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# Design and analysis of an elliptical-shaped linear ultrasonic motor

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ABSTRACT

A linear ultrasonic motor (LUSM) with an elliptical-shaped metallic stator and two orthogonal vibration modes is presented in this research. The driving tip's desired vibration is generated by the excitation of two piezoelectric actuators installed inside the stator by two sinusoidal voltages with $\pm\pi/2$ phase difference. The working principle of the motor is described and mathematically formulated. Furthermore, finite element analysis and parametric optimization are performed to finalize the motor design. A prototype of the motor is fabricated and evaluated by identification and operation tests. The experimental and numerical characteristic curves of the motor are presented and compared. Based on the experimental results, the prototype has a no-load speed of 40 mm/s and maximum thrust force of 1.55 N under excitation voltage of 70 $V_p$ and preload of 12 N.

## 1. Introduction

Piezoelectric motors are considered a suitable choice for positioning or motion control systems that may require linear or rotary motion with a long travel range combined with high accuracy. In such actuators, a periodic motion with micro-scale amplitude is generated by piezoelectric elements in the stationary part of the motor, which is called a stator. The motion turns to final movement of the motor through the interaction between the stator and rotor (moving part of the motor). Depending on the type and working principle of motor [1] the periodic micro-scale motion has a frequency between a few hundred Hz to several hundred kHz, which leads to the rotor movement with both high resolution and reasonable speed simultaneously.

Ultrasonic piezoelectric motors are the main type of piezoelectric motors with operating frequency above the human hearing range (20 kHz) [2]. The working principle of these motors is based on two energy conversion processes: the conversion of electrical energy into mechanical vibrations in the stator's piezoelectric actuator(s) and the subsequent conversion of vibrational energy into linear or rotary motion of the rotor caused by friction effect [3]. Unique features, such as high force density, good position accuracy, quick dynamic response, unlimited travel range, simple mechanical construction, direct drive operation, small size and light weight, no backlash, negligible magnetic interaction with the environment and the capability to maintain position when the power is turned off, have attracted special attention to ultrasonic motors in precise positioning applications [4–7]. Ultrasonic motors can be utilized in modern industrial applications, such as optics systems, precision positioning systems, aerospace actuators, modern manufacturing and machining systems, precision manipulators and micro robots [8,9].

Linear ultrasonic motor (LUSM) is a major category of ultrasonic motors, which comprises a stator and a linear slider (generally called a rotor). LUSMs with plate or beam shape structures are among the most common designs presented in this area. He et al. studied a single-phase bi-directional LUSM with a simple structure and driving technique [10]. Their motor had a plate-type stator using bending vibration mode B3 or B4 to generate a diagonal motion on the stator projections. A composite plate-type linear ultrasonic motor was developed by Roh and Kwon with a simple construction and identical performance in both moving directions [11]. The working principle of the motor was derived theoretically and the final motor design was achieved using ANSYS finite element software. Motor fabrication and characterization were also carried out. Zhai et al. proposed a beam-shaped multi-mode linear motor with two orthogonal vibration modes (L1 and B4) [12]. FEM simulations were performed and the authors fabricated a prototype to investigate the behaviors of the motor. Lu et al. [8] designed an LUSM with double-driving feet and a metallic plate-shaped stator. The orthogonal mode shapes of the stator consisted of the first longitudinal in-plane mode and the second bending mode. The researchers calculated the motor dimensions by FEM modal analysis and experimental verification was performed on a fabricated sample. Shi and Zhao developed a linear ultrasonic motor with

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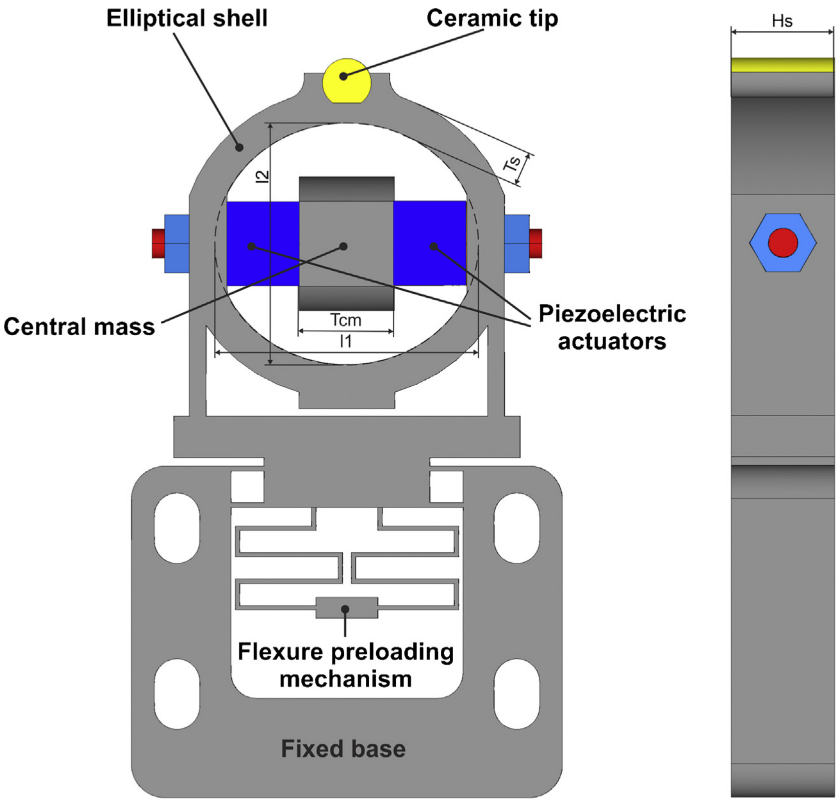

**Fig. 1.** Schematic of the stator of the proposed ultrasonic motor.

a working principle based on the combination of two orthogonal modes (L1 and B2) of a plate-shaped stator [13,14]. In this design, an isosceles triangular structure was added on the stator to amplify the horizontal vibration. FEM simulation and parametric optimization on the structure, and also some experimental investigations were performed. Furthermore, some studies on LUSMs with beam or plate structures have been carried out and characteristics of the fabricated prototypes presented [15–18].

Other structures with suitable mode shapes for correct ultrasonic motor operation have also been discussed. Kurosawa et al. proposed a sandwich-type linear ultrasonic motor with two symmetrical and anti-symmetrical vibration modes [19]. The reported no-load speed and thrust force of the motor were 3.5 m/s and 39 N respectively, at a driving voltage of 500 Vrms. Another sandwich-type LUSM with a continuous variable cross-section stator was presented by Yao et al. [20]. The work focused on analyzing the effects of the stator's cross-section and profile design on motor performance. Ho proposed an elliptical linear ultrasonic motor and minimized the difference of frequencies of two vibration modes by adjusting the length of the major and minor axes of the ellipse [21]. Fernandez and Perriard presented a V-shaped LUSM and performed a sensitivity analysis and optimization of the stator dimensions to maximize the vibration amplitudes on the driving tip [22]. Ho and Jan [23] designed a precise LUSM with two operating drive modes. The motor had two normal and tangential mode shapes excited by two piezoelectric actuators. A prototype was fabricated and based on the reported results for a DC driving mode (at 100 Hz), the motor had a resolution of 6 nm.

As shown by these works, due to the novelty of the topic, most researchers focus on innovating and introducing new designs, developing new analysis and optimization methods, and also fabricating prototypes and carrying out experimental evaluations.

In the present work, a new linear ultrasonic motor based on the orthogonal vibration modes of an elliptical shaped stator is proposed and tested. The normal and tangential modes are excited simultaneously by two piezoelectric actuators that are installed and prestressed in the stator to generate a desired vibration on the stator tip. This motor can operate with two different driving methods including single actuator and two actuators modes. Furthermore effective piezoelectric prestressing method and precise preload adjustment system based on the flexure mechanism are the novelty of the design. In addition to the structure design aspects, one of the important points of this study is formulation of the interaction between the stator and the rotor, to develop and solve rotor equation of motion. This article is organized into the following sections: Section 2 describes the structure and working principle of the proposed ultrasonic motor, Section 3 includes the finite element analysis and optimization performed on the motor to finalize the design of the motor, Section 4 presents the experimental tests of the fabricated prototype and the results, and finally, the research conclusions are presented in Section 5.

## 2. Structure and working principle

The proposed linear ultrasonic motor is composed of an elliptical-shaped stator and a linear slider as rotor. Fig. 1 represents a schematic of the stator as the main motor component. The stator is made of steel AISI 4340 and composes of an elliptical shell connected to a fixed base via flexible beams. Inside the elliptical shell and in line with the major axis, two multilayer PZT-4 piezoceramic actuators separated by a central mass are installed to generate vibrations in the stator. The piezoelectric actuators are ring-shaped and prestressed between the elliptical shell and central mass by a stud screw mechanism. The advantage of this adjustable prestressing mechanism is that it ensures the complete transmission of micro-scale actuator vibrations to the structure and prevents lost motion. It should be noted that if the prestress is too high, it may cause a greater risk of crack initiation and consequently