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Ultrasonic Motors

Technologies and Applications

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(超声电机技术与应用)

With 564 figures, 14 of them in color

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Preface

As a new type of micro-motor, the Ultrasonic Motor (USM) has gained rapid development and wide applications since the 1980's. Unlike traditional motors with electromagnetic effect, USM is driven by ultrasonic vibration and piezoelectric effect. This new type of motor covers a wide range of subjects, including mechanical vibration, tribology, materials science, mechanical design, electronics, automatic control, super-precision process, etc. Ultrasonic motors have many excellent performances and features, such as simple construction, high torque density at low speed, direct drive without speed reduction gears, quick response, better electromagnetic compatibility, high holding torque while power off, quiet running, efficiency insensitive to the size, etc. They have been applied to robots, exact facilities, medical instruments, etc.

With the development of new materials, advanced technologies, and new structural types, the construction and performance of ultrasonic motors will be improved and their applications will be broadened to encompass a wider area including space vehicles, MEMS, semiconductor manufacturing, life sciences, etc.

During my visit at MIT from 1992 to 1994, I started research on ultrasonic motors. I came back to China in 1994 and continued my research at Nanjing University of Aeronautics and Astronautics (NUAA). I built a research group in 1995. My group designed and manufactured a traveling wave rotary ultrasonic motor with integrated construction that operated properly by the end of that year. In 1997, I founded the Ultrasonic Motors Research Center (UMRC) in NUAA. In 1999 I organised the First Chinese Workshop on Ultrasonic Motor Techniques (CWUMT) with the support of National Natural Sciences Foundation of China (NSFC). The research and development in this area has rapidly advanced since then, and our Research Center was further promoted to be the Ultrasonic Motors Engineering Research Center of Jiangsu Province in 2001. Five years later, the Research Center was renamed the Precision Driving Laboratory (PDLab). The 4th International Workshop on Piezoelectric Materials and Applications in Actuators (IWPMA4) was held at NUAA on September 2007.

For the past 15 years, our research team has systematically studied ultrasonic motors in depth and obtained considerable achievements, including motion mechanism, electromechanical coupling model, optimal design of structural parameters, driving/control techniques, etc. We have developed more than 30 types of new ultrasonic motors with independent intellectual property rights and corresponding drivers. We have 71 invention patents either awarded or pending in China and more than 500 papers published in journals and conferences. Our project of "Research on Ultrasonic Motors" was awarded multiple national awards.

The achievements of our team can be concluded as follows:

1. In Theory

On the basis of dynamic substructure theory, a comparatively well designed electromechanical coupling model of the traveling wave type rotary ultrasonic motor is built. A new friction interface model which takes the stator teeth and the radial sliding between the stator and rotor into consideration is proposed, and this model can precisely predict the output performances of the type of ultrasonic motors. Instead of the traditional concept of "resonance point/constant voltage ", a new concept of "anti-resonance point/constant current ", which is more effective for improving the efficiency and stability of the traveling wave ultrasonic motor, is put forward. An effective frequency automatic tracking method which can lower the instability of ultrasonic motor's speed (within 5%) is found, and this method succeeds in solving the bottleneck of the ultrasonic motor (the speed is down while the temperature is up). A method on solving the mode mixture in the near frequency of the ring stator or circular plate stator is obtained, and this method can improve the stability of the ultrasonic motor. The elliptical motion equation of a bar-type traveling wave ultrasonic motor is derived, and the concept of the effective ellipse orbit which provides a theoretical basis to the optimization of the bar-type ultrasonic motors is proposed.

2. Design Methods

An optimal design of structure parameters for the ultrasonic motor put forward and the corresponding software is developed. By applying the sensitivity analysis of structure parameters and structural dynamic modification technique to the design of the ultrasonic motors, an effective method which can adjust the stator's two-phase or multi-phase modal frequencies to be the same. To propose that the design of piezoelectric ceramic components used for the ultrasonic motors should be in accordance with the strain mode of stator instead of its displacement mode; To put forward a method which simultaneously utilizes different types (extension-contraction, bending and torsion) of vibration modes in-/out-of-planes for designing all types of ultrasonic motor; To point out that the design of the flexible rotor is very important, and to present some design methods for it; To provide the concept and design principles of the step ultrasonic motors.

3. Testing Techniques

A series of test devices is developed independently or cooperatively. Some effective test methods have been proposed, including modal tests with nm amplitude in ultrasonic frequency area, load characteristics tests in low speed and ultrasonic frequency area, response time tests at power on/off of the ultrasonic motors, measurement devices and methods of the dynamic friction between the stator and rotor, life test equipment and methods for the ultrasonic motor, test methods of the ultrasonic motor under an extreme environment(vacuum, high/low temperatures), and performance measurement methods and preparation devices of new friction materials.

4. Applications

Two series of the ultrasonic motors (TRUM and BTRUM) have been independently developed, and some of them are applied to industry, medical and precision instruments. Moreover, we have also provided prototypes of the ultrasonic motors to some companies. This creates favorable conditions for realizing the ultrasonic motor industrialization in China. At the same time, we have investigated some precision position and constant speed control systems with multi-variable (speed, frequency and phase) using the ultrasonic motors as actuators, including a position control system used for suppressing a two-dimensional wing's flutter, a constant speed control system used for injector of nuclear magnetic resonance, a composite control system based on FNN and Fuzzy control strategies which is used for drive/control a robot, a control system for automatically tracking targets based on vision, a fuzzy control system applied to portable gasoline generators, etc.

In addition to the achievements and innovations mentioned above, this book also fully absorbs the most advanced and important results in this area over all world in order to enrich the content.

There are 15 chapters in the book.

Chapter 1 is an introduction, which describes the history, classification, characteristics and applications of ultrasonic motors.

Chapter 2 describes the fundamentals of piezoelectricity and piezoelectric materials used for ultrasonic motors, and emphasizes the influence of piezoelectric materials on the performance of ultrasonic motors. The knowledge on how to select the piezoelectric materials used for USM is also introduced.

Chapter 3 introduces the fundamentals of tribology and tribomaterials used for ultrasonic motors. Some tribomaterials for ultrasonic motors are proposed. In addition, the components and produce process of two new kinds of friction materials are provided.

Chapter 4 introduces the fundamentals of vibration and wave applied to ultrasonic motors. It expounds the displacement and strain modes of elastic bodies such as a common rectangular, circular, ring plates and a cylindrical shell which are used for the stator of ultrasonic motors. The strain mode is a basis of the piezoelectric component polarization division for effectively exciting the stator. Moreover, some important concepts are analyzed, such as the relation between standing wave and traveling wave, mode superposition, mode separation and wave propagation in elastic bodies.

Chapters 5-11 describe the motion mechanism, electromechanical coupling model, optimal design of structure parameters and testing for different types' ultrasonic motors, including the disk-and bar-type traveling wave ultrasonic motor, the longitudinal-torsion hybrid type ultrasonic motor, the linear ultrasonic motor, the step ultrasonic motor, the non-contact ultrasonic motor, the surface wave ultrasonic motor, etc. These chapters are the most important as they represent our academic achievements and innovations.

Chapters 12-13 describe the driving and control techniques of the ultrasonic motors. Chapter 13 introduces the drive principles and design methods of the drivers in detail, and provides an actual driver circuit which is in use at PDLab.

Chapter 14 introduces various tests of the ultrasonic motors, including testing principles, methods, and equipment and the analysis of testing results.

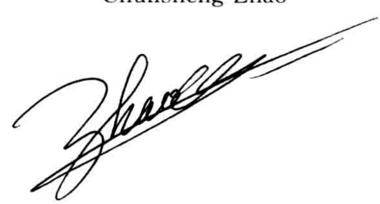
Chapter 15 summarizes the practical applications of ultrasonic motors and looks to the future of this area.

This book is a comprehensive tutorial for practicing engineers and researchers developing the ultrasonic motor technologies and applications. It is also an up-to-date reference for graduates taking a course on ultrasonic motor technologies.

Finally, I tell my readers that I will greatly appreciate your comments and suggestions.

June 5, 2010

Chunsheng Zhao



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Symbols

The following symbols are commonly used with the attached definitions, unless otherwise specified in the text.

x, y, z	Spatial coordinates in a global system
u, v, w	Displacements in x, y, z directions
U_0, V_0, W_0	Amplitudes in x, y, z directions
u_0, v_0, w_0	Displacements of neutral layer
$\dot{u}, \dot{v}, \dot{w}$	Velocities in x, y, z directions
$\ddot{u}, \ddot{v}, \ddot{w}$	Accelerations in x, y, z directions
$V(V_{s\tau}, V_\tau)$	Tangential velocity
$n(n_a, n_i, n_l)$	Rotating speed (Speed)
l	Length
b	Width
h	Height, thickness
$r(r_c)$	Radius
$D(d)$	Diameter
m	Mass
M_i	i th modal mass
K_i	i th modal stiffness
F_i	i th modal force
C_i	i th modal daming
S	Area
ρ	Density of material
E	Young's modulus
μ	Poisson ratio
G	Shear modulus of elasticity
$I(I_x, I_y, I_z, I_p)$	Inertia moment
$c(c_l, c_\tau, c_s, c_r)$	Velocity of wave propagation
λ	Wave length
k	Wave number
$\mu(\mu_d, \mu_s)$	Friction coefficient
$\boldsymbol{\sigma}(\sigma_i, \tau_{ij})$	Stress matrix
$\boldsymbol{\varepsilon}(\varepsilon_i)$	Strain matrix
$F(F_n, F_\tau)$	External force

F_f	Friction force
$f(x), f(y), f(z)$	Distributed forces in x, y, z directions
$P(P_0)$	Pre-pressure (Preload)
$M(M_x, M_x, M_z)$	Bending moment
M_T	Torque
t	Temporal variable
$\varphi_A(\theta)$	Voltage sign function of the polarization of phase A
$\varphi_B(\theta)$	Voltage sign function of the polarization of phase B
e	Code of the tooth cell
$\boldsymbol{\Phi}_s$	Shape function of annular cell
$\boldsymbol{M}^j$	Mass matrix of annular cell
$\boldsymbol{\delta}^a$	Displacement column matrix of substructure a
$\boldsymbol{M}^a$	Mass matrix of substructure a
$\boldsymbol{K}^a$	Stiffness matrix of substructure a
$\boldsymbol{M}^e$	Mass matrix of tooth e
$\boldsymbol{a}^e$	Displacement column matrix of nodes of tooth e
$\boldsymbol{a}^e_I$	Displacement column matrix of inner nodes of tooth e
$\boldsymbol{\Gamma}^e$	Condensed matrix of tooth e
$\bar{\boldsymbol{K}}^e$	Condensed stiffness matrix of tooth e
T	Kinetic energy
V	Potential energy
f	Frequency (Friction force)
ω	Angular frequency
$\phi_n(x)$, ϕ_n	nth mode shape
$f_n(\omega_n)$	nth mode frequency
$\boldsymbol{\Phi}$	Mode shape matrix
$\varphi(\varphi_n)$	Phase angle
$q(t)$	Modal coordinate
B_{mn}	Bending mode
$\boldsymbol{Q}_m$	Mechanical quality factor
$\boldsymbol{\kappa}(\kappa)$	Force coefficient matrix
$\boldsymbol{\Phi}_m$	Shape function matrix
p_j	Variable for structure design
S_{p_j}	Sensitivity with respect to p_j
$S^R_{p_j}$	Relative sensitivity with respect to p_i
$\boldsymbol{N}$	Radial shape function matrix
$\boldsymbol{\delta}^j$	Node column matrix of annular cell
$\boldsymbol{K}^j$	Stiffness matrix of annular cell
$\boldsymbol{\delta}^b$	Displacement column of substructure b
$\boldsymbol{M}^b$	Mass matrix of substructure b
$\boldsymbol{K}^b$	Stiffness matrix of substructure b

$\boldsymbol{K}^e$	Stiffness matrix of tooth *e*
$\boldsymbol{a}_J^e$	Displacement column matrix of boundary nodes of tooth *e*
$\boldsymbol{\psi}^e$	Static condensed matrix of tooth *e*
$\overline{\boldsymbol{M}}^e$	Condensed mass matrix of tooth *e*
$\boldsymbol{\epsilon}^{\varepsilon}$	Dielectric constant matrix under ε=constant
L	Lagrange function
δW	Variational Work
$Q(Q_A, Q_B)$	Charge on electrode
$\boldsymbol{\delta}_s$	Generalized coordinate column matrix
$\boldsymbol{K}_s$	Generalized stiffness matrix
$\boldsymbol{e}_r$	Radial unit vector
$\boldsymbol{e}_z$	Axial unit vector
$\boldsymbol{e}_\theta$	Circumferential unit vector
$\boldsymbol{P}(P)$	Polarization intensity vector
$\boldsymbol{E}(E_i)$	Electric field intensity vector
$\boldsymbol{D}(D_i)$	Electric displacement vector
$\boldsymbol{S}(S_i)$	Strain tensor
$\boldsymbol{T}(T_i)$	Stress tensor
$\boldsymbol{s}(s_{ij})$	Flexibility coefficient matrix
$\boldsymbol{c}(c_{ij})$	Stiffness coefficient matrix
k	Electromechanical coupling coefficient
$\boldsymbol{d}(d_{ij})$	Piezoelectric constant matrix
f_m	Minimum impedance frequency
f_n	Maximum impedance frequency
f_s	Series resonance frequency
f_r	Resonance frequency
f_a	Anti-resonance frequency
f_p	Parallel resonance frequency
$\boldsymbol{\varepsilon}(\varepsilon_{ij})$	Dielectric constant matrix
V	Voltage
V_{PP}	Peak-peak value of voltage
V_0	Voltage amplitude
V_A, V_B	Voltage of phase A or B
$\boldsymbol{I}(i, i_0)$	Current matrix
$\boldsymbol{I}$	Unit matrix
$R(R_1, R_d, R_m)$	Resistance
$C(C_0, C_1, C_m)$	Capacitance
$L(L_1, L_m, L_p, L_s)$	Inductance
Y	Admittance

$Z(Z_m)$	Impedance (Mechanical impendance)
$W(W_k)$	Work (electric potential energy)
D	Duty cycle
T_I	Integral time constant
T_D	Differential time constant
K_I	Integral coefficient
K_D	Differential coefficient
K_P	Scale factor
V_f	Isolated electrode voltage

Contents