Journal of Sound and Vibration 382 (2016) 140–157

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Modeling stick-slip-separation dynamics in a bimodal standing wave ultrasonic motor

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ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form
6 June 2016
Accepted 1 July 2016
Handling Editor: D.J. Wagg
Available online 22 July 2016

Keywords:
Vibration
Friction
Stick-slip
Dynamic modeling
Ultrasonic motor

ABSTRACT

Ultrasonic motor (USM) is an electromechanical coupling system with ultrasonic vibration, which is driven by the frictional contact force between the stator (vibrating body) and the rotor/slider (driven body). Stick-slip motion can occur at the contact interface when USM is operating, which may affect the performance of the motor. This paper develops a physically-based model to investigate the complex stick-slip-separation dynamics in a bimodal standing wave ultrasonic motor. The model includes both friction nonlinearity and intermittent separation nonlinearity of the system. Utilizing Hamilton's principle and assumed mode method, the dynamic equations of the stator are deduced. Based on the dynamics of the stator and the slider, sticking force during the stick phase is derived, which is used to examine the stick-to-slip transition. Furthermore, the stick-slip-separation kinematics is analyzed by establishing analytical criteria that predict the transition between stick, slip and separation of the interface. Stick-slip-separation motion is observed in the resulting model, and numerical simulations are performed to study the influence of parameters on the range of possible motions. Results show that stick-slip motion can occur with greater preload and smaller voltage amplitude. Furthermore, a dimensionless parameter is proposed to predict the occurrence of stick-slip versus slip-separation motions, and its role in designing ultrasonic motors is discussed. It is shown that slip-separation motion is favorable for the slider velocity.

1. Introduction

The ultrasonic motor has been of interest in industry due to its advantages such as simple design, high torque at low speed, quick response, accurate positioning, no electromagnetic and auto-locking on power outage. Functionally, USM can be divided into two categories: traveling-wave ultrasonic motor (TWUM) and standing-wave ultrasonic motor (SWUM). The principle of USMs is based on two-stage energy conversion [1,2]. In the first stage, piezoelectric elements convert electrical energy into a high-frequency (ultrasonic range) mechanical vibration. In the second stage, the high-frequency oscillatory vibration is rectified into macroscopic rotary or linear motion of a driven component. The second energy conversion is based on friction mechanism occurring at the interface between the stator and the rotor/slider.

With regard to their contact mechanics, USMs fall into two categories [3]. One is the “traveling wave” contact type, in which the distributed contact area between the stator and the rotor/slider moves with the traveling wave on the stator, and

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http://dx.doi.org/10.1016/j.jsv.2016.07.003
0022-460X/

the two bodies are always in contact near the wave crests. The second is an “intermittent” contact type, in which the two bodies are in contact intermittently and the region of the stator generally in contact remains the same. Clearly, the contact type of TWUMs is “traveling” contact type and that of SWUMs belongs to “intermittent” contact type. The mathematical models of the contact mechanics of USMs are important to understand the principles of energy transfer at the friction interface and evaluate the performance of the motors. Various contact models have been proposed to study the contact mechanics of USMs [4–11]. In 1992, Maeno et al. [5] studied the stator/rotor contact in a TWUM using finite element method, and the results showed that the distribution of the stick/slip exists in the contact area. Cao and Wallaschek [7] developed a visco-elastic contact model in 1995, in which stick-slip behavior was investigated in detail. They indicated that three different slip and two different stick zones exist. With a visco-elastic foundation model for the contact layer of TWSM, Storck and Wallaschek [10] pointed out the distribution of stick and slip regions differs fundamentally depending on the height and modulus of elasticity of the contact layer, the contact width and normal force. In 2006, by a similar visco-elastic contact model, Qu et al. [11] investigated the influence of contact mechanics on the performance of TWSM taking into account the stick-slip behavior of the interface. They proposed a new function to judge whether the conversion between stick zone and slip zone, and derived the shearing strength in stick zone. Considering that the majority of the publications in this field are devoted to the study of TWUMs, and the details of stick-slip dynamics of SWUMs have not been considered so far, this paper will focus on the stick-slip dynamics of a bimodal standing wave ultrasonic motor.

One well-known design of SWUMs is a bimodal ultrasonic motor with longitudinal and bending mode vibration developed by the Israeli Company Nanomotion in 1995 [12]. Fig. 1 depicts a schematic of the bimodal standing wave ultrasonic motor, which consists of a stator with a driving tip, a preload spring, a slider and a linear guide. The stator is the model-SP1 made by Nanomotion, Yoknearn, Israel, and is a rectangular plate of dimensions $30 \times 7.5 \times 3$ mm^3. The principle of the motor is to excite the stator by applying one pair of sinusoidal signals with a single driving frequency close to the natural frequencies of the first-order longitudinal mode (L1-mode) and the second-order bending mode (B2-mode) to the electrodes 1–4. The longitudinal mode is excited with an approximate 90 temporal phase shift with the bending mode. Under such an excitation, the driving tip on the stator will produce an elliptic motion as shown in Fig. 1. Consequently, a friction force is produced at the contact interface under a preload that can drive the slider to perform a macroscopic linear motion. Additionally, the motion direction of the slider can be changed by applying the excitation signals to the electrodes 2–3. Based on the operating mechanism of the bimodal motor, the mechanical models of the stator, the driving tip, and the slider are shown in Fig. 2. In the figure, the stator is assumed to be a Timoshenko beam and the driving tip is assumed to be a rigid column. Slider is static in the x direction due to the constraint of the linear guide.F_N is the interface normal force, F_T is the tangential force resulting from the interface friction. M_L is the applied moment and is equal to $F_T l$. F_f is the dynamic

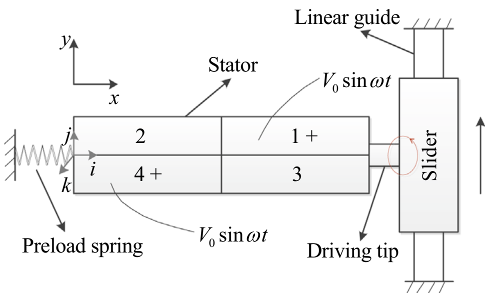

Fig. 1. Schematic diagram of the bimodal ultrasonic motor.

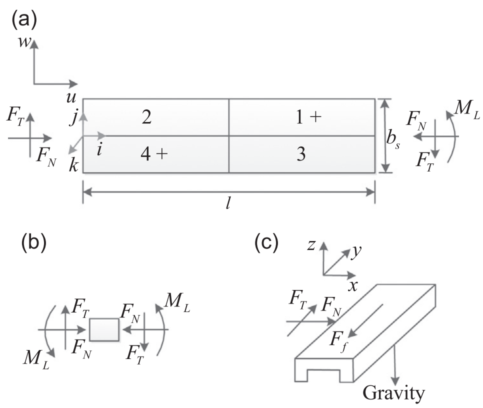

Fig. 2. Mechanical models of the main components of the motor: (a) stator, (b) driving tip, (c) slider.