Design of Adaptive Fuzzy Sliding Mode Control for a Traveling-wave Ultrasonic Motor

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Abstract— **In this paper, we propose an adaptive fuzzy sliding mode control scheme for a traveling-wave ultrasonic motor. Because external disturbances and parameter variations, it is difficult to design a conformable model-based control scheme. In order to deal with this problem, the proposed control law is combined a fuzzy logic and the sliding mode control (SMC). Firstly, the equivalent controller is obtained by a fuzzy strategy. Secondly, we use a boundary layer approach to avoid chattering problem and satisfactory trajectory tracking. An on-line adaptive tuning algorithm for the consequent parameters in the fuzzy rules is designed. Simulation studies have shown that the presented adaptive design of fuzzy sliding mode controller performs very well in the presence of unknown disturbances.**

Keywords—Sliding Mode Control; Fuzzy Control; Traveling-Wave Ultrasonic Motor.

I. INTRODUCTION

The Piezoelectric traveling-wave ultrasonic motor (TUSM) 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 [1].

Nevertheless, the control characteristics of TUSM are complex and no-linear. The motor parameters are time-varying due to increase in temperature and change of motor drive operating conditions [2-6]. In order to overcome these problems, several control systems have been proposed [6-8]. But the complexity of these algorithms is far beyond the fixed parameters PID control requiring higher on-line calculation ability and the resulting increase of the cost of hardware as well as software of the system. In [9-11] authors tray to use the nonlinear characteristic of fuzzy and neural control to deal with the nonlinear problems of TUSM control, except that we must find a compromise between the complexity of the algorithm proposed and its real time implementation.

In this work, an adaptive fuzzy sliding mode control (AFSMC) scheme is proposed for a traveling-wave ultrasonic motor type USR60. The proposed control law is based to combine a fuzzy logic and the SMC. Firstly, in order to realize the control law without the model of system, a fuzzy logic controller is designed to estimate the equivalent controller. The fuzzy parameters are estimated on-line by the adaptive laws. Secondly, a sliding mode control is used, but this control scheme suffers from chattering problems. In order to guarantee the stability of the sliding mode system, the boundary of the uncertainties has to be estimated.

The paper is organized as follows. In section 2, a mathematical model of USR60 is presented and a reference model is proposed in order to control the motor. Section 3 introduces the proposed adaptive fuzzy sliding mode 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 excited 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

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

with ξ 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.

TABLE I. SPECIFICATIONS OF USR60

Drive frequency	[kHz]	40.0
Drive voltage	[Vrms]	100
Rated torque	[Nm]	0,32
Rated speed	[rpm]	130
Rotor inertia	[Nms^2]	7,2.10^{-6}
Rotor damping in spinning direction		0.05

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. Fig.2 shows the relation between speed and torque measurements when the driving frequency is 40 kHz .The speed versus drive frequency for different applied load torques is represented in Fig.3. The speed of the TUSM has its maximum at the mechanical resonant frequency of the motor. So, any deviation from this frequency degrades the motor performance. However, this effect seems more serious for frequency decrements. The characteristic curves in Fig.2 and Fig.3 are derived from calculations using the Matlab-simulink model represented in Fig.1.

III. DESIGN OF ADAPTIVE FUZZY SLIDING MODE CONTROL

A. Design of Sliding Mode controller

In order to apply sliding mode control, let us write (3) as

$$\dot{\omega} = -a\omega + bu + h(t) \qquad a, b > 0 \tag{4}$$

where $h(t) = -T_L J_r^{-1} - J_r^{-1} \Delta J \dot{\omega} - \Delta a \omega + \Delta bu$ is the equivalent disturbance torque, ΔJ , Δa, and Δb are the parameter variations from normal value. Fig.4 shows the block diagram of motor speed control using AFSMC, where ω_c denotes the given speed, ω denotes the actual speed. Considering $e = \omega - \omega_c$ as speed tracking error, the time-varying surface of the sliding mode control is introduced as [12-13]

$$s = \dot{e} + \beta e \tag{5}$$

with β is a strictly positive constant, whose choice we shall interpret later. If sliding mode exists, the following condition satisfies

$$\dot{s} = \ddot{e} + \beta \dot{e} = 0 \tag{6}$$

Therefore, the control law is obtained as [13]

$$u = u_e + u_s \tag{7}$$

where $u_e(t)$ is a solution of (6) and called the equivalent controller.

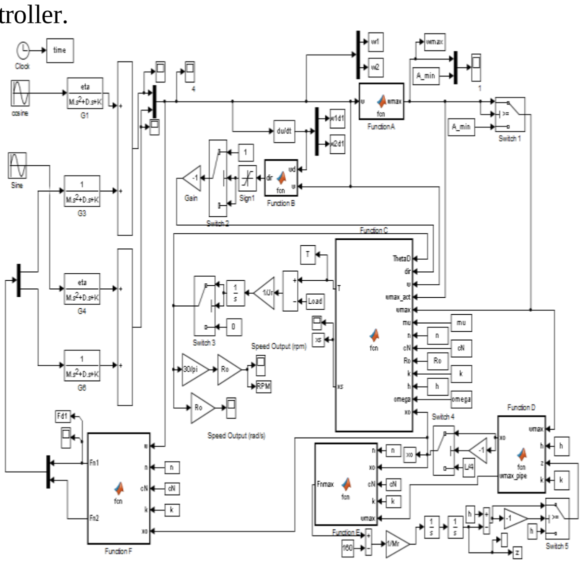

Fig. 1. Matlab-simulink model of USR60

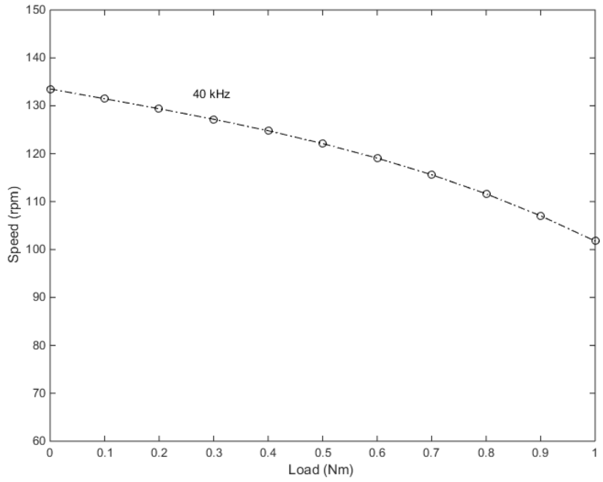

Fig. 2. Speed-torque characteristics

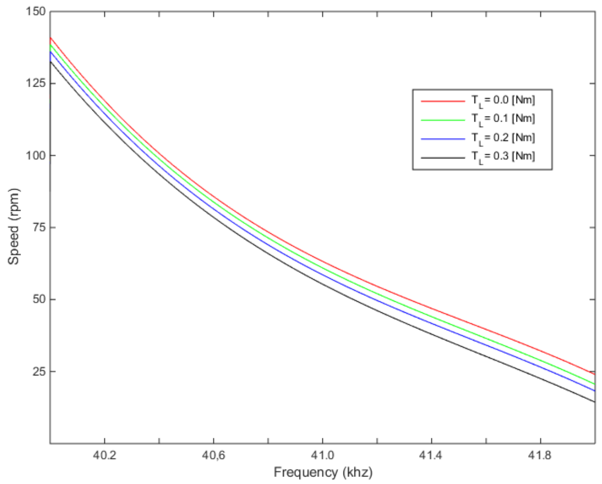

Fig. 3. Speed-frequency characteristics

The term $u_s(t)$ is called the hitting controller and obtained as

$$u_s = -K_0 sgn(s) \tag{8}$$

where sgn is the sign function

$$sgn(s) = +1 \quad \text{if } s > 0$$

$$sgn(s) = -1 \quad \text{if } s < 0$$

In order to ensure the existence condition of sliding mode using (8), the condition $s\dot{s} < 0$ must be satisfied [12-13].

$$\begin{aligned} s\dot{s} &= s(\ddot{e} + \beta\dot{e}) \\ &= s(-a(\beta - a)\omega + (\beta - a)d(t) - b(\beta - a)K_0 \, sgn(s)) \end{aligned} \tag{9}$$

where $(\beta - a)d(t) = h'(t) + (\beta - a)h(t) - \ddot{\omega}_c - \beta\dot{\omega}_c$ and assumed to be bounded.

So with

$$bK_0 > | -a\omega + d(t) | \tag{10}$$

the value of s and $\dot{s}$ have opposite signs and the state reaches the sliding line $s = 0$ after a finite time interval. Inequality (10) determines the frequency needed for enforcing the sliding mode; as a result, the control error is steered to zero.

While control law (7) achieves the target dynamics (5) exactly, the presence of the switching term $K_0\,\mathrm{sgn}(s)$ implies that in practice undesirable control chattering will occur. To suppress the chattering and obtain a band-width-limited controller that best approximates the exact behavior described above, the switched action $K_0\,\mathrm{sgn}(s)$ is replaced by a smooth interpolation in a boundary layer neighboring the sliding surface as [13]

$$u_s = -K_0 sat(s) \qquad (11)$$

The sat function is defined as

$$sat(s) = \sigma^{-1}s \qquad if\ \ |s| < \sigma$$
$$sat(s) = \mathrm{sgn}(s) \qquad if\ otherwise$$

where σ is the boundary layer thickness.

B. Adaptive Fuzzy Sliding Mode control

According to the universal approximation of TS-fuzzy systems [14], an optimal fuzzy controller $\hat{u}_e$ exists such that the approximation error of fuzzy controller can be defined as

$$u_e = \hat{u}_e + \varepsilon \qquad (12)$$

where ε is the approximation error and assumed to be bounded. In this work, there are nine rules in a fuzzy base and they have the following form

$$Rule\ i\ :\ if\ s\ is\ A^i\ and\ \dot{s}\ is\ B^i\ \ then\ \ \hat{u}_e = \theta_1^i s + \theta_2^i \dot{s}$$

$1 \le i \le 9$

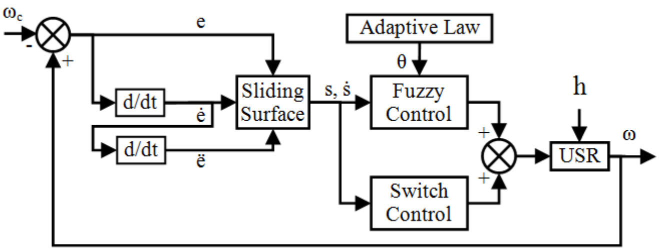

Fig. 4. Speed control block diagram

where s and $\dot{s}$ are the inputs variables of the fuzzy system and $\hat{u}_e$ is its output variable. The linguistic terms A^i and B^i are defined as

$$A^i, B^i \in \{N(\text{negative}),\ Z(\text{zero}),\ P(\text{positive})\}$$

and they are characterized by their corresponding membership functions

$$\mu_N(s) = \exp(-0.5\rho^{-2}(s+1)^2);\quad \mu_N(\dot{s}) = \exp(-0.5\rho^{-2}(\dot{s}+1)^2)$$

$$\mu_P(s) = \exp(-0.5\rho^{-2}(s-1)^2);\quad \mu_P(\dot{s}) = \exp(-0.5\rho^{-2}(\dot{s}-1)^2)$$

$$\mu_Z(s) = \exp(-0.5\rho^{-2}s^2);\quad \mu_Z(\dot{s}) = \exp(-0.5\rho^{-2}\dot{s}^2)$$

where ρ is the membership function's width.

The local control of fuzzy system is defined as

$$\hat{u}_e^i = \theta_1^i s + \theta_2^i \dot{s} \qquad (13)$$

The local control actions θ_s^i and θ_s^i which are contained in the parameters vector $\theta = \left[\theta_1, \theta_2\right]^T$ are calculated on-line by the following least squares algorithm

$$\hat{\theta}(i) = \hat{\theta}(i-1) + \frac{P(i-1)*\psi(i-1)*(\omega(i)-\psi(i-1)^T*\hat{\theta}(i-1))}{\lambda(i)+\psi(i-1)^T*P(i-1)*\psi(i-1)}$$

$$P(i) = P(i-1) - \frac{P(i-1)*\psi(i-1)*\psi(i-1)^T*P(i-1)}{\lambda(i)+\psi(i-1)^T*P(i-1)*\psi(i-1)}$$

with P is a covariance matrix, $\hat{\theta}$ is an estimation of the vector parameters θ, and λ denotes the forgetting factor. By fuzzification, the fuzzy inputs s and $\dot{s}$ are obtained. The fuzzy equivalent controller is obtained by defuzzification

$$\hat{u}_e = \frac{\sum_{i=1}^{9} \mu_{A^i}\,\mu_{B^i}\,\hat{u}_e^i}{\sum_{i=1}^{9} \mu_{A^i}\,\mu_{B^i}} = \theta^T \psi \qquad (14)$$

where $\psi = [s\ \dot{s}]^T$.

Finally the control law in (7) becomes

$$u = \theta^T \psi - K_0 sat(s) \qquad (15)$$

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 USR60 is shown in Table I. Choose the sliding surface as $s = \dot{e} + 5e$. The control parameters: $K_0 = 0.02$, and $\sigma = 0.01$. The initial values: $\hat{\theta}(1) = 0$, and $P(1) = 1000I$. The unknown disturbances are modeled by the *randn* function from Matlab library. Fig.6 shows the speed tracking response by applying the control law (15) represented in Fig.5. The dynamic response is good. The speed characteristics of motor changed when the load torque is applied or small parameter variations occur, but the control gains of the fuzzy sliding mode controller also changed to compensate the parameter variations. Adaptive parameters θ_1 and θ_2 are represented in Fig.7 and Fig.8 respectively.

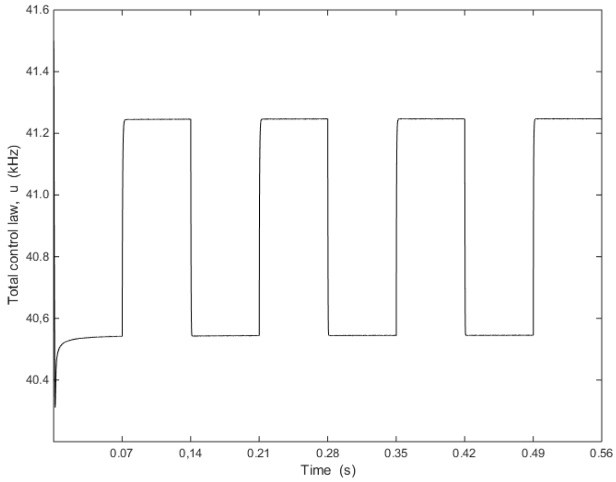

Fig. 5. Total control law u

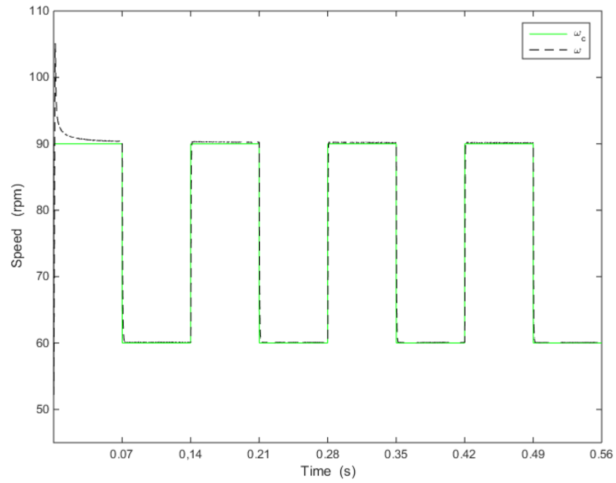

Fig. 6. Speed tracking response

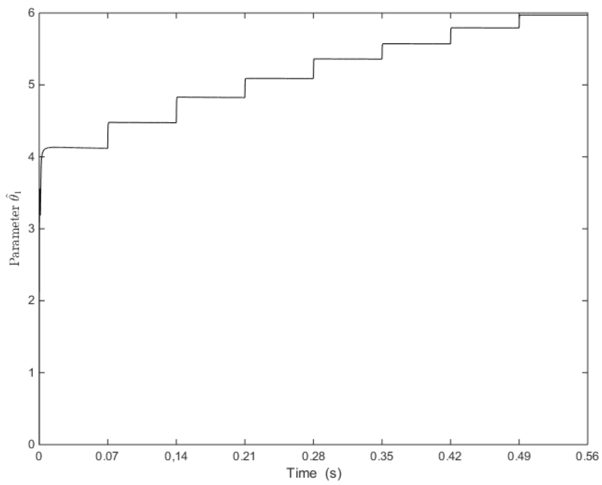

Fig. 7. Evolution of θ_1

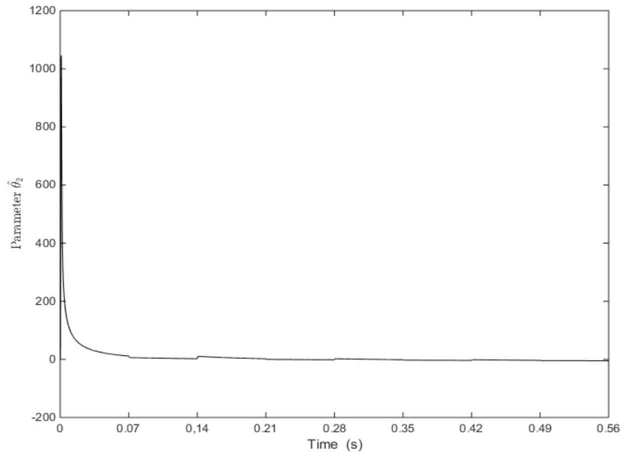

Fig. 8. Evolution of θ_2

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

V. CONCLUSIONS

In this paper, an adaptive fuzzy sliding mode structure has been proposed for speed control of a traveling-wave ultrasonic motor USR60. The strategy of control is based to combine the fuzzy logic and the sliding mode control to guarantee the stability and the tracking performance. The main advantages of the proposed speed controller are robustness to parameter variations and external load disturbances. Simulation results confirm the abovementioned claims for the control scheme in TUSM control drive.

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