Fusion Engineering and Design 101 (2015) 80–87

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Analysis of eddy currents in the two-half isolated vacuum vessel of an iron core tokamak

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ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 3 October 2015
Accepted 13 October 2015
Available online 10 November 2015

Keywords:
Eddy currents
Iron core tokamak
Vacuum vessel
Analytical method

ABSTRACT

Eddy currents in the vacuum vessel can cause many problems in plasma diagnostics and control, the fast analysis of eddy current is very important. In this paper, the characteristic of eddy currents in the thin shell of a two-half isolated vacuum vessel and the iron core's effect on eddy currents are analyzed, then an analytical method is used to calculate toroidal eddy currents in the vacuum vessel. Using this method, the eddy currents can be calculated rapidly which will benefit more accurate plasma reconstruction and real-time control. The calculated results by this method agree well with finite element method simulations based on J-TEXT configuration.

1. Introduction

Due to the structure of a vacuum vessel, eddy currents are inevitable during the operation of a tokamak device especially during plasma disruption and the start-up stage of discharge. Eddy currents can cause many problems such as: mechanical problems due to large electro-magnetic force [1], diagnostic problems of magnetic probes and flux-loop coils by introducing extra magnetic-field [2]. Although many works have been done by using numerical codes like TSC, TYPHOON or commercial soft wares like ANSYS to simulate eddy currents in the vacuum vessel during discharge [3–7], an analytical method for fast calculating and estimating the effects of eddy currents in the vacuum vessel is very important for real-time plasma diagnostics and subsequential plasma control. Finite element methods (FEMs) are accurate and can deal with very complex geometry, but when we need an intuitive understanding of the magnitude and distribution of eddy currents very fast and even real-time computing for plasma control and reconstruction, this method is no more suitable to be used for these purposes.

The iron core in a tokamak device can cause a lot of problems in analytic methods, for it not only changes the distribution of magnetic line but also makes the magnetic field nonlinear. The nonaxisymmetrical iron core can also make the magnetic field nonaxisymmetrical. The calculation of magnetic field in iron core tokamaks and the effect of iron core on magnetic field have been studied in many early researches [8–11]. In this paper, the eddy current problems in the thin shell of two-half isolated vacuum vessel of an iron core tokamak device are discussed. The effect of iron core on eddy currents is analyzed, and the characteristic of the eddy currents in the two-half isolated vacuum vessel is discussed. The toroidal eddy currents problems are described by a non-homogeneous integral equation and it can be solved by converting it into two set of circuit equations. The matrix coefficients of circuit equations are calculated by analytical method based on an infinitely long cylinder core model. Once the matrix coefficients of circuit equations are calculated, the eddy currents can be calculated quickly by solving the circuit equations by using Runge–Kutta-method finally, and the matrices just need calculation once. By this method, toroidal eddy currents in the vacuum vessel can be calculated rapidly to analyze its effects on plasma diagnostics and control.

The structure of the article is as follows: in Section 2 a simple description of the tokamak device with an iron core and a simple analysis of the eddy current problems are given, in Section 3 the analytical method for calculating toroidal eddy currents in the vacuum vessel is introduced in detail, and in Section 4 the calculated results of spatial and temporal distribution of the toroidal eddy currents for two typical cases by this method are given, and for comparison the results using FEMs are also presented. At the end of this paper, a summation is given.

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http://dx.doi.org/10.1016/j.fusengdes.2015.10.011
0920-3796/

2. Structure of iron core tokamak and Fourier representation of its vacuum vessel

The tokamak device for solving eddy current problems in this article is a midsize tokamak with an iron core. Its major radius is 1.05 m, and the minor radius is 0.26 m. The iron core is very similar to a three-legged standard transformer core. As shown in Fig. 1, the iron core is composed of central column, iron yokes and back arms. The iron core is composed of steel sheets and the central column has approximately 0.8 m diameter cross-section. The thickness of the sheet is 0.8 mm and the eddy currents in the iron core can be neglected.

The poloidal magnetic field coils consist of ohmic heating (OH) coils, vertical field (VF) coils and horizontal field (HF) coils which respectively have 40 turns, 16 turns, and 32 turns. The vacuum vessel is composed of 14 ports and two keystones as shown in Fig. 2. The vacuum vessel is separated into two isolated parts by keystones. The material of the vacuum vessel is stainless steel which has permeability near vacuum and resistivity of 0.73×10^{-6} Ωm at room temperature.

The thickness of the vacuum vessel is 0.012–0.025 m and the eddy current problems discussed in this article is not so fast which can be taken as a quasi-static magnetic field. Due to the large distinction between the overall dimension and thickness, the non-uniformity of eddy currents in the vacuum vessel along thickness direction can be neglected. In fact, when considering the effects of eddy currents on signals of magnetic probes, we only concerned about the integral value of eddy currents along thickness direction. Furthermore, all poloidal magnetic field coils are axisymmetric and the vacuum vessel is axisymmetric overall except for some local non-axial symmetry. The iron core is nonaxisymmetrical due to the iron yokes and back arms, but this perturbation along the toroidal direction which has a mode equal to 2 is a small quantity and what we concerned more about is the integral mean value over the whole toroid. According to Maxwell's argument, this perturbation along the toroidal direction has no effect on the distribution of toroidal eddy currents and it can only cause a component of poloidal eddy currents.

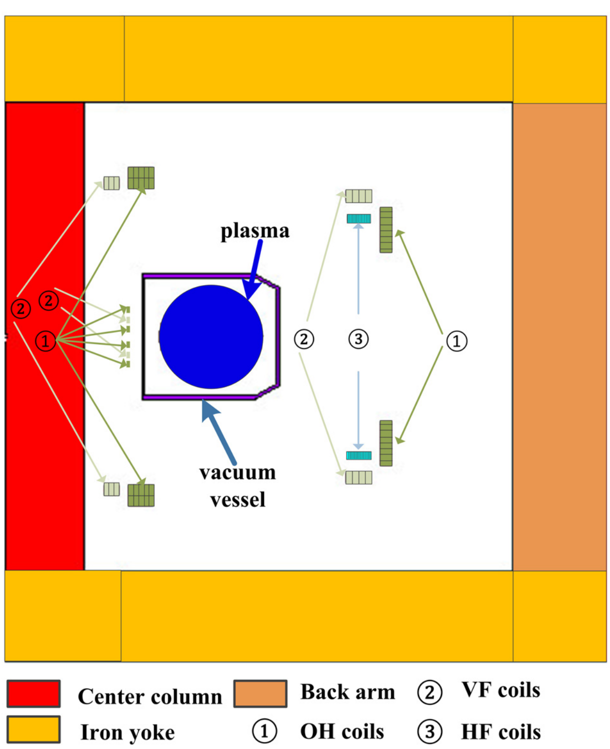

Fig. 1. Schematic diagram of the J-TEXT cross-section with iron core, vacuum vessel, plasma and poloidal field coils. The OH, VF and HF coils respectively have 40 turns, 16 turns, and 32 turns.

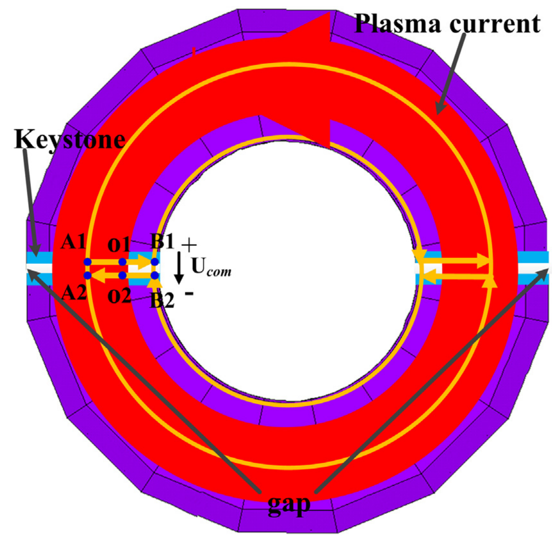

Fig. 2. The schematic diagram of vacuum vessel and definition for U_{com}, $U_{A1A2} \approx U_{O1O2} \approx U_{B1B2}$. The yellow lines represent the path of eddy current. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Based on this viewpoint, the eddy current problems can be decomposed into two parts: one is the toroidal component which is an axisymmetric problem, and the other is the poloidal component which is not axisymmetric but approximately cyclic symmetry. What we are more concerned about is the toroidal component because it is the main component of eddy currents. As the two halves of the shell are isolated from each other, the eddy currents in the vacuum vessel must form current loops in each half of the vacuum vessel. As shown in Fig. 2, the two current loops are separated from each other, and it is assumed that the poloidal component of eddy currents for eddy currents return back only exists at the end of vacuum vessel so the non-uniformity of toroidal eddy currents along the toroidal direction is ignored. Because the path for poloidal eddy currents is very short when compared with the path for toroidal eddy currents, the ohmic potential drop due to poloidal eddy currents can be ignored which means the cross-section of vacuum vessel at the location of keystone can be approximated as equipotential plane. When neglecting the non-uniformity of eddy currents in thickness direction, the toroidal eddy currents are decreased to a one-dimension problem. In this paper, the toroidal eddy currents are calculated in two cases, case 1: generated by change of plasma current and ohmic heating coils currents together and the current of plasma is the form of exponential decay function; case 2: generated by change of plasma current and ohmic heating coils currents together and the current of plasma is the form of linear decay. The two cases model the current quench stage of plasma disruption for two typical forms of currents decay.

In order to describe location of computational domain in calculation of eddy currents, it is necessary to use a one-dimension coordinate system to describe the location of the cross-section of vacuum vessel. Thus a new coordinate system was introduced as shown in Fig. 3, and through coordinate transformation, the location of the vacuum vessel in cylindrical coordinate system can be expressed by coordinate θ. The relationship between the cylindrical coordinates and the new coordinate can be expressed by form of Fourier series as shown in formula (2.1). R_0 is the major radius, and the typical number of Fourier series of 20 is enough for good