ISTANBUL UNIVERSITY –
**JOURNAL OF ELECTRICAL & ELECTRONICS ENGINEERING**

**YEAR : 2006 (1 - 6)**
**VOLUME : 6**
**NUMBER : 1**

# STUDY ON THE DRIVING MODEL OF ULTRASONIC MOTOR

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## *ABSTRACT*

*The interface contact model between the stator and the rotor of traveling wave ultrasonic motor is presented, assuming that the rigid stator contacts the flexible rotor over an area, and the frictional material is regarded as distributed linear spring and without shearing deformation, from which the mechanical characteristic of the motor and the interface transmission efficiency are derived. And then the effects of the motor's parameters on its performance are investigated, which will be helpful to the design of the ultrasonic motor.*

***Keywords:*** *Ultrasonic motor; Driving model*

## 1. INTRODUCTION

As a novel motor, ultrasonic motors UltraSonic Motors (USM) exhibit advantages over conventional electromagnetic motors. For example, USM can produce a relative high torque at a low speed with a high efficiency, and the torque produced per unit weight is high. Since the frictional force between the stator and the rotor is used to drive the motor, the property of the frictional material and the characteristic of the contact area will govern the motor's working character and operating life. How to increase the frictional force and the transmission efficiency of the contact interface between the stator and the rotor is a key in the study of ultrasonic motor. Establishing the frictional driving model between the stator and the rotor to predicate the motor's output characteristic will be helpful to the USM's design.

Up to now, the analysis about the USM's friction and many conclusions were achieved only based on experiments and tests[1-3]. In 1992, Maeno, etc. employed FEM to calculate the motor's mechanical characteristic, in which, static friction coefficient and kinetic one were used to introduce the shear deformation of the contact layer[4,5]. After then, they adopted LDA to measure the dynamic tangential and normal displacement of the particles in the contact area[6]. Nesbitt presented energy analysis model by introducing a symbolic function, which express the relationship of the relative velocity of the stator/rotor particles among the contact area.

The USM's torque is produced by the friction between the stator and rotor. Under certain driving voltage and preload, the motor has different speed with different load, which characteristic is one of the basic characteristics. In this paper, the contact mechanism between the stator and rotor is analyzed, the torque and the

*Received Date : 18.02.2004*
*Accepted Date: 09.12.2005*

conversion efficiency of the contact area are deduced, and the effects of the motor's parameters on its performance are investigated, which will be helpful to the design of the motor.

## 2. THE MECHANICAL CHARACTERISTIC OF ULTRASONIC MOTOR

The traveling wave ultrasonic motor consists of stator, which generates traveling wave, and rotor, under which adhered frictional material. The traveling wave on the surface of the stator drive the rotor through tangential force. Among the contact area between the stator and rotor, the frictional material deforms due to the preload. When the rigid stator contacts the compliant rotor, the waveform of the stator does not change, as shown in Fig.1. To analyze the drive mechanism through the frictional force, the frictional material is regarded as distributed linear spring [7], and the mechanical characteristic of the motor is derived on this basis.

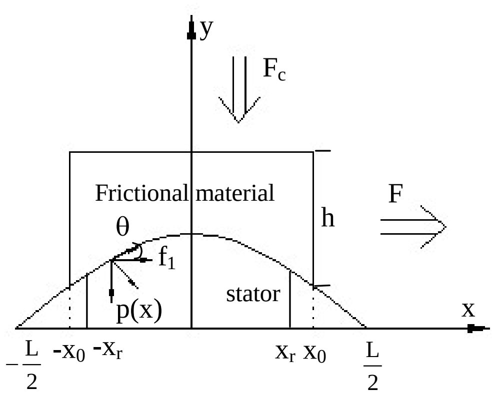


***Fig.1. Contact model of stator and rotor***

Taking no account of shearing deformation of the frictional material, a simplex slide friction exists between the stator and rotor. Introducing one piece of ceramic, that is half wavelength (L), to analyze the tangential force produced by the stator.

Fixing the coordinate to the stator, the longitudinal displacement of the stator under forced vibrations can be expressed by:

$$u_y = A_m \cos\frac{\pi}{L}x = A_m \cos kx \quad (1)$$

where $k = \frac{\pi}{L}$ is wave number.

When the preload applied to half wavelength of the rotor is $F_c$, and according to Fig.1, the pressure gained by the rotor within the contact area per length will be:

$$p(x) = k_f A_m (\cos kx - \cos kx_0) \quad (2)$$

where,

$k_f = \frac{E_f}{h}$ is the elastic coefficient of the frictional material

Ef Young's modulus of the frictional material

h the thickness of the frictional material

2x0 the contact width of the stator and rotor within half wavelength circumferential

Therefore, the preload can be written as:

$$F_c = b\int_{-x_0}^{x_0} p(x)dx = \frac{2bE_f A_m}{h}\left(\frac{1}{k}\sin kx_0 - x_0 \cos kx_0\right) \quad (3)$$

where, b is the width of the contact area, and contact length x0 is the function of preload Fc.

According to coulomb model and Fig.1, the tangential force per length applied by the particles on the surface of the stator to the rotor is:

$$f_1 = \mu_d \, p(x)\cos^2\theta \quad (4)$$

where, $\mu_d$ is the dynamic frictional coefficient between the stator and frictional material, $\theta = \frac{\partial u_y}{\partial x}$ is inflection angle.

Since the $\theta$ is very small, and $\cos\theta \approx 1$, equ (4) can be rewritten as:

$$f_1 = \mu_d \, p(x) \quad (5)$$

The rotor slides on the surface of the stator. When a particle on the surface of the stator has a tangential speed greater than that of the rotor, it push the rotor. Otherwise, it drags the rotor. So the tangential force applied by the stator to the rotor is:

$$F = b\int_{-x_0}^{x_0} sign[\upsilon_s(x) - \upsilon_r] f_1 dx \quad (6)$$

where $\upsilon_s(x)$ is the speed of the particle on the surface of the stator, $\upsilon_r$ is the rotor's speed and sign(x) symbol function.

The tangential speed $\upsilon_s(x)$ is:

$$\upsilon_s = \frac{\partial u_x}{\partial t} = -h_c \frac{\partial^2 u_y}{\partial t \partial x} = \upsilon_{sm}\cos(\omega t - kx) \quad (7)$$

where,

$$\upsilon_{sm} = kA_m h_c \omega \quad (8)$$

is the amplitude of $\upsilon_s$, $\omega$ is the angular velocity of the vibration, $h_c$ the distance between the upper surface and the interface plane of the vibrator ring, which is the function of the stator's dimensions.
At one moment, the tangential speeds of the particles are:

$$\upsilon_s = \upsilon_{sm} \cos kx \quad (9)$$

Substitute equ(5), (9) into equ(6), we will get:

$$F = 2b\int_0^{x_0} sig[\upsilon_s(x) - \upsilon_r] f_1 dx = 2b\int_0^{x_r} f_1 dx - 2b\int_{x_r}^{x_0} f_1 dx$$

$$= \frac{2b\mu_d E_f A_m}{h} \cdot \left(\frac{2}{k}\sin kx_r - 2x_r \cos kx_0 - \frac{1}{k}\sin kx_0 + x_0 \cos kx_0\right) \quad (10)$$

where, $x_r$ is the horizontal coordinate of a particle on the surface of the stator which speed is equal to the rotor's speed.
Therefore:

$$\upsilon_r = \upsilon_{sm} \cos kx_r \quad (11)$$

and $$x_r = \frac{1}{k}\cos^{-1}\frac{\upsilon_r}{\upsilon_{sm}} \quad (12)$$

The motor's output torque is:

$$T = F \cdot r \quad (13)$$

where $r$ is the radius of the contact region.
The input power from the vibrator to the rotor is:

$$P_{in} = 2b\int_0^{x_0} sign[\upsilon_s(x) - \upsilon_r] f_1 \cdot \upsilon_s(x) dx$$

$$= \frac{2bE_f \mu_d A_m \upsilon_{sm}}{h}\left[(x_r - \frac{1}{2}x_0)\right.$$

$$\left. + \frac{1}{4k}(2\sin 2kx_r - \sin 2kx_0) - \frac{1}{k}\cos kx_0(2\sin kx_r - \sin kx_0)\right] \quad (14)$$

and the motor's output power:

$$P_{out} = F \cdot \upsilon_r \quad (15)$$

So we can get the conversion efficiency of the contact surface.

$$\eta = \frac{P_{out}}{P_{in}} \quad (16)$$

We can find in Fig.1 that the particles inside the region of [-$x_r$ $x_r$] will push the rotor for their speeds are greater than that of rotor, whenas the particles within the regions of [-$x_0$ -$x_r$] and [$x_r$ $x_0$] will drag the rotor for their speeds are less than that of rotor. So there must be one point $x_{r0}$ within the contact area, at which the pulling force equals to the dragging force and the motor's output torque is zero:

$$2b\int_0^{x_{r0}} f_1 dx = 2b\int_{x_{r0}}^{x_0} f_1 dx \quad (17)$$

When $x_r$ equals to $x_0$, since the speeds of whole particles within the contact area are greater than that of rotor, and the push force reaches its maximum, the corresponding torque is the maximum under certain preload.

$$T = \frac{2b\mu_d E_f A_m}{h} \cdot \left(\frac{1}{k}\sin kx_0 - x_0 \cos kx_0\right) \cdot r = \mu_d F_c r \quad (18)$$

From this equation, we can conclude that the maximal torque is proportional to preload and dynamic frictional coefficient. When the preload reaches a certain value that makes $x_0 = L/2$, the maximal torque obtained at this preload is the one that this motor can gain. Let $x_0 = L/2$ in equ(18), we can derive the motor's maximal torque:

$$T_{\max} = \frac{2b\mu_d E_f A_m}{kh} \cdot r \quad (19)$$

And the preload which makes $x_0 = L/2$ is what the motor can be applied:

$$F_{c\max} = \frac{2bE_f A_m}{kh} \quad (20)$$

Thus it can be seen from above equations that bigger Young's modulus of frictional material, wider width of contact area, higher dynamic frictional coefficient contribute bigger torque.

## 3. THE INFLUENCES OF THE MOTOR'S PARAMETERS TO ITS PERFORMANCE

To find the qualitative relationship between the motor's parameters and its performance, some simulations are carried out based on above equations. The motor's parameters are given in Table1, and the simulation results are shown from Fig.2 to Fig.7.

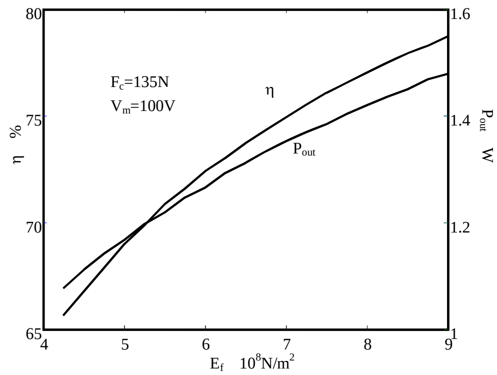


***Fig.2 relations of maximal output power and maximal efficiency to $E_f$***

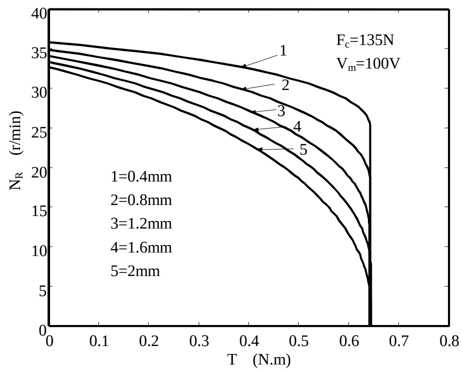


***Fig.3 mechanical characteristics with different thickness of frictional material.***

***Table 1 main specifications of the traveling wave ultrasonic motor***

| | |
|---|---|
| Outer diameter: 80mm | Inner diameter 60mm |
| Thickness of the vibrator: 6mm | Thickness of PZT: 1mm |
| Width of the vibrator: 10mm | Width of PZT: 10mm |
| Young’s modulus of the vibrator: | Young’s modulus of PZT: $7.5\times10^{10}$ N/m$^2$ |
| Shear modulus of the vibrator: | Shear modulus of PZT: $2.8\times10^{10}$ N/m$^2$ |
| Density of the vibrator: $8.5\times10^3$kg/m$^3$ | Density of PZT: $7.5\times10^3$kg/m$^3$ |
| Deepness of the groove: 2.3mm | Width of tooth: 1mm |
| Amplitude of driving voltage: 100V | Piezoelectric strain constant $d_{31}$: $1.23\times10^{-10}$m/V |
| Number of teeth: 72 | Vibration mode: 9 |

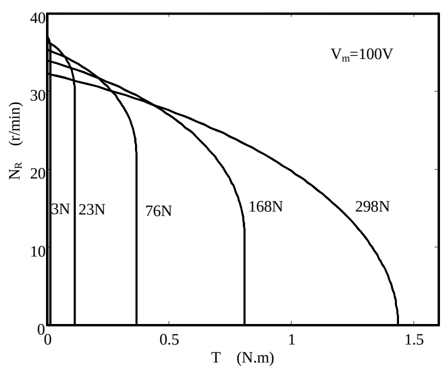


***Fig.4 mechanical characteristics under different preload***

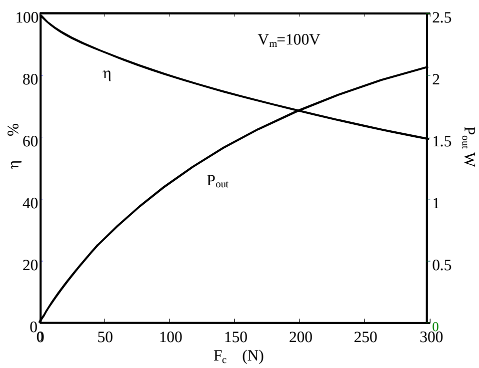


***Fig. 5 relations of maximum efficiency and maximum output power to preload***

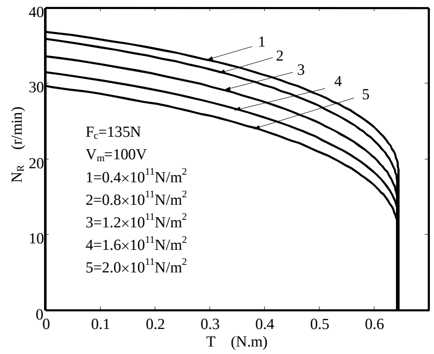


***Fig.6 relationship between the vibrator's Young's modulus and the motor's mechanical characteristics***

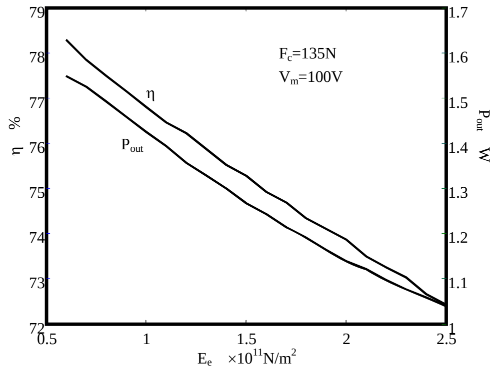


***Fig.7 relations of maximum efficiency and maximum output power to the vibrator's Young's modulus***

## 4. CONCLUSIONS

Therefore, we can draw some conclusions from above analysis that:

(1) The mechanical characteristics of USM is similar to electromagnetic motor, but it is more soft;

(2) The Young's modulus of the frictional material influences the motor's performance greatly. Bigger Young's modulus leads more output power and higher efficiency;

(3) The increasing of preload results in the increasing of contact angle, maximum torque and maximum output power, but the decreasing of runaway speed and efficiency;

(4) The thinner of the frictional material, the better of the mechanical characteristics and the higher runaway speed;

(5) The motor's maximum torque is constant under certain preload.

(6) The bigger of vibrator's Young's modulus and rigidity, the less of runaway speed, maximum torque and efficiency.

Therefore, it is better to use the vibrator with less Young's modulus and thinner frictional material with bigger Young's modulus. As to the preload, it is necessary to balance the weights of torque, runaway speed and efficiency.

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