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# A novel multi-mode differential ultrasonic motor based on variable mode excitation

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ABSTRACT

A novel multi-mode differential ultrasonic motor (USM) with two sandwich-type transducers has been developed. The salient feature of this motor is that it can work at three operation modes and provide three different output characteristics by changing the excitation method. Then, the motor can realize three-step speed regulation by switching the operation mode, and drive two rotors rotating or two sliders moving with same or contrary direction. The stator contains two sandwich-type transducers which are connected by two metal isosceles triangular beams. Four AC voltage signals are needed to excite eight piezoelectric ceramic pairs of the stator. By changing the connection way and frequency of the applied AC voltage signals, the longitudinal and bending vibration modes of the stator can be excited and degenerated. The variable mode excitation method and the working principle of the motor are analyzed. A prototype of the motor was designed and fabricated. The no-load speed and maximal thrust force of the prototype motor at three operation modes are tested.



## 1. Introduction

Compared with the conventional electromagnetic motors, ultrasonic motors (USM) have some merits of high torque at low speed, quick response, no electromagnetic interference and self-locking when powered-off [1–3]. The operation principle of piezoelectric ultrasonic motors is based on a two-stage electromechanical energy conversion. First, electrical energy is converted into mechanical energy by piezoelectric transducers which excite high-frequency mechanical oscillations of the stator. Depending on the geometry of the vibrator and the piezoelectric excitation, generally two orthogonal vibration modes are superposed on an elliptical motion of the surface. In a second step, the oscillations are converted to continuous linear or rotary motion by friction forces generated in the contact interface of the stator and a driven moveable body which is pressed against the oscillator. In recent years, USM have been applied in the fields of focusing system of camera, space explorations, ultra-precision measurement, medical equipment, etc. [4–7].

From the earliest days of the USM, engineers have been interested in the torque-speed characteristic and speed adjustment. The USM characteristics are strongly dependent on the driving parameters (frequency, voltage, temperature, pre-pressure, etc.) and the driven load [8]. Generally, there are two common control methods to change the torque-speed characteristic of USM, frequency control and voltage control [9]. If the excitation frequency changes, the input power of motor changes due to the variation of admittance and phase difference between the voltage and the current. The output power also changes [10]. Then the speed and torque change with the shift of frequency. To gain high amplitudes of the micro-motion at moderate input voltages, the ultrasonic vibrator should be driven near the eigen frequency of its mode. So, the efficiency of motor with voltage control is higher than frequency control. Besides the variable voltage control and variable frequency control, the variable mode control is another effective method, which is suitable for multi-mode USM. However, there are not many reports about multi-mode USM, and the variable mode control method is short of systematic research.

The idea of multi-mode USM originates from multi-degree-of-freedom (DOF) USM. Takemura and Maeno proposed a 3-DOF USM [11]. Two orthogonal second bending vibration modes and the first longitudinal vibration mode of a bar-shaped stator can be excited. By combing two of the three modes, the stator can drive the rotor rotating around three perpendicular axes. A ring type rotary ultrasonic motor with multiple wavenumbers proposed by Duan et al. is a typical single-DOF multi-mode rotary USM [12]. By changing the operation mode, the disk type USM can provide two different groups of speed-torque characteristic: higher no-load speed and

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lower maximum torque with wave number 10, and lower no-load speed and higher maximum torque with wave number 5. In this way, the step speed regulation can be realized by the novel variable mode control method. The wobble USM is another typical kind of USM with pairs of orthogonal bending modes, which can be utilized in variable mode control. Shi et al. reported a linear ultrasonic motor with wheel-shaped stator, which excites a pair of orthogonal fourth-bending modes to generate the elliptical motion of two wheels [13]. Dong et al. proposed a bar-shape USM for precision positioning, which is excited into the rotating third-bending mode of the stator [14].

A number of different USM capable of driving two rotors or sliders have been developed or proposed in recent years [5,15,16]. However, the moving directions and speeds of the two moveable bodies are the same. No USM was used to drive two moveable bodies with different speed or direction. A differential USM has the potential to replace the differential mechanism, and to drive a small size two-wheel vehicle moving linearly or turning.

In this paper, a novel multi-mode differential USM with two sandwich-type transducers has been developed, which can utilize the diverse combination of four vibration modes, symmetrical and anti-symmetrical first longitudinal modes, symmetrical and anti-symmetrical second bending modes. The salient feature of this motor is that it can realize three-step speed regulation with different speed-thrust force characteristics by switching the operation mode. Then the motor can drive two rotors or sliders moving with same or contrary direction. The three different excitation method and the working principle of the motor are analyzed. Structure of the USM was simulated by Ansys10.0 in order to determine the dimensions and the operation frequency. Based on the simulation results, a prototype motor has been fabricated and its performance characteristics in different modes have been investigated.

## 2. Structure of the stator

Fig. 1 shows the structure of the stator. The composite piezoelectric stator has a symmetrical structure. It contains two sandwich-type transducers which are connected by two metal isosceles triangular beams. The piezoelectric ceramics polarized in the thickness direction can be divided into eight pairs. Each pair of piezoelectric ceramic plates clamps a bronze electrode. Then, eight electrodes (A to H) are arranged in the stator, as shown in Fig. 1.

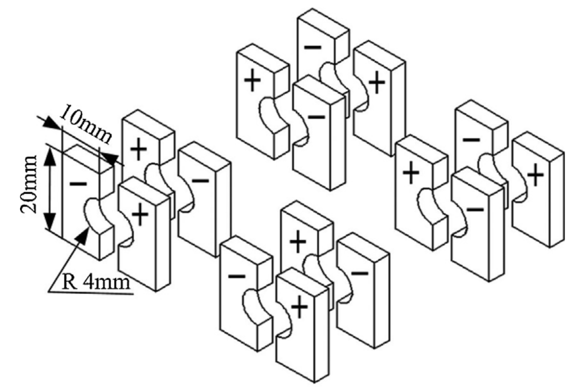


**Fig. 2.** Arrangement of the polarized ceramics in axial direction.

Two ground electrodes are arranged adjacent to the middle beams. All the PZT element groups (a pair of piezoelectric ceramics and an electrode) are clamped between the middle beam and end beam parts by screws. The mounting brackets are used to fix the stator. They are located at the nodal position to avoid the influence on the vibration modes and to minimize the vibration amplitude decrease caused by clamping the stator. The thin isosceles triangular connecting beams between the two transducers are used as driving feet. The driving foot B is shown in Fig. 1, and the driving foot A is the other triangular beam. The longitudinal and bending deformation of the two transducers can be superposed by the triangular beams to generate elliptical motion at the vertexes of the driving feet.

Fig. 2 shows the arrangement of the piezoelectric ceramics, which should be excited by the corresponding electrodes in Fig. 1. The polarized directions are signed as "+" and "−". In addition, all the beams must be grounded for voltage input.

## 3. Working principle

For this multi-mode differential motor, two functions are designed to be realized. First, three-step speed regulation based

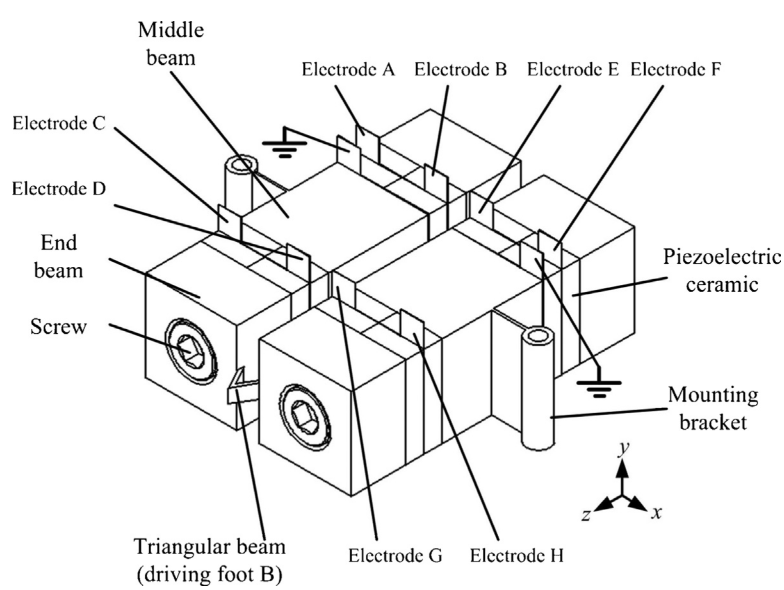


**Fig. 1.** Structure of the stator.