DESIGN OF A LINEAR HIGH PRECISION ULTRASONIC PIEZOELECTRIC MOTOR

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1 INTRODUCTION

Piezoelectric standing wave motors generate motion using a combination of flexural, torsional and/or longitudinal vibrations of a piezoelectric actuator. One of the vibration components produces a normal force, while the other vibration component generates motion (or thrust force) that is perpendicular to the normal force. This combination creates a friction based driving force between one stationary component, the motor, and the slideway to be moved [1]. Piezoelectric standing wave motors have the potential to achieve both high velocities (1m/s) and sub-µm resolution in a small, compact and inexpensive package. The operation of these motors is absolutely silent, if the operating frequency is above the audible spectrum, typically around 40kHz. Although commercially available piezoelectric standing wave motors, such as a motor made by Nanomotion Ltd. [2], perform very well at high slideway velocities, fine positioning requires additional features and advanced control algorithms.

2 MOTOR DESIGN

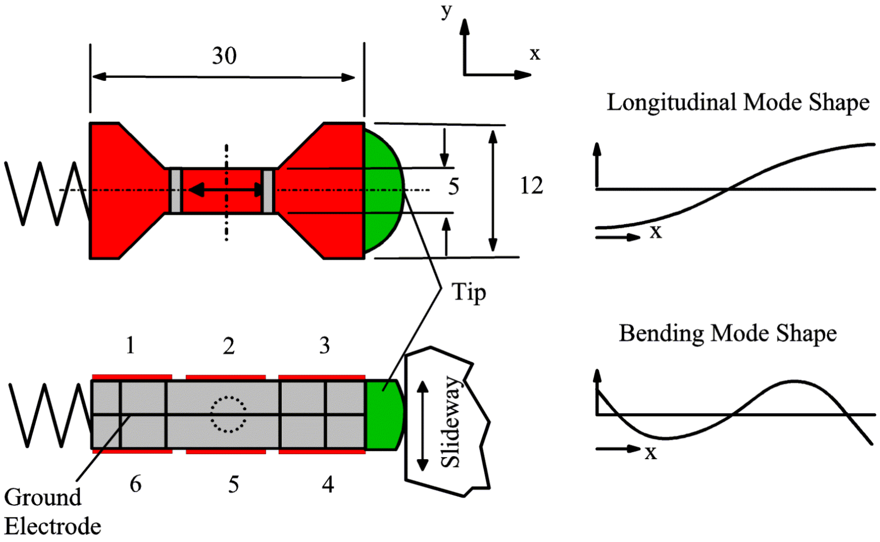
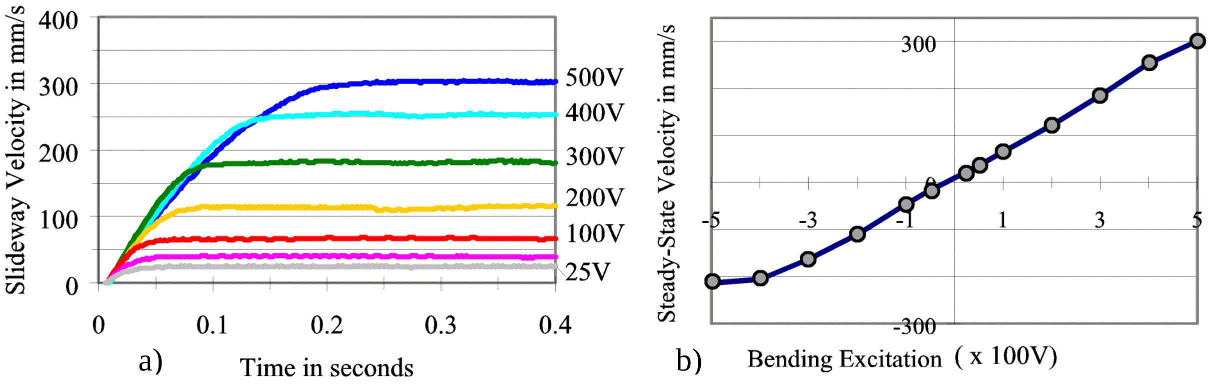


Figure 1. Actuator Design and Operating Modes (dimensions are in mm)

The ultrasonic motor, as shown in Figure 1, uses a bimorph type actuator that allows separate excitation of the first longitudinal mode of vibration and the second bending resonance. Exciting electrodes 2 and 5 with a sinusoidal excitation voltage excites only the longitudinal vibration mode. This allows the adjustment of the dynamic normal force at the tip such that the normal force alternates between almost no compression and twice the preload. The bending vibration is effectively excited with a sinusoidal voltage at electrodes 1 and 4 and with the inverse of this voltage at electrodes 3 and 6. Variation of the bending excitation amplitude or the phase between bending and longitudinal excitation can be used to control the slideway velocity. In either case, once per cycle the normal load goes to zero and even a small thrust force will initiate sliding between motor tip and slideway. The most efficient motor operation can be achieved when the phase is close to 90º and variation in the amplitude of the bending vibration is used to set the slideway velocity.

3 OPEN LOOP PERFORMANCE

Figure 2 shows series of measurements of the slideway velocity when a different, but constant, bending excitation is applied to an initially motionless slideway. In this experiment, an air bearing spindle is used as the slideway. The inertia is equivalent to that of a linear slideway with a mass of 2.28 kg. When the excitation voltage is applied, the slideway accelerates until a steady state velocity, which is linearly proportional to the bending excitation, is reached. This becomes apparent when the steady-state slideway velocity from the measurement in Figure 2(a) is plotted as a function of the excitation voltage as done in Figure 2(b). It should be noted that the initial acceleration is virtually independent of the excitation amplitude. Instead, it depends on the preload, the accelerated mass, the coefficient of friction and the phase.



a) b)

Figure 2. Slideway Velocity for Constant Bending Excitation

The measurements show that unlike other standing wave motors, any excitation of the bending amplitude or thrust force results in slideway motion. The smallest obtainable constant slideway velocity is limited by the noise and the linearity of the electric components that generate and amplify the sinusoidal excitation voltage.

4 CLOSED LOOP POSITION CONTROL

To evaluate the ability of the motor to position the slideway, it was tested in a closed loop control system using simple control algorithms. A block diagram of this system is shown in Figure 3. The computer/motor interface transforms the control parameter into the motor drive signals. The two voltages that oscillate at the motor frequency of 40kHz are modulated such that the control parameter is proportional to either the phase angle between both motor vibrations or to the amplitude of the signal that excites the thrust force. A sampling rate of 500Hz was chosen. Three power amplifiers were used to achieve a maximum output voltage of +/- 500V at the actuator. The slideway position was measured using an incremental encoder with a resolution of

11 µm and compared to the commanded position. Error is defined as the difference between commanded and measured slideway position and is the input to the control algorithm to compute the appropriate motor control value.

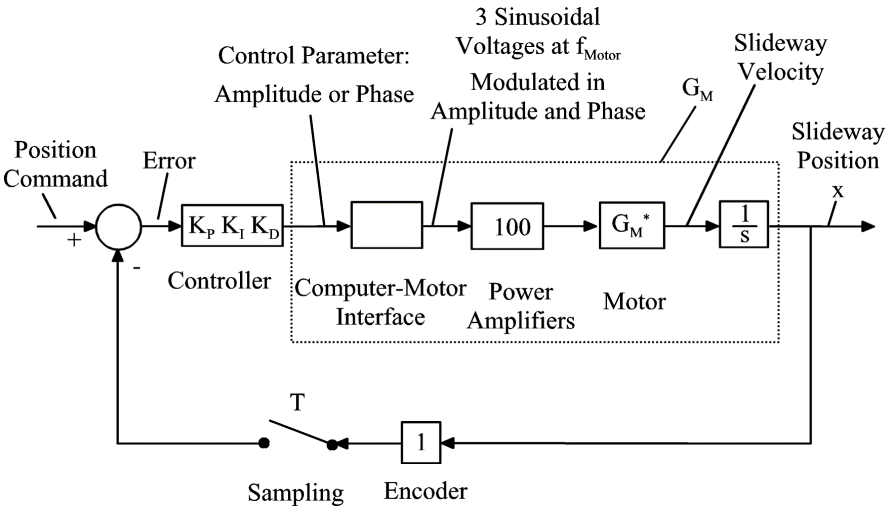


Figure 2. Block Diagram for Motor-Slideway System

A single transfer function was used to represent the behavior of the computer-motor interface, the power amplifiers and the motor-slideway system. This transfer function $G_M(s)$ describes the slideway position (x) as a function of the control parameter (bending amplitude). As sketched in Figure 2, excitation of the bending mode amplitude leads to a slideway velocity. The slideway position is proportional to the integral of the actuator excitation. If a proportional gain controller is used, any position error results in an actuator excitation (proportional to the error). Because the motor generates slideway motion until the error is zero, the steady state error will be driven to zero for an ideal implementation of this principle. In this respect, the ultrasonic standing wave motor resembles an electromagnetic motor.

5 CLOSED LOOP SYSTEM RESPONSE

Initial measurements were performed using a proportional gain controller. The gain was empirically adjusted to yield the fastest response time without overshoot. Despite nonlinearities in the transfer function of the system and saturation of the power amplifiers for large stepsizes, measurements showed that the proportional gain algorithm leads to a stable, responsive positioning system. However, a small steady-state position error was observed. This error is a result of misalignment of the motor and coupling between the two motor vibrations, creating tip motion in the slideway direction. The result is a slow slideway velocity (up to about 3mm/s) that is independent of the motor control input. Applying a PID-controller eliminated the steady state errors but caused a significant amount of overshoot.

A gain scheduling control strategy [3] combines the advantages of the proportional gain controller for large position errors and the PID controller to avoid steady-state errors. The response of the slide to step input commands of different magnitudes is shown in Figure 3a). A straight line means that the control parameter is at its maximum and the slideway moves at maximum velocity. Figure 3b) shows the position error as a function of time. The curves show that the position error approaches zero. The overshoot of 150 μm maximum can be reduced by increasing the derivative gain without significantly reducing the response time.

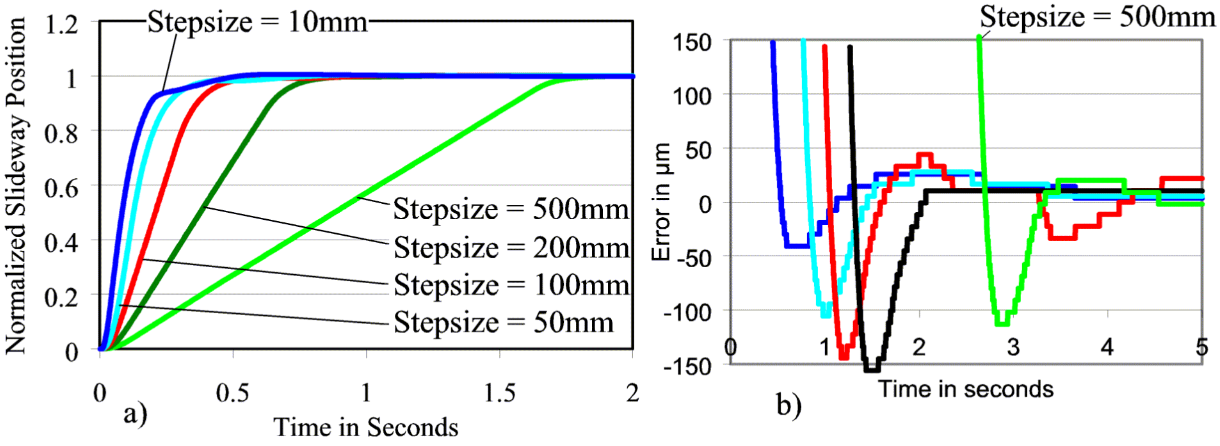


Figure 3: System Response using a Gain Scheduling Control (K_P=0.15, K_I=1,K_D=0.02) Motor Preload = 10N, Slideway Mass = 2.28kg

5 CONCLUSION

This research shows that it is possible to design ultrasonic standing wave motors whose slideway velocity is linearly proportional to the excitation voltage. This is possible by designing an actuator that allows independent excitation of two orthogonal vibration modes at the same frequency. The quality of the operation of the motor depends on the separation of these vibrations. Coupling between longitudinal and bending vibrations creates slideway motion, which is responsible for a small steady-state position error that cannot be eliminated using a proportional gain feedback controller. Despite saturation of the control input and nonlinearities in the dynamics of the motor-slideway system, it was shown that a simple feedback control system is stable and suitable for controlling the slideway position. A gain-scheduling controller, which is based on a PID-algorithm, can be used to achieve a steady-state error within one encoder increment while maintaining the overall performance shown for the proportional-gain controller.

With overall dimensions of about 35x30x6mm, and a mass of 13g, the final prototype actuator comes in a small and light package that can be used to accelerate any slideway, rotational or linear, to a velocity of 500mm/s with a maximum force of 5N. In addition, the motor is insensitive to changes in the frictional properties and changes in the surface. At this point, the maximum force is limited by the physical strength of the actuator; however, multiple motors can be used to produce larger forces. The motor generates a constant slideway velocity over a range from 1mm/s to 500mm/s, a speed which is linearly proportional to the control input.

REFERENCES

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2. US Patent #5616980, April 1, 1997
3. William Levine, *The Control Handbook*, CRC Press 1995, p. 393ff