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Microcontroller based digitally controlled ultrasonic motor drive system

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Abstract Piezoelectric driven ultrasonic motors have been attracted as considerable actuators for the servo speed and position applications in recent years. These motors have important features and advantages to be preferred in the special movement applications. Ultrasonic motors have different operating principles and different drive and control systems than the electromagnetic motors. In this study, microcontroller based digitally controlled drive system has been proposed for a travelling-wave ultrasonic motor. Drive system includes power circuit, interface electronics circuits and microcontroller parts. Power circuit is combined from half-bridge serial-resonance inverter to provide high-frequency two-phase voltages. Interface circuits include gate drive, direction control, opto-coupler and filter circuits. Microcontroller is programmed to generate required digital control signals for overall control of the motor. Related to the reference speed, the microcontroller generates control signal resulting proper driving frequency. Consequently, the actual motor speed tracks the reference speed precisely. The speed feedback is taken from optical encoder and transmitted to the controller as digital speed and position signals. The developed drive system has been tested experimentally. The obtained results show the effectiveness and reliability of the proposed system. The microcontroller based drive system can be applied easily and successfully to the ultrasonic motor.

Keywords Ultrasonic motor · PIC microcontroller · Speed control · Inverter

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 [1–3].

The operation principle of piezoelectric ultrasonic motors is based on a two-stage electro-mechanical energy conversion. First electrical energy is converted into mechanical energy. This is achieved by piezoelectric actuators which excite high-frequency mechanical oscillations of a vibrating member. In a second step the oscillations are converted to continuous linear or rotary motion by friction forces generated in the contact interface of the vibrating member and a second body which is pressed against the

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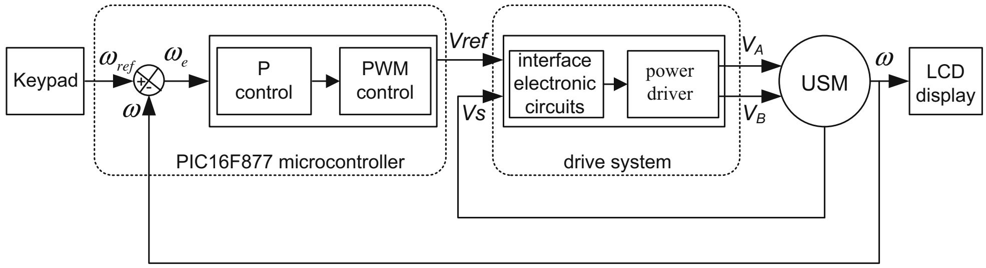

Fig. 1 Block diagram of PIC controlled USM drive system

oscillator. Usually the vibrating part is stator and the second part is rotor [4].

Several speed and position control techniques have already been proposed to drive and speed/position control of USMs. Digital signal processors [5–7], computers and microcomputers [8–10] or special microcontroller/microprocessors have been used to achieve that drives and controls. An USM servo drive using field programmable gate array (FPGA) have designed and implemented. Electrical equivalent circuit of the USM has been used to design the driving circuit. An experimental dynamic model of the drive system is established [11]. PC based driving circuit and control system has been developed for USM A proportional-integral derivative and sliding mode control are applied to control loop [12]. A novel method for driving ultrasonic motor by using a piezoelectric transformer instead of the DC/AC converter type driver using conventional electromagnetic transformer has been proposed [13]. Analog electronic stages have been developed for an USM. The open-loop behavior is measured and detailed. Then closed-loop and servo-control are experimented, measured and adjusted by using microcontroller [14].

In the proposed study, speed control application of a traveling-wave ultrasonic motor (TWUSM) has been designed and realized by using a low-cost 8-bit PIC microcontroller. The aim of the study is to obtain simple, reliable, cost-effective, digitally controlled, user friendly, compact, adaptable and accurate novel control system for the TWUSM. For this aim; a power drive system of USM has been designed. Then interface electronics circuits which control the power driver have been designed. To achieve speed control PIC16F877 microcontroller has been programmed and integrated into USM drive system. After all an experimental test setup has been constructed. The proposed speed control scheme has been tested with various experiments. The obtained results have been given systematically to show effectiveness and reliability of the PIC controlled USM drive system.

2 Travelling-wave ultrasonic motor

Ultrasonic motor is a special type of motor that driven by mechanical vibration force of piezoelectric ceramic in the

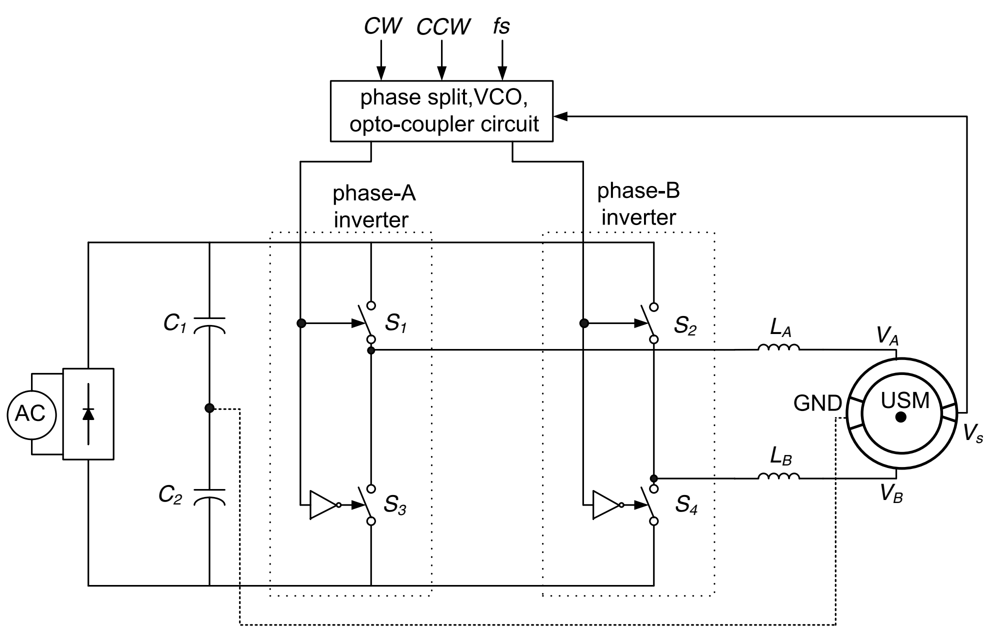

Fig. 2 Drive system of TWUSM

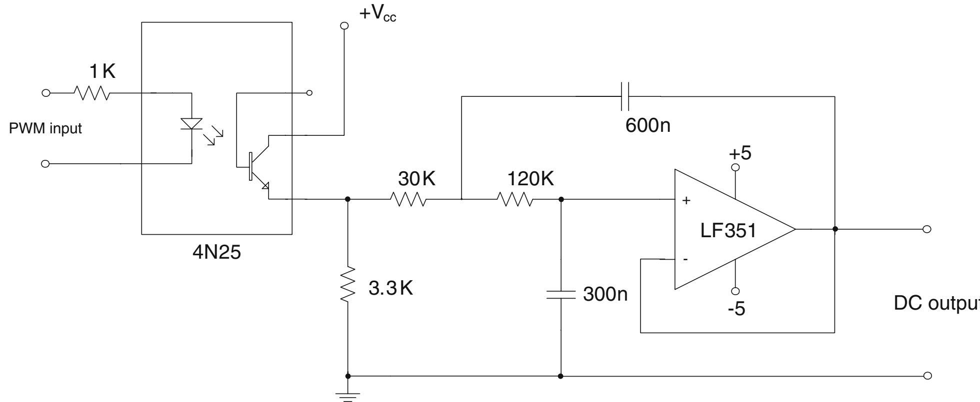

Fig. 3 PWM-DC reference voltage conversion circuit (LP filter)

stator. Although several USM types are designed, the rotary type TWUSM is most used USM type. To generate a travelling-wave within the stator, it is necessary to have control of two mechanical orthogonal modes. Electrode pattern A provides the cos$k\theta$, and the pattern B sin$k\theta$. By driving these two modes with 90° out of phase, a travelling-wave is produced. Each pattern provides standing wave individually. The superposition of these standing waves produce a travelling-wave used in TWUSMs [4, 15].

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. The speed of TWUSM is controlled via;

- Frequency of two-phase voltages
- Amplitude of two-phase voltages
- Phase angle between two-phase voltages

Many studies using these control methods have been presented in literature [16–20]. In this study driving frequency control method has been used to control the speed of the USM. For this aim a PWM signal has been generated from PIC microcontroller and then applied to the electronics interface circuits. The detailed information about microcontroller part of the system and drive and control system of the USM are given in the following sections.

3 PIC16F877 microcontroller

Microcontrollers are embedded digital control devices which have a central processing unit, interrupts, counters, timers, I/O ports, RAM, ROM/EPROM are used to systems' control. The PICs (peripheral interface controllers) are the integrated circuits based on CMOS technology. The main components of a PIC are RAM, EPROM, EEPROM, and Peripheral Interface Adaptor (PIA). These components are inserted in the same integrated circuit to reduce the size, the cost of the system and make design of system easier.

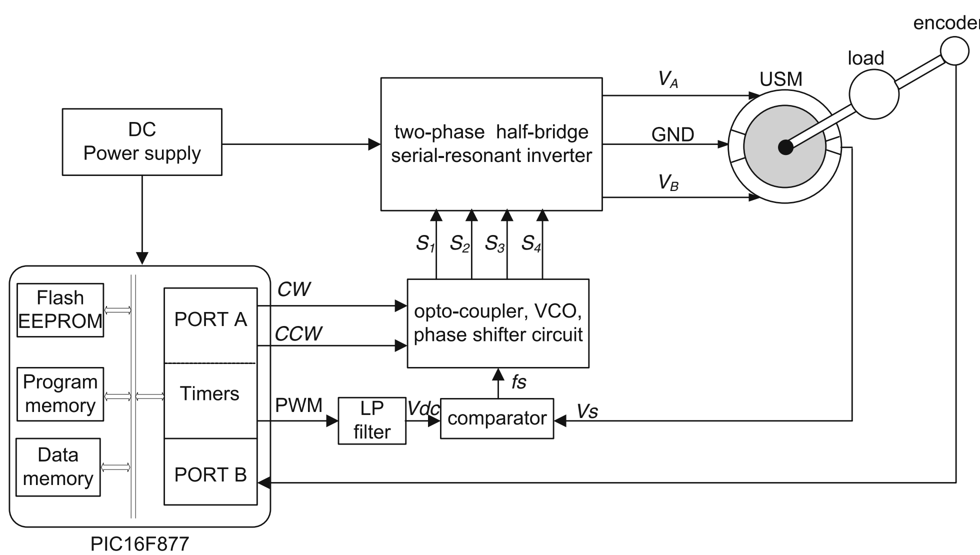

Fig. 4 Microcontroller based drive and control system of the USM

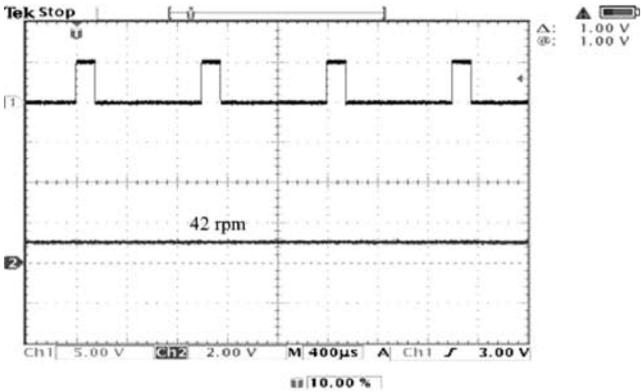

Fig. 5 PWM signal and motor speed (42 rpm)

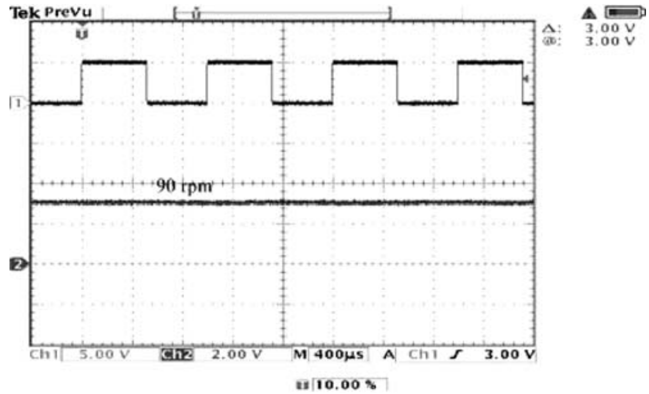

Fig. 7 PWM signal and motor speed (90 rpm)

The address bus, the data bus and the control bus connecting the components are placed into the PIC circuit by the manufacturer. Because of these advantages, PICs have been preferred devices in practical control applications. The PIC16F877 used in this work operates at 20 MHz clock frequency and runs each instruction as fast as 200 ns. Flash Program Memory is up to 8K×14 words. Data memory is partitioned into four banks which contain the General Purpose Registers and the Special Function Registers. Bits RP1 and RP0 are the bank select bits. Each bank extends up to 7 Fh (128 bytes). It contains 1 K EEPROM as a program memory, 15 special hardware registers, 36 general purpose registers and 64 byte EEPROM as a data memory. PICs have been mostly preferred control devices because of their low cost, less energy consumption and having small volume in design [21, 22].

In the study, PIC16F877 microcontroller has been used for speed control application of USM. The block diagram of the developed system is shown in Fig. 1. The control system of the USM mainly includes keypad, microcontroller, drive system, USM and LCD display parts. The reference commands are entered from the keypad. The actual speed and direction of the motor are measured by digital encoder and sent to the microcontroller. Microcontroller processes the speed value and compares it with the reference speed entered from the keypad. According to this comparison the speed error is generated. Proportional control algorithm has been used and programmed into the microcontroller to achieve the control. The software developed in microcontroller calculates proportional gain as a P-control to generate required PWM signal. The generated PWM signal is then applied to the drive system. Drive system generate required two-phase voltages with suitable driving frequency according to the reference commands. USM is rotate at the reference speed and this speed is monitored on the LCD to show reliability and accuracy of the system. Feedback voltage (*Vs*), 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 required driving frequency value. The applied voltages are adjusted with drive system of USM according to the reference speed and direction commands.

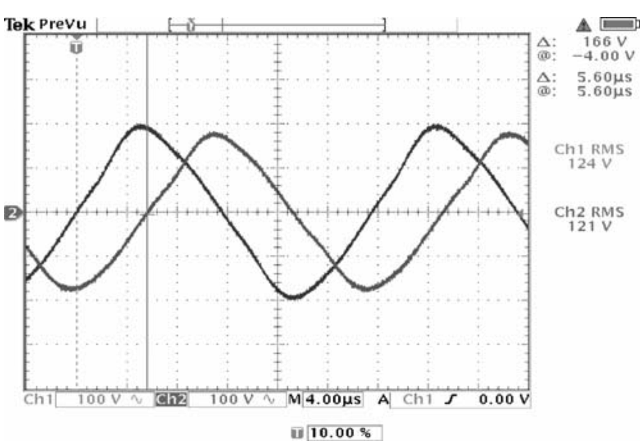

Fig. 6 Two-phase output voltages for 42 rpm (f_s=42.37 kHz)

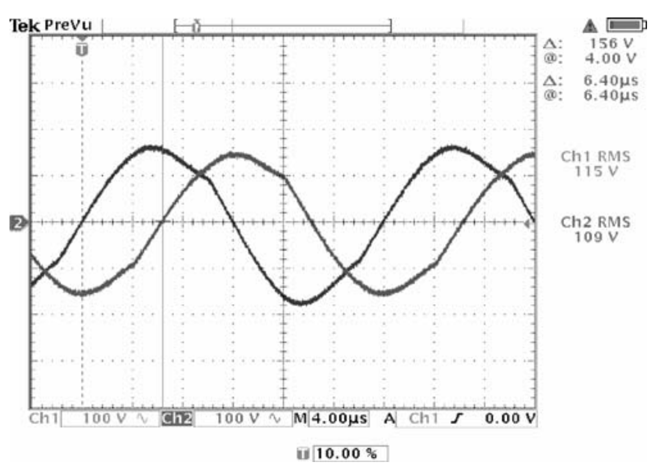

Fig. 8 Two-phase output voltages for 90 rpm (f_s=41.66 kHz)

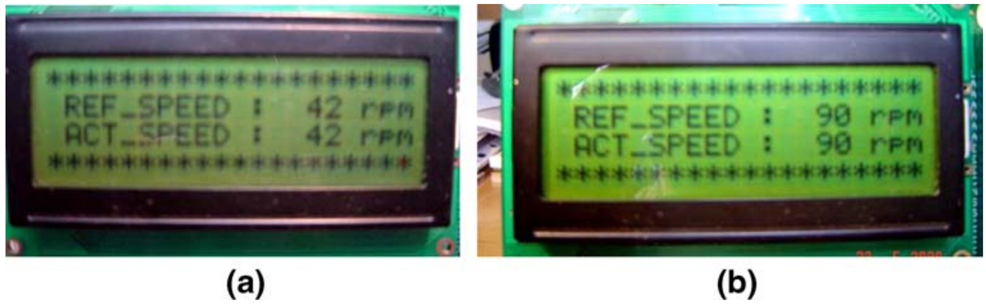

Fig. 9 LCD display of reference and actual speeds (**a**) 42 rpm (**b**) 90 rpm

4 USM drive and control system

In the present study Shinsei's USR60 travelling wave type USM has been used. To drive this motor two-phase high frequency inverter has been designed. Each phase voltage of the motor provided with two power switches. Power switches are designed as half-bridge to obtain two-phase voltages with defined phase angle. Figure 2 shows the main circuit of two-phase half-bridge inverter used for USM. This inverter includes the effective functions of pulse width modulation (PWM) and pulse frequency modulation (PFM) control techniques. The mechanical vibration system of USM is represented as a capacitive load due to properties of piezoelectric ceramic used in the stator. Two inductances L_A and L_B are connected with each phase of USM in series to compensate damping capacitance of USM. V_A end V_B phase voltages of the USM, where Vs is feedback voltage of USM. This inverter produces two-phase high-frequency voltages. The amplitude, frequency and phase difference between two-phase voltages can be changed for 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 are complementary such as S_1 and S_3. However, the signal of S_1 is inverted by NOT gate and then applied to the S_3. The dead-band between switches 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.

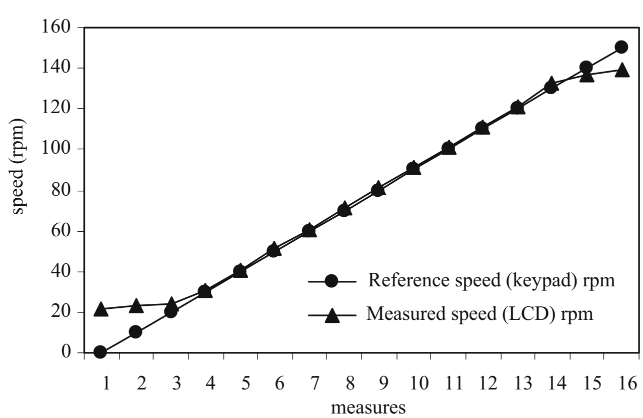

Fig. 10 Reference and measured speeds

Control input of the drive system is switching frequency, f_s. This control input obtained from comparison of feedback electrode voltage (Vs) and reference DC voltage. According to the demanded speed, the value of switching frequency is adjusted. This is achieved by changing value of reference DC voltage. To change value of reference DC voltage, the duty cycle of PWM signal is changed. So, according to the duty ratio of PWM signal, the DC output of low-pass (LP) filter is controlled. The designed filter circuit is shown in Fig. 3. As seen from figure, the input of filter is controllable PWM signal. According the duty ratio of this signal, filter produces reference DC voltage. When the duty ratio of PWM signal increases, the DC output value of filter increases [16].

Several speed and position control techniques have been reported in recent years. Generally computers, digital signal processors or sophisticated microcomputer/microprocessor devices have been used to achieve that controls. In the present study USM drive system has been controlled by PIC16F877 microcontroller. The proposed control system is new and original. With respect to developed system very simple and reliable control system has been developed. The PIC microcontroller based USM control scheme is very simple, cost-effective, lightweight, reliable, and practicable. By the proposed method, USM can be driven and controlled with very simple control technique.

The block diagram of PIC controlled USM drive system has been given in Fig. 4. PWM signal, CW and CCW direction signals are produced by GPIO ports of PIC microcontroller. The digital input pins of microcontroller have been used for encoder signals. Encoder is 500-ppr and has two quadrature encoder signals and an index signal. The actual and reference speed are shown on LCD display. The overall power required to drive and control system provided with a single DC power supply.

5 Experimental results

In this section, the experimental results of PIC microcontroller based digitally controlled USM drive system are presented. Two-phase output voltages and speed graphics are given for two different duty cycle of PWM signal to show relation between duty ratio and speed of motor.

Figure 5 gives PWM signal and motor speed. In this manner the reference speed is 42 rpm. The actual speed is measured and demonstrated on LCD screen. USM rotates with 42 rpm as the reference speed. Figure 6 shows the output two-phase voltages on this speed. As seen from the figure, the phase voltages are 124 V and 121 V respectively. The period of phase voltage is 23.6 μs resulting 42.37 kHz driving frequency.

The reference sped is varied to 90 rpm to demonstrate reliability of the system. Figure 7 shows PWM signal and motor speed at this reference The actual speed is measured as 90 rpm and represented on the LCD. Figure 8 shows the output two-phase voltages on this speed. The output voltages of the inverter are 115 V and 109 V respectively. The period of phase voltage is 24 μs resulting 41.66 kHz driving frequency. It is clear seen from the results that, the driving frequency of the motor is decreased to provide increase in the motor speed.

Figure 9 shows both the reference and actual speeds measured on the LCD for 42 rpm and 90 rpm reference speeds. As seen from this figure, the measured actual speed equal to the reference speed. Drive system has been tested for different speed values. Figure 10 shows compatible between reference and actual speed for different measurements. As seen from that figure, the actual speed follows the reference speed especially in the control area of the USM which can be described as between 30 rpm and 130 rpm speed range.

6 Conclusions

In this paper a PIC microcontroller based digital control system of TWUSM has been designed and implemented. To drive USM high-frequency voltage-fed serial-resonant inverter has been designed. The speed of USM has been controlled by the driving frequency. The value of driving frequency is controlled by PWM output of microcontroller. By changing the duty cycle of PWM signal, the driving frequency is changed. As a result the speed of USM is controlled.

The performance of proposed driving and control system has been demonstrated with experiments. Phase voltages, PWM duty ratio and motor speed have been measured. Two measurement samples results have been given and discussed. The reference and actual speeds are shown on LCD to show reference and actual speeds are equal. The developed control scheme has been also tested for the different operating conditions. The developed drive and control system have been applied to the speed control loop of USM. The experimental results have demonstrated that the proposed drive and control system gives accurate and rapid speed characteristics for USM. The PIC microcontroller based digital control of USM control scheme is simple, cost-effective, reliable and convenient to be used in practical applications.

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