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Investigation of a rotary ultrasonic motor using a longitudinal vibrator and spiral fin rotor

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ABSTRACT

A Langevin transducer can provide longitudinal vibration with larger amplitude while also possessing a greater fatigue life than other types of piezoelectric vibrators. A novel rotary Ultrasonic Motor (USM) was proposed based on the use of a longitudinal transducer (acting as the stator) and a spiral fin rotor: the front cover of the Langevin transducer was designed as a double-layer cup-shaped structure, with the rotor sustained by the inner-layer, and the bearing cover fixed to the outer-layer; the rotor consisted of a shaft and spiral fins which acted as the elastic coupler. It is different from a traditional traveling USM, because the stator provides longitudinal vibration and the rotor generates the elliptical motion. This paper analyzed the motion locus equation of the fin contact points. Additionally, a theoretical analysis was performed in regards to the mechanism and the motor's rotor motion characteristics, which demonstrates the relationships among the motor's driving force, the torque, the revolution speed, and the motor structure parameters. A motor prototype has been manufactured and surveyed to demonstrate the motor performance. The relationships between the amplitude and the preload on the rotor, the free revolution speed, and the torque of the motor have also been studied.

1. Introduction

With the advantages of high torque at low speed and no electromagnetic interference, the USM has been widely applied to a variety of consumer electronics, precise instruments, man-made satellites and other high-tech products [1,2] and has been also proposed for higher requirements for torque, reliability and fatigue life. Given different stator structures, USM can be divided into two categories: a ring-type USM and the Langevin transducer type USM. The ring-type USM [3–7] is composed of piezoelectric ceramic rings bonded on a metal substrate, using the d_{31} working mode of piezoelectric ceramics (PZT), which leads to shortening the USM fatigue life. Using the d_{33} working mode, the Langevin transducer can provide greater amplitude with a bolt-clamped structure, higher reliability and other merits, which have become hot topics in USM research recently [8–12]. The vibrating model is important to the Langevin transducer type USM; most of them are longitudinal and have bending integrated, such as reference [8–10] proposed USMs, which were constructed using bending vibration Langevin transducers. A cylindrical traveling wave USM has been presented [11] with the longitudinal and bending integrated transducers. According to these references, the stator is usually composed of Langevin transducers, which are made of longitudinal or/and bending PZT; the structure of the front cover is machined to have many uniformly distributed driving teeth as the elastic couplers form an elliptical motion. This structure is similar to the substrate teeth adopted ring-type USM; this increases the processing difficulty of the front cover.

In an ultrasonic levitation experiment, a suspended plate can revolve slowly along its axis above the vibrating face; inspired by the phenomenon, we propose a rotary ultrasonic motor with spiral fins acting as the elastic coupler between the stator and the rotor, using only a longitudinal vibrating model transducer with no teeth on the front cover.

2. Structure of USM with the spiral fins

The rotary USM with spiral fins consists largely of the longitudinal vibrating mode Langevin transducer (acting as the stator) and the rotor (including the spiral fins and a shaft), as shown in Fig. 1.

In order to support the rotor shaft steadily and reduce the vibrating disturbance on output performance, the inner-layer cup-shape structure was machined at the front cover to hold the rotor; the transducer worked in longitudinal vibration mode while

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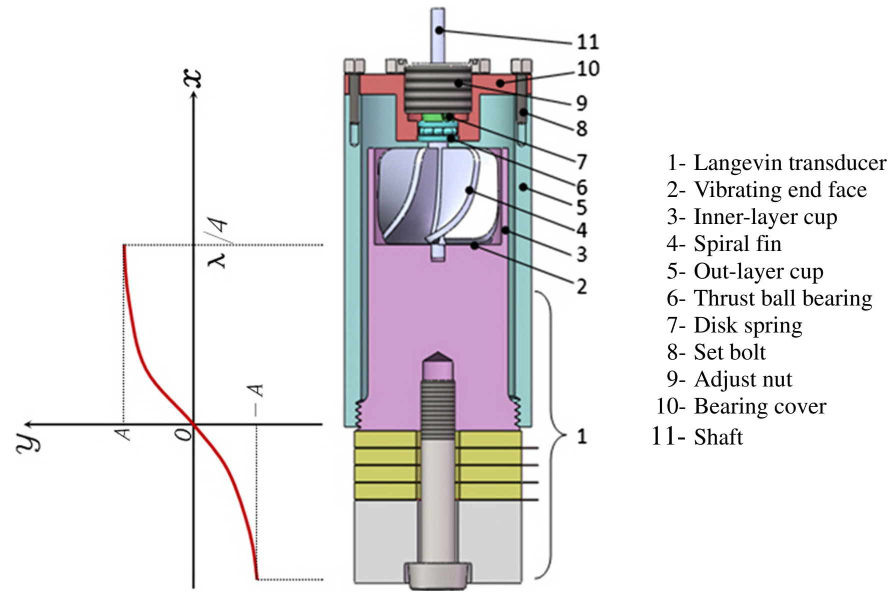

Fig. 1. Structure diagram of rotary ultrasonic motor with spiral fins.

the bottom of the cup (vibrating the end face) was located at the peak of the wave to enhance the vibrating strength and obtain enough amplitude and/or force, which acts on the rotor. The out-layer cup-shape structure was a sleeve with an internal thread line connected to the front cover at the node position, while the bearing cover was fixed at the other end of the sleeve by the set bolt in order to support one end of the shaft with the thrust ball bearing. Because the vibrations produce an antifriction effect between the two contact surfaces, the other end of the shaft was directly inserted into a blind hole located at the center of the vibrating end face without the bearing support, contacting the spiral fins with the vibrating end face. A disk spring pressed the thrust ball bearing and provided the preload force on the rotor by changing the position of the adjust nut.

According to the design principle of the Langevin transducer and the longitudinal vibration theory of the bar [2], the material of the front cover is an aluminum-magnesium alloy; the vibration mode is shown at the left in Fig. 1, so the amplitude of the front cover can be described as:

$$y(x) = A\sin\left(\frac{2\pi x}{\lambda}\right) \tag{1}$$

where λ is the wavelength of the front cover, A is the amplitude of the vibrating end face of the font cover and can be measured using a laser measuring instrument.

This paper illustrates the mechanism and motion characteristics of this USM based on the contact-separate process between the vibrating end face and the spiral fins.

3. Mechanism of the motor

As shown in Fig. 1, the stator (Langevin transducer) provides the longitudinal vibration; the spiral fins work as the elastic coupler to convert the longitudinal vibration into an elliptical motion of the contact point while rotating the rotor. This mechanism is different from all of the Langevin transducer type USMs presented previously.

3.1. Mechanism analysis

For each vibration period, there are two phases during the contact process between the rotor fins and the vibrating end face; one is the contact phase and another is the separation phase. In the contact phase, under the action of vibrating force F from the vibrating end face, the rotor fins will generate the forced vibration deformation so as to exert the elastic coupling effect. Due to the symmetric structure of the spiral fins, however, this paper will take one piece of the fin to use as an example for analysis; the model is as shown in Fig. 2(a). Assume that the fins are evenly located around the shaft; the inner diameter of the fins R_1 is equal to the radius of the shaft, the outer diameter R_2 is smaller than the inside diameter of the inner-layer cup, γ is the contact angle between the fin and the vibration end face, β is the angle of the inclination of the fin along the shaft, B is the effective contact thickness, S is the contact area, K_2 is the equivalent stiffness of the fin material; E_1 is the material elastic modulus of the front cover of the Langevin transducer, A is the longitudinal vibration amplitude of the vibrating end face of the Langevin transducer, and ω_1 is the frequency, thus the vibration displacement u [2] and the vibrating force F can be written as:

$$\begin{cases} u = A(\sin\omega_1 t - \cos\frac{\gamma}{2}) \\ F = K_2 S u = K_2 A S(\sin\omega_1 t - \cos\frac{\gamma}{2}) \end{cases} \tag{2}$$

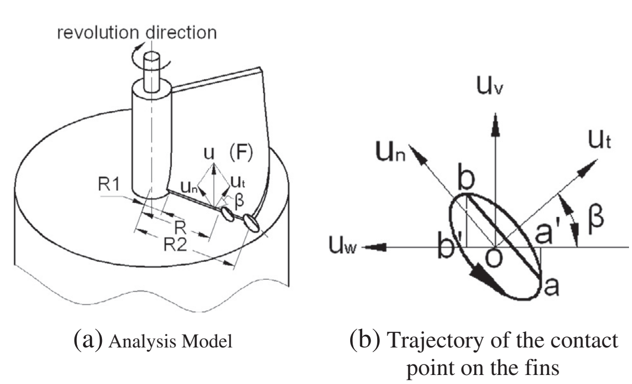

Fig. 2. Rotor motion analysis model.