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Design, Optimization, and the Prototyping of a Small Tuning-Fork Ultrasonic Piezoelectric Linear Motor

James R. Friend* Daniel S. Stutts†

Abstract: The design, optimization, and properties of a prototype small traveling-wave ultrasonic piezoelectric linear motor design are described. A method for optimizing the geometry of the motor to maximize its mechanical output for a given electrical input is described, as is the inherent properties of the design to maximize the motors durability and utilization of the piezoelectric material. Results from testing the motor demonstrate the design and indicate a maximum speed of 2.5 cm/s with a preload of 16 g due to an applied voltage of 80 V_{RMS} at an applied current of 15 mA.

Introduction

The first practical piezoelectric motors appeared in the early 1970's, creations of H. V. Barth [1] in 1972 at IBM's Watson Laboratory and Galutva et al. [2], in the Soviet Union, among others. However, they were not the first. Williams and Brown patented what is generally believed to be the first piezoelectric motor in 1948 [3].

Discovering the initial work performed on piezoelectric motor systems, research began in earnest in Japan, quickly overwhelming the meager efforts in the U.S. and elsewhere. Shoji Mishiro, at Taga Electric, designed several transducer systems in the 1970's [4] and motor systems in the 1980's [5], but the revolutionary traveling-wave motor design by Toshiiku Sashida et al. [7] was among the first successful piezoelectric motor designs.

To this day, however, many motor systems suffer from durability problems and are expensive. The construction of a motor system that addresses these problems while still providing decent performance would allow the advantages of the piezoelectric motor system to be available for applications that demand inexpensive and durable components. The purpose of this paper is to describe the design, construction, and testing of a linear traveling-wave motor system with these properties in its design.

Design

The design of the motor system is focused upon the design of the *stator*—the vibrating part of the motor system. The *slider*—the part moved by the stator or the part that the stator moves upon—is assumed to be compatible with the stator.

Initial Concept

Virtually all piezoelectric motors require elliptical motion to be generated along the output surfaces of the stator. The generation of that motion from the extensional, planar, and shearing motions that piezoelectric materials are capable of developing has been the genesis of many motor designs over the past twenty years. The magnitude of the vibrations that piezoelectric materials can generate is tiny—always less than one-hundred micrometers along the output surface—but the frequency of the vibrations is typically ultrasonic. Acting upon another surface, the elliptical motion will cause significant motion since it is at such a high speed and appears to be in a single direction.

Obtaining enough elliptic motion to cause the movement of the slider from the minuscule strain that the piezoelectric material can develop—one-tenth of one percent—is a challenge. The initial concept amplifies the output of the piezoelectric

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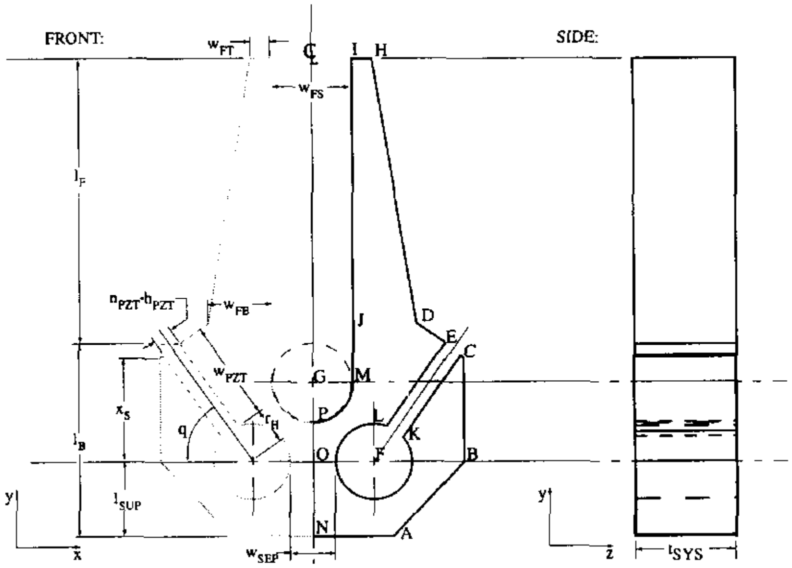

Figure 1: The basis set and points along the solid model of the miniature tuning fork motor

material through a lever arm, and, near resonance, the motion is further amplified through the inertia of the arms.

Parametric Design and Optimization

With the initial design, shown in Figure 1, the process of optimizing it through parametric design can begin. It is necessary to form a *basis*, a group of independent parameters that define the design completely, and an objective function that describes how "good" the motor design is. With these definitions, the relationship between the parameters and the quality of the design can be explored through finite-element analysis that eventually may lead to a suitable design for prototyping.

The definition of the basis for the miniature tuning fork motor is somewhat complicated. First, a set of assumptions can be made about the geometry;

- The geometry is symmetric about the y axis.
- The geometry has the same thickness throughout in the z direction.
- The center of the piezoelectric stack is aligned along a radius of the circle about the point F.
- The angle of the edge $\overline{AB}$ is 45° from the x axis towards the y axis.
- The angle of the edge $\overline{ED}$ matches the angle that the edge $\overline{CE}$ forms at the end of the piezoelectric stack.
- Edges $\overline{BC}$ and $\overline{IJ}$ are aligned with the y axis and edges $\overline{NA}$ and $\overline{HI}$ are aligned with the x axis.

With these assumptions, the number of independent variables that describe the geometry is reduced to twelve parameters as indicated in Figure 1.

Figure 2 illustrates how the parameters control the design. The ability of these parameters to accurately represent the design model with a solid model over the possible domain of the basis parameters is absolutely necessary. The design model represents the *desired* geometry of the design for a particular basis, but the solid model only represents whatever the geometric equations deliver. It is easy to define a set of equations that, for some chosen basis, either define ridiculous geometries or do not replicate the design model accurately.

The objectives of the design analysis are to maximize the magnitude of the output motion of the ends of the stator forks compared to the magnitude of the input motion from the piezoelectric material vibration, i.e., the transfer function of the stator, place the frequency of operation above the audi-

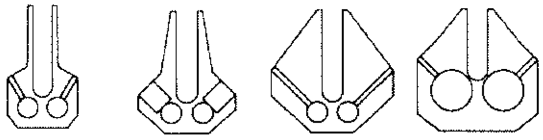

Figure 2: Result of changing the geometry through its parameters; (a) an increase in θ from 45° to 60°, (b) an increase in n_{PZT} from two to eight, (c) an increase in w_{PZT} from 25 to 50, and (d) an increase in r_H from 10 to 20

ble frequency range, obtain elliptical motion out of the ends of the forks with a low ellipticity or a decent aspect ratio, and obtain suitable mode shapes, a subjective requirement. The first three requirements can all be included in an objective function, the magnitude of which is related to how well the design meets the requirements.

Choosing all of the stator's geometric parameters as variables would present twelve degrees of freedom, so many that the optimization is almost guaranteed to fail. Narrowing down the number of parameters to four that are the most influential, r_H, θ, l_F, and w_{SEP}, the optimization becomes more tenable. It is also necessary to specify a reasonable range of values for each parameter for the analysis; together, the ranges become the parameter space for the problem. An objective function must also be defined; one way to define the function such that it considers the resonant frequencies of the modes of the stator and the transfer function of the motion in the stator is with the following equation:

$$\Phi = A_1 f_{FXN} + A_2 X_{FXN}, \quad (1)$$

where Φ represents the objective function composed of the constants A_1 and A_2 each multiplied with a function; the first, f_{FXN}, dependent upon the resonant frequencies, the second, X_{FXN}, dependent on the input-output transfer function of the stator.

The optimization of the stator using such an objective function improved the performance of the stator dramatically over only eight iterations. The displacement transfer function increased from a value of 8.09 to 37.69, the frequency function increased from 2.24 to 3.07, and the desired mode shapes were still present despite the changes. Comparing the values of the design variables before and after the optimization, Table 1 shows that there was not a significant change in the hole's radius or fork separation distance. The length of the forks and the angle of the piezoelectric material were both increased, however.

Table 1: Values of the design variables before and after the optimization

Parameter	Before	After
r_H (mm)	1.0	0.96
w_{SEP} (mm)	1.0	1.02
l_{FORK} (mm)	6.0	7.53
θ (degrees)	45	56

Final Design

The resonant frequencies and the associated modes of the final design chosen for prototyping are illustrated in Figures 3. Two modes are very close together near 16.4 kHz, but only the lower-frequency mode at 16,297 Hz should appear owing to the configuration of the piezoelectric material; the mode at 16,557 Hz requires a twisting motion that the piezoelectric material cannot force in the stator structure.

Testing

Two prototype stators were machined to the specifications of the final design for testing. Unfortunately, the machine shops available were incapable of machining the prototypes to the correct scale. A decision was made to increase the size of the prototypes by a factor of four, since scaling affects only the size of the output motion and the resonant frequencies of the stator. At a frequency of twenty-six kHz, the motor traveled in both directions (along the x-axis) depending on the phase. The applied voltage, about one hundred volts, RMS, developed a current of around ten milliamperes on each side. A speed of five centimeters per second was achieved with the motor

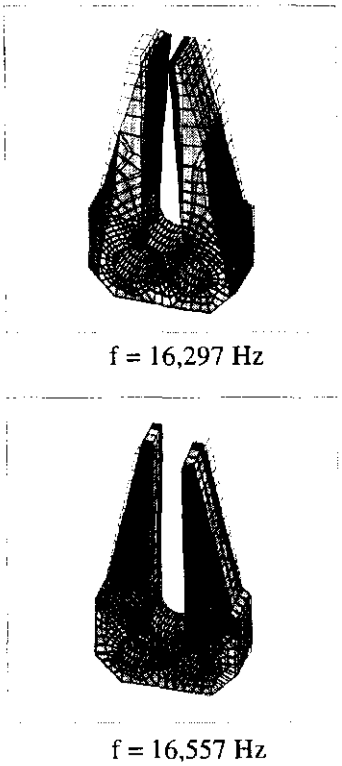

Figure 3: The lowest two resonant frequency modes of the final design of the miniature tuning fork motor with open-circuited piezoelectric material

with a load of sixteen grams on the contact interface between the stator and the glass counterface (the *preload*).

Conclusions

The miniature tuning fork motor design was a success, as was the effort to design the motor to protect the fragile piezoelectric material while dramatically amplifying its output. An optimization technique was used to improve the motor's design; the PZT-input to stator-output transfer function was increased from about 1:8 to 1:35 at resonance. A scaled-up version of the design was tested, which moved at a speed of five centimeters per second under a load of sixteen grams, despite using a different mode shape for the motor's operation.

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