Analysis and Optimization for Uniformity of Magnetic Field Driving the Giant Magnetostriction

L Wang, H Ye, Y T Liu and S M Yao
Institute of Ultra-precision Optoelectronic Instrument Engineering Harbin Institute of Technology, Harbin 150001, China
E-mail: yeahelton@gmail.com

Abstract. Giant magnetostrictive actuator based on material Tb$_{0.27}$Dy$_{0.73}$Fe$_2$ and electromagnetic transform has characteristics of high frequency response, large output power and etc, but it has a high demand for the uniformity of magnetic field driver and magnetic intensity. Object to the problem, a multi-scale external concavity structure is proposed, by means of inducting the hollow column coil structure, building the model of coil magnetic distribution and analyzing by finite element analysis method. The analysis results show that uniformity of the model magnetic field is dependent upon magnetic intensity and scales, and the boundary condition of material. As the scale increases, magnetic uniformity is enhanced, but the magnetic intensity is decreased. Taking consideration both of magnetic field distribution and magnetic intensity, three-scale structure is determined as optimum structure.

1. Introduction
Giant magnetostrictive actuator based on Tb$_{0.27}$Dy$_{0.73}$Fe$_2$, has characteristics of high resolution, large output force, wide motion range and etc. It has a broad application foreground in ultra precise positioning field. Compared with piezoelectric ceramic actuator, Giant magnetostrictive actuator is more suitable for nanometer range positioning with big load and big inertia. Giant magnetostrictive actuator with column electric coil has high frequency response, large output force, which can achieve fast and precise positioning.

Micro-displacement actuator on basis of Giant magnetostrictive with column electric coil structure is shown in Figure 1 [1]. According to magnetostriction operating principle, the structure of actuator comprises four portion: high performance magnetostrictive rod (Tb$_{0.27}$Dy$_{0.73}$Fe$_2$), hollow column coil structure (generates driving magnetic field), pretightening structure (provides initial compression stress) and flexibility hinge structure (transfers strain to output motion).

The driving principle of electrifying column coil generating magnetic field is: transferring electric energy to magnetic energy then to mechanical energy. The performance of giant magnetostrictive actuator has direct relationship with magnetic field. The uniformity and linearity of magnetic intensity determines the sensitivity and linearity of the output motion. Accordingly, the paper develops a method of using magnetic field generated by hollow column coil as the driving magnetic field of terfenol-D. Meanwhile, introduce the magnetic distributing model of hollow column coil, and give optimization analysis. Considering the uniformity and linearity, induct a magnetic field structure based
on multi-scales outward concave structure of giant magnetostrictive material. Analyzing the uniformity of magnetic field by finite element method, an appropriate coil structure is attained.

**Figure 1.** Principle of structure.

### 2. Hollow Column Coil Model

Hollow column coil model is shown in Figure 2. The magnetic intensity B of arbitrary point P in electriﬁying hollow column coil can be calculated by equation (1). In column coordinate system, set the axis of symmetry of coil as z axis; set the planum where P located as x-o-y planum which is cross P and vertical to z axis, and set the crossing point as origin of coordinates. In the current distributing area V, select an arbitrary point Q(ρ’, φ’, z’), whose volume element is dV’. Suppose vector QP = \( \mathbf{r} \), according to Biot-Savart law:

\[
\begin{align*}
B_\rho &= \frac{\mu_0}{2\pi} \int_0^\pi \int_0^{\rho_1} \int_{z_1}^{z_2} \left( -\rho' z' \cos \theta \right) \frac{d\theta d\rho' dz'}{r^3} \\
B_\phi &= 0 \\
B_z &= \frac{\mu_0 I}{2\pi} \int_0^\pi \int_0^{\rho_1} \int_{z_1}^{z_2} \left( \rho' - \rho \cos \theta \right) \frac{d\theta d\rho' dz'}{r^3}
\end{align*}
\]

(1)

where \( r = (\rho'^2 + \rho^2 - 2\rho \rho' \cos \theta + z^2)^{1/2} \)

\( \theta = \phi' - \phi \)

\( z_1 \) — coordinates of coil bottom

\( z_2 \) — coordinates of coil top

**Figure 2.** Sketch map of hollow column coil.
According to equation (2), the interior magnetic field distributing of the hollow column coil is shown in Figure 3. Suppose the parameters of column coil are: $a_1 = 5\, \text{mm}$, $a_2 = 8\, \text{mm}$, $b = 40\, \text{mm}$, and the current density in the coil area is $J = 4 \times 10^4\, \text{A/m}^2$. As Figure 3 illustrated, the magnetic of hollow column coil is symmetrical to z axis, and the farther apart the center, the smaller of the magnetic intensity is, which is non-uniform.

\begin{align}
B_z(0,\varphi,z) &= \frac{\mu_0 J}{2} \left[ (b-z) \ln \frac{a_2 + \sqrt{a_2^2 + (b-z)^2}}{a_1 + \sqrt{a_1^2 + (b+z)^2}} 
+ (b+z) \ln \frac{a_2 + \sqrt{a_2^2 + (b+z)^2}}{a_1 + \sqrt{a_1^2 + (b+z)^2}} \right] \\
B_{\mu}(0,\varphi,z) &= 0
\end{align}

(2)

3. Homogeneity analysis

Equation (3) quantifies the uniformity of magnetic field in respond to a field point $P(r, \theta)$ input. The uniformity increases as space of the field point to center increases. $\varepsilon(r, \theta)$ presents a biasing magnetization level of the field point to the magnetization of center $o$. The bias decreases as $\varepsilon$ decreases, and the uniformity increases.

As the Figure 3 and Equation (3) depicted, the magnetic uniformity of hollow column coil is not good, with a high magnetic intensity in center and weak intensities at ends. A magnetic analysis on hollow column coil is carried out by finite element analysis method as illustrated in Figure 4~5. Disuniformity of magnetic field in coil may cause the magnetic intensity is uneven to each point of giant magnetostrictive rod, and strain of every point is inhomogeneous. As a result, the displacement of giant magnetostrictive material varies nonlinearly.

Object to the disuniformity of magnetic field of hollow column coil, a multi-scale external concavity structure is proposed. Within this structure, coils at two ends are multilayer as depicted in

![Figure 3. Magnetic induction intensity distribution.](image-url)
Figure 7–9. As the layers increase, the magnetic intensity of the center is more close to the ends, which make the magnetic more uniformed. The uniformity is dependent upon the layer number $n$ and the size of every scale (length $a$, width $b$), the relationship of every quantum is complex. A magnetic analysis on multi-scale external concavity coil is carried out by finite element analysis method.

Figure 4. Lattice division of column coil.

Figure 5. Magnetic induction intensity distribution of column coil.

Figure 6. Original magnetic field intensity distribution.

Figure 7. One scale outward concave structure.

The structure of analyzed model is depicted in Figure 6–9 with the coil structures of none scale concavity, single-scale, two-scale and three-scale external concavity separately. The Internal medium is giant magnetostrictive material and the external is yoke magnetizer, based on which the boundary condition is determined in finite element analysis.

Figure 6–9 shows the magnetic field intensity distribution of each structure by finite element analysis. As the scales increase, a larger uniformity range of internal magnetic can be obtained, but the magnetic intensity is decreased.
4. Conclusion
Figure 6 shows the magnetic distribution of original structure, and Figure 7~9 show the magnetic
distribution of single-layer, two-layer and three-layer external concavity structure separately. In the
original magnetic distribution, the biggest magnetic intensity is 0.79 T. Under same size, current
density and boundary condition, the biggest magnetic intensity of single-layer, two-layer and three-
layer structure gradually decrease, but the region of the maximum value increases, resulting in
enhancement of uniformity.

Figure 10 shows the distribution curve of original structure, one-scale, two-scale and three-scale
outward concave structure separately. In the picture, curve with sign "0" is original structure, curves
with signs "1", "2", "3" are one-scale, two-scale and three-scale structure separately. As depicted in
the picture, the original structure has a bad uniformity of magnetic field, and in single-layer, two-layer
and three-layer structure there is a gradual increase of uniformity, and the magnetic intensity of three-
scale is higher than two-scale structure. As a result, uniformity is enhanced due to the scale increasing,
but the magnetic intensity is restricted by the size.

As the scale increasing made the structure design and machining more complex, considering both
uniformity and magnetic intensity, three-scale structure is determined as optimum structure.

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