Acta Technica 62, No. 3B/2017, 619–628

Design and experiment of vertical drive rotary piezoelectric motor[1]

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Abstract. In order to realize the low frequency and high power output of the piezoelectric motor, this paper designs a kind of vertical drive rotary piezoelectric motor. The rotary motor has simple structure and is driven by a low frequency power supply. Firstly, the structure of low frequency rotary drive motor is designed, and its working mechanism is analyzed. Then, the dynamics and kinematics model of the system and the rotor are established, and the expressions of the output displacement and the natural frequency of the system are derived. The condition of rotor rotation is obtained.The condition of rotor rotation is obtained. At last, we produced a prototype and tested it. The experimental results show that the optimal operating frequency of the rotary piezoelectric motor is 262 Hz. When the driving voltage is 180 V, the maximum speed is 15.3 rpm and the output torque is 0.022 Nm.

Key words. Piezoelectric drive, rotary motor, dynamics, kinematics, experimental study.

1. Introduction

Piezoelectric drive motor is a new type of driver which drives the motion of the rotor depending on the friction between the stator and rotor. Compared with the traditional electromagnetic driver, it has the advantages of simple structure, fast response, high control precision, and no electromagnetic interference. It has broad application prospects in the fields of aerospace, micro robots and electronic devices.

At present, the most research is the ultrasonic motor, which has the advantages

[1]This work is funded by the National Science Foundation of China (51607010) and Scientific research project of the Education Department of Jilin Provincial (JJKH20170489KJ), which is named "Driving Mechanism and Experimental Study of Power Frequency Piezoelectric Motor" and "Study on nonlinear dynamic characteristics of piezoelectric fatigue testing machine system".

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of small torque, no noise, no electromagnetic interference and other advantages. It has been widely concerned at home and abroad. Since Williams and Brown applied for a patent for a piezoelectric motor in 1942, the German Siemens company and Matsushita company, the IBM company of the United States and the Canon Co. of Japan have developed the piezoelectric ultrasonic motor, and made great progress. However, the vibration frequency of the ultrasonic motor is generally greater than 20 kHz, which needs to be equipped with special high frequency power supply to drive. In most cases, this kind of high frequency power supply is more expensive and larger than the ultrasonic motor body. The above reasons led the ultrasonic motor to be restricted in applications.

In recent years, many domestic and foreign scholars have carried out the research of low frequency piezoelectric motor [1-–4]. Professor Chunsheng Zhao and others have developed a clutch driven piezoelectric motor [5], which can work in a lower frequency state, etc. In recent years, there have been some research on the vibration motor [6–7], which aims at reducing the driving frequency, etc. Its operating frequency is usually several thousands Hertz [8–13]. The frequency is relatively high, still need higher frequency drive power supply to drive.

In this paper, a vertical drive rotary piezoelectric motor is presented, which can be used to vibrate at lower frequencies. It is driven by low frequency drive power supply. The system is simple in structure and low cost. It should be a new type of actuator that can be applied in a wider range.

2. Structural design and working principle

In this paper, the rotating piezoelectric motor is shown in Fig. 1. It consists mainly of the rotor bracket, bracket, bearing, rotor, ring, center shaft upper nut, piezoelectric vibrator, central shaft, bracket nut, resonant spring plate, base, spring plate fixing nut, adjustable spring plate, etc. The adjustable spring plate can adjust the amplitude of piezoelectric vibrator on the exciting source and store the energy of the system, not to adjust the preload of the rotor.

The bracket is fixed on the base, the bearing is fixed on the bracket and contacts with the stator ring. In order to minimize the influence of the radial clearance of the bearing, a large preload is applied between the bearing and the stator ring. When the voltage and frequency are adjusted, the bearing can rotate quickly, which indicates that the structure can form the driving force to drive the rotor to rotate.

Working principle:

An alternating signal is applied to the piezoelectric vibrator, and the piezoelectric vibrator generates a vertical vibration. Which drives the four resonant spring sheets to produce oblique motion. The bending vibration of the resonant reed causes the stator to be inclined. When the stator moves upward, the rotor is forced to move, due to the influence of the structure, the resonance spring sheet can also generate tiny torsion. When the stator moves downwards, the upper and the lower displacement are limited due to the connection between the rotor and the base, resulting in the rotor not moving downward with the stator, but a small rotation of the rotor in a vibration period. This situation continues the formation of the continuous rotation

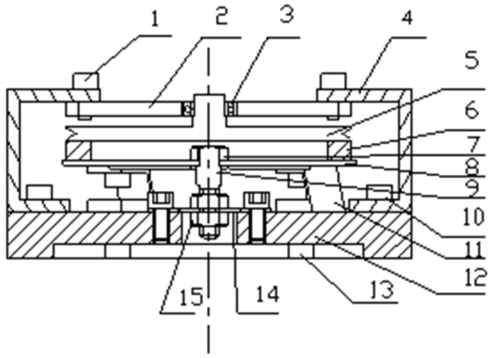

Fig. 1. Structure diagram of vertical drive rotary piezoelectric motor: 1–bolt, 2–rotor bracket, 3–bearing, 4–bracket, 5–rotor, 6–ring, 7– center shaft upper nut, 8–piezoelectric vibrator, 9–center shaft, 10–bracket nut, 11–resonant spring plate, 12–base, 13–spring plate fixing nut, 14–adjustable spring plate, 15–adjusting nut

of the rotor, resulting in macro displacement, to achieve the purpose of rotor rotation and output torque.

3. Kinetic analysis

3.1. System dynamics analysis

Since the piezoelectric vibrator is driven by an alternating signal, the vibration generated by the system is a simple harmonic vibration. The physical model of the system is shown in Fig. 2. Here, F is the excitation force of the system, x is the displacement of the system, m is the equivalent mass of the system, and C is the damping of the system.

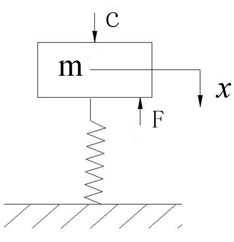

Fig. 2. Physical model of driving motor

The differential equation of the system is

$$m\ddot{x} + kx + C = F(t) = F \sin \omega t \,. \tag{1}$$

Because the system is in steady state response, the solution is

$$x = X\sin(\omega t - \phi) + C_1\,. \tag{2}$$

In the formula, X is the amplitude, ϕ is phase difference and C_1 is a constant.

Introducing

$$F\sin\omega t = F\sin[(\omega t - \phi) + \phi] \tag{3}$$

we get

$$[(k - m\omega^2) - F\cos\phi]\sin(\omega t - \phi) + F\sin\phi\cos(\omega t - \phi) = 0\,. \tag{4}$$

Now we can easily obtain

$$X = \frac{F}{k - m\omega^2}\,, \tag{5}$$

and

$$C_1 = -C/k\,. \tag{6}$$

Now (5) can be transformed into the form

$$X = \frac{F/k}{1 - (\omega/\omega_{\mathrm{n}})^2}\,. \tag{7}$$

$\omega_{\mathrm{n}} = \sqrt{k/m}$.

Finally, after substituting into (2) we have

$$X = \frac{F/k}{1 - (\omega/\omega_n)^2}\sin(\omega t - \phi) - C/k\,. \tag{8}$$

It can be concluded that under the excitation of harmonic vibration, the forced vibration is also a simple harmonic vibration, and the frequency of vibration is the same as the exciting frequency. If the spring steel pieces connecting the bottom of the rotor have suitable stiffness, then the natural frequency of the system follows from the formula

$$\omega_{\mathrm{n}} = \sqrt{k/m}\,. \tag{9}$$

When the driving frequency is the same as the natural frequency of the system, the system is in the resonance state, and the system is in the best working condition (the rotor can rotate at a high speed).

3.2. Force analysis of rotor

As the piezoelectric vibrator performs simple harmonic vibration, the rotor can be considered to do corresponding harmonic vibrations. In the XY coordinate system, the rotor force analysis follows from Fig. 3.

The stator harmonic vibratios are described by formula

$$S = A\sin\omega t\,. \tag{10}$$

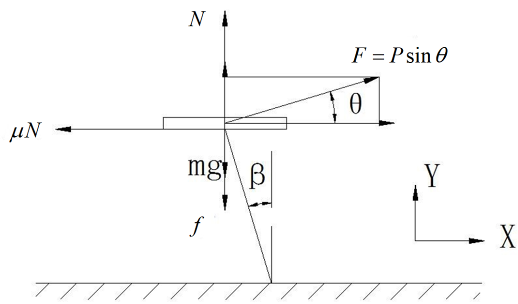

Fig. 3. Rotor force analysis diagram

Here, A is the amplitude, ω is the angular vibration frequency and t is the time.

The rotor is subjected to the periodic impact force of the stator and the restoring force of the bottom spring plate. The corresponding differential equation is may be written in the form

$$m\ddot{y} + ky + f + mg - p\sin\omega t\sin\theta = 0\,. \tag{11}$$

In the above formula, f is the tensile force of the bottom spring plate and k is the stiffness coefficient of the bottom spring plate.

When the formula (11) is equal to zero, the rotor is at the edge of the throw. When the formula (11) is less than zero, the rotor can be thrown. When the formula (11) is larger than zero, and the rotor cannot be thrown off.

When the stator drives the rotor, the force of the rotor in the y direction is

$$N = f + ky + m\ddot{y} + mg - P\sin\omega t\sin\theta\,. \tag{12}$$

When the rotor is subjected to force in the X direction, then

$$P\sin\omega t\cos\theta - \mu N > 0\,. \tag{13}$$

At this point the rotor will rotate forward.

Substituting formula (11) into formula (12) and substituting $f + mg = c$ into formula (13), we obtain

$$kA\sin\omega t\sin\theta + c < (P + mA\omega^2)\sin\omega t\sin\theta\,. \tag{14}$$

When $C = 0$, the rotor and stator do not exhibit any gap or preload, so that in the first half of this cycle

$$k < \frac{P}{A} + m\omega^2\,. \tag{15}$$

When $C \neq 0$, then

$$C < (P + mA\omega^2 - kA)\sin\omega t \sin\theta\,. \tag{16}$$

In this way we can obtain

$$f < P + mA\omega^2 - kA - mg\,. \tag{17}$$

Now

$$P\sin\omega t\cos\theta - \mu(f + mg - P\sin\omega t\sin\theta) > 0\,. \tag{18}$$

When the formula (18) is less than zero, the rotor will no longer rotate, because

$$P\sin\omega t(\cos\theta + \mu\sin\theta) < \mu(f + mg)\,. \tag{19}$$

Hence

$$P < \mu(f + mg)/\sqrt{1 + \mu^2}\,. \tag{20}$$

The above analysis leads to the following conclusions:

(1) When the stiffness of the bottom spring plate is small, the rotor is a slight spiral motion, the preload force needs to be $f < P + mA\omega^2 - kA - mg$. When $P < kA - mA\omega^2$, the piezoelectric vibrator driving force is too small, the rotor can not rotate.

(2) When the stiffness of the bottom spring plate is very large and the driving force provided by the stator is $P < \mu(f + mg)/\sqrt{1 + \mu^2}$, the rotor will no longer rotate, it will follow the stator to do reciprocating motion. Similarly, when the driving force provided by the stator is too small, the rotor will not form a rotation, that is, when $f > \frac{P\sqrt{1+\mu^2}}{\mu} - mg$, the rotor will no longer rotate, so the pre tightening force between the rotor and stator has a maximum value.

4. Experimental study

4.1. Prototype making

The design of the rotary drive motor prototype is shown in Fig. 4. The two parameters of the experiment are the stiffness of the bottom adjusting spring plate and the resonant spring plate.

According to the design principle of low frequency piezoelectric motor, low frequency, high torque and high speed represent the reasonable parameters for the whole machine. After a simple test, the thickness of the resonant spring plate is 0.5 mm and thickness of the adjusting spring plate is 0.8 mm.

4.2. Experimental test

4.2.1. Test of the relationship between frequency and speed. The voltage is fixed to 180 V. We tested the relationship between the speed and the driving frequency

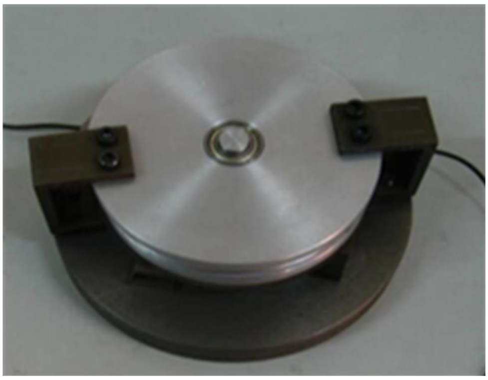

Fig. 4. Vertical drive rotary piezoelectric motor prototype

and the test results are shown in Fig. 5.

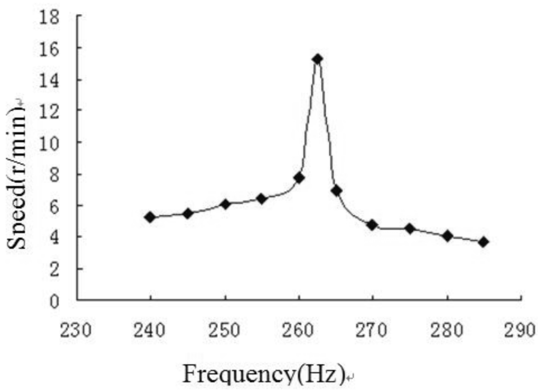

Fig. 5. The relation curve between speed and driving frequency

When the frequency is is 240 Hz, the speed is 5.1 rpm, then it increases first approximately linearly and then grows fast. When the frequency is 262 Hz, the speed reaches its maximum value 15.3 rpm, and with further growth of frequency the speed decreases.

4.2.2. Test of the relationship between frequency and output torque. The voltage is fixed to 180 V, test the relationship between the output torque with the driving frequency changes. It can be seen from the figure that the output torque increases first with the driving frequency and then decreased, the driving frequency is 262 Hz, the maximum output torque of $0.022\,\mathrm{N}\cdot\mathrm{m}$.

The output torque increases first with the driving frequency and then decreases For driving frequency 262 Hz, the maximum output torque is 0.022 Nm. Thus, the resonance frequency of the system is 262 Hz.

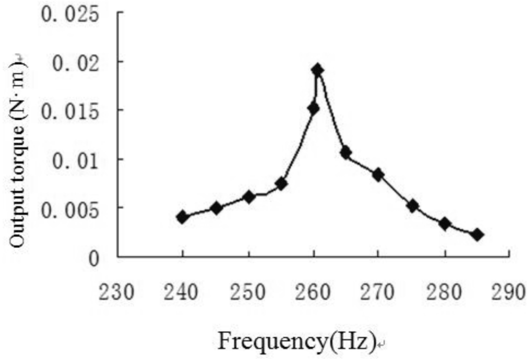

Fig. 6. The relation curve between output torque and driving frequency

4.2.3. Test of the relationship between voltage and output speed. The resonance frequency of the system is adjusted to 262 Hz, we tested the relationship between voltage and speed. The test results are shown in Fig. 7.

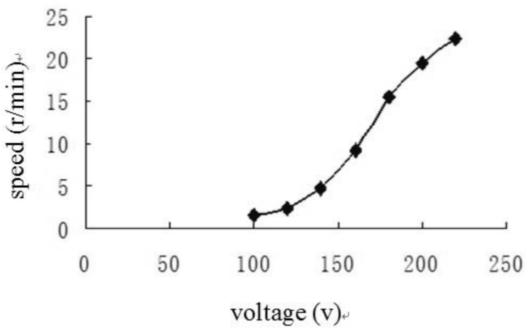

Fig. 7. The relation curve between output speed and driving voltage

As can be seen from the graph, the rotational speed increases with the increase of the driving voltage, and the dependence is basically linear.

4.2.4. Test of the relationship between voltage and output torque. The resonance frequency of the system is adjusted to 262 Hz, we tested the relationship between voltage and output torque. The test results are shown in Fig. 8.

As can be seen from the graph, the output torque increases with the increase of the driving voltage, and the curve is also almost linear.

5. Conclusion

(1) Made the dynamics and kinematics analysis on the rotary drive piezoelectric motor system and rotor, and concluded that the rotor rotation is determined by the

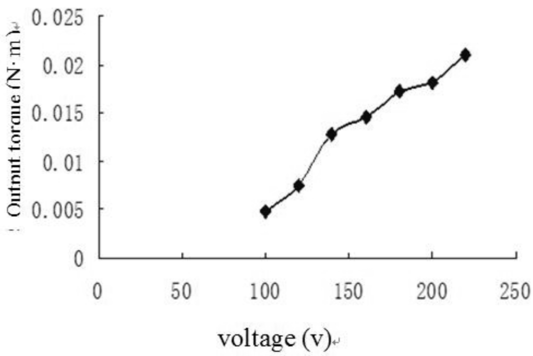

Fig. 8. The relation curve between output torque and driving voltage

preload between the stator and rotor.

(2) The rotary drive piezoelectric motor can work under low frequency, the resonant frequency is 262 Hz, the maximum output speed is 15.3 rpm, the maximum output torque is 0.022 Nm. It can achieve low frequency, high speed and high torque output. It may be a new type of driver that can be used in a wider range of applications.

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Received April 30, 2017