Research on a Linear Ultrasonic Motor with Double Cantilever Vibrators.

Umar Jibril Mohammed and Rabiu S. Zakariyya

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Mohammed Umar Jibril
Department of Engineering and Space System,
National Space Research and Development Agency
Abuja, Nigeria 900110
Email: umarjibrilmohd@yahoo.com

Rabiu S. Zakariyya
Department of Electronic Science and Technology,
University of Science and Technology of China
Hefei, China 230026
Email: rabiu123@mail.ustc.edu.cn

***Abstract*—This paper presents an idea on the development of a new type of a linear ultrasonic motor with double cantilever vibrators. The vibrator is first designed theoretically and then simulated using finite element analysis software (ANSYS) to obtain the modal frequency and mode shape. The resonance frequencies of the vibrators are determined to be 21.33kHz, and this is also the frequency in which the two vibrators are driven to determine the output parameter such as driving force and velocity. The frequency difference between the first and the second vibrator is found to be almost zero. Based on the analysis of the theory, a proof- of-principle prototype of stator is fabricated and the mode testing results verifies that the proposed principle of operation is successfully implemented.**

***Index Terms*—Ultrasonic motor, traveling wave, double vibrators, cantilever beam, bending mode**

I. Introduction

Industrial requirements have in the past focused mainly on improving the quality and quantity of electromagnetic motors. This has resulted in a huge amount of motors found in almost all areas of applications. Recently, the advance in the field of smart structures and active materials has led to new kinds of motors. Indeed, over the last decades, the demand for piezoelectric motors has been increased significantly. There exist numerous examples from different application areas where piezoelectric motors developed recently have shown to be superior to their electromagnetic counterparts.Linear ultrasonic motor is an important class of ultrasonic motor formed from the ultrasonic vibration force of piezoelectric ceramic elements and the mechanical friction effect to drive an exact linear transmission system [1].

With the exception of the characteristics it shares with rotary ultrasonic motors, linear ultrasonic motors have the following characteristics [2]: (a) its capable of a direct and straight drive; (b) a highly precision and accuracy up to nanometer level; (c) it has good control characteristics due to no movement errors from auxiliary parts, such as transmission belt, etc; (d) a simple structure and the variability of shape, allowing easy miniaturization and weight loss.

A. Operational Principle and analysis of the second bending mode

Several commercial piezoelectric motors also adopted different modes of piezoelectric vibration. In this paper, the focus is put on a second bending mode of a beam; the traveling waves in an elastic non self-moving vibrator are generated to form the elliptical motion of a driving projection. The operation mode is excited by four pieces of rectangular piezoelectric ceramic gluing onto the plate surfaces of each stator. Hence, Motors of this class always have compound structure with piezoelectric pieces gluing onto their surfaces of metal bodies [2-3]. In particular, quite a few linear ultrasonic motors have been proposed and widely applied as direct driving actuator in many aspect of application, such as optic focusing and medical equipment, semi conductor, precision positioning stage and some equipments test. Fig. 1 shows an example to explain the operational principle of the vibrator in its complete process.

(1) The dotted line circle represents the equilibrium position of the driving foot when the vibrator is not working, in (a) to (b) the process of bending vibration in the horizontal direction from the left to the middle at the maximum displacement gradually moving the equilibrium position, the bending vibration in the vertical direction from the equilibrium position gradually moves to a position above the maximum displacement. In the 1/4 period process, the driving feet is close to the motion and the driver moves to the right. (2) In (b) to (c) process, the horizontal bending vibration gradually moves from the middle equilibrium position to the maximum displacement of the right end, and the vertical bending vibration gradually moves to the middle equilibrium position from the maximum displacement above. In these 1/4 periods, the driving feet gradually move away from the motion and continue to move the motion to the right. (3) In (c) to (d) process, the horizontal bending vibration gradually moves to the middle equilibrium position from the maximum displacement of the right end, and the vertical bending vibration gradually moves from the middle balance point to the maximum displacement at the bottom. In

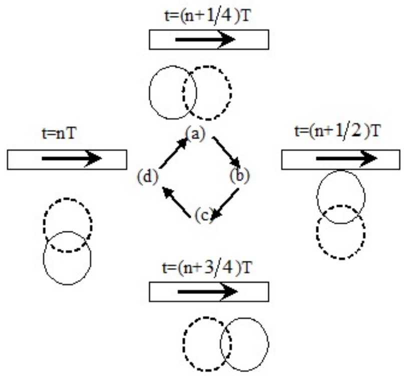

Fig. 1. A periodic process of driving vibrator

these 1/4 cycles, the driving direction of the oscillator moves from the right to the left, but because the oscillator has been separated from the mover, the driving force cannot move to the left, because the inertia continues to move to the right.

B. Analysis of the Second Bending Mode

It is known that there is a need for a dynamic model as a basis for the optimization problem of the ultrasonic motors. The analytical method is one of the dynamics modeling methods to calculate some of parameters in the analysis process to ensure the accuracy of the calculation. In the case of beam with fixed end, the shape of the deflection curve can be obtained from Equation (1). The combined rigid body is characterized as

$$X = C_1 + C_2 x \tag{1}$$

This expression represents the displacement, together with which can be superimposed on the free vibrations.

II. Vibrator Simulation Using ANSYS

The finite element method (FEM) is the most effective one, on which some highly sophisticated software, such as NASTRAN, ANSYS, ATILA, etc., is based. For proper and accurate finite element simulation of the stator, it is required to model the stator using finite element analysis software for the simulation to be carried out perfectly, the finite element analysis software FEM (ANSYS) is the software used to confirm and validate the operating principle of the proposed motor. Trajectories of the driving tip are also calculated. The length of the vibrator is set to 34.0 mm.

FEM software (ANSYS) is used to build a three-dimensional finite element model of the vibrator and to run a simulation and different structure are displayed in figures below (Fig. 4 and Fig. 5) in vertical and horizontal motion. Modal frequency analysis of the vibrators is performed and the short circuit type electric boundary conditions are also applied, i.e., a constant voltage of zero is applied at each of the piezoelectric element. Numerical study includes the theoretical and modal frequency analysis. The second bending frequency

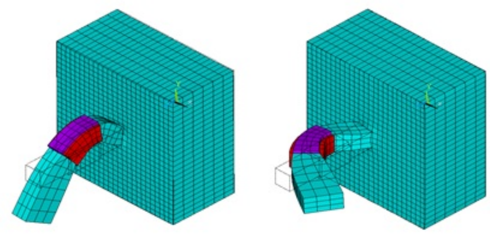

Fig. 2. Isometric views of horizontal and vertical motion of the second bending mode of the vibrator

obtained is within the ultrasonic frequency range, the simulation based result obtained from finite element analysis software is used for prototype analysis.

III. Construction of the Motor

A prototype of a linear ultrasonic motor with symmetrical cantilever vibrators has been devised and manufactured in highly uniformity and manufacturing accuracy. The general construction of a prototyped linear ultrasonic motor involves different machining operations depending on the characteristics required. The output power, the speed and the nature of the output (sliding) could be the main decisive factors of production.

The double independent symmetrical vibrators with a metal material of aluminum alloy have been selected for its good conductivity and light weight to drive an exact linear transmission system in a second bending mode to control the motion. Each vibrator consisting of four piezoelectric flat pieces of ceramics is placed on a smooth surface at the middle of the four sides of the beam.

The piezoelectric ceramic on both parts are configured into phase A and B, the phase A and B of the first part are connected to the phase A and B of the second part respectively. As the sinusoidal alternating voltage applied to the piezoelectric ceramic of phase A, the excitation frequency is found closed to the resonance frequency of the second bending mode and the stator vibrates in the left and right directions. Likewise as phase B is imposed by a cosine voltage with the same frequency and amplitude, the stator also vibrates in the front and behind directions. The two vibration modes are excited simultaneously as the two voltage signals applied on the piezoelectric ceramic components at the same time, thus the elliptical motion of the particles on both driving feet was formed in the same direction.

IV. Experimental Analysis

A proof of principle prototype is fabricated according to preliminary simulation result. The verification test in order to confirm the theoretical concept is carried out, the general performance of the motor is determined and the testing is hereby conducted in the following experimental setup (see Fig. 3), and the devices used are as follows:

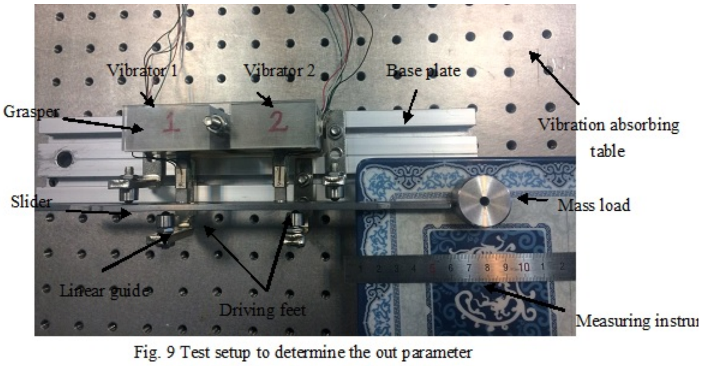

Fig. 3. Test setup to determine the out parameter

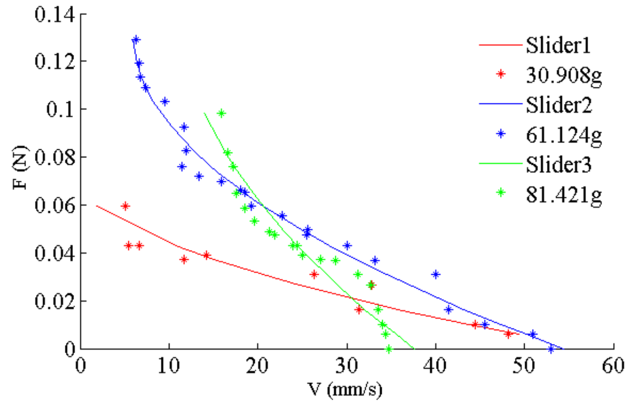

Fig. 4. 10 Load characteristics of a double cantilever linear ultrasonic motor

1) Vibrometer sensor head OFV-5000, Modular vibrometer controller OFV-5000
2) Power amplifier type 2713
3) Digital storage oscilloscope

After all the connections between the components and instruments are properly made for experimental investigation, the vibrator is placed in an appropriate position under the vibrometer sensor head to observe the frequencies and amplitude of vibrations.

From the testing results shown in Fig. 3, the prototype reaches its maximum thrust and no load velocity when the driving voltage is applied to the vibrators at a certain frequency. The input parameters and tabulated result is presented based on the three categories of the sliders. The experimental parameters:

1) Peak to peak input voltage = 40V
2) Frequency =21330Hz
3) Slider 1 = 20.517 (g)
4) Slider 2 = 61.124 (g)
5) Slider 3 = 81.641 (g)

with operation frequency of 21.330kHz at 40V. It can be seen that the linear USM has a different load performance based on three categories of sliders. For three investigated performances, it further illustrates that the prototype motor was fabricated based on the optimal design. The result exhibits considerably high dynamic performance, such as no-load speed of 52.6743 mm/s in combination with slider 1, maximal thrust of 0.129N at 6.3 mm/s in combination with slider 2. In combination with slider 3, the motor appears to have a relative higher driving power at higher loads due to its higher frictional contact, but its unfortunately limited to maximal thrust force 0.098 N at 15.90 mm/s. While comparing the difference between ANSYS (FEM) simulation frequency (21.584kHz) to the resonance frequency (21.330kHz) is just 254Hz which is approximately.

V. Conclusion

Because of its unique characteristics and excellent performance, ultrasonic motors have been favored by many industries in research and development of science and technology. In this paper, the research on a new type of linear piezoelectric ultrasonic motor was successfully proposed, designed, simulated, manufactured and tested. The constructions along with detail arrangements of each part were introduced; the principle of this motor was analyzed in detail. The frequencies difference from the test was found to be zero. This is the test frequency difference between the first and the second vibrators. Both analytical and modal solution verified the principle, and the testing result validated the analysis. A prototype was fabricated, which has 0.12921N thrust at 6.3 mm/s and no-load velocity of 52.6743 mm/s.

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