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Design of Magnetic Coil System for CHS-qa

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Abstract
A modular coil system for a quasi-axisymmetric stellarator, CHS-qa, is designed. In the design process of modular coils, the normal component of produced magnetic field is evaluated on the outermost magnetic surface that is given from the configuration design. However, such an evaluation of the normal component on the surface is not sufficient to obtain the designed quasi-axisymmetric configuration in a good precision. It is because the mirror ripple component produced by modular coils does not largely affect the normal component of magnetic field on the surface. To improve the modular coil design, the evaluation of mirror ripple component at magnetic axis is included.

Keywords:
advanced stellarator, quasi-axisymmetry, CHS-qa, modular coil

1. Introduction

Recent development of computer technology expanded the designing freedom of 3-D configuration of toroidal confinement. Based on such a progress, many advanced stellarator configurations [1-6] were proposed. Design objectives of these configurations are better property in the neoclassical transport and improved MHD stability for high beta plasma.

A quasi-axisymmetric configuration [4,5] is one of these advanced stellarator concepts. It has the axisymmetric field strength in Boozer coordinates [7] and therefore has good neoclassical transport similar to tokamak. At NIFS, the quasi-axisymmetric device, CHS-qa [8,9], with a major radius of 1.5 m and an average aspect ratio of 3.2 was proposed and its design work has been continued. An advanced stellarator configuration is usually designed using the equilibrium solving code based on the data of outermost magnetic surface shape. When the magnetic configuration is determined, the next important step is the design of coil system to produce the magnetic field which realizes all physical properties of advanced stellarator. Modular coils are normally used for the coil system of advanced stellarators.

The shape of outermost magnetic surface uniquely determines all magnetic field configuration inside of the surface. The modular coil system is designed to reduce the normal component of produced magnetic field on the outermost magnetic surface. When the normal component on the surface is reduced to be zero, the designed quasi-axisymmetric magnetic configuration is produced in an experimental device [10]. However, the total number of modular coils is limited. Moreover, from the engineering point of view, conditions are imposed for the radius of curvature and the distance between coils. Therefore, the perfect reduction of the normal component cannot be achieved in the real modular coil design. Due to such a residual normal components on the surface caused by the technical

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constraint of the coils, the possibility comes out that some physical properties could not be reproduced correctly by minimizing the normal components on the surface. In this paper, it is reported that adjustment of the mirror component based on the evaluation of the normal component on the outermost magnetic surface is difficult and that the separate treatment of this component is required to design a good modular coil system.

2. Modular coil optimization including an evaluation of mirror ripple component

The modular coil system of CHS-qa consists of 20 coils. This number is determined by considering magnitude of bumpy ripple produced by discrete coils. By the stellarator symmetry, these coils have only 5 types of shapes. A shape of modular coil is expressed using Fourier series on a toroidal surface. In the designing process of modular coils, values of Fourier coefficients are varied, and finally a set of coefficients which gives the minimum normal component of magnetic field on the outermost magnetic surface, is obtained as a result of optimization process. An example of modular coil system is shown in Fig. 1. In this figure, five different types of coils are marked by coil 1 through coil 5. The coils having same type of shape are marked same coil number.

Because of the technical reason described above, the threshold level of the normal component of magnetic field is set at 1 ~ 2 % of toroidal magnetic field strength. This level is comparable to the magnitude of bumpy ripple produced by discrete toroidal field coils in tokamak. To reduce this level lower, number of coils must be increased or the size of coils must be larger. However, it causes other difficulties of coil manufacturing: larger size and higher total cost. Therefore we select the tolerant magnitude of normal component to this level. Among several physical properties of magnetic field, it was found that a variation of mirror ripple component make very little change in the normal component of magnetic field on the surface. The magnetic field strength can be expressed by using Fourier series in Boozer coordinates as $|B| = \sum_{m,n} B_{m,n}(\rho) \cos(m\theta - nN\phi)$. Here, θ and ϕ are poloidal and toroidal angle in the Boozer coordinates respectively. N is the toroidal periodic number of configuration and it is 2 for CHS-qa. The m and n are the poloidal and toroidal mode number respectively. The mirror ripple component is expressed by $B_{0,1}$. Even if modular coils are optimized so that the normal component on the surface satisfies the tolerant level (1~2 %), the mirror ripple component at the magnetic axis remains in a finite level. Figure 2(a) shows the variation of magnetic field strength along the magnetic axis for the first version of modular coil. Horizontal axis

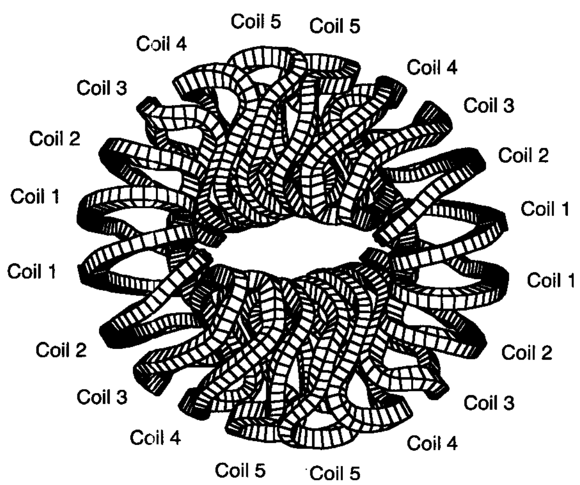

Fig. 1 Top view of 20 modular coils for CHS-qa.

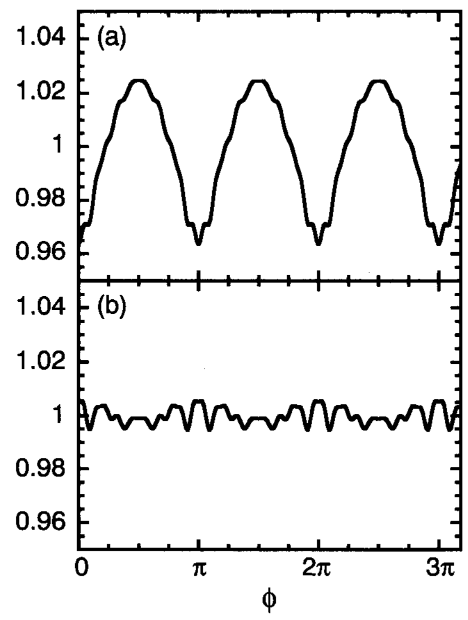

Fig. 2 Variation of magnetic field along magnetic axis produced by modular coils. (a) magnetic field produced by modular coils which is optimized by only the evaluation of normal component on the outermost magnetic surface. (b) magnetic field produced by modular coils with the evaluation of mirror component.

corresponds to the toroidal angle in Boozer coordinates. The magnitude of mirror ripple is about 3% of the toroidal magnetic field that is more than the acceptable level for the quasi-axisymmetry. To reduce this mirror ripple at magnetic axis, the evaluation of this ripple is included in the coil optimization process. By this inclusion, the mirror ripple at magnetic axis is greatly reduced. In Fig. 2(b), the result is shown for the improved version of modular coils. The other Fourier components of magnetic field and physical properties such as rotational transform, magnetic well depth are retained to be the same. The constraint imposed on coil structure from the engineering point of view, such as the distance between coils and the radius of modular coils are also the same.

The profiles of normal component of magnetic field on the outermost magnetic surface are compared for these two cases. In Fig. 3(a), $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$ on the surface is shown for the case that the mirror ripple exists. Here, $\boldsymbol{n}$ is the normal unit vector of the surface. In Fig. 3(b), the case that the mirror ripple is reduced is shown. Average values of $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$ on the surface are 1.45% for both cases. A clear difference is not seen between these figures. The dominant contribution to $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$ is the bumpy ripple produced by discrete modular coils. The difference of mirror ripple between two cases does not clearly appear in $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$ structures which is the reason why the mirror ripple is not correctly determined by the minimization procedure for the normal component of magnetic field.

To investigate the relation between the average value of normal component on the surface and the mirror ripple at the magnetic axis, the mirror ripple is introduced artificially by changing the current ratio of two groups of modular coils. The improved version of modular coil system is used in this study. Modular coils are separated into two groups (group A and B). Group A consists of coil 1, coil 2 in Fig. 1. These coils are beside vertically elongated cross-section and the total number of coils is 8 for full torus. Group B consists of the other coils, namely coil 3, coil 4, coil 5, and the total number is 12. Current of group A is reduced and the mirror ripple component is artificially controlled. By changing current as this, a mirror ripple, B_{01}, is added. The averaged value of normal component on the outermost magnetic surface as a function of mirror ripple at the magnetic axis is shown in Fig. 4. Each open circle corresponds to the case that current of group A is reduced to the level of 97.5 %, 95.0 %, 92.5 %, 90.0 %, 85.0 %, 80.0 % (written here in order of B_{01}/B_{00}) of

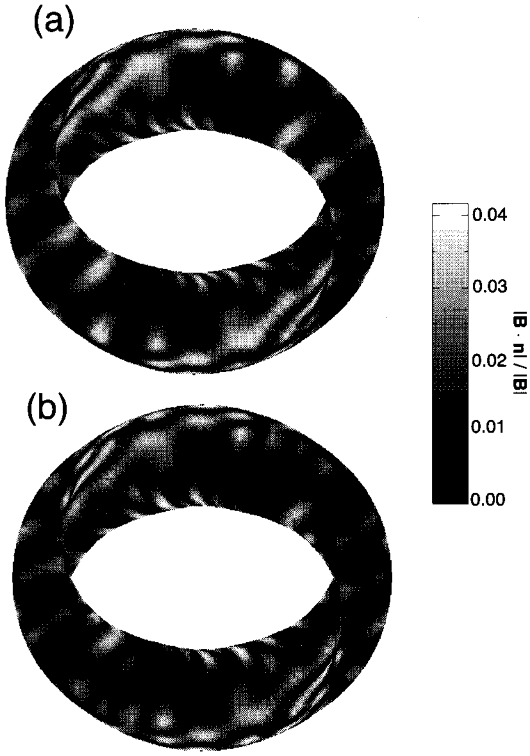

Fig. 3 Normal component ($|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$) of produced magnetic field on the outermost magnetic surface. (a) for modular coils that produces a mirror ripple on the magnetic axis. (b) for modular coils that is designed to reduce a mirror ripple at the magnetic axis.

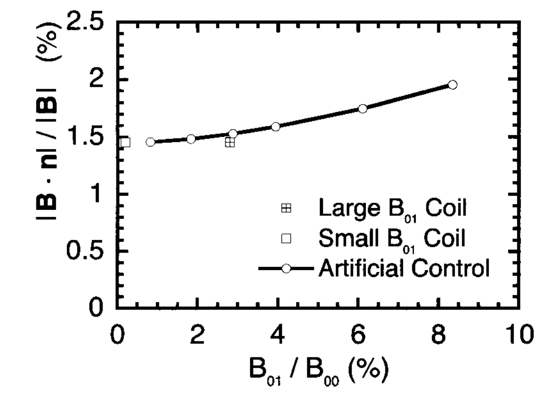

Fig. 4 Averaged normal component when mirror ripple at magnetic axis is artificially controlled (symbols of white circle). Mirror ripple is controlled by the ratio of currents in two groups of modular coils. The white rectangle symbol corresponds to improved modular coil system. The crossed rectangle symbol corresponds to modular coil system that produces a mirror ripple on the magnetic axis.

current of group B. Open circles show that the mirror ripple has small effect on $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$ when the mirror ripple is smaller than 3 %. Even if the mirror ripple B_{01}/B_{00} is decreased from 3 % to 1 %, the accompanying change in $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$ is only 0.1 %.

In this Figure, the white rectangle corresponds to improved modular coil system. The crossed rectangle corresponds to the first version of coil system that produces mirror ripple at the magnetic axis (Magnetic field is same to one shown in Fig. 2(a)). Since the dependence of B_{01} on $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$ is very weak where $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}| \sim 1.5$ %, the B_{01} can not always be reduced below 2 % by only reducing $|\boldsymbol{B}\cdot\boldsymbol{n}|/|\boldsymbol{B}|$. The amount of 2 % is the level of largest component in other non-axisymmetric components, and it is the maximum allowable level for the B_{01} component. It is not effective to reduce the mirror component (namely, to reproduce the designed quasi-axisymmetric configuration) by only evaluation of the normal component, therefore a direct evaluation of B_{01} is needed and included in our coil optimization process.

3. Conclusion

A modular coil system is designed by minimizing the normal component of produced magnetic field on the outermost magnetic surface. However, the magnetic field produced by this modular coils has mirror ripple at the magnetic axis which is not negligible for the quasi-axisymmetry.

It is found that the modification of the shape of outermost magnetic surface caused by the change of mirror ripple component, B_{01}, is very small. Therefore, the optimization of modular coils by only the evaluation of the normal component on the outermost magnetic surface does not effectively suppress mirror ripples. In order to reduce the mirror ripple on the magnetic axis, the evaluation of this ripple is included in the optimization process of modular coils. By this inclusion, improved modular coils are designed and the quasi-axisymmetric configuration is obtained with a good precision.

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