Analysis of disruptions including nonlinear and 3D effects

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Abstract

In this paper we use a novel mathematical and numerical formulation able to couple a non-linear axisymmetric plasma evolution with eddy currents evolution in the three-dimensional structures surrounding the plasma region. Several validations and test cases are presented, suggesting the potential of the method in the analysis and study of events like disruptions.

Introduction

The high performances of future nuclear fusion devices require a special care in their design. In this sense, the electromagnetic interactions between the plasma and the three-dimensional structures play a crucial role. Firstly, this interaction intervenes in the so-called magnetic control including the breakdown phase, the active and passive control of MHD modes (e.g. vertical instability, Resistive Wall Modes, ELMs, etc.) or scenario evolution (shape control, plasma current ramp-up and ramp-down, etc.). Another example in this respect is represented by the plasma disruption events. The sudden loss of the magnetic confinement leads to the release of the plasma magnetic energy on the structures surrounding the vacuum region resulting in significant electromagnetic forces and thermal loads, which in turn may have a significant impact on the operational lifetime of several components. Several numerical modelling approaches are available for the analysis of these events, but they cannot be applied to all cases of interest due to their limitations and range of applicability. In this paper we use a computational tool, the CarMa0NL code, which can treat self-consistently a nonlinear evolution of an axisymmetric plasma in presence of three-dimensional conductors surrounding the plasma. Such code can be used to carry out a comprehensive study of events in which both nonlinear effects in the plasma and three-dimensional effects come into plays simultaneously, disruptions in particular.

Formulation

With reference to Fig.1, the mathematical model is:

$$L\psi = j_\varphi(\psi) \text{ in } \Omega, \; \psi|_{\partial\Omega} = \hat{\psi} \tag{1}$$

where ψ is the magnetic flux per radian, L is the Grad-Shafranov operator [1] and $j_\varphi(\psi)$ is the toroidal density current in the plasma region [2], depending nonlinearly on ψ.

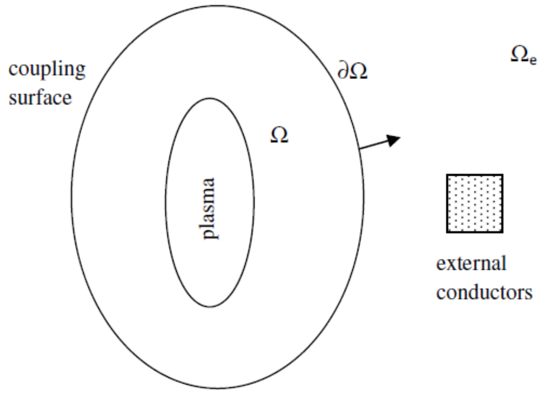

Figure 1: *Reference geometry*

The unknown quantity ψ can be expressed as $\hat{\psi} = \hat{\psi}_p + \hat{\psi}_e$, where the suffix "*p*" (resp. "*e*") indicates the contribute of plasma current inside Ω (resp. external currents in Ω_e). Developing the weak formulation of (1), giving a 2D finite elements discretization of Ω and using the Galerkin method, (1) becomes [3]:

$$\underline{\underline{A}}\,\underline{\psi} = \underline{g}(\underline{\psi}, \underline{s}, \underline{w}) - \underline{\underline{\hat{A}}}\,\underline{\hat{\psi}} \tag{2}$$

with the vector quantity $\underline{g}(\underline{\psi}, \underline{s}, \underline{w})$ linked to the toroidal density current in Ω which depends on the numerical vector of nodal fluxes $\underline{\psi}$, $\underline{s}$ is a parameter depending on the total plasma current and $\underline{w}$ is a set of profile parameters determining the plasma internal inductance l_i and poloidal β_p; $\underline{\underline{A}}$, $\underline{\underline{\hat{A}}}$ are suitable stiffness matrices. The "plasma" and "external" contributions to $\underline{\hat{\psi}}$ can be written as [3]:

$$\underline{\hat{\psi}}_p = \underline{\underline{K}}\,\underline{g}(\underline{\psi}, \underline{s}, \underline{w}) \tag{3}$$

$$\underline{\hat{\psi}}_e(\underline{\psi}, \underline{s}, \underline{w}) = \underline{\underline{Q}}\left(\underline{\underline{L}} + \Delta t\,\underline{\underline{R}}\right)^{-1}\left[\underline{b} - \underline{\underline{K}}'\,\underline{g}(\underline{\psi}, \underline{s}, \underline{w})\right] \tag{4}$$

where $\underline{\underline{K}}$, $\underline{\underline{K}}'$ and $\underline{\underline{Q}}$ are suitable matrices coming from Biot-Savart integrals, $\underline{\underline{L}}$ and $\underline{\underline{R}}$ are matrices representing 3D structures, $\underline{b}$ is a known term and Δt is the time step.

Assuming known in time the quantity $\underline{w}$, (2)-(4) constitute a self-consistent system adding another equation specifying the time evolution of the total toroidal plasma current. The CarMa0NL code solves the resulting system of equations via Newton-Raphson method.

Model Validation and Applications

We report some examples of application of the CarMa0NL code to the ITER tokamak. The reference equilibrium configuration is defined by plasma current I_p=15 *MA*, poloidal beta $\beta_p=0.595$, internal inductance $l_i=0.795$, position of current centroid (R_C,Z_C) = (6.293,0.566) m. The plasma region is discretized with a 2D triangular mesh made of 8162 nodes (coinciding with the number of non-linear equations solved for each time step), while the trace of the coupling surface consists of 309 nodes just outside the vacuum chamber and not crossing external conductors.

2D Validation

We consider a set of three-dimensional conductors, which reproduce an axisymmetric situation: in this way, it is possible to compare the results of CarMa0NL with the axisymmetric linearized code CREATE_L [4]. Here we consider the event in which there is an uncovered instantaneous I_p drop of 2 MA, keeping β_p and l_i almost constant (Figure 2 and Figure 3). The agreement with CREATE_L is satisfactory until the divertor-to-limiter transition occurs, which is intrinsically non-linear.

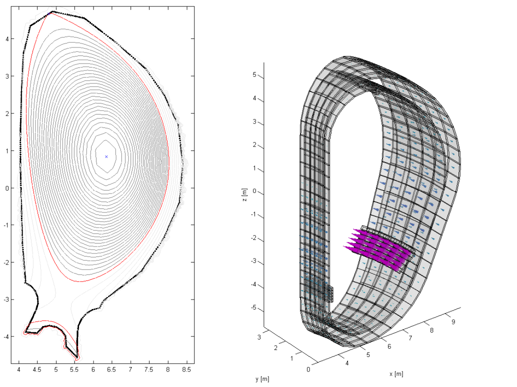

Figure 2: *Plasma configuration and current density in the structures at t = 0.15s*

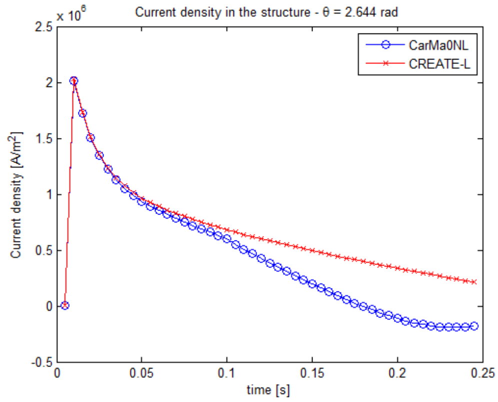

Figure 3: *Current density behavior in the inner shell of the vessel. At t=100ms the plasma hits the wall, switching from diverted to limiter configuration.*

3D Effects

With reference to the same event, we introduce more detailed 3D description of the conductive structure of ITER (Fig. 4). The mesh includes the vessel shells, the ribs, the outer triangular support, the copper cladding, the port extensions, the axisymmetric in-vessel coils with a total of 6645 hexahedral volumetric elements, giving rise to 7712 three-dimensional degrees of freedom. The mesh spans 20° in the toroidal direction; with a mirror symmetry condition at the center of the port plus 9 rotation symmetries, the whole torus is taken into account. Fig. 4 and 5 report some details.

Disruption

We apply the CarMa0NL code to a disruptive event imposing the time behaviour of I_p. shown in Fig. 6. This scenario is similar to the so-called slow-fast disruptions in ITER. Halo currents are not included, since they are not allowed in the present version of the formulation. Fig. 7 and Fig. 8 show a comparison of plasma centroid evolution, with a 3D and a 2D mesh, to highlight the differences.

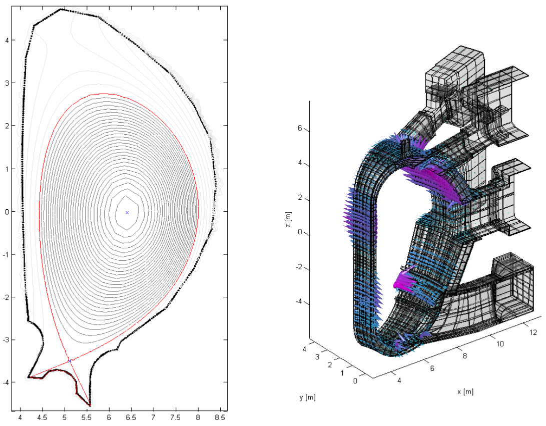

Figure 4: *Sample plasma configuration and current density distribution, just before divertor-to-limiter transition*

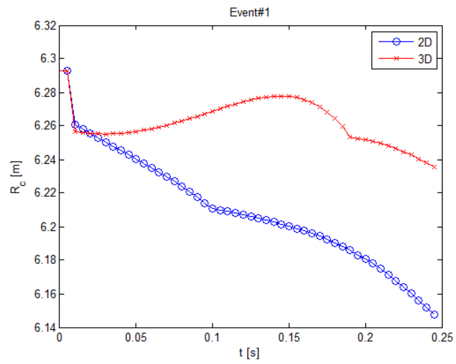

Figure 5: *Comparison of plasma current centroid radial position in 2D and 3D cases*

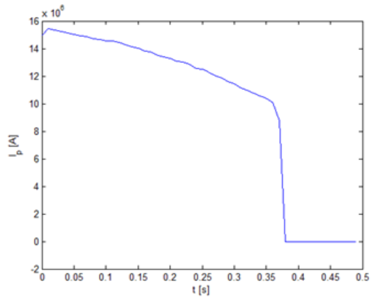

Figure 6: *Slow-fast disruption (time behaviour of plasma current)*

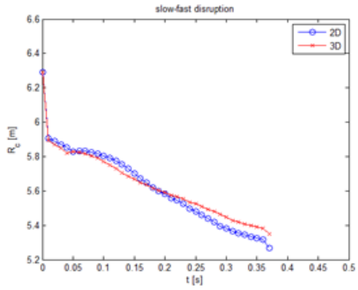

Figure 7: *Comparison of plasma current centroid evolution in 2D and 3D cases, for slow-fast disruption (r-coordinate)*

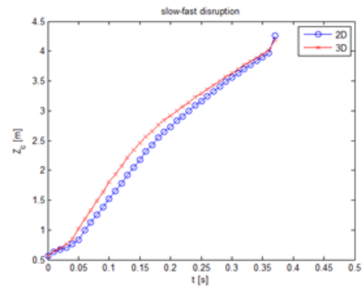

Figure 8: *Comparison of plasma current centroid evolution in 2D and 3D cases, for slow-fast disruption (z-coordinate).*

Several points will deserve further attention in future activity. We will introduce halo currents, to make the results even more relevant for disruption analysis, and we will compute forces acting on 3D structures following such events. The inclusion of ferromagnetic materials will be pursued. We will also apply the code to other existing and future devices, like JET and DEMO.

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