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Model Identification of Traveling Wave Ultrasonic Motor Using Step Response

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Abstract

Ultrasonic motor's model adapting to control application is the foundation of the motor's high performance control. Ultrasonic motor's frequency-speed control model gives a signification to improve speed control performance. This paper shows the design of stepping response experiments, and also explains the model identification of USM by the way of characteristic point method. Considering its time-varying characteristic, model parameters can be fitted using functions with the independent variable is frequency or speed. Consequently, non-linearity can reflect in speed control model appropriately.

Keywords*: ultrasonic motor, speed control, model, identification*

1. Introduction

The ultrasonic motor (USM) is a kind of special motor which use the inverse piezoelectric effect of the piezoelectric material to make the stator generate mechanical vibration which is in the ultrasonic frequency band. And the rotor is driven through the friction between the stator and rotor [1-4]. The USM contains a series of nonlinear process such as piezoelectric energy conversion, friction energy transfer and so on. Those nonlinear characteristics make the USM become a controlled object which is nonlinear, time-varying and strong coupling, and it is difficult to realize the motion control with high precision.

The mathematical model of the controlled object is the important foundation of the control system's analysis, design and performance assessment. We must get the USM's mathematical model which is suitable for control applications to improve the performance of the USM's movement control device and study more reasonable control strategy [2], [5-7]. The USM's modeling problem has not been solved mainly because of the particularity and complexity of its operation mechanism and the history of the USM's research is short. Most of the research is theoretical modeling and numerical modeling which adopt finite element method and other methods [8-10]. They are based on the theoretical knowledge of piezoelectric and friction and try to establish the model which can completely describe the USM's running process. We have made great progress and these models have become a powerful tool for analyzing and designing the USM. But these models are too complex and difficult to be directly applied to the control. And because of we haven't thorough understood USM's nonlinear characteristics or the nonlinear representation of the model is not comprehensive enough, so these models still have the potential to improve.

From the perspective of control application, the USM's modeling can also adopt other methods, such as system identification. The USM's input and output signals can reflect the dynamic characteristic of the motor system, and if we select the appropriate form of the input signal, the input and output signal can completely contain the USM's non-linear characteristics which are our concerns [2-3], [11]. So we can use the input and output data which is obtained from the test to model the USM's model. And the model can be directly applied to control.

Speed control is the core of the motor motion control. In the USM's speed control, the frequency of the driving voltage is often used as a control variable to achieve the regulation of speed. The USM's speed control model with frequency as the input variables is of great significance for improving the speed control performance. In this paper, we established the USM's speed control model which appropriately contains nonlinear characteristics through the

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identification modeling method. The model with frequency as input variables, is of great significance for improving the performance of frequency modulation (FM) speed control.

2. Experiments Design For Identification

In this paper, we intended to establish the USM's frequency-speed control model through the identification method, so the frequency and speed which are measured by experiments are the input and output signals, respectively. The motor speed is the output response which generated in a specific frequency of the input signal. Adopting different forms of input signal, the output response will be different. In order to make the measured data completely reflect the characteristics of the USM, we must use appropriate form of the frequency signal as input. The selected input signal must be sufficient to motivate all the dynamic characteristics of the USM. It means that the frequency range of the input signal be able to cover the part of our concern which is in the USM's dynamic frequency range. Step input signal is a common signal to meet the above requirements. The form of step signal is simple. Besides it is achieved easily and easy to analyze and research. So it is more appropriate as input signal. In this paper, we use the frequency step signal as input, and measure the step response data of speed under the open loop control of the motor's speed to identify the motor's model.

In this paper, Shinsei USR60, two-phase traveling wave ultrasonic motor, is used as the experiment motor. And the homemade H-bridge phase-shift PWM circuit is used as drive control circuit. DC tacho-generator is coaxial rigid connection with the motor, and it is used to measure the motor's speed. The frequency of the driving voltage is set to a desired value by adjusting the circuit. In order to ensure the accuracy of the identification, we need to obtain the exact value of the actual driving frequency. In the experiment, the waveform of the motor's drive voltage is measured in real-time, and the frequency value is obtained by processing the recording waveform. In order to make the measurement data can accurately reflect the dynamic characteristics of the USM, thereby ensuring the credibility of the motor model which is obtained by identifying. We need to determine the parameters of input signal such as step amplitude, sampling time, length of data records according to the prior knowledge and the control performance before the experiment.

USM's operating frequency is generally larger than its mechanical resonant frequency, the higher the frequency, the lower the motor speed. If the step amplitude of frequency input is too large, the speed is too low, and the signal-to-noise ratio of the measured signal will decrease, and it is not conducive to improve the accuracy of the identification. If the given frequency is too low, the corresponding desired speed too high, then the variation of the motor's speed will be large and may make the open-loop running USM suddenly stall. Experiment with the motor whose operating frequency range is 41.5-44kHz The selected step range of the frequency input is 42.3-43.3kHz by trying the open-loop operation. USM has different performance characteristics under the condition of different input frequency due to it has complex nonlinearity. Therefore, we need to measure the input and output data respectively under the condition of different input step frequency in the experiment, in order to fully reflect the motor's characteristics. In the meanwhile, taking into account the uncertainties and random perturbations which may occur in the testing process, we need measure multiple sets of data under each frequency to eliminate those data which has obvious deviation. The values of the step input frequency which are set in experiment and the motor's steady-state speed which corresponding to the step input frequency are shown in Table 1.

Table 1. Tested Data of Stepping Response

Number	Frequency(kHz)	Speed(r/min)
1	43.1	22.4
2	43.2	20.3
5	43.3	18.5
13	42.7	37.1
14	42.8	32.6
15	42.9	30.3
17	42.4	53.6
18	42.5	46.9
19	42.6	43.2
21	42.3	62.8

The data recording time need to be long enough to contain the complete step response process. But the longer the time, the bigger the data quantity. It will bring unnecessary burden to the calculation of model identification and may affect the accuracy of identification. The experiments show that the time of the experimental motor's step response not more than 100ms, so the selected length of the data recording time is 200ms.

In the experiment, the data recording is completed through the A/D sampling, and the sampling time directly affect the accuracy of identification. Sampling theorem requires that the sampling frequency should be at least twice the cutoff frequency of the object. If the sampling time is too large, will make the information loss too much and reduce the accuracy of identification. And in the case of the same recording time, decrease the sampling time will increase the amount of data. At the same time, because of the limitations of the hardware's response speed and the computation speed, the sampling time can not be too small. For the experiment motor, the required control response bandwidth is not greater than 500Hz. And further taking into account we need to obtain frequency information from the measured voltage waveform, so the selected sampling frequency is 10MHz in the experiment to ensure the measurement accuracy.

In the experimental, we capture the motor's drive voltage and tachogenerator output voltage signal synchronously, the measured step response curve is shown in Figure 1. In order to make the waveform clearly visible, the figure shows only a part of the time data.

3. The Motor's Model Identification Based on the Step Response

We need to preprocess these data before the model identification. As seen in Figure 1, the measured data contains noise. The noise becomes more obvious when the amplitude of the tachogenerator's output signal is small. Taking into account the required bandwidth of the control response is not greater than 500Hz, we take low pass filtering for the measured speed signal and the filter's cutoff frequency is 1000Hz. On the other hand, the start time of data recording earlier than the action time of step input to ensure the integrity of the data measurement. So there is a section of zero speed data at the beginning of the recording data, this section is useless for identification. If we reserve that data, it would affect the accuracy of identification, and should be deleted. Meanwhile, the DC component existing in the measurement data, it will also affect the accuracy of identification and can be removed using the average method. After the preprocessing, we obtained step response data of speed as shown in the in Figure 2. These data can be used for the model identification.

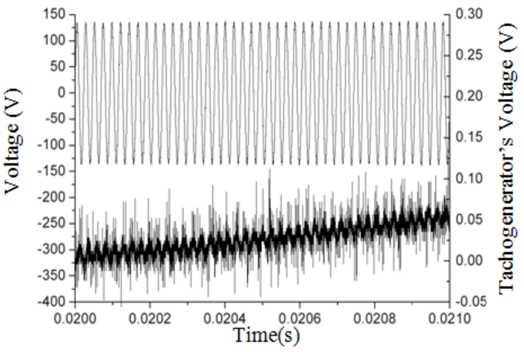

Figure 1. Tested Step Response

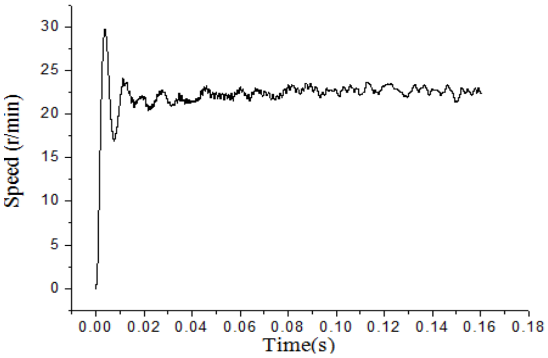

Figure 2. Step Response after Data Pretreatment

As mentioned, USM is a kind of nonlinear and time-varying objects. In order to achieve high-performance control for this kind of object, the control algorithm should have the ability of online correction. It means that the control algorithm is self-adapting. Consider it from this perspective, the selected motor model is second-order. It is used for identification.

There are many methods which use step response data to identify the model, such as area method, characteristic point method, etc. The area method can take full advantage of data information of every point to identify the model, and have strong ability to suppress noise. But it is not an optimization algorithm, and it is not specific to the specified order model. If the model order is equal or close to the order of the actual object, we can obtain more desirable results by using the area method. But during the actual control system design, we often use a low-order model to simulate the high-order object to simplify the control process. Then the obtained low-order model will inevitably have a deviation and the model accuracy is not high by using the area method. Taking into account the measured step response curve has characteristics of damping and oscillation, so we can use characteristic point method to identify the motor's model. This method is specific to second-order underdamping model.

The transfer function of the USM's frequency-speed control model can be described as:

$$G(s) = K\frac{{\omega_0}^2}{s^2 + 2\xi\omega_0 s + {\omega_0}^2}e^{-\tau s} \tag{1}$$

Where: $K = h_1 / f$, h_1 is the steady-state speed value, f is a given frequency step value; τ is the delay time; K and τ can be obtained directly from the measured data. ξ and ω_0 are model parameters to be identified, wherein $\xi = a_1 / 2\sqrt{a_2}$; $\omega_0 = 1/\sqrt{a_2}$; ξ is damping coefficient; ω_0 is natural frequency. For the convenience of identification, the equation (1) is normalized. Consequently, we obtain the standard unit transfer function of the second-order underdamping model

$$G_1(s) = \frac{{\omega_0}^2}{s^2 + 2\xi\omega_0 s + {\omega_0}^2} \tag{2}$$

The step response time domain expression of the normalized object as shown in the Equation (2) is:

$$h(t) = 1 - \frac{e^{-\xi\omega_0 t}}{\sqrt{1-\xi^2}}\sin(\sqrt{1-\xi^2}\,\omega_0 t + \phi) \tag{3}$$

Where: $\tan\phi = \frac{\sqrt{1-\xi^2}}{\xi}$.

Let Y_1^* and Y_2^* be respectively the height of the step response curve's first and second wave crest relative to the steady-state value (i.e. 1), and the interval time is T_0. By Equation (3) we can obtain:

$$Y_1^* = e^{-\frac{\pi\xi}{\sqrt{1-\xi^2}}} \tag{4}$$

$$Y_2^* = e^{-3\frac{\pi\xi}{\sqrt{1-\xi^2}}} \tag{5}$$

From the above two equations and T_0, get:

$$\xi = \frac{1}{\sqrt{1+(\pi/\mathrm{Y}_1^*)^2}} \tag{6}$$

$$\omega_0 = \frac{2\pi}{T_0\sqrt{1-\xi^2}} \quad (7)$$

The motor model is set as the Equation (2). We have obtained model parameters by using the characteristic point method to identify and calculate the measured frequency and speed data. The model parameters are shown in Table 2.

Figure 3 and Figure 4 show the comparison of the identification model step response simulation results with the measured values of the two sets of data. And the results are satisfied.

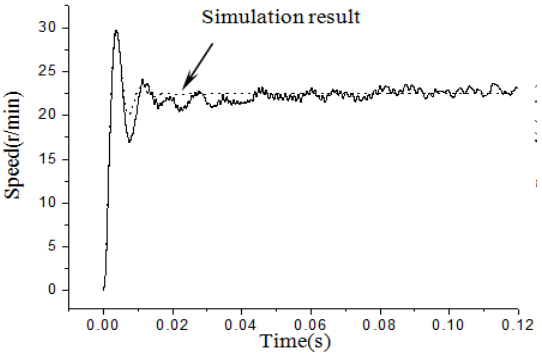

Figure 3. Tested and Simulated Step Response

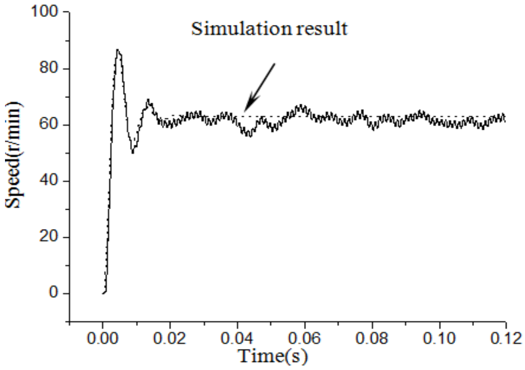

Figure 4. Tested and Simulated Step Response

Table 2. Model Parameters Identified using Characteristic Point Method

Number	ξ	ω_0(rad/s)	K	τ (s)
1	0.3373	887.533	0.5200	0.0138
2	0.3753	842.917	0.4707	0.0138
5	0.3241	837.550	0.4275	0.026
13	0.3912	825.563	0.8678	0.013
14	0.3744	865.378	0.7610	0.0137
15	0.4238	867.111	0.7064	0.0135
17	0.1999	738.785	1.2636	0.0172
18	0.2873	783.711	1.1021	0.019
19	0.3156	824.616	1.0137	0.021
21	0.2935	752.881	1.4855	0.022

Table 2 shows that the motor model parameters are time-varying. It is caused by the USM's nonlinearity. In order to make the model fully reflect the motor's nonlinear characteristics, the time-varying characteristics of parameters need to be expressed in the motor model. Because of the motor under different input frequency will show different characteristics. So we can consider using the variation of model parameters along with the change of frequency to characterize the time-varying nonlinearity. And in the control process, the given value of frequency is the output of the speed controller. If we ignore the dynamic process of frequency regulating, we can consider the given value of frequency as the actual value, so the frequency value is known. Therefore, the frequency f can be used as variable to fit the parameters ξ and ω_0, and they are expressed with $\xi(f)$ and $\omega_0(f)$ respectively. According to the change rule of the model parameters, we choose the quadratic polynomial function to fit ξ and ω_0 to make the fitting function be easy to calculate online with the control chip such as DSP, and obtain the fitting function as shown in Equation (8) and (9).

$$\xi(f) = -336.67384 + 15.65764f - 0.18186f^2 \tag{8}$$

$$\omega_0(f) = -115374.23674 + 5339.94183f - 61.36374f^2 \tag{9}$$

The comparison of the before and after fitting model step response curve is shown in Figure 5. In the figure, the dashed line is the response which is obtained by calculating the fitting data. It can be seen that both coincide basically and the model fitting effect is good. The model parameter values which are calculated from the fitting function (8) and (9) are shown in Table 3 The relative error is the relative error between the identified values and the fitted values of the model parameters.

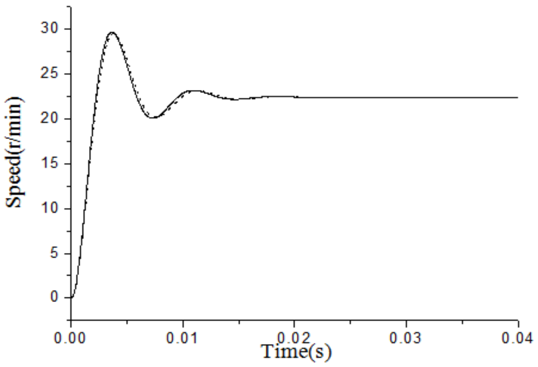

Figure 5. Step Response with Fitting Parameters

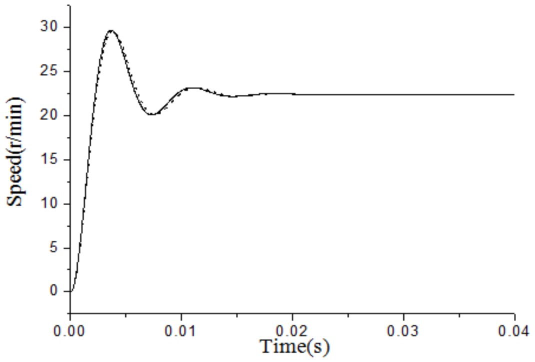

Figure 6. Step Response with Fitting Parameters

Table 3. Model Parameters Fitted by Frequency Fitting Function

Number	ξ^f		$\omega_0^{\ f}$ (rad/s)	
	Value	Relative error	Value	Relative error
1	0.3442	2.0457%	858.000	3.3276%
2	0.3402	9.3525%	856.416	1.6014%
5	0.3326	2.6226%	851.380	1.6512%
13	0.3310	15.3885%	831.025	0.6616%
14	0.3407	9.0011%	845.207	2.3308%
15	0.3431	19.0420%	849.303	2.0538%
17	0.2817	40.9205%	768.024	3.9578%
18	0.3062	6.5785%	798.463	1.8823%
19	0.3202	1.4575%	816.424	0.9935%
21	0.2492	15.0937%	728.803	3.1981%

In the USM speed control system, the measured speed value is necessary to constitute a closed-loop control. Since the speed data is known, of course, we can also use the speed n as the independent variable to fit the model parameters ξ and ω_0, and expressed with $\xi(n)$ and $\omega_0(n)$ respectively. Adopting the output fitting function is likely to get better control effect for some of the control strategy. According to the identified model parameters, we choose the quadratic polynomial function to fit ξ and ω_0. The fitting functions are shown in Equation (10) and (11).

$$\xi(n) = 0.29595 + 0.00359n - 7.00675e - 5n^2 \tag{10}$$

$$\omega_0(n) = 847.29469 + 1.83959n - 0.05952n^2 \tag{11}$$

The comparison of the before and after fitting model step response curve is shown in Figure 6. The model fitting parameters which use the speed n as the independent variable are shown in Table 4.

Table 4. Model Parameters Fitted by Speed Fitting Function

Number	ξ^n		$\omega_0{}^n$ (rad/s)	
	Value	Relative error	Value	Relative error
1	0.3412	1.1562%	858.607	3.2592%
2	0.3400	9.4058%	860.085	2.0367%
5	0.3384	4.4122%	860.950	2.7938%
13	0.3327	14.9540%	833.592	0.9725%
14	0.3385	9.5887%	843.949	2.4762%
15	0.3404	19.6791%	848.354	2.1632%
17	0.2869	43.5218%	774.702	4.8617%
18	0.3101	7.9360%	802.549	2.4037%
19	0.3201	1.4259%	815.493	1.1064%
21	0.2447	16.6269%	727.717	3.3423%

4. Conclusion

In this paper, we use the characteristic point method to identify the USM model according to the frequency step input data and the speed output data, the conclusions are as follows:

1) We need to select the appropriate input signal form to sufficiently motivate the motor's characteristics by using the method of system identification to model the motor. The step signal is a kind of input signal which meet the requirement of identification;

2) Characteristic point method is a kind of identification method and it aimed at the set motor model (second-order underdamped model), the identification effect is better;

3) Results of identification show that the model parameters are time-varying. Therefore, we use the frequency and speed as independent variables to fit the polynomial function for the model parameters, respectively. And we seek time-varying rules to properly reflect the nonlinear characteristics of the motor. It is simple to implement and has good results.

References

[1] Guo M, Hu J, Zhu H, Zhao C, Dong S. Three-degree-of-freedom ultrasonic motor using a 5-mm-diameter piezoelectric ceramic tube. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*. 2013; 60(7): 1446-1452.

[2] Shi J, Zhao F, Shen X, Wang X. Chaotic operation and chaos control of travelling wave ultrasonic motor. *Ultrasonics*. 2013; 53(6): 1112-1123.

[3] Tomonobu Senjyu, Mitsuru Nakamura. Mathematical model of ultrasonic motors for speed control[C]. *IEEE, Applied Power Electronics Conference and Exposition, Dallas, TX, United States*. 2006.

[4] Maas, Jürgen. Model-based control for ultrasonic motors. *IEEE/ASME Transactions on Mechatronics.* 2000; 5(2): 165-180.

[5] Xia, Chang-Liang, Qi,Wen-Ya, Yang Rong, Shi Ting-Na. *Identification and model reference adaptive control for ultrasonic motor based on RBF neural network.* Proceedings of the Chinese Society of Electrical Engineering. 2004; 24(7): 117-121.

[6] Shi, Jingzhuo, Lü,Lin. *Dynamic fuzzy modelling for speed control of ultrasonic motor*. Proceedings of the Chinese Society of Electrical Engineering. 2011; 31(33): 109-114.

[7] Zhang,Jiantao, Zhang,Tiemin, Xie,Zhiyang, Wu,Wei. *Multivariable nonlinear model of ultrasonic motor based on Hammerstein model and uniform design*. Proceedings of the World Congress on Intelligent Control and Automation. Jinan. 2010; 5794-5799.

[8] Wenyu Zhang, Jingzhuo Shi. Model Reference Adaptive Speed Control of 2-PhasTravelling Wave Ultrasonic Motor. *Telkomnika*. 2013; 11(11): 6337~6343.

[9] Shi Jingzhuo, Zhang Caixia. Low-Frequency Pulse Width Modulation Control Methods of Ultrasonic Motor. *Telkomnika*. 2013; 11(9): 5150~5160.
[10] Pigache F, Giraud F, Lemaire-Semail B. Modelling and identification of a planar standing wave ultrasonic motor. *EPJ Applied Physics.* 2006; 34(1): 55-65.
[11] Zhang, Jian-Tao, Zhang, Tie-Min, Liang Li. Nonlinear modeling and generalized predictive control of ultrasonic motor. *Electric Machines and Control.* 2011; 15(6): 50-56.