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A novel contact model of piezoelectric traveling wave rotary ultrasonic motors with the finite volume method

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ABSTRACT

The operating principle of the piezoelectric traveling wave rotary ultrasonic motor is based on two energy conversion processes: the generation of the stator traveling wave and the rectification of the stator movement through the stator-rotor contact mechanism. This paper presents a methodology to model in detail the stator-rotor contact interface of these motors. A contact algorithm that couples a model of the stator which is discretized with the finite volume method and an analytical model of the rotor is presented. The outputs of the proposed model are the normal and tangential force distribution produced at the stator-rotor contact interface, contact length, height and shape of the stator traveling wave and rotor speed. The torque-speed characteristic of the USR60 is calculated with the proposed model, and the results of the model are compared versus the real torque-speed of the motor. A good agreement between the proposed model results and the torque-speed characteristic of the USR60 was observed.

1. Introduction

Modeling of the contact of the piezoelectric traveling wave rotary ultrasonic motor (PTRUSM) is a current challenge because the existing models of the motor are just focused in describing the behavior of certain parts of the motor, or the models have several assumptions that degrade the accuracy of these models. It was founded that there is no detailed non-empirical multi point of contact model of the PTRUSM capable of being used as a reference to develop a model-based control strategy to operate these motors. Because of that, the development of a detailed non-empirical multi-point of contact model of the stator-rotor contact interface is motivated. A brief literature review regarding the existing models of the contact of the PTRUSM and proposed control strategies is presented in the next paragraphs.

In [1] an equivalent circuit used to model the stator-rotor contact interfaces was proposed. The major problem with the proposed approach is that this is a one point of contact model where the parameters of the circuit need to be determined empirically. One can find in [2] a one point of contact model of the stator-rotor contact interface. The rotor (metal) was modeled as a rigid body, and the contact layer was modeled as a linear spring. The rotor was considered to be vertically fixed, and reactions from the rotor to the stator were neglected. The overlap between stator and rotor was assumed to be the contact zone of the stator-rotor contact interface. This model is very simple, but at the same time it is very inaccurate due to the assumptions and simplifications previously mentioned, refer to [3].

In order to model the contact, Hagood [4] proposed a one point of contact model where the stator is assumed to be rigid (i.e. the shape of the stator is assumed to be independent of the contact forces). The advantage of this model is that a transient response can be obtained with it. Nevertheless, the author did not provide a comparison between the torque-speed characteristic of the motor versus the torque-speed characteristic obtained with the proposed model.

More sophisticate contact models of the PTRUSM stator-rotor contact interface are treated by Schmidt and Sattel [5,6]. The stator was modeled as a Bernoulli-Euler beam, the rotor was assumed to be rigid, and the contact layer attached to the rotor was modeled as a viscoelastic layer. These authors used contact algorithms to model this nonlinear problem, these algorithms are explained in detail in [7,8]. The advantage of these models is that the system of equations is solved with interactions, which means that the authors attempt to consider the nonlinearity of the stator-rotor contact zone. The main drawback of the proposed method is the simplified stator model used as part of the contact model and the lack of a model for the piezoelectric material.

A 3D contact model using finite element software was proposed in [9]. The disadvantages of this proposed model are that the model of the stator is inaccurate because a model of the stator piezoelectric material was not included, and the computational effort required to solve the 3D contact model is very high. Other contact models of the motor, comparable to the ones presented in this literature review can be found in

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[10–16]. In summary, the main drawbacks of these proposed models include: simplified stator models, assumed rigid stator and rotor, lack of piezoelectric material models, the need to determine the parameters of the model empirically and the one point of contact assumption.

Since the invention of these motors, researchers have proposed different control techniques. These control techniques are mainly based on empirical knowledge. Usually, fuzzy control strategies are proposed to control the motor speed. As mentioned before, the current models of the PTRUSM are not accurate enough to be used to develop a model-based control strategy to operate this motors, refer to [3]. A summary with the current proposed control techniques is presented in the next paragraphs.

In [17] a speed control strategy of the ultrasonic motor is presented. This approach is based on fuzzy logic concepts. The speed of the motor is controlled through amplitude modulation of the input voltages. Cha [18] proposed a fuzzy controller, where the output speed was controlled using frequency modulation of the driving voltages.

Most recently, the problem of controlling the speed of the PTRUSM when subject to a temperature change is treated in [19]. A proportional, integral and derivative (PID) control strategy was proposed here. An empirical equation was obtained to model the rotor speed. Amplitude modulation of the driving voltages was used to control the motor output velocity, but this approach only considers the situation of the unloaded motor.

In [20] a speed control strategy of the PTRUSM using a fuzzy neural network was proposed. The control strategy is based on a proportional and integral (PI) control with auto-tuning. The auto-tuning is based on fuzzy logic using a neural network. The speed of the motor was controlled using frequency modulation of the driving voltages. The fuzzy rules were obtained just for the unloaded motor case. Other control strategies of the motor comparable to the ones presented in this literature review can be found in [21–23].

The rest of the paper is organized as follows. The models of the stator and rotor are presented in Sections 2 and 3, respectively. In Section 4 the normal and tangential contact algorithms are shown. Section 5 presents the numerical results. Finally, Section 6 contains the conclusion.

2. Modeling of the stator

The stator of the PTRUSM is formed by two bonded rings made with piezoelectric and metal materials, where the metallic ring has a bridge that is attached to the case of the motor, refer to Fig. 1. The stator is modeled with the static and dynamic models of the stator presented in [24]. In this approach, the stator is modeled as a 2D continuum made of piezoelectric and metal materials discretized with the finite volume method (FVM). The bridge of the stator is modeled with a spring foundation equation derived for this system of equations. The system of equations that models the stator is shown in Appendix A.

Fig. 1. USR60 stator.

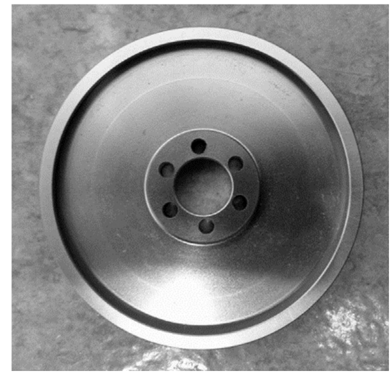

Fig. 2. USR60 rotor.

3. Modeling of the rotor

The rotor of a PTRUSM is a metallic disc with variable thickness, as shown in Fig. 2. The edge of the disc is thicker than the rest of it. The edge is the only part of the rotor that is in contact with the stator. In order to improve the wear properties of the contact zone, the rotor bottom edge is covered with a friction resistant material, usually called contact layer. The PTRUSM contact layer is a composite material; it is composed of a matrix, reinforced filler and a friction regulator (refer to [25]).

The PTRUSM rotor (metal) and contact layer suffer a vertical deformation when in contact with the stator traveling wave. Therefore, the rotor (metal) and contact layer were both modeled as a layer of discrete spring elements attached to a rigid body. That means that the elasticity of both, metal and contact layer is considered into the model. The number of springs of the rotor model is finite because the stator is modeled with a finite number of control volumes. The purpose of using a rigid body is to consider the vertical displacement of the rotor when in contact with the stator traveling wave. This degree of freedom (i.e. vertical displacement of the rotor) was not considered for most of the authors presented in the literature review. Fig. 3 shows the PTRUSM rotor model.

4. Modeling of the stator-rotor contact interface

Modeling of the stator-rotor contact interface is a high non-linear problem that demands to be mathematically described with inequalities. In order to model the contact, a moving reference coordinate system on top of the stator traveling wave is introduced (Fig. 4). This simplifies the steady-state modeling, because one can reduce a time dependent problem into a time independent problem [8]. Therefore, time independency motivates the use of a static contact model.

4.1. Normal contact problem

Due to the absence of adhesion between the stator and contact layer, unilateral normal contact is used to describe the PTRUSM stator-rotor contact. As shown in Fig. 5, three contact zones can be used to model the PTRUSM stator-rotor contact:

$$g = 0 \qquad F_n = 0 \tag{1}$$

$$g > 0 \qquad F_n = 0 \tag{2}$$

$$g < 0 \qquad F_n < 0 \tag{3}$$

where g refers to the gap between the stator and contact layer, and F_n refers to the normal force produced over the contact zone. A gap equal to zero is the theoretical point where both body surfaces touch each other but no penetration is present in the materials. The normal force is zero when having a gap equal to zero. A gap bigger than zero refers to the non-contact zone. The third zone models the rotor penetration. In