# DESIGN OF A LINEAR HIGH PRECISION ULTRASONIC PIEZOELECTRIC MOTOR

Markus G. Bauer, Thomas A. Dow
North Carolina State University, Raleigh, NC 27695

## INTRODUCTION

Ultrasonic piezoelectric motors can be designed to use either traveling waves or standing waves to generate motion. Piezoelectric standing wave motors, the emphasis of this work, use a combination of flexural, torsional or longitudinal vibrations of a piezoelectric actuator. One vibration produces a normal force, while the other vibration generates motion that is perpendicular to the normal force. This combination creates a friction based driving force between one stationary component, the motor, and the object to be moved. The amplitudes of the vibrations and the phase between them are the most important parameters that influence the performance of the motor. Variation of the phase alone can be used to control the motor. A phase of 0° between force and motion will not generate slideway motion, 90° results in maximum slidway velocity in one direction and 180° changes the direction of slideway motion.

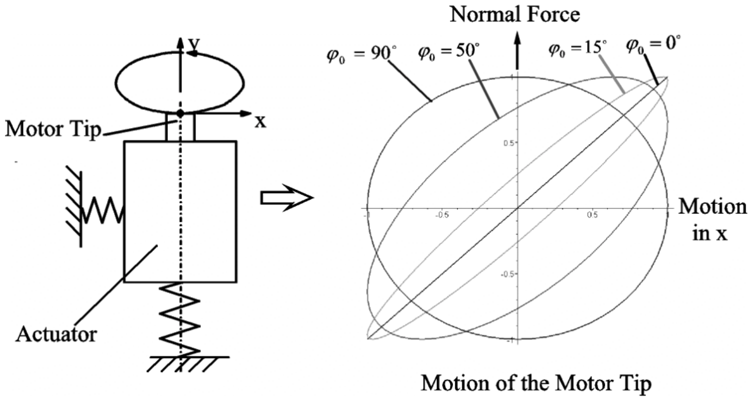

**Figure 1:** Influence of the phase between normal force and motion

Generally speaking, any structure that can be made to vibrate in orthogonal directions with sufficient magnitude can be used as a motor. A standing-wave motor produced by Nanomotion Ltd. [1] is illustrated in Figure 2. This motor uses the first longitudinal resonance of the piezoelectric material to generate a sinusoidal normal force and the third bending resonance to generate a force in the direction of motion. It is made from a single block of piezoelectric material divided into 4 sections. Applying the voltage to different sections changes the direction of motion of the slideway. However, because both vibrations are excited using a single voltage, the phase between force and motion cannot be changed.

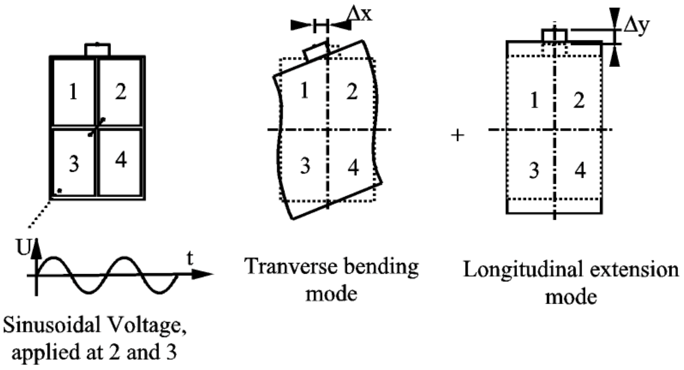

**Figure 2:** Nanomotion Motor, Mode Shapes [1]

## DESIGN OF NEW ACTUATOR

The objective of this project is to design an actuator that allows normal force and sliding motion to be controlled independently. The normal force can then be kept at an optimal level while the amplitude of the sliding motion and the phase angle between sliding motion and normal force can be used to control slideway direction and speed.

### METHODS OF ANALYSIS

To implement the design objective, the motor must have one mode shape that will generate a normal force and one mode shape that generates only sliding motion (and no component of normal force). The resonant frequencies of these two modes must be close enough to each other (~500 Hz) so that a single excitation frequency will amplify the stroke in each direction by the resonance effect.

Analytical models of the actuators were used to approximate the system response. It is necessary to model the motor as a continuous dynamic system to include all natural frequencies. To allow an exact prediction of both natural frequencies and mode shapes, it is necessary to include all details of the design such as any glue joints that exist. As the motors grew in complexity, finite element analysis (FEA) was used to numerically determine all natural frequencies and mode shapes. The results were then analyzed and the dimensions of the system are optimized. This process was repeated until a system was obtained for which the two desired modes are at similar frequencies and have coincident nodes that can be used to attach a support.

### PROTOTYPE DESIGNS

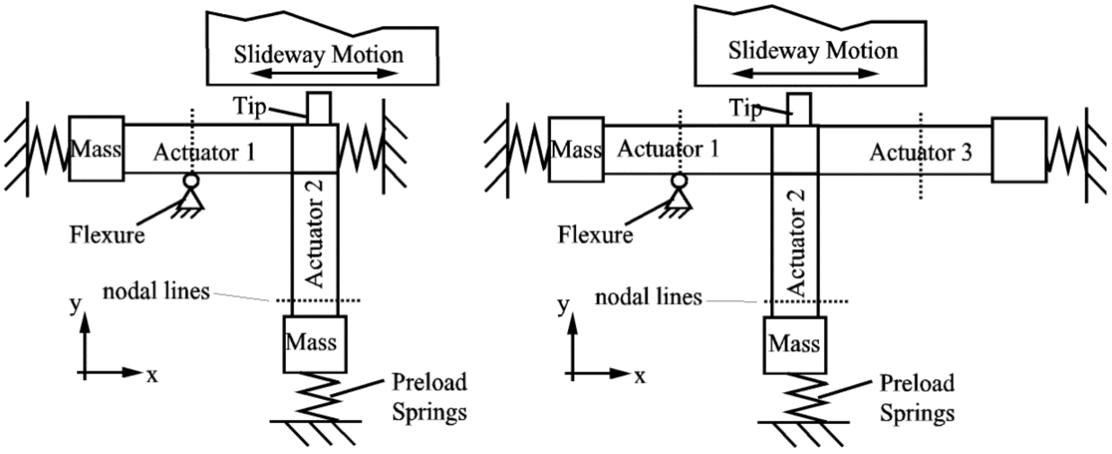

**Figure 3.** Prototypes 1 at the left and Prototype 2 at the right.

### Prototype 1

The principle for the first two prototypes of the standing wave motor was to use two orthogonal actuators, as shown in Figure 3, and to excite each at one longitudinal resonance. Prototype 1, shown on the left, used two orthogonal piezoelectric actuators glued at right angles to a metal block to which the tip was attached. The two masses at the ends were added to adjust the position of the vibration nodes or points of zero amplitude. The location of these nodes is an important aspect of the design because this is where the motor is attached to the frame to support the drive loads.

Actuator 1 provides excitation in the direction of slideway motion, and Actuator 2 changes the normal load at the contact point between the ceramic tip on the motor and the slideway drive surface. Motion of the slideway to the right or the left depends on the phase angle between the motion of the drive piezoelectric actuator (Actuator 1) and the loading actuator (Actuator 2). The springs are used to preload the two actuators to keep them in compression and avoid damage to the brittle ceramic.

Experiments showed that when Actuator 2 was excited with +/- 100V at 44.8kHz, the motor produced considerable slideway motion (in only one direction) and a pushing force of 5N. The excitation of actuator 1 does not influence the motor's performance significantly. A change in phase between both excitations changes the magnitude of the pushing force and slideway velocity to some extent, but does not allow a reversal of the direction of motion.

**Prototype 2**

The T-shaped geometry in Prototype 2 was introduced to create symmetry with respect to the bending motion of Actuator 1 when Actuator 2 is excited. In this design, the tip does not bend and no sliding motion is caused by excitation of Actuator 2. It is not possible to improve the behavior of the other actuator in the same way, because the tip has to be pressed against the slideway. When Actuators 1 and 3 are excited to generate sliding motion, bending motion occurs in Actuator 2. The dimensions of the motor can be chosen such that rotation of the tip is small, but it cannot be eliminated entirely by symmetry (as done for the other direction). Consequently, longitudinal excitation of Actuators 1 and 3 results in bending motion of Actuator 2, which in turn leads to bending in Actuators 1 and 3. Since bending of these is part of the mode that generates the normal force at the tip, the longitudinal excitation of Actuators 1 and 3 also results in a dynamic normal force at the tip. Thus, both modes are still coupled, although the advantage of this prototype is that the effect of one mode on the other is much smaller than in Prototype 1.

Experiments showed that a dynamic normal force of +/- 30N can be generated with a voltage of +/-100V applied at Actuator 2. Unlike Prototype 1, the excitation of Actuator 2 in Prototype 2 generates predominantly a dynamic normal force at the tip (the thrust force is very small). A maximum slideway velocity was measured at about 0.5m/s, when both actuators were simultaneously excited. The slideway velocity is about 15 to 20% higher in one direction than in the other, due to the coupling of both modes.

The major disadvantage of this motor is that the natural frequency of the mode that generates the thrust force is about 1.5 kHz above the natural frequency that generates the normal force. This difference has to be minimized to at most 500 Hz for the motor to function. No matter how well the analysis is done to develop the motor it is virtually impossible to build it such that both resonances are at exactly the same frequency. It must be possible to modify the length or width of one actuator or the attached mass to fine-tune the frequencies. A way to do this has not been found, because all alterations of Prototype 1 and 2 influenced both mode shapes and resonant frequencies to about the same extent. If, for example, the length of one actuator is reduced, each individual resonance increases, but the difference between both resonances does not change significantly.

### Prototype 3

The goal for Prototype 3, illustrated in Figure 4, is to eliminate the problem of the coupling between different mode shapes. The shape is basically the T-shaped Prototype 2 without the lower half of the T. This design also eliminates the glue joints found in the first two prototypes. It consists of two piezoelectric plates with a thin brass electrode between them. The electric field is applied between one of the electrodes on the outer surface (1) or (2) and the brass electrode in the center. Applying a sinusoidal voltage at the outer electrodes (1) extends and contracts the upper half of the actuator and thus excites the bending mode. An electric field that extends across the actuator will excite the longitudinal mode of vibration. This is done by applying voltage to the inner electrodes (2). Prototype 3 uses the fifth bending mode to generate a dynamic normal force and the 2nd longitudinal mode to generate sliding motion in a very similar manner to Prototype 2. Because these two modes are orthogonal, it is virtually impossible to have any interaction between them.

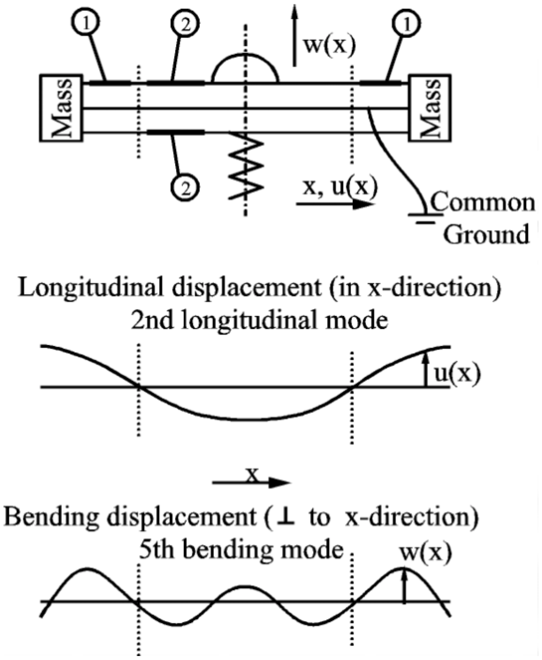

**Figure 4: Prototype 3**

Initial measurements of the frequency spectrum for the forces at the tip indicate that the resonances for the normal force and for the thrust force differ by about 2 kHz. This difference can be reduced by carefully adjusting the mass at the ends of the motor. Once the motor has been modified so that the normal force is large enough, and so that the difference between the resonance for the normal force and the resonance for the thrust force is less than 500 Hz, its performance can truly be assessed.

## CONCLUSION

Prototype 1 and Prototype 2 are capable of producing a very large dynamic normal force, which exceeds the strength of the motor when the maximum electrical field is applied. Symmetry is used to reduce coupling between modes in Prototype 2. However, for these prototypes the extent of coupling between both modes of interest depends on specific dimensions of actuators and masses.

Coupling is no longer an issue for Prototype 3, because the bending mode and the longitudinal mode are naturally orthogonal and thus independent of one another. Further experiments are underway to adjust both resonances to the same frequency and to evaluate the ability of Prototype 3 to generate the desired slideway motion.

## REFERENCES

1) US Patent #5616980, April 1, 1997