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Model Reference Adaptive Speed Control of 2-Phase Travelling Wave Ultrasonic Motor

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Abstract

Adopting relatively simple motion control algorithm, helps reduce the cost of ultrasonic motor system including the drive control circuit, so as to promote its industrialization. For this purpose, this paper presents a simple model reference adaptive control strategy. The small amount of calculation of the policy, and with a certain degree of adaptive capacity, improves the system cost-effective.

Keywords: *ultrasonic motor, adaptive control, model reference, amount of calculation*

1. Introduction

Ultrasonic motor (USM) which research started in the 1990s [1-3], development to today, has been gradually moving towards industrialization [4, 5]. Industrial production is not only required to adapt the control performance in applications, but also inevitable requirement acceptable costs, especially the cost of hardware. Obviously, the lower cost device, the ultrasonic motor industrialization more broad prospects. Necessary part of the control device as an ultrasonic motor movement, the cost of the drive control circuit, of course also should be maintained at a low level compatible with the applications.

Because of the ultrasonic motor in the process of running show the complex nonlinear, time-varying characteristics, more and more complex control strategy is used in the ultrasonic motor control to get better control performance [6-8]. The proposed control strategy, significantly improve the control performance of the ultrasonic motor. However, with the upgrade of the control performance, complex control strategy also brings greater online computation [9,10]. In order to meet the requirements of real-time, more high-end microprocessor chip must be used to perform the appropriate control procedures, resulting in a more substantial increase of the drive control circuit hardware costs applicable to high-end motion control applications. Well, for the performance requirements slightly lower in the low-end motion control occasions, whether it is possible to design a relatively simple ultrasonic motor control strategy to achieve relatively good control performance at the same time, reduce the online computation to reduce hardware costs, improve the cost performance of the drive control circuit? This initial attempt, an ultrasonic motor based on the MIT model reference adaptive control speed control strategy, the algorithm computes a small amount. The experiments show that the effectiveness of the proposed control strategy.

2. The Ultrasonic Motor MIT Adaptive Speed Control Strategy

As a kind of model reference adaptive control method, the MIT control strategy adjusts controller parameters online according to appropriate adaptive rules, so the actual speed response of the ultrasonic motor speed control system can track the expected response process expressed by the reference model, thereby the adaptive servo of the ultrasonic time-varying characteristic is achieved and performance is improved. The MIT strategy controller is a simple proportional controller excluding online parameter identification links, so the control algorithm is simple, online computation is small. Figure 1 shows the basic structure of the ultrasonic motor MIT adaptive speed control system.

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In the Figure 1, k_c is a closed-loop proportion controller, k_c is a gain adjusted online by adaptive rules according to the generalized error from the speed output side. The output variable of the controller is the driven voltage frequency of the ultrasonic motor. Reference model and the dynamic portion of the ultrasonic motor model of *N(s)/D(s)* are identical, only the gain is different, respectively, *k* and k_v. The reference model of the gain *k* is a constant, the ultrasonic motor gain k_v is time-varying, and varying with the motor of its own characteristics and the emergence of a variety of disturbance varies. The function of the adjusted gain k_c lies in compensation for the varying of k_v and to make the product of k_c and k_v equal to (actually approaching) reference model gain *k*, in order to overcome time-variable nonlinear effect ultrasonic motor and to make the motor response process consistent with the expected characteristics of reference model.

Thus, the ultrasonic motor MIT adaptive speed control strategy of the design mainly is to design appropriate adaptive rules and to determine the representatives expect to control the performance of the reference model.

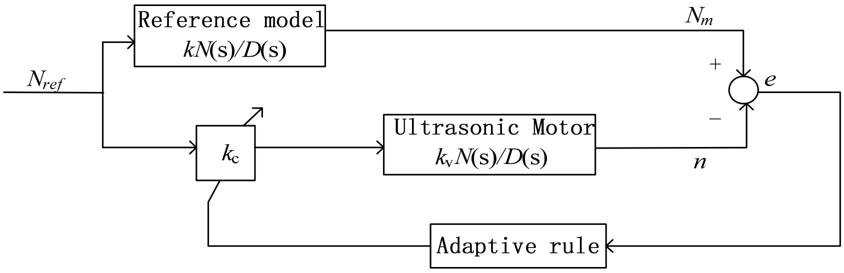

Figure 1. The MIT Adaptive Speed Control Structure of Ultrasonic Motor

2.1. The Design of the Adaptive Rules

Shown in Figure 1, a reference model and the ultrasonic motor model respectively:

$$G_m(s) = \frac{kN(s)}{D(s)} \tag{1}$$

$$G_p(s) = \frac{k_v N(s)}{D(s)} \tag{2}$$

The generalized error is defined as:

$$e = N_m - n \tag{3}$$

In Equation (3), N_m is the output speed in the reference model when the speed given signal takes action, *n* is the ultrasonic motor actual speed, the generalized error *e* is the deviation between reference model output and the actual motor output.

The control purpose of the system shown in Figure 1 is to make *e* converge to zero by adaptive rules adjustment. Select as below form performance index function to represent the process and degree of *e* to converge to zero.

$$J = \frac{1}{2}\int_{t_0}^{t} e^2(\tau)d\tau \tag{4}$$

In Equation (4), t_0 is the starting time of the control process, and *t* is the current time. If an adaptive rule is designed to adjust the gain k_c in order to make performance index *J* reach to minimum, the control objective is achieved. To do this, find the gradient of *J* to adjustable variable k_c

$$\frac{\partial J}{\partial k_c} = \int_{t_0}^{t} e(\tau)\frac{\partial e(\tau)}{\partial k_c} d\tau \qquad (5)$$

Known, k_c value by the gradient method should be along the formula (5) shown in the gradient descent direction (that is, negative) changes to make J gradually approaches minimum. Thus, the variable quantity of k_c, Δk_c, is shown as following:

$$\Delta k_c = -\lambda \frac{\partial J}{\partial k_c} = -\lambda \int_{t_0}^{t} e(\tau)\frac{\partial e(\tau)}{\partial k_c} d\tau \qquad (6)$$

Where λ is the step size, and $\lambda>0$. Thus the adjusted value of k_c

$$k_c = -\lambda \int_{t_0}^{t} e(\tau)\frac{\partial e(\tau)}{\partial k_c} d\tau + k_{c0} \qquad (7)$$

In the equation, k_{c0} is the initial value of adjusted gain k_c and $\Delta k_c = k_c - k_{c0}$. If can get $\dot{k}_c$ derivative gain expression, also can get the adaptive rule online changing k_c. For this reason, the both sides of the formula (7) against time t derivative to give:

$$\dot{k}_c = -\lambda e(\tau)\frac{\partial e(t)}{\partial k_c} \qquad (8)$$

The right side of the formula (8), $\frac{\partial e(t)}{\partial k_c}$ is unknown. Figure 1 shows the open-loop transfer function of the ultrasonic motor MIT adaptive control system.

$$\frac{E(s)}{N_{ref}(s)} = \frac{(k - k_c k_v)N(s)}{D(s)} \qquad (9)$$

$$D(s)E(s) = (k - k_c k_v)N(s)N_{ref}(s) \qquad (10)$$

Through the inversion of Laplace transformation to formula (10) to obtain the time domain expression.

$$D(p)e(t) = (k - k_c k_v)N(p)N_{ref}(t) \qquad (11)$$

Where p is the differential operator $\frac{d}{dt}$. After derivative calculus on k_c , the result is:

$$D(p)\frac{\partial e(t)}{\partial k_c} = -k_v N(p)N_{ref}(t) \qquad (12)$$

From Figure 1, the following time domain relationship between input and output of the reference model:

$$D(p)N_m(t) = kN(p)N_{ref}(t) \qquad (13)$$

By the formula (12) and (13), $\frac{\partial e(t)}{\partial k_c}$ and $N_m(t)$ are the proportional relationships.

$$\frac{\partial e(t)}{\partial k_c} = -\frac{k_v}{k} N_m(t) \qquad (14)$$

Defining the adaptive coefficient $\mu = \lambda k_v / k$, on the formula (8) and (14) to obtain the adaptive rule

$$\dot{k}_c = \mu e N_m \tag{15}$$

Using formula (15), it can realize online adjustment for the k_c, as shown in Figure 2. Specifically, if the previous time value is recorded as k_{c_last}, the current time adjusted value through the controller computation, k_c is:

$$k_c = k_{c\_last} + \mu e N_m \cdot dt = k_{c\_last} + \mu T_C e N_m \tag{16}$$

Wherein, T_c is a control cycle, *dt* is the time interval through two successive adjusting k_c. The k_c values adjustment is performed before each controller calculates, and therefore $dt=T_c$.

In formula (16), both μ and T_c are pre-designed fixed value, the product of the two numbers can be calculated off-line for online operation. Then, using formula (16) for online adaptive adjustment of the k_c value, only two times multiplication, one addition, and the calculation amount is extremely small.

For the MIT model reference adaptive control strategy of the ultrasonic motor speed control, it should be pointed out that the adaptive rule can be designed to be so simple, is the result of the controller is an adjustable gain proportional component The reason that reference model trace using so simple controller can be realized is based on the assumption of the same dynamic component but different gain between the reference model and the ultrasonic motor model. To satisfy this assumption, the reference model design of this control strategy is not arbitrary, which is possibly incompatible with the requirement called “reference model characterized control expectation”.

While in successful applications of the MIT control strategy for the other fields, it is also noted that the actual controlled object usually has a time-varying dynamic link in addition that the model gain is time-variable. It is shown that the concise MIT control strategy has strong robustness, and to some extent the strategy can play a role in un-modeled control process. From another perspective, the MIT reference model control strategy design can have a certain degree of arbitrariness, the dynamic aspects of the reference model and the plant model can have differences, in order to meet this requirement "reference model Characterization control expectations" to achieve control requirements.The dynamic link differences can be seen as un-modeled dynamics into the system control robustness consideration.

2.2. Reference Model Design

The purpose of the reference model adaptive control, is the combination of controllers, ultrasonic motor has the same as the reference model of control performance. Therefore, the reference model should reflect the expectations ultrasonic motor control is a key part of the system design. Considering the design simplicity and the online achieved calculation amount, the reference model *G_m(s)* usually is designed as the following second order transfer function form:

$$G_m(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{17}$$

In the equation, ζ is damp ratio, ω_n is undamped natural oscillatory frequency.

In this paper, the performance requirement of the ultrasonic motor is that speed step response without overshoot and the adjusted time within 0.3s. Using the basic knowledge of classical control theory about the second-order system parameters design, it is easy to get the reference model meeting the performance requirement.

$$G_m(s) = \frac{2427}{s^2 + 96s + 2427} \tag{18}$$

2.3. The Simulation on Adaptive Control Parameter Value Selections

After the adaptive coefficient μ is set and the adjustable gain initial k_{c0} is valued, the design as above may be applied to the actual motor control. Because computer is widely used, using relevant software tools to control performance simulation has become at present the commonly used method to determine the control parameter selection [11, 12]. Using the ultrasonic motor control model given in article [13, 14], using Simulink simulation of the control system shown in Figure 2, and gradually adjusting the value of μ, k_{c0}, the motor speed performance and the reference model tracing result can be observed. Simulation shows that the μ smaller the value, the longer the time of the adjustment of the speed response; μ value increases, the speed rise time shortened. When the μ value is excessively large, the large overshoot is shown and showed obvious oscillation convergence process. According to the simulation results, set to μ = 0.08, k_{c0}= 1.

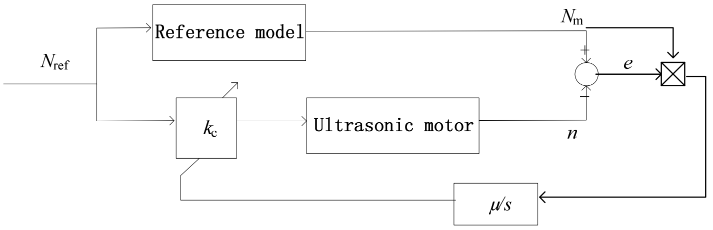

Figure 2. The MIT Speed Control Adaptive Rule of Ultrasonic Motor

3. The MIT Speed Control Experiment

In real tests, the two phase traveling wave ultrasonic motor typed Shinsei USR60 is used as the test motor, the H bridge driven control circuit is adapted which control chip is DSP56F801, and the DSP program is written in accordance with the aforementioned control strategy.

Simulation calculation process is not limiting the rate of change of the controller output control amount (motor driven frequency value), which can set a large adaptive coefficient, thereby to obtain a sufficiently large adjustable gain and the rate of change of the driven frequency, so that speed response process fast enough. But in fact, too large variation amount of the drive frequency causes the motor to stall. So at the beginning of the experiment, the adaptive coefficient μ is set to 0.0008 that is 1/100 of simulation value. Subsequently, according to the control effect, μ is gradually increased to the appropriate value.

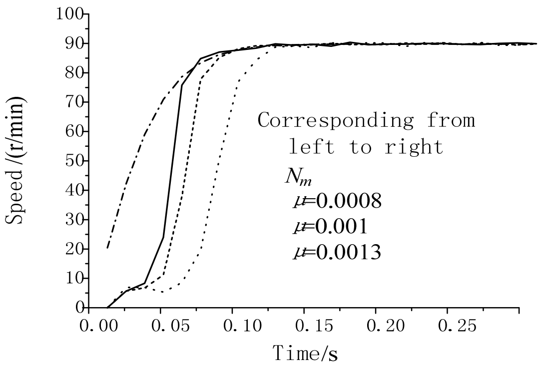

Figure 3. Speed Step Response on Different Measured μ Value

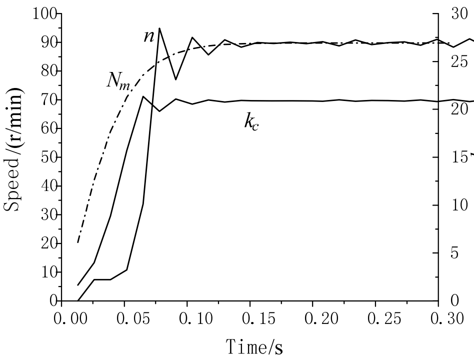

Figure 4. Measured Speed Step Response on μ=0.0016

Set the speed value 90r/min for the speed step response experiment. 90r/min is in the middle of the area in experimental motor adjustable speed range of 0~120r/min and is more representative. Figure 3 shows the measured speed step response when *μ* take different numerical cases. It can be seen that as the *μ* values increase, the response process gradually speed up, in the figure the response process is relatively good when *μ*=0.0013. When the *μ* value continues to increase, overshoot and oscillation convergence appears in the speed step response, as shown in Figure 4 *μ*=0.0016. Thus, can be set to *μ* = 0.0013.

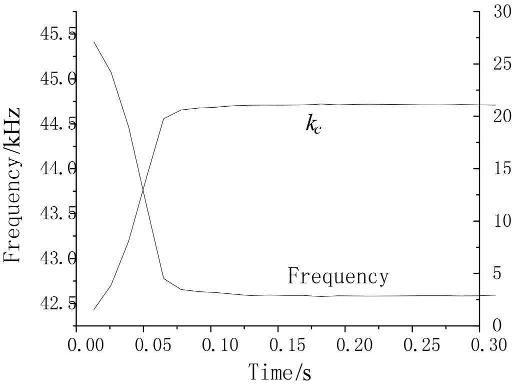

Figure 5. Parameters Change Process on μ=0.0013

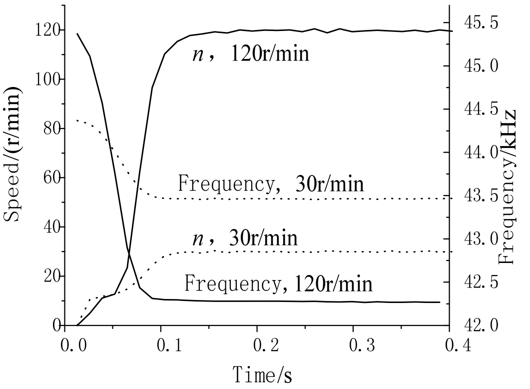

Figure 6. Measured Speed Step Response

Figure 5 shows the change process of the adjusted gain k_c and the control variable measured (motor driven frequency) at the same time with speed response curve shown in Figure3 on *μ*=0.0013. Seen the k_c value gradually increases in speed start rising stage, in order to adapt to the motor driven frequency values, when the speed reaches the given value, k_c tends to be stable and the whole change process becomes smooth and steady. And in the speed response appears overshoot, shown in Figure 4, due to the larger value of *μ* lead k_c increased too fast in the initial stage, causing the speed overshoot while k_c also exhibits an upward oscillation convergence process. Figure 6 shows the speed for a given value respectively, 30, 120r/min, the step response and the motor driven frequency change process. Seen a different speed to the circumstances of a given value, speed step response with no overshoot, the adjusting time are around 0.15s, shows that this control strategy's ability to adapt to the different speed conditions.

4. Conclusion

In the paper, an online, small calculation adaptive control strategy is illustrated for the application needs of the ultrasonic motor industrialization. In this control strategy, an adjustable proportional component is used as the controller, adaptive rules are designed according to gradient optimization method, and the reference model is designed to be second order for the desired control performance. The experiments show that the effectiveness of the control strategies suitable for demanding medium and low-end applications.

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