3-D ELECTROMAGNETIC TRANSIENT CHARACTERISTICS OF IN-VESSEL COMPONENTS IN TOKAMAK REACTOR

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Abstract

On a disruption with vertical displacement events (VDE), the three-dimensional (3-D) electromagnetic transient characteristics of in-vessel components in tokamak reactor have been studied numerically by using the finite element method. In this study, the in-vessel components are treated as the 3-D structure and the plasma halo region is modeled as the helical path of halo current can be treated. As a result, it is shown that there is difference in the electromagnetic stress of the divertor cassette between the current with helical path and the current with only the poloidal path. This difference is caused by the electromagnetic response of 3-D in-vessel components due to the helical path of halo current. It is essentially important for the design of tokamak reactors to treat the in-vessel components as the 3-D structure and to consider the helical path of halo current.

1. INTRODUCTION

A tokamak plasma with non-circular cross section basically becomes unstable for vertical motion, and the changes of pressure and current profiles cause losses of the plasma position and of the shape control. When the loss of the plasma position occurs (for example, a vertical displacement event (VDE) disruption), the plasma will come in contact with the in-vessel components. Consequently, the helical current with the poloidal component (so-called halo current) enters the in-vessel components. Then, the halo current interacts with the strong toroidal field and induces the electromagnetic forces in the tokamak machine. The electromagnetic forces induced by halo current during VDE may destroy the in-vessel components. For example, it is expected that the magnitude of the total forces is about 100MN in the case of the International Thermonuclear Experimental Reactor (ITER). Therefore, the evaluation of the electromagnetic forces due to plasma disruptions is one of the main subjects in the design of the tokamak reactors. Furthermore, the induced eddy currents and the halo currents transferred from the plasma halo region to the in-vessel components during the VDE are the most dangerous sources of the electromagnetic forces on the tokamak machine. Therefore, we should pay attention to the halo current phenomenon on the electromagnetic transient characteristics of in-vessel components and it is necessary for the design of future tokamak reactors to analyze the phenomenon sufficiently.

In general, the modeling for the analysis of the electromagnetic transient on the halo current phenomenon consists of three parts: a) the core plasma, b) the in-vessel components and c) the plasma halo region. One of the essential parts for this analysis is the modeling of the in-vessel components with high accuracy. The characteristics of halo current significantly depend on the structure of the in-vessel components since the halo current enters the part of the in-vessel components and the halo current pattern is helical. Therefore, it is important to consider the 3-D structure of in-vessel components. Furthermore, it is also important to treat the plasma halo region as the halo current has the helical current path.

In previous studies, there are some models for the analysis of the electromagnetic forces in the tokamak machine. For example, in the case of Tokamak Simulation Code (TSC, [1]), all parts

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are represented by an axisymmetric model. However, the 3-D in-vessel components are not taken into account. In the analysis by the finite element method [2-4], the 3-D model and the 2-D equilibrium model or the simple filament model are adopted for the in-vessel components and the plasma, respectively. However, the plasma halo region is not modeled and only the value of halo current in poloidal direction is given as input parameter.

In this paper, the eddy current analysis has been carried out by using the 3-D structure of the in-vessel components and by modeling the plasma halo region simultaneously, although the core plasma model is the multi-filament model. Especially, the electromagnetic responses of the 3-D in-vessel components by the helical current path of the halo current have been investigated.

This paper is arranged as follows: The numerical model and method are described in Section 2. Section 3 presents numerical results and discussions. Conclusions are given in the last section.

2. NUMERICAL MODEL

In this study, the model of the core plasma used is the multi-filament currents model, which can reconstruct the result on 2-D equilibrium analysis. The time evolution of the filament currents is given by the results of the 2-D transport analysis. The model used on the in-vessel components was the 3-D thin shell approximation and the tool used was the EDDYCAL code by the finite element method [5]. For the motion of plasma halo region, it is very difficult to solve the multi-dimensional equation of the motion, directly. In this paper, instead of solving the equation of motion, the plasma halo region is modeled by the thin shell approximation in the same manner as the in-vessel components and the time evolution is represented by giving the shape and the electric resistivity of the plasma halo region at each period. However, it should be noted that the halo region is essentially the 2-D mesh model because the toroidal symmetry is assumed. The helical current path of the halo current is modeled by considering the inhomogeneity of the electric resistivity in the plasma halo region. That is, it is assumed that the electric resistivity of the direction along the magnetic field line is different from the electric resistivity of the perpendicular direction with respect to the magnetic field line.

To evaluate this process at first, we consider the ITER design parameters [6]. Figure 1 shows the single thin shell mesh models for the plasma halo region and the in-vessel components used in this study. In Fig.1, the model represents an 18-degree sector of torus and includes the vacuum vessel, the back plate, a part of the blanket modules, the gas seal, the divertor cassette and the plasma halo region.

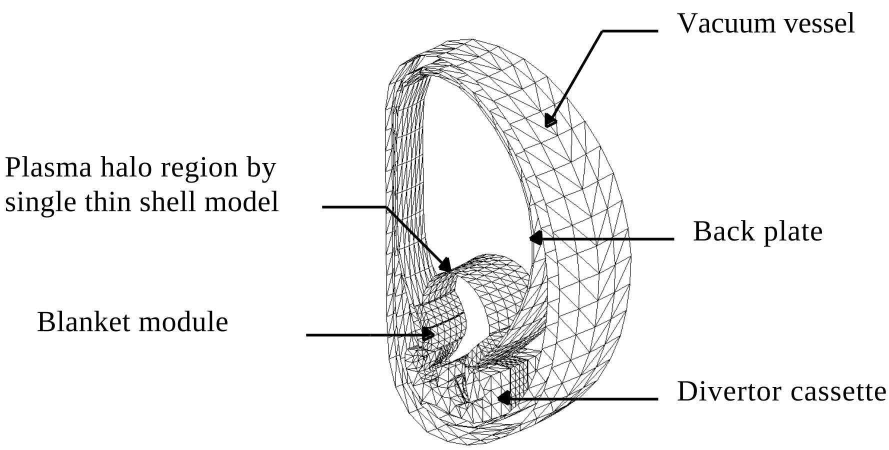


FIG.1. Single thin shell mesh model used in this study.

It is assumed that the plasma configuration is the end of burn (EOB) of the ITER and the plasma current decays to zero in 50 ms, linearly. The direction of the magnetic field line ($\left(B_T/B, B_P/B\right)$, that is, the halo current path) in the plasma halo region is determined as

$q = (a \times B_T)/(R \times B_p)$, where B_T, B_P, B, q, a and R are the toroidal, poloidal and total fields, the safety factor, the plasma minor radius and the plasma major radius, respectively. Here, a and q are given as the input parameters and R is given by the shape of plasma halo region. The electric resistivity in the plasma halo region is defined as the maximum poloidal current takes 30% of the plasma current. On the other hand, the time evolution of the electric resistivity in the plasma halo region is defined as the poloidal component of the halo current becomes the maximum (~6.3MA) at 30ms and it decays to zero at 50ms, linearly. The linkage flux induced by the motion of the plasma halo region in the toroidal field is also considered and it decays to zero in 50ms, linearly. The initial value is estimated at 18.75Wb in this case and is given as the input parameter.

3. NUMERICAL RESULTS

Figure 2 shows the time evolution of halo and eddy currents in some components in the case of q = 1.5. In Fig 2(a) and 2(b), the toroidal and poloidal components of the currents are shown, respectively. As shown in Fig.2(a), the peak toroidal current in the halo region is 40% of the total current at 30ms and can not be neglected. In addition, the largest peak toroidal current is found in the back plate and the largest peak poloidal current except the halo region is found in the divertor cassette, respectively.

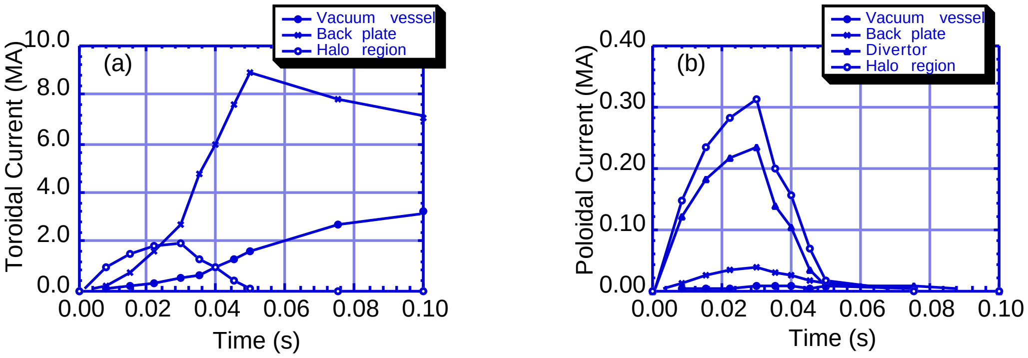


FIG.2. Time evolution of halo and eddy currents. (a) Toroidal and (b) poloidal components.

We checked the validity of the single thin shell model by comparing with the double thin shell model since there is a possibility that the multi-thin shell model is better approximation regarding the motion of plasma halo region. Figure 3 shows the comparison of the single thin shell model with the double thin shell model. As shown at right hand side in Fig.3, the plasma halo region is modeled by the double shell in the case of the double thin shell model. In the figure, the time evolution of the total electromagnetic forces is shown and the maximum electromagnetic force per divertor cassette is 1.6 MN at t = 30ms in the case of q = 1.5 using the single thin model. The difference between the maximum forces of both models is expected to be around 12 %, so that it is effective concern to apply the double shell model if the force induced by the halo current is crucial.

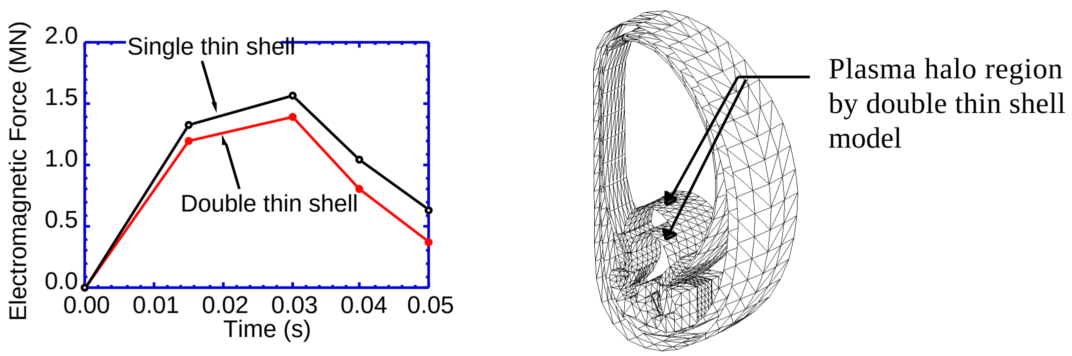
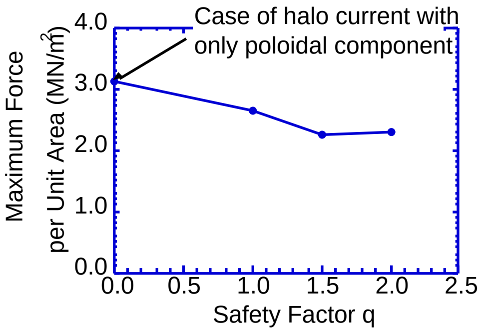


FIG.3 Comparison of single thin shell model with double thin shell model(right hand side).

Figure 4 shows the effect by the helical path of halo current on the 3-D in-vessel components as the objective described in Section 1. The safety factor q represents the direction of the halo current in the halo region as described in previous section. The case of $q = 0$ corresponds to the case of the halo current path without toroidal component (only poloidal current path) and the calculation conditions is close to the conditions of the previous studies [1-4]. From this figure, it is shown that the maximum force per unit area (stress by the electromagnetic force) decreases by changing the path of the halo current. The maximum force per unit area in the case of $q = 1.5$ is equivalent to 72% of the one in the case of $q = 0$, although the maximum electromagnetic force per divertor cassette in both cases are almost the same results within 3%. The eddy current pattern in the case of $q = 0$ is different from the one in the case of $q = 2$ and the magnitude of the eddy current decreases with increasing q value. For example, the eddy current patterns on the outboard of divertor cassette change as shown in Figure.5. Obviously, this change appears by considering the 3-D in-vessel components and can not appear by using the 2-D structure.



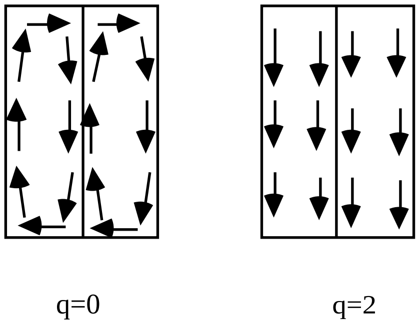


FIG.4 Effect by helical path of halo current. FIG.5 Typical change of eddy current pattern.

For a candidate of this cause, it is considered that the magnetic flux by the toroidal component of halo current partially cancels the magnetic flux by the toroidal current of core plasma in the initial period (t=0~30ms).

4. CONCLUSIONS

The 3-D in-vessel components and the 2-D plasma halo region have been modeled by the thin shell approximation and the eddy current analysis during the VDE has been carried out. Especially, it is shown that there is difference in the electromagnetic response of the 3-D in-vessel components by considering the helical path of the halo current. As a conclusion, it is essentially important for the design of tokamak reactors to treat the in-vessel components three-dimensionally and to model the plasma halo region, simultaneously. In addition, the 3-D effects on the blanket modules are also important since the blanket modules have the 3-D structure essentially. Furthermore, although only the 18-degree sector is considered in this study, it is necessary to carry out the calculations for the whole circumference concerning the toroidal direction (full model) since the halo current has the toroidal distribution. In the case of the full model, there is a possibility that the effect of helical current path becomes even stronger and the stress by the electromagnetic force decreases. Future works will address these problems.

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