Online Controller for a Piezoelectric Motor

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Abstract— **Traveling-wave ultrasonic motor has nonlinear characteristics, which varies with driving conditions associated the variations of temperature and applied load torque. In this work, a simple online speed controller is designed to improve the control performance of the motor. First, this paper suggests a Matlab-Simulink model of a traveling-wave ultrasonic motor, which defines the reference model. Then the controller based on an online tuning method is proposed to identify the plant parameters and detect the parameter variations of the motor immediately, so as to compensate it. Finally, the simulation results are described to confirm the effectiveness of the proposed method. The drive frequency is used as the input for the speed control scheme.**

Keywords— ***Ultrasonic Motor, Speed Control, Tuning Algorithm.***

I. INTRODUCTION

The traveling-wave ultrasonic motor has excellent performance and many useful features such as high holding torque, high torque at low speed, quiet operation, simple structure, compact size, and no electromagnetic interferences. However, the dynamical characteristics of the traveling-wave ultrasonic motor are complicated and highly nonlinear, and the motor parameters are time-varying due to temperature rise and changes in motor drive operating conditions [1]. Therefore, it is difficult to predict the performance characteristics of this motor under various working conditions.

The classical PID-control has more applications because the simple structure is easier for engineering design. But the fixed PID gains are hard to deal with the traveling-wave ultrasonic motor because the nonlinear and time-varying characteristics. Thus the control performance is not good. Therefore control strategies such as using adaptive PID-control, sliding mode control, fuzzy control and neural network control algorithms are put forward successively, which have obviously improved ultrasonic motor control performances [2-7]. But the complexity of these methods is great. For example, the fuzzy- neural control [7] combines the advantages of fuzzy logic and neural network, which can greatly increase control accuracy. However, it requires a large amount of calculation which increases the cost of hardware and software. This kind of control is expensive and confined only to high-precision applications.

In this paper, the speed control of a traveling-wave ultrasonic motor (USR60) based on an online algorithm is designed. This control algorithm compensates the speed characteristic variations of the motor with on-line parameters identification. The proposed control scheme, therefore, has robustness in terms of parameter variations. The model reference is obtained by Matlab-simulink model simulations, and the driving frequency is adopted as the control input.

The paper is organized as follows: in section 2, a mathematical model of the motor is presented and a reference model for USR60 is proposed, so as to control the motor. Section 3, introduces the proposed online controller. Simulation results are presented in section 4. Section 5 offers our concluding remarks.

II. USR60 MODEL

Traveling-wave ultrasonic motors are complex electromechanical devices in which a mechanical resonant vibration is exited in the stator through proper forcing piezoelectric ceramics. This stator vibration is transformed into a rotation through friction contact between the stator and rotor.

The model of piezoelectric and stator can be described by the following equation

$$M\ddot{\zeta} + D\dot{\zeta} + C\zeta = \mathrm{H}v + F_d \tag{1}$$

with ζ represents the modal amplitude of the vibrating system (ceramics and stator), M is the total mass matrix of system(ceramics and stator), D is the structural damping matrix assumed to be diagonal, and C is the total stiffness matrix. H is the electromechanical coupling matrix and v is the voltage excitation vector. The term F_d is a nonlinear modal force vector to consider the interaction between the stator/rotor-contact. In dealing with the dynamics of the rotor, two degrees of freedom must be taken into account: first the rotation of the rotor and second the motion in z-direction. The motion in z-direction is represented by the quantity w.

The dynamics of the vertical rotor motion is obtained by the following equation

$$m_r\ddot{w} + d_z\dot{w} = F_z - F_n \tag{2}$$

with m_r is the mass of the rotor, d_z is the damping of the vertical motion, and F_n is the applied axial force. The equation of rotational motion is calculated by

$$J_r\dot{\omega} + d_r\omega = T_r - T_l \tag{3}$$

where J_r is the rotor inertia, d_r denotes the damping in spinning direction, and T_l is the applied torque.

In Fig. 1 the Matlab-simulink model of USR60 is described. The curves in Fig. 2 are derived from calculations using the Matlab-simulink model.

The speed versus drive frequency for different applied load torques is represented in Fig. 2. The speed of the motor has its maximum at the mechanical resonant frequency (40 kHz). It is due to the fact that the revolving speed of the motor is proportional to the vibration force of piezoelectric elements. So, any deviation from this frequency degrades the motor performance. However, this effect seems more serious for frequency decrements. To avoid the consequence of these phenomena, the drive frequency variation is restricted to the extent of $40 \le f \le 42$ kHz.

The effect of temperature is shown in Fig. 3 for a phosphor bronze comb-tooth stator [1]. From this figure, it is concluded that the frequency-temperature characteristic is almost linear from 20°C to 80°C, and it can be approximated by the following equation

$$f - f_r = 50 - 2.5T(°C) \qquad (4)$$

where f_r is the resonant frequency (40 kHz).

III. DESIGN OF ONLINE CONTROLLER

In order to design the control law, let us write (3) as

$$\omega(t) = -a\,w(t-1) + b\,u(t-1) \qquad (5)$$

It is convenient to introduce the vectors

$$\theta = col[a_1 ... a_p\; b_1 ... b_r]$$

and

$$\varphi(t) = col[-\omega(t-1) ... -\omega(t-p)\; u(t-1) ... u(t-r)]$$

Then (5) can be written

$$\omega(t) = \theta^T \varphi(t) \qquad (6)$$

The prediction model of (6) is

$$\hat{\omega}(t) = \hat{\theta}^T \varphi(t) \qquad (7)$$

with

$$\hat{\theta} = col[\hat{a}_1 ... \hat{a}_p\; \hat{b}_1 ... \hat{b}_r]$$

is the estimation vector of θ.

The criterion

$$V_t = \sum_1^t \| \omega(s) - \hat{\omega}(s) \|^2 = \sum_1^t \| \omega(s) - \hat{\theta}^T \varphi(s) \|^2 \qquad (8)$$

is minimized with respect to θ to give the estimate $\hat{\theta}$.

It is well-known how the sequence of estimates can be written recursively [8]

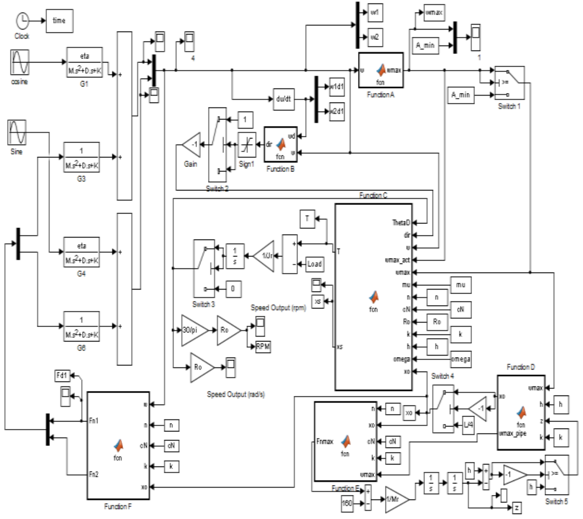

Fig. 1. Matlab-simulink model of USR60

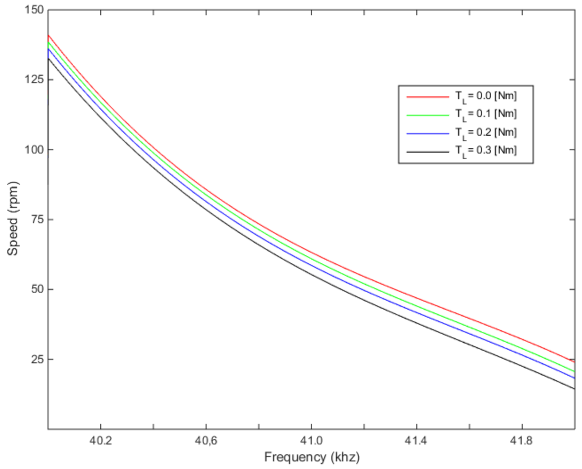

Fig. 2. Speed-frequency characteristics

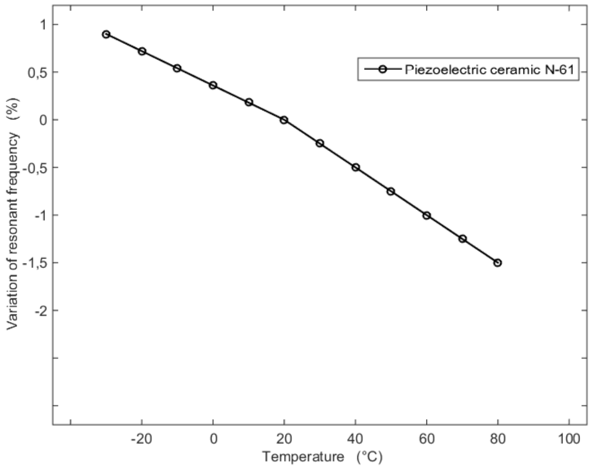

Fig. 3. Temperature-dependance of resonant frequency, using a standard motor (type USR60) manufactured by Shinsei Industries Co. Ltd.

$$\hat{\theta}(t) = \hat{\theta}(t-1) + \mu_0 S(t)\varepsilon(t, \hat{\theta}(t-1))$$

$$S(t) = \frac{R(t)^{-1}\varphi(t)}{1 + \mu_0(\varphi(t)^T R(t)^{-1}\varphi(t) - 1)}$$

$$R(t) = R(t-1) + \frac{1}{t}(\varphi(t)\varphi(t)^T - R(t-1))$$

$$\varepsilon(t, \hat{\theta}(t-1)) = \omega(t) - \hat{\theta}(t-1)^T \varphi(t)$$

The factor μ_0 corresponds to exponential forgetting of past data, with the base $1 - \mu_0$, and is added to algorithm above because tracking slowly time-varying motor parameters.

Fig.4 shows the block diagram of motor speed control scheme, where ω_C denotes the given speed, ω denotes the actual speed.

The presented approach is a simple identification method to avoid the unknown motor parameters.

IV. SIMULATION RESULTS

In order to evaluate the performance of our control scheme, the simulation results, of the proposed controller are achieved. The simulation study of the system was implemented using Matlab. The specification of the USR60 is shown in Table I. The simulation was done for 6 seconds.

The control parameters: $\mu_0 = 0.98$, $p = r = 10$.

The initial values: $\hat{\theta}(1) = 0$, and $R(1) = 1000I$.

Fig. 6 shows the speed tracking response by applying the control law represented in Fig. 5. The motor speed tracks the given speed very much. The parameter variations of USR60 are estimated on-line, so as to compensate it.

It is clear that the proposed control scheme introduces excellent performance where the controller variables track their reference values exactly in a very short time.

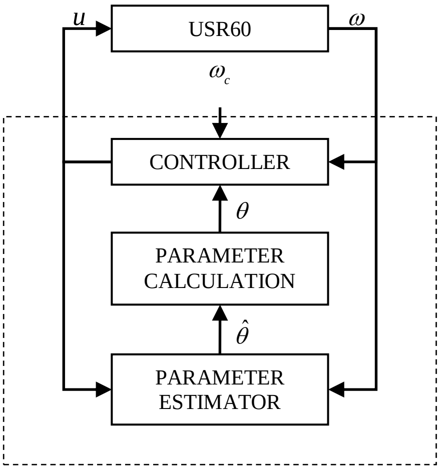

Fig. 4. Speed control block diagram

TABLE I SPECIFICATIONS OF USR60

Drive frequency	40kHz
Drive voltage	100Vr.m.s
Rated torque	0.32Nm
Rated speed	130r.p.m
Weight	240g

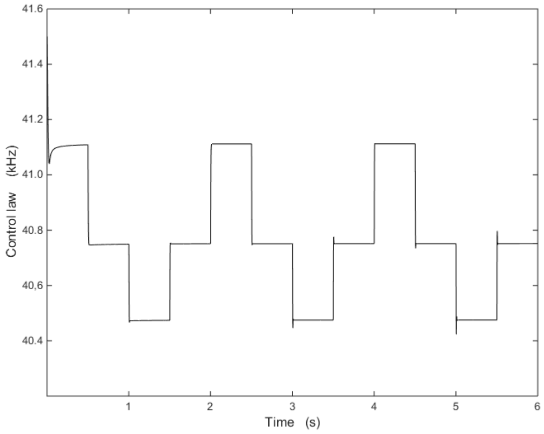

Fig. 5. Total control law u

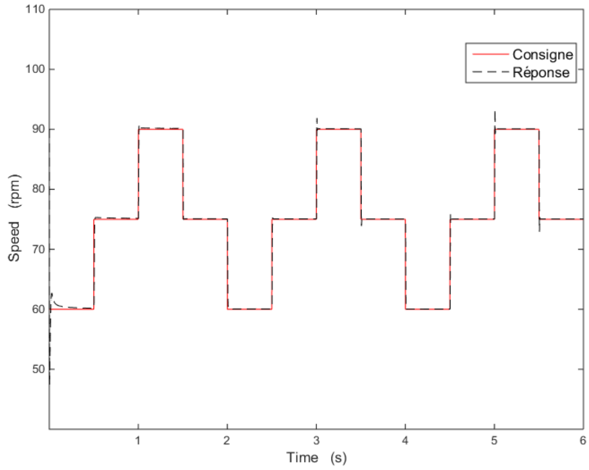

Fig. 6. Speed tracking response

V. CONCLUSIONS

In this paper, an online controller has been proposed for speed control of a traveling-wave ultrasonic motor USR60. The presented algorithm of control determinates the prediction model parameters on-line and compensates the motor parameter variations. A reference model is deduced from a Matlab-simulink model. Simulation results confirm the abovementioned claims for the control scheme in traveling-wave ultrasonic motors control drive.

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