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

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 character-

istics 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,](#9) [2](#9)].

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 theoret-

ical background of USMs has been given in the second

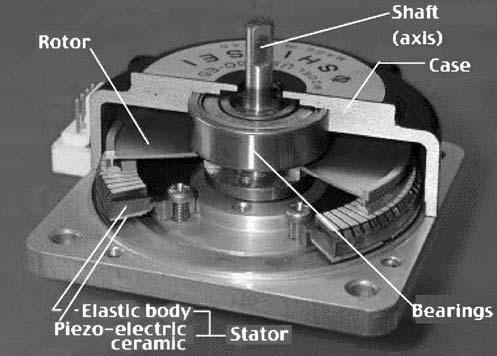
section. Modeling studies have been investigated and

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

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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 electro-

mechanical 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](#9)]:

(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](#2). The motor mainly consists of

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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].](#9)

The electrode arrangement in disc type piezoelectric

ceramic is shown in Fig. [2](#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 superpo-

sition 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].](#9)

ϖ ¼ cos ωt cos kθ þ sin ωt sin kθ ð1Þ

ϖ ¼ cos ðωt kθÞ ð2Þ

Fig. 1 Cutaway view of Shinsei’s USR60 TWUSM

k ¼

2p

l

ð3Þ

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Where; ϖ is the travelling wave, k is the wave number of

piezoelectric ceramic, 1 is the wavelength of the (+) and (−)

polarized one section. If the amplitude of the traveling-

wave is represented by J and radial shape factor by Rr, the

tangential motional equation of traveling-wave can be

written as follows.

ϖðr; θ; tÞ ¼ Rrξ cos ðωt kθÞ ð4Þ

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](#9)]. 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].](#9) Kagawa et al. [[7](#9)] have presented finite

element simulation of dynamic responses of piezoelectric

actuators. A high power TWUSM is proposed in [[8].](#9) 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 inves-

tigations. Wallaschek [[9](#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 piezoelec-

tric USMs. Working principle and mathematical modeling

of the stator of TWUSM has been presented by Hagedorn

and Wallaschek [[10].](#9) Nakamura et al. [[11](#9)] 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

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Hagood and McFarland [[12]](#9) 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].](#9) 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](#9)]. 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].](#9) 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],](#9) 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 param-

eters. A method of numerical computation of the natural

frequencies, depending on the most important running

parameters for an USM, is described in [[17].](#9)

Performance estimation of a rotary TWUSM based on

two-dimension analytical model has been reported by Ming

and Peiwen [[18](#9)]. 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].](#9) 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]](#9)

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].](#9) 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

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evaluation of traveling-wave piezoelectric USMs with

analytical method has been implemented by Sun et al.

[[22](#9)]. 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.

*V*

*Cd*

*Lm*

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*r0Cm*

Equivalent circuit based characteristics estimation of a

TWUSM has been presented by Hirata and Ueha [[23](#9)]. 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]](#9) 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](#9)]. 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](#9)] 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](#9)]. 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 Cmand Cd. 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 piezoelec-

tric 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](#4). Detailed

model derivation, explanation and obtained results can be

found in reference [[27].](#9)

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

Fig. 3 ECM of the TWUSM

model successfully, accurate and precise characteristics can

be obtained.

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 piezoelec-

tric 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 meth-

ods using inverter-fed USM are presented including sensor

and sensorless schemes [[28].](#9) A driving circuit has been

designed and a hybrid controller has been proposed for

USM by Lin and Cuo [[29].](#9) The hybrid controller combines

the advantages of variable-structure system and adaptive-

model following control. Ferreira and Minotti [[30](#9)] 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 cas-

cade 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].](#9) 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]](#9)

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–

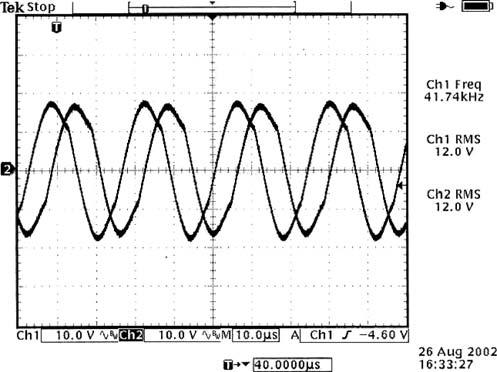
pull dc–dc power converter and a current-source two-phase

friction

temperature

pressure

load

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parallel resonant inverter, is presented by Lin et al. [[33].](#9) 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](#9)]. LLC resonant inverter [[35](#9)] and

LLCC resonant circuit [[36]](#9) 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](#9)]. 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].](#9)

Figure [4](#5) shows a high-frequency voltage-fed serial-

Fig. 5 Output voltages of two-phase inverter

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resonant inverter drive system of USM. This inverter

featured with direct PWM control techniques. LAand LB

inductances are connected in series with each phase to

become resonant with the damping capacitance (Cd) of

USM. Inverter outputs are two-phase high frequency ac

voltages with 90° phase difference. The rotating direction is

controlled by letting VAor VBlead. 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].](#9) Figure [5](#5)

Fig. 4 Two-phase serial-reso-

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).

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.

PWM

nant inverter driver for TWUSM

*CW CCW*

*fs*

comparator

*Vdc*

*Vs*

filter

AC

*C1*

*C2*

phase split,VCO,

opto-coupler circuit

phase-A

inverter

*S1*

*S3*

phase-B

inverter

*S2*

*S4*

*LA*

*LB*

GND

USM