Construction and Study a Regression Model of Construction Accuracy of Dynamic Characteristics of Magnetization

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Abstract. The purpose of the research is to build a regression model of the approximation error dynamic characteristic of magnetization, where we take the maximum total error as the dependent variable, the degree of the polynomial and the number of points as independent. This model will optimize, in terms of accuracy, the choice of the number of points of the dynamic characteristic of magnetization and the degree of approximating polynomial. This model was obtained using the software Statistica, which allows for factor experiments to obtain and further analyze the regression models of synergetic systems. Synergetic systems are complex open non-equilibrium self-organizing systems that are capable of responding to external influence by self-organizing structures.

1. Introduction

Despite the large number of synergistic systems, we will focus on hydraulic, as the hydraulic drive combines various processes, such as thermal, electrical, energy, and of course magnetic [1–3].

In the works of many authors the connection of most of the characteristics of electromagnets with the dynamic characteristic of magnetization (DCM) is shown [4–8]. This characteristic can be obtained by using the working winding of an electromagnet as the primary measuring transducer. DCM is a reflection of the trajectory of the working point of any electromagnet, which proves the close relationship of DCM with the electrotechnical parameters of the electromagnet. The characteristics obtained during acceptance tests, state diagnostics or research activities depend on the electrical parameters of the electronic signature, which in turn can be determined with sufficiently high accuracy by analyzing the DCM.

Since synergistic systems are described by complex systems of equations and a large number of characteristics and parameters, it is necessary to compress this information with the least loss in accuracy of readings. Such data can be minimized by using neural networks, or using the principal component method [9–20]. Approximation is necessary so that instead of characteristics with a large number of points we get one point in three-dimensional space.

The purpose of the research work is to build a regression model of the approximation error DCM, where we take the maximum total error as the dependent variable, the degree of the polynomial and the number of points as independent.

2. Materials and methods

The object of the study are electromagnets. To conduct an experiment, we introduce the concept of an electromagnet. Electromagnets are devices that are designed to create a magnetic field in a certain space
using a winding streamlined by an electric current. Electromagnets are diverse in design, scope and, as a result, in characteristics and parameters. Therefore, the classification facilitates the study of the processes occurring during their work.

We introduce the concept of the dynamic characteristics of magnetization (DCM) $\Phi = f(I)$, shown in fig. 1. It reflects changes in the magnetic flux depending on the current in the working winding of the electromagnet in the process of making it anchor the standard operating cyclic movement, the ascending branch 0-3 is nothing more than a phase trajectory of the electromagnet.

![Figure 1. Dynamic characteristic of magnetization of an electromagnet.](image)

After power is applied, the current in the winding reaches the value of the breakaway current to which point 1 corresponds. At this point, the armature begins to move, during which the working gap $\delta$ decreases, the inductance of the winding increases, and the current in it drops until the armature is pulled to the core, to which point 2 corresponds. During the movement of the armature, the connection between the magnetic flux $F$ and the current $i$ is determined by curve 1-2. At the end of the armature movement, the current starts to increase again, reaching the steady-state value at point 3. After turning off the electromagnet’s power, the current in the winding drops and when the release current $i_{\text{opt}}$ value is reached (point 4), the armature starts moving and the working gap increases from the minimum $\delta_{\text{min}}$ up to maximum $\delta_{\text{max}}$. Point 5 corresponds to the end of the movement of the armature of the electromagnet. Further, the current drops to zero, which corresponds to point 6. Due to the residual magnetization of the magnetic circuit, the flux corresponding to point 6 is higher than zero due to the presence of the residual magnetization of the magnetic circuit of the electromagnet. In the works of many authors shows the relationship between DCM and processes, the flow of which is reflected in the characteristics defined by GOST. For example, how to use DCM to determine the electromagnetic force, i.e. static and dynamic traction characteristics of an electromagnet.

Let us consider the application to DCM approximation by a power polynomial and piecewise polynomial approximation.

The piecewise polynomial approximation method consists in replacing each section with 0-1, 1-2, 2-3 DCMs with approximating curves described by polynomials of the types:

$$i(\psi) = \sum_{k=1}^{m} k_{q} \psi^{q} + b$$

where $k_{q}$ - coefficients describing the slope and curve of the curve; $b$ - coefficient describing the mixing of the curve relative to the axis of abscissa; $m$ is the maximum degree of a polynomial. In addition to the coefficients for constructing piecewise polynomial approximation, it is necessary to know the values of current $i$ and flux linkage $\Psi$ at the points of transition from one section of DCM to another (while to describe the three sections, you need to know two currents and flux linkages).

The method of approximation by a power polynomial is to replace the entire DCM with the expression:
\[ i(\psi) = \sum_{i=1}^{n} k_i \psi^i \]

To describe the ascending branch of DCM (sections 0–1, 1–2, 2–3) using the piecewise-polynomial approximation method, nine values of the approximating polynomial coefficients and four values defining the points of connection of the sections are required.

As the factors of the experiment, we take the number of points \( K \) and the degree of the polynomial \( n \). As a response, we take the approximation error \( \delta \). Approximation error is determined according to clause 1.3.

To construct a polynomial containing squares of factors, each factor is required to vary on three levels. The choice of levels occurs depending on what properties you need to give the plan:

1. Orthogonal planning is designed to obtain an orthogonal plan.
2. Rotatable planning ensures the constancy of dispersions at equidistant points from the center of the plan.

A second-order polynomial contains the first and second degrees of factors and the number of coefficients:

\[ N_2 = C_i^2 + 2k + 1 \]

To build such plans, you can use three-level plans:

\[ N_3 = 3^k. \]

But \( N_3 \) is always greater than \( N_2 \) and their difference grows rapidly with increasing \( k \), therefore, instead of full factor experiment (FFE) \( 3^k \), different compositional plans are used, which have less redundancy. The basis (core) of such a plan is taken by the FFE \( 2^k \) or divisional factor experiment (DFE) \( 2^{k-p} \). The core is complemented by star points and a point in the center of the plan. If the star points are located symmetrically with respect to the center of the plan, then this is the orthogonal central compositional plan (OCCP) (Fig. 2).

![Figure 2. OCCP for k = 2.](image)

For the experiment, a DCM of a proportional electromagnet consisting of 1000 points was taken (Fig.3).
To build an experiment plan, it is necessary to obtain 9 characteristics with the following parameters: DCM, consisting of 100 points and approximated by a polynomial of 9 degrees (Fig. 4).

**Figure 3.** DCM from 1000 points.

DCM consisting of 55 points, approximated by a polynomial of 9 degrees (Fig. 5).

**Figure 4.** DCM from 100 points, approximated by a 9 degree polynomial.

DCM consisting of 10 points, approximated by a polynomial of 9 degrees (Fig. 6).

**Figure 5.** DCM from 55 points, approximated by a 9 degree polynomial.

DCM, consisting of 100 points, approximated by a polynomial of 5 degrees (Fig. 7).

**Figure 6.** DCM from 10 points, approximated by a 9 degree polynomial.
Figure 7. DCM from 100 points, approximated by a polynomial of 5 degrees. DCM, consisting of 55 points, approximated by a polynomial of 5 degrees (Fig. 8).

Figure 8. DCM from 55 points, approximated by a polynomial of 5 degrees. DCM, consisting of 10 points, approximated by a polynomial of 5 degrees (Fig. 9).

Figure 9. DCM, consisting of 10 points, approximated by a polynomial of 5 degrees. DCM, consisting of 100 points, approximated by a polynomial of 1 degree (Fig. 10).

Figure 10. DCM from 100 points, approximated by a polynomial of 1 degree. DCM consisting of 55 points, approximated by a polynomial of 1 degree (Fig. 11).
Figure 11. DCM from 55 points, approximated by a polynomial of 1 degree. DCM consisting of 10 points, approximated by a polynomial of 1 degree (Fig. 12).

Figure 12. DCM from 10 points, approximated by a polynomial of 1 degree. Calculate the approximation error, for each characteristic, according to clause 1.3 (table 1).

Table 1. Calculation of the Approximation Error.

| $d\psi, \text{mWb}$ | $\psi, \text{mWb}$ | $dI, \text{A}$ | $I, \text{A}$ | $\gamma, \%$ |
|-------------------|-------------------|----------------|----------------|----------------|
| 0,4               | 7,53              | 0,0074         | 0,039          | 19,70392       |
| 0,4               | 7,53              | 0,0075         | 0,039          | 19,95096       |
| 0,2               | 7,53              | 0,0026         | 0,039          | 7,176281       |
| 0,2               | 7,53              | 0,0025         | 0,039          | 6,938728       |
| 0,4               | 7,53              | 0,0045         | 0,039          | 12,70253       |
| 0,4               | 7,53              | 0,0044         | 0,039          | 12,47008       |
| 0,95              | 7,53              | 0,0139         | 0,039          | 37,80808       |
| 0,9               | 7,53              | 0,0137         | 0,039          | 37,10587       |

Let us summarize the resulting values in the table of the experiment plan with artificial variation of the approximation error of 5%, which is acceptable for magnetic measurements (Table 2).

Table 2. Plan of the Experiment With the Found Values of the Error of Approximation and the Error of the Model.

| $X_1$ | $K$ | $X_2$ | $n$ | $\gamma, \%$ |
|-------|-----|-------|-----|----------------|
| -     | 10  | +     | 9   | 19,70392       |
| -     | 10  | +     | 9   | 20,689116      |
| -     | 10  | +     | 9   | 18,718724      |
| -$\alpha$ | 10 | 0     | 5   | 19,95096       |
| -$\alpha$ | 10 | 0     | 5   | 20,948508      |
| -$\alpha$ | 10 | 0     | 5   | 18,953412      |
| 0     | 55  | +$\alpha$ | 9   | 7,176281       |
| 0     | 55  | +$\alpha$ | 9   | 7,5350951      |
| 0     | 55  | +$\alpha$ | 9   | 6,817467       |
Experiment planning is performed using the Statistica 10 software environment. Next, we calculate the estimates of the regression coefficients, based on coded initial values of factors (Fig. 13).

![Table of the resulting model in coded values.]

Then we calculate the estimates of the regression coefficients, based on uncoded (physical) initial values of the factors (Figure 14).

![Table of the resulting model in physical values.]

We also check the model for adequacy using ANOVA analysis (Figure 15).

![Table assess the adequacy of the model.]

The regression equation for the coded values of the factors is:
The regression equation for the physical values of the factors is:

\[
Y = 12.8450 - 3.5318X_1 + 3.2943X_1^2 - 12.9930X_2 + 9.2248X_2^2 - 5.9102X_1X_2
\]

In fig. 16–18 shows the surface response in various positions.

**Figure 16.** Response Surface.

**Figure 17.** Response surface (side view).

**Figure 18.** Surface response (top view).
The intersection of the MS column and the Lack of Fit line in Figure 15 corresponds to the variance of the adequacy of $S_{ad}^2$. The intersection of the MS column and the Pure Error line corresponds to the dispersion of reproducibility $S_{ful}^2$. To test the model on the adequacy of the formula, we find the Fisher $F$ test:

$$F = \frac{S_{ad}^2}{S_{ful}^2}$$

As a result, we obtain $F = 7.940$, using the table of values of the Fisher criterion, compare the values and give a conclusion that the model is adequate.

As a result, we calculate the error of the model and put everything in the table of the experiment plan without taking into account the variation of the error of approximation (Table 3).

**Table 3. Final Plan of the Experiment.**

| $X_1$ | $K$ | $X_2$ | $n$ | $\gamma,\%$ | $\gamma_m,\%$ | $\delta,\%$ |
|-------|-----|-------|-----|-------------|-------------|-------------|
| -     | 10  | +     | 9   | 19,70392    | 18,85797    | 4,293308    |
| -a    | 10  | 0     | 5   | 19,95096    | 19,6711     | 1,402712    |
| 0     | 55  | +a    | 9   | 7,176281    | 9,076797    | -26,4833    |
| +     | 100 | +     | 9   | 6,938728    | 5,884162    | 15,19826    |
| 0     | 55  | 0     | 5   | 12,70253    | 12,84501    | -1,12165    |
| +a    | 100 | 0     | 5   | 12,47008    | 12,60746    | -1,10165    |
| -     | 10  | -     | 1   | 37,80808    | 38,93389    | -2,97768    |
| 0     | 55  | -a    | 1   | 37,10587    | 35,06288    | 5,505849    |
| +     | 100 | -     | 1   | 36,86322    | 37,78041    | -2,48809    |

### 3 Conclusion

In the course of the course work, a regression model was constructed for the error of approximation of the dynamic characteristic of the magnetization of a proportional electromagnet. With the help of a full factorial experiment, an OTCC was constructed and the influence of the number of points and the degree of the polynomial on the approximation error was revealed. The model is adequate, and the relative error of the coefficients did not exceed the permissible values.

It can be concluded that the approximation error depends linearly on the number of points, and quadratically on the degree of the polynomial, which is confirmed by the constructed model.

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