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An efficient modeling of fine air-gaps in tokamak in-vessel components for electromagnetic analyses

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ABSTRACT

A simple and efficient modeling technique is presented for a proper analysis of complicated eddy current flows in conducting structures with fine air gaps. It is based on the idea of replacing a slit with the decoupled boundary of finite elements. The viability and efficacy of the technique is demonstrated in a simple problem. Application of the method to electromagnetic load analyses during plasma disruptions in ITER has been successfully carried out without sacrificing computational resources and speed. This shows the proposed method is applicable to a practical system with complicated geometrical structures.

1. Introduction

In case of plasma disruption events, large amount of electromagnetic (EM) force is exerted on conducting structures in tokamaks such as plasma facing components (PFC), in-vessel components, vacuum vessel (VV) and supporting structures. Such an EM load can be described as the Lorenz force, $\mathbf{j_1} \times \mathbf{B_0}$ which is originated from halo currents [1–3] and inductive eddy currents during the plasma disruption. Here, $\mathbf{j_1}$ is the disruption-induced current density and $\mathbf{B_0}$ is a pre-disruption equilibrium magnetic field. In tokamaks, disruption-induced EM loads overwhelm other mechanical loads, such as gravity, seismic and thermo-hydraulic ones. Thus, estimating disruption-induced EM loads is an essential part of the design process of aforementioned major mechanical components of tokamaks, including ITER [4–6].

Usually, a time-dependent EM load analysis is performed on the basis of time-varying parameters of disrupting plasma, such as plasma shape and current distribution, provided by plasma simulation codes. Some commercially available FEM tools are often beneficial to relatively large-scale analyses, in practical point of view, to implement a numerical model based on the drawings of design model. Due to the presence of thick shield/breeding blankets, the design of a reactor-grade plasma device in the future, as much as ITER, will prefer solid mesh FEM tools to any shell model [6–8] which describes induced current solving set of Maxwell equations [7,8] or coupled circuit equation matrix on 2D surfaces [9], in spite the shell is likely to be applicable to the design of present-day tokamaks due to the small width of conducting structures compared with characteristic dimension of a device. In addition, the commercial software such as ANSYS-EM™ [10] also can be applied to an integrated analysis of EM loads and ensuing mechanical or thermo-hydraulic loads. Throughout this paper, we assume that the ANSYS code is used for the EM load analysis.

In many cases, the design of PFCs in tokamak considers how to reduce the EM load applying narrow air gaps to their conductive structure to make constraints upon the flow of induced currents. For instance, to the present design of ITER shield blanket modules (BM), they introduced vertical slits as current breaks [11]. Hence, the presence of such thin slits has to be carefully taken into account in implementation of the numerical model for EM load analysis, because it will significantly limit the flow pattern of induced currents as well as the total magnitude of them. So, the distribution of EM forces and torques cannot be estimated properly without any reflection of those slits in the numerical calculation. A main drawback in setting up an ANSYS-EM™ computational model in such a case is that it requires undesirable air meshes to represent narrow slits, which is not necessary in the shell model. In principle, a brute force modeling air gaps to represent slits is possible but such a calculation necessarily involves a very massive numerical modeling generating a very large number of elements. So, it is recommended to develop more efficient way of modeling that can accurately evaluate induced currents in the presence of thin slits, *i.e.* the air-gaped structures. The primary objective of this paper is to present such a scheme of numerical model.

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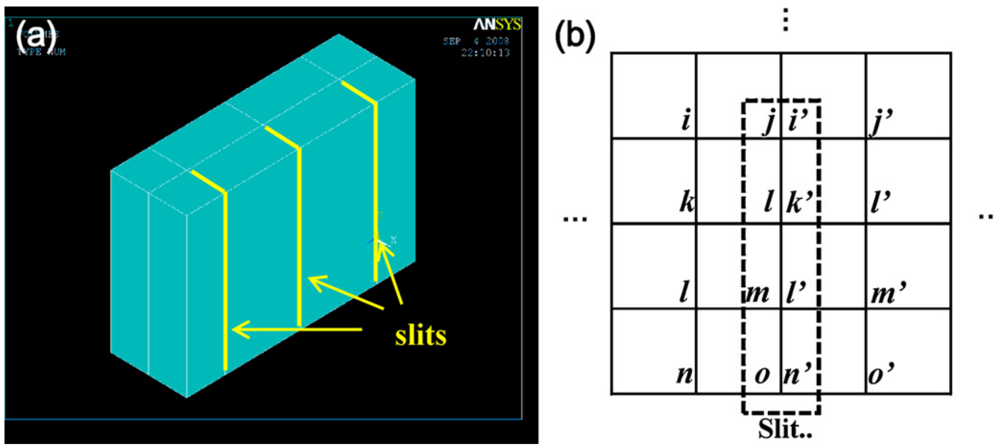

Fig. 1. (a) A conducting block with some slits on it. (b) A comprehensive illustration of "Element Separation" representing the top view of slit area – elements at the interface are decupled by the separation of shared node as (j, i'), (l, k'), (m, l') or (o, n'), where each node in a pair has the same position but belongs to different elements.

This paper is organized as follows: in Section 2, we present a numerical technique which can accurately take into account the effects of thin slits on eddy currents without invoking the idea of equivalent resistivity. This numerical technique is called hereafter the *element splitting method* (ESM). A test problem is then solved using a model of simple geometry to demonstrate the viability of ESM in the calculation of eddy current and their flow pattern when slits are present. Section 3 is devoted to the application of ESM to a practical EM load analysis on ITER components based on its complete geometrical structures. The ITER diagnostic upper port plug (DUPP) [12] and neighboring BM are modeled using ESM, and EM loads on DUPP is calculated during a plasma disruption in ITER. Benchmarking the results with those obtained from the other method shows that ESM yields accurate results saving computational resources and time as well. We conclude this paper in Section 4 with a brief summary of main results in this paper and on-going works.

2. Element splitting method

Let us consider a conducting solid block having some thin slits on it, as shown in Fig. 1(a). To perform an EM analysis using ANSYS-EM™, a slit is to be represented as narrow space of air meshes (*i.e.* an air gap) which should be set up to evaluate electromagnetic fields in the proper way avoiding the error by simplification of fine structure. Even though this can be done in principle, it is undesirable because it (1) requires a time consuming modeling process generating a large number of elements to represent slits, (2) reduces computation speed significantly, and (3) leads to the degradation of computational precision due to the large aspect ratio of elements at air-gaps itself as well as the abrupt transition of mesh size close to the air-gaps, which is almost unavoidable because of the limit of total number of elements that can be provided by ANSYS-EM™ environment. So, an efficient numerical method that can count the effect of slits has to be developed to be capable of performing EM analysis for conducting structures with thin slits.

Until recently, the effective resistivity method (ERM) [13,14] has been employed as a well-known method to compensate simplification of neglecting fine structures in EM analysis, in spite of its physical limit that, for instance, the effective resistance may not be exactly consistent with the realistic behavior depending on the time constant of the time varying magnetic flux. In the framework of ERM, anisotropic assignment of the resistivity has been regarded as a quite natural way applying the effective resistivity instead of their bulk resistance with respect to the disturbance of current flow due to the fine structures, for instance eddy current breaks or air gaps. Usually, the effective resistivity scheme is taken considering the resistance along the 'hard-axis' as the perpendicular direction to air gap planes or across eddy current breaks, which may have the largest effective resistivity. It is found as a typical procedure to solve first the FE model with equivalent electrical excitation for the target components including their detail structures. Loading linear time varying external current along a certain axis, the overall voltage drop can be evaluated with a constraint for the time derivative of MVP, which is imposed as a constant voltage, so that one can estimate the effective resistivity along the specific axis of a simplified model without fine structure [13,14]. In spite of advantage of its simplicity, the current flow pattern of the effective resistivity calculation will not be consistent with the actual distribution of eddy current in the fine structure so that an exact estimation of the effective resistivity is not so trivial to be approximated to the anisotropic DC resistance. In particular as an example, the mutual induction of the opposite current paths between the faces across any air gap is forced to be ignored under the approximation based on ERM, even though there is little difference in self-inductance of the current path on the anisotropic bulk comparing with the case of realistic current flow along the complex structure.

The goal of this section is to present another numerical technique that is more accurate, yet requiring no additional computational resources.

Fig. 1(b) depicts the schematic view representing the basic idea of the element splitting method (ESM). If the width of a slit is negligible compared with other dimension of a block under consideration, we can regard the slit as an interface of the contiguous surfaces of solid structure. Then, it is possible to construct a FE model considering the slit as an interface between the elements, as shown in Fig. 1(b). The key to the ESM technique is *logical* separation of the common nodes on the slit interface [*i.e.* (j, i'), (l, k') and so on in Fig. 1(b)] which are physically placed at the same position. Adjacent couples of elements sharing the nodes at a slit are now separated by assigning a set of common nodes to one element [*i.e.* nodes (j, l, m, n) in Fig. 1(b)] and allocating its duplication to the other [*i.e.* nodes (i', k', l', n') in Fig. 1(b)]. Next, we assign the coupled degree of freedom (DOF) for the magnetic vector potential (MVP) to the pairs of separated nodes, whereas there is not any constraint to the electric potential. Of course, the boundary condition of the electrical potential is automatically applied to every outer surface of conductive structures in ANSYS model, to satisfy the solenoidal