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Stator/Rotor Interface Analysis for Piezoelectric Motors

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Abstract:

Based on a literature survey, this paper presents the implementation of analytical modeling approaches of the contact between a stator and a rotor in piezoelectric motors. These modeling approaches are validated by comparison to experimental results obtained on a specially designed piezoelectric motor. Two types of measurements are presented: the displacement of contact point, and the friction force. The second measurement is used to evaluate the friction coefficient and its dependence upon several parameters such as sliding velocity and pre-compressive force. Both the friction coefficient and the displacement of contact point are used as input in the modeling. The comparison of the predicted and measured no-load speed for different pre-compression levels shows a close agreement.

Keywords: tribology, sliding speed, pre-compressive force, friction model, interface reaction forces, universal stator.

Introduction

Due to the growing demand of high performance motors, with minimum mass, minimum size and high service lifetime, scientists and researchers have started to investigate the potentialities of piezoelectric motors. In order to achieve optimal operation of the motor in terms of torque density, efficiency and lifetime, there is a number of key factors to address.

A literature survey shows that contact factors such as material properties, dimension of friction layer and pre-compressive force are crucial for motor performance ([1], [2], [3]).

In a first part, this paper presents the implementation of these key factors into a new model of friction drive for piezoelectric motors. In a second part, a first set of validation experiments is proposed. These experiments allow studying the tribology characteristics of contact materials in order to analyze the modeling input parameters. A comparison between modeling and experimental results is finally performed.

Friction drive model

The friction drive model of a piezoelectric motor allows predicting its operation characteristics once the vibration displacements of contact points and the properties of contact materials are known.

Note that this paper only deals with the development of friction drive models and does not address the identification of contact point displacements.

There are four basic models of friction [4] from which other models can be derived in order to simulate as accurately as possible the contact interface.

The first model (see Fig. 1.a) is the most classical dry friction model. With tangential force F applied, the contact can keep adherence (stick) until F exceeds particular value from which the contact slides (slip). In this last case, F doesn't vary with the relative velocity of contact points which is defined here as the sliding velocity.

The static/dynamic model (see Fig. 1.b) is based on the fact that the sticking forces of contact are higher than the sliding ones. This model is widely used in the modeling of traveling waves ultrasonic motors [1], [2].

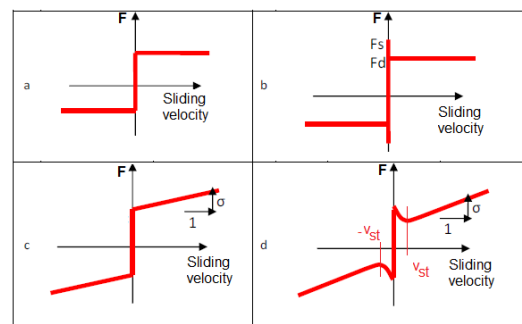


Fig. 1: Basic friction models: a) Coulomb, b) static/dynamic, c) viscous friction, d) LuGre.

The viscous friction model (see Fig. 1.c) differs from the previous models by the fact that F evolves linearly with the sliding velocity. This model is often used in the modeling of the lubricated contact for applications such as guiding devices (bearings, sliders). This model has already been used in impact drive motor with lubricated interface [5] and in superposed modes piezoelectric motors [1].

The LuGre representation (see Fig. 1.d) is the simplest model that can integrate all the previously mentioned aspects. This model is used in the friction modeling of several motor types, especially, inertial type motors [6], [7], [8].

In addition, some friction interface modeling of piezoelectric motors are based solely on empirical results for the relation between the friction coefficient and operation parameters such as the sliding velocity, vibration amplitude, excitation frequency, normal force, etc. [9], [10].

Friction model: implementation and results

The proposed model is represented in Fig. 2: the stator and the rotor (slider) are considered as two rigid blocks between which is located a spring with equivalent stiffness of contact K_{sr} and equivalent damping coefficient C_r . Attached to the stator, the spring can slide on the rotor face with friction coefficient μ .

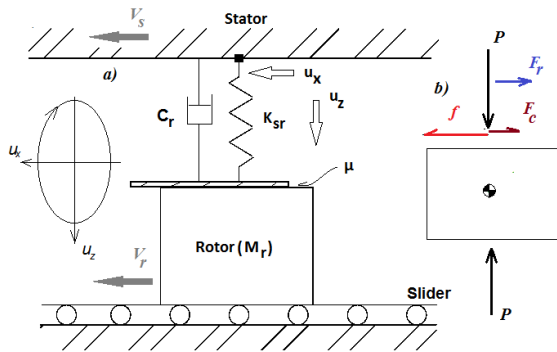


Fig. 2: a) Friction drive representation, b) applied forces summary.

The rotor of mass M_r is subject to external load force F_r , damping force F_c , inertial force due to the rotor acceleration \dot{V}_r , normal load P and friction force f . On the opposite side, the contact points of the stator perform an elliptical motion of normal axis u_z and tangential one u_x . Due to the stator/rotor friction, the rotor moves at a speed V_r .

According to the fundamental principle of dynamics:

$$\bar{f} + \bar{F}_c + \bar{F}_r = M_r \bar{V}_r \quad (1)$$

$$M_r \bar{V}_r + C_r \bar{V}_r = \bar{F}_r + \mu P \text{sign}(\bar{V}_s - \bar{V}_r) \quad (2)$$

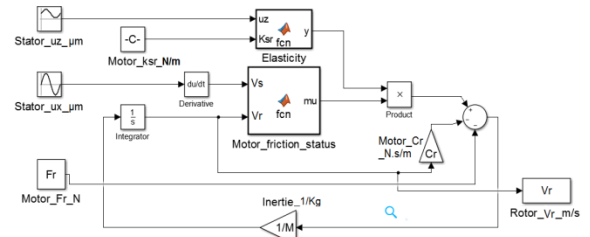


Fig. 3: Friction drive Simulink model.

The friction drive model is implemented into Matlab-Simulink (see Fig.3). Input data are: F_r , u_z , u_x and the interface material properties (Young modulus and Poisson ratio for the rotor (E_r , ν_r) and for the stator (E_s , ν_s) and friction coefficient μ). K_{sr} is a function of contact materials elasticity and of the shape and dimensions of the contact surface [11].

As we have seen in the previous section, the choice of the friction model is based on the operation mode of the motor. As a first approximation, μ is considered following the static/dynamic friction model (see Fig.1.b).

The results are shown in Fig. 4 and 5. P_0 is the pre-compressive force applied to maintain contact between the stator and the rotor. In this paper C_r is not taken into consideration.

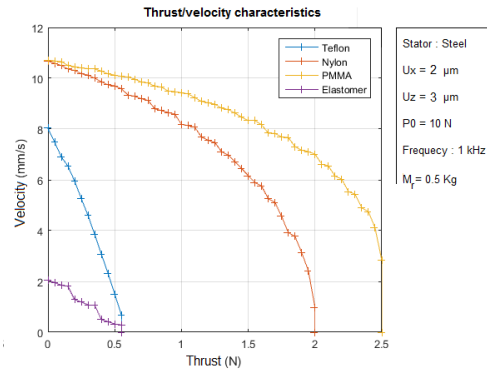


Fig. 4: F_r/V_r characteristics for several materials of friction layer.

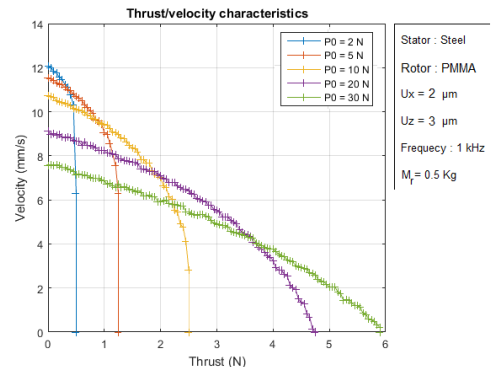


Fig. 5: F_r/V_r characteristics for different pre-compressive forces.

Fig. 4 shows the thrust/ velocity characteristics of the rotor for different friction materials. For the corresponding operation conditions, it can be seen that, by using the Plexiglas, the motor gives the best performance (in terms of thrust and velocity). It must be mentioned that the characteristics of the motor are highly impacted by the operation conditions such as the pre-compression (see Fig. 5), elliptical motion of contact, rotor mass, etc.

Experimentation

The conducted experiment is done on a specially designed piezoelectric motor (see Fig.6, 7)

The universal stator is a triangular shaped structure. Two piezoelectric actuators are placed along two sides of the triangle. It is capable of creating a vibrating elliptical motion at the tip of the stator on which the rotor is frictionally in contact. This kind of displacement is ensured by quadrature phase-shifted excitations of two piezoelectric actuators.

The test bench (see Fig. 6) is designed to achieve measurements such as the tip displacements (\mathbf{u}_x , \mathbf{u}_z) and contact reaction forces (\mathbf{P} , \mathbf{f}). The interesting variables to test are the friction materials (\mathbf{E}_r , \mathbf{E}_s , \mathbf{v}_r , \mathbf{v}_s , $\boldsymbol{\mu}$), the supply voltage (Amplitude U_0 , Phase φ , pulsation ω) and the pre-compressive force \mathbf{P}_0 :

Tip displacement measurement

The tip displacement measurements are performed with a laser vibrometer (see Fig. 6.b) [12] in both directions **1** and **2**, normal to the faces of the tip. Therefore, \mathbf{u}_x and \mathbf{u}_z are estimated as being the sum of the projection of \mathbf{u}_1 and \mathbf{u}_2 , along x and z directions respectively.

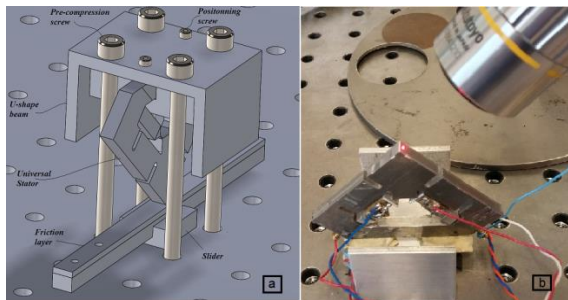


Fig. 6: a) Universal stator type motor, b) tip displacement measurement.

Friction coefficient measurement

At the contact interface, a reaction force is created by frictional interaction between the stator and the slider. Let \mathbf{P} and \mathbf{f} be the projections of this reaction force, respectively, along the normal and tangential directions of the contact surface of the slider. By

application of the fundamental principle of dynamics (see Fig. 7):

$$f = \frac{d}{2H} (P_2 - P_1) \quad (3)$$

$$P = P_1 + P_2 \quad (4)$$

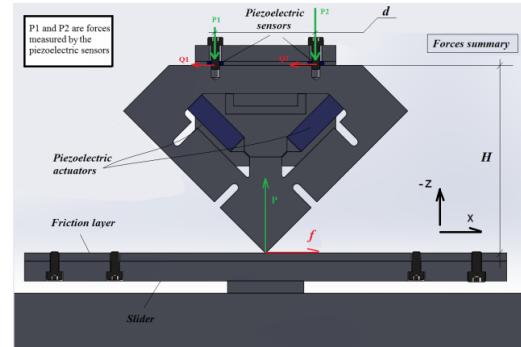


Fig. 7: Force measurement.

Therefore, $\boldsymbol{\mu}$ can be defined as follows:

$$\boldsymbol{\mu} = \frac{f}{P} \text{sign}(V_r - V_s) \quad (5)$$

Measurements results

In order to obtain $\boldsymbol{\mu}$, \mathbf{P}_0 is applied using pre-compressing screws. Afterwards, the slider is forced to move along x axis in both directions at a speed V_r . A sample of Plexiglas is tested and the results are shown in Fig. 8. With $V_s = 0$, the equation (5) becomes: $\boldsymbol{\mu} = \frac{f}{P} \text{sign}(V_r)$. With an amplitude of 21 mm/s for V_r , we can see that $\boldsymbol{\mu}$ varies along a quasi-straight line for V_r close to zero, and, quickly, saturates at a value of 0.2.

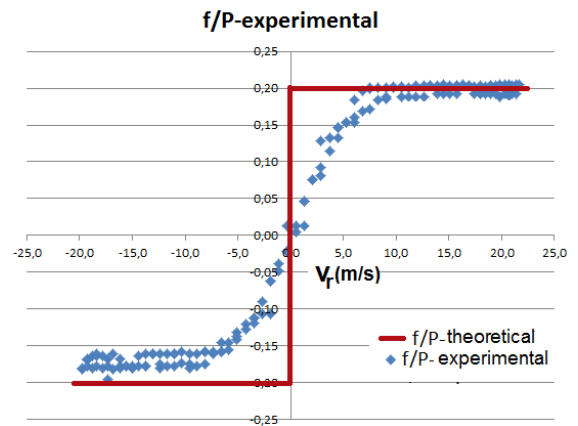


Fig. 8: $f/P(V_r)$ for PMMA.

Attributing the linear variation of $\boldsymbol{\mu}$ close to the origin to technical limits, we will consider $\boldsymbol{\mu}$ as constant ($=0.2$) with respect to V_r . In fact, due to dimensional gaps in the system, close to the end of

the slider stroke (where the sliding velocity is low), the contact is loosened and thus f drops.

Similarly, below certain limits, μ is considered independent of P_0 (see Fig. 9). However, the value of μ drops under excessive amount of P_0 .

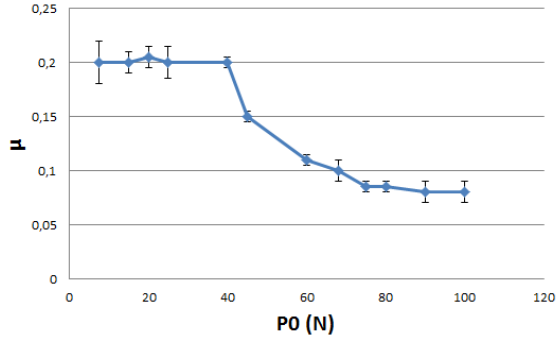


Fig. 9: $\mu(P_0)$ for PMMA.

In order to verify the no-load speed versus pre-compression motor characteristics obtained by the proposed modeling approach, the universal stator is run at a frequency of 1 kHz under an alternative supply voltage of 60V (pk-pk). Under these loading conditions, we find: $U_x=0.9 \mu\text{m}$, $U_z=2.4 \mu\text{m}$.

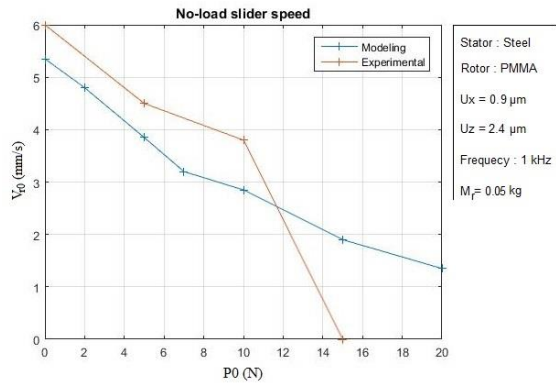


Fig. 10: No-load speed comparison between modeling and experimental results for different values of pre-compression for PMMA.

The comparison, in Fig. 10, between modeling and experimental results shows a good approximation of V_{r0} with respect to P_0 . However, at 15N of P_0 and beyond, the motor reaches its limit of operation and experiences blocking situation. This phenomenon is not included in the modeling approach.

Conclusion

In this paper, we have studied the impact of friction material choice on motor performance. In order to model the frictional interaction between the stator and the rotor of a piezoelectric motor, the contact vibration displacements and the properties of contact materials are needed as input of the model. The

friction coefficient variation of a pair of materials in contact has been, experimentally, investigated. We can say that the friction coefficient is unrelated to the sliding speed and the pre-compressing as long as the piezoelectric motor is used in a limited range of velocity and pre-compression levels. The modeling and experimental results for no-load speed with respect to pre-compression have been compared with satisfying agreement.

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