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Design and performance analysis of a rotary traveling wave ultrasonic motor with double vibrators

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ABSTRACT

This paper presents the development of a rotary traveling wave ultrasonic motor, in which a vibrating stator and vibrating rotor are combined in one motor. The stator and rotor are designed as similar structures an elastic body and a piezoelectric ceramic ring. In exciting of the piezoelectric ceramics, the elastic body of the stator and rotor will generate respective traveling waves, which force each other forward in the contact zone. Based on the elliptical rule of particle motion and matching principle of vibration, the design rules of two vibrators are determined. The finite element method is used to design the sizes of vibrators to ensure that they operate in resonance, and the simulation is verified by measuring the vibration with an impedance analyzer. It is found out that to maintain an appropriate contact between the stator and rotor, two vibrators need to be designed with close resonance frequencies, different vibration amplitudes, and be driven by an identical driving frequency. To analyze this innovative contact mechanism, particle velocity synthesis theory and contact force analysis using Hertz contact model are carried out. Finally, a prototype is fabricated and tested to verify the theoretical results. The test results show that the output performance of the motor driven by the two vibrators is significantly improved compared to the motor driven by a sole stator or rotor, which confirms the validity of the double-vibrator motor concept.

1. Introduction

Ultrasonic motors (USMs) have attracted considerable research attention due to their distinct advantages including high torque at low speed, quick response, quiet operation, compact size, light weight and no electromagnetic compatibility problems [1–7]. However, the low performance limit some special applications of ultrasonic motors.

Exploring new structures is an effective method to improve performance of USMs. Typical examples of new structures are USMs with Langevin transducers, which use longitudinal or bending vibration mode or both of them for vibration excitation. Kurosawa et al. [8] proposed a USM using two sandwich-type vibrators for large thrust applications. Satonobu et al. [9] proposed a USM with symmetric hybrid transducers. Iula and Pappalardo [10] proposed a high-power traveling wave USM with several transducers. Liu et al. [11] proposed a square-type rotary USM with four driving feet. Lu et al. [12]. proposed a novel dual stator-ring rotary USM which uses four bending mode Langevin transducers to excite the ninth order flexural mode traveling waves in the two stator-rings to drive its two rotors. These techniques can improve the performance of USMs to some extent, but they introduced problems such as complex structure and driving strategy.

The other methods improve performance of USM without increasing the complexity of the structure or driving strategy, which include using other vibration mode of piezoelectric ceramic, changing the contact surface between the stator and rotor, employing the rotor as vibrator, or designing two vibrators in one motor. Chen et al. [13] proposed a new traveling wave USM using a thick ring stator with nested piezoelectric ceramic stacks, which provides powerful mechanical output by using the d_{33} mode of piezoelectric ceramic. But the main disadvantage is the inaccuracy in fabrication because a total of 64 piezoelectric ceramic stacks and 64 block springs are nested in the stator. Hojjat et al. [14] proposed a novel USM with a roller interface, in which the traveling wave of stator surface causes rotation in the rollers, which rotate the rotor. Although the elliptical motions of stator surface rotate the rollers more effectively than the flat-ring rotor, applying rollers in the interface prevent USM applicability in light work without holding torque. Chen et al. [15] proposed a new configuration of traveling wave USM, in which the motor shell is used as the stator and the rotor serves as the vibrator. The vibrating rotor considerable (and innovatively) enhanced the motor's output

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performance, but its special structure and low speed limit its application. Bai et al. [16]proposed a new USM, in which the rotor rotation speed is locked by the phase-velocity difference between the two traveling waves propagating on the stator and the rotor. Bai first mentioned the concept of new structure motor using two vibrators. However, his research only includes reports on the experiment process, results, and discussions of the new structure motor. There has been no reasonable theoretical analysis to guide the design of structure and no quantitative performance analysis of the motor.

In this paper, the design methods of the double-vibrator structure are described in detail. The vibration characteristics of two vibrators are determined by finite element method (FEM). The analytical model of double-vibrator motor is established based on elliptical distribution rule of surface point velocity, linear superposition of motions and contact force analysis under Hertz contact theory. Complied with these design principle, a prototype is fabricated. Corresponding experiments are designed to confirm the validity of the proposed model. Major output performances of the prototype have been measured and discussed.

2. Double-vibrator ultrasonic motor design

The structure of proposed motor is shown in Fig. 1. The stator is fixed on the base, and the rotor is connected to the drive shaft. Adjusting the shaft's location along the axial direction creates varying pressure to the contact zone between the stator and rotor. Electric slip rings supply electric signal to the rotor: One electric slip ring consists of an outer ring and inner ring, a configuration which prevents power lines from been knotted in the motor. The outer ring is fixed on the inner wall of the motor, and the inner ring rotates with drive shaft when the motor is running. The output torque is transferred by the drive shaft.

2.1. Stator design

Similar to a traditional RTWUSM, there are two parts in the stator: An elastic body and a piezoelectric ceramic circle. In a traditional stator, a series of teeth drive the rotor by friction, to avoid scraping and wearing on the rotor surface and make full use of the interaction of the two wave surfaces, the new stator and rotor should be designed as smooth surfaces. Uniformly distributed holes allow adjustment to the vibration frequency and increase the vibration amplitude of the vibrator, which mimic the effects of teeth [17]. The structure of the stator is shown in Fig. 2(a).

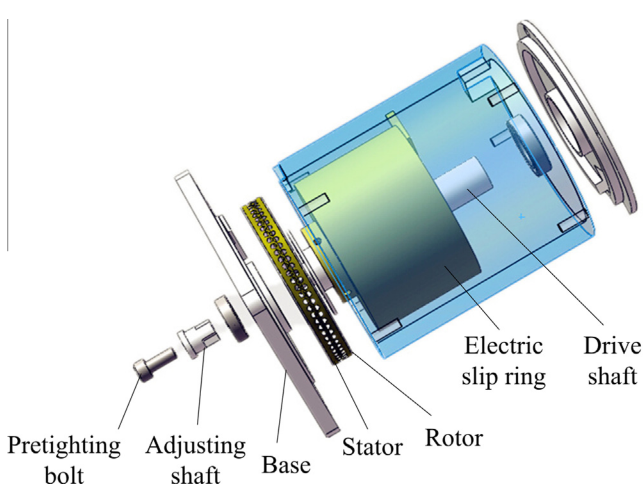

Fig. 1. Structure of the novel type RTWUSM.

In order to determine the working vibration mode and modal frequency, ANSYS software is utilized for calculation. The main parameters for calculation are as follows. Size parameters: 30 mm outer stator radius; 20 mm inner radius; 4 mm thickness of the elastic body; 0.5 mm thickness of the piezoelectric ceramic; 0.5 mm radius of each uniformly distributed hole; 0.75 mm distance between the hole center and the top surface of the elastic body; 72 holes in total. Material parameters: Copper alloy material for the elastic body; PZT-4 piezoelectric material; piezoelectric constant of the piezoelectric ceramic $d_{33} = 289 \times 10^{-12}$ C/N; electromechanical coupling factor $k_{33} = 0.70$; mechanical quality factor $Q_m = 500$; dielectric dissipation factor $\tan\delta = 0.4\%$; density = 7500 kg/m^3; and Curie Point = 328 °C. The calculated result of the working mode is shown in Fig. 2(b).

2.2. Rotor design

The rotor is the innovative part of the motor. As mentioned above, the structure of the rotor is similar to the stator, which is also designed as a vibrator. But taking consideration of the vibration matching, there is a little different from the structure of the stator.

As is known, not the entire contact zone plays the drive effect when the motor is running. The contact zone between stator and rotor is divided into driving and braking zones. To determine the location of the driving and braking zones on the wave crest, the horizontal velocities of surface-point are compared with velocity of the rotor. The surface point horizontal velocities on the wave crest are higher in magnitude than that of the rotor causing a driving effect between the stator and rotor surfaces. The stator forces the rotor forward in that region. Conversely, the surface point horizontal velocities are lower in magnitude than the rotor causing a braking effect between the stator and rotor surfaces. Fig. 3(a) illustrates this phenomena. If two vibrators, i.e., the stator and rotor, are designed as the same structure, the contact zone will extend to the whole wave. Based on the symmetry of the traveling wave and the elliptical distribution rule of surface point velocity, the contact zone will can be re-divided as shown in Fig. 3(b): as a result, the driving effect is cancelled out in the expanded braking zone of the new motor. Accordingly, there should be some difference in the characteristics of the two traveling waves.

There should not only be some shared vibration characteristics in the stator and rotor to achieve reasonable contact of two traveling waves, but some differences to ensure considerable output. In this study, to ensure appropriate disparity in vibration characteristics, two vibrators with different vibration amplitudes are designed by utilizing FEM; the respective vibration amplitudes of the stator and rotor are shown in Fig. 4(a) and (b). The vibration amplitude of the stator (1.42 μm) is larger than that of the rotor (1.0 μm) to facilitate the contact between the two vibrators shown in Fig. 5, and to avoid any unwanted enlargement of breaking zone to secure the appropriate driving effect.

2.3. Working principle

Two phase sinusoidal voltages with a 90° phase difference are supplied to the piezoelectric ceramic groups A and B respectively, a traveling wave is generated. In the proposed motor, not just one traveling wave is generated in the stator, but another traveling wave is also generated in the rotor. Four phase sinusoidal voltages with certain phase differences are supplied to piezoelectric ceramic groups A, B, A′, and B′, respectively, in the stator and rotor. Signals A ($\sin(\omega t)$) and B ($\cos(\omega t)$) are supplied to the stator, and signals A′ ($\sin(\omega t + \varphi)$) and B′ ($\cos(\omega t + \varphi)$) are supplied to the rotor. This generated two respective traveling waves in the stator