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Development of an ultrasonic linear motor with ultra-positioning capability and four driving feet

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ABSTRACT

This paper presents a novel linear piezoelectric motor which is suitable for rapid ultra-precision positioning. The finite element analysis (FEA) was applied for optimal design and further analysis, then experiments were conducted to investigate its performance. By changing the input signal, the proposed motor was found capable of working in the fast driving mode as well as in the precision positioning mode. When working in the fast driving mode, the motor acts as an ultrasonic motor with maximum no-load speed up to 181.2 mm/s and maximum thrust of 1.7 N at 200 $V_{p\text{-}p}$. Also, when working in precision positioning mode, the motor can be regarded as a flexible hinge piezoelectric actuator with arbitrary motion in the range of 8 μm. The measurable minimum output displacement was found to be 0.08 μm, but theoretically, can be even smaller. More importantly, the motor can be quickly and accurately positioned in a large stroke.

1. Introduction

The linear piezoelectric motor (LPM) is a new type of micromotor that converts electrical energy to linear movement by frictional forces via inverse piezoelectric effect [1,2]. This type of motor is advantaged by its small size, light weight, quick response, high energy density, compact structure, anti-electromagnetic interference, and self-locking (at power off state), among other qualities [3–5]. These merits make LPMs excellent candidates for ultra-precision positioning in special environments and lend it considerable potential in terms of aerospace mechanisms, optical instruments, biological equipment, and micro electromechanical systems [6–8]. The speed and the control accuracy of the piezoelectric motor influence each other due to inertia, making it particularly difficult to achieve high control accuracy.

Based on the output speed, existing LPMs can be split into three categories: the ultrasonic piezoelectric motor (UPM), quasi-static piezoelectric motor (QPM), and flexible hinge piezoelectric actuator (FHPA). Generally, UPMs have relatively high speed. Zhao built a circular linear ultrasonic motor with a maximum speed of 374 mm/s [9], for example; Lee later proposed a butterfly-type linear ultrasonic motor with a maximum speed of 88 mm/s [10] and Chen proposed a U-type linear ultrasonic motor with no-load speed of up to 854 mm/s [11]. The control accuracy of a typical UPM is more than 1 μm, and it is difficult to meet the requirements of ultra-precision positioning in certain environments.

There are also two distinct categories of QPMs. The first is the inertial actuator, such as the dome-shaped actuator developed by Yoon et al. [12] and the bimorph-disk motor developed by Mazeika and Vasiljev [13]; the second is the inchworm actuator, like the walking-type actuator designed by Zhang and Zhu [14] and the lever-type actuator designed by Moon et al. [15]. The output speed of QPMs is usually less than 1 mm/s, but their control accuracy is higher than that of UPMs. Also, the QPMs typically have complex structure and relatively small no-load thrust force. By driving the stage directly via the deformation of piezoelectric ceramics, the required displacement of FHPAs can be output by controlling the input voltage and the minimum displacement can reach the nano scale. The lever-amplification principle actuator designed by Choi et al. [16] is a good example of this, as well as the bridge-amplification principle actuator designed by Kim et al. [17] and the triangle-amplification principle actuator designed by Jin et al. [18]. Unfortunately, FHPAs are limited in real-world application by their output displacement, which is generally within 100 μm. Current researchers, considering the advancements made thus far and what is left to be desired, tend to focus on the pursuit of high speed, high control accuracy, and large stroke in developing innovative micro-motors.

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In this study, we designed a new linear ultrasonic motor with two working principles in effort to integrate advantages of both UPMs and the FHPAs. We also built a prototype of the motor and subjected it to several tests to determine its performance, as discussed below. By switching between these two working modes, the motor can not only move at high speeds, but is also suited to ultra-precision positioning. The proposed motor additionally has a simple structure, stable performance, is easily clamped, and shows markedly improved practicability over similar pre-existing motors.

2. Structure and moving mechanism

2.1. Motor structure

The stator of the motor and its dimensions are shown in Fig. 1(a). The motor is comprised of a comb-type copper substrate, eight pieces of piezoelectric ceramics, and four ceramic driving tips. These dimensions were optimized via FEA in ANSYS 14.5.7 software. The comb-type copper substrate was manufactured with T2, which has an elastic modulus of 1.08×10^{11} Pa, Poisson's ratio of 0.377, and density of 8960 kg/m^3. Its favorable mechanical performance makes it very suitable for the piezoelectric motor stator. For the piezoelectric ceramic, PZT-8 plates (Bao Dding HengSheng Acoustics Electron Apparatus Co., Ltd) with two electrode partitions were selected and polarized along the thickness direction. The PZT-8 ceramic is a hard type, which can be used at application temperatures higher than soft type ceramics [19,20]. We utilized a zirconia driving tip, which has high wear resistance and machinability, and designed it with a "T" shape to create linear contact between the stator and mover in order to ensure large force output. Eight identical piezoelectric ceramics and four driving tips were bonded together to the comb-type copper substrate with slow drying epoxy. The motor was designed as a comb-type structure with four driving feet; each foot is composed of a copper substrate, two pieces of piezoelectric ceramic, and a ceramic driving tip. The motor is driven by the vibration modes of the driving feet. Clamping the base-box of the comb-type copper substrate has little influence on the working vibration modes of each driving foot or the mechanical performance of the motor, so the motor was easily fixed on the stage.

2.2. Moving mechanism

2.2.1. Working in the fast driving mode

The LPM has four driving feet each with a uniform movement mechanism, so one driving foot can be selected to analyze the motion mechanism of the motor. According to the structure (Fig. 1), any one driving foot can be simplified into a cantilever beam as shown in Fig. 2(a). When adding one electrical signal (Fig. 2(b)), the first longitudinal (L_1) vibration mode and the second bending (B_2) vibration mode can be simultaneously excited. (Experimental results with an impedance analyzer confirmed this, as reported in Section 4.1.1.) This behavior is expressed in Eqs. (1) and (2) [21], respectively:

$$Y = U_Z \sin \omega t \tag{1}$$

$$X = -U_W \sin \omega t \tag{2}$$

where U_W and U_Z are the amplitude of the cantilever beam under bending vibration and longitudinal vibration, respectively.

The driving foot can also be simultaneously supplied with two voltage signals, V_1 and V_2, as shown in Fig. 2(c). V_1 excites the first group of longitudinal and bending vibrations and V_2 excites the second group. Because V_1 and V_2 have the same voltage amplitude, the amplitudes of the two bending vibrations and the amplitudes of the two longitudinal vibrations are identical. A total of four mechanical vibrations are thus superimposed over each other in the driving foot.

The B_2 vibration and the L_1 vibration excited by V_1 are expressed as Eqs. (3) and (4), respectively:

$$X_1 = -U_W \sin \omega t \tag{3}$$

$$Y_1 = U_Z \sin \omega t \tag{4}$$

Another two vibrations excited by V_2 are expressed as Eqs. (5) and (6), respectively:

$$X_2 = U_W \cos \omega t \tag{5}$$

$$Y_2 = U_Z \cos \omega t \tag{6}$$

And accordingly, the horizontal and vertical deformations of point Q (Fig. 2) are determined as follows:

$$\begin{cases} X = X_1 + X_2 = U_W(\cos \omega t - \sin \omega t) \\ Y = Y_1 + Y_2 = U_Z(\cos \omega t + \sin \omega t) \end{cases} \tag{7}$$

So, the trajectory of point Q can be described by Eq. (8), which indicates that the movement trajectory is elliptical. The proposed motor notably differs from previous, similar motor designs because it has four superimposed vibrations, which allow it to achieve a larger output – most previously reported coupled mode-driven piezoelectric motors have only two superimposed vibrations. When

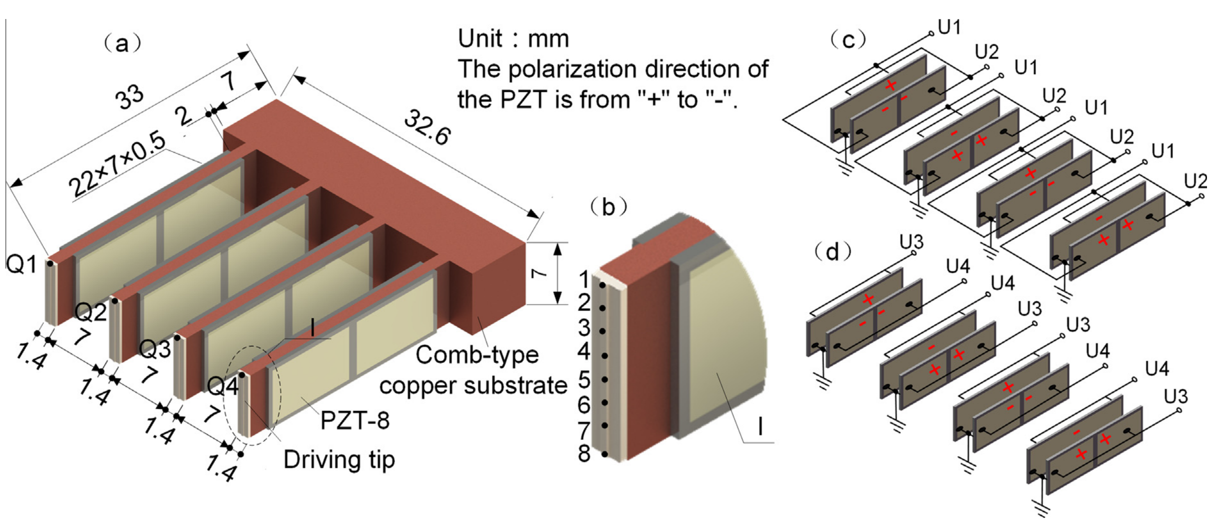

Fig. 1. (a) Structure of the proposed motor; (b) defined points of the driving tip; (c) electric input for fast driving mode; (d) electric input for precision positioning mode.