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Finite element modelling of a rotating piezoelectric ultrasonic motor

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Abstract

The evaluation of the performance of ultrasonic motors as a function of input parameters such as the driving frequency, voltage input and pre-load on the rotor is of key importance to their development and is here addressed by means of a finite element three-dimensional model. First the stator is simulated as a fully deformable elastic body and the travelling wave dynamics is accurately reproduced; secondly the interaction through contact between the stator and the rotor is accounted for by assuming that the rotor behaves as a rigid surface. Numerical results for the whole motor are finally compared to available experimental data.

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1. Introduction

Piezoelectric materials belong to the larger domain of *smart materials*, i.e. materials based on the systematic response to particular inputs [1–6].

A specific field in which piezoelectric materials show an increasing importance is that of piezoelectric motors. The travelling wave ultrasonic motors (TWUSM) represent a new generation of motors, suited for many applications [7,8] and their technology has experienced growing interest in the last decade due to the particular advantages that new piezoelectric materials offer. Ultrasonic motors have been commercially employed for automated focusing systems of cameras, for special instruments and X–Y positioning systems, while practical researches aiming at producing systems for transport and office automation are now being undertaken. Anyway, a large-scale employment has been somehow hindered so far by some problems related to their long-term reliability and high cost (see e.g. the review in [9]).

Even if they do not represent, at present, a global alternative solution to electromagnetic motors, their features are preferable for specific tasks. Piezoelectric motors have several unique properties such as: high output torque (at least one order of magnitude larger than conventional electromagnetic motors of the same size and weight [10]), large breaking torque due to the friction force without energy consumption (self-breaking motors), low leakage of magnetic flux. The high output torque makes it possible to eliminate reduction gears from the transmission system, which means a reduction in noise level and the possibility to construct a positioning system with high rigidity. Moreover, some ultrasonic motors have unique shapes, such as thin disks or rings, that are difficult to produce with electromagnetic motors.

The travelling wave ultrasonic motors are based essentially on the sequence of two energy conversions: (i) electromagnetic energy conversion employing a film of piezoceramics to induce the propagation of a

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travelling wave in a vibrating stator, driven to resonance to improve performances; (ii) mechanical energy conversion taking place at the stator–rotor interface. The wave transports energy which is transmitted to a free rotating disk, called rotor, by means of frictional forces acting on the rotor along the hoop direction.

A wealth of contributions have been published in the literature on the analytical or semi-analytical modelling of TWUSM. The simulation of the complete response of a TWUSM is indeed greatly complicated by the complexity of the assemblage and strong linearities in contact between the stator and the rotor. Hence most contributions aim at developing simplified models concentrating non-linearities in ad-hoc constitutive modelling for the contact region. Sun et al. [11] discuss stator vibrations by approximating the stator as a series of beams; Kurosawa [12] uses distributed linear springs to model the interface between the stator and the rotor without addressing the stick-slip alternative. Hagood and McFarland [13] and Hagedorn et al. [14,15] propose alternative formulations to account for friction phenomena, in the latter case also considering the rotor deformability; Le Moal and Cusin [16] also solve an optimization problem to establish the proper shape of the rotor to improve contact conditions.

Anyway, all these models require an accurate calibration through variation of the parameters involved which somehow limit their predictive ability for new motors.

Quite surprisingly, on the contrary, relatively few contributions have appeared concerning purely numerical analyses for the assembled TWUSMs. Due to the non-linearities involved, finite element methods (FEM) are generally employed. For example Maeno et al. [17] utilize the commercial code NASTRAN to evaluate the dynamical properties of the stator simulated as a ring with a suitable distribution of teeth; a second code is then employed to analyse contact with the rotor.

The aim of the present paper is to provide a contribution towards the understanding of the potentialities of an overall FEM simulation which should eventually serve as an optimization and predictive tool for the production of new TWUSMs. A finite element model of the motor is proposed with a reduced set of simplifying assumption and with particular reference to the structural aspects, to the numerical modelling of the essential components (motor and stator) and to the representation of the electro-mechanical coupling matrix by means of a thermo-mechanical equivalence.

An outline of the paper is as follows. In Sections 2 and 3 the description of principles on which TWUSM are based is briefly presented, together with the mathematical description of the piezoelectric problem and its thermo-mechanical equivalence. Section 4 is devoted to the presentation of the 3D finite element (FE) model used for numerical simulations and of the main results obtained. Finally, closing remarks are presented in Section 5.

2. Schematic description of the ultrasonic motor

The TWUSM analysed essentially consists of a stator, a rotor, a spring and a piezoceramic ring as depicted in Fig. 1, where the drawing represents a partial section of the motor displayed in the lower picture.

The stator is a vibrating metallic lamina which is bound in the centre to a rigid support preventing any rigid body motion while a piezoelectric thin wafer is glued to its lower surface.

A friction layer of plastic material is interposed between the metallic rotor and the stator, which are pressed together by an external spring consisting of an aluminium thin plate. The rotor is free to pivot around its axis, while out of plane rotations are elastically controlled by the spring. The assembly is closed into a rigid cover.

Ultrasonic motors basically transform elastic energy of the vibrating body (stator) into kinetic energy of a rigid disk (rotor). As explained in detail in the sequel, a travelling wave (TW) is induced in the stator through electric input to the piezoelectric wafer; then TW transmits the driving torque to the rotor by means of frictional forces.

The piezoelectric ring consists of two regions, Phases A and B, respectively (Fig. 2a). Both regions are a sequence of piezoelectric sectors (of length $\lambda/2$, where λ represents a suitable wavelength) with alternating polarisation direction. Positive signs in Fig. 2 correspond to a positive polarization, in agreement with the

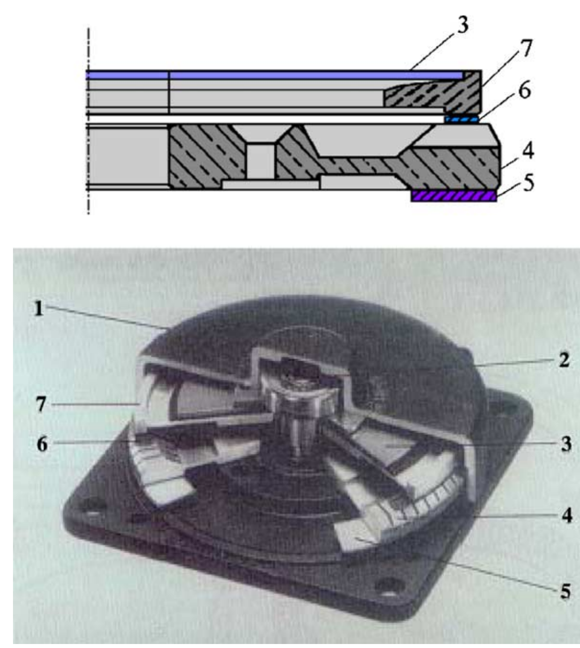

Fig. 1. Section of a TWUSM: (1) cover; (2) bearing; (3) spring; (4) stator; (5) piezoelectric ring; (6) friction layer; (7) rotor, from [11].