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Electromagnetic and structural analyses of the vacuum vessel and plasma facing components for EAST

Weiwei Xu*, Xufeng Liu, Yuntao Song, Jun Li, Mingxuan Lu

Institute of Plasma Physics, Chinese Academy of Science, Shushanhu Road 350, Hefei 230031, PR China

HIGHLIGHTS

- The electromagnetic and structural responses of VV and PFCs for EAST are analyzed.
- A detailed finite element model of the VV including PFCs is established.
- The two most dangerous scenarios, major disruptions and downward VDEs are considered.
- The distribution patterns of eddy currents, EMFs and torques on PFCs are analyzed.

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ABSTRACT

During plasma disruptions, time-varying eddy currents are induced in the vacuum vessel (VV) and Plasma Facing Components (PFCs) of EAST. Additionally, halo currents flow partly through these structures during the vertical displacement events (VDEs). Under the high magnetic field circumstances, the resulting electromagnetic forces (EMFs) and torques are large. In this paper, eddy currents and EMFs on EAST VV, PFCs and their supports are calculated by analytical and numerical methods. ANSYS software is employed to evaluate eddy currents on VV, PFCs and their structural responses. To learn the electromagnetic and structural response of the whole structure more accurately, a detailed finite element model is established. The two most dangerous scenarios, major disruptions and downward VDEs, are examined. It is found that distribution patterns of eddy currents for various PFCs differ greatly, therefore resulting in different EMFs and torques. It can be seen that for certain PFCs the transient reaction force are severe. Results obtained here may set up a preliminary foundation for the future dynamic response research of EAST VV and PFCs which will provide a theoretical basis for the future engineering design of tokamak devices.

1. Introduction

Experimental Advanced Superconducting Tokamak (EAST) is an advanced steady-state plasma physics experimental device which has been built in ASIPP CAS. Its main objective is the wide investigation of both the physics and technology for state advance tokamak. EAST has Plasma Facing Components (PFCs) mainly including inner limiter, divertor, passive stabilizer and horizontal protective plate to protect the vacuum vessel (VV), heating systems and diagnostic components from the plasma particles and heat loads. All PFCs are composed of graphite tiles, heat sink, support and cooling system. Fig. 1 shows the elevation view of EAST PFCs. The PFCs are designed up-down symmetrical to the midplane, to meet the requirement of operation with single or double null plasma shape [1,2].

During plasma disruptions, time-varying eddy currents are induced on VV and PFCs. Additionally, halo currents will flow along the scrape layer to these structures and return to the scrape layer during the vertical displacement events (VDEs). Eddy currents and halo currents interact with high toroidal magnetic field will cause large electromagnetic forces (EMFs) and torques on VV and PFCs. As these forces change drastically with time, the structural response is dynamic [3]. This response determines important design drivers such as the reaction forces of supports, the displacements and stress of the structure.

In this paper, analytical and numerical methods are used to calculate eddy currents and the resulting EMFs on EAST VV and PFCs including the supports. A detailed finite element model of EAST VV including double-walls, the ribs between the walls, all major PFCs and their supports which allow the currents flow through them between VV and PFCs is established. Two most dangerous situations: major disruptions (MD) and downward VDEs are examined in detail.

* Corresponding author. Tel.: +86 551 5592013.
E-mail address: wwxu@ipp.ac.cn (W. Xu).

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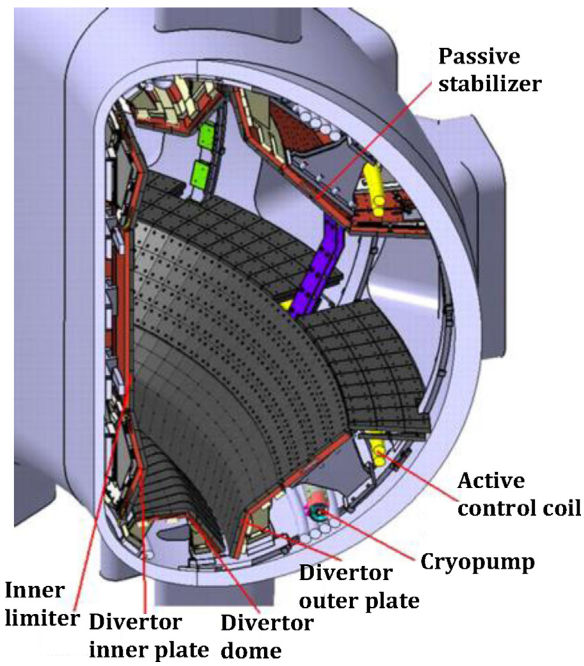

Fig. 1. Elevation view of EAST PFCs.

2. Analytical analysis of eddy currents for VV during MD

Major disruption is a typical load case for the electromagnetic analysis of Tokamak VV and PFCs. During MD, the plasma current is modeled by one coil of which the current varies rapidly with time but the position in space is constant. The sudden change of plasma current will induce eddy currents and result in electromagnetic forces on conducting structures around the plasma. According to the principle of electromagnetic induction, by simplifying the double-shell of VV to several dozens of circular coils, the distribution of eddy currents and their effects on the background magnetic field can be simulated, and the resulting electromagnetic forces can be calculated with Fortran software codes. Here, the vacuum vessel is divided into 120 conducting rings, and a current couple model is established to calculate eddy currents for different conducting elements. The current couple model is given as:

$$L_i \frac{dI_i}{dt} + \sum_{j(j \neq i)} M_{ij} \frac{dI_j}{dt} + M_{i,plasma} \frac{dI_{plasma}}{dt} + R_i I_i = 0 \quad (1)$$

where R, I, L and M represent the resistance, current, self-inductance and mutual inductance respectively.

For EAST, the current decay of plasma during MD can be supposed as below:

$$I = I_0 e^{-t/\tau} \quad (2)$$

where $I_0 = 1$ MA, $\tau = 3$ ms.

Eddy currents can be calculated from Eq. (1). The total eddy current on VV and eddy current density at different positions of the upper half vessel can be obtained, just shown in Fig. 2. Results show that when plasma current decays exponentially, eddy currents firstly grow rapidly and then decrease over time. The maximum total eddy current on VV is 0.71 MA at about 7 ms. The maximum current density occurs at the center of inner limiter at about 5 ms and the value is 21 MA/m^2. The amplitude and response velocity of eddy currents on every coil have an inverse relationship with its distance to the plasma. At the same position, inner shell will reach the peak current earlier than outer shell.

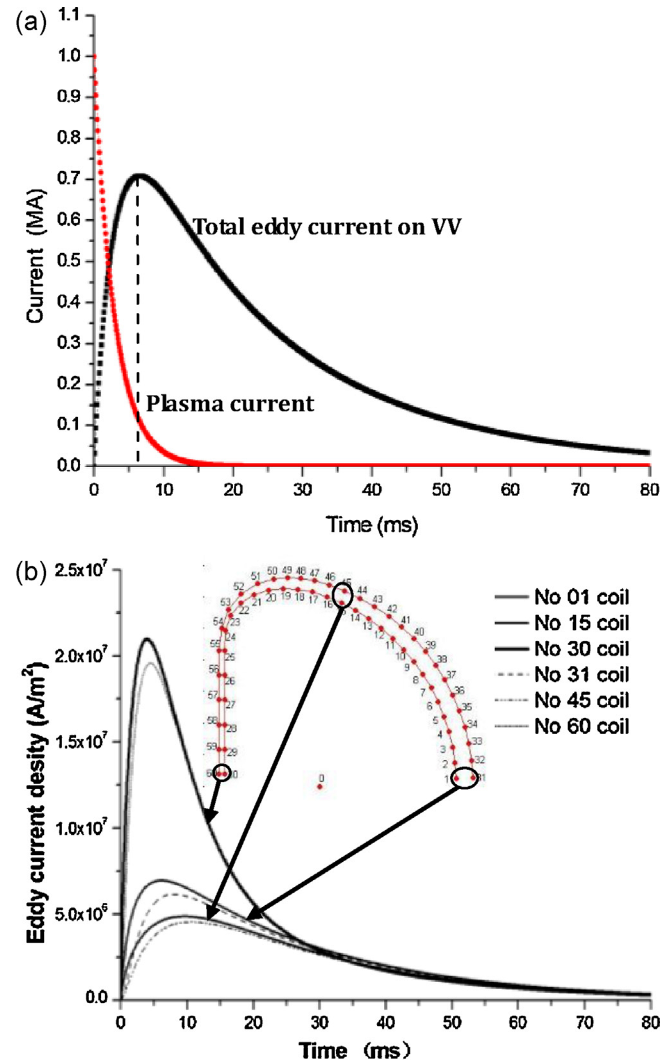

Fig. 2. (a) Total eddy current on VV and (b) eddy current density at different positions.

When the large toroidal eddy currents interact with high poloidal magnetic field, large electromagnetic forces will emerge on VV. Since the background magnetic field caused by plasma current changes sharply as plasma current decay, the total magnetic field's direction may even reverse at some places [5], which result in the electromagnetic force there reversing. Fig. 3 has shown how the stress distribution changes gradually. The pressure at region A points inward at first and gradually turns outward, while the pressure at regions B and C points outward and inward respectively all

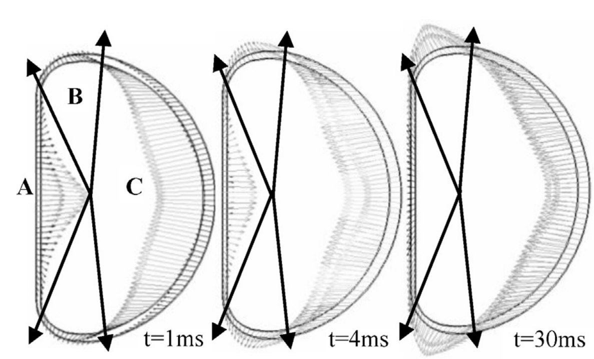

Fig. 3. Force distribution on PFCs at different time during MD.