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3D effects of conducting structures on RWMs control in ITER

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Abstract

The CarMa code, a self-consistent coupling between the MHD code MARS-F and the 3D eddy currents code CARIDDI, is applied to ITER geometry for the evaluation of the effects of 3D conducting structures on Resistive Wall Modes (RWM) control.

Introduction

Eddy currents induced by plasma perturbations in a conducting, nearby wall have a stabilizing effect with respect to ideal, pressure driven external kink modes and they increase the maximum achievable β_N in tokamaks. Since eddy currents decay due to the finite conductivity of the surrounding wall, the resulting resistive wall modes (RWM) grow on a time scale of the order of the wall time. In present and future devices, non-axisymmetric coils can be used to actively stabilize such modes.

To study this class of instabilities it is of paramount importance to model accurately the 3D electromagnetic features of the conducting structures surrounding the plasma, as well as those of the feedback control coils. To this purpose, we have coupled the MHD code MARS-F [1] and the 3D eddy current code CARIDDI [2], via a novel coupling procedure [3] that allows a rigorous and self-consistent treatment of any three dimensional conducting structure. A similar coupling procedure was already successfully implemented for the vertical (*n=0*) plasma instability [4] and the resulting state-space model is formally analogous to the *n=0* case [5], hence allowing an extension to RWM analysis of well established concepts and techniques. Several open and closed loop simulations performed for ITER are presented, showing a strong influence of the 3D features of the conducting structures (e.g. ports, saddle coils etc.) that can affect the controllability of high pressure plasmas.

1. The computational model

MARS-F [1] solves the single fluid MHD equations, including the effects of plasma rotation using various damping models to approximate the ion Landau damping [6]. The code has been extensively used in the past to predict the critical rotation speed required to stabilize the RWM, as well as to model the resonant field amplification experiments on JET and DIII-D. Another feature is the presence of feedback coils, which have been used for RWM studies on several devices including ITER [7]. The main limitation of the code is the 2D representation of the conducting structures, including the vacuum vessels and the feedback coils, since the code assumes exp(j n φ) dependence for the n-th harmonic along the toroidal angle φ. Also, a thin wall approximation is assumed for the wall along the radial coordinate.

CARIDDI is a 3D time-domain eddy currents finite elements code based on an integral formulation [2]. It requires a finite elements discretization only of the conducting structures and allows an easy coupling with external feeding systems [8]. The introduction of a two-component electric vector potential and the use of edge elements give rise to a very accurate (imposing the right continuity conditions) and effective (requiring a minimal number of unknowns) code.

The CarMa computational tool self-consistently couples the two aforementioned codes. The coupling strategy is as follows; more details can be found in [3].

The main assumption made is to neglect plasma mass. This is a good approximation as long as the time scale of interest (the RWM growth rate) is much slower than the Alfvén time related to plasma inertia (typically microseconds). Doing so, the plasma response to a given input is instantaneous. A surface S is chosen, in between the plasma and the conducting structures, through which the plasma/structures interaction can be decoupled as follows.

- The plasma (instantaneous) response to a given magnetic flux density perturbation on S is computed as a plasma response matrix, which contains the dynamics of all (unstable and stable) eigenmodes;
- Using such plasma response matrix, the effect of 3D structures on plasma is evaluated by computing the magnetic flux density on S due to 3D currents;
- The currents induced in the 3D structures by plasma are computed via an equivalent surface current distribution on S providing the same magnetic field as plasma outside S.

The overall plasma response model can be recast in state-space form [3]:

$$\begin{aligned} \frac{d\underline{I}}{dt} &= \underline{\underline{A}}\,\underline{I} + \underline{\underline{B}}\,\underline{V} \\ \underline{y} &= \underline{\underline{C}}\,\underline{I} \end{aligned} \tag{1}$$

where $\underline{I}$ is the vector of discrete currents in the 3D structure (state vector), $\underline{V}$ is the vector of control coil voltages (input vector), $\underline{y}$ is the vector of magnetic field perturbations at given measurement points and $\underline{\underline{A}}$, $\underline{\underline{B}}$, $\underline{\underline{C}}$ are the dynamical, input and output matrices respectively.

2. Results

First of all, we verify the correctness of the proposed approach on a fictitious 2D circular case, analysed also in previous works [9]; this allows us to use the results of MARS-F with n=1 as reference. The plasma major radius is R_0 = 2 m, the minor radius is a = 0.4 m; the vessel has a minor radius of 1.3*a, a thickness of 1 cm, and a resistivity equal to 6.53e-7Ωm. Giving a 3D mesh of the axisymmetric vessel, we were able to compute the eigenvalues and eigenfunctions of the dynamical matrix (1), and to compare these quantities with the corresponding results of pure MARS-F calculations. Table 1 and Figure 1 show the very good agreement on the unstable eigenvalues and eigenfunctions; a similar positive comparison holds also for the other stable modes. The CarMa computations were carried out with two different coupling surfaces (located at 1.1*a and 1.2*a), providing very similar results.

Then, we applied the CarMa code to the ITER geometry. A cross-check with pure MARS-F results on a fictitious 2D case gave a similar agreement as in the previous circular example.

Figure 2 reports the cross section of the double shell and the overall mesh with six non-axisymmetric coils for RWM control and pure holes to represent the ports. Table 2 reports the RWM growth rate for different (non-optimized) equilibria, showing that the 3D geometry can increase the growth rate of a factor above 2. In the highest pressure case, the CarMa code predicts a fictitiously stable system, since the growth rate is on the time scale related to plasma mass which is neglected in the present approach.

MARS-F [s^{-1}]	Coupling surface 1 [s^{-1}]	Coupling surface 2 [s^{-1}]
292.7	291.2 ± j 3.6e-4	293.3 ± j 7.5e-4

Table 1. Unstable eigenvalues for the 2D circular case.

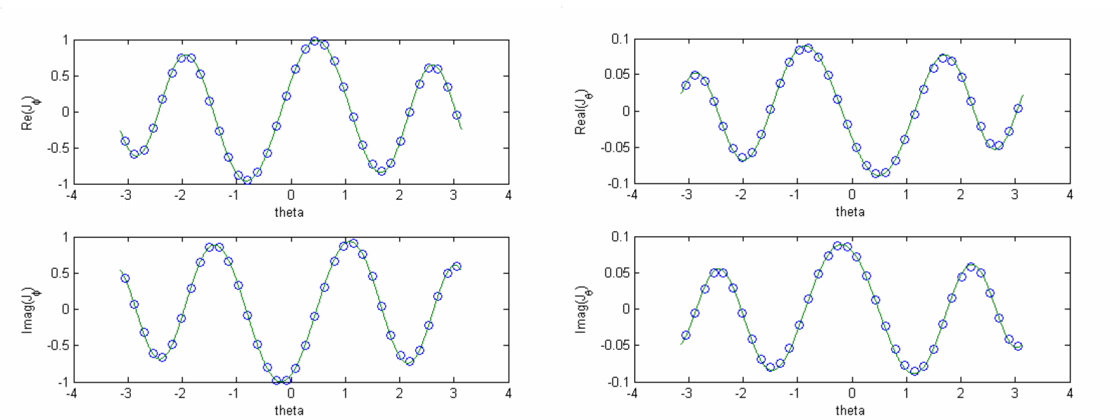

Figure 1. Unstable mode comparison for the circular case (solid: MARS-F; circles: CarMa). The toroidal and poloidal current densities are reported as a function of poloidal angle, after normalization to the maximum of the toroidal component.

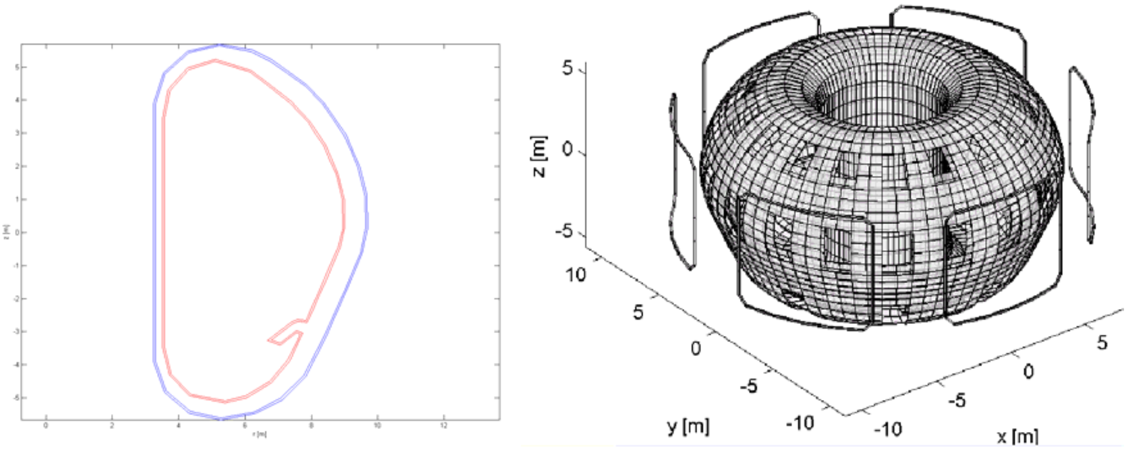

Figure 2. ITER cross-section and 3D mesh.

Equilibrium	*2D results [s^{-1}]*	*3D mesh [s^{-1}]*
β_N=2.87,C_β=0.35	5.36	9.12 ± j 0.44
β_N =3.17,C_β=0.60	20.9	40.3 ± j 1.38
β_N =3.33,C_β=0.73	42.5	97.0 ± j 2.75
β_N =3.48,C_β=0.86	117	N.A.

Table 2. 3D effects on the growth rate for different equilibria

3. Conclusions

The CarMa code has been applied to ITER geometry to self-consistently analyse the effects of 3D conducting structures to RWM evolution and control. The results show a significant influence of the 3D features on RWM controllability, hence calling for a deeper analysis with even more realistic assumptions on the geometry (e.g. including the tubular extension of the ports, the blanket modules, etc.) and with special emphasis on active control. This work was supported in part by CREATE and MiUR under PRIN grant#2006094025.

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