Method of technological control of proportional electromagnets for control systems of their production

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Abstract. This article describes the algorithm of the method of technological control of proportional solenoids to control their production process. An important element in the process of production of proportional solenoids is to identify deviations from the nominal mode of its occurrence. This situation shows the relevance of developing a method of technological control of proportional solenoids providing information on process control in a short time. The proposed algorithm consists of four steps: measuring the dynamic characteristics of the magnetization of electromagnet testing, the use of principal component analysis to reduce the dimension of the analyzed information, the classification of products by the condition and sub-standards, the definition of the numerical values of the manufacturing process variations using a calibration method. This approach allows us to determine the type and the degree of impairment of the mode of the process that will lead to effective management of the production process of the electromagnetic actuators.

1. Introduction

Identification of deviations from the nominal flow regimes of the process of proportional solenoid production is an integral part of enhancing the quality of products. This requires an effective method of process control, which allows determining the place and the degree of deviation from the nominal values of the process conditions for further management [6].

An important element of the production process is the management system of proportional solenoids production, it was the system that makes up the management modes of production equipment. We will consider the application of the developed method of process control as part of production process control system. The proposed block diagram of the process control system of production of proportional solenoids is shown in Figure 1. It contains dynamic characteristics of the magnetization determination device (MDD) [5, 8] and the information processing apparatus for generating the control action.

The detection device measures the dynamic characteristics of the magnetization of each electromagnet DCM and transmits the measurement result to the information processing apparatus and generates the control action. This in turn selects articles having deviations in operating parameters, and thus carries the information about the violation of the manufacturing process. These deviations are detected by means of a mathematical model obtained by the calibration method that connects the operating parameters with the parameters of the electromagnet and its manufacturing process. In addition, the control action processing
unit collects and analyzes the information on the change of technological modes in case of the appearance of sustainable trends in their change process, which generates a control signal to eliminate the possibility of visiting lots of sub-standard products.

![Diagram](image_url)

**Figure 1.** Block diagram of process control system production of proportional electromagnets.

Controllable process parameters are the deviation of the magnetic characteristics of the magnetic material parts of the electromagnet (casing, armature, yoke), arising from violations of their modes of machining and the number of operating winding turns. They are controlled by adjusting the process operating modes of winding equipment, and equipment machining workpieces annealing or adding operations.

2. Methods and results
The proposed method of process control involves four basic steps. The first step is measuring DCM of the electromagnetic drive, because it contains latent information on the majority of the electromagnetic parameters of the drive. The fact that the dynamic characteristics of the magnetization of the electromagnetic actuator has a complex character is not unique. In the second step, we reduce the dimension of the analyzed data using the projection method. In the third step, we carry out classification of groups of measured characteristics to highlight products that carry information on deviations of sustainable production process of proportional solenoids. In the final step, the numerical values are determined by deviations from the normal process with the help of calibration.

Application of DCM in an array of pairs of points (magnetic flux current) for further processing is difficult, because the use of large amounts of data (DCM measured with an accuracy of ± 3%, contains about 15,000 pairs of points) places high demands on the processing performance of funds. In this
connection, it is advisable to obtain the measurement result in the form of approximating expressions, allowing one to reduce the processing time measurement information.

Let us consider obtaining step DCM. A mathematical model of the electromagnet is based on the method of harmonic balance [7]. The model is based on the equation of the circuit with a nonlinear inductance which approximate DCM to the degree of the polynomial:

\[
\begin{aligned}
&u = iR + \frac{d\Phi}{dt}, \\
&i(\Phi) = \sum_{k}^{m} k_{q}\Phi^q,
\end{aligned}
\]

where \( u \) – the voltage applied to the operating coil of the electromagnet, \( R \)– the resistance of the operation of the electromagnet coil, \( \Phi \) – the value of the magnetic flux, \( k \) – approximation polynomial coefficients of the power, \( m \) – the maximum degree of the approximating polynomial.

The algorithm of natural-model tests [1-4, 9, 10] in relation to the problem of determining the proportional electromagnets of DCM is as follows: during operation, the electromagnet coil is energized, obtains a predetermined shape, and current versus time \( i_{\text{meas}}(t) \) is measured. Electromagnet voltage is introduced into the mathematical model, and it generates output current \( i_{\text{model}}(t) \). With the optimization algorithm (simplex optimization method) approximation coefficients \( k_q \) changes achieving coincidence of the measured \( i_{\text{meas}}(t) \) and formed model of current electromagnet \( i_{\text{model}}(t) \). The level of current differences \( i_{\text{meas}}(t) \) and \( i_{\text{model}}(t) \) determined by the value of functional \( J \) is:

\[
J = \frac{\int_{0}^{T_f} (i_{\text{model}}(t) - i_{\text{meas}}(t)) \, dt}{\int_{0}^{T_f} i_{\text{meas}}(t) \, dt}.
\]

At each iteration, the optimization condition is tested:

\[
J \leq \varepsilon,
\]

where \( \varepsilon \) – current measurement accuracy \( i_{\text{meas}}(t) \).

Let us consider the adaptation in the method of a submission form of harmonic balance current. We turn to the discrete representation of functional form \( J \):

\[
J = \frac{\sum_{m=1}^{n} |I_{(2m-1)\text{model}} - I_{(2m-1)\text{meas}}|}{\sum_{m=1}^{n} I_{(2m-1)\text{meas}}},
\]

where \( I_{(2m-1)\text{meas}} \) and \( I_{(2m-1)\text{model}} \) – harmonic measurements (2m-1) and calculations of the current model in the coil proportional solenoid.

If condition (1) is not satisfied, then the parameters of the mathematical model change, defining the shape of dynamic characteristics of the magnetization, newly defined relationship \( i_{\text{model}}(t) \) and performed functional calculation \( J \). If condition (1) is satisfied, the dynamic characteristic of the magnetization proportional solenoid is found.

Due to the fact that an electromagnet is proportional to DCM complex hysteresis, the second step is to reduce the dimension of the analyzed information. For this, a projection applied approach uses principal component analysis (PCA). The essence of the method of the principal component consists of a transition from the original variables to new values - the principal components (PC), which are linear combinations of the original variables, with the maximum possible dispersion.

The application of the PCA to the group comprising \( k \) DCM of proportional solenoid actuators. On each original DCM, \( n \) fixed values of magnetic flux \( \Phi_d = d \cdot \Delta \Phi \) are selected:

\[
\Delta \Phi = \frac{\Phi_{\text{max}}}{n},
\]
where $\Phi_{\text{max}}$ – the maximum possible flow value for all studied characteristics, $n$ – the selected number of fixed flow values, $d$ – the point number.

Determined current values $i_j(\Phi_d)$, which are the elements of vector-column matrix $\mathbf{I}$ dimensionality $n \times k$, where $n$ is the number of recorded pixels, $k$ is the number of the test curves:

$$
\mathbf{I} = 
\begin{bmatrix}
  i_1(\Phi_1) & i_2(\Phi_1) & \cdots & i_j(\Phi_1) & \cdots & i_k(\Phi_1) \\
  i_1(\Phi_2) & i_2(\Phi_2) & \cdots & i_j(\Phi_2) & \cdots & i_k(\Phi_2) \\
  \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
  i_1(\Phi_d) & i_2(\Phi_d) & \cdots & i_j(\Phi_d) & \cdots & i_k(\Phi_d) \\
  \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
  i_1(\Phi_n) & i_2(\Phi_n) & \cdots & i_j(\Phi_n) & \cdots & i_k(\Phi_n)
\end{bmatrix}.
$$

Application of polynomial approximation of DCM allows us to calculate the missing values by interpolation vectors $i_j(\Phi_d)$, if $\Phi_{j\text{max}}$ less than $\Phi_{\text{max}}$.

The connection between original matrix $\mathbf{I}$ and matrix values of principal components $\mathbf{Z}$ performed by a matrix of eigenvectors $\mathbf{B}$ has the form:

$$
\mathbf{Z} = \mathbf{B}^T \cdot \mathbf{I}.
$$

Projection procedure is to find the PC matrix with the largest variances. To do this, we find the matrix of variances $\mathbf{D}$ and $\mathbf{Z}$:

$$
\mathbf{D}(\mathbf{Z}) = \mathbf{B}^T \cdot \mathbf{D}(\mathbf{I}) \cdot \mathbf{B}.
$$

Considering that the dispersion of $n$ random variables is their covariance, the previous expression can be written as follows:

$$
\mathbf{D}(\mathbf{Z}) = \mathbf{B}^T \cdot \mathbf{S} \cdot \mathbf{B}.
$$

To find the covariance $\mathbf{S}$ vector of calculated sample means, rows $\bar{\mathbf{I}}_d$, and deviations from the mean for each case are summarized in matrix $\mathbf{F}$, which has formulated the elements as follows:

$$
f_{dj} = I_j(\Phi_d) - \bar{\mathbf{I}}_d, \quad d = 1 \div n, j = 1 \div k.
$$

Then, the estimate of covariance $\mathbf{S}$ is:

$$
\mathbf{S} = \frac{\mathbf{F} \cdot \mathbf{F}^T}{k - 1}.
$$

Not all PC calculated according to expression (2) are significant. Based on the evaluation matrix dispersion values of $\mathbf{D}$, we leave only $(n-l)$ PC with the largest variances, whereupon the matrix $\mathbf{Z}$ is:

$$
\mathbf{Z} = 
\begin{bmatrix}
  z_{11} & z_{21} & \cdots & z_{l1} \\
  z_{12} & z_{22} & \cdots & z_{l2} \\
  \vdots & \vdots & \ddots & \vdots \\
  z_{1n-l} & z_{2n-l} & \cdots & z_{ln-l}
\end{bmatrix}.
$$

The dimension of matrix $\mathbf{Z}$ is significantly less than that of original matrix $\mathbf{I}$, $(n-l) = 1 \div 3$. As a result of this step, we get a new space of principal components, each of which is a point of particular products DCM.

The second step is the classification of manufactured products by conditions and products with deviations of parameters as conditioning products do not carry information about deviations in the process. To do this, let us turn to the DCM, projected into space PC method discrimination - formally independent modeling of class analogies (FIMCA).

The application of FIMCA to the resulting matrix is in previous step $\mathbf{Z}$. Let us find magnitude $h$ (difference between the highest and lowest values of observations), each column vector of matrix $\mathbf{Z}$:
\[ h = \sum_{i=1}^{n-1} \left( \frac{z_i}{\sqrt{\lambda_i}} \right)^2, \]

where \( \lambda_i \) – eigenvalues \( Z \), \( z_i \) – elements of \( Z \).

Using training set \( Z \), we will find the \( p \) range of \( h_1, \ldots, h_p \) and \( v_1, \ldots, v_p \). As it is possible to estimate the corresponding average values:

\[ h_i = \frac{1}{p} \sum_{j=1}^{p} h_j, \quad v_i = \frac{1}{p} \sum_{j=1}^{p} v_j, \]

and the corresponding values of the dispersions:

\[ S_h = \frac{1}{p-1} \sum_{j=1}^{p} (h_j - h)^2, \quad S_v = \frac{1}{p-1} \sum_{j=1}^{p} (v_j - v)^2. \]

The numbers of degrees of freedom \( N_h \) and \( N_v \):

\[ N_h = \frac{2h^2}{S_h}, \quad N_v = \frac{2v^2}{S_v}. \]

Accounting ratio \( f \), over which ranking is calculated as:

\[ f = N_h \frac{h}{h_0} + N_v \frac{v}{v_0}. \]

The critical factor \( f \) is given by:

\[ f_{cr} = \chi^2(\alpha, N_h + N_v) \]

where \( \chi^2(\alpha, n) \) – \( \alpha \)-quantile of the chi-square distribution with \( n \) degrees of freedom.

The classification rule in FIMCA: A sample is taken as belonging to the class, if:

\[ f < f_{cr}. \]

In the next step of the method of process control for stable detection of deviations of the process, we get information about the numerical values of the deviations of process parameters of the manufacturing process of products. For this calibration method, we use a regression to latent structures (RLS). The method consists in obtaining a model linking matrix \( Z \) with DCM coordinates of points in a space projected PC and matrix parameters \( Y \), characterizing the process of manufacturing modes of proportional electromagnets.

The RLS model is based on the training set \((Z_o, Y_o)\), for which there is a matrix of multiple regression coefficients \( \Lambda \):

\[ \Lambda = f(Z_o Y_o). \]

Determination of process parameters \( Y_t \) for the next electromagnet with DCM, projected into the space of the PC \( Z_t \), we use mathematical models of RLS:

\[ Y_t = Z_t \Lambda. \]

3. Conclusions

Thus, the developed method of process control involves four basic steps. In the first step, the dynamic characteristic are measured by magnetization of the electromagnet, since it contains the information on the most latent electromagnetic drive parameters. The dynamic characteristics of the magnetization of the electromagnetic actuator has a complex character are not unique; in the second step, we reduce the dimension of the analyzed data using the projection method. In the third step, we carry out classification of the groups of measured characteristics to highlight products that carry information on sustainable production process deviations proportional to solenoids. In the final step, the numerical values are determined by deviations from the normal process with the help of calibration. Application of the
proposed method of technological control of proportional solenoids control systems as part of their production will improve the quality and quantity of proportional electromagnets.

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