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Inclusion of 3D Effects of Conducting Structures in the Analysis of RWM

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Abstract

In this paper we present some results illustrating the convergence properties of a weak coupling between the MHD stability code MARS-F and the three-dimensional eddy currents code CARIDDI, aimed at the inclusion of the effects of 3D conducting structures in the analysis of Resistive Wall Modes.

1. Introduction

The maximum normalized β_N achievable in tokamaks is limited by ideal external kink instabilities of low $n \neq 0$ toroidal mode numbers. This limit can be mitigated by eddy currents induced by plasma perturbations in a stabilizing conducting wall. Such eddy currents decay due to the non-vanishing resistivity of any real wall. Hence, the resulting Resistive Wall Modes (RWMs) grow at the time scale of the wall time. In actual and future devices, this time scale is long enough to allow an active stabilization of such modes with saddle coils providing a suitable magnetic field. As a consequence, it is fundamental to give a correct description of the three-dimensional conducting structures (walls) surrounding the plasma, and of the feedback coils.

To this purpose, recently [1] the toroidal stability code MARS-F [2] and the three-dimensional magneto-quasi-static code CARIDDI [3] have been successfully coupled. In [1] only the consistency of the proposed coupling scheme was demonstrated, while its convergence was still an open issue. Aim of this paper is to describe some results illustrating the convergence of a weak coupling scheme between the two codes, with the final goal of analysing Resistive Wall Modes in the presence of 3D conducting structures.

The paper is organized as follows. Section 2 briefly describes the formulations used by MARS-F and CARIDDI, and the basic idea of the weak coupling scheme. In Section 3 some results are presented, while Section 4 draws the conclusions and illustrates perspectives and future work.

2. Formulation

MARS-F is an extension of the stability code MARS [4], that solves the single fluid MHD equations. This code has been modified to study stabilization of the RWM by plasma rotation [5, 6], using various damping models to approximate the ion Landau damping. Another extension is the addition of feedback coils [2], thus allowing feedback control of the RWM to be studied by solving both MHD equations and the feedback equation in a single code.

MARS-F has been used 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, and also for numerical simulation of RWM in ITER [7].

One limitation of the code is the 2D representation of the conducting structures, including the vacuum vessels and the feedback coils, described assuming a exp(jnφ) dependence for the n-th harmonic along the toroidal angle φ. Also, a thin wall approximation is made for the wall along the radial coordinate and a Fourier representation of the feedback coils along the poloidal angle is given.

CARIDDI is a 3D eddy currents finite elements code based on an integral formulation [2], hence requiring a discretization only of the conducting structures and allowing an easy coupling with external circuitry [8]. The introduction of a two-component electric vector potential and the use of edge elements allows the imposition of the right continuity conditions with a minimal number of unknowns. CARIDDI has been extensively used for fusion applications, also coupled with the CREATE-L 2D linearized plasma response model [9].

The overall system of equations can be symbolically written as [4]:

$$Ax = \gamma Bx \tag{1}$$

where x represents the unknowns, γ is the growth rate and A and B are suitable linear operators (matrices once discretized). The eigenvalue problem (1) is solved using the inverse iteration scheme:

$$(A - \gamma_0 B)x_{n+1} = Bx_n, \qquad \gamma_{n+1} = \gamma_0 + \alpha_{n+1}, \quad \alpha_{n+1} = \frac{x_{n+1}^* x_n}{x_{n+1}^* x_{n+1}} \tag{2}$$

where γ_0 is a suitable starting guess. This system can be split in a "plasma" part (p are the plasma unknown quantities) and an "external" part (e are the unknown currents in the wall):

$$\begin{cases} (A_{pp} - \gamma_0 B_{pp})p_{n+1} + (A_{pe} - \gamma_0 B_{pe})e_{n+1} = B_{pp} p_n + B_{pe} e_n \\ (A_{ep} - \gamma_0 B_{ep})p_{n+1} + (A_{ee} - \gamma_0 B_{ee})e_{n+1} = B_{ep} p_n + B_{ee} e_n \end{cases} \tag{3}$$

The first set of equations are those solved by MARS-F, while the second one are those of CARIDDI. Instead of inverting system (3) as such, the weak coupling scheme consists of inverting the diagonal blocks only, making simplifying estimations of the off-diagonal blocks, on the basis of previous iterations. In this way, each of the two codes can be run separately, solving its own set of equations assuming the results of the other code as inputs, thus minimizing the modifications required.

The coupling terms in (3) are computed by means of equivalent shell currents on a suitable coupling surface placed in between the plasma and the wall, providing the same magnetic field of wall currents on plasma and vice-versa.

3. Results

We consider a circular plasma with a major radius R_0 = 2 m and a minor radius a = 0.4 m, surrounded by a circular axisymmetric vessel, described by CARIDDI with a fully 3D mesh (see Fig. 1, where a typical current density pattern is also reported); this allows us to use the results of MARS-F as reference. The vessel has a minor radius of 0.52 m; its thickness is 1 cm, while its resistivity is 6.53e-7 Ω m.

The results presented in [1] demonstrated the consistency of the coupling scheme. Here, we study its convergence. Fig. 2 shows the behaviour of the estimated growth rate (normalized to the Alfvèn time τ_A = 1 μs) as a function of iteration number, starting from an initial guess γ_0 = 250 s^{-1}. Evidently, the scheme is able to converge to the right value γ = 295 s^{-1} after some iterations. Unfortunately, no convergence was obtained when starting from an initial guess γ_0 = 350 s^{-1}, in which case the procedure spuriously converges to the starting guess.

4. Conclusions and perspectives

In this paper we have presented some results illustrating the convergence properties of a weak coupling scheme of the MARS-F stability code with the CARIDDI three-dimensional eddy currents code. This coupling scheme has been demonstrated to be convergent if a suitable starting guess has been chosen. This conclusion, together with the relatively slow convergence observed, suggest us to focus on a strong coupling scheme, in which no approximations are made in the resolution of the overall system of equations. This approach is presently under investigation.

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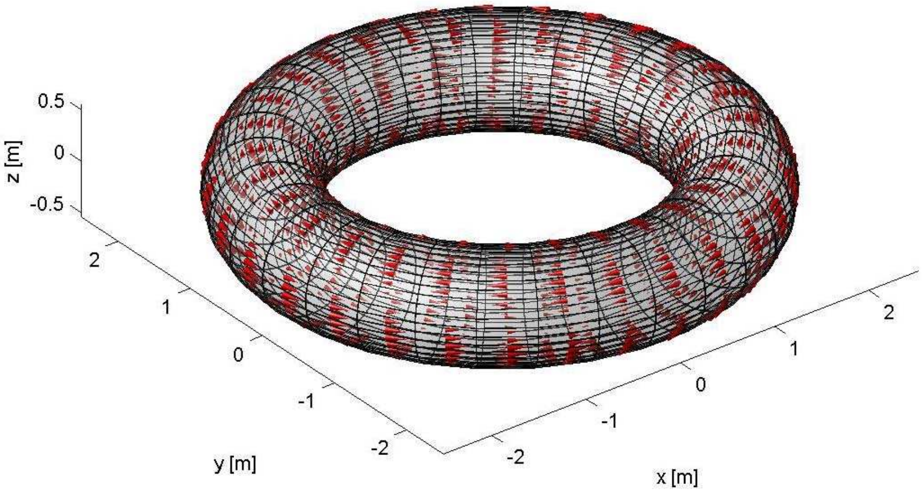

Figure 1. 3D view of the vessel mesh and current density (imaginary part)

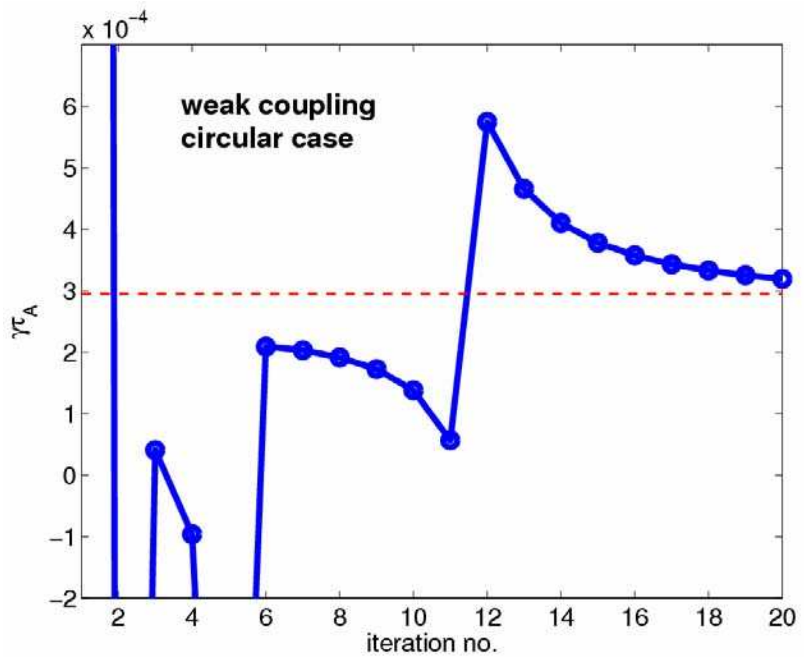

Figure 2. Estimated normalized growth rate: the dashed line represents the reference value

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