Design of a cryogenic giant magnetostrictive actuator using HTS

Jiongjiong Cai Zhitong Cao Hongping Chen Guoguang He

Institute of Applied Physics, Zhejiang University, China, 310027

In this paper a Cryogenic Giant Magnetostrictive Materials (CGMM) actuator using HTS was designed, taking into account both the coupled field characteristics of the CGMM and the anisotropy of the investigated Bi2223/Ag HTS tapes. Then an optimal structure, which costs the least HTS tapes while still make the CGMM to the state of saturation, is realized by combining the genetic algorithm (GA) with the coupled field iteration of FEM.

INTRODUCTION

Cryogenic Giant Magnetostrictive Materials (CGMM), especially the family of $Tb_xDy_yZn_z$ with magnetostrain of 0.5 percent or more, has Curie temperatures 200K. These materials can be machined to many shapes, afford large transverse load, which provide the great flexibility for application design. They show great promise for cryogenic actuator applications, especially they can be combined with high temperature superconducting (HTS) tapes to create kinds of transducers, actuators, and motors that are characterized by high efficiency and high power density[1].

The properties of the Bi2223/Ag multifilamentry tapes have shown anisotropy in the critical current versus applied external magnetic field [2]. Numerous studies were performed in order to determine the main factors limiting the critical current of the magnets made of anisotropic Bi-2223/Ag tapes [3]. It is shown that special attention has to be paid to the study of the magnetic field distribution in the magnet and in particular to the radial component of the magnetic field when the magnet is wound in the form of a cylindrical solenoid [4].

In this paper the radial component of the magnetic field on the HTS magnet is reduced greatly by a magnetic circuit using laminated silicon iron. So the parallel component become an important factor limiting the critical current too owing to much larger magnitude, which is more than 10 times the radial component. Since both the two components have to be considered, a HTS solenoid of simple cylindrical configuration is designed, which is used to provide the CGMM a magnetic field of good uniformity making it to the state of saturation. According to the previous researches [5], we have developed the valid coupled field iteration of Finite Element Method (FEM) for the coupled field calculation of the smart material like the GMM. In this paper the coupled field iteration of FEM will be combined with an optimal design method, the genetic algorithm (GA)concerning the anisotropy of the HTS tapes, to find the specific size and place of the HTS solenoid costing least materials.

CGMM ESSENTIAL LAW AND THE COUPLED FIELD ITERATION OF FEM

The CGMM essential law can be described as follows.

$$B = \lambda T + \mu^T H \tag{1}$$

$$S = s^H T + \lambda H \tag{2}$$

where s^H, μ^T and λ are compliance at fixed value of H, permeability at a fixed value of T, magnetostrictive coefficient, respectively. The first item of right side in equation (1) is the magnetic flux density resulting from the stress T. The second item of the right side in equation (2) is the strain resulting from the magnetic field H. The nonlinear coupled characteristics of above parameters of CGMM is described through the coupled field iteration of FEM [5], the flowchart is shown as Fig1.

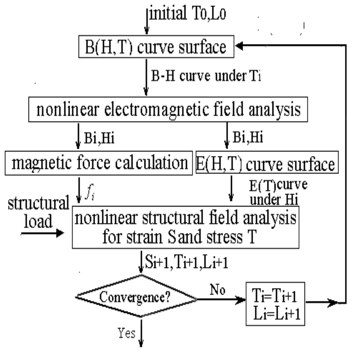

Figure 1 FEM analysis model for coupled field calculation

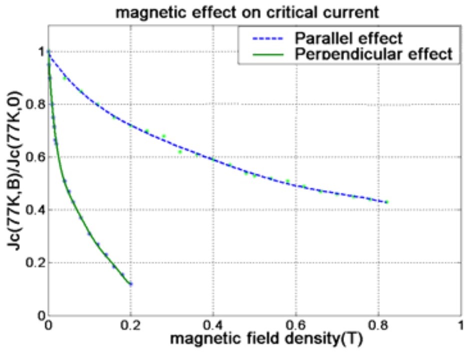

Figure 2 anisotropic characteristics of the Bi-2223/Ag($Jc(77k,0) = 7000A/cm^2$)

ANISOTROPY OF THE HTS TAPE

As shown in Fig.2 [6], the approximation function of the B-J characteristic of Bi-2223/Ag at 77k with the magnetic field B is set as follows:

$$J_{c//} = -0.97 B_{//}^3 + 1.9194 B_{//}^2 \; 1.5956 B_{//} + 0.9751 \quad \text{(for parallel)} \tag{3}$$

$$J_{c\perp} = 2.6021*10^5 B_\perp^6 - 1.8576*10^5 B_\perp^5 + 5.2756*10^4 B_\perp^4 - 7.6118*10^3 B_\perp^3 + 5.9553* B_\perp^2 - 27.1754 B_\perp + 1.0107 \quad \text{(for perpendicular)} \tag{4}$$

STRUCTURE DESIGN OF AN ACTUATOR

The preliminary design of an actuator is shown in Fig.3. The radical component of the magnetic field, which is perpendicular to the HTS tapes, is exhibited in Fig.4 after electromagnetic field analysis by coupled field iteration of FEM. Fig.5 is the map of the radical component of HTS when there is no magnetic circuit of laminated iron, which is used for comparison.

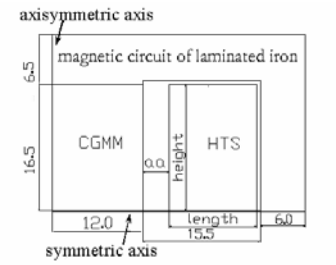

Figure 3 The preliminary design of an actuator

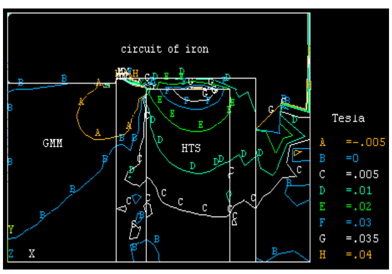

Figure 4 The contour lines of perpendicular component when with the iron made circuit

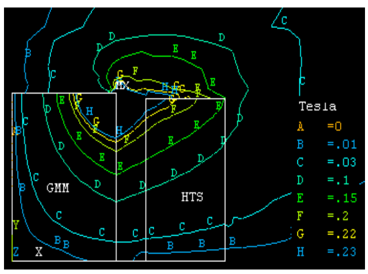

Figure5 The contour lines of perpendicular component when without the iron made circuit

The radial component of the magnetic field is reduced greatly by a magnetic circuit using laminated silicon iron. The parallel component become an important factor limiting the critical current too owing to much larger magnitude, which is more than 10 times the radial component. So the effect from both the two components have to be considered for the design of an actuator.

OPTIMAL DESIGN USING GENETIC ALGORITHM FOR AN ACTUATOR

In the electromagnetic design of an actuator, the optimization process is realized by genetic algorithm combined with coupled field iteration of FEM. The purpose of optimization is to find out the specific size and place of the HTS solenoid, which can make the CGMM to the state of saturation while costing least HTS tapes.

Mathematical description of the optimization of the investigated actuator

The structure of CGMM is shown in Fig.3, the mathematical description of the above optimization is:

min: $S_{hts} = length \times height$ st: 0< $length$ <0.01550m, 0< $height$ <0.01700m, 0< aa <0.01550m,

0< $length + aa$ <0.01550m, $B_y|_{CGMM} \geq 2.00000$T, $J_{permissive} < \min(J_{c\perp}, J_{c//})$

GA process and flowchart

The optimization of the CGMM actuator is realized using the GA [7], combined with coupled field iteration of FEM. The flowchart is shown as Fig6.

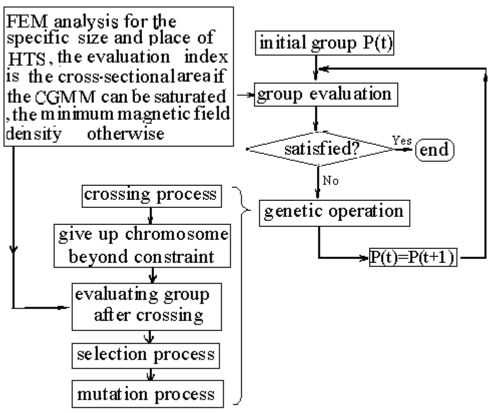

Figure 6 the GA process flowchart

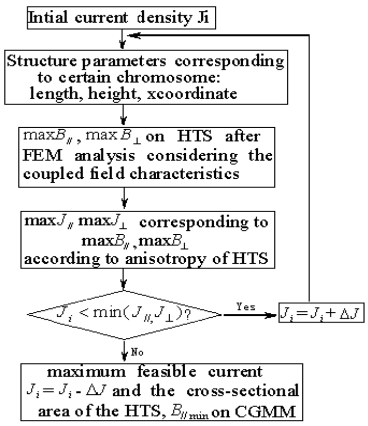

Figure 7 evaluation process flowchart

Evaluation process is shown in Fig.7, the evaluation function is the cross-sectional area S_{HTS} if the CGMM is saturated, the magnetic field density in CGMM if unsaturated.

Optimization result

The parameters of the optimal structure are: aa =0.00339m, $height$ =0.01594m, $length$ =0.00920m. Contour lines of the parallel component, by (see Fig.8), and the perpendicular component, bx (see Fig.9), are mapped below respectively.

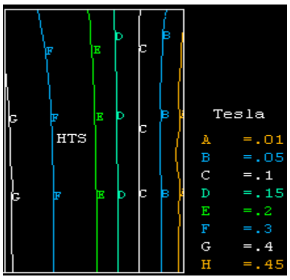

Figure 8 contour lines of the parallel component (by)

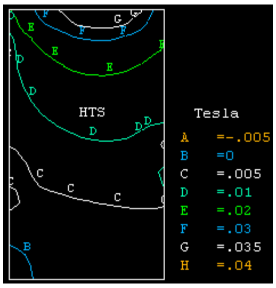

Figure 9 contour lines of perpendicular component (bx)

The maximum values of the parallel component in HTS area, $bx_{\max} = 0.04057\text{T}$, and the perpendicular component, $by_{\max} = 0.40871\text{T}$, are gotten and the permissive input current density $\text{J}_{\text{permissive}} = 3700 A/cm^2$ is found out. Then the critical currents corresponding to the two components of the magnetic field, $J_{c\perp} = J_{bx\max} = 3708.439 A/cm^2$ $J_{c//} = J_{by\max} = 4041.548 A/cm^2$, are calculated respectively. It is obvious that $J_{permissive} < \min(J_{c\perp}, J_{c//})$.

CONCLUSION

In this paper the radial component of the magnetic field is reduced greatly by a magnetic circuit using laminated silicon iron. So the parallel component become an important factor limiting the critical current too owing to much larger magnitude, which is more than 10 times the radial component.

The genetic arithmetic concerning HTS anisotropy characteristic combined with the coupled field iteration of FEM is used for optimization. The analysis result shows CGMM can be saturated with field of good uniformity when the HTS has the parameters of aa=0.00339m, height=0.01594m, length=0.00920m, which cost the least HTS tapes. It is also found that the maximum current density is permissive $3700 A/cm^2$ with these optimized parameters.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China(50077019)

REFERENCES

1. Voccio, J.P., Joshi, C.H. and Lindberg, J.F., application of high-temperature superconducting wires to magnetostrictive transducers for underwater sonar, IEEE trans. On Mag. (1994) ,30 1693-1698
2. Pitel, J., Kovac, P., Melisek,T., et al. Influence of the Winding Geometry on the Critical Current and Magnetic Fields of Cylindrical coils made of Bi(2223)Ag anisotropic tapes, IEEE Trans. On Applied superconductivity (2000), 10 478-481
3. Fabbricatorc, P., Priano, C., Testa, M. P., Musebich, R., et al. Field distribution effect on the performances of coils wound with Ag/Bi-2223 tape, Supercond. Sci. Technol. (1998), 11 304-310
4.So Noguchi, Makoto Yamashita, Hideo Yamashita, et al., An Optimal Design Method for Superconducting Magnets Using HTS Tape, IEEE Trans. on Appl. Superconductivity(2001),11 2308-2311.
5. Zhitong Cao, Jiongjiong Cai, Youtong Fang, FEM Analysis and Design Optimization of an Actuator Made of GMM, record of the ASAEM'2003, oct 22-25,2003, Seoul, Korea, p53
6. http://www.amsuper.com/html/products/htsWire/103419095991.html
7. Ling Wang, Intelligent Optimization Algorithm with Application, Tsinghua University Press, Beijing, China (2003) 36-37