Optimum Design of Transmission Coil for Giant Magnetostrictive Actuator

Zeng Fan\textsuperscript{1a}, Shi Feng\textsuperscript{1b} and Hui Ying\textsuperscript{1c}

\textsuperscript{1}Navy Submarine Academy, Qingdao, China, 266042
\textsuperscript{a}zhilinwenchu777@sina.com, \textsuperscript{b}47012518@qq.com, \textsuperscript{c}yhcathy@163.com

Abstract. The driving coil is optimized by replacing the magnetic field with ampere turns. For a variety of wire diameter, select the appropriate trade-off between the ampere-number maximization and the power minimization when the volume is closest to its allowable value and does not exceed the maximum output current of the power supply. It is calculated that 1mm diameter coil has the minimum power consumption. Therefore, choose 1mm diameter enameled wire to wound coil.

1. Introduction
The giant magnetostrictive actuator has great advantages in terms of response speed, load carrying capacity and conditions of use. In particular, it has been studied in detail for the structure, model and control theory of giant magnetostrictive actuator. The application of vibration with Submarine machinery and equipment is of great significance for our military development.

The magnetostatic actuator is driven by a magnetic field. The design of magnetic field includes driving the magnetic field and the bias magnetic field. The driving magnetic field is usually generated by the input current of the hollow cylindrical electromagnetic coil. Therefore, the driving coil is a carrier of an electric-magnetic conversion. The magnetic induction strength with current excitation determines the magnitude of the output of the giant magnetostrictive actuator, so the design of the drive coil becomes critical\textsuperscript{[4-6]}. At the same time, the geometric size of the coil is an important factor affecting the magnetic field strength and the efficiency of a magnetic conversion. It is also the main influence factor of the GMA volume. In practical application, the wound wire on the coil inevitably has the resistance loss, so the temperature of the GMA (giant magnetostrictive actuator) is also an important impact. In this paper, the drive coil is optimized from three aspects: coil volume, driving capacity and power consumption.

2. Optimization of Drive Coil
Optimization of drive coil magnetic circuit is considered from the following points: the magnetic field is uniform on telescopic rod; high magnetic field strength produced by coil; coil drive current does not exceed the maximum output drive current; coil heat is small, that is to say, low coil power dissipation. Geometric parameters are known: skeleton length, diameter, wire diameter. Electrical parameters are laid out: coil maximum allowable current, coil power supply voltage. The number of layers of the coil
\[ n = \frac{D - d_u}{4d} \]
D is the outer diameter (m) of the coil, da is the inner diameter (m) of the coil, and d is the diameter of the coil wire (m). Actuator frequency response range around the coil, the thread and the tail are at the same end of the skeleton, so the number of layers should be even

\[ M = 2n \]  

(2)

The geometrical size determines the maximum volume of the coil, since the diameter of the wire can only be a limited amount of dispersion, which determines that the number of layers can only be discrete. When optimizing, the coil volume is not necessarily the largest volume, and the maximum values are used as candidate volumes. Therefore, the number of layers is used as the loop argument to calculate the parameters. The drive coil is as shown in Figure 1.

\[ N = \frac{MH}{d} \]  

(3)

\[ D = d_a + 2Md_a \]  

(4)

\[ L = \frac{4\pi N^2 R_c (\pi R_k - t(0.693 + c))}{H} \]  

(5)

\[ t = \frac{D - d_a}{2} \]  

(6)

\[ R_a = \frac{D + d_a}{4} \]  

(7)

Fig. 1 Schematic diagram of the drive coil

L is the inductance (H) of the coil, R is the average radius of the coil (m), H is the height of the coil (m), N is the total number of turns of the coil, t is the thickness of the coil (m), k is the length (Determined by 2R / l), c is the self-inductance (coefficient determined by l / t).

\[ l = \frac{M (2d_a + 2Md_a)H}{2\pi d} \]  

(8)

\[ R = lR_0 \]  

(9)

\[ Z = \sqrt{(2\pi fL)^2 + R^2} \]  

(10)

\[ I = \frac{E}{Z} \]  

(11)

\[ P = I^2 R \]  

(12)
\[ NI = \frac{MHI}{d_o} \]  

(13)

Where \( l \) is the total length of the coil, \( Z \) is the coil impedance, \( f \) is the excitation frequency, \( I \) is the coil current, \( E \) is the supply voltage, \( P \) is the coil power, and \( NI \) is the total current of the coil.

The performance of the actuator depends on the driving magnetic field, and the intensity of the driving magnetic field is determined by the number of turns of the coil. Since the relationship between the driving magnetic field and the ampere-turns is complicated, and the larger the ampere-turns is, the greater the magnetic field strength. With ampere turns instead of magnetic field strength, the drive coil is designed optimistically. For a variety of wire diameter, select the appropriate trade-off between the ampere-number maximization and the power minimization when the volume is closest to its allowable value and does not exceed the maximum output current of the power supply. The objective function is:

\[ F = aNI + (1 - a)P \]  

(14)

3. Optimization calculated of Drive Coil Diameter

Using MATLAB software to write the drive coil optimization program, the program flow chart is as shown in Figure 2.

![Program flow chart](image-url)
When the outer diameter of the coil is 63mm, the optimized parameters are listed in Table 1. Where \(D\) is the coil diameter (mm), \(R_0\) is the conductor resistance (\(\Omega/m\)), \(M\) is the number of coils, \(N\) is the number of coils, \(I\) is the coil current (A), \(\omega_1\) is the coil ampere turns, \(I\) is the length of coil (m), \(D\) is the coil diameter (mm), \(R\) is the total resistance of the coil (\(\Omega\)), \(L\) is the coil inductance (mH), \(Z\) is the coil impedance (\(\Omega\)), and \(P\) is the coil power consumption (W).

Table 1 Optimize the results of coil maximum diameter of 63mm

| \(d\) | \(R_0\) | \(M\) | \(N\) | \(I\) | \(\omega_1\) | \(I\) | \(D\) | \(R\) | \(L\) | \(Z\) | \(P\) |
|------|-------|------|------|-----|--------|-----|-----|-----|-----|-----|-----|
| 0.50 | 0.087 | 44   | 7920 | 0.026 | 208    | 1020.138 | 63   | 88.752 | 642.800 | 1372 | 0.061 |
| 0.53 | 0.078 | 42   | 7312 | 0.104 | 739    | 924.475  | 64   | 71.638 | 526.483 | 347  | 0.769 |
| 0.60 | 0.061 | 36   | 5400 | 0.037 | 201    | 688.763  | 62   | 41.643 | 294.246 | 966  | 0.058 |
| 0.67 | 0.049 | 32   | 4299 | 0.041 | 175    | 546.108  | 62   | 26.481 | 185.294 | 886  | 0.044 |
| 0.71 | 0.043 | 30   | 3803 | 0.438 | 1664   | 481.469  | 62   | 20.789 | 144.235 | 82   | 3.979 |
| 0.75 | 0.039 | 30   | 3600 | 0.323 | 1164   | 469.354  | 64   | 18.159 | 135.373 | 111  | 1.899 |
| 0.85 | 0.030 | 26   | 2753 | 0.684 | 1884   | 355.458  | 63   | 10.710 | 77.963  | 53   | 5.016 |
| 0.90 | 0.027 | 24   | 2400 | 0.115 | 278    | 306.117  | 62   | 8.225  | 58.123  | 313  | 0.109 |
| 0.95 | 0.024 | 24   | 2274 | 0.057 | 129    | 298.577  | 65   | 7.202  | 54.617  | 634  | 0.023 |
| 1.00 | 0.022 | 22   | 1980 | 2.065 | 4089   | 255.035  | 63   | 5.552  | 40.175  | 17   | 23.685 |
| 1.12 | 0.017 | 20   | 1607 | 0.367 | 590    | 209.028  | 64   | 3.627  | 26.877  | 98   | 0.490 |
| 1.18 | 0.016 | 18   | 1373 | 3.971 | 5451   | 173.557  | 61   | 2.713  | 18.755  | 9    | 42.767 |
| 1.25 | 0.014 | 18   | 1296 | 0.700 | 907    | 168.967  | 64   | 2.354  | 17.544  | 51   | 1.153 |
| 1.32 | 0.013 | 16   | 1091 | 0.154 | 168    | 137.499  | 61   | 1.717  | 11.787  | 233  | 0.041 |
| 1.40 | 0.011 | 16   | 1029 | 0.090 | 93     | 133.778  | 64   | 1.485  | 11.009  | 398  | 0.012 |
| 1.50 | 0.010 | 12   | 720  | 0.137 | 99     | 83.692   | 55   | 0.831  | 4.526   | 262  | 0.016 |
| 1.62 | 0.009 | 14   | 778  | 0.682 | 530    | 101.844  | 64   | 0.866  | 6.362   | 53   | 0.402 |
| 1.68 | 0.008 | 12   | 643  | 0.190 | 122    | 79.087   | 59   | 0.626  | 3.941   | 189  | 0.023 |
| 1.74 | 0.007 | 12   | 621  | 3.580 | 2222   | 77.764   | 61   | 0.573  | 3.780   | 10   | 7.344 |
| 1.88 | 0.006 | 12   | 574  | 0.726 | 417    | 75.005   | 64   | 0.473  | 3.455   | 50   | 0.250 |
| 1.95 | 0.006 | 12   | 554  | 0.167 | 93     | 73.774   | 66   | 0.433  | 3.315   | 215  | 0.012 |
| 2.02 | 0.006 | 8    | 356  | 0.216 | 77     | 39.371   | 51   | 0.215  | 1.026   | 167  | 0.010 |
| 2.10 | 0.005 | 10   | 429  | 0.761 | 326    | 53.856   | 61   | 0.273  | 1.811   | 47   | 0.158 |
| 2.26 | 0.004 | 8    | 319  | 0.287 | 91     | 37.112   | 55   | 0.162  | 0.889   | 125  | 0.013 |
| 2.44 | 0.004 | 10   | 369  | 1.048 | 386    | 50.291   | 68   | 0.189  | 1.526   | 34   | 0.207 |

From Table 1, it can be seen that the maximum number of ampere turns is 4089 and the diameter is 1mm, which can be used as the candidate wire diameter for coil design. Then calculate the relevant parameters with 60mm, 61mm, 62mm, 64mm, 65mm, 66mm respectively, and obtain the parameters corresponding to the maximum diameter of the ampere turns under different coil diameters, which is as shown in Table 2.

Table 2 Optimization results of different coil outer diameter

| \(d\) | 60   | 61   | 62   | 63   | 64   | 65   | 66   |
|------|------|------|------|------|------|------|------|
| 1.120| 1.120| 1.180| 1.000| 1.250| 1.250| 1.250|
| R0   | 0.017| 0.017| 0.016| 0.022| 0.014| 0.014| 0.014|
| M    | 18   | 18   | 18   | 22   | 18   | 18   | 18   |
| N    | 1446 | 1446 | 1373 | 1980 | 1296 | 1296 | 1296 |
As can be seen from Table 2, within the allowable volume range, the diameter is 1.25mm and the ampere-turns maximum is 7309, but at the same time its power consumption is big; Determined the from the coil power, minimum is 23.68W and line Diameter is 1mm. Respectively, take three different sets of ampere-turns, and re-check the above four kinds of diameter coil power consumption, the results are as shown in Table 3.

| NI  | d(mm) | N | I(A) | R(Ω) | P(W) |
|-----|-------|---|------|------|------|
| 7500| 1     | 1980| 3.79 | 5.55 | 79.66|
|     | 1.12  | 1446| 5.19 | 3.09 | 83.06|
|     | 1.18  | 1373| 5.46 | 2.71 | 80.94|
|     | 1.25  | 1296| 5.79 | 2.35 | 78.82|
|     | 1     | 1980| 2.9  | 5.55 | 46.8 |
|     | 1.12  | 1446| 3.98 | 3.09 | 48.86|
|     | 1.18  | 1373| 4.19 | 2.71 | 47.53|
|     | 1.25  | 1296| 4.44 | 2.35 | 46.26|
|     | 1     | 1980| 2.02 | 5.55 | 22.66|
|     | 1.12  | 1446| 2.77 | 3.09 | 23.64|
|     | 1.18  | 1373| 2.91 | 2.71 | 23.02|
|     | 1.25  | 1296| 3.09 | 2.35 | 22.42|

It can be seen from Table 3, with the same ampere turns different diameter power consumption is not very different, which provide a certain degree of flexibility for the purchase of wire diameter, but 1mm diameter is the common diameter. Finally, we get the conclusion: the coil power consumption is minimal with 1mm diameter, so choose 1mm diameter of the enameled wire to wound drive coil.

4. Summary
The drive coil is optimized from three aspects: coil volume, driving capacity and power consumption. Considering ampere turns instead of magnetic field strength and power consumption, we get the best optimization choice of coil diameter, which establishes the base for the generation of the driven magnetic field, the giant magnetostrictive actuator of dynamic response and the cooling of the drive coil.

References
[1] Zhang Xuhui. Study on Crucial Technology of Active Vibration Isolation System Based on Structure-Optimized Giant Magnetostrictive Actuator [D]. Beihang University, Dissertation Submitted for the Degree of Doctor, 2008:20-25
[2] Wu Yijie, Liu Chuhui. Study on Design Approach of Giant Magnetostrictive Actuator [J]. Journal of Zhejiang University (Engineering Science), 2004, 38(6):747-751
[3] Zhifeng Tang. Fundamental Theory and Experiments Study of Giant Magnetostrictive Actuator, Zhejiang University [D], Dissertation Submitted for the Degree of Doctor, 2005, 34-39
[4] Lu Quanguo. Research and Application of Micro-Actuation Based on GMM [D], Wuhan University of Technology, Dissertation Submitted for the Degree of Doctor, 2007:23-28
[5] Yu Peiqiong, Mei Deqing and Chen Zichen. Design of a Micro-displacement Actuator Based on Giant Magnetostrictive Material [J]. Transaction of the Chinese Society for Agricultural Machinery, 2003, 34(3):105-108
[6] Yang Wang. The Design and Optimization of Straight-GMM Transducer Used in Vibration Welding [D]. Zhejiang University, A Thesis Submitted for Master Degree, 2007:32-34