Ultrasonics 65 (2016) 277–281

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

A cylindrical traveling wave ultrasonic motor using bonded-type composite beam

Xiaohui Yang, Yingxiang Liu *, Weishan Chen, Junkao Liu

State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001, Heilongjiang Province, China

ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form 14 September 2015
Accepted 22 September 2015
Available online 28 September 2015

Keywords:
Ultrasonic motor
Traveling wave
Bonded-type
Vibration characteristic

ABSTRACT

A cylindrical traveling wave ultrasonic motor using bonded-type composite beam is proposed in this work. In this new design, a new exciting mode for L-B (longitudinal-bending) hybrid vibrations using bonded-type is adopted, which requires only two pieces of PZT ceramic plates and a single metal beam. In the new motor, the traveling wave of a cylinder can be excited by the L-B vibrations of a bonded-type beam. When two alternating voltages with phase difference are applied, the longitudinal and bending vibrations of the beam can be generated synchronously based on the new exciting mode for L-B hybrid vibrations, and the temporal phase difference of the two vibrations is always 90°. Finite element method is adopted to realize the modal degeneration in order to confirm the final structural parameters of the motor, and analyze the motion trajectory of the driving tip. After the fabrication of a prototype, the vibration characteristics and mechanical output ability are measured. The maximum no-load speed and maximum output torque of the prototype are 342 rpm and 6.26 mN m at a voltage of 100 V_{rms}.

1. Introduction

Ultrasonic motors are new type actuators worked via the converse piezoelectric effect of the PZT elements. The stator is usually a composite of piezoelectric ceramic and metal block in special shape. The elliptical vibration motion at the driving area of the stator can drive the runner by the frictional force, which is different from the conventional electromagnetic motors. Moreover, ultrasonic motors exhibit merits such as simple construction, high torque density at low speed, quick response, no electromagnetic radiation, high holding torque while power off and higher position accuracy [1–3]. These merits make them good candidate for application in fields of aerospace mechanism, robot, ultra-precision machine [4] and medical instrument.

From the viewpoint of vibration characteristics, ultrasonic motors can be divided into standing wave type ones [5–7], traveling wave type ones [8–12] and composite vibration modes type ones [13–23]. In recent years, several traveling wave ultrasonic motors using sandwich transducer had been proposed [24–31], in which longitudinal or bending vibrations of the transducer were used to excite the flexural mode of a metal ring or a cylinder. These motors can be seen as the combination of the traveling wave type one and the composite vibration modes type one. For example, a cylindrical traveling wave ultrasonic motor using longitudinal and bending composite transducer was proposed and tested by the authors in a previous work [27]. A traveling wave was generated in a metal cylinder with a bolt-clamped transducer. However, all these motors adopted the bolt-clamped structure, which made them difficult to be used in small system due to their large sizes.

Based on a new exciting mode for L-B hybrid vibrations, a cylindrical traveling wave ultrasonic motor using bonded-type composite beam is proposed in this study. The proposed motor has similar working principle with the previous work [27], and the traveling wave in the cylinder is still produced by the longitudinal and bending vibrations of the beam. Differently, there are only two pieces of PZT ceramic plates on the stator, which are excited by two alternating voltages with phase difference, and the longitudinal and bending vibrations are generated synchronously. In the previous work, the longitudinal and bending vibrations were excited by different PZT ceramics respectively, the number of which was six pieces. Furthermore, the new exciting mode for L-B hybrid vibrations makes the assembly process easier than ever before. The proposed motor is designed and analyzed by using finite element method. After the fabrication of a prototype, its vibration characteristics and output performance are investigated through experiments.

2. A new exciting mode for L-B hybrid vibrations

The fundamental principle of the new exciting mode for L-B hybrid vibrations using bonded-type is shown in Fig. 1. Two pieces

* Corresponding author.

http://dx.doi.org/10.1016/j.ultras.2015.09.014
0041-624X/

of ceramic plates are bonded on a metal beam, the polarization directions of which are along the thickness direction. Two alternating voltages, which are named as Phase A and Phase B, are applied on the two ceramic plates respectively. And the metal beam connects the ground. When the phase difference is 90°, the vibration shapes in one exciting cycle are shown in Fig. 2. When $t = t_1$ or $t = t_3$, $V_A = V_B$, the bonded-type beam will reach the limit positions of longitudinal vibration. When $t = t_2$ or $t = t_4$, $V_A = -V_B$, the limit positions of bending vibration are presented.

As shown in Fig. 1, when $t = 0$, $t = t_5$, $t = t_6$, $t = t_7$, and $t = t_8$, one of two voltages, V_A or V_B, is zero. When $0 < t < t_5$ and $t_6 < t < t_7$, vibration of the bonded-type beam is nearly longitudinal mode, and these time ranges are called longitudinal time. Similarly, the time ranges, $t_5 < t < t_6$ and $t_7 < t < t_8$, are called bending time. When the phase difference of two voltages is 90°, the longitudinal and bending times are equal. If the phase difference is reduced, the longitudinal time is compressed and the bending time is extended, the ratio of the longitudinal and the bending vibrations of the beam will be decreased. Conversely, if the phase difference is increased, the ratio of the longitudinal and the bending vibrations will be increased. So, the phase difference of the voltages can tune the ratio of the longitudinal and the bending vibrations of the beam. In this new exciting mode for L-B hybrid vibrations, the formations of longitudinal and bending vibrations are not independent anymore, but are correlated with each other. Thus, the longitudinal and bending vibrations of the composite beam can be inspired effectively by only two pieces of ceramic plates when these two vibrations have close resonance frequencies. Furthermore, the two vibrations of the beam always have a temporal phase difference of 90°, whatever the phase difference of two alternating voltages is.

3. Motor structure and operating principle

The structure of the proposed motor is shown in Fig. 3. The stator consists of a metal base and two ceramic plates. The metal base contains two parts: the cylinder as the component to spin the rotor, and the beam aiming at the constitution of the composite beam with ceramic plates. The internal teeth of the cylinder can amplify the vibration amplitude. The connection between the cylinder and the beam is the small end tip of the horn, which makes for the efficient transmission of the vibration and energy. The entire metal base is fabricated from a duralumin alloy block by using linear cutting machine. The polarizations of PZT ceramics are along their thickness directions, as shown in Fig. 3. Two conic rotors are pressed in contact with the teeth of the cylinder via a spring and nut system.

The operating principle of the new motor employs three basic vibrations, which are the first longitudinal vibration and the third bending vibration of the beam, and the sixth radial flexural vibration of the cylinder respectively. As shown in Fig. 4, the longitudinal vibration of the composite beam can excite one standing wave in the cylinder, and the bending vibration can generate the other one; and these two standing waves have a spatial phase difference of 90°. Meanwhile, the two standing waves excited by two vibrations of the composite beam must have a temporal phase difference of 90° because of the new exciting mode for L-B hybrid vibrations. A traveling wave will be formed, as long as the frequencies and the amplitudes of the two standing waves are same. Then, the cylinder can rotate the rotor via the driving teeth.

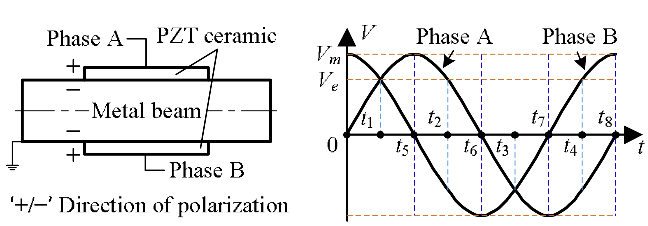

Fig. 1. A new exciting mode for L-B hybrid vibrations by two alternating voltages with temporal phase shift.

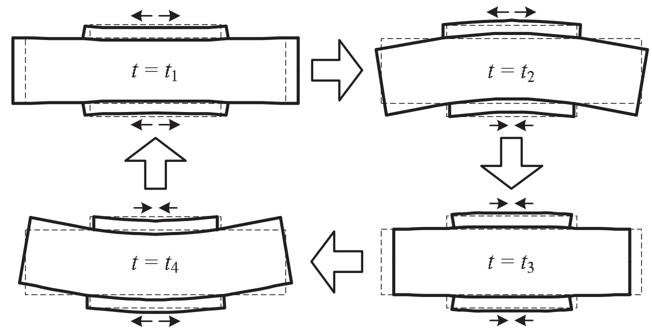

Fig. 2. Deformation sequence under the new exciting mode for L-B hybrid vibrations.

4. Design analysis process

Finite element method (FEM) is used to carry out the design process of the proposed motor, with the purpose of forming the traveling wave. Firstly, modal analysis is developed to accomplish the modal degeneration. The structure parameters of the stator model are adjusted until Mode-A and Mode-B have close resonance frequencies. Finally, under the parameters listed in Fig. 5 (the height of stator is 10 mm, and the number of teeth is 24), modal analysis result indicates that the resonance frequencies of Mode-A and Mode-B are 57.209 kHz and 57.093 kHz, respectively.

Secondly, transient analysis can investigate the motion behaviors of particles on the driving teeth, in order to ensure the generation of the traveling wave. In this new design, two standing waves excited by the longitudinal and the bending vibrations have the same frequency and 90° phase difference in both space and time. However, when the phase difference of two alternating voltages is 90°, the two standing waves don't have the same amplitude, which is the necessary condition to generate the traveling wave. Based on the new exciting mode for L-B hybrid vibrations, the phase difference of the alternating voltages can tune the ratio of the longitudinal and the bending vibrations of the beam, and further achieve the same amplitudes of two standing waves. When the frequencies of the voltages are 57.151 kHz, the amplitudes of two standing waves are tuned to be very close under a phase difference of 75°. Fig. 6 shows the motion trajectories of six selected particles on six evenly distributed teeth in the last simulation period.

In Fig. 6, the elliptical trajectories of selected nodes have the same rotary direction, which is coincident with the driving principle of traveling wave. However, the vibration amplitudes of selected nodes are different, especially in the radial direction. This feature indicates the wave excited in the cylinder is not a standard traveling wave. In other words, the standing waves are not ideally excited by two vibrations of the composite beam. The deformation may be caused by the asymmetrical excitation as only one composite beam is set.

5. Experiments

According to the final structure parameters, a prototype motor was fabricated, as shown in Fig. 7. The weight of the prototype is about 51.5 g, while the stator is about 23.5 g.