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Improving the accuracy of servo drives of metalworking machines

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Abstract
Synchronous motors with permanent magnets are widely used in electromechanical systems with high requirements for quality control due to the high power factor, high-performance of angular velocity control, etc. For servo systems with synchronous motors and permanent magnets necessary signals for the feedback are defined according to the rotor position and angular velocity. Traditional approaches to this problem include the use of an optical incremental, absolute or combined encoder. However, the use of encoders as the speed sensors has its own peculiarities associated with the work at low angular velocities, since in this mode the existing methods do not provide sufficient accuracy. Therefore, the question of improving the properties of servo drives with synchronous motors and permanent magnets is relevant and important scientific and technical problem. Theoretical generalization and the solution of the actual scientific and technical problem of increasing the accuracy of control over the synchronous machines with permanent magnets and an absolute or incremental encoder were implemented. The point of the research is to introduce in the control system of self-adaptive Kalman observer that can significantly improve the control quality indicators.
Keywords: SYNCHRONOUS MOTOR, VECTOR CONTROL, STATE OBSERVER, ENCODER

The problem and its connection with scientific and practical problems

Synchronous motors with permanent magnets are widely used in electric drives of machine tools with high requirements regarding the quality of regulation. For servo drives with these types of engines the feedback signals for rotor position and angular velocity are necessary. Traditional approaches to solving this problem include the use of an optical incremental encoder (digital sensor of position), absolute or combined encoder.

Analysis of studies and publications

Recently, studies on the speed measurement methods and increasing its accuracy affect mainly incremental encoders [1], and the studies of absolute encoders are mainly focused on the issues of their structure design [2]. Traditional methods for the identification of the angular velocity based on counting the number of pulses per period of time, the period of a single pulse or a combination of these approaches lead to the occurrence of time delay and errors in measurement. To overcome the shortcomings of traditional methods of the angular velocity measuring, a number of methods was proposed by the researchers: the use of nonlinear observers [4], observers with sliding mode [5].

Formulation of the problem

Since the error signal of the optical encoder can be regarded as white Gaussian noise, the optimal estimation of the angular velocity and load moment can be obtained using the Kalman filter from successive signals of the rotor position. The objective of the work is to develop a self-adaptive observer based on Kalman filter to improve the accuracy of servo drives on the basis of synchronous motors with permanent magnets.

The presentation material and results

Coded disk of n-bit absolute encoder comprises n circles which are evenly distributed grooves, which can conduct or non-conduct light. Values of coded channels are formed in accordance with certain rules that allow putting in correspondence with each angular position only one binary code associated with it. Therefore, the range of codes changes is 0 - (2n-1). Then the resolution of n-bit encoder is 1 / 2n.

From the analysis of signals form an absolute encoder can be concluded that it varies when changing of the rotor position value to a value equal to the quantization error, i.e.

$$\Delta = {}^{2\pi}/_{2^n} \quad \text{radian.}$$

Euler method is based on the algorithm for finding the average velocity using changes in position over the moment of time, which corresponds to the measurement period T_m:

$$\omega(m) = \frac{\theta(m) - \theta(m-1)}{T_m}, \tag{1}$$

where T_m– time interval between *(m-1)*-th and *m*-th a change in position of the rotor. The error in determining the angular velocity e_{EM} (*m*) can be evaluated as:

$$e_{\mathrm{EM}}(m) = \frac{\Delta\theta(m) - \Delta\theta(m-1)}{T_m}. \tag{2}$$

The variation of the measurement error can be defined as follows:

$$R_{\mathrm{EM}} = E[(e_{\mathrm{EM}} - E[e_{\mathrm{EM}}]) \cdot (e_{\mathrm{EM}} - E[e_{\mathrm{EM}}])^T] = \frac{\Delta^2}{3T_1^2}. \tag{3}$$

Thus, the velocity identified using the Euler method contains a considerable error.

Another existing method of estimating the angular velocity using the encoder signal is a method of changing the period. There to reduce the errors inherent in the Euler method the change of position for several periods is calculated, further averaging the result obtained. Mathematically this can be written as follows:

$$\omega(m) = \frac{\sum_{h=j+1}^{m}(\theta(h) - \theta(h-1))}{\sum_{h=j+1}^{m} T_h} = \frac{\theta(m) - \theta(j)}{\sum_{h=j+1}^{m} T_h}, \tag{4}$$

Variation of error for this method can be written as follows:

$$R_{TDPM} = \frac{\Delta^2}{3\left((m-j)T_1\right)^2}. \tag{5}$$

Taking into account (5), we can conclude that method of period change improves the accuracy of determining the angular velocity and it is increased by developing the measurement period, but it causes a greater time delay.

Another existing method of the angular velocity periods identification is periods overlay method, which in order to reduce the time delay inherent in the previous method calculates the angular velocity of the current and several previous measurement periods and then perform averaging of the data obtained. Mathematically, it can be written as follows:

$$\omega(m) = \frac{1}{v}\sum_{z=0}^{v-1}\left(\frac{\theta(m-z)-\theta(j-z)}{\sum_{h=j-z+1}^{m-z} T_h}\right), \quad (6)$$

Dispersion of measurement error in this case can be defined as follows:

$$R_{\text{ро}} = \frac{\Delta^2}{3v\left((m-j)T_1\right)^2}. \quad (7)$$

Thus, none of the methods does not provide satisfactory accuracy. The solution of the problem in the work is done by introduction of the Kalman filter in the control system. The equations describing the dynamics of the processes in the synchronous motor with permanent magnets have the following form:

$$\frac{d}{dt}\begin{bmatrix}\theta\\ \omega\\ M_l\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & -\frac{c}{J} & -\frac{1}{J}\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \omega\\ M_l\end{bmatrix} + \begin{bmatrix}0\\ K_M\\ 0\\ M_l\end{bmatrix} i_q,$$

where ω– rotor angular velocity, i_q – projection of the stator current vector on q-axis; J – inertia moment of the mechanical part of the drive; c – coefficient of viscous friction; K_M – transfer coefficient of the electromagnetic torque; M_l – load moment, which is assumed to be constant in the interval of system discreteness:

$$\frac{dM_l}{dt} = 0$$

After discretization, the observer based on the Kalman filter can be described by the following equations:

$$\boldsymbol{x}(k+1) = \boldsymbol{Ax}(k) + \boldsymbol{Bu}(k) + \boldsymbol{w}(k),$$
$$\boldsymbol{y}(k) = \boldsymbol{Cx}(k) + \boldsymbol{r}(k),$$

where k – number of discreteness period;

$$\boldsymbol{x} = \begin{bmatrix}\theta\\ \omega\\ M_l\end{bmatrix}$$ – system state vector;

$\boldsymbol{u} = [i_q]$– vector of control actions; $\boldsymbol{y} = [\theta]$ – observer signal; w – noise of the process, which takes into account the effect of observer parametric errors on the quality of the assessment; $\boldsymbol{r}$ – measuring noise, which takes into account the measurement error and other factors affecting the accuracy of the identification of input and output variables of the system state.

When working at low angular velocity the digital signal processor is not able to receive from the encoder position signal update at each interval of discreteness. In these cases, the position signal is taken into account in the control system contains a large error. The proposed version of the system based on the Kalman filter allows the system getting rid of this drawback by indirect identification of the rotor position in those measurement periods when the encoder position signal has not been updated for the interval of discreteness.

Another positive effect of the use of the Kalman filter is the ability to assess with its help of load moment and the system synthesis of the perturbation for subsequent compensation. In the conventional system of vector control the feedback on speed and the current processed by the PI controller are used. The speed regulator cannot create the conditions for the precise development of the reference signal when the influence of load moment during his abrupt changing. For the successful solution of the problem, it is necessary to build a system of disturbance and rejection, considering the load moment estimated by the Kalman filter as the disturbance signal.

Conclusions and directions for further research

The theoretical generalization and the solution of an actual scientific and technical problem of increasing the accuracy of synchronous control machines with permanent magnets and an absolute or incremental encoder were implemented. The point of the research is to introduce the self-adaptive Kalman observer into the control system, which allows significant improving the quality indicators of regulation.

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