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Experimental investigation of input–output characteristics of a travelling-wave ultrasonic motor

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Abstract Speed, position and load characteristics of the ultrasonic motor is considerably influenced from the input characteristics such as driving frequency, magnitude and phase difference of phase voltages. Input and output characteristics of a traveling-wave ultrasonic motor have been investigated from the experimental point of view in the present study. For this aim, a half-bridge serial-resonance inverter based drive system has been designed and then implemented. The inverter is featured with pulse width modulation and pulse frequency modulation techniques. The frequency, amplitude and phase angle of two-phase sinusoidal output of the driver has been designed to be changed for the control purpose. Then the measuring circuits and tools have been set up to obtain required measurements. Input characteristics such as duty ratio of control signal-dc reference voltage, dc reference voltage-driving frequency and output characteristics such as driving frequency-rotor speed, driving frequency-feedback voltage, phase voltage-rotor speed are obtained from the experiments. Also load characteristics are studied with experiments. Afterwards these characteristics are discussed in details. This study gives a systematical experimental approach in order to demonstrate operating and control principles and characteristics of the travelling-wave ultrasonic motor.

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1 Introduction

Piezoelectric ultrasonic motors, especially rotary type travelling-wave type ultrasonic motors have important features such as high specific torque, high holding torque, high torque at low speed, silent operation, compact size and no electromagnetic interference. Travelling-wave ultrasonic motor is driven by the two-phase high-frequency sinusoidal voltages with defined phase difference. The torque of USM is 10 to 100 times larger than the conventional electromagnetic motors of same size or same weight. Due to these features USMs have recently begun to be used for industrial, medical, robotic, space and automotive applications [1, 2].

In the other hand USMs have some disadvantages must be overcome. 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 cannot be obtained easily 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, 4].

Several researches have been published dealing with operating characteristics and performance of the USM. Contact models have been used to predict the motor characteristic in [5]. The coefficient of friction and the modulus of elasticity have been adopted from the measurements. 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 [6]. A method using an equivalent circuit is proposed for estimating the performance of the motor. Using this method, a systematic approach is achieved for estimating the performance, including the electrical and the mechanical parts of the motor [7]. An equivalent circuit model of travelling-wave ultrasonic motor and its application to the estimation of motor characteristics has been presented. The performance of ultrasonic motor under different speed and load conditions has been obtained from the proposed method [8]. Speed control methods of a travelling wave ultrasonic motor are examined experimentally in [9]. Three speed control methods have been compared and results have been presented. An automated test system for piezoelectric motors allowing the experimental characterization of its electromechanical behaviors has been described [10]. An alternate approach to creating and fitting a model: an experimental–statistical investigation, using design of experiments [11] and theoretical and experimental research on a disk-type non-contact ultrasonic motor [12] have been presented. Due to complexity and non-linear characteristics of the USM, the application of TWUSM faces certain problems in dynamic modeling, analysis and optimization, design of driving system and control strategy [13].

The aim of the study is to obtain operating characteristics and performance of TWUSM in view of experimental approach. To achieve this aim, an original and systematical experimental test bench has been set. With respect to this study, optimum operating parameters of TWUSM is obtained. As a result, favorable drive system can be designed and precise control strategy can be developed. The main advantage of the study is; it doesn't require sophisticated mathematical models to build up a drive and control system for the TWUSM. Besides, the proposed study includes both mechanical and electrical parameters to obtain accurate characteristics. In addition, it brings a systematical test system for common used Shinsei's TWUSM called USR60. Also, the behavior of the motor have been obtained to clarify operating points under the different input parameters.

In the present study input and output characteristics of a traveling-wave ultrasonic motor have been studied. Components of USM drive system and measurement tools have been integrated to provide experimental test bench. Obtained experimental results have been given as graphics in sequent. As a result the operating points, principles and characteristics can be viewed and tracked easily from these graphics. Performance of the motor can be estimated from these figures at any operating conditions. The main advantage of the study is to guide for designing precise drive system and developing control algorithms.

2 Travelling-wave ultrasonic motor

Although several USM types are designed, the rotary TWUSM is commonly used ultrasonic motor type. The TWUSM is driven by high frequency two-phase sinusoidal voltages with 90° phase difference. The speed of USM is controlled by amplitude, frequency and phase difference between the two-phase voltages [14, 15].

In the operation of the USMs two-stage energy conversion is formed. First is the electro-mechanical energy conversion where electrical energy is converted to mechanical energy. This is achieved by excitation of the piezoelectric ceramic with ultrasonic range frequency. Second is the mechanical energy conversion where the mechanical vibrations are converted to linear or rotary motion by friction force generated in stator–rotor interface [5]. The elliptic motion of points on the surface of the stator is generated by the travelling-wave in the stator. The vibrations are excited by a piezoelectric ceramic layer bonded to the lower surface of the stator. The rotor is pressed against the stator by means of a disc spring and is driven by frictional forces in the contact layer. The rotation direction of rotor is opposite to the direction of the travelling-wave.

To understand motor parameters and characteristics an equivalent circuit representation of USM is important. A single-phase equivalent circuit model of the USM is shown in Fig. 1. Each phase of USM is represented by damping capacitance C_d, which is due to dielectric properties of piezoelectric ceramic. This capacitance is measured when the ceramic element is fixed so that no vibration can occur. In this condition there is no motion in the system. Damping capacitance of each phase of USR60 USM was measured as 9 nF. r_d represents dielectric loss of piezoelectric ceramic. The combination of C_d and r_d is called the blocking impedance. r_d can be neglected for the frequency range of USMs. C_m is equivalent capacitor represents spring effect of stator assembly, L_m is equivalent inductor representing mass effect of stator assembly. In the piezoelectric effect for a polarized element creating a hysteresis loop which results in losses. Furthermore mechanical losses occur between metal and piezoelectric ceramic. These losses are represented by r_0 in equivalent circuit. This component is also

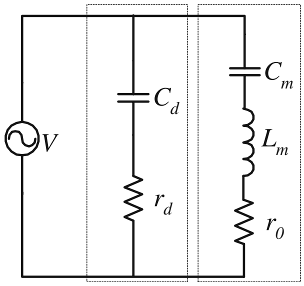
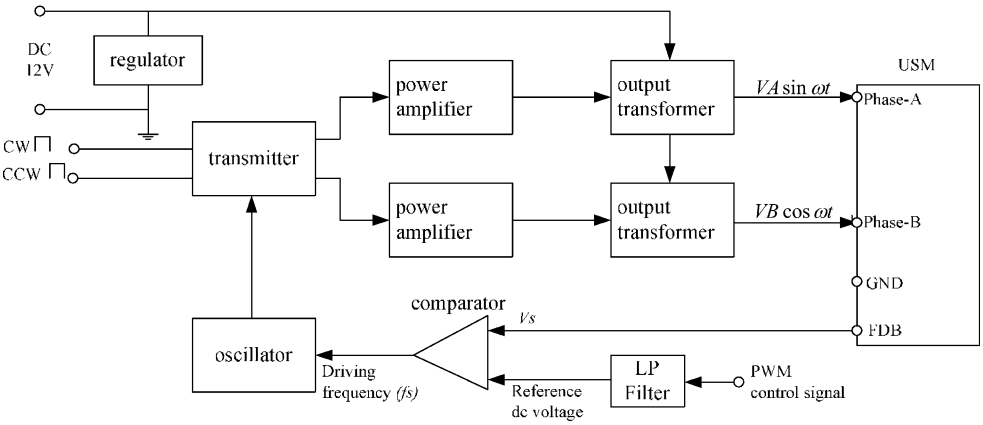


Fig. 1 Equivalent circuit representation of USM

Fig. 2 USM drive system



known as internal resistor. The impedance combination of C_{m}, L_{m} and r_0 is called as motional impedance [9].

$C_{\mathrm{m}}=A^2/s$ and $L_{\mathrm{m}}=m/A^2$, where s spring constant of stator, m mass of metal assembly and ceramic of stator, A is force factor. The force factor is generally determined not only by the dimensions and material properties but also by the properties of the metal plate combined with it. To provide high efficiency in the USM drive system, USM should be driven at the near frequency creating resonance between C_m and L_m in the equivalent circuit. The mechanical resonance frequency is expressed as

$$f_{\mathrm{m}}=\frac{1}{2\pi\sqrt{L_{\mathrm{m}}C_m}}=\frac{1}{2\pi\sqrt{m/s}} \tag{1}$$

Blocking admittance Y_{d} and motional admittance Y_{m} of equivalent circuit are found as follows,

$$Y_d=1/r_{\mathrm{d}}+j\omega C_{\mathrm{d}} \tag{2}$$

$$Y_{\mathrm{m}}=\frac{1}{(r_0+j\omega L_m+1/j\omega C_m)} \tag{3}$$

$$Y_m=\frac{r_0}{r_0^2+(\omega L_m-1/\omega C_{\mathrm{m}})^2}+j\frac{1/\omega C_{\mathrm{m}}-\omega L_m}{r_0^2+(\omega L_m-1/\omega C_{\mathrm{m}})^2} \tag{4}$$

The sinusoidal current flowing into the motional branch causes motor movement called as motional current which is expressed by,

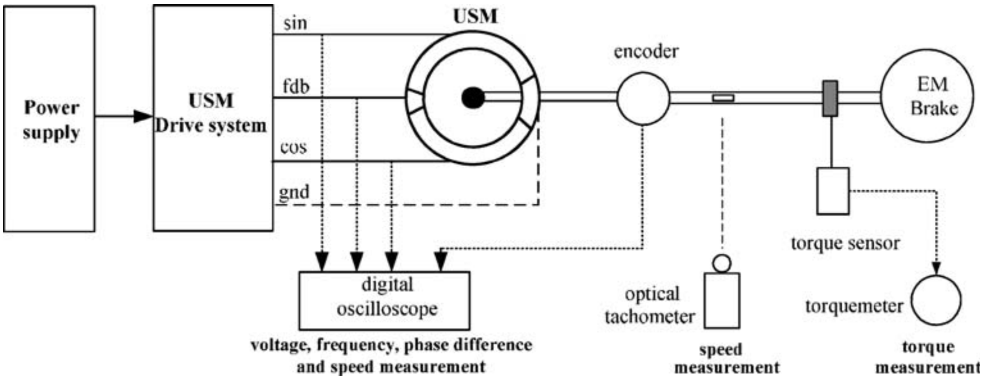
$$I_m=V\times Y_m \tag{5}$$

3 USM driver and test set-up

To determine of the inherent characteristics of the motor, a suitable and well defined power supply and drive circuit is required. The drive system should provide two orthogonal sinusoidal waves to avoid simultaneous excitation of vibration modes of the stator. Additionally, it should provide the ability of varying the amplitude, frequency and phase angle of excitation phases. For that purpose Shinsei's D6060 driver has been used to drive USM [16]. This driver has both pulse frequency modulation and pulse width modulation methods. The driver provides two-phase high frequency AC voltages with 90° out of phase. The driver has been designed to be controlled digitally. Direction control circuit and PWM control circuit have been integrated to the driver to achieve digital control of USM. Figure 2 shows the USM drive system used in this study.

Then an experimental test set-up which contains the electromechanical system and measurement tools has been designed. The block scheme of the experimental test set-up has been shown in Fig. 3. The frequency, amplitude and

Fig. 3 Experimental test set-up for USM drive system



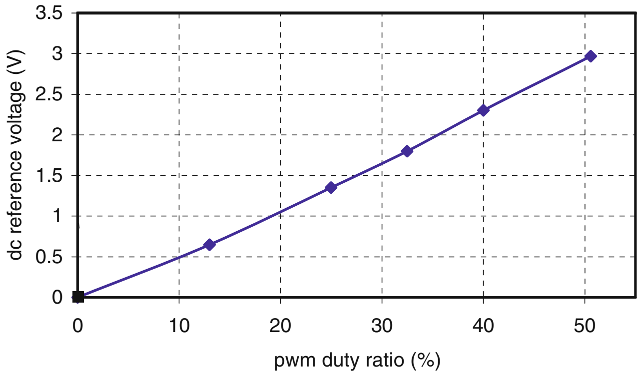


Fig. 4 dc reference voltage versus PWM duty ratio

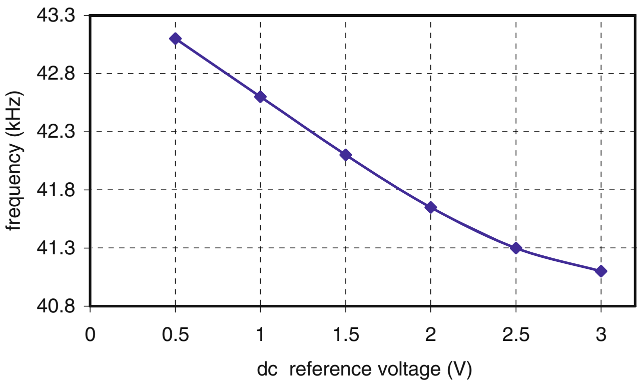


Fig. 5 Driving frequency versus dc reference voltage

phase difference of the voltages are measured by digital oscilloscope. The speed of motor is measured by optical tachometer and frequency of the encoder pulses. The mechanical part of the motor is loaded by an electromagnetic (EM) brake. This unit allows to obtain and analysis of the torque-speed characteristics of the motor [17].

4 Experimental results

In this section, the experimental results taken from the USM test set-up have been presented. In the study, PWM signal has been used for speed control of the motor. PWM signal is compared with the feedback voltage of feedback sensor mounted on USM. As a result, required and demanded driving frequency values are provided.

Firstly the relation between duty ratio of PWM signal and resulting dc reference voltage has been given. The duty cycle of PWM control signal has been changed from 0 to 50% in defined values, and dc reference voltage has been measured for these values. Figure 4 shows the relation between PWM duty ratio and reference dc voltage. As seen from the figure, when PWM duty ratio increased, the value of dc reference voltage increase from 0 to 3 V. There is a linear relation between dc reference voltage and duty ratio of PWM signal.

When the level of the dc reference signal increases the value of the driving frequency of drive system decreases. Consequently, the speed of motor increases. Figure 5 shows relation of driving frequency versus dc reference voltage and Fig. 6 shows the relation between dc reference voltage and motor speed. As seen from the figures with increasing dc reference voltage, the driving frequency has been decreased as a result the speed of the motor has been increased. While dc reference voltage changed from 0 to 3 V. The driving frequency of drive system has been changed from 43.1 to 41.1 kHz and speed of motor has been measured in range of 0 to 130 rpm. It is obvious that, when duty cycle of PWM signal is increased, the reference dc voltage increases and the frequency of output voltages decrease. As a result, the speed of motor increases.

The variation between motor speed and driving frequency has been given in Fig. 7. As mentioned above, the speed of USM decreases when the driving frequency increases. This relation is not linear. While frequency has been changed between 41–43.1 kHz, the speed of the motor changes from 125 to 38 rpm. Speed–frequency characteristic is very important characteristic. It has a key role for designing drive and control system of the USM. This characteristic shows that the driving frequency can be used as a control input for drive and control applications of the motor.

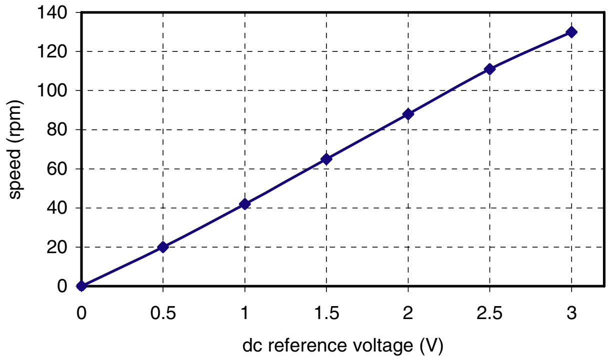


Fig. 6 Motor speed versus dc reference voltage

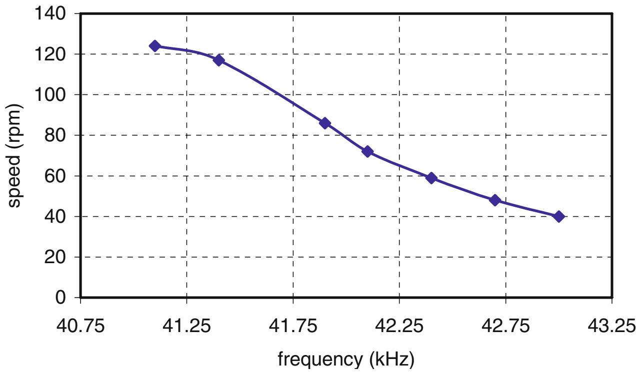


Fig. 7 Motor speed versus driving frequency

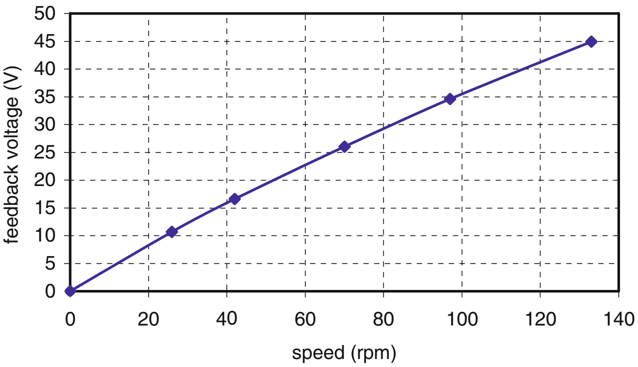


Fig. 8 Feedback voltage versus motor speed

In the USR60 USM a feedback electrode is mounted addition to the A and B sections. This electrode produces high frequency AC voltage when mechanical vibrations acting on the stator surface due to the piezoelectric effect. The value of this voltage is proportional to the speed of motor. To show the relation between the rotary speed and amplitude of feedback voltage, experimental measurements are made for different speed values. This relation has been given in Fig. 8. As seen from the figure, while speed of motor changed from 0 to 130 rpm, the rms value of the feedback voltage has changed from 0 to 45 V. By using this characteristic, the speed control of the USM can be achieved without using extra speed sensor. It is clear that the feedback voltage of the USM is linear with rotating speed. This relation is important due to observe the motor speed without additional speed sensor. So, it can be used as a feedback signal for analogous drive and control techniques.

The load performance of USM also has been studied from the experimental view. The USM has been loaded from 0 (no load) to rated torque (0.4 Nm) and results given in Fig. 9. As seen from this figure, the motor speed has decreased from 130 to 100 rpm, which is the rated speed value of the USM used in this study. This characteristic likes typical speed–torque characteristics of conventional rotating motors. Load torque should be considered when designing drive and control system for the USM. Also, this characteristic proves the nameplate of the motor. Rated speed (100 rpm) has been obtained at the rated torque (0.4 Nm).

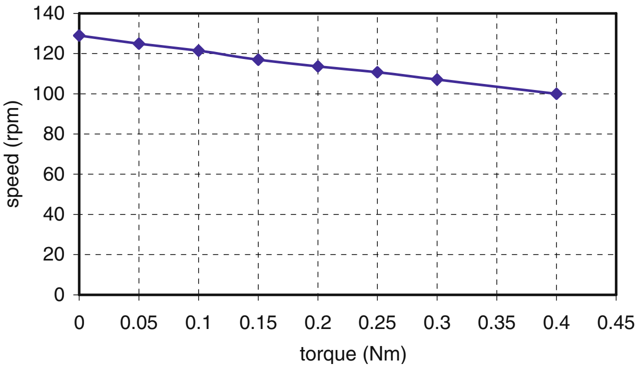


Fig. 9 Motor speed versus load torque

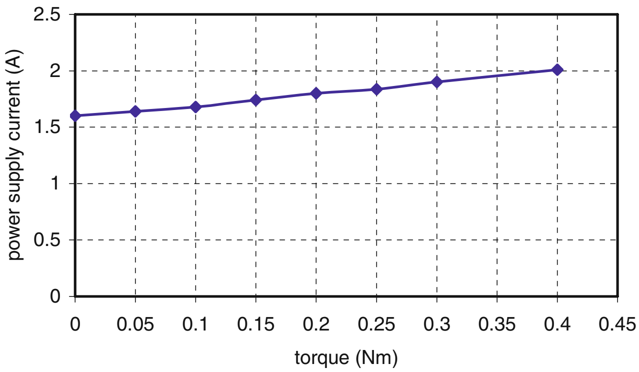


Fig. 10 Power supply current versus load torque

The power supply current has been measured while the motor loaded from no-load to rated load. Figure 10 gives the relation of power supply current and load torque. The power supply current has varied from 1.6 to 2 A while load torque has been increased from 0 Nm to the 0.4 Nm.

5 Conclusions

In this study the input and output characteristics of travelling wave type ultrasonic motor have been investigated experimentally. For experiments, a experimental test bench including USM, drive system, load and measurement tools has been set-up. To drive ultrasonic motor two-phase voltage-fed high-frequency serial-resonant inverter has been used. This driver has been converted to be controlled digitally.

Experiments have been taken for different speed values. To control speed of motor driving frequency method has been used. The value of driving frequency is controlled by PWM output of digital controller. By changing the duty cycle of PWM signal, the dc reference voltage and resulting driving frequency is changed. As a result the speed of USM is controlled.

Duty ratio of PWM control signal-dc reference voltage, dc reference voltage-driving frequency, motor speed-dc reference voltage, motor speed-driving frequency, driving frequency-feedback voltage, motor speed-load torque and power supply current-load torque characteristics have been obtained from the experiments. The study gives a systematic experimental approach to show operating characteristics of the USM.

From experimental results; increase in duty cycle of PWM signal decreases the driving frequency and increase speed of USM. Motor speed and feedback voltage have linear relation that can be controlled in speed control applications. When loaded the speed of motor decreases while the power supply current increases.

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