Microcontroller-based full control of ultrasonic motor with frequency and voltage adjusting

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Abstract

In this study, PIC16F628 microcontroller-based control of a traveling-wave ultrasonic motor has been implemented. A drive system including power supply, power electronic drives, and interface electronic circuits have been designed. The microcontroller has been integrated with drive system to achieve overall control of ultrasonic motor. Microcontroller generates start/stop, direction, and speed/position control signals for the motor drive system. Driving frequency and amplitude of two-phase voltages have been adjusted to realize speed and position control. Reference input signal has been generated directly with programmable on-chip voltage reference module of microcontroller. By using this method, control of the drive system has been successfully achieved without using additional interface digital/analog or filter circuits. Proposed drive and control system have been tested for various direction, speed, and position conditions. Transient responses and steady state operating conditions have been examined as well. The experimental results verify that the developed system is simple, reliable, and suitable for the control of the ultrasonic motor.

Keywords: Ultrasonic motor; Microcontroller; Frequency control; Voltage control; Speed/position control

1. Introduction

Newly developed piezoelectric driven ultrasonic motors (USMs) have many important physical features and operating performances such as high torque at low speed, high torque/volume ratio, fast and accurate speed/position responses, holding torque without power supply or additional brake, excellent start/stop dynamics, simple mechanical design, compact size, and no electromagnetic noise. USMs have attracted special interest as direct drive type actuators for servo applications in industrial, medical, consumer, robotic, space, and automotive applications in recent years. The performance, control technique, and operating principle of newly developed USMs are basically different from commonly used conventional electromagnetic motors [1,2].

For practical operation of the USM, a specific individual power supply and high-quality semiconductor devices that can follow the optimum operating point of the motor are required. It is difficult to drive the piezoelectric ceramic owing to its high damping capacitance. To drive piezoelectric ceramic easily, resonant frequency approach is used. For this reason a serial or parallel inductance is connected with each phase of the USM to provide resonant frequency. The drive system of two-phase high-frequency voltage-fed serial-resonant inverter of the USM generally includes pulse width modulation (PWM), pulse frequency modulation (PFM), and hybrid (PWM/PFM) control techniques [3].

In the proposed study, speed, position, and direction control application of the traveling-wave USM (TWUSM) have been designed and realized by the microcontroller successfully. To achieve this aim, a power drive system was designed, and then electronic circuits controlling the power driver were built. Instead of high-priced and complicated controllers, a PIC16F628 microcontroller was used and integrated into the USM drive system to achieve speed and position control. Both driving frequency and amplitude of two-phase voltages were controlled to improve the control system. The control signal was produced by using internal voltage reference unit from the microcontroller directly, which eliminates additional interface analog–digital and filter circuits. As a result, very fast speed and position responses have been obtained. In addition, the drive system was simplified and a low cost drive and control system

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was built. The proposed speed control scheme was tested with various experiments for different speed, position, and direction conditions. The obtained results have been given systematically to show effectiveness and reliability of the PIC microcontroller-based USM drive system.

2. State of the art

Several driving circuits for the TWUSM, using series or parallel resonant techniques have been reported in recent years. A special driving circuit designed for TWUSM has been reported in [4]. A boost-chopper circuit was used to adjust the amplitude of the applied voltage and a half-bridge inverter was used to regulate the driving frequency. A driving circuit was designed and a hybrid controller, which combines the advantages of variable-structure system and adaptive model following control, has been proposed for USM by Lin and Kuo [5]. Ferreira and Minotti [6] have described inverter-fed USM servo control implementation with two control strategies from a practical point of view. A speed tracking servo control system was presented for the USM. Power conversion circuit presented in the study includes boost-chopper and two-phase inverter circuits [7]. Kato and Sase have proposed a frequency tracking scheme based on detection of the maximum current proportional to the motor torque [8]. A driving circuit for the TWUSM, which consists of a push–pull dc–dc power converter and a current-source two-phase parallel resonant inverter, has been presented by Lin et al. [9]. Electronic and software control for the rotary piezoelectric motor has been proposed in [10]. PC-based digital I/O card was used to improve control system. A highly effective load adaptive servo drive system incorporating high-frequency two-phase serial-resonant inverter of the USM has been presented in [11].

The speed and position of the USM can be controlled by the amplitude, frequency, and phase difference of two-phase voltages. The USM is generally controlled by driving frequency method or by combining two control methods called “hybrid” or “dual control” methods. Several speed and position control systems have been proposed in recent years. Model-based PI, direct PWM, sliding mode, fuzzy, adaptive fuzzy, neural network (NN), and fuzzy neural network controllers have been applied to the speed/position controls of the USM in recent years. Computers, microcomputers, special microcontroller/microprocessors, and digital signal processors (DSP) have been used to achieve drives and controls.

A PWM method for speed control of the TWUSM has been presented in [12]. This method on-line adjusts the duty ratio of each ultrasonic switching cycle, which drives the two-phase inverter to achieve voltage amplitude control of the TWUSM. DSP was used in the control system. Senjyu et al. [13] have described the maximum efficient drive of the USM. The paper presents speed control method with maximum efficiency by the PWM control of dc source voltage combined with drive

![Fig. 1. Drive system of the TWUSM.](image)

![Fig. 2. Block diagram of the USM control system.](image)
frequency control. A PWM technique is presented for DSP controlled drive system of the TWUSM in [14]. The driving frequency was selected as control input both for the speed and position control loops. A robust controller was developed to perform a complete design for an ultrasonic servo motor system. In the experimental validation, a field programmable gate array (FPGA)-based controller was implemented to validate the feasibility of the design [15]. Quick and precise position control method of controlling both the driving frequency and the phase difference of the applied voltages with microcomputer has been presented, a method referred to as the dual-mode control [16]. Servo control implementation incorporating software-based fuzzy reasoning concept is described from a practical point of view in [17]. Fuzzy logic controller using the DSP was used to control position of the TWUSM [18]. Fuzzy adaptive model following controller using PC with servo control card [19] have been presented for position control of the USM. Model reference adaptive control with fuzzy inference was applied to position control of the USM [20] with the PC. The NN control system was designed using two NNs to control the rotor position of the USM [21]. The NN control system was implemented in a DSP-based control computer to demonstrate the control and learning abilities of the proposed control system. A dual-mode neuro-fuzzy controller (NFC) was proposed and implemented for speed tracking control of the TWUSM, using a single-chip DSP-based microcontroller [22]. The key is to simultaneously employ both the driving frequency and voltage amplitude as the dual-mode control variables to handle system nonlinearities and parameter variations. The proposed controller is implemented by a single-chip DSP-based microcontroller.

3. The USM drive system

Although several of the USM types are designed, the rotary TWUSM is a commonly used type of USM. The TWUSM is driven by high-frequency two-phase sinusoidal voltages with 90° phase difference. Three control methods; driving frequency control, phase difference control, and applied voltage control are used for speed and position control of the motor. These control methods can be applied individually or together, for the motor, to provide effective and reliable control.

In the present study Shinsei’s USR60 traveling-wave type USM has been used. To drive this motor a two-phase high-frequency inverter was designed. Each phase voltage of the motor was provided with two power switches. Power switches are designed as a half-bridge to obtain two-phase voltages with defined phase angle. Fig. 1 shows the main circuit of the two-phase half-bridge inverter used for the USM. This inverter includes the effective functions of the PWM and the PFM control techniques. The mechanical vibration system of the USM is represented as a capacitive load, due to properties of the piezoelectric ceramic used in the stator. Two inductances $L_A$ and $L_B$ are connected with each phase of the USM in series to compensate damping capacitance of the USM. $V_A$ and $V_B$ are phase voltages of the USM, where $V_s$ is feedback voltage of the USM. This inverter produces two-phase high-frequency voltages. The amplitude and frequency between two-phase voltages are adjusted for the control purpose. CW and CCW inputs provide direction control signals by letting $V_A$ or $V_B$ lead.

To provide sinusoidal output voltages, the input signal of $S_1$ is inverted and applied to $S_3$, and input signal of $S_2$ is inverted and applied to $S_4$. Upper and lower switches in a leg such as $S_1$ and $S_3$, are complementary. However, the signal of $S_1$ is inverted by NOT gate and then applied to the $S_3$. The dead-band between switches is provided by this switching technique. Also, to avoid short-circuit operation, fast recovery type free wheeling diodes are connected in parallel. Two-phase output voltages with 90° phase difference are obtained with respect to this switching technique.

![Fig. 3. Configuration of PIC16F628 microcontroller.](image-url)
The main control input of the drive system is switching frequency, $f_s$. This input is obtained from comparison of the feedback electrode voltage ($V_s$) and reference dc voltage. In addition, amplitude of phase voltages is adjusted to obtain accurate speed/position responses in both CW and CCW directions. According to the reference command, the value of switching frequency and phase voltages are adjusted. This is achieved by changing the value of reference dc voltage. Reference dc voltage has been generated from the microcontroller using the programmable internal voltage reference module ($V_{ref}$) of the microcontroller. In previous studies, this voltage was generated with additional filter circuits. In the present study, the dc reference voltage has been generated and controlled without using additional digital–analog or filter circuits. As a result, very fast speed and position responses have been obtained. Alongside this, the drive system has been simplified and a low-cost drive and control system has been constructed.

4. Microcontroller-based USM control system

The block diagram representation of the USM control system is given in Fig. 2. In this study, two control loops have been used to achieve effective speed and position control of the motor. One of these is an external loop which tracks the digital encoder signals, the other is an internal loop which tracks the feedback voltage of the motor. Control of the motor was adjusted and optimised by using these two control loops together. The developed control scheme does not require knowledge of the parameters of the USM, and can provide the effective speed characteristics on-line against various drive conditions.

The drive system of the motor is a two-phase serial-resonant inverter with a frequency and voltage controller. The actual speed and direction of the motor are measured by digital encoder and sent to the microcontroller. The microcontroller processes the speed value and compares it with the reference speed. According
to this comparison the speed error is generated. A proportional control algorithm has been used and coded into the microcontroller to achieve the control. The software developed in the microcontroller calculates proportional gain by the P-controller to generate the required PWM signal. The generated PWM signal is then converted to the reference control signal.

In addition, feedback voltage \( V_s \), which is proportional to the motor speed, is sensed and applied to the drive system as a second control loop. The feedback voltage and reference voltage are compared to obtain the required driving frequency value. The applied voltages are adjusted with voltage control oscillator (VCO) according to the reference speed and direction command.

This controller can operate a second motor, as well as the first, without additional control parameters and can properly work on similar types of USMs, such as USR30, USR45.

PIC16F628A microcontroller devices have integrated features to reduce external components, system cost, power consumption, and enhance system reliability. In this study, the advantages of this device have been used to achieve cost effective and reliable drive and control system for the USM. PIC16F628A used in this study has the following features: 20 MHz maximum operating frequency, 2048 words flash program memory, 224 bytes RAM data memory, 128 bytes EEPROM data memory, three timer modules TMR0-TMR2, 10 interrupt sources, USART, 16 I/O pins with individual direction control, 16-bit capture/compare, 10-bit PWM module, analog comparator module with two analog comparators, programmable on-chip voltage reference \( V_{ref} \) module, selectable internal or external reference. The general parts of the microcontroller and pin configuration used in the present study have been given in Fig. 3.

The period of encoder signals is changed related to the actual speed of the motor. Timer-1 has been set as a counter to count the external signal on RA6 pin of the microcontroller. Timer-2 has been set to 50 ms, as a timer. When Timer-2 generates 20 interrupts, a 1 s time delay is obtained. The content of Timer-1 is read and set to zero at the end of this time. This value gives the frequency and period values of the encoder signals. The actual speed of the motor is calculated with respect to these values. Number 0, 1, and 3 pins of Port-A are used to drive a two-line LCD with two 4094 serial–parallel converters. The LCD is

Fig. 6. (a) Reference and actual speeds (50 rpm, CCW). (b) Two-phase voltages for 50 rpm reference (CCW).

Fig. 7. (a) Reference and actual speeds (100 rpm, CW). (b) Two-phase voltages for 100 rpm reference (CW).
operated with 8-bit data. In this way, the measured motor speed is shown on LCD.

RA2 pin of the PIC microcontroller is used as an internal reference voltage generator. This pin is a 4-bit digital–analog converter. This integrated feature is important to reduce external devices. The reference voltage value is compared with the feedback voltage of the motor to generate driving frequency of the USM drive system. The microcontroller compares the reference and measures actual motor speeds to make control process. Basically, if the measured speed is less than the reference speed, the reference voltage value is increased. If the motor speed is over the reference value, the reference voltage value is decreased. Time-based proportional calculation method is used to achieve this procedure. The flowchart of the software program written into the microcontroller has been given in Fig. 4.

5. Experimental results

In this section, the experimental results obtained from the microcontroller-based USM drive system are presented. Two-phase output voltages and speed graphics are given for different speed and direction references. Also, the multiple speed references response of the motor has been given to demonstrate the fast response of the proposed system.

Since the two-phases construction of the USM are coupled mechanically and the reactions from the electrical to the mechanical parts are unbalanced for two-phases, the equivalent two-phase loads of the rotor are unbalanced and the equivalent resistor values are varied for different rotating directions, rotor speeds, load torque, applied voltages, and static pressure force between the stator and rotor [23]. Thus, the two-phase sinusoid output voltages are unbalanced under the same switching frequency. It is difficult to obtain robust speed characteristics due to this limitation. To avoid this problem, two-phase voltages are controlled in addition to controlling driving frequency. Hence, good and accurate speed characteristics are obtained for both CW and CCW directions.

The experimental results of the 50 rpm reference speed are described first. The reference and actual rotor speeds are shown in Fig. 5a for CW rotating direction. As seen from figure, speed response is very fast and actual speed tracks the reference speed.

![Fig. 8. (a) Reference and actual speeds (100 rpm, CCW). (b) Two-phase voltages for 100 rpm reference (CCW).](image)

![Fig. 9. (a) Reference and actual speeds (125 rpm, CW). (b) Two-phase voltages for 125 rpm reference (CW).](image)
accurately. The output voltages provided from the two-phase inverter for this reference speed and direction are shown in Fig. 5b. The phase voltages are 136 V and 130 V, respectively, and driving frequency is 42.44 kHz. The reference and actual rotor speeds are shown in Fig. 6a for 50 rpm CCW rotating direction. As seen from figure, the speed response is very fast and actual speed tracks the reference speed accurately, as in the CW direction. The output voltages presented in Fig. 6b are 127 V and 140 V, respectively, and driving frequency is 42.39 kHz.

To show the effectiveness of the proposed system, the speed responses are investigated for rated speed (100 rpm) of the USM. The reference and actual rotor speeds are shown in Fig. 7a for CW rotating direction. As seen from figure, the speed response is very fast and actual speed follows the reference speed precisely. The output voltages provided from the two-phase inverter for this reference speed and direction are shown in Fig. 7b. The phase voltages are 128 V and 122 V, respectively and driving frequency is 41.69 kHz. The reference and actual rotor speeds are shown in Fig. 8a for 100 rpm CCW rotating direction. As seen from figure, the speed response is again very fast and actual speed follows the reference speed. The output voltages presented in Fig. 8b are 121 V and 131 V, respectively and driving frequency is 41.66 kHz.

The speed responses are also examined for 125 rpm speed of the USM. The reference and actual rotor speeds are shown in Fig. 9a for CW rotating direction. The output voltages provided from the two-phase inverter for this reference speed and direction are shown in Fig. 9b. The phase voltages are 127 V and 119 V, respectively and driving frequency is 41.37 kHz. The reference and actual rotor speeds are shown in Fig. 10a for 125 rpm CCW rotating direction. As seen from figures, speed responses are rapid and actual speed traces the reference speed accurately. The output voltages presented in Fig. 10b are 119 V and 129 V, respectively and driving frequency is 41.41 kHz.

As can be seen from Figs. 5–10, the main control input is driving frequency. Driving frequency has been varied from 42.44 kHz to 41.69 kHz for 50 rpm to 125 rpm speed references. In addition, the amplitude of phase voltages was adjusted to obtain accurate characteristics in different rotating directions.

To show the strength of the proposed method a multiple reference and actual position response of the motor are also given. Fig. 11 shows the speed responses of the motor under multiple reference speeds 50 rpm, 100 rpm, and 125 rpm. Actual rotor speeds follow the references precisely and rapidly.

USR60 speed variation induced by thermal drifts generally occurs over a longer time period. The proposed controller controls the motor speed over a longer time without error. USM has been operated at 100 rpm with 41.6 kHz driving frequency for 10 min. The speed of the USM was measured every minute to demonstrate reliability of the controller. The experiments show that, the motor speed is 100 rpm for all measurements. So, the controller has kept the motor speed as a reference value over a longer operating time.

Fig. 12 shows the 2π radian stepwise position response of the USM. The USM follows the reference position command correctly and the response of the motor is rapid for both start and stop responses. Value of the feedback voltage (Vf) of the USR60 is proportional to the motor speed. This relationship has
been discussed in detail in previous studies [3,14]. This value has been directed with an electronic circuit and used for actual speed and position signals. A reference signal has been produced with a microcontroller. As a result the reference command signal and actual position signal do not have to be equal. Time accordance and correctness of the tracking reference signal are important to show accuracy of the position response.

6. Conclusions

In this paper, a PIC microcontroller-based digital control system of the TWUSM has been designed and implemented. To drive the USM, a high-frequency voltage-fed serial-resonant inverter has been designed. The speed of the USM was primarily controlled by the driving frequency. Furthermore, the amplitudes of two-phase voltages were adjusted when required. The uncertainties, which occur from the nonlinearity of the USM, under the different rotating directions, have been removed.

The control signal was produced using an internal voltage reference unit of the microcontroller directly, to eliminate additional interface electronic circuits. With respect to this control technique, the drive system has been simplified and a low cost drive and control system has been set-up. With the software developed for the proposed method, fast speed and position responses have been obtained.

The performance of the proposed driving and control system has been demonstrated with a set of experiments. Sample speed and position results have been given and discussed. The developed control scheme has been tested for the different operating conditions. The experimental results have demonstrated that the proposed drive and control system give accurate and rapid speed characteristics for the USM. The PIC microcontroller-based USM control scheme is simple, cost-effective, lightweight, reliable, and practicable. Using this proposed method, the USM can be driven and controlled with a very simple control technique. Moreover, the proposed controller does not have the disadvantages when compared with more sophisticated controllers.

References

Biography

**Erdal Bekiroglu** was born in Hasankeyf, Turkey, on 13 June 1973. He received his BSc, MSc, and PhD degrees in electrical technologies from Gazi University, Ankara. He worked as a research assistant at Gazi University between 1996 and 2003. He joined the Department of Electrical and Electronics Engineering, Faculty of Engineering and Architecture, Abant Izzet Baysal University as an assistant professor in 2004. He is currently head of the Department of Electrical and Electronics Engineering. His research interests are fuzzy logic, digital signal processors, and drive and control of special electrical motors.