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Plasma response models for current, shape and position control in JET

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Abstract

This paper presents the features and the performance of the Joint European Torus (JET) plasma response models based on an upgraded version of the CREATE-L code. It takes into account a number of aspects, including an equivalent axisymmetric model of the iron core and the eddy currents induced in the passive structures. The input quantities are the poloidal field circuit currents (or voltages) and two parameters related to the plasma current density profile. The output quantities include the signals provided by the magnetic diagnostic system of JET (fields, fluxes and flux differences) as well as plasma current and shape. The equivalent axisymmetric model of JET and the plasma response models have been assessed on a set of JET pulses, by comparing the simulated open loop response of the magnetic measurements and the plasma shape to the experimental measurements. The electromagnetic analysis shows that the axisymmetric model of the iron is satisfactory. The linearized plasma response model provides a reliable base for the design and the assessment of a new current, shape and position control system in JET, and accurately predicts the growth rate of the vertical instability of an elongated JET plasma.
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Keywords: JET; Plasma response model; Plasma control; Vertical instability

1. Introduction

In the next future, some physical experimental activities on Joint European Torus (JET) will require ITER-like plasmas with high triangularity and elongation. There is a project aimed at investigating the possibility of obtaining extremely shaped plasmas with the existing active circuits and control hardware [1]. To achieve this objective, it is planned to enhance the present shape control and vertical stabilization systems on the basis of a reliable plasma response model.

Here we present the features and the performance of the JET plasma response models based on an upgraded version of the CREATE-L code [2], which takes into account several aspects:

- an equivalent axisymmetric model of the iron core;
- the response to the coil currents and to the plasma current density profile parameters;

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– the set of magnetic diagnostics available;
– the eddy currents induced in the passive structures.

The equivalent axisymmetric model of JET has been assessed from the electromagnetic point of view on a set of dry runs, with both linear and nonlinear magnetostatic and eddy current analyses. The response to the coil currents and the main plasma current density profile parameters, i.e. the plasma response model of interest to the shape control, has been assessed on a set of JET pulses, by comparing the simulated open loop response of the magnetic measurements and the plasma shape to the experimental measurements.

2. JET equivalent iron model geometry and assessment

The JET iron core is an eight-limbed magnetic circuit, and is treated as an equivalent axisymmetric structure as described in [3]. However, the equivalent 2D axisymmetric model [4] used for this work (Fig. 1) has the real shape of the polar shoes (previously modeled as straight lines) in order to reproduce the concavity of the cross section. In addition, the geometry of the plasma facing side of the limbs (previously shifted away and tilted) is straight and located as in the real 3D geometry to ensure a correct boundary condition (field lines perpendicular to air/iron interface) when the iron is not saturated. The equivalent axisymmetric model of JET has been assessed from the electromagnetic point of view on a set of dry runs, with both linear and nonlinear magnetostatic and eddy current analyses (Fig. 2).

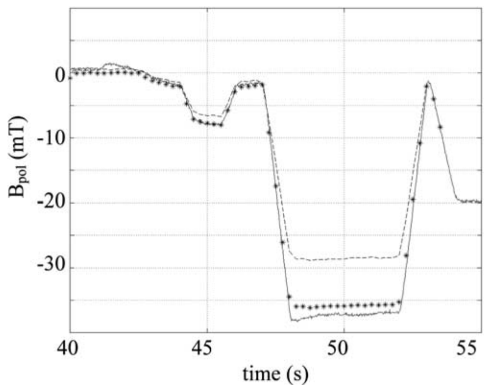

Fig. 2. JET shot #52550. Effect of the geometry on the time evolution of the signal given by the sixth field sensor, which is locates in the vicinity of the upper polar shoe: experimental data (continuous line) vs. simulations based on the old (dashed line) and new (stars) geometry.

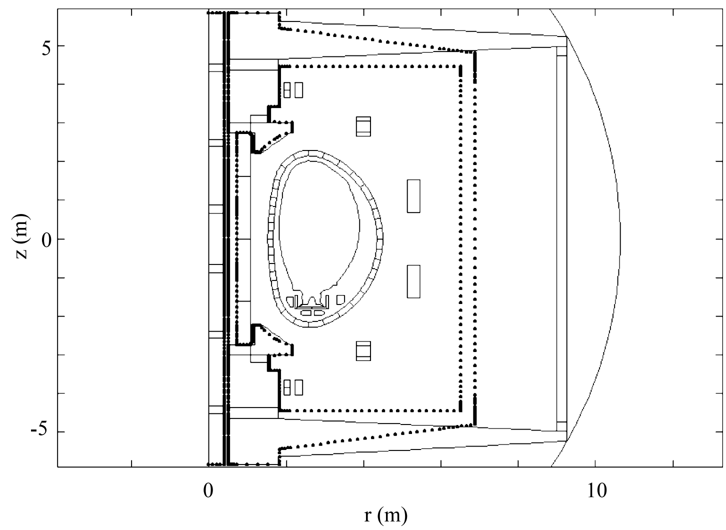

Fig. 1. Equivalent 2D axisymmetric models of JET magnetic circuits: model used before (solid line) vs. geometry used in the present study (dotted line).

3. JET plasma response model for shape control

In [1] the plasma was supposed to have a linear response to the PF circuit currents I, to the plasma current I_p, to the poloidal beta β_p, and to the internal inductance l_i. This approximation is not acceptable in the presence of large excursions of the plasma current, because for instance the effect of a poloidal beta drop is amplified by the plasma current. In an air core tokamak, it is reasonable to assume the geometric quantities (e.g. the plasma/wall gaps G) to have a linear response on I/I_p, β_p, and l_i. The same treatment can be made for all magnetic quantities scaled by the plasma current (e.g. for the measured fields B_{pol}, etc.):

$$dG = C_G d(I/I_p) + F_G d[\beta_p, l_i]^T \quad (1)$$

$$d(B_{pol}/I_p) = C_B d(I/I_p) + F_B d[\beta_p, l_i]^T \quad (2)$$

However, due to the presence of the iron core with associated magnetization currents, we prefer to take a slightly different linear model:

$$d(G\, I_p) = C_G d[I^T, I_p]^T + F_G d[\beta_p I_p, l_i I_p]^T \quad (3)$$

$$d(B_{pol}) = C_B d[I^T, I_p]^T + F_B d[\beta_p I_p, l_i I_p]^T \quad (4)$$

where the additional column of the output matrices multiplying dI_p takes account of the iron magnetization. For an air core tokamak this column is rigorously zero, because multiplying all currents I and I_p by an arbitrary factor, the field is multiplied everywhere by the same factor, therefore, both the equilibrium and the shape of the flux lines are not altered. This is not true for an iron core tokamak because the relationship between field and currents is not linear.

The shape and current control oriented model assumed the ten PF circuit currents and the plasma current I_p as state variables, taking as input quantities the applied voltages (or, alternatively, the circuit currents) and the time behaviors of the two quantities $\beta_p I_p$ and $l_i I_p$. The simulated open loop response of plasma shape and magnetic measurements resulted to be in excellent agreement with the experimental measurements in various plasma shots after assuming a correct interpretation of JET signal BETAP2 (Fig. 3):

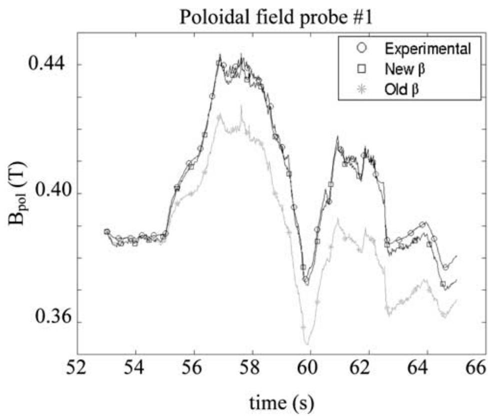

Fig. 3. Magnetic measurements in shot #52310. Comparison between experimental values and the simulations obtained assuming BETAP2 = β_{pol} (CREATE definition) and BETAP2 = $\beta_{pol} l_i$ (JET definition) with models linearized at t = 58 s.

$$\mathrm{BETAP2} = \int p\,dV/(\mu_0 R I_p^2/2) \quad (5)$$

which corresponds to the product $\beta_p l_i$, (assuming the definition of poloidal beta and internal inductance used in the CREATE-L code).

The agreement on the open loop simulations is noteworthy, as in most cases the separate contributions to the output signals are more than one order of magnitude higher than the difference between simulation and experiment. Therefore, the model looks adequate enough to allow closed loop control of the plasma shape, because the terms of the *C* and *F* matrices appear to be calculated with a good accuracy, otherwise the cancellation errors would be dramatically worse.

4. Growth rate prediction

For the design and the assessment of the vertical stabilization system, a model was set up including the eddy currents in the passive conductors (vessel and Mark II structure) as state variables, simulating the open loop growth rate of the vertical instability [5].

Some tests have been made against the experimental data available for vertical displacement events in the absence of feedback control. It was found that the saddle currents in the rigid sectors

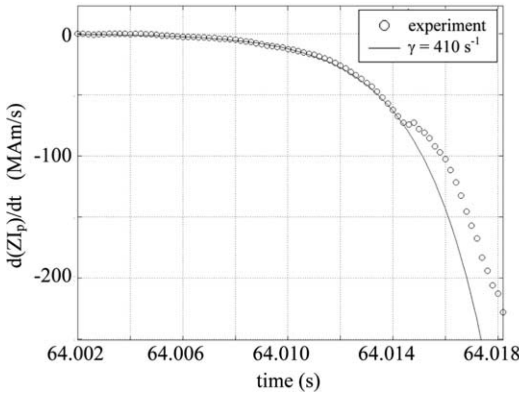

Fig. 4. Pulse #54283. Time behavior of the plasma current moment vertical speed $d(ZI_p)/dt$ during a VDE, compared with an exponential fit with a growth rate of 410 s^{-1}. The fit is excellent until $t = 64.0142$ s (corresponding to a vertical displacement of about 12.5 cm, probably sufficient to hit the wall).

of the vacuum vessel slow down the vertical instability of elongated plasmas by a factor of 2. The growth rate prediction was calculated within an accuracy of less than 5% in various JET pulses. The model could also predict the vertical velocity when the plasma hits the wall (Fig. 4).

After a comprehensive series of tests, which should also include closed loop simulations, the model might be used to provide a reliable test bed for assessing the performance of the enhanced vertical control system.

5. Conclusions

The main results of this analysis are that:

– a good axisymmetric model of the iron is obtained assuming the correct geometry of the polar shoes, limbs and legs;
– it is possible to reliably predict the growth rate of the vertical instability of an elongated JET plasma taking into account the effect of saddle currents induced in the vacuum vessel;
– the model provides a reliable base for the design and the assessment of a new current, shape and position control system in JET.

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