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A finite volume method and experimental study of a stator of a piezoelectric traveling wave rotary ultrasonic motor

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ABSTRACT

Piezoelectric traveling wave rotary ultrasonic motors are motors that generate torque by using the friction force between a piezoelectric composite ring (or disk-shaped stator) and a metallic ring (or disk-shaped rotor) when a traveling wave is excited in the stator. The motor speed is proportional to the amplitude of the traveling wave and, in order to obtain large amplitudes, the stator is excited at frequencies close to its resonance frequency. This paper presents a non-empirical partial differential equations model for the stator, which is discretized using the finite volume method. The fundamental frequency of the discretized model is computed and compared to the experimentally-measured operating frequency of the stator of Shinsei USR60 piezoelectric motor.

1. Introduction

Since the invention of the piezoelectric traveling wave rotary ultrasonic motor there have been many attempts to model the stator of the motor based on experimental results and on pure analytical concepts. In [1], the authors present an empirical equivalent circuit model for the motor of a piezoelectric traveling wave rotary ultrasonic motor. The model consists of two equivalent RLC circuits (one for each phase). The equivalent inductor represents the mass effect of the ceramic body and metal ring, the equivalent capacitance represents the spring effect of the ceramic body and metal ring, and the resistance represents the losses that occur within the ceramic body and metal ring. Simulations of the model are not presented.

In [2], an empirical equivalent circuit for the stator of a piezoelectric traveling wave rotary ultrasonic motor is presented. The equivalent circuit allows for the estimation of the motor's characteristics. The equivalent circuit takes into account the external forces applied to the stator: the normal force of the rotor against the stator and the torque-generating tangential friction force between the stator and the rotor. The motor model allows for the estimation of the motor's characteristics in two operation modes: constant voltage and constant current operation. However, the model has some limitations. For example, the model does not calculate the operating frequency of the motor; rather, it is determined experimentally and then given to the model as an input parameter. Built into the model is the fact that the amplitude of the feedback signal is proportional to the speed of the motor and that the speed drop is proportional to the applied torque, but the proportionality coefficients need to be determined experimentally.

In [3,4], the authors present an enhanced empirical equivalent circuit model of a piezoelectric traveling wave rotary ultrasonic motor. The paper highlights the importance of the electromechanical coupling factor responsible for the energy conversion in the motor. Also, the model includes the effect of temperature on the mechanical resonance frequency; this effect is important for motors that operate for a long period of time. Simulations of the model show agreement with experimental measurements in the range of torques and frequencies of interest.

A drawback of empirical approaches is that such models must be developed in conjunction with experiments on the system of interest. And so a question about an operating regime that is outside the regime of the original experiments (and hence of the model) must be studied experimentally rather than with the model. In contrast, "first principles" models allow for computer explorations of a wide operating regime. These explorations can then be validated against experiment.

One type of first principles model uses Hamilton's principle. For example, the model in [5] uses the constitutive equations of piezoelectricity, Hamilton's principle, the strain–displacement relations,

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and the assumed vibration modes of the stator. This yields two matrix equations: an actuator equation and a sensor equation. The stator model developed in this paper is a very good tool for the design and optimization of this type of stators for a variety of geometries and materials. In [6] the authors present a model of the stator of a traveling wave ultrasonic motor based on the first-order shear deformation laminated plate theory applied to annular subdomains of the stator. The model uses the constitutive equations of piezoelectricity, Hamilton's principle, and the Ritz Method to obtain approximate solutions for the modified Hamilton's principle. The overall accuracy of the model is comparable to that of finite element methods (FEM) and is within 4.5% as compared with experimental data.

The models presented in [5,6] are very good for simulation but can be hard to use in developing a controller for a practical application. Specifically, the models that arise from Hamilton's principle or from FEM approaches have the unknowns multiplied by either an inertia matrix or by a mass matrix, making a direct use of the model by a controller more difficult.

This paper proposes a method of modeling the stator of a piezoelectric traveling wave rotary ultrasonic motor by building upon the finite volume method (FVM) model of a unimorph plate presented in [7]. The goal of the modeling is to approximate the operating frequency of the stator of the motor; simulations of the model are compared to experimental measurements of an ultrasonic motor Shinsei USR60. These experiments show that the operating frequency of the real stator was within 1% by the simulations of the model.

In the FVM model presented here, the region of interest is divided into subregions and the unknowns are the average displacement of each subregion. Such averaged quantities are often exactly what a sensor or controller needs to work with. The FVM approach then yields a system of first-order ordinary differential equations that the average displacements satisfy. These differential equations can be interpreted directly as equivalent circuits and used by a controller.

It was shown in [8,9,7] that the finite volume method has the following strengths when it comes to modeling piezoelectric devices:

(a) The FVM ordinary differential equations can be interpreted intuitively in terms of coupled circuits that represent the piezoelectric system [8]. These circuits can then be implemented using schematic capture packages. This makes it easier to interface the FVM model of the piezoelectric system with control circuits.
(b) The flux continuity is preserved across the boundaries exactly thus allowing complex boundary conditions to be handled with more precision. Therefore, this method may be more suitable to model an ultrasonic motor because the operating principle of the motor is based on the friction mechanism that takes place at the common contact boundary between the stator and the rotor.

2. Modeling an ultrasonic motor stator

The stator of an ultrasonic motor Shinsei USR60 is studied. The stator is made of a piezoelectric ring bonded with an adhesive to a metal ring (see Fig. 1). The adhesive layer is thin compared to the metal and the piezoelectric rings. For this reason, the metal and piezoelectric rings are modeled, but the adhesive layer is not. The piezoelectric ring is divided into two semicircular sectors A and B, as shown in Fig. 2. Each sector contains eight "active regions" labeled by "+" or "−" in Fig. 2. The "+" or "−" labellings reflect the fact that the regions have opposite polarizations. This means that if a positive DC voltage is applied to both regions, the "+" regions will expand and the "−" regions will contract; seen from the side, the resulting deformation will look like that shown in Fig. 3a. All eight active regions of sector A are electrically connected by a common electrode; the supply voltage is applied simultaneously to all eight. As a result, when a positive DC voltage is applied to sector A, each of the eight active regions in sector A will deform as shown in Fig. 3a. Alternatively, when a negative DC voltage is applied to sector A, the active regions in sector A will deform as shown in Fig. 3b. Because sector A is coupled to the rest of the stator, the entire stator will deform.

If an AC voltage is applied to sector A at the operating frequency, then a standing wave with nine wavelengths will form in the entire stator. Similarly, the eight active regions of sector B are also electrically connected by their own common electrode and so, if either sector A or sector B is driven with an AC voltage at the operating frequency then a standing wave forms. However, if they are driven with equal-amplitude AC voltages that are at the same operating frequency but are out of phase by 90° then a traveling wave can form, allowing the motor to operate as a two-phase motor. The 90° phase difference is determined by the length of the passive region at the top of the rotor (see Fig. 2); it is a quarter wavelength. The goal of the modeling in this article is to find a relatively simple model that will identify this operating frequency of the stator.

Each ± pair of active regions corresponds to one ninth of the total ring and, for modeling simplicity, the stator is viewed as having nine "wavelength sectors"—the extra wavelength's worth of passive material at the top and bottom of the ring shown in Fig. 2 is replaced by a wavelength sector. In this way, the full stator can be modeled as nine identical wavelength sectors, each one coupled to its flanking sectors (see Fig. 2). Fig. 4a shows a sector of width w_s. Its outer length (marked λ) is $2\pi R/9$ and its inner length is $2\pi r/9$ where R and r are the outer and inner radii, respectively. Because each wavelength sector behaves the same way, rather than

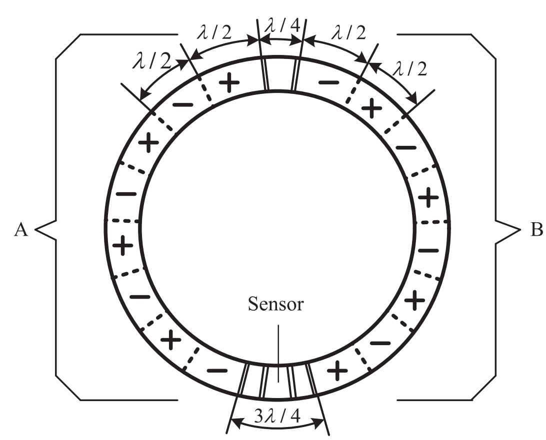

Fig. 2. The piezoelectric ring has an external diameter of 60 mm, an internal diameter of 45 mm, and a thickness of 0.5 mm. The regions A and B are composed of active regions denoted by "+" and "−". There are nine wavelengths: $9\lambda = 2\pi R$ where R is the outer radius. The regions A and B are separated by a passive region of width $\lambda/4$ at the top and a passive region of width $3\lambda/4$ at the bottom. The bottom region is used as a sensor, generating a voltage proportional to the amplitude of the traveling wave.

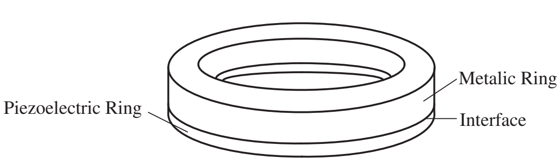

Fig. 1. Ultrasonic motor stator structure.