CHARACTERISTICS ESTIMATION OF TRAVELLING-WAVE ULTRASONIC MOTOR USING EQUIVALENT CIRCUIT MODEL

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ABSTRACT

The estimation of ultrasonic motor characteristics as a function of input parameters, such as the voltage amplitude and driving frequency and as a function of operating conditions, such as load torque and temperature is so important for control of ultrasonic motors. This paper deals with an equivalent circuit model of travelling-wave ultrasonic motor and its application to the estimation of motor characteristics. The performance of ultrasonic motor under different speed and load conditions has been obtained in a systematic approach from proposed method in this study.

I. INTRODUCTION

Ultrasonic motor (USM) is newly developed an actuator that uses mechanical vibrations in the ultrasonic range as its drive source. USMs have important features such as high holding torque, high torque at low speed, compact size, silent operation and no electromagnetic noise [1]. The torque of USM is 10 to 100 times larger than the conventional electromagnetic motors of same size or same weight [2]. Due to the features mentioned above, USMs have recently begun to be used for industrial, medical, robotic, space and automotive applications.

However it is difficult to derive complex mathematical and the lumped models of USMs. Moreover, the control characteristics of USMs are complicated and highly non-linear. The exact values of motor parameters are difficult to obtain and the motor parameters are time-varying due to increase in temperature and changes in motor drive operating conditions such as driving frequency, source voltage and load torque [3-8].

How the performances are affected by operating conditions mentioned above is an important subject for the high effectiveness applications and the control of USMs [9]. Several theoretical and experimental studies have been reported recently [10-15]. Three methods have proposed to estimate motor characteristics. The first one is finite element method, where no electrical parameters are considered. The second is energy conversion method, which is too complicated to estimate motor characteristics under different driving frequencies. The third one is equivalent circuit model. If there is a sufficiently applicable equivalent circuit model (ECM) for expression of practical operations of the USMs, it will be very useful for the design and the estimation of motor characteristics [16].

The purpose of present study is to propose an ECM for the estimation of the motor characteristics under different input parameters. The ECM based on Shinsei's travelling-wave type USR60 USM is derived. Then, the characteristics of USM, provided from ECM, are reported for different working conditions. To make precise control these characteristics should be taken in consideration.

II. EQUIVALENT CIRCUIT MODEL (ECM)

ECM of USM is based on the piezoelectric elements and mechanical vibration system given in Fig. 1. When the piezoelectric elements are excited by an electrical supply with ultrasonic frequency, an ultrasonic vibration is produced in mechanical vibration system, composed of rotor and stator. The stator amplifies the mechanical vibrations and transmits them as a driving force to the rotor.

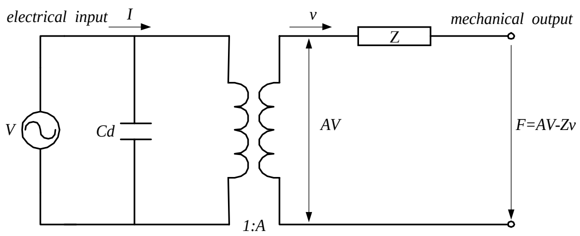

Fig. 1. Equivalent circuit of piezoelectric system

According to the electromechanical conversion theory of this system the following equations can be written [1],

$$F=AV-Zv \qquad (1)$$

$$I=Y_d V+Av \qquad (2)$$

$$Y_d=1/j\omega C_d \qquad (3)$$

Where,
A = force factor
F = force at mechanical terminal
v = velocity at the mechanical terminal
I = the current at the electrical terminal
Z= the mechanical impedance of piezoelectric ceramic
Y_d = the damping admittance of piezoelectric ceramic
C_d= the damping capacitance of piezoelectric ceramic

Force factor can be obtained from piezoelectric equations of ceramics as follows;

$$A=bd_{31}Y_{11} \qquad (4)$$

Where,
b = the width of piezoelectric ceramic
d_{31} = piezoelectric strain constant
Y_{11} = Young's modulus of piezoelectric ceramic

It should be known that the force factor is generally determined not only by the dimensions and properties of the piezoelectric ceramic, but also by the properties of the metal plate which is assembled with ceramic[1]. The electromechanical behaviour of a piezoelectric ceramic can be modelled by means of equivalent circuit as illustrated in Fig 2.

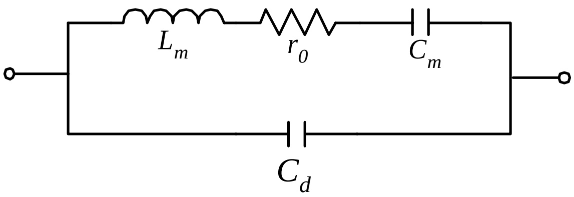

Fig. 2. Equivalent circuit model of piezoelectric ceramic

In Fig 2, L_m, r_0 and C_m is respectively equivalent inductance, equivalent resistance and equivalent capacitance. C_d was measured 9nF for each phase of USR60 USM.

$$L_m=\frac{m}{A^2}, \qquad r_0=\frac{r}{A^2}, \qquad C_m=\frac{A^2}{s} \qquad (5)$$

Where, m = mechanical mass, r = mechanical resistance, s = stiffness. Resonance frequency of equivalent circuit is,

$$f_r = 1/2\pi\sqrt{LC} = \sqrt{K/m}\ /2\pi \qquad (6)$$

In a complex notation, the damping admittance and the motional admittance are written by,

$$Y_d=1/\mathrm{j}\omega C_d \qquad (7)$$

$$Y_m=\frac{1}{(r_0+j\omega L_m+1/j\omega C_m)} \qquad (8)$$

$$Y_m=\frac{r_0}{r_0^2+(\omega L_m-1/\omega C_m)^2}+j\frac{1/\omega C_m-\omega Lm}{r_0^2+(\omega L_m-1/\omega C_m)^2}$$

A current causes rotation of USM is called as a motional current which is determined by,

$$I_\mathrm{m}= V\times Y_m \qquad (9)$$

Relation between vibration velocity (mm/s) and motional current is found as follows,

$$v=I_m/A \qquad (10)$$

Finally the rotary speed of USM is,

$$\omega_r= v/R \qquad (11)$$

where, ω_r = rotary speed of USM (rad/s), R = radius of USM.

Travelling-wave

To generate a travelling-wave within the stator, it is necessary to control two mechanical orthogonal modes A and B. Electrode pattern A provides the $\cos k\theta$ and pattern B provides the $\sin k\theta$ mode. By driving these two modes 90° out phase temporally, a travelling-wave with f frequency is produced [15].

$$\cos k\theta\cos\omega t+\sin k\theta\sin\omega t=\cos(\omega t-k\theta) \qquad (12)$$

The speed of travelling-wave can be expressed mathematically as follows,

$$\varpi(r,\theta,t)=R_r A\cos(\omega t-k\theta) \qquad (13)$$

$$\frac{d\varpi}{dt}=-\omega R_r A\sin(\omega t-k\theta) \qquad (14)$$

$$v=\omega R_r A \qquad (15)$$

Where, $\varpi(r,\theta,t)$ = the speed of travelling-wave
R_r = radial shape factor of stator
k = wave number of stator

k=9 for USR60 USM. Using vibration velocity of stator (Eqn. 15), the speed of travelling-wave is written as

$$\frac{d\varpi}{dt}=-v\sin(\omega t-k\theta) \qquad (16)$$

By changing the sign one of the drive signal, the direction of the travelling-wave and thus the direction of rotor reverses.

Complete motor
When rotor pressed against the stator with a normal forcing (160N for the motor given in appendix), frictional losses occur between the rotor and stator. These losses are represented by friction in final ECM. Also, the effect of the temperature that take place within the body of the stator are introduced in final ECM. Due to the internal losses and friction at rotor-stator interface, working temperature of USM increases. This causes an increase of the C_m and C_d. So the mechanical resonance frequency of USM decreases. As a result, the rotary speed of motor decreases if the motor is powered at a fixed driving frequency. In this study, temperature-resonance frequency and temperature-time characteristics of NEPEC'61 piezoelectric ceramic, used in USR60 USM, are integrated in ECM.

Finally, the load torque and others due to pressure, temperature and friction are added to stator's equivalent circuit as shown in Fig. 3.

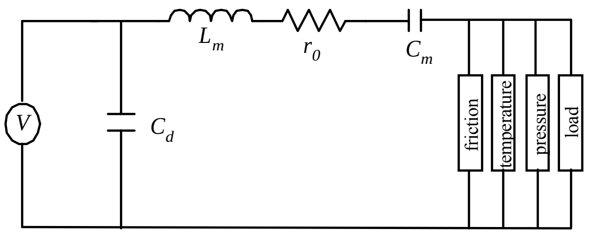

Fig. 3. Final ECM of USM

III. SIMULATION RESULTS

Fig. 4 shows relation between driving frequency and rotary speed. Speed-frequency characteristic of USM is not linear. In practice applications speed of USM is controlled in 40-42.5 kHz frequency range.

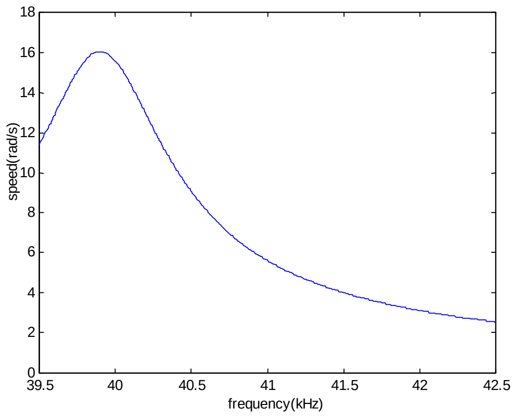

Fig. 4. Speed-frequency characteristic of USM

Fig. 5 shows speed-frequency characteristics of USM under different load torques. Rotary speed decreases as the load torque increases.

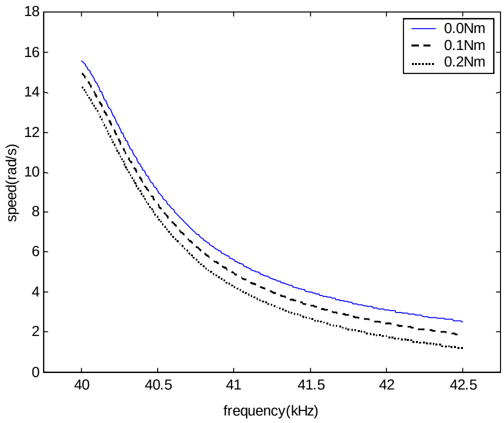

Fig. 5. Speed-frequency characteristics of USM under different load torques

As mentioned above, variations in driving frequency changes speed of USM. Fig. 6 represents speed-torque characteristics of USM for various driving frequencies. Load torque is changed between no load and rated torque (0-0.32Nm).

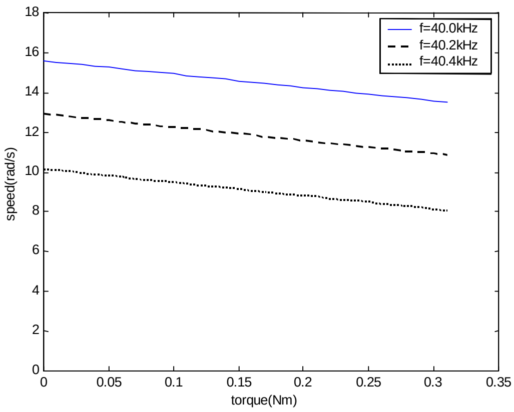

Fig. 6. Speed-torque characteristics of USM under different driving frequencies

As previously described, the mechanical resonance frequency of USM decreases due to temperature increases within the body of stator. Speed-frequency characteristics of USM under different working temperature are given in Fig. 7. As seen from this figure, resonance frequency of USM shifts towards left depending on increase in temperature.

Operating temperature inherently increases in time. Fig 8 shows temperature dependent speed characteristics of USM, varied in accordance with time. It is evident that speed of motor decreases according to the time dependent temperature rises.

Fig. 9 represents speed-time characteristic of USM with applied step-wise loading torque. As expected the motor speed decreases as load torque increases.

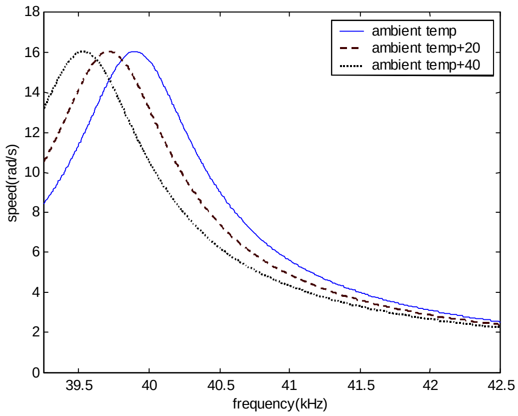

Fig. 7. Speed-frequency characteristics of USM under different working temperatures

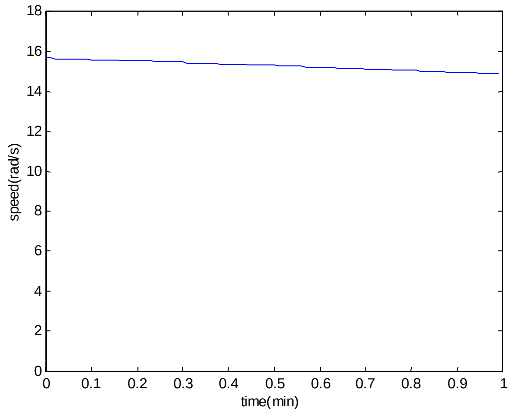

Fig. 8. Speed-time characteristic of USM

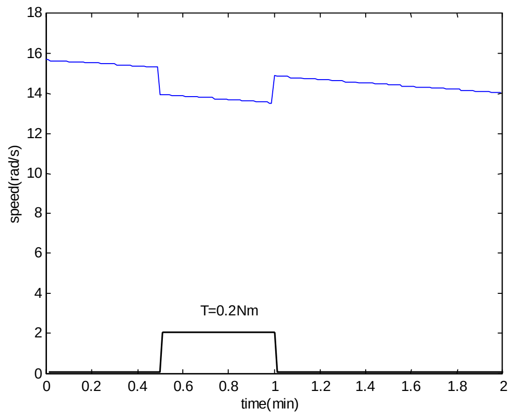

Fig. 9. Speed-time characteristic of USM under applied step-wise torque (for t>0.5 and t<1, T=0.2Nm)

Speed of USM is also changed by applied voltage. Fig. 10 represents speed-frequency characteristics of USM under different applied voltages.

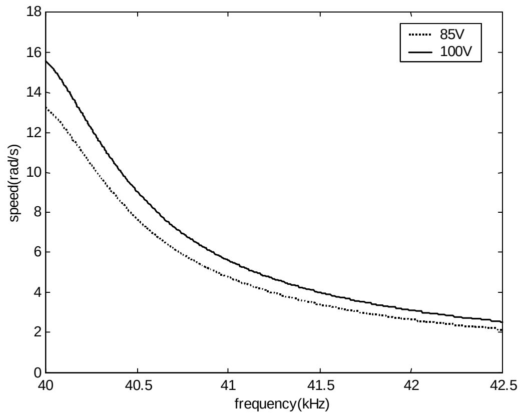

Fig. 10. Speed-frequency characteristics of USM for various applied voltages

When speed characteristics of USM compared according changes in driving frequency and applied voltage, it is clear that speed control of USM with driving frequency is much considerable than the supply voltage. In other words, the speed of USM doesn't change in widely range with supply voltage as changes with driving frequency.

IV. CONCLUSION

In this paper, an equivalent circuit model of travelling-wave type USR60 USM is derived and the characteristics obtained from this model are reported. The model based on specifications of piezoelectric ceramic (NEPEC-61) and electrical inputs such as voltage and driving frequency.

The effect of the temperature on the mechanical resonance frequency, in other words time varying temperature effect on the motor speed, is integrated in ECM. Furthermore, the effects of driving frequency, load torque and applied voltage are identified.

It should be noted that to make precise control of USM, working characteristics so important. By using the ECM developed in this paper, a systematic approach is achieved for the estimating performances of USM.

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Appendix

Design specifications of Ultrasonic Motor (USR60 USM)

Driving frequency	40kHz
Driving voltage	100Vrms
Rated torque	0.32Nm
Rated output power	4W
Rated speed	10rad/s
Weight	230g