Torque Characteristics Analysis of a Traveling Wave Type Ultrasonic Motor Impressed High Load Torque in Low Speed Range

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***Abstract*— As an alternative to an electromagnetic motor, a rotary traveling wave type ultrasonic motor (USM) has been attracted considerable attention. The rotary traveling wave type is more commonly used in industrial applications. In this paper, the USM impressed high load torque in low speed range is modeled using an equivalent circuit and a new torque control method is proposed to implement for a robot manipulator.**

Firstly, the USM is modeled using the equivalent circuit based on a piezoelectric equation and a mechanical model. In mechanical approach, the ratio of vibration speed of the vibrator to rotational speed of the rotor is assumed as 1: n, where n is a smaller variable than 1. According to this proposed equivalent circuit, if vibration amplitude of the vibrator is constant, output torque is proportional to voltage magnitude applied to piezoelectric ceramics and rotational speed of the rotor. Secondly, three parameters of two sinusoidal voltages: frequency, magnitude and phase difference are determined to control output torque. Finally, an experiment is conducted to verify the equivalent circuit model. Experimental results show that output torque of the USM is proportional to applied voltage magnitude. Therefore, the proposed model is shown to be valid and will be applied to robot manipulators.

Keywords-ultrasonic motor; traveling wave type; torque control; equivalent circuit; vibration amplitude

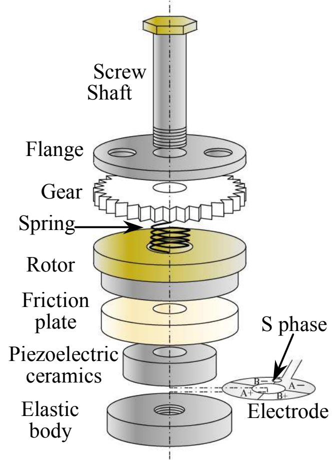

Fig.1 MicroUSMⅡ whole assembly

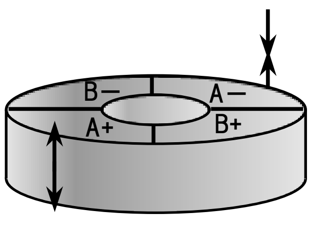

Fig.2 Polarization pattern of piezoelectric ceramics

I. Introduction

In recent years, electromagnetic motors are applied to most industrial machines such as robot manipulators and position control devices. Electromagnetic motors generate low torque and are energy efficient in high-speed range. When the motor is set in robot manipulators, a gearbox is required to maintain high driving torque at low speed. However the gearbox makes it difficult to miniaturize mechanical apparatuses and to achieve high accuracy due to backlash.

As an alternative to the electromagnetic motor, the ultrasonic motor has been attracted considerable attention. The USM is suitable to a direct-drive mechanism that makes it possible to solve several problems, because it generates high torque and is energy efficient in low speed range. Due to the features of flexible free form and high holding torque caused by frictional force, it is preferable that the USM is used as an actuator in specific devices that require miniaturization and low power consumption. Furthermore, the USM drives silently and does not generate electromagnetic noise, so it can be used in medical devices running in strong magnetic field. In fact, the USM will be applied to specific mechanical apparatus, e.g. a miniature manipulator impressed high load torque at low speed in strong magnetic field.

J. Maas and P. Ide et al reported the traveling wave type USM modeled using an equivalent circuit [1]. In their report, they assumed piezoelectric effect and resonance curve as a linear phenomenon. However, in fact, the characteristics of piezoelectric ceramics vary with temperature itself. And resonance frequency of the vibrator also varies with load

Table I Specification of Micro USMⅡ

Size	ϕ11×14mm
Weight	4.7g
Natural frequency	56-57kHz
Rotor diameter	ϕ10
Maximum torque	10.8mNm
Revolution speed with no load	625rpm

torque. Y. Kyodo reported torque control analysis based on the concept of an equivalent circuit and mechanical internal resistance, but experimental results appear to be correspondent to his concept only in case that the USM is impressed low load torque [2]. Thus conventional approaches are lack of adequate consideration of characteristics changes, especially effects of load torque on the resonance. To apply the USM in torque control devices running with high load torque at low speed, a new model and control method of the USM are required.

In this paper, the USM is modeled using an equivalent circuit based on electromechanical conversion theory. In addition, a new concise rotor/vibrator contact model is proposed. A torque control method is developed based on the equivalent circuit model. A torque control experiment in which the USM is impressed high load torque in low speed range is conducted to verify the proposed method. Finally, the conclusions and future works are briefly discussed.

II. Driving Mechanism

The traveling wave type USM (Micro USM II) used in the experiment described in chapter 5 is shown in Fig. 1. Specifications of Micro USM II are shown in Table I. The USM consists of an elastic body, an electrode, piezoelectric ceramics, a friction plate, a rotor, a coil spring, a gear, a flange and a screw shaft. The elastic body, the electrode, piezoelectric ceramics and the friction plate compose a vibrator. Piezoelectric ceramics is polarized into quarters in radius direction as shown in Fig. 2. There are two counter-polarizations: + and - in A phase. So are there in B phase.

When two sinusoidal voltages are supplied in each phase with phase difference, two orthogonal vibration modes are excited to resonance by piezoelectric ceramics. If two sinusoidal voltages have any phase difference, the vibrator synthesizes a traveling wave on the friction plate with vibrating at resonance frequency as shown in Fig.3. The rotor contacting the vibrator on the crest of the traveling wave under pressure of the coil spring is driven by frictional force. Driving force is transmitted to the gear rotating with the rotor.

III. T-N Characteristics

As described ever, The USM has non-linear characteristics due to the friction driving and so on. T-N characteristics are measured using Micro USM II to comprehend how is the non-linear characteristics and the results are shown in Fig.4. In the Fig.4, T-N characteristics are shown in case frequency, magnitude and phase difference of two sinusoidal voltages are respectively from 57.6kHz to 58.4 kHz every 2 kHz, 15Vp-p and 90deg. At low load torque, every curve is likely linear. However at high load torque, every curve is non-linear and rotational speed seem to steeply become small. Fig. 4 can be divided into three ranges: high-speed range with low load torque (Area I) and low speed range with high load torque (Area II) and the other. All of the USM are usually unlike to be used in Area II for the reason that the driving life gets to be shorter. However, the driving life of Micro USM II is highly longer because it has the friction plate whose face does not get bad quickly. In fallowing chapter, a new model and control method are represented to control torque of Micro USM II.

IV. Equivalent Circuit Model

As one example of the USM that has piezoelectric ceramics as an actuator, firstly, Micro USM II is modeled using an equivalent circuit based on a piezoelectric equation and mechanical model. Based on electromechanical conversion theory, the piezoelectric effect is expressed as

$$F = AV + Zv \tag{1}$$

$$I = Y_d V + Av \tag{2}$$

where, F is a force in z direction, A is a force factor ,V is voltage applied in piezoelectric ceramics, Z is mechanical impedance, v is vibration speed in z direction, I is current flows in piezoelectric ceramics, Y_d is admittance of piezoelectric ceramics as a dielectric. The two equations (1), (2) are called piezoelectric equation [3]. Features such as the form and the dielectric constant of piezoelectric ceramics define the force factor A.

The vibrator is modeled in the equivalent circuit shown in Fig.6. In the equivalent circuit model, piezoelectric ceramics is expressed condenser capacity C_d. Inductance L_m, condenser capacity C_m and resistance R_m are respectively equivalent mass, equivalent spring and equivalent resistance. F is a driving force to be transmitted to the rotor and the external spring. Two conversion equations are derived as

$$Z = R_m + \left(\omega L_m - \frac{1}{\omega C_m}\right)j \tag{3}$$

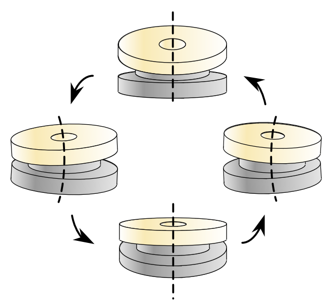

Fig. 3 Vibration mode of Micro USM II

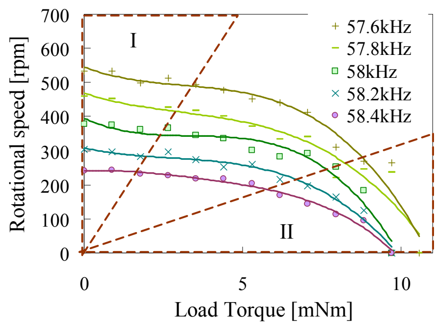

Fig. 4 T-N characteristics of Micro USM II

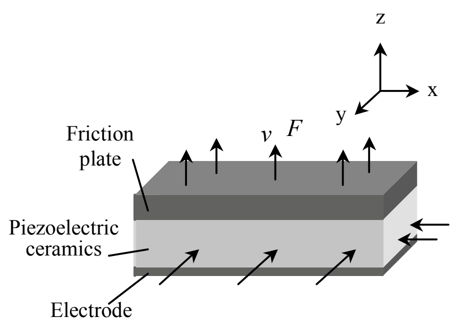

Fig.5 Piezoelectric effect

$$Y_d = j\omega C_d \tag{4}$$

where, j is imaginary unit and ω is angular velocity of the following applied sinusoidal voltage.

$$V = V_0 \sin \omega t \tag{5}$$

To deduce how the force F is physically converted to output torque of the rotor, a mechanical model of Micro USM II is introduced as shown in Fig.7. Energy by the force F converts elastic energy of two springs connected in serial between the vibrator and the flange, frictional loss and driving energy of the rotor. Hence, we obtain the equivalent circuit model in which condenser C_L equivalent to the two springs, resistance R_F equivalent to the frictional force and the voltage equivalent to the driving force of the rotor are connected in parallel as shown in Fig.8. The rotor is driven by frictional force in crosswise direction in Fig.7. In this regard, n % of the force F is transmitted to the driving force of the rotor. In other words, the ratio of vibration speed of the vibrator to rotational speed of the rotor is assumed as 1: n, where n is a smaller variable than 1. The following equation is obtained.

$$v = YF + n\omega_r \tag{6}$$

where,

$$Y = j\omega C_L + R_F \tag{7}$$

is used to discussed easily. When substituting the equation (6) to the equation (1),

$$F = \frac{AV + Zn\omega_r}{1 - ZY} \tag{8}$$

are obtained. If impedance Z and admittance Y are constant, the force F is proportional to voltage V.

We advance concrete discussions on what condition should be assumed to keep impedance Z and admittance Y constant. L_m, C_m and C_L are not absolutely variable. If ω is known in advance, R_m and R_F should be constant. It is realized on the condition that the vibration amplitude is constant because frictional loss is changeable due to dynamics of vibration. Besides, the force F is proportional to vibration speed ω_r if n is constant.

The equivalent circuit model of the rotor is shown in Fig.8. Inductance L_r and resistance R_r represent respectively equivalent mass and frictional loss of the rotor. We obtain

$$nF = (j\omega L_r + R_r) \cdot \omega_r + Load \tag{9}$$

where, $Load$ is equal to output torque of the USM.

In the following chapter, we describe an experiment to verify the equivalent circuit model and the formula indicating relationship between voltage V and vibration speed ω_r.

V. Equivalent Circuit Model

A. Experimental Setup

An experiment is carried to verify the equivalent circuit model and the equation (8). We produce an experimental apparatus as shown in Fig.9. This apparatus is composed of a gear, a rotary optical encoder and a torsion spring, which are set on the same shaft. The gear meshes with the gear of Micro USM II and drives the shaft. The encoder rotates with the shaft. One end of the torsion spring is attached on a supporting plate. The other end is attached on the shaft. When Micro USM II rotates the other end, the torsion spring generates restoring torque and stops rotating on an equilibrium state of restoring torque and the output torque of Micro USM II. The rotation angle of the torsion spring is proportional to output torque and so output torque is measured by means of counting pulses of the encoder. Resolution of the encoder is 2000 pulses per revolution. Two sinusoidal voltages are supplied via amplifiers from oscillators to Micro USM II.

B. Results

In this section, we describe experimental condition and results. Firstly, experimental condition is determined to confirm that the force F is proportional to voltage V based on the condition described in previous chapter. There are three parameters of the sinusoidal voltage. Phase difference of two sinusoidal voltages is 90 deg to keep the driving efficient. Frequency of two sinusoidal voltages is appropriately modulated to keep vibration amplitude constant. Vibration amplitude is measured from a sensor attached on the electrode as shown in Fig.1 using an oscilloscope. On this condition output torque is measured with changing magnitude of two

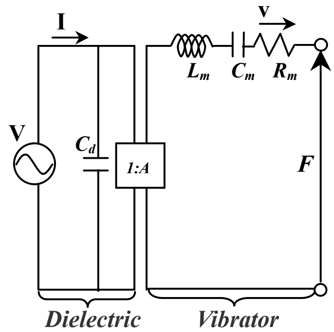

Fig. 6 Equivalent circuit (a)

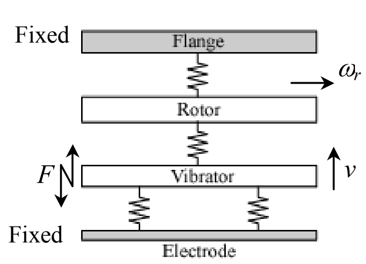

Fig.7 Mechanical model of traveling-wave- type USM

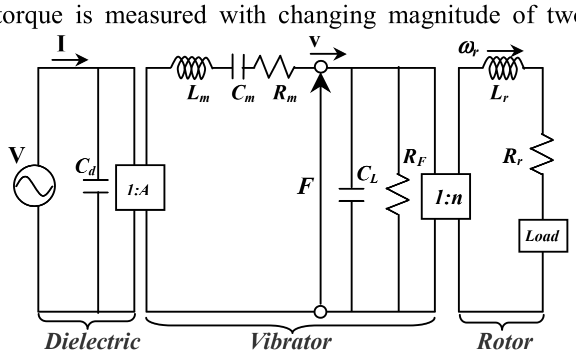

Fig. 8 Equivalent circuit (b)

sinusoidal voltages. Rotational speed is 0 to indicate simply validity of the equivalent circuit model in this experiment.

Secondly, Experimental results are shown in Fig.10. There are results in the case that magnitude of the two sinusoidal voltages is 2Vp-p, 3Vp-p and 4Vp-p respectively. Average squared errors and linear approximation formulas are also shown in Fig.10. As shown in Fig.10, output torque appears to be proportional to magnitude of the sinusoidal voltage. Three lines have the almost same gradient. However, we cannot neglect that output torque seem to have nonlinear terms in the case that magnitude of the two sinusoidal voltages is 3Vp-p and 4Vp-p. It is thought to be aftereffects of jarring of the experimental apparatus or anything. We should solve this problem but are almost certain that the equivalent circuit model is valid.

VI. Control Method

This section introduces control method for torque control of the USM. Torque control method is developed based on the equation (8) whose validity is confirmed on the experiment. Principles of the method are simple. The vibration amplitude is kept constant. Magnitude of the two sinusoidal voltages is controlled in accord with a value calculated from output torque and rotational speed.

A block diagram of the control method is shown in Fig.11. The voltage magnitude of the sensor indicating vibration amplitude is fed back and an error between this value and desired magnitude of the voltage of the sensor is taken to the oscillation controller. Frequency of the sinusoidal voltage is appropriately modulated to keep this taken error zero. For example, PID controller is suite to follow the desired value rapidly. Phase difference of the applied sinusoidal voltage is 90 deg because of described above reason. Magnitude of the applied sinusoidal voltage is fed back to the oscillation controller. And an error between this value and a desired magnitude of the applied sinusoidal voltage calculated from a desired torque and rotational speed of the rotor in a voltage controller is taken to the oscillation controller. Two sinusoidal voltages are generated as frequency, magnitude and phase difference is respectively determined.

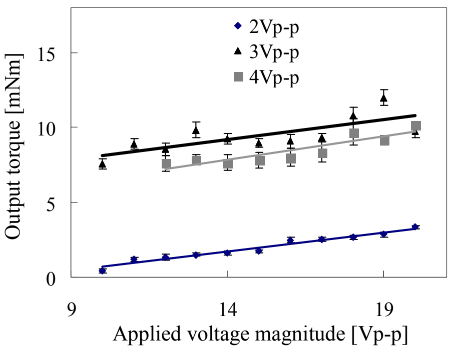

Fig.10 Output torque vs. applied voltage magnitude

VII. Conclusions and Future Works

The equivalent circuit model of a rotary traveling wave type ultrasonic motor impressed high load torque in low speed range is proposed, and is shown to be valid in this experiment. This model is also shown to have suitable characteristics for torque control. Finally, a new torque control method is proposed based on results derived in this paper.

Further, we will conduct an experiment adding a condition that the rotor rotates to make the proposed model more valid. Controlling system of the proposed control method will be setup using field programmable gate array (FPGA) and digital signal processor (DSP) which rapidly process complex tasks in real time. A controller with FPGA and DSP is suitable to a motor driver [4]. In the future, this proposed control method would be implemented to applications described in the chapter 1, e.g. a robot manipulator impressed high load torque in low speed range.

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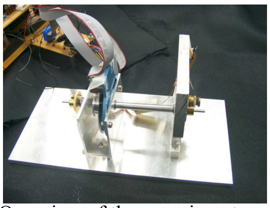

Fig. 9 Overview of the experiment apparatus

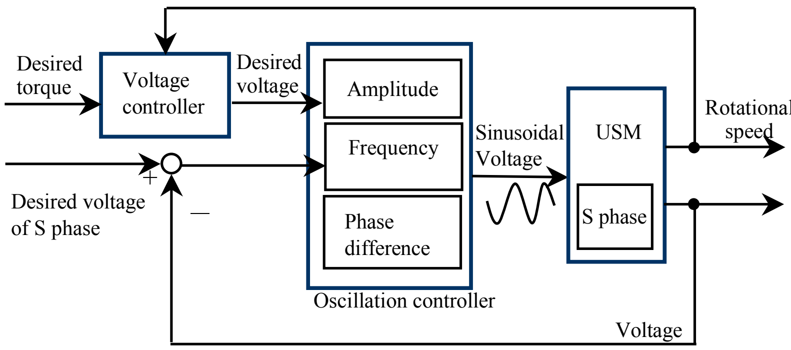

Fig. 11 Block diagram of control method