DIAGNOSTICS OF ACTUATORS OF MACHINE TOOLS DRIVES ACCORDING TO THE IDENTIFIABILITY CRITERION BY THE STATE SPACE

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Currently, in view of the fact that almost all the tasks of the practice of controlling CNC machine and robot drives cannot be accurately represented by linear models, and there is no solution to non-linear models in the general case, a very important task is to develop control algorithms based on discrete models. Discrete models of nonlinear systems assume variable state, control, and measurement matrices that determine an infinite number of variants of this model. Therefore, some tool is needed to calculate the degree of adequacy of mathematical models and real objects. The paper considers theoretical statements related to the main directions of research in the field of theoretical issues - the study of the dynamics of CNC machine and robot drives and their modeling. The paper studies the drives of CNC machine and robots by the criterion of identifiability based on a discrete digital control model. Criteria of observability, controllability and identifiability of drives are considered as a function of the rank of an extended state matrix with a measurement matrix, in which the relative errors of the information-measuring system are analytically taken into account. An algorithm for calculating the identifiability criterion for a nonlinear control system in a discrete linearization version is proposed. It is proposed to use identification in terms of the correspondence of the mathematical model to the results of the operation of the object. Drive control by means of a discrete vector-matrix algorithm involves the calculation of the state matrix at each step. Therefore, at each step, the determinant of the extended matrix is calculated, which is compared with a constant that numerically divides the space of the state matrices. Thus, the operation of the drives itself makes it possible to determine its identifiability. As a criterion for the optimality of the identification algorithm, a decision-making optimality criterion is chosen in combination with an identifiability criterion for an optimal control algorithm by the criterion of minimum quadratic form. The vector-matrix model of drives in the state space is presented taking into account the relative accuracy of measuring the state of the information-measuring subsystem of drives. It is proposed for practical problems to determine the identifiability criterion by modeling the state matrix for cases when the state matrix parameters exit the space of realizable parameters of serviceable drives. The linearized model of CNC machine and robot drives has limitations in accordance with technical characteristic, for example, restrictions on the strength of electric current and voltage. The obtained research results can be used to build diagnostic systems for CNC machine and robot drives.

KEYWORDS

identification, CNC machine, robot drives, DC motor, state space, discrete model, diagnostics

1 INTRODUCTION

CNC machine and robot drives work offline, sometimes in extreme conditions. To ensure their high reliability, an effective diagnostic system is required. For the diagnosis of CNC machine and robot drives, an algorithm is proposed for deciding on their identifiability on the basis of a discrete digital control model, based on the approach of matching an a priori model of an object with operating results, that is, the diagnostic process determines the adequacy of the applicability of the model to the object. The algorithm is based on the calculation of the value of the identifiability criterion for a discrete nonlinear model in the state space.

Models of systems for the diagnostics of mechatronic are developed based on examples of CNC (Computer Numerical Control) machine diagnostics and mechatronic modules based on the fuzzy inference system, concluding with a solved example of the multi-criteria optimization of diagnostic systems. Algorithms for CNC machine diagnostics are implemented and intended only for research into precisely determined procedures for monitoring the lifetime of the mentioned mechatronic systems [Nikitin 2020, Peterka 2020a].

A prerequisite for solving the problems of synthesis of control and diagnostic systems is the process of their identification. Moreover, in the synthesis of drive control systems, various assumptions are possible (and sometimes necessary) aimed at simplifying the mathematical model in order to obtain a constructive result. When developing algorithms for diagnosing drives, it is advisable to avoid any assumptions, since the accuracy of identification entirely determines the depth and reliability of the generated diagnosis. That is, the process of deep and accurate identification of drives is fundamental in the development of algorithms for their diagnosis, providing the necessary reliability of the generated diagnosis.

The method of identification in the state space has been actively developed over the past two decades and has been successfully implemented in many industries. One of the first P. Eikhoff performed the theoretical justification of identification, developed algorithms and methods of identification [Eykhoff 1974, Eykhoff 1981]. The identification of dynamical systems is devoted to the work of the following authors: [Graupe 1976, Ljung 1999, Sage 1971a, Sage 1971b], and among Russian authors: [Cypkin 1984, Rajbman 1970, Steinberg 1987] and others. In the 1980's and early 1990's, the main approaches to quantitative diagnostics were developed: an observer-based approach, a parameter estimation method, etc. Some important works in this direction are Frank [Frank 1990], Isermann [Iserman 2006], and Besseville [Besseville 1993]. The developed methods are well theoretically justified and are classic diagnostic methods. These techniques are based on analytical redundancy, which is a model that describes the diagnosed technical system. Developments in the field of technical diagnostics of electric motors are published in [Abramov 2014, Abramov 2015, Costa 2016, Krasovskij 1987, Luo 2017, Sage 1993, Trefilov 2007, Trefilov 2018, Turygin 2018].

2 MATERIALS AND METHODS

2.1 *Research problem statement*

DC motors are widely used in CNC machine and robot drives. Let us write the control equations for their continuous nonlinear systems - differential equations of control and observation in the state space

$$\dot{\mathbf{x}}(t) = \mathbf{A}(t)\,\mathbf{x}(t) + \mathbf{B}(t)\,\mathbf{u}(t), \quad (1)$$

$$y(t) = \mathbf{C}(t)\,\mathbf{x}(t),$$

where :

A(t) is a functional matrix of size n×n, called the state matrix of the object;

B(t) is a functional matrix of size n×r, called a control (input) matrix;

C(t) is a functional matrix of size m×n, called the state output matrix or the measurement matrix.

The classical DC motor model with constant parameters does not correspond to reality in the entire DC motor working range. Therefore, nonlinearity associated with viscous friction was added.

In the study of drives, the provisions of tribomechanics associated with the main stable laws in the law of dry friction - the dependence of the friction forces on the sliding speed - are taken into account.

The following differential equations of the first order were used for the CNC machine and robot drive model based on DC motor:

$$L\frac{dI}{dt} = -RI - k_E\omega + U \quad (2)$$

$$J\frac{d\omega}{dt} = k_M I - k_{fr}\omega - M \quad (3)$$

The equation (3) takes into account viscous friction in the form.

To build the DC motor models, a pair of equations (2) and (3) is used.

The dynamic model of the CNC machine and robot drive is presented in the state space in the classical vector-matrix form. The scalar value, the supply voltage of the drive U, is specified as the control vector.

In general terms, when at least one of the matrix **A**(t), **B**(t), **C**(t) is time-dependent, the problem is non-linear and has only particular solutions. To find the equation of state, we represent equations (1) in a discrete form, and the sampling time *T* tends to zero, and the trajectory on each discrete section is linear.

We write the solution for the nonlinear problem in a discrete form, when the matrixes A, B, C are constant at time instants *k*, *k = 0,1,2,3, ...*

$$\frac{\mathbf{x}_{k+1} - \mathbf{x}_k}{T} = \mathbf{A}_k\mathbf{x}_k + \mathbf{B}_k\mathbf{u}_k, \quad (4)$$

or

$$\mathbf{x}_{k+1} = \widetilde{\mathbf{A}}_k\mathbf{x}_k + \widetilde{\mathbf{B}}_k\mathbf{u}_k, \quad (5)$$

where $\widetilde{\mathbf{A}}_k = T\mathbf{A} + \mathbf{E}$, $\widetilde{\mathbf{B}}_k = T\mathbf{B}_k$.

This equation relates the transition of the system from state $\mathbf{x}_k$ to state $\mathbf{x}_{k+1}$. On the segment T, we take the values of the matrices $\mathbf{A}_k$, $\mathbf{B}_k$ and $\mathbf{C}_k$ to be constant. For convenience, in the following entries we remove the "wavy line" sign.

We assume that the matrix at each step k does not change; it is determined by the information-measuring system and can be represented as

$$\mathbf{C}^{-1} = \mathbf{E} + \xi_n \quad (6)$$

where is a random vector representing the random nature of the measurements by the information-measuring system included into drives.

2.2 *Identification of drive based on DC motor*

Let us consider the issue of identification of drives based on DC motors from the point of view of the analysis of equation (1), where at each linearization step, the criterion of identifiability and observability is the rank of the extended matrix.

$$rank\left[\mathbf{C}_k^{\mathrm{T}} \quad \mathbf{A}_k^{\mathrm{T}}\mathbf{C}_k^{\mathrm{T}} \quad (\mathbf{A}_k^{\mathrm{T}})^2\mathbf{C}_k^{\mathrm{T}} \quad \ldots \quad (\mathbf{A}_k^{\mathrm{T}})^{n-1}\mathbf{C}_k^{\mathrm{T}}\right] = n. \quad (7)$$

The matrix is completely determined by the information-measuring system, that is, a relative measurement error or accuracy class. We write the model of the information-measuring system in the form **y** = **Cx**,

or

$$\begin{bmatrix} y_1 \\ y_2 \\ \ldots \\ y_n \end{bmatrix} = \begin{bmatrix} 1+h_1\xi_1 & 0 & \ldots & 0 \\ 0 & 1+h_2\xi_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & 1+h_n\xi_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \ldots \\ x_n \end{bmatrix}, \quad (8)$$

where

h_i is the relative measurement error,

ξ_i is implementation of a normally distributed random variable with standard deviation $\sigma_i = \frac{h_i}{3}$, $i = \overline{1,n}$.

Let us consider the worst case for all measurement channels, given the continuous and infinite nature of the implementation of a normally distributed random variable. We assume that most measurement values fall in the interval $-3\sigma_i \le \xi_i \le 3\sigma_i$, $i = \overline{1,n}$. We will obtain results for the maximum measurement errors taken in smaller and larger directions.

Then, for maximum measurement errors, we can write down approximately

$$\mathbf{C}_n = \begin{bmatrix} 1-h_1 & 0 & \ldots & 0 \\ 0 & 1-h_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & 1-h_n \end{bmatrix}. \quad (9)$$

In our case, the measurement channels are independent and the determinant of the matrix will be equal to

$$\det\mathbf{C}_n^{\mathrm{T}} = (1-h_1)(1-h_2)\ldots(1-h_n). \quad (10)$$

Let us open the brackets in (10), exclude the terms of the second and higher order of smallness, we obtain

$$\det\mathbf{C}_n^{\mathrm{T}} = 1 - h_1 - h_2 - \ldots - h_n = 1 - \sum_{i=1}^{n} h_i. \quad (11)$$

If the relative accuracy over all measuring channels is the same, $h_i = h$, $i = \overline{1,n}$, then from (11), we obtain

$$\det\mathbf{C}_n^{\mathrm{T}} = 1 - nh. \quad (12)$$

Similarly, for maximum errors, n the worst case, for all measuring channels, we can write

$$\det \mathbf{C}_n^{\mathrm{T}} = 1 + h_1 + h_2 + \ldots + h_n = 1 + \sum_{i=1}^{n} h_i \cdot \tag{13}$$

$$\det \mathbf{C}_n^{\mathrm{T}} = 1 + nh \cdot \tag{14}$$

The value of the determinant in (13) and (14) is always greater than unity, since the value of relative accuracy is always positive, $h_i > 0$, $i = \overline{1,n}$.

Thus, the identifiability condition (11) in the case

$$\det \mathbf{A}_k^{\mathrm{T}}(n)^i > 0, \; i = \overline{1,n} \cdot \tag{15}$$

will be a condition

$$\det \mathbf{C}_n^{\mathrm{T}} = 1 - \sum_{i=1}^{n} h_i > 0 \tag{16}$$

or

$$\sum_{i=1}^{n} h_i < 1 \cdot \tag{17}$$

Considering that in many practical control tasks, the dimensions of the tasks do not exceed ten, and the relative measurement accuracy is equal to units of percent, we can conclude that only the state matrix affects the identifiability

$$\mathbf{A}_k^{\mathrm{T}}, \; k = \overline{1,n}, \tag{18}$$

which will ultimately determine the rank of the matrix (5).
It is proposed for practical tasks to determine identifiability in the form

$$\min \det \mathbf{A}_k^{\mathrm{T}}(n)^n \det \mathbf{C}_k^{T}(n) > \gamma, \tag{19}$$

where
k is the step number in the nonlinear model;
n is the dimension of the model;
γ is the identifiability criterion, selected by modeling the state matrix for cases when the parameters of matrix **A** exit from the space of realizable values of a working object.

3 RESULTS AND DISCUSSION

3.1 Diagnostics of drives based on DC motor

Different machining technologies such as turning, milling, drilling, broaching [Kolesnyk 2020, Sentyakov 2020, Peterka 2020b, Peterka 2020c, Vopat 2014] place different requirements on the quality of the cutting tool. Geometric properties (dimensions, angles, radius after rectification etc.) are usually considered. From the point of view of cutting theory, the surface roughness of the cutting tools itself is also important.

Let us consider the diagnostics of drives of feed drives of CNC machine tools based on a direct current motor (DC motor) in the state space. Since the drive controller must provide control, to ensure movement along the programmed path of the robots or CNC machine tools [Bozek 2013, Bozek 2016, Nemeth 2018, Nemeth 2019, Pokorny 2008], in terms of torque, rotation speed and angular displacement, the armature current I, the armature speed ω, and the angular displacement ϕ are chosen as generalized coordinates. The control is the voltage at the armature U, the disturbance is the load resistance moment M. The control is the voltage at the armature U, the disturbance is the load resistance moment M. The model parameters are the active resistance and inductance of the circuit and the armature, denoted by R and L, respectively, as well as the reduced moment of inertia J and design constants k_E and k_M. By resolving the original system with respect to the first derivatives, the DC motor equation in the state space is obtained.

The classical DC motor model with constant parameters does not correspond to reality in the entire working range of the DC motor. Therefore, nonlinearity associated with viscous friction was added.

The vector-matrix model of DC motor is written in the form (1)

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{I} \\ \dot{\omega} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} -\dfrac{R}{L} & -\dfrac{k_E}{L} & 0 \\ \dfrac{k_M}{J} & -\dfrac{k_{e\_mp}\omega - M_H}{J\omega} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I \\ \omega \\ \varphi \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} \\ 0 \\ 0 \end{bmatrix} \mathbf{u}, \tag{20}$$

$$\mathbf{y} = \begin{bmatrix} I \\ \omega \\ \varphi \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{x}, \tag{21}$$

The vector-matrix model of DC motor is written in the form (3).

$$\boldsymbol{x}(k+1) = \begin{bmatrix} I(k+1) \\ \omega(k+1) \\ \phi(k+1) \end{bmatrix} = \begin{bmatrix} 1 - T\frac{R}{L} & -T\frac{k_E}{L} & 0 \\ T\frac{k_M}{J} & 1 - T\frac{k_{e\_mp}\omega + M_H(k)}{J\omega(k)} & 0 \\ 0 & T & 1 \end{bmatrix} \rightleftarrows \begin{bmatrix} I(k) \\ \omega(k) \\ \phi(k) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} \boldsymbol{u}(k) \tag{22}$$

$$\mathbf{y}(k) = \begin{bmatrix} \hat{I}(k) \\ \hat{\omega}(k) \\ \hat{\varphi}(k) \end{bmatrix} = \begin{bmatrix} 1 + h\xi & 0 & 0 \\ 0 & 1 + h\xi & 0 \\ 0 & 0 & 1 + h\xi \end{bmatrix} \mathbf{x}(k), \tag{23}$$

where $M_H(k) = (\omega(k+1) - \hat{\omega}(k))\dfrac{J}{T}$;

$\hat{I}(k), \hat{\omega}(k), \hat{\varphi}(k)$ are the measured value of current, angular velocity and displacement;

$\omega(k+1)$ is the planned value of the angular velocity.

If the matrix **A** is equal to zero, then this leads (16) to an unidentifiable drive for the model in the state space.

The expression gives the relationship between the mechanical parameters of the DC motor; it allows for determining the interval of change of values without the loss of identifiability. Although, it is necessary to take into account restrictions on the maximum rotation speed, current and voltage of this drive.

3.2 Computational experiments on the study of the DC motor model in discrete form

The scheme of the DC motor model for calculating the determinant of the state matrix A, A*A is built in the SimInTech software product. The influence of the desired speed on the determinant of state matrices A, A*A is investigated.

Figure 1 shows the dependence of the determinant of the state matrix A on the magnitude of the required angular velocity at the next instant of time.
An analysis of the dependence of the determinant of the state matrix A on the magnitude of the required angular velocity $\omega(k+1)$ at the next moment of time shows that this determinant is zero at an angular velocity $\omega(k+1)$ = 320 rad/s, i.e. 2 times the nominal angular velocity.

Analysis of the magnitude of the required angular velocity from the previous value of the angular velocity shows that the maximum value of the required angular velocity $\omega(k+1)$ can be only 2 times greater than the previous value of the angular velocity $\omega(k)$.

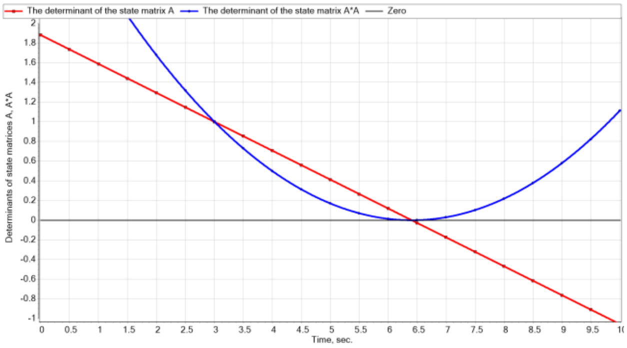


Figure 1 Determinant of the state matrix A vs. the magnitude of the required angular velocity, w(k+1)=50*Time, rad/s

Figure 2 shows a flowchart for calculating the determinants of matrices A and A*A.

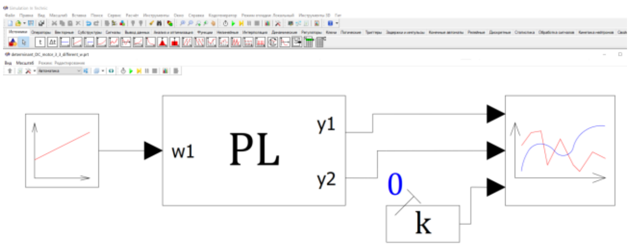
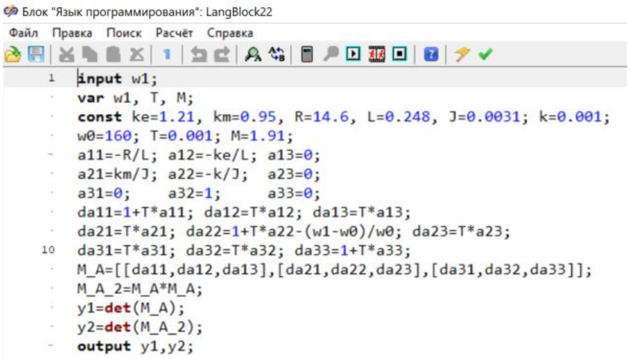


Figure 2 Flowchart for calculating the determinants of matrices A and A*A

Fig. 3 shows the programme that is implemented in the PL software block.




```
input w1;
var w1, T, M;
const ke=1.21, km=0.95, R=14.6, L=0.248, J=0.0031; k=0.001;
w0=160; T=0.001; M=1.91;
a11=-R/L; a12=-ke/L; a13=0;
a21=km/J; a22=-k/J;  a23=0;
a31=0;    a32=1;     a33=0;
da11=1+T*a11; da12=T*a12; da13=T*a13;
da21=T*a21; da22=1+T*a22-(w1-w0)/w0; da23=T*a23;
da31=T*a31; da32=T*a32; da33=1+T*a33;
M_A=[[da11,da12,da13],[da21,da22,da23],[da31,da32,da33]];
M_A_2=M_A*M_A;
y1=det(M_A);
y2=det(M_A_2);
output y1,y2;
```

Figure 3 Program for calculating the determinants of matrices A and A*A

4 CONCLUSIONS

Currently, in view of the fact that almost all the tasks of the practice of controlling CNC machine and robot drives cannot be accurately represented by linear models, and there is no solution to non-linear models in the general case, a very important task is to develop control algorithms based on discrete models. Discrete models of nonlinear systems of the form (4) assume variable state, control, and measurement matrices that determine an infinite number of variants of this model. Therefore, some tool is needed to calculate the degree of adequacy of mathematical models and real objects.

This paper presents:

- an algorithm for identifying nonlinear complex objects based on a discrete digital control model.

As a criterion for the optimality of the identification algorithm is selected:

- a decision-making criterion, the equation (19),
- in combination with an identifiability criterion for the control algorithm, equation (16).

Identification criteria, equations (16) and (17), allow for determining:

- the degree of conformity of the models to the control object by the model:
  - either of the measuring matrix or
  - by the combination of models of the state matrix and measuring matrix.

The sensor system we designed was used to measure the electric current, the speed of rotation of the drive shaft and its angular movement. From a mathematical point of view, this sensor system forms:

- an output matrix or
- a measuring matrix by a space of states taking into account measurement errors. Based on the state vector and the measuring matrix, the output vector of the drive is created in the state space.

The specific sensors included in the sensor system should be selected on the basis of the maximum values:

- of the electric current,
- the rotational speed of the drive shaft and
- its angular movement in the event of faults.

Further research is related to the identification of CNC machine and mobile robot model. It is planned to develop mathematical CNC machine and mobile robot models, synthesis schemes and procedures for detecting fault, fault-tolerant control of mechatronic, CNC machine and robotic systems. An algorithm will be developed for predicting the residual life of CNC machine and mobile robot drives based on the synergistic unity of recognition and forecasting algorithm based on a sequential decision-making algorithm and forecasting random processes from training samples using Parzen estimates.

It is also planned to address joint research in related fields [Pivarciova 2019], which would include our proposed mathematical models and modeling of composite materials [Fedosov 2020] in relation to the stability and diagnostics of systems.

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