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RWM analysis with 3D conductors, plasma flow and kinetic damping

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Resistive Wall Modes (RWM) often set performance limits to advanced scenarios of present and future fusion devices (e.g. ITER). Hence, it is fundamental to make reliable predictions on the growth rates of such MHD instabilities, and to carry out the design of suitable stabilization feedback controllers.

In view of both these goals, it is crucial to have accurate numerical models able to describe the evolution of RWM. In this respect, two are the main issues that are currently being actively investigated. The first one is the effect of three-dimensional features of the conducting structures surrounding the plasma, which can be very significant [1]. The second one is the mode damping physics resulting from the plasma flow and the drift kinetic resonance effects [2].

The CarMa code [3] is able to take rigorously into account a detailed 3D volumetric description of the conductors geometry. However, it makes the assumption that no plasma flow is present, the plasma mass is disregarded and no kinetic damping is taken into account. In this paper we present an enhancement of such code, aimed at including the aforementioned effects. From the theoretical point of view, this changes qualitatively the properties of the plasma response, which is no longer static. To take this into account, two different approaches are proposed and compared, each with distinctive advantages and drawbacks: the first one along the line proposed in [3] ("forward" coupling), the other according to an alternative path as described in [4] ("backward" coupling).

The resulting upgraded CarMa code allows, for the first time to our knowledge, a rigorous analysis of RWM with simultaneous inclusion of volumetric 3D conductors and MHD-kinetic hybrid description of the plasma.

The CarMa code: "forward" and "backward" procedure

The "backward" coupling scheme [4] consists of the following two steps. First, we run the eddy current code to compute the response of 3D structures to a given coil current (the 3D coil geometry, such as finite extensions and gaps along the toroidal angle, complicated coil winding in some cases, also enters into the field computation), and to a set of unit perturbations from the plasma itself. The unit perturbations from the plasma are defined on the coupling surface, and represented by an equivalent surface current perturbation, defined on the same coupling surface. In other words, the plasma response field, outside the coupling surface, is completely represented by the field generated by the equivalent surface current [3]. At the second step, we compute the normal and the tangential components of the *total* perturbed field, defined on the coupling surface and composed of contributions from the plasma (the equivalent surface), the 3D eddy currents from 3D structures, and the coil current. A matrix-based, linear (w.r.t. the eigenvalue) relation between the field components and the coil current can then be formed and used as the boundary condition for the MHD code, in order to carry out the stability, RFA response, or feedback computations. The coupling surface serves the computational boundary of the final MHD problem, with inertial, flow, and kinetic effects included.

The "forward" coupling scheme is an extension of the method proposed in [3], where plasma flow and mass are neglected and no kinetic damping is considered; as a consequence, the resulting plasma response matrices are static, i.e. do not depend on the frequency of the excitations used to compute them. Conversely, here we remove such hypotheses, hence allowing the effects of plasma mass, flow and damping to come into play. To this purpose, all the quantities involved in plasma response matrix computation are allowed an arbitrary variation with the complex Laplace variable *s*. This dependence is approximated by means of a suitable matrix-based Padé fit – in the present paper, for the sake of simplicity we use a 1st order approximation, although theoretical considerations [4] suggest that a higher order would be preferable. In the end, the system is recast in state-space form, in which the dynamical matrix (and hence the RWM eigenvalues and eigenvectors) depend on the Padé fit.

Examples of applications

A plasma with a circular cross-section has been considered, circumvented by a conformal conducting vessel; the details of the configuration are reported in [3]. First of all, we report some results of the backward coupling procedure. Figure 1 compares the

RWM eigenvalues versus the plasma rotation frequency, assuming either the parallel sound wave damping or the drift kinetic damping model. A 2D complete wall is used. In this case we run both MARS-K to compute the mode stability directly, and the CarMa code with the backward coupling procedure. As expected, two codes give almost identical results, for both the mode growth rates and the mode frequency. These results benchmark the CarMa code with backward coupling.

Figure 2 compares the computed RWM eigenvalue with two different 3D wall models, and with a self-consistent drift kinetic damping model. The 3D wall model B has more holes than the wall model A. The computed RWM is more unstable with more holes in the wall, through the whole range of the rotation frequency considered here. 3D walls also enhance the mode rotation with respect to the wall. It is interesting to notice that the kinetic effects (thermal particle precessional drift resonances with the mode in this case) occur strongly at very slow rotation frequency for all wall models. This frequency range agrees with that of the thermal particle precession drift frequency. For this specific example, the drift kinetic effects can bring a full stabilisation of the mode at vanishing plasma rotation.

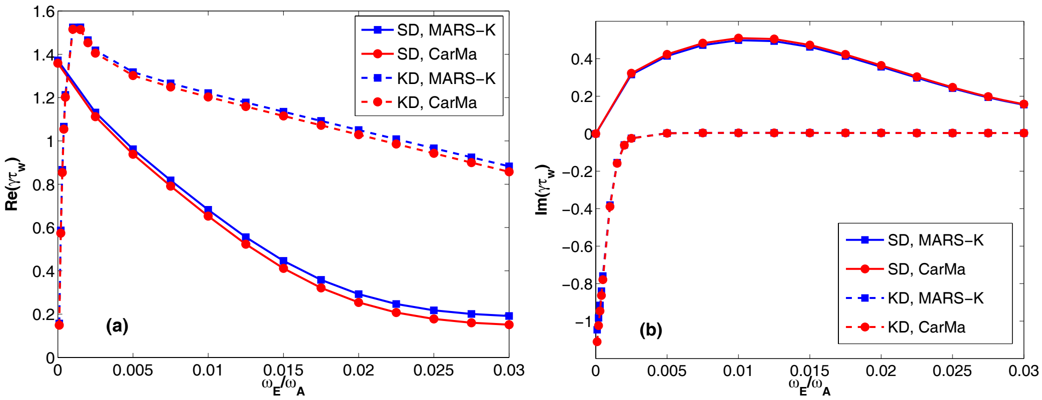

Fig.1. Benchmark CarMa with backward coupling, with MARS-K, with a 2D wall.

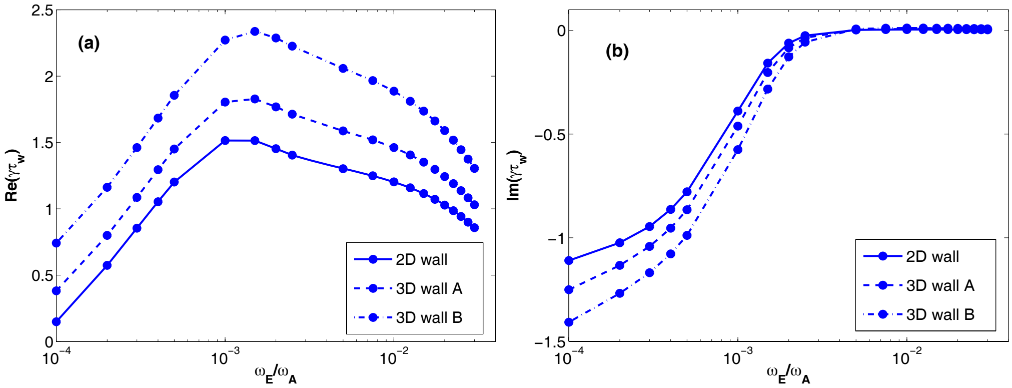

Fig.2. Effect of 3D walls on the RWM eigenvalue, with a drift kinetic damping model.

For the forward coupling procedure, first of all we consider a case with no plasma flow. A scan in the plasma resistivity of the vessel, assumed as axisymmetric (although described by a 3D mesh), has been carried out; in the limit of infinite resistivity, the no-wall growth rate of the ideal kink mode must be recovered, which obviously depend on plasma mass and hence on dynamical effects. Fig. 3 reports the growth rate as estimated by the forward procedure and MARS-F. We also report the estimate of static CarMa results, which obviously do not take dynamical effects into account, producing unacceptable results.

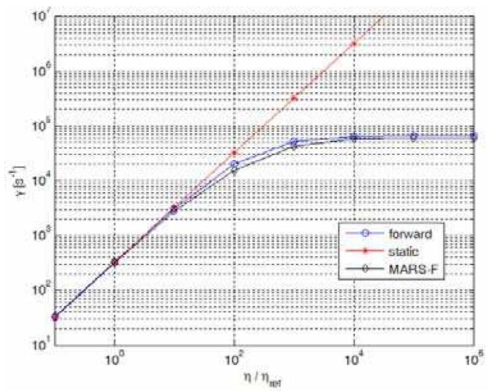

Fig. 3. Resistivity scan – no damping.

Other computations have been carried out, including plasma flow and various kinetic damping models and/or considering a 3D geometry obtained including holes in the vessel. Fig. 4 and Table 1 report the main results. In particular, in Fig. 4 we notice that the agreement on the real part of the unstable eigenvalue is excellent, while the imaginary part suffers from the limited quality of the first order Padé fit.

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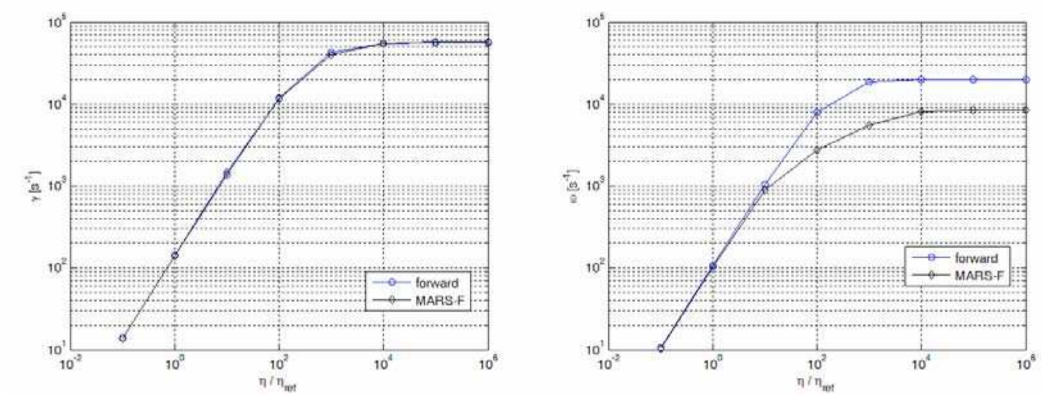

Fig. 4. Resistivity scan – 2D wall – sound wave damping case.

Damping	Ω_E/Ω_A	*Geometry*	*CarMa* $\gamma\,[s^{-1}]$	*Ref.* $\gamma\,[s^{-1}]$
Sound wave	1e-2	2D	138 + 104 i	140 + 103 i
Sound wave	1e-2	3D	199 + 166 i	195 + 165 i
Drift kinetic	2e-4	2D	119 – 208 i	121 – 202 i

Table 1. Estimated unstable eigenvalues (both real part and imaginary part). The reference values are from MARS-F in 2D cases and from backward coupling procedure for 3D cases.