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Resonant Responses for an Electromechanical Integrated Harmonic Piezodrive System

***Abstract**. An electromechanical integrated harmonic piezodrive system is proposed. The principle of the drive system is introduced. A FEM analysis package, ANSYS, is used to study resonant responses of the vibrator for the drive system. The effects of the system parameters on the resonant responses are analyzed. The results show that the exciting voltage and the size parameters of the vibrator have obvious effects on the resonant responses. In order to obtain a good resonant behavior, these size parameters and the exciting voltage should be selected properly.*

***Streszczenie.** Przedstawiono piezoelektryczny element elektromechaniczny. Analizowano wpływ napięcia pobudzającego, wymairy oraz właściwości rezonansowe. (**Odpowiedź rezonansowa elektromechanicznego systemu piezoelektrycznego)**.*

Keywords: Resonant response, Piezodrive, Electromechanical integrated.
Słowa kluczowe: element piezoelektryczny, rezonans.

Introduction

Ultrasonic piezoelectric actuators and their related devices are currently used in many industries and research fields. Sashida developed a standing wave ultrasonic motor and a travelling-wave ultrasonic motor [1, 2]. Based on travelling-wave ultrasonic motor proposed by Sashida, Ishe proposed a ring-shaped travelling-wave ultrasonic motor in which the teeth were manufactured on the vibrator. It enlarged the vibrating amplitudes of the vibrator and the motor efficiency was increased [3].

However, the friction drive between the stator and the rotor is a weak link of the piezoelectric motors which limits the output torque and the operating life. Hence, Yamayoshi proposed a non-contact ultrasonic motor in which the fluid between the stator and the rotor is used to transmit torque and a speed of 3000rpm was obtained under the excitation voltage of 100V [4]. Ueha proposed a non-contact ultrasonic linear motor which can move the weight of 8.6g at a velocity of 0.7m/s [5]. Yang investigated a micro non-contact ultrasonic motor based on B22 vibration mode in which the rotor speed of 3569 rpm was given at the input voltage of 20V and the driving frequency of 45.6 kHz [6]. Hojjat proposed a rolling-contacting ultrasonic motor in which the rollers are located between the grooves of stator, and the elliptical motion of the stator surface causes the rollers to rotate, and the rollers drive the rotor to rotate [7].

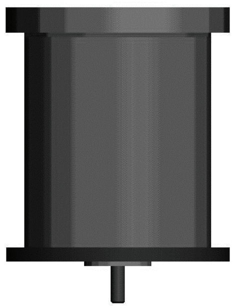
In a word, the non-contact ultrasonic motors and the rolling-contacting ultrasonic motors have high operating life and efficiency in spite of the small output torque, and they are proper for application fields of high speed and small load. However, in the exploration of the ultrasonic motors with large output torque, there is not a realized drive type to be given yet.

Therefore, the Authors propose an electromechanical integrated harmonic piezodrive system in which the piezodrive principle is combined with the harmonic drive and the movable tooth drive principles, and a reduction ratio is realized. Compared with other piezoelectric motors, there are three main advantages: rolling contact, transmitting load by meshing, and reduction. It makes the drive system have high operating efficiency and output torque.

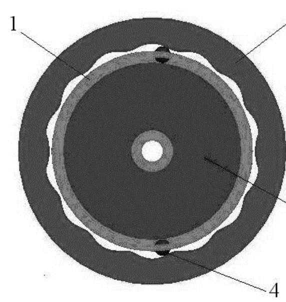
In the drive system, the piezoelectric vibrator is a key element. Its vibration drives the total system to work. In order to design and control the drive system, the resonant response problem of the drive system should be investigated.

Operating principle

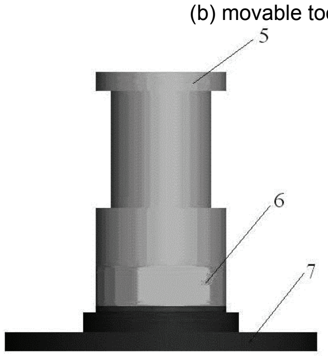
The configuration of the proposed electromechanical integrated harmonic piezodrive system is shown in Fig. 1, which consists of three main parts: the vibrator(stator), the harmonic movable tooth drive without wave generator, and the flexible ring between the vibrator and the movable tooth drive. Four ring-typed piezoelectric ceramics with two separated electrodes are placed in 90° to each other. They are used to excite the bending vibrations of the vibrator in two directions vertical to each other. When two input signals with a phase difference of 90° are applied to two pairs of the ring-typed piezoelectric ceramics, the motion of the traveling wave is produced in the vibrator of the bar-type ultrasonic motor. The vibrator contacts with a flexible ring at its roof, so the motion of the traveling wave causes the periodic elastic deformation of the flexible ring. Thus, a large periodic elastic displacement occurs at the top of the flexible ring (see Fig. 1).



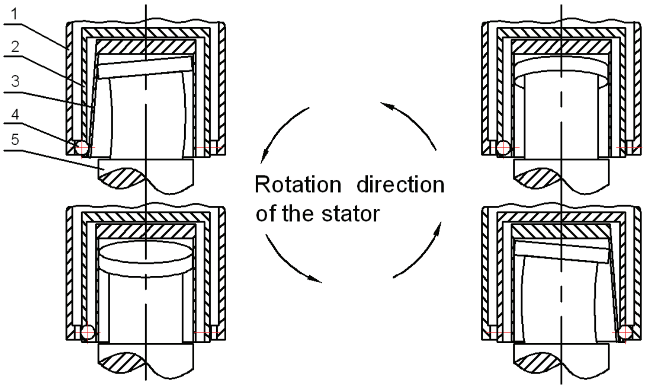
(a) 3D model



(b) movable tooth drive



(c) stator(vibrator)



(d) Rotation of the stator
Fig.1. The operating principle of the drive system
1 rotor；2 rigid gear；3 flexible ring；4 movable tooth；5 upper weight；6 piezoelectric ceramics；7 lower weight

The flexible ring top contacts with the movable teeth of the harmonic movable tooth drive. The periodic elastic displacement of the flexible ring top drives the movable teeth to mesh with the rigid gear, and the rotor on which the movable teeth are retained is driven to rotate. One circle of the vibrator corresponds to one tooth distance of the movable tooth motion. Hence, a reduction ratio occurs and a large output torque can be obtained.

Resonant response analysis

In this investigation, a FEM analysis package, ANSYS, is used to study the resonant responses of the vibrator for the drive system. The Values of the vibrator size parameters are shown in Table 1. The vibrator size parameters of the vibrator are denoted in Fig. 2. FEM models and mesh-dividing patterns for resonant response analysis of the vibrator are shown in Fig. 3.

Table 1. Values of the Vibrator Size Parameters

l1 [mm]	l2 [mm]	l3 [mm]	l4 [mm]
3	16-20	21-22.5	8.1
l5 [mm]	l6 [mm]	l7 [mm]	d1 [mm]
7	1-5	3	10
d2 [mm]	d3 [mm]	d4 [mm]	d5 [mm]
14-17	10.5-13.5	4	2
d6 [mm]	d7 [mm]		
12	24		

For the vibrator, all the freedom degrees of its lower end surface are removed. In FEM analysis package, ANSYS, the resonant response analysis model is used. The vibrator is made with steel. The physical parameters of the steel are given：density 7.8Kg/m^3, modulus of elasticity 2.1×10^{11} Pa, Poisson ratio 0.3. The physical parameters of the piezoelectric ceramics are given in stiffness matrix [c], piezoelectric constant matrix [e], and dielectric constant matrix [ε].
Here

$$[c]=\begin{bmatrix}13.21 & 7.0 & 7.3 & 0 & 0 & 0\\ 0 & 13.21 & 7.3 & 0 & 0 & 0\\ 0 & 0 & 11.6 & 0 & 0 & 0\\ 0 & 0 & 0 & 3.06 & 0 & 0\\ 0 & 0 & 0 & 0 & 2.6 & 0\\ 0 & 0 & 0 & 0 & 0 & 2.6\end{bmatrix}\times 10^{10}\,Pa$$

$$[e]=\begin{bmatrix}0 & 0 & -4.21\\ 0 & 0 & -4.21\\ 0 & 0 & 14.12\\ 0 & 0 & 0\\ 0 & 10.51 & 0\\ 10.51 & 0 & 0\end{bmatrix} c/m^2$$

$$[\varepsilon]=\begin{bmatrix}7.213 & 0 & 0\\ 0 & 7.213 & 0\\ 0 & 0 & 5.823\end{bmatrix}\times 10^{-9}\,F/m$$

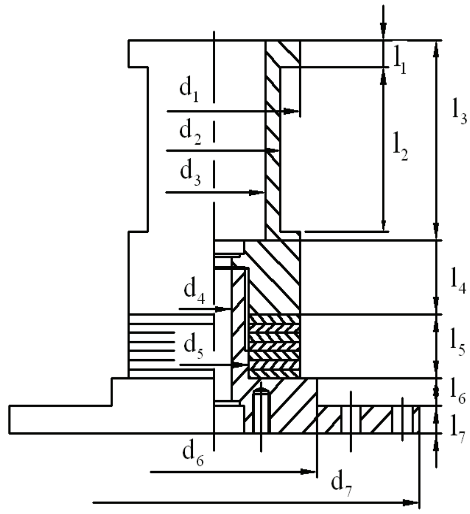


Fig.2. Vibrator and its size parameters

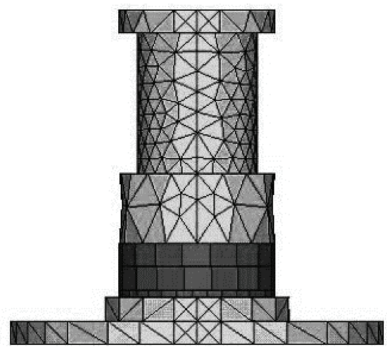


Fig.3. FEM model and initial mesh division

By above FEM model and restraint conditions, the resonant responses of the vibrator under the voltage excitation are analyzed. Here, two input signals of 220V with a phase difference of 90° are applied to two pairs of the ring-typed piezoelectric ceramics. Changes of the radial vibrating amplitude of the vibrator along with the excitation frequencies and other parameters are investigated (see Fig. 4). It shows:

(1) As the different material of the vibrator is used, the resonant frequency and the vibrating amplitude of the vibrator are changed. For the vibrator made with copper, the resonant frequency is the smallest and the vibrating amplitude is the largest. For the vibrator made with steel, its resonant frequency is larger than that of the vibrator made with copper, and smaller than that of the vibrator made with Al. For the vibrator made with steel, its vibrating amplitude is smaller than that of the vibrator made with copper, and larger than that of the vibrator made with Al. The vibrating

amplitude of the vibrator made with copper is about two times of the vibrating amplitude of the vibrator made with Al, 1.5 times of the vibrating amplitude of the vibrator made with Fe. It is because the copper vibrator has a large mass density and a small modulus of elasticity.

(2) As the fillister length l_2 of the upper weight of the vibrator is increased, the resonant frequency of the vibrator drops, and its vibrating amplitude first grows then drops. The vibrating amplitude of the vibrator is the largest for the fillister length of l_2=18mm. So, a moderate fillister length should be selected in order to obtain a larger vibrating amplitude of the vibrator.

(3) As the fillister diameter d_2 of the upper weight of the vibrator is increased, the resonant frequency of the vibrator first does not change then drops, and its vibrating amplitude first drops then grows. The vibrating amplitude of the vibrator is the largest for the fillister diameter of d_2=14mm. So, a small fillister diameter should be selected in order to obtain a larger vibrating amplitude of the vibrator.

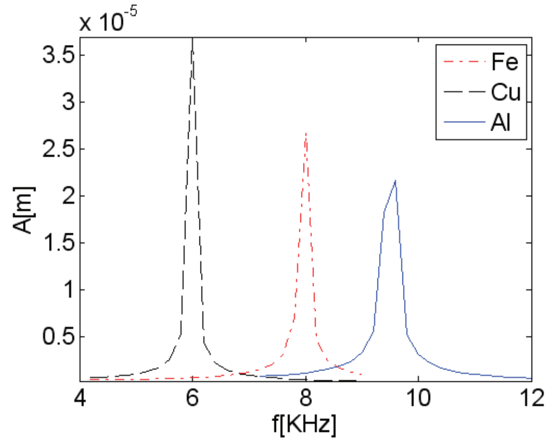
(4) As the inner hole diameter d_3 of the upper weight is decreased, the resonant frequency of the vibrator drops, and its vibrating amplitude grows. The vibrating amplitude for the hole diameter of d_3 =10.5mm is about 4 times of the vibrating amplitude for the hole diameter of d_3 =13.5mm. It shows that a smaller inner hole diameter of the upper weight is good for increasing the vibrating amplitude of the vibrator.

(5) As the inner hole height l_3 of the upper weight is increased, the resonant frequency of the vibrator changes slightly, and its vibrating amplitude first grows then drops. The vibrating amplitude for the inner hole height of l_3 =21.9mm is the largest. It gets to about 2 times of the vibrating amplitude for the inner hole height of l_3=21mm or 22.5mm. It shows that an optimum inner hole height of the upper weight should be taken for increasing the vibrating amplitude of the vibrator.

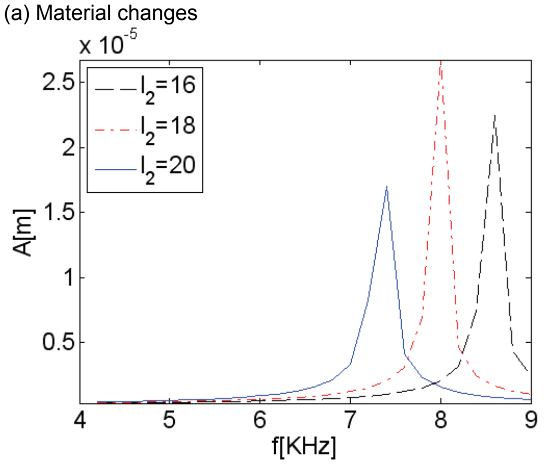
(6) As the height l_6 of the lower weight of the vibrator is increased, the resonant frequency of the vibrator and its vibrating amplitude first drops then grows. For a small height l_6 of the lower weight, the vibrating amplitude and its resonant frequency of the vibrator is the largest. So, a small height of the lower weight should be selected to obtain a larger vibrating amplitude of the vibrator.

(7) As the excitation voltage on the piezoelectric ceramics is increased, the resonant frequency of the vibrator does not change, and its vibrating amplitude grows obviously. The vibrating amplitude of the vibrator for the excitation voltage of U =300V is about 3 times of the vibrating amplitude for the excitation voltage of U =100V. It shows that the excitation voltage on the piezoelectric ceramics only changes the vibrating amplitude of the vibrator, but it does not change the resonant frequency of the vibrator. So, the excitation voltage is a realized control parameter of the resonant response for the drive system.

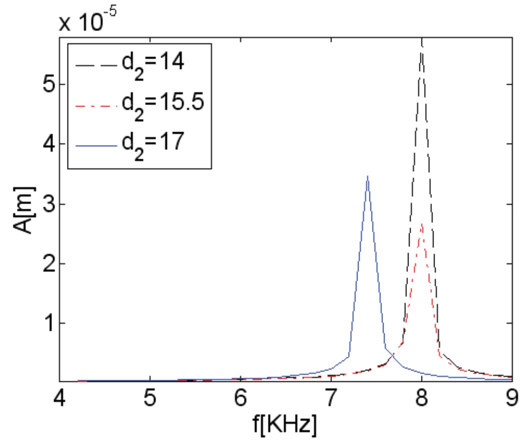
In a word, for the vibrator made with copper, the resonant frequency is the smallest and the vibrating amplitude is the largest which is a good material for producing the vibrator of the drive system; the size of the vibrator has obvious effects on its resonant frequency and its vibrating amplitude, so a team of the optimum size parameters should be taken in order to obtain a good resonant response; the excitation voltage only changes the vibrating amplitude of the vibrator which is a good control parameter of the resonant performance of the vibrator.



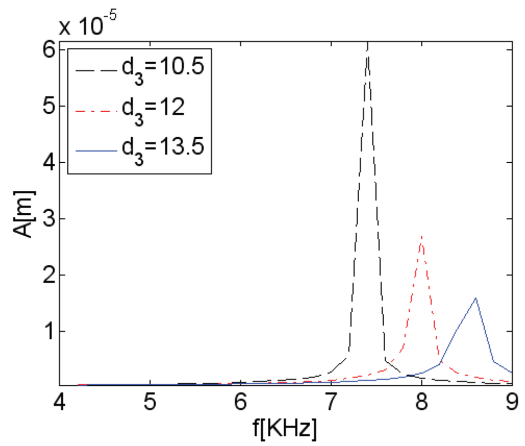
(a) Material changes



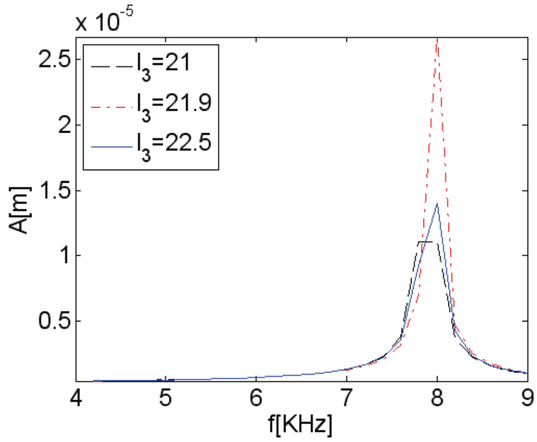
(b) l_2 changes



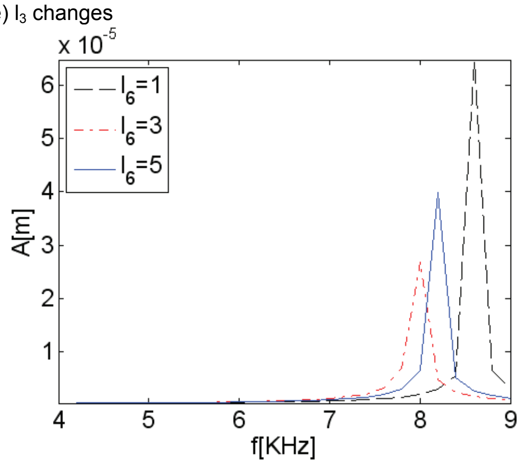
(c) d_2 changes



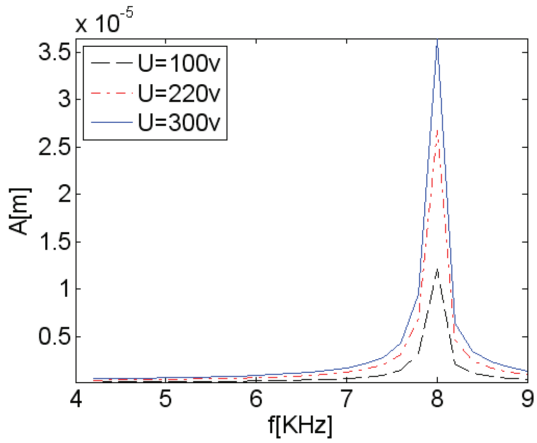
(d) d_3 changes



(e) l_3 changes



(f) l_6 changes



(g) U changes

Fig.4. Changes of the vibrating amplitude along with the excitation frequencies and other parameters

Conclusions

In this paper, an electromechanical integrated harmonic piezodrive system is proposed. The principle of the drive system is introduced. A FEM analysis package, ANSYS, is used to study electromechanical coupled resonant response performances of the drive system. The effects of the system parameters on the resonant response of the vibrator for the drive system are analyzed. The results show:

(1) For the vibrator made with copper, the resonant frequency is the smallest and the vibrating amplitude is the largest. It is a good material for producing the vibrator of the drive system.
(2) The size of the vibrator has obvious effects on its resonant frequency and its vibrating amplitude. In order to obtain a good resonant response, a team of the optimum size parameters should be taken.
(3) The excitation voltage only changes the vibrating amplitude of the vibrator, it is a good control parameter of the resonant performance of the vibrator.

These results are useful for design and manufacture of the novel electromechanical integrated harmonic piezodrive system.

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