Modeling for Servo System of ICT based on Gray Identification

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Abstract

The parameter of servo control system is an important flag to weigh the performance of ICT system. Aimed at the puzzle of being difficult to analyze and optimize for the control system, the paper proposed a modeling method with using theory modeling and system identification technology. The method is based on the online measurement data of the ICT system, the online measurement device was adopted to obtain the input and output data used for identifying system parameters, and the CAR model was taken as the control object model. Then the variable step-size recursive algorithm of forgetting factor with the analysis of system frequency characteristics and theory analysis would be used to identify the parameters of model. In the paper, it constructed a CD-300BXR industrial CT system, and made the parameter identification experiment of translation axis. The test data demonstrated that under the condition of same square signal input when the amplitude is 1 and the frequency is the 1HZ the max error between the real experiment and identification simulation would be 1.33%, while the movement scope of the correlation of residual error with input data would be around 0.5%. The simulation result shows that the effectiveness of proposed identification model is validated.

Keywords: Industrial Computed Tomography, Servo System, System Identification, Mathematic Model, Online Measurement

1. Introduction

ICT which is the abbreviation of industrial computed tomography is considered as one of the best means for non-destructive testing in industrial field [1, 25, 26]. ICT technology can show the inner structure and defect of tested object clearly. However, the precision of ICT servo system as one of the most important sub-systems will influence directly the performance of system, meanwhile, ICT servo system is complex compared with other control system. Therefore, establishing accurate model of ICT servo system is necessary [1-3, 27].

Nowadays, the model of ICT servo system is often acquired by mechanism analysis method, which can meet the demand of system to some extent[19, 20, 21]. However, with the development of DR imaging technology and the three-dimensional imaging technology, the traditional method will be hard to meet the new demand [4, 5, 6]. The single sampling time of accelerator CT is 4~100ms [22, 23, 24], the number of detector of existing accelerator CT is above 500 with high rotation precision of CT imaging, so the typical 512×512 picture can reach 30rpm at the most fast velocity [7, 8, 9]. But the reality is under 30rpm while considering the interference and mechanism inertia, and so on [10, 11, 12]. The weight of piece can reach 1000kg, the layer thickness of DR scanning is often 1-4mm [13, 14, 15], the scanning velocity is 2m/s if the sampling time is 20ms. For the three-dimensional scanning [16, 17, 18], the detector must be increasing and the scanning velocity will add one times if the detectors add one times [4-6].

Aimed at the deficiency of the traditional method, the paper proposed a sort of model identification method based on the online measurement for servo system of ICT. In fact, the gray system identification method has been widely applied in lots of industrial fields. We can get the input and output data of identified system by means of the online measurement system and identify the parameters through the variable step-size recursive algorithm on forgetting factor. The result of experiment showed that the method is feasible and reasonable in the ICT servo system.
2. System description

Figure 1 is the frame of servo system of ICT. ICT control system contains four main shafts which are indexing, translation, ray source and detector axis. The indexing movement which is the turning of work-piece is rotary position movement controlling in the two generation of scanning while being continuous rotation movement in the three generation of scanning. The translation movement is the continuous translation of work-piece to accomplish the data sampling of different position. The layered movement is the synchronization up-and-down movement to choose the position of scanning tomography. In the figure 1, the industrial computer which transmits the control command to the actuator is the PC of motion control, and the driver controls the electric machinery after receiving command. Meanwhile, the measurement data is feedback to the PC by data measurement device after the optical grating measured the position data.

![Figure 1. Frame of ICT Servo System](image)

In order to establish the accurate math model of the ICT position servo system, taking the variable step-size least squares recursive algorithm on forgetting factor with the analysis of system frequency characteristics to identify the order number of system model. Figure 2 is the structure of system identification of ICT servo system. In the figure, \( d_s \) stands for the set value, \( d_f \) stands for the feedback value, and \( \theta_f \) stands for the feedback value of rotational angular. To get the model of the whole system, considering the AC servo driver and AC electric machinery, transmission mechanism as the identification object, therefore, this method can avoid the influence of ignored factor in the mechanism. Analyzing the structure of control system, we will find that the relationship between open loop transfer function of position loop \( G(S) \) and closed loop transfer function of speed loop \( H(S) \) is Formula (1).

![Figure 2. Structure of System Identification](image)

\[
G(S) = H(S) \ast G_t(S)
\]  

(1)

In which, \( G_t(S) \) is the relationship type between speed loop and position loop.
3. Establish the model based on system identification

From the description of servo system of ICT, we can find that the model of the whole servo system is constituted by driver, motor, transmission mechanism, and load. Mechanism modeling appears to be difficult and complex because of the nonlinear of transmission mechanism. Therefore, in the design, we analyze the model of transmission mechanism, coupling and ball screw is the main part of the transfer function of transmission mechanism and load, because of the connection between motor shaft and ball screw and the micro deformation factors of coupling and ball screw. The establishing of the transfer function is to comply with the following paragraphs:

The friction torque of ball screw and the motor is formula (2) and (3), so the formula (4) and (5) is respectively the torque balance equation of motor shaft and ball screw. We can consider the formula (6) as the big rigidity of coupling of CT and the short link distance, we can get the formula (7) while combining formula (4) and (5) with (6).

\[
T'_{1} = B_{m} \theta_{1} \\
T'_{n} = B_{n} \theta_{2} \\
T_{em} = M_{a} + B_{n} \theta_{1} + J_{m} \dot{\theta}_{1} + T_{d} = J \dot{\theta}_{1} + B \theta_{1} + T_{d} \\
M_{m} = J_{f} \ddot{\theta}_{2} + B_{m} \dot{\theta}_{2} + T_{e2} \\
\theta_{1} = \theta_{2} \\
T_{em} = J \dot{\theta}_{1} + B \theta_{1} + T_{d} \\
T_{e}(S) = JS^{2}\dot{\theta}(S) + BS\theta(S) + T_{e}(S) \\
\omega_{d} = \frac{d\theta}{dt} \\
G(S) = \frac{1}{JS + B}
\]

In the formula (2)~(10):
- \( B_{m} \) — the motor of the viscous damping coefficient;
- \( B_{n} \) — ball screw and coupling damping coefficient;
- \( B = B_{m} + B_{n} \) — the motor shaft damping coefficient;
- \( T_{d} \) — disturbance of load;
- \( \theta_{1} \) — the rotation of a motor shaft angle;
- \( \theta_{2} \) — the ball screw shaft angle;
- \( K_{1} \) — coupling torsion stiffness;
- \( M_{a} \) — the output torque of motor shaft;
- \( T_{e1} \) — the internal disturbance torque motor;
- \( T_{e2} \) — the transmission mechanism and the load disturbance;
- \( J = J_{m} + J_{f} \) — the rotor and the load on the motor shaft of the equivalent moment of inertia.
We can get formula (8) after doing the laplace transform of the differential equation (7) while getting the transfer function of transmission mechanism (10) after combining the formula (8) with (9).

According to the analysis we can know that ICT servo system is a single input single output control system, considering the math model of dynamic characteristics as the CAR according to the character of ICT model, Formula (11) is the differential equation of CAR model.

\[ z(k) + a_1 z(k-1) + \ldots + a_n z(k-n) = b_1 u(k-1) + \ldots + b_n u(k-n) + v(k) \]  

(11)

Taking the he variable step-size recursive algorithm on forgetting factor in which it will correct the parameter after each \( l \) steps, the algorithm can be deducted from formula (12), formula (13) and formula (14).

\[ P^{-\lambda}(k) = H_{k-1}^T H_k = \sum_{j=1}^{k} \Lambda(i) h^T(i) h(i) \]  

(12)

\[ P^{-\lambda}(k-l) = H_{k-l}^T H_{k-l} = \sum_{i=0}^{k-l} h^T(i) h(i) \]  

(13)

\[ P^{-\lambda}(k) = P^{-\lambda}(k-\ell) + H_{k,l}^T H_{k,l} \]  

(14)

In which, \( h(i) \) is the input-output data matrix.

Model parameter \( a_1, a_2, \ldots, a_n, b_1, b_2, \ldots, b_n \) can be estimated by the variable step-size recursive algorithm on forgetting factor data, and the formula (15) is the algorithm [7-25].

\[ \theta(k) = \theta(k-\ell) + K(k)[z_{k,l} - H_{k,l} \theta(k-\ell)] \]  

(15)

\[ K(k) = P(k-\ell) H_{k,l}^T / (P(k-\ell) H_{k,l} + \mu_{k,l}) \]  

(16)

\[ P(k) = \frac{1}{\mu} [I - K(k) H_{k,l}] P(k-\ell) \]  

(17)

\[ 0 < \mu = \beta^2 < 1 \]  

(18)

In which, \( \ell \) is the positive integer, \( \mu_{k,l} \) is the forgetting factor diagonal matrices.

In the system identification experiment, the input signal is the M sequence while the noise signal is \( v(t) \), and the sampling cycle is 100HZ, and \( e(t) \) is the random white noise signal.

\[ v(t) = \frac{1}{1 - 0.9e^{-t}} e(t) \]  

(19)

### 3.1. Collection of identification data

Because of many uncertainty factors of ICT servo system, identification data is collected by closed loop system, and motion position is measured by one multi-axis motion parameter online measurement method based on ARM processor. Online measurement method will be described in other paper. Figure 3 is the data collection of closed loop.
Figure 3. Data Collection of Closed Loop

Considering the AC servo driver and AC electric machinery, transmission mechanism as the identification object, Input signal is the M sequence, and the output signal is the motion states including position $d$ and velocity message of movement axis.

3.2. Analysis of system order

According to the above-mentioned identification principle, we can get speed loop math model of the single axis which can derive the figure 4 frequency characteristics of system, from the figure 4, we can find that amplitude frequency characteristic of two, three and four order are similar in the low frequency band, and combining the above-mentioned theoretical analysis of the transfer function of transmission mechanism. Therefore, we choose the two order speed loop as the real system, and the position loop is three orders.

Figure 4. Frequency-amplitude Characteristic of Different Order

4. Experiment test

According to the above mentioned method, we make the parameter identification experiment of translation axis on CD-300BXR industrial CT system. The whole system is composed of the AC servo driver and AC electric machinery, motion controller, photoelectric encoder, long grating, transmission mechanism. The motion controller which transmits command to the actuator is the main controller of servo system while long grating measures the motion position of translation. The experiment takes the speed loop model as the example, when the drive load $J$ is $8.3 \times 10^{-4}$ kgm the last identification transfer function is:

$$G(Z) = \frac{64.705Z}{Z^2 - 0.535Z + 0.2187} \quad (20)$$
In order to validate the effectiveness of above mentioned identification model, and the figure 5 is the output curve of mechanism and identification model when they are under the same input signal which is square signal that amplitude is 1 and the frequency is the 1HZ, from the figure 5, the max error between the real experiment and identification simulation is 1.33% while the max error between the real experiment and mechanism simulation is 1.33%. Formula (21) is the correlation of residual error with input data. The figure 7 shows that the movement scope of the correlation of residual error with input data is around 0.5%, and which validates the effectiveness of identification model. Formula (22) is the residual error.

\[ R_{\infty}(\lambda) = \frac{1}{N} \sum_{t=1}^{N} \epsilon(t)u(t - \lambda) \]  

\[ \epsilon(k) = z(k) - z(k) - h^T(k) \hat{\theta} \]  

In which, \( z(k) \) is the output of the real system, \( z(k) \) is the output of identification model, \( h^T(k) \) is the above mentioned, \( \hat{\theta} \) is the model identification parameter.

5. Conclusions

The input-output data of online identification method with the variable step-size least squares recursive algorithm on forgetting factor proposed in this design is obtained by the online measurement method. The proposed identification method solved the inapplicability and inaccuracy with ignored factor of mechanism in DR imaging technology, and the three-dimensional imaging technology provides a good theory evidence for the design of ICT servo system controller and the correction of
system, the characteristic of the method that deserves to be used for reference in project is easy in
calculation, nice in online, fine in precise and small in cost, and so on. Which gives a nice tool for
the optimization of ICT system, but the error between the real system and the identification model
parameter still exists as the optimization of model parameter which is the emphasis of next research is
not enough.

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