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TORQUE CHARACTERISTICS ANALYSIS FOR TRAVELLING WAVE ULTRASONIC MOTOR

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***Abstract* – This paper presents a set of results regarding the torque of travelling wave ultrasonic motor. It is known the fact that at this type of motor there are a set of phenomena which requires some advanced investigations. The analysis of torque characteristics requires precision measure methods, torquemeters or dinamometers. The torque dependence and influence of specifical parameters are presented. Also for the analized motor there are given a set of graphical results.**

Keywords: *travelling wave, ultrasonic motor, torque*

1. INTRODUCTION

As a novel motor, ultrasonic motors have many notable features compared with conventional electric ones.
For example, they can produce a relative high torque at a low speed with a high efficiency and the torque produced per unit weight is high. It would therefore appear that USMs have the huge potential for uses as actuators for functional automotive parts. However, applications in the large torque field are limited at present because most of the currently available USM cannot provide sufficiently absolute high torque yet.
Ultrasonic motors perform a two-step energy conversion. In the first stage electrical energy is converted into mechanical vibrations of the stator. In the second stage, high frequency oscillatory vibrations of the stator are transformed into unidirectional macroscopic motion of the rotor.
The micromachines mentioned work by converting small amplitude, high frequency vibration (of 10 kHz and higher) of a stator with piezoelectric elements into unidirectional linear or rotary motion using friction.
Additionally, with no voltage applied, an inherent holding torque is present due to the frictional driving mechanism. Generally, the main scope for testing the ultrasonic piezoelectric motors is the understanding of the stator-rotor interface phenomenon, torque characteristics followed by the conception of new optimized models and applications. The use of traveling wave ultrasonic motors (TWUSM) is present especially at high-precision systems and in robotics (fig. 1).

Figure 1: Traveling wave ultrasonic motor. Compact view.

2. FORCES AND TORQUES AT TWUSM

Ultrasonic motors have torque densities three to ten times higher than standard DC motors. Therefore, smaller ultrasonic motors can take the place of DC motors and still exhibit higher torque outputs.
The study of the torque of this motors are very extended [3,5,6,8] and for control technique also[11, 12, 13, 14].
First, we must tell that piezoelectric ultrasonic motors are friction motors. This means, that there is mechanical contact between stator and rotor and the torque produced by this micromachine is determined by the friction force at the rotor stator interface. (motor's construction [2]).
Practically, it is easy to understand that the torque depends on the applied normal force of the rotor against stator and the voltage.
The variation of these parameters are interesting for torque analysis but the authors didn't have those possibilities.
The real case of the mechanical contact at the twusm is characterized by the following relations.
The normal force is related to the pressure distribution by the integral of the pressure distribution over the contact area (fig. 2):

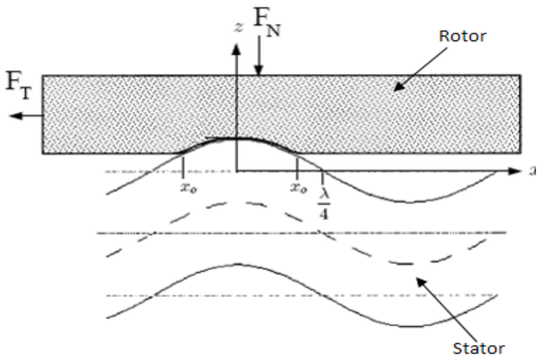

Figure 2: Forces at traveling wave ultrasonic motor. Contact mechanics. [4]

The normal force is given:

$$F_N = -\int_{-x_0}^{x_0} p(x)dx$$

If we consider hertzian contact model, the resulting friction (tangential in this case) force is:

$$F_t = -2 \cdot \mu_d \int_0^{x_0} \text{sgn}[\Delta v(x)] \cdot p(x)dx$$

The signum function is defined as:

$$\text{sgn}[\Delta v(x) = \begin{Bmatrix} 1 & v_{stator}(x) > v_{rotor} \\ 0 & v_{stator}(x) = v_{rotor} \\ -1 & v_{stator}(x) < v_{rotor} \end{Bmatrix}]$$

The relative velocity $\Delta v(x) = v_{stator}(x) - v_{rotor}$ where $v_{stator}(x)$ signifies the horizontal component of the stator velocity.

So, it must be told that the if the rotor contacts the stator only at the apex of the travelling wave, the rotor velocity will be equal to the horizontal velocity, of the stator surface as long as there is no slipping [4]. Also, in the case considered, only the normal component of the pressure distribution $p(x)$ is considered.

The reason for this consideration is that the curvature of the stator is small and the stator is almost flat in the contact zone. The model of contact applicable in this case is that of hertzian contact of a cylinder contacting an elastic half space and where the stator is deformed as a cylinder of equivalent radius of curvature.

The rotor is considered as an elastic half space contacting the cylinder over an area of width, when a force F_N is applied [4]. The maximum torque depends on the normal force, radius of the rotor and friction coefficient:

$$M_{\max} = \mu_d \cdot F_N \cdot r$$

The mechanical output power can be determined as the product of rotor torque and rotor speed:

$$P = M \cdot \Omega_r$$

The efficiency is known as the ratio of mechanical power output to power input:

$$\eta = \frac{P_m}{P_{in}} = \frac{P_m}{P_p + P_m}$$

The frictional heating loss P_p can be determined using the rotor torque and the relative velocity of the stator and rotor.

$$P_p = 2 \cdot \mu_d \cdot r \int_0^{x_0} \text{sgn}[\Delta\omega(x)] \cdot p(x) \cdot \Delta\omega(x)dx$$

where $\Delta\omega(x)$ is the relative velocity between the stator and rotor.

$$\text{sgn}[\Delta\omega(x) = \begin{Bmatrix} 1 & \omega_{stator}(x) > \omega_{rotor} \\ 0 & \omega_{stator}(x) = \omega_{rotor} \\ -1 & \omega_{stator}(x) < \omega_{rotor} \end{Bmatrix}]$$

P_p may be written as:

$$P_p = 2A\mu_d r \int_0^{x_r} [\cos(kx) - \cos(kx_0)][\omega_{sm}\cos(kx - \omega_r)]dx$$
$$-2A\mu_d r \int_{x_r}^{x_0} [\cos(kx) - \cos(kx_0)][\omega_{sm}\cos(kx - \omega_r)$$

where x_r is a no-slip point, ω_{sm} is for $\omega_{stator\max}$ and ω_r is for ω_{rotor}.

After a series of mathematical operations, P_p can be expressed as:

$$P_p = \frac{\mu_d F_N r}{\phi(x_0)}[2\Phi(x_r) - \Phi(x_0)]$$

where we substituted $\Phi(x)$ for:

$$\Phi(x) = \frac{1}{2}kx\omega_{sm} + \frac{1}{4}\omega_{sm}\sin(2kx) - [\omega_{sm}\cos(kx_0) + \omega_r] \cdot$$
$$\sin(kx) - kx\omega_r\cos(kx_0)$$

$$\phi(x) = \sin(kx) - kx\cos(kx_0)$$

Finally the efficiency may be written as:

$$\eta = \frac{M \cdot \Omega_r}{\frac{\mu_d F_N r}{\phi(x_0)}[2\Phi(x_r) - \Phi(x_0)] + M \cdot \Omega_r}$$

Generally the efficiency of a travelling wave ultrasonic

motor presents values between 35...40%.
In no-load case, the motor will spin at a no-load speed value. But if the load is increasing it can be measured the point where we have the stall torque.
In the case of varying the normal applied force, the no-load speed will change and at a maximum point the rotor will not spin at all.
So, at a maximum value of F_N there is a minimum value of speed. The maximum torque for the motor analyzed (USR 60) is $10Nm$ and the retention torque has the same value.
So, if the motor is powered(excitation voltage) and the stator is pretensioned on the rotor with a normal force, there will be a set of speed-torque operating points at which the motor will function, depending on the load.
As a conclusion, the speed torque curves will depend by the model of the deformation and the friction laws we choose.

Characteristics of TWUSM in load conditions.
As described in technical literature, the ultrasonic motor has non-linear characteristics due the frictional driving.
In order to have the load conditions there has been used precision weights, a torquemeter and digital multimeters.
The results in the case of load conditions are obtained at nominal values (voltage $U = 100V$, phase shift $\varphi = 90^\circ$) using the workbench showed in figure 3.

Figure 3: The workbench for measuring the speed in load conditions.

As we all know, the rotor is pressed on the stator with a normal force to ensure that the friction force between the rotor and the stator.
If the output load is too high, the rotor will start to slip, this thing determines the maximum output torque of the travelling wave ultrasonic motor. Usually an elastic lining material is placed on the rotor to prevent wear.
Thus the rotor speed is lower than the maximum tangential speed. The twusm has a minimum speed below which it blocks.
When the motor is turned off the friction between the rotor and the stator prevents the rotation of its output, the twusm has a holding torque.
Another important thing is that this type of micromachine is non backdriveable.
The results are obtained at nominal values (voltage $U = 100V$, phase shift $\varphi = 90^\circ$) using the workbench shown in figure 3.
Analyzing the figure 4, we observe that for different excitation frequencies $f = 42...44\ kHz$, the characteristics are almost parallel, which means that the effect of load torque can be determinated using a constant speed drop factor.

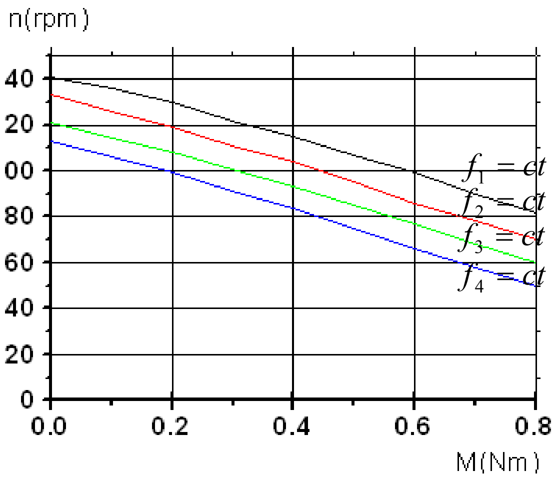

Figure 4: The rotary speed vs. load torque at constant different values of frequency:
$f_1 = 42.08kHz,\ f_2 = 42{,}61kHz,\ f_3 = 43kHz,$
$f_4 = 43{,}67kHz$

The feedback electrode gives also a series of informations about the piezoelectric direct effect, in fact there is a voltage signal (which also can be measured). It is known that the piezoelectric effect refers to the production of an electrical potential when stress is applied.
It is important to know the dependence of amplitude of signal and excitation frequency.
Similarly to measured parameters mentioned, the conditions for this experimental test are: voltage $U = 100V$ and phase shift $\varphi = 90^\circ$).
The feedback voltage-frequency characteristics are given next and it must be told that the linearity is observed which means that there is a constant drop in the amplitude voltage of feedback signal proportional to the load torque (fig. 5).
Next, we examine the influence of load torque if we consider two other parameters of the travelling wave ultrasonic motor. As we mentioned before, the feedback electrode is an element which must be analyzed from many points of view.

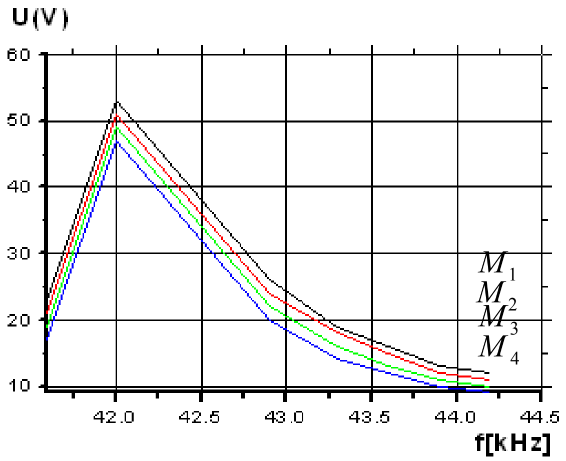

Figure 5: Amplitude of feedback voltage vs. excitation frequency at constant different values of torque: $M_1 = 0Nm, M_2 = 0{,}15Nm, M_3 = 0{,}3Nm$ $M_4 = 0{,}45Nm$

Now, the authors measured the voltages and rotary speed and it has been observed that there is a linear dependency between their values in load conditions (fig. 6).
Similarly to measured parameters mentioned, the conditions for this experimental test are: voltage $U = 100V$ and phase shift $\varphi = 90^\circ$).

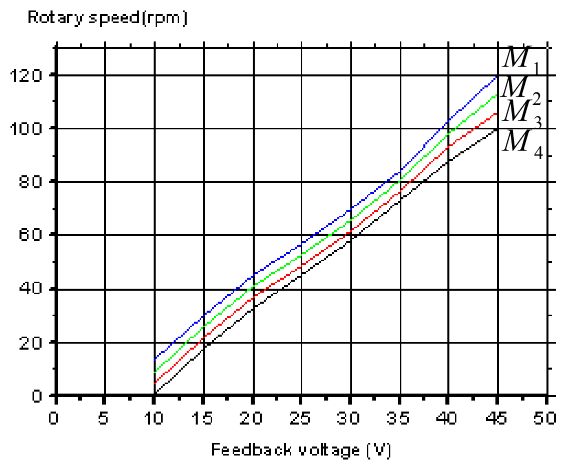

Figure 6: Rotary speed vs. amplitude of the feedback signal at constant different values of torque: $M_1 = 0Nm, M_2 = 0{,}15Nm, M_3 = 0{,}3Nm$ $M_4 = 0{,}45Nm$

3. CONCLUSIONS

In this paper we studied in a short mode, the forces which appear at the contact between stator and rotor at a travelling wave ultrasonic motor.
An ultrasonic motor consists of a rotor and a stator being ultrasonically excited by piezoelectric elements. Ultrasonic vibration produced by the piezoelectrical elements provides the driving force which then drives the motor using friction.
Due to the ample advantage that the ultrasonic motor offers, much research and development have been made in this area.
In the characteristics presented in this paper there has been observed liniarities which means that we can consider a constant drop(if we consider the influence of temperature, it is possible to have different values).
Temperature and friction are main problems of this types of motors.
The feedback electrode gives also a series of informations about the phenomenons whic characterize the function of ultrasonic motor.
In order to obtain precision results, it must be used precision apparatus (torquemeters and dynamometers) because the small values of the measured motor parameters may be easy influenced by the external factors.
These motors have applications domains like robots, precision systems, as a precision actuator in Canon camera, control valves [10, 15, 16, 17, 18, 19, 20, 21].

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