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Ultrasonic motors: Their models, drives, controls and applications

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Abstract In the last decades piezoelectrically driven ultrasonic motors have become alternative actuators to the conventional electromagnetic motors especially for precise and accurate servo positioning applications. Different types of ultrasonic motors have been constructed and manufactured. Several drive systems have been designed, implemented and proposed for these motors. A variety of control techniques have been applied to them. The research given in this study covers bases of the ultrasonic motors. Theoretical background, modeling, drive systems, control techniques and applications of the ultrasonic motors have been introduced. Firstly, the general overview has been given. Then, modeling studies focused on performance estimation and analysis of ultrasonic motors have been examined. Afterwards, drive systems and control techniques of ultrasonic motors have been investigated. Furthermore, an example drive and control system has been presented. This drive system has been designed as to be controlled digitally. In addition, the important industrial and research applications of these motors have been included. The presented study has been arranged as a review of ultrasonic motors. The important points of specifications, models, drive systems and control methods of the ultrasonic motors have been emphasized.

Keywords Ultrasonic motor · Modeling · Drive · Control · Application

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1 Introduction

Ultrasonic motors (USMs) are new type of actuators that use ultrasonic level mechanical vibrations as their driving source. USM has different construction, characteristics and operating principles than the conventional electromagnetic motors. USM have important advantages such as; high holding torque, high response characteristics, high torque density, silent operation, no electromagnetic noise and compact size. Consequently, USMs have attracted for precise and accurate speed and position applications in recent years. On the other hand, USMs have disadvantages that must be practically eliminated. The control characteristics of USMs are complex. The motor parameters are time-varying owing to increase in temperature and changes in motor drive operating conditions such as driving frequency, source voltage and load torque. The contact mechanisms of these motors limit the motor life [1, 2].

The research and applications studies of USMs have increased in the last decades. The investigations and applications are focused on; working for materials design, properties and new types of the USMs, modeling studies providing high efficient operating points of the motor, drive systems and control techniques researches to obtaining effective, reliable, robust, and precise practical applications.

This paper reviews recent developments of the USMs. The study concentrated on traveling-wave type ultrasonic motors (TWUSMs). The paper arranged as follows. After a general introduction given in the first section, the theoretical background of USMs has been given in the second section. Modeling studies have been investigated and simple equivalent circuit model (ECM) of USM has been introduced in the third section. Research studies related to drive systems of the motor have been discussed and a two-phase serial-resonant inverter has been offered in the fourth section. Control techniques and properties have been given in the fifth section. In addition, a DSP control of USM has been proposed. In the sixth section, research and practical applications of the motor have been introduced. Finally, the general evaluation and conclusions have been presented in the last section.

2 Ultrasonic motors

In the operation of the USM two-stage energy conversion is formed. In the first stage, the electrical energy is converted into mechanical energy by excitation of the piezoelectric ceramic with ultrasonic range frequency, called as electromechanical energy conversion. In the second stage, the mechanical vibrations are converted to linear or rotary motion by friction force generated in the stator–rotor interface, called as mechanical energy conversion.

There are various categories to classify ultrasonic motors such as [3]:

(1) Operation: Rotary type and linear type
(2) Device geometry: Rod type, π-shaped, ring and cylinder types
(3) Generating wave: Standing wave type and traveling wave type.

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

The cutaway view of common used Shinsei's USR60 TWUSM is shown in Fig. 1. The motor mainly consists of

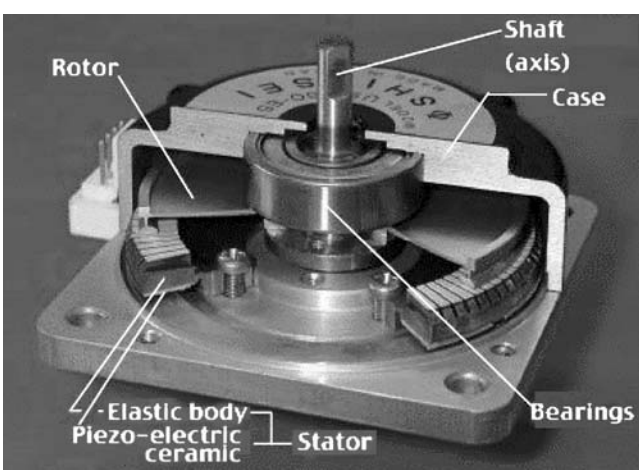


Fig. 1 Cutaway view of Shinsei's USR60 TWUSM

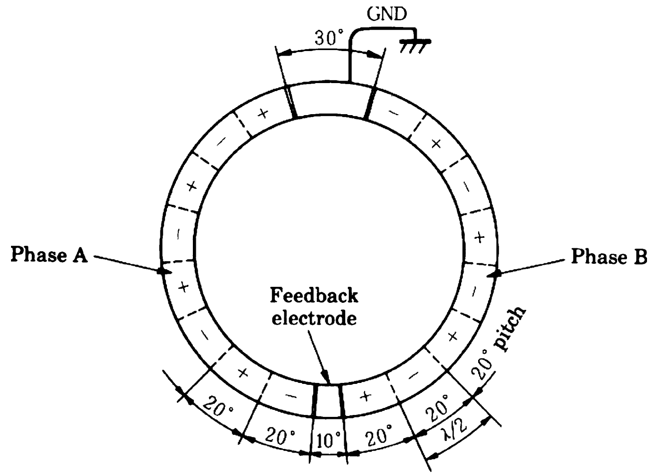


Fig. 2 Piezoelectric disc and electrode arrangement of USM

stator and rotor components. The stator consists of the piezoelectric ceramic and the elastic body. The rotor is made from bronze material and pressed against the stator. When two-phase voltages applied to two orthogonal modes of piezoelectric ceramic of USM, elliptical waves occur on the stator surface. The rotor is driven by the tangential force at the contact surface resulting from the elliptical motion at the wave crests. The rotation direction of rotor is opposite to the direction of the traveling-wave [4].

The electrode arrangement in disc type piezoelectric ceramic is shown in Fig. 2. (+) and (−) signs show the polarized directions. When a positive voltage applied to a segment indicated by (+), it will be expand. With a negative voltage it will contract. The reverse occurs for a segment (−). The 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. The value of this voltage is proportional to the speed of motor.

To generate a traveling-wave within the stator, it is necessary to have control of two mechanical orthogonal modes. Electrode pattern A provides the *coskθ*, and the pattern B *sinkθ*. By driving these two modes 90° out of phase temporally a traveling-wave is produced. Pattern A and B provides standing wave individually. The superposition of these standing waves produce a traveling-wave used in TWUSMs. By changing the sign one of the drive signals the direction of traveling-wave and thus direction of rotor changes [4].

$$\varpi = \cos\omega t \cos k\theta + \sin\omega t \sin k\theta \quad (1)$$

$$\varpi = \cos(\omega t - k\theta) \quad (2)$$

$$k = \frac{2\pi}{\lambda} \quad (3)$$

Where; ϖ is the travelling wave, k is the wave number of piezoelectric ceramic, λ is the wavelength of the (+) and (−) polarized one section. If the amplitude of the traveling-wave is represented by ξ and radial shape factor by R_r, the tangential motional equation of traveling-wave can be written as follows.

$$\varpi(r, \theta, t) = R_r \xi \cos(\omega t - k\theta) \quad (4)$$

3 Modeling studies of the ultrasonic motors

This section deals with modeling studies of USM and their application to the estimation of motor characteristics. How the performances are affected by operating conditions is an important subject for the high effectiveness applications and the control of USMs. Several theoretical and experimental modeling studies have been reported recently. In these studies finite element method (FEM), energy conversion method including contact mechanism, and equivalent circuit model (ECM) have proposed to estimate motor characteristics.

FEM Analysis of rotor/stator contact in a ring type USM has been presented by Maeno et al. [5]. Mechanical characteristics of stator and elastic contact between rotor/stator have been modeled with FEM to obtain important motor performances. Another example of FEM modeling of stator and contact layer is presented by Krome and Wallaschek [6]. Kagawa et al. [7] have presented finite element simulation of dynamic responses of piezoelectric actuators. A high power TWUSM is proposed in [8]. It is composed of an annular-shaped stator and two cone-shaped rotors that are pressed in contact to the borders of the inner surface of the stator. The vibrational behavior of the stator as well as the traveling wave generation has been simulated with the FEM software.

In the research on USMs the mathematical modeling of the contact mechanics and the optimization of lifetime and operational characteristics of the motors by a proper choice of contact materials and design parameters have been significant subjects. Analytical, numerical and experimental methods have been employed in the investigations. Wallaschek [9] presented contact mechanics model of piezoelectric USMs to summarize the state of the art in the understanding of some fundamental processes governing the contact mechanics of piezoelectric USMs. Working principle and mathematical modeling of the stator of TWUSM has been presented by Hagedorn and Wallaschek [10]. Nakamura et al. [11] reported a model for estimation load characteristics of an USM by measuring transient responses. The paper presents a method to estimate the load characteristics of the USM instantly by measuring its step responses. An important model for rotary type USM have been presented by Hagood and McFarland [12] for the purpose of predicting motor performance as a function of design parameters. The Rayleigh-Ritz assumed mode energy method has been used to model the distributed piezoceramics and the traveling wave dynamics of the stator. A study on the friction control mechanism of the USM has been presented by Nakamura and Ueha [13]. The authors attempt to estimate the theoretical limit of motor performance from the point of view of the friction control mechanism. The derivation of a mathematical model for traveling wave USMs and its experimental validation has been reported by Kandare and Wallaschek [14]. The motor has been structured into subsystems and models for the individual components have been derived, simplified and described mathematically in their study. The resulting sub models have been then joined into an overall unified model of the motor, which allows us to study the impact of diverse motor parameters and control variables on the motor performance. The effect of tangential elasticity of the contact layer between stator and rotor in TWUSM has been presented by Storck and Wallaschek [15]. The aim of the paper is to point out the importance of the tangential elasticity of the contact layer which is responsible for the formation of stick zones and also for the amount of friction losses and overall efficiency. In [16], a different torque estimator has been proposed. This estimator does not rely on the mechanical load characteristics, nor on the stator/rotor contact mechanism, but on the stator parameters. A method of numerical computation of the natural frequencies, depending on the most important running parameters for an USM, is described in [17].

Performance estimation of a rotary TWUSM based on two-dimension analytical model has been reported by Ming and Peiwen [18]. Model is constructed with the forced response of the stator produced by piezoceramics bonded under the stator and with the distributed spring-rigid body contact model between the stator and the rotor. Analytical modeling of mechanical energy transductions in standing wave ultrasonic motors (SWUSMs) have been reported by Moal et al. [19]. The study aims at describing mechanical energy transductions at the stator/rotor interface of SWUM. Theoretical approaches assume the decoupling of the out-of-plane and tangential behaviors. Moal and Cusin [20] have proposed a three-dimensional analysis of the contact mechanism at the stator-rotor interface of TWUSM. The paper has investigated optimization rules and new design methodologies dealing with the contact mechanics in rotating TWUSM. The proposed approaches focus on the design of the rotor. Complete modeling of rotary USM has been reported by Bao and Cohen [21]. To predict the motor performance with reasonable accuracy for motor design, a hybrid analytical model has been developed to address a complete USM as a system. Modeling and performance evaluation of traveling-wave piezoelectric USMs with analytical method has been implemented by Sun et al. [22]. The proposed model consists of two parts: one is for modeling mechanical vibrations of the stator with forced vibration equations, and the other is for modeling the contact between the stator and the rotor with consideration of the stick-slip behavior.

Equivalent circuit based characteristics estimation of a TWUSM has been presented by Hirata and Ueha [23]. The purpose of the paper is to propose a method of calculation of the load characteristics for TWUSM. A systematic procedure for estimating performance, including electrical and mechanical parts of the motor has been established. Aoyogi et al. [24] reported a simplified equivalent circuit of an USM and its applications. The circuit can be applied to show practical operation of the USM. An enhanced ECM of a rotary traveling wave piezoelectric USM is derived by Elghouti and Helbo [25]. This paper highlights the importance of the electromechanical coupling factor, which is responsible for the electrical to mechanical energy conversion. The emphasis is put on the difference between the effective coupling factor and the modal coupling factor. Juang and Gu [26] presents an ECM of a new disc-type USM and discusses its applications in evaluation of the stator's frequency characteristics. An ECM of TWUSM and its application to the estimation of motor characteristics has been reported by Bal and Bekiroglu [27]. The performance of USM under different speed and load conditions has been obtained in a systematical approach from proposed method in this study.

When rotor pressed against the stator with a normal forcing, frictional losses occur between the rotor and stator. These losses are represented by friction in final ECM. Also, the effects 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. Temperature-resonance frequency and temperature–time characteristics of piezoelectric ceramic 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. Detailed model derivation, explanation and obtained results can be found in reference [27].

When deriving mathematical model of the USM, both mechanical and electrical parameters should be considered. Also, the time dependent heat effect, contact mechanism, structure of the motor and load conditions have to be added to obtain precise and reliable model. If the effect of the input electrical parameters; phase-difference, driving frequency and phase voltages are combined with the mathematical model successfully, accurate and precise characteristics can be obtained.

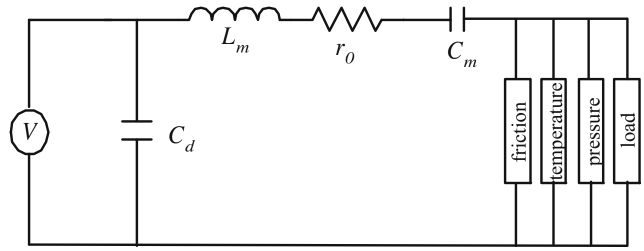


Fig. 3 ECM of the TWUSM

4 Drive systems of the ultrasonic motors

For practical operation of the USM a specific and 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 USM to provide resonant frequency. Drive system of two-phase high-frequency voltage fed serial-resonant inverter of USM generally includes pulse width modulation (PWM), pulse frequency modulation (PFM) and hybrid (PWM/PFM) control techniques.

Several driving circuits for the two-phase USM using series or parallel resonant techniques have been reported. Two automatic resonant frequency tracking control methods using inverter-fed USM are presented including sensor and sensorless schemes [28]. A driving circuit has been designed and a hybrid controller has been proposed for USM by Lin and Cuo [29]. The hybrid controller combines the advantages of variable-structure system and adaptive-model following control. Ferreira and Minotti [30] have described inverter-fed USM servo-control implementation with two control strategies from practical point of view. A high-frequency boost-chopper and two-phase inverter cascade configuration has been designed for the operating frequency and two-phase AC outputs with phase difference. A speed tracking servo control system has been presented for USM [31]. Power conversion circuit presented in that study includes boost chopper and two-phase inverter circuits. Speed control scheme use both driving frequency control loop with variable-gain strategy and the applied voltage control with reduction strategy. Kato and Sase [32] proposed a frequency tracking scheme based on detection of the maximum current proportional to the motor torque by the open-loop frequency scan and seek technique. 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, is presented by Lin et al. [33]. An energy feedback circuit is proposed to reduce the quality factor in the parallel-resonant circuit to resolve the difficulty of the amplitude variation and phase shift in the output voltage of the parallel-resonant inverter. An USM drive using a two phase current-source parallel-resonant inverter is proposed in [34]. LLC resonant inverter [35] and LLCC resonant circuit [36] are implemented to build a high-frequency two-phase voltage-source inverter for the USM. A highly effective load adaptive servo drive system of USM has been presented in [37]. The drive system incorporates high frequency two-phase serial-resonant inverter. A digital signal processor (DSP) is adapted to USM drive system. Instead of the direct current/alternating current (DC/AC) converter type driver using conventional electromagnetic transformer, a compact disc-type piezo-electric transformer is used to obtain high voltage output for driving the USM in [38].

Figure 4 shows a high-frequency voltage-fed serial-resonant inverter drive system of USM. This inverter featured with direct PWM control techniques. L_A and L_B inductances are connected in series with each phase to become resonant with the damping capacitance (C_d) of USM. Inverter outputs are two-phase high frequency ac voltages with 90° phase difference. The rotating direction is controlled by letting V_A or V_B lead. Clock-wise (CW) and counter clock-wise (CCW) inputs provide direction control signals. In practice, the driving frequency is set to higher than resonant frequency of mechanical vibration system due to basic operating characteristics of USM [39]. Figure 5 shows waveforms of these output voltages with the frequency of 41.74 kHz, which is equal to switching signal frequency. The output voltages are equal and 120 V (rms).

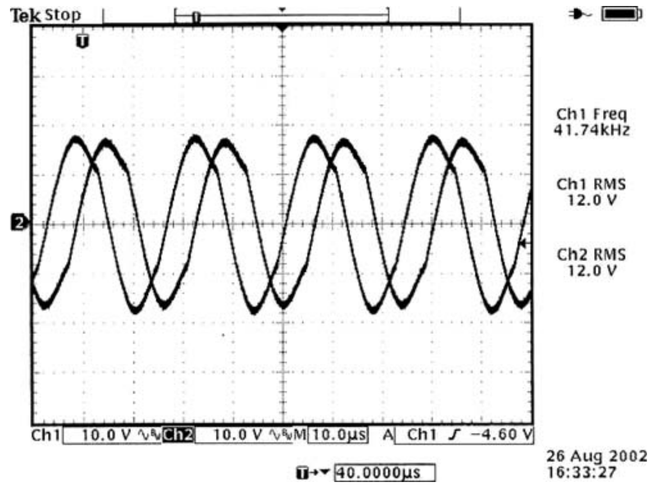
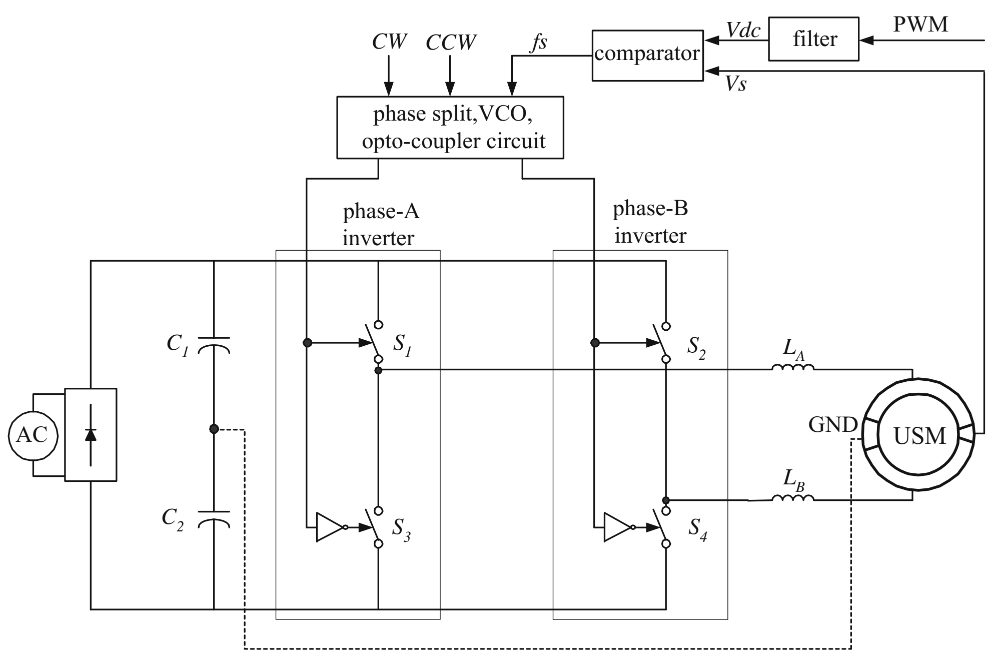


Fig. 5 Output voltages of two-phase inverter

Drive system of the TWUSM is basically two-phase high-frequency inverter. Serial or parallel resonant techniques can be used in the drive system. The key point is to generate two-phase voltages with proper driving frequency. When designing drive system, mechanical resonant frequency of the USM should be considered. Half-bridge serial-resonant inverter driver is good choice to drive the USM. Driver can be designed as to be controlled analogously or digitally.

Fig. 4 Two-phase serial-resonant inverter driver for TWUSM



Digitally controllable drive system is more flexible and precise solution for the USM.

5 Control methods of the ultrasonic motors

The speed and position of USM can be controlled by the amplitude, frequency and phase difference of two-phase voltages. Since changing driving frequency method gives more flexible control range than the other methods, USM is generally controlled by driving frequency method or by combining two α called as hybrid or dual control methods. Several speed and position control systems have been proposed. Model based, PI, direct PWM, sliding mode, fuzzy, adaptive fuzzy, neural network and fuzzy neural network controllers have been applied to the speed/position controls of USM in recent years. Digital signal processors, computers, microcomputers, special microcontroller/microprocessors have been used to achieve that drives and controls. The important contributions of literature related to control strategies of USM are given as follows.

The authors propose a simplified mathematical model for the USM in [40], which is expressed by a difference equation, and they then design a speed controller based on adaptive control theory. Adaptive control is attractive for controlling the USM because its speed characteristics vary with drive conditions. A complete model-based control for TWUSM is presented in [41]. The control scheme consists of inner control loops with respect to the oscillation systems, and outer control loops for torque and speed. Performance comparison of PI and adaptive controller for adjustable speed drives of USMs have been given in [42].

A PWM method for speed control of the TWUSM has been presented in [43]. This method online adjusts the duty ratio of each ultrasonic switching cycle which drives the two-phase inverter to achieve voltage amplitude control of the TWUSM. The focus is to propose a control method for amplitude control of the voltage sources. A simple PI control algorithm is adopted for system control. Senjyu et al. [44] have described the maximum efficient drive of USM. The paper presents speed control method with maximum efficiency by pulse width modulation (PWM) control of DC source voltage combined with drive frequency control. A PWM technique is presented for digital signal processor controlled drive system of TWUSM [45]. The driving frequency has been selected as control input both for the speed and position control loops. Experimental results revealed that the proposed drive and control system gives superior steady-state and transient performances in the speed and position control of USM. In [46] PIC microcontroller based simplified speed control system has been proposed for a TWUSM.

A robust controller is developed to perform a complete design for an ultrasonic servo motor system [47]. In the experimental validation, a field programmable gate array based controller is implemented to validate the feasibility of the design. An USM driven and controlled by the phase velocity difference between two traveling waves have been presented by Bai et al. [48]. Senjyu et al. [49] present a quick and precise position control method of controlling both the driving frequency and the phase difference of the applied voltages, a method refer to as the dual mode control. They adopt a PI controller to simplify the control system. Position control of USMs using sliding mode control with multiple control inputs has been proposed by Senjyu et al. [50].

Servo control implementation incorporating a software based fuzzy reasoning concept is described in [51] from practical point of view. A compact USM actuated software system implementation using fuzzy reasoning-based controller has been presented by Furuya et al. [52]. Fuzzy logic controller using DSP has been used to control speed [53] and position [54] of TWUSM. Fuzzy adaptive model following controller using PC with servo control card [55] have been presented for position control of USM. Model reference adaptive control with fuzzy inference has been applied to position control of USM [56]. The dead-zone is compensated by fuzzy inference, whereas model reference adaptive control performs accurate position control.

NN controller has been applied to speed control of USM. This paper adopts the driving frequency as control input in order to simplify the drive system [57]. NN controller has also applied to position control of USM. To further improve the motor performance, both the driving frequency and phase difference of the two-phase voltages are used [58]. A robust control system is designed using two NNs to control the rotor position of the USM [59]. The NN control system is implemented in a DSP-based control computer to demonstrate the control and learning abilities of the proposed control system.

The fuzzy neural network (FNN) position controller is implemented to control the USM drive to reduce the influence of parameter uncertainties and external disturbances [60]. A dual-mode neuro-fuzzy controller (NFC) controller is proposed and implemented for speed tracking control of the TWUM [61]. The key is to newly incorporate NFC and direct PWM as well as 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 low-cost single-chip DSP based microcontroller. A position control scheme for the USMs that eliminates the problem due to dead-zone by employing FNN proposed in [62]. To achieve the accurate position control when drive conditions vary, FNN can adjust the membership function for the antecedent part. The training of FNN is achieved using online back propagation algorithm. The dead-zone is compensated by FNN, and PI controller performs the accurate positioning of the drive system. In [63], remote control of USM has been implemented by using a standard GSM mobile phone. This system is flexible to be controlled with both GSM and DTMF based phones. With the developed drive and control system the overall control of the USM has been achieved.

The block diagram of the PWM control for speed control of USM is represented in Fig. 6. The speed of USM is measured and compared with the reference speed. PWM controller generates appropriate PWM and resulting reference dc signal by using PI control. Frequency controller compares the reference dc signal and ac feedback signal to produce and apply the necessary frequency value to the motor. The developed control scheme does not require the knowledge of the parameters of the USM, and can provide the effective speed characteristics online against various drive conditions. USM drive system has been controlled by 16-bit fixed point TMS320F243 EVM DSP has been proposed in the present study. TMS320F243 DSP is especially useful for motor and motion control applications. The block diagram of TMS320F243 controlled USM drive system is given in Fig. 7. The event manager and general purpose I/O (GPIO) units of DSP have been used for controlling of USM. The PWM signal is produced by GP timer-1. The GP timer has been set in continuous-up count mode to provide asymmetric PWM signal. CW and CCW direction signals are produced by GPIO. The quadrature encoder pulse QEP circuit of event manager is used for encoder signals.

Driving frequency, phase-voltages and phase difference can be used individually to control speed or position of the USM. Driving frequency control input gives wide control area to the designers. So, it can be preferred as a control input. As well as, hybrid or dual control methods with multiple control inputs can be used as alternative control methods. PI control algorithm is simple and can adaptable easily to the USM control system. Also, fuzzy and neural network control algorithms can be considered in complicated control applications of the USM. Single chip microprocessor and microcontroller devices can be used to achieve control applications of the USM successfully.

6 Applications of the ultrasonic motors

USMs are particularly superior in high holding torque and precise speed/position responses. Thus, USMs have attracted considerable attention for servo-drive applications. Due to their features, USMs have recently begun to use for industrial, robotic, space medical and automotive applications.

The piezoelectric actuators and USMs have been developed by private industries in Japan, aiming at the applications to precision positioners and compact motors, and are too practical to be supported by Japanese government. A paper which reviews recent development trend of the piezoelectric actuators/ultrasonic motors viewed from Japanese patent disclosure, and predict their future market have been presented by Uchino [64].

The excellent high torque at low speed and high holding torque characteristics of the USM make it more suitable as the actuator for an accurate motion control system in the possible applications where high holding torque property is required without any shift-gears or stoppers. A USM driving two-axis motion control system with reference-word circular interpolation technique is proposed for the possible two-axis motion control applications of high torque at low speed [65]. Piezoelectric USMs have great potential for space-based robot applications. The motors are light in weight and mechanically simple. The motors possess high friction when static, and therefore, can also function as mechanical brakes [66, 67]. Jang et al. [68] describe the control system used to operate a number of USMs that move the joints of a robotic arm. The system consists of a control board and a high-speed data bus board paired with each USM. Development of a robot finger for five-fingered hand using USMs has been presented in [69]. Piezoelectric micro motors have been investigated and fabricated for micro robots in [70]. By combining new robot control systems with piezoelectric

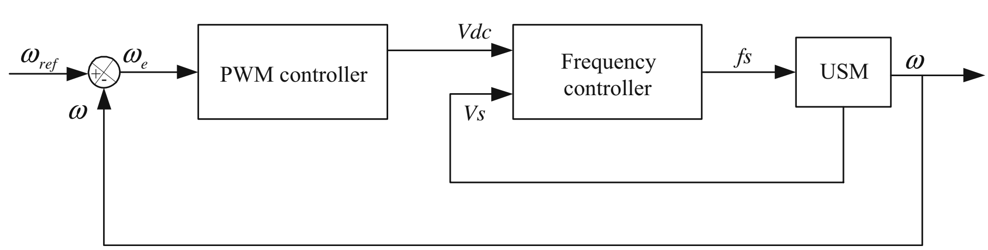


Fig. 6 Block diagram of PWM control scheme

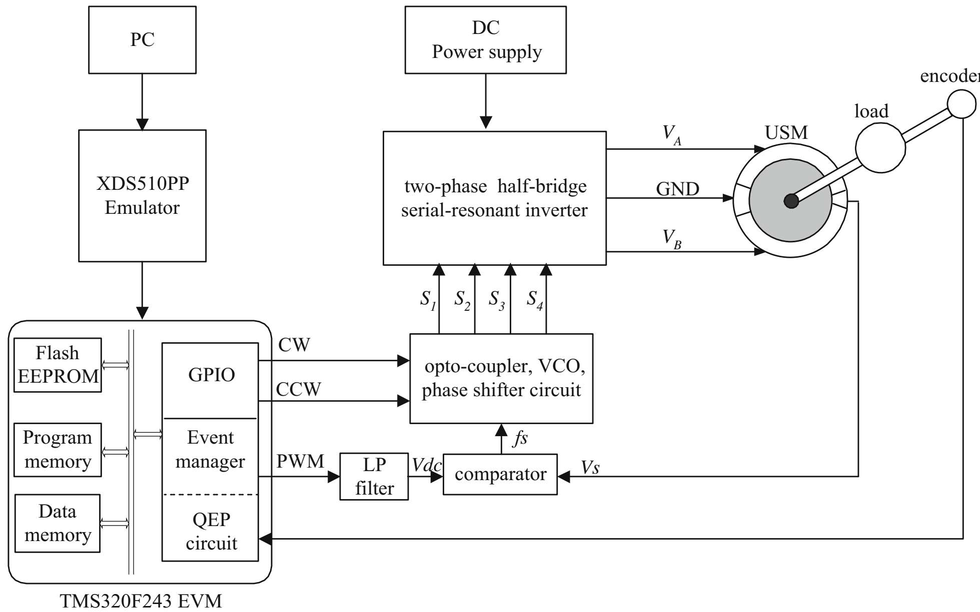


Fig. 7 DSP controlled USM drive system

motors and micromechanics, authors propose creating micromechanical systems that are small, cheap and completely autonomous.

USMs are considered for medical applications and have been applied to the practical applications in recent years. Izawa et al. [71] described the development of an magnetic resonance (MR) compatible manipulandum actuated by the USMs, which can able to work within MRI scanner and to perform MR imaging task continuously during finger movements. In [72], the design, construction, and experimental characterization of the first mechanical scanning probe for ophthalmic echography based on a small piezoelectric USM have been reported.

In following, different research and commercial applications of USM have been given. The automatic focusing mechanism incorporating rotary TWUSM has developed and reported for the Canon camera [1]. In [73], authors propose new optical cross-connect switches using ultrasonic micro motors. They take advantage of self hold, precise control, and low electric power consumption features of USM. Analysis and phase control of a TWUSM for haptic-stick application has been presented in [74]. Haptic or force feedback systems offer many improvement possibilities in different areas such as avionics, cars, or dangerous learning situations. The active feedback needs actuators which can produce real forces or torque, often at very low speeds, to simulate the real system reactions. USMs have a quick response, however, a torque free condition that gives no feeling to a user doesn't exist on USM. One of solutions of this problem is to have a static clutch mechanism within a USM. A novel USM equipping with a clutch mechanism has been proposed and examined in [75]. The principle of the adopted USM, the development subjects, design procedure, experimental results, and details of the application to the motor-driven potentiometer have been described in [76]. Development of a self-oscillating ultrasonic micro-motor and its application to a watch has been reported by Iino et al. [77]. They succeeded in further miniaturization of the ultrasonic micro-motor to simplifying the motor structure, especially the rotor pressuring mechanism and bearing. Additionally, they have realized mass production of these motors and applied it to some functions in watches. In [78], the design and characteristics of a p-shaped USM which is applicable to optical zoom operation of lens system for mobile phone are investigated.

7 Conclusions

In this study, an overview on recent development in the field of USMs has been presented. First the general features of the USMs have been given. Next, modeling studies of USMs have been surveyed. FEM, analytical, and equivalent circuit based modeling studies of USM have been investigated. In addition, an example ECM of the USM has been given. Then, driving systems of USMs have been studied and an example two-phase high-frequency serial resonant driver for TWUSM has been proposed. Thereafter, PC, DSP and microprocessor/microcontroller based PI, sliding-mode, fuzzy, neural-network, neuro-fuzzy speed/position control techniques for USMs have been represented. Also, DSP based digital control scheme of USM has been introduced. Furthermore, the applications of USMs have been summarized. The present study has been arranged in systematical method and intended to be an important review study of the USMs.

For the future applications of USMs, systematic researches and studies on the following issues will be necessary: Developing high resistance and long life piezoelectric materials; obtaining high accuracy and comprehensive models; designing high frequency, high power, and high efficient drive systems; improving rapid response, cost-effective and reliable control techniques.

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