Frequency-Speed Control Model Identification of Ultrasonic Motor Using Step Response

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Abstract：Control model of ultrasonic motor is the foundation for high control performance. The frequency of driving voltage is commonly used as control variable in the speed control system of ultrasonic motor. Speed control model with the input frequency can significantly improve speed control performance. Step response of rotating speed is tested. Then, the transfer function model is identified through characteristic point method. Considering time-varying characteristics of the model parameters, the variables are fitted with frequency and speed as the independent variables, and the variable model of ultrasonic motor system is obtained, with consideration of the nonlinearity of ultrasonic motor system. The proposed model can be used in the design and analysis of the speed control system in ultrasonic motor.

Key words：ultrasonic motor (USM)；speed control；characteristic point method

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0 Introduction

Ultrasonic motor (USM) is a kind of special motor，and it uses the inverse piezoelectric effect of the piezoelectric material to make the stator generate mechanical vibration within the ultrasonic frequency band. The rotor is driven through the friction between the stator and the rotor[1-4]. USM contains a series of nonlinear processes such as piezoelectric energy conversion，friction energy transfer，and so on，so it is nonlinear，time-varying and strong coupling. Therefore，it is difficult to realize high-precision motion control.

The mathematical model of the control object is an important foundation of the control system analysis，design and performance evaluation. More reasonable control strategies can also use the model[5-11]. But the modeling problem of USM has not been solved mainly because of the complexity of its operation mechanism and its short research history. The existing researches mainly concentrate on theoretical modeling and numerical modeling. These methods are all based on piezoelectricity and friction theoretical knowledge，and trying to establish a model completely describing the running process of USM[12-21]. Great progress has been made，and it has become a powerful tool for the analysis and design of USM. But these models are too complex and difficult for direct control applications. On the other hand，since our understanding of USM′s nonlinearity is not thorough enough and the expression of it is not comprehensive，the model still has potential.

From the perspective of control application，the modeling of USM can also adopt other methods，e. g. system identification. The input and output signals of USM can reflect the dynamic characteristics of the motor system，and if we can select the appropriate form of the input signal，the input and the output signals can completely contain the non-linear characteristics of USM which we concern[2, 3, 13]. Therefore，we can use

the input and the output data obtained from the test to simulate the model of USM. And the model can be directly applied to control.

Speed control is the core of motor motion control. In the USM speed control，frequency of the driving voltage is often used as a control variable to regulate speed. The speed control model with an input frequency can significantly improve speed control performance. We adopt the identification modeling method to establish the speed control model of USM which appropriately contains nonlinear characteristics.

1   Design of Data Test

We intend to establish the frequency-speed control model of USM through identification method. Therefore，we need to measure the input and the output signals in the experiments as frequency and speed，respectively. The speed of the motor is the output response at a specific frequency input signal. Adopting different forms of input signal，the output response will be different. We must adopt an appropriate form of the frequency signal as the input to make sure the measured data completely reflect the characteristics of USM. The selected input signal must be sufficient to motivate all the dynamic characteristics of USM. It means that the frequency range of the input signal should be able to cover the part that we concern in the dynamic frequency range of USM. Step input signal is a common signal meeting the above requirements. The form of step signal is simple. Besides it is easy to achieve，analyze and research. Therefore，it is more appropriate as an input signal. In this paper，we use the frequency step signal as input，and measure the step response data of speed under open loop control of the speed to identify the model of motor.

Shinsei USR60，a 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 actual driving frequency. In the experiment，the waveform of the motor's driving voltage is measured in real-time，and the frequency value is obtained by processing the recorded waveform. In order to ensure the measurement data to accurately reflect the dynamic characteristics of USM，and the credibility of the motor model which is obtained by identifying，we need to confirm 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 experiment.

Operating frequency of USM 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，and the speed is too low，the signal-to-noise ratio of the measured signal will decrease. It is not conducive to improve the accuracy of the identification. If the given frequency is too low，and the desired speed corresponding is too high，the variation of the speed of motor will be large and may suddenly stall the open-loop running USM. The operating frequency range of experimental motor is 41.5—44 kHz. The selected step range of the frequency input is 42.3—43.3 kHz after open-loop operation. USM has different performance characteristics under different input frequencies due to its complex nonlinearity. Therefore，we need to measure the input and the output data，respectively，under different input step frequencies in the experiment，and to sufficiently reflect the characteristics of motor. Meanwhile，considering the uncertainties and random perturbations which may occur in the testing process，we need to measure sets of data under each frequency to eliminate those obvious deviations. The seted values of the step input frequency in experiment and the corresponding steady-state speed values of the motor are shown in Table 1.

Table 1 Tested data of stepping response

No.	Frequency/kHz	Speed/(r · min⁻¹)
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 needs to be long enough to contain the complete step response process. But it will bring unnecessary burden to the calculation of model identification and may affect the accuracy of identification if the time is too long and data quantity is too big. The experiments show that the step response time of the experimental motor is no longer than 100 ms. Therefore, the selected data recording time is 200 ms.

In the experiment, the data recording is completed by the A/D sampling, and the sampling time directly affects the accuracy of identification. The sampling frequency should be at least twice that of the cutoff frequency of the object according to sampling theorem. If the sampling time is too large, it will cause excessive loss of information and reduce the accuracy of identification. And in the case of the same recording time, decreasing the sampling time will increase the amount of data. At the same time, because of the limitations of response speed and calculation speed of hardware, the sampling time cannot be too small. For the experiment motor, the required control response bandwidth is not greater than 500 Hz. And further taking into account that we need to obtain frequency information from the measured voltage waveform, the selected sampling frequency is 10 MHz in the experiment to ensure the accuracy of measurement.

In the experiment, we collect the driving voltage of motor and tacho-generator output volt-age signal synchronously, the measured step response curve is shown in Fig. 1. It only shows part of the time data to make the waveform clearly visible. A four-character indent is recommended for all paragraphs except the first one that immediately follows a section title or a subsection title.
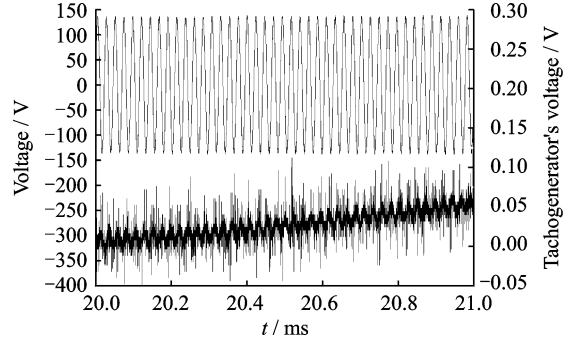

Fig. 1 Tested step response

2 Model Identification of Motor Based on Step Response

We need to preprocess these data before model identification. In Fig. 1, the measured data contains noise. The noise becomes more obvious when the amplitude of the tacho-generator's output signal is small. Since the required bandwidth of the control response is not greater than 500 Hz, we take low pass filtering for the measured speed signal and the cutoff frequency of filter is 1 000 Hz. On the other hand, the start time of data recording is earlier than the action time of step input to ensure the integrity of the measurement data. Therefore, there is a section of zero speed data at the beginning of the recording data, this section is useless for identification. If we reserve those data, they would affect the accuracy of identification. Therefore, they should be deleted. Meanwhile, the DC component existing in the measurement data will also affect the accuracy of identification and can be removed using the average method. After the preprocessing, the obtained speed step response data are shown in Fig. 2. These data can be used for model identification.
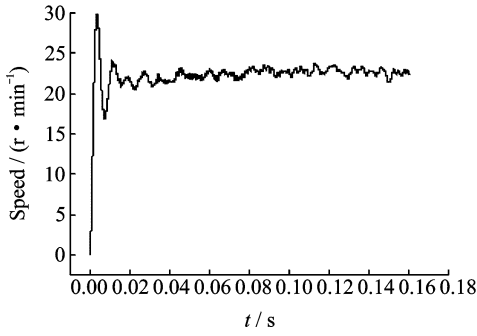
Fig. 2   Step response after data pretreatment

As mentioned before，USM is a kind of nonlinear and time-varying object. In order to achieve high-performance control，the control algorithm should have the ability of online correction. It means that the control algorithm is self-adapting. Therefore，the identification motor model is selected as second-order.

There are many different methods to identify the model，such as area method，characteristic point method，etc. These methods all utilize step response data. 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，and it is not suitable to the specified order model. If the selected model order is equal or close to the order of the actual object，more desirable results can be obtained 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. Since the measured step response curve has attenuation oscillation characteristics，we can adopt characteristic point method which is specific to second-order underdamping model to identify the model of motor.

The transfer function of the frequency-speed control model of USM is set to

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

where $K = h_1/f$, h_1 is the stable value of speed，f the given value of frequency step signal，and τ the

delay time. K and τ can be obtained directly from the measured data. ξ and ω_0 are all model parameters to be identified，where $\xi = a_1/2 \sqrt{a_2}$，is the damping coefficient and $\omega_0 = 1/\sqrt{a_2}$，the natural frequency. For the convenience of identification，Eq. (1) normalizes to obtain the standard unit transfer function of the second-order underdamping model

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

The time domain expression of this normalized object's step response is

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

where $\tan\varphi = \dfrac{\sqrt{1-\xi^2}}{\xi}$.

Let Y_1^* and Y_2^* separately represent the values of the first and the second peak of the step response curve relative to the stable value (that is 1)，and the interval from Y_1^* to Y_2^* is T_0. By Eq. (3) we can obtain

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

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

From Eqs. (4,5) and T_0，we can obtain

$$\xi = \frac{1}{\sqrt{1 + (\pi/Y_1^*)^2}} \qquad (6)$$

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

Using the characteristic point method and the selected motor model of Eq. (2) to identify and calculate the measured frequency and speed data. The model parameters are shown in Table 2.

Table 2   Model parameters identified by characteristic point method

No.	ξ	$\omega_0/(\text{rad} \cdot \text{s}^{-1})$	K	τ/s
1	0.337 3	887.533	0.520 0	0.013 8
2	0.375 3	842.917	0.470 7	0.013 8
5	0.324 1	837.550	0.427 5	0.026
13	0.391 2	825.563	0.867 8	0.013
14	0.374 4	865.378	0.761 0	0.013 7
15	0.423 8	867.111	0.706 4	0.013 5
17	0.199 9	738.785	1.263 6	0.017 2
18	0.287 3	783.711	1.102 1	0.019
19	0.315 6	824.616	1.013 7	0.021
21	0.293 5	752.881	1.485 5	0.022

The frequency-speed control model of ultrasonic motor system can be obtained by putting the model parameters (shown in Table 2) into the model Eq. (2). By adopting this model, the step response of ultrasonic motor system can be calculated. Then the accuracy of the model can be verified by comparing the calculated response with the measured step response. Figs. 3, 4 show the comparison of the two kinds of step response. In Figs. 3, 4, solid line is the curve of measured step response, and dotted line is the step response which is calculated by identification model. It is thus clear that, the model reflects the main dynamic characteristics of actual system except the irregular fluctuations during the steady-state operation of motor.

Table 2 shows that the motor model parameters are time-varying. It is caused by the nonlinearity of USM. In order to make the model fully reflect the nonlinear characteristics of motor, the time-varying characteristics of parameters need to be represented in the motor model. Since the motor shows different characteristics under different input frequencies, we can use the variation of model parameters along with the change of frequency to represent 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 a variable to fit the parameters ξ and ω_0, and they are expressed with $\xi(f)$ and $\omega_0(f)$, respec-
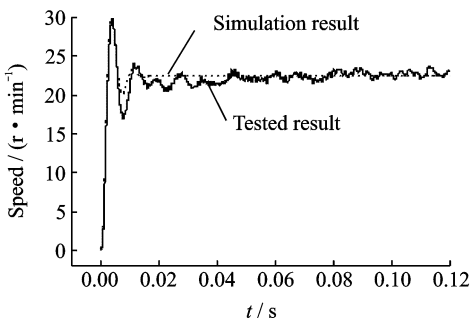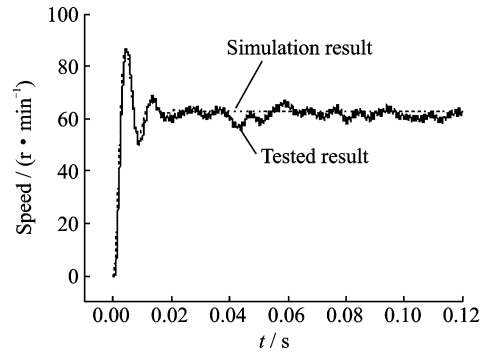

Fig. 4　Tested and simulated step response with $n = 62.8$ r/min

tively. To make the fitting function be easy to calculate online by using the control chip, e. g. DSP, we choose the quadratic polynomial function to fit according to the change rule of the model parameters, and the obtained fitting function as shown in Eqs. (8, 9).

$$\xi(f) = -336.673\,84 + 15.657\,64f - 0.181\,86f^2 \tag{8}$$

$$\omega_0(f) = -115\,374.236\,74 + 5\,339.941\,83f - 61.363\,74f^2 \tag{9}$$

The comparison of the before and the after fitting model step response curve is shown in Fig. 5. In Fig. 5, 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 Eqs. (8, 9) are shown in Table 3. In the table, the variance is between the step response data which is calculated by using fitting model and the measured data, the relative error is between the identification value of model parameters and the fitting values of model parameters.
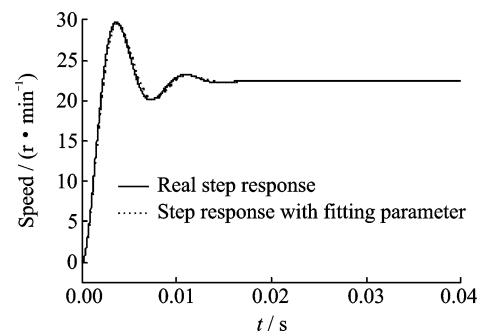

Fig. 3　Tested and simulated step response with $n = 22.4$ r/min

Fig. 5　Step response with f as fitting parameter

Table 3   Model parameters fitted by frequency fitting function

No.	Variance	ξ^f		$\omega_0^f/(\text{rad} \cdot \text{s}^{-1})$	
		Value	Relative error/%	Value	Relative error/%
1	1.619 7	0.344 2	2.045 7	858.000	3.327 6
2	1.943 3	0.340 2	9.352 5	856.416	1.601 4
5	1.675 9	0.332 6	2.622 6	851.380	1.651 2
13	3.636 2	0.331 0	15.388 5	831.025	0.661 6
14	1.982 2	0.340 7	9.001 1	845.207	2.330 8
15	1.645 8	0.343 1	19.042 0	849.303	2.053 8
17	4.258 4	0.281 7	40.920 5	768.024	3.957 8
18	2.786 9	0.306 2	6.578 5	798.463	1.882 3
19	1.741 9	0.320 2	1.457 5	816.424	0.993 5
21	2.658 8	0.249 2	15.093 7	728.803	3.198 1

Table 4   Model parameters fitted by speed fitting function

No.	Variance	ξ^n		$\omega_0^n/(\text{rad} \cdot \text{s}^{-1})$	
		Value	Relative error/%	Value	Relative error/%
1	1.145 9	0.341 2	1.156 2	858.607	3.259 2
2	1.647 3	0.340 0	9.405 8	860.085	2.036 7
5	1.987 4	0.338 4	4.412 2	860.950	2.793 8
13	3.624 8	0.332 7	14.954 0	833.592	0.972 5
14	1.445 6	0.338 5	9.588 7	843.949	2.476 2
15	1.524 5	0.340 4	19.679 1	848.354	2.163 2
17	4.264 3	0.286 9	43.521 8	774.702	4.861 7
18	2.630 0	0.310 1	7.936 0	802.549	2.403 7
19	1.649 3	0.320 1	1.425 9	815.493	1.106 4
21	2.972 8	0.244 7	16.626 9	727.717	3.342 3

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

$$\xi(n) = 0.295\ 95 + 0.003\ 59n - 7.006\ 75 \times 10^{-5} n^2 \tag{10}$$

$$\omega_0(n) = 847.294\ 69 + 1.839\ 59n - 0.059\ 52n^2 \tag{11}$$

The comparison of the before and the after fitting model step response curve is shown in Fig. 6. The model fitting parameters which adopt the speed n as the independent variable are shown in Table 4. In the table，the variance is between the step response data which is calculated by fitting model and the measured data，the relative error is between the identification value of model parameters and the fitting values of model parameters.
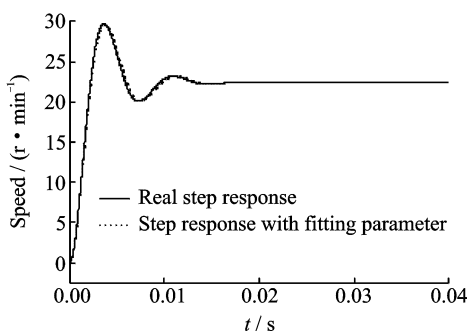
Fig. 6   Step response with n as fitting parameter

3   Conclusions

In the paper，we adopt 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 an appropriate form of input signal to sufficiently excite characteristics of motor by using the method of system identification to model the motor. The step signal is a kind of input signal which meets the requirement of identification.

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

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

Acknowledgement

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