Structure Optimization of Electromagnetic Railgun Armature Based on Machine Learning

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Abstract. The armature is an important part of the electromagnetic railgun. It may break, wear, and transition during the working process, which increases the difficulty of maintaining the railgun and impairs the service life of the railgun. Therefore, studying the armature structure of the electromagnetic railgun is of great significance to the design of the electromagnetic railgun. This paper selects the five armature structure parameters of armature shoulder thickness, tail length, wing tip thickness, front end thickness, and interference, and focuses on "using armature structure parameters to predict prestress" and "using prestress and other armature to predict the interference of structural parameters". This paper uses the linear regression method in machine learning to construct the model, and uses the normal equation method and the regularized normal equation method to optimize the loss function. The results show that the normal equation method is generally effective for the electromagnetic railgun structure optimization problem discussed in this paper.

Keywords: Machine learning, electromagnetic railgun, armature.

1. Introduction
The electromagnetic railgun is an excellent new concept weapon. The armature is an important part of the electromagnetic railgun. The upper and lower rails of the armature jointly form an energization circuit, and at the same time, it continuously pushes the projectile to accelerate, thereby launching the projectile. However, the armature may break, wear, and transition during the working process, which increases the difficulty of maintaining the railgun and damages the service life of the railgun. Therefore, studying the armature structure of the electromagnetic railgun is of great significance to the design of the electromagnetic railgun. This paper is a structural model. Five armature structure parameters are selected: armature shoulder thickness, tail length, wing tip thickness, front end thickness, and interference. In order to obtain the data set, this paper adopts the orthogonal experiment method, which uses the five-factor four-level orthogonal table to design the experiment. The experiment was carried out through COMSOL's finite element simulation method, and 16 corresponding prestresses were finally obtained. Prestress refers to the initial contact pressure between the armature and the guide rail due to the interference fit. Aiming at the two tasks of "using armature structure parameters to predict prestress" and "using prestress and other armature structure parameters to predict interference", this paper uses the linear regression method in machine learning to construct

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the model, and after importing the data set, it adopts regular Equation method and regularized normal equation method to optimize the loss function. In the task of "using prestress and other armature structure parameters to predict interference", this article uses Marshall's rule to determine the input prestress, that is, for every 1kA current, the required contact pressure is at least 10N. The results show that the normal equation method is generally effective for the electromagnetic railgun structure optimization problem discussed in this paper.

2. Solid armature structure

There are many types of railgun armatures. Generally speaking, armatures can be divided into four categories. One is a pure solid metal armature. The second is the plasma armature. The third is the hybrid armature. The hybrid armature is made by mixing solid metal and plasma. The fourth is the transitional armature. The transition armature is solid at low speeds and plasma at high speeds.

The armature studied in this paper is a C-shaped solid armature. The structure of the C-shaped armature is simple, and it is easier to study and design. Before, many researchers have studied the structure of C-shaped armature. This is conducive to the development of this article.

The material of the solid metal armature is a whole piece of solid metal. During operation, the solid armature maintains sliding contact with the rail interface. Generally speaking, solid armatures are made in C shape (also called U shape) or V shape. In recent years, some H-shaped and saddle-shaped armatures have also been designed. The resistance of a solid armature is small. This results in a very low voltage drop of the armature and low energy consumption. Moreover, the solid armature has a simple shape, which is convenient for research and design. However, due to the existence of frictional resistance during launch, the speed of the solid armature is restricted.

The parameters of the C-shaped solid armature are shown in Figure 1:

![Figure 1. Schematic diagram of armature.](image-url)

- $d_a$ is the thickness of the wing tip,
- $d_t$ is the length of the tail,
- $d_s$ is the thickness of the front end,
- $d_b$ is the thickness of the shoulder,
- $\Delta$ is the interference,
- $W$ is the height of the front end, which is also the distance between the upper and lower guide rails. According to existing research:
  1. The longer the length of the armature tail, the smaller the mechanical preload between the armature and the track. [1]
  2. The thickness of the wing tip increases, and the prestress does not change much.
  3. The prestress increases almost in proportion to the increase in interference.
  4. The longer the tail, the slower the growth of prestress.
  5. The greater the thickness of the shoulder, the faster the growth of the prestress. [2]
(6) The thickness of the wing tip has basically nothing to do with the growth rate of the prestress.

3. Simulation analysis of electromagnetic railgun prestress

The whole simulation involves three geometric bodies, namely the upper rail, the lower rail and the armature. The upper and lower guide rails are both 200mm long, 15mm high and 30mm wide. The simulation in this article does not consider the influence of W, so the size of W is taken as a constant and set to 30mm uniformly.

In order to arrange the experiment, this paper uses an orthogonal table with five factors and four levels, and a total of sixteen experiments. The test results are shown in Table 1.

| Test No. | Shoulder Thickness/mm | Tail Length/mm | Wing Tip Thickness/mm | Front End Thickness/mm | Interference/mm | Prestress/N |
|----------|-----------------------|----------------|-----------------------|------------------------|-----------------|-------------|
| 1        | 9                     | 30             | 1                     | 15                     | 1               | 4646        |
| 2        | 9                     | 35             | 2                     | 18                     | 1.5             | 6637        |
| 3        | 9                     | 40             | 3                     | 21                     | 2               | 7625        |
| 4        | 9                     | 45             | 4                     | 24                     | 2.5             | 8349        |
| 5        | 10                    | 30             | 2                     | 24                     | 2               | 17765       |
| 6        | 10                    | 35             | 1                     | 21                     | 2.5             | 14541       |
| 7        | 10                    | 40             | 4                     | 18                     | 1               | 4839        |
| 8        | 10                    | 45             | 3                     | 15                     | 1.5             | 5008        |
| 9        | 11                    | 30             | 3                     | 24                     | 2.5             | 26966       |
| 10       | 11                    | 35             | 1                     | 21                     | 2               | 12642       |
| 11       | 11                    | 40             | 4                     | 24                     | 1.5             | 10170       |
| 12       | 11                    | 45             | 2                     | 21                     | 1               | 6195        |
| 13       | 12                    | 30             | 4                     | 41                     | 1.5             | 21777       |
| 14       | 12                    | 35             | 3                     | 24                     | 1               | 10300       |
| 15       | 12                    | 40             | 2                     | 24                     | 2.5             | 16949       |
| 16       | 12                    | 45             | 1                     | 21                     | 2               | 9721        |

The factor levels of the orthogonal table are arranged in Table 2.

| Level | d0 | d1 | d2 | d3 | d4 | Δ   |
|-------|----|----|----|----|----|-----|
| 1     | 9  | 30 | 1  | 15 | 1  | 1   |
| 2     | 10 | 35 | 2  | 18 | 1.5| 1.5 |
| 3     | 11 | 40 | 3  | 21 | 2  | 2   |
| 4     | 12 | 45 | 4  | 24 | 2.5| 2.5 |

Using the intuitive analysis method, the calculated results are shown in Table 3.

| Factor | d0 | d1 | d2 | d3 | Δ   |
|--------|----|----|----|----|-----|
| K1     | 6814| 17788 | 10343 | 9766 | 6495 |
| K2     | 10538 | 10985 | 11887 | 12040 | 10898 |
| K3     | 13948 | 9896 | 12475 | 12534 | 11893 |
| K4     | 14686 | 7318 | 11284 | 11646 | 16701 |

| Range  | 7872 | 10470 | 2132 | 2768 | 10206 |

3
It can be seen that as the thickness of the shoulder increases, the prestress will also increase. And this increase is almost proportional. As the tail length increases, the prestress continues to decrease. The extreme difference of the empennage is relatively large, which has a great influence on the prestress. The wing tip thickness has a small range and has little effect on the prestress. The thickness of the front end is the same as the thickness of the wing tip, and the range is small, which has little effect on the prestress. The greater the interference, the greater the prestress. And the growth of prestress is almost proportional to the growth of interference. Arrange the factors according to the range, in order of tail length, interference, shoulder thickness, front thickness, wing tip thickness.

In summary, the magnitude of the influence of the various structural parameters of the armature on the prestress is the length of the tail, the amount of interference, the thickness of the shoulder, the thickness of the front, and the thickness of the wingtip. The longer the tail wing, the smaller the prestress. The prestress increases almost proportionally with the amount of interference. The greater the thickness of the shoulder, the greater the prestress. The thickness of the wingtip and the thickness of the front have no significant effect on the prestress.

4. Machine learning algorithm design and analysis

4.1. Using structural parameters to predict prestress

This article first realizes the prediction of prestress using structural parameters. First, this article constructs a multi-dimensional linear regression model.

Because the armature structure parameter selected in this paper is 5, the number of features of the model is 5.

Construct the Hypothesis function as follows:

\[ h_\theta(x) = \theta_0 + \theta_1 x_1 + \theta_2 x_2 + \theta_3 x_3 + \theta_4 x_4 + \theta_5 x_5 \]  

Force:

\[ x_0 = 1 \]

Force:

\[ x = \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} \]  

\[ \theta = \begin{bmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{bmatrix} \]
Then, the Hypothesis function can be written as:

$$h_{\theta}(x) = \theta^T x$$

(4)

At this time, the cost function is:

$$J(\theta) = \frac{1}{2m} \sum_{i=1}^{m} (h_{\theta}(x^{(i)}) - y^{(i)})^2$$

(5)

4.2. Solve linear regression using normal equations

Because the $\theta$ values obtained are all relatively large, they are all integers. The parameters obtained are shown in Table 4.

| $\theta_0$ | $\theta_0$ | $\theta_0$ | $\theta_0$ | $\theta_0$ | $\theta_0$ |
|-----------|-----------|-----------|-----------|-----------|-----------|
| -6160     | 2703      | -691      | 1365      | 0          | 6732      |

Enter \([1 \ 10 \ 33 \ 1.5 \ 15 \ 1]\), 1 is the input value that needs to be added to the normalization equation method, 10 represents the shoulder thickness of 10mm, 33 represents the tail length of 33mm, 1.5 represents the wing tip thickness of 1.5mm, and 15 represents the front end thickness of 15mm, and 1 means the interference is 1mm. It can be predicted that the prestress is 6846.5N, and its value is reasonable. It can be considered that it meets the requirements initially, so the analysis can continue below.

4.3. Solve linear regression using regularized normal equations

Enter \([1 \ 10 \ 33 \ 1.5 \ 15 \ 1]\), 1 is the input value that needs to be added to the normalization equation method, 10 represents the shoulder thickness of 10mm, 33 represents the tail length of 33mm, 1.5 represents the wing tip thickness of 1.5mm, and 15 represents the front end thickness of 15mm, and 1 means the interference is 1mm. Setting the parameter $\lambda=10$, the prestress can be predicted to be 10842N. Setting the parameter $\lambda=1$, the prestress can be predicted to be 7814N. Set the parameter $\lambda=0.2$. It can be predicted that the prestress is 7066N. Setting the parameter $\lambda=0.1$, the prestress can be predicted to be 6956N.

4.4. Use prestress and other structural parameters to predict interference

The parametric model is constructed as a model for predicting prestress. Because the basic function definition is consistent with the above, this section will not be repeated.

4.4.1. Solving linear regression using normal equations. $\theta$ is taken to 6 decimal places. The parameters obtained are shown in Table 5.

| $\theta_0$ | $\theta_0$ | $\theta_0$ | $\theta_0$ | $\theta_0$ | $\theta_0$ |
|-----------|-----------|-----------|-----------|-----------|-----------|
| 1.037081  | -0.329886 | 0.084851  | -0.183822 | 0.002621  | 0.000122  |

Enter \([1 \ 10 \ 33 \ 1.5 \ 15 \ 15000]\), 10 means the shoulder thickness is 10mm, 33 means the tail length is 33mm, 1.5 means the wing tip thickness is 1.5mm, 15 means the front end thickness is 15mm, and 15000 means the prestress is 15000N. It can be predicted that the interference is 2.131892mm, which
is reasonable and can be considered to meet the requirements initially, so the analysis can be continued below.

4.4.2. Solving linear regression using regularized normal equations. Enter \([1 \ 10 \ 33 \ 1.5 \ 15 \ 15000]\), 1 is the input value that needs to be added to the normalization equation method, 10 represents the shoulder thickness of 10mm, 33 represents the tail length of 33mm, 1.5 represents the wing tip thickness of 1.5mm, and 15 represents the front end The thickness is 15mm, and 15000 means the prestress is 15000N. Adjusting \(\lambda=10000\), the interference can be predicted to be 1.91723mm. Setting the parameter \(\lambda=1000\), the interference can be predicted to be 1.904136mm. Adjusting the parameter \(\lambda=100\), the interference can be predicted to be 1.894509mm. Adjusting \(\lambda=10\), the interference can be predicted to be 2.019464mm.

4.5. Analysis of the algorithm
When predicting the prestress by structural parameters, the model trained by the formal equation predicts the prestress between 6000N and 17000N, and the prestress is approximately proportional to the increase in interference increase. When the interference is predicted by prestress and other structural parameters, the predicted interference is between 1.2mm and 2.8mm, and the predicted increase in interference is approximately proportional to the increase in the input prestress. The results predicted by the normal equation method in these two tasks are relatively reasonable, and the trend of change is in line with the existing research conclusions.

It can be found that for the task of predicting interference with known prestress and other structural parameters, the non-regularized normal equation predicts the best effect. For the task of using armature structure parameters to predict the prestress, the prediction effect obtained by the regularized normal equations with \(\lambda\) taking 0.1 and 0.2 is very good, and the parameters are adjusted continuously to obtain \(\lambda=0.17\). At this time, the value of \(\theta\) obtained by the regularized normal equation is Table 6.

| \(\theta_0\) | \(\theta_1\) | \(\theta_2\) | \(\theta_3\) | \(\theta_4\) | \(\theta_5\) |
|------------|------------|------------|------------|------------|------------|
| -5580.48   | 2679.97    | -689.589   | 1327.43    | 5.31251    | 6500.03    |

In summary, it can be explained that the normal equation method is generally effective for the electromagnetic railgun structure optimization problem discussed in this article. In the use of armature structure parameters to predict the prestress problem, the regularized equation is the best solution, and \(\lambda=0.17\) should be selected. In the use of prestress and other armature structure parameters to predict the interference, the non-regularized normal equation is the best solution.

5. Conclusion
After selecting the parameters in this article, 16 different armature models were constructed using SOLIDWORKS according to the orthogonal table. After that, this article loaded these models into COMSOL, and performed some COMSOL software settings, and analyzed and calculated these 16 samples. Starting from the two tasks of "known armature parameters, predicting prestress" and "predicting prestress and other armature parameters, predicting interference", this paper designs a variety of algorithms that can achieve the tasks. After the design of the algorithm is completed, this article carries out the specific realization of the code, the debugging of the parameters and the test analysis of the algorithm performance. In the task of "using prestress and other armature structure parameters to predict interference", this paper uses Marshall's rule to determine the input prestress, that is, for every 1kA current, the required contact pressure is at least 10N. This article found that the normal equation can fit the data provided in this article well, and regardless of whether it is regularized or not, it can make the prediction result fall within an acceptable range.
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