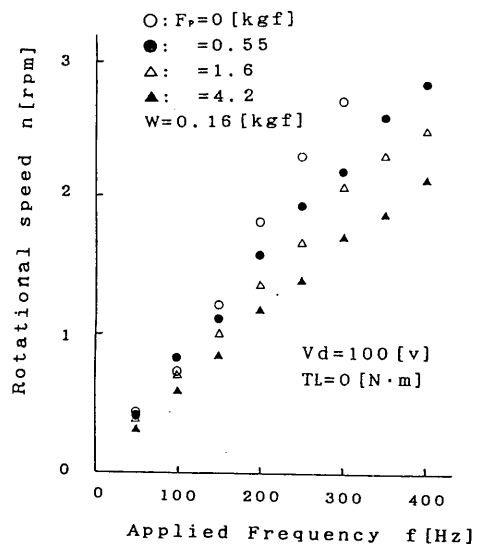


Fig. 10. Characteristics of rotational speed versus applied frequency for various forces applied to the plane P

Though 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]. This indicates that considerably large loss is produced in the resistors inserted in series with the piezoelectric devices. In practice, the resistors should be replaced by reactors. In addition, from the point of view of efficiency, the motor is desirable to be operated in resonant mode.

Fig.11 (a), (b) and (c) show characteristics of the rotational speed n versus the load torque T_L for various values of the force F_F applied to the plane P, dc voltage V_d of the inverter and the applied frequency f , respectively. The speed droop in accordance with increase of the load torque is considered mainly due to reduction of the ΔX caused by application of the tangential forces to the flexspline at the contact points. It is because there are regions where the speed remains zero in spite of increase of the load torque, especially in the case of large F_F , as shown in Fig.10(a). It is possible that the slip also causes speed reduction at the contact points in the case of small F_F . The stall torque T_S is defined as the torque where the rotational speed reach zero from the positive (in the same direction as the generated torque). On the other hand, the torque where the rotational speed leaves zero to the negative (in the opposite direction) is called maximum stall torque

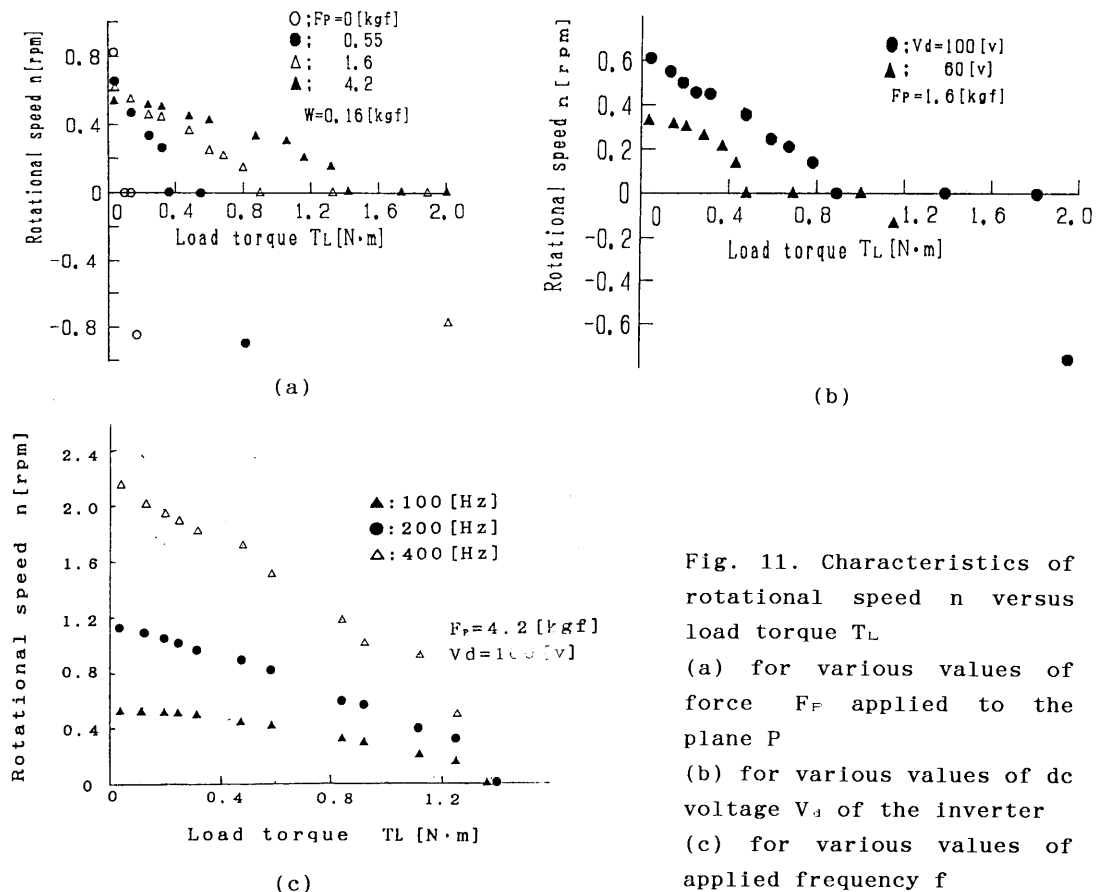


Fig. 11. Characteristics of rotational speed n versus load torque T_L

(a) for various values of force F_F applied to the plane P

(b) for various values of dc voltage V_d of the inverter

(c) for various values of applied frequency f

and denoted as T_{SM} . The stall torque T_S is almost independent of the applied frequency, as shown in Fig.11(c).

Fig.12 shows characteristics of the stall torque T_S and the maximum stall torque T_{SM} versus the applied frequency f . The solid line in the figure is numerical result of the maximum frictional torque T_{FM} given by (9) in the case that $\mu = 0.1$ and $X_0 = 17.0$ [mm], which is almost same as T_{SM} . The stall torque increases with the force applied to the plane P added dead-weight W of the rotor, as shown in Figs.11(a) and 12. Referring to (7), increase of the stall torque is considered because of increase of the generated force f_a (i.e. ΔF) of the piezoelectric devices due to reduction of the displacement x_a (i.e. ΔX) caused by increase of F_P . However, the stall torque is much smaller than the theoretical maximum frictional torque T_{FM} as shown in Fig.12.

Therefore, behavior of $\sin 2\phi$ in (7) should be also taken into consideration, which is, however, very complicated because it is related to the electromechanical characteristics of the piezoelectric devices and the elastic characteristics of the flexspline and the circular spline. Since in the experiment the circular spline is made of iron, whose Young's modulus is much smaller than that of the piezoelectric device, it is also considered to be transformed a little, so that the $\sin 2\phi$ is probably small.

The experimental results indicate that if the applied force is large and the elastic characteristics of the circular spline and the friction coefficient and the durability at the contact points are improved, considerably large torque could be produced because the generated force of the piezoelectric device is very large.

5. Conclusions

A new type of motor which utilize piezoelectric devices and mechanism of the strain wave gearing and can operate in variable frequency is proposed. Configuration, basic operation, and torque generation mechanism of the motor are described. Feasibility of the proposed motor is verified by experiments. It is found that the rotational speed of the proposed motor is very low and proportional to the applied frequency and that very large torque can be expected. However, from the point of view of efficiency, it is desirable that the motor is improved to operate in resonant mode.

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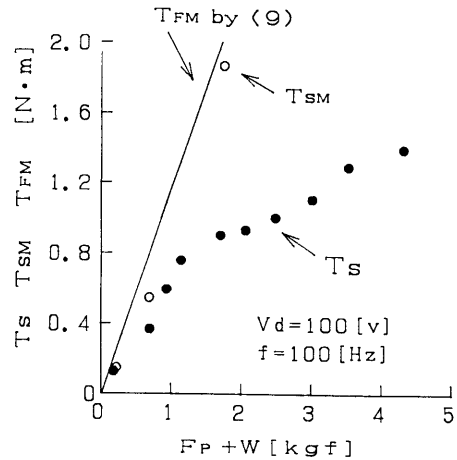


Fig. 12 Characteristics of stall torque T_S versus applied frequency f

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