ITER passive and active RWM analysis with the CarMa code

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Abstract

We use the CarMa code to analyse RWM evolution using the latest ITER conducting structures, including vessel with ports, in-vessel coils and thick blanket modules. Both open-loop ("passive" analyses) and closed-loop ("active" analyses) are carried out, highlighting the effects of 3D geometrical details (holes, ports, extensions, thick blanket modules). Whenever needed, we use fast/parallel computational techniques to make the computations affordable.

Introduction

The steady-state advanced scenario in ITER aims at plasmas with high pressure and high fraction of bootstrap current, in order to achieve higher fusion power production and steady-state operation. Both requirements lead to a high value of the normalized beta, normally exceeding the Troyon no-wall beta limit for the ideal external, pressure-driven kink mode. Consequently, the resistive wall mode (RWM) (a mode growing on a time scale of resistive diffusion in conducting structures surrounding the plasma), is unstable; the steady-state operation hence requires this mode to be controlled.

The objective of this work is to perform an as realistic as possible analysis of the RWM for ITER, with the latest geometry of the active control coils and passive conducting structures. To this purpose, we use the CarMa code [1], which is able to provide a model of the RWM evolution in the state space (hence quite convenient for feedback controller studies [2]), including very detailed models of the conducting structures [3].

Open-loop analyses

We consider the latest available geometry for the ITER passive structures; Fig. 1 shows a cutaway of the overall mesh, which spans 360° in the toroidal direction. In red we show the in-vessel ELM coils which are used here for RWM control. The plasma equilibrium is a Scenario-4 ITER configuration with $\beta_N = 2.94$ and a growth rate around 15 s^{-1} [3].

We have computed the input-output transfer functions between the current in the active coils and the magnetic field measured at various locations around the torus. Specifically, we feed each set (upper, equatorial, lower) of the active coils with a unit n=1 current; due to the discreteness of the coils, this is not equivalent to the imposition of a pure n=1 current pattern, as 2D codes like MARS-F [4] do. Similarly, the magnetic field measured at given spatial points is Fourier-decomposed along the toroidal angle and the n=1 harmonic is considered.
To evaluate the effect of coil discreteness, we compared the transfer function as computed by MARS-F and CarMa for a test plasma configuration, using the same 2D description of the passive conductors – the only intentional difference hence being the representation of the active coils. Evidently, using a measurement point far from the coil the agreement is very satisfactory, while using a measurement point close to the coil (approximately at the center of the coil itself) the differences can be quite significant, even in the static gain.
Using the CarMa code, we were able to quantify the differences in the input-output transfer functions due to various 3D conducting structures, assuming as outputs the reference position of the ITER RWM sensors (six sensors around the torus, located at r=8.916 m, z=0.550 m). In particular, we compared three different cases: Case 1 (2D mesh), Case 2 (3D mesh with ports), Case 3 (3D mesh with ports and thick blankets). The related results are reported in Fig. 3. The overall effect of thick blanket modules can be quite different depending on the quantity of interest, ranging from being rather irrelevant to overcompensating the presence of ports [3].

Closed-loop analyses

In order to keep the computational load to acceptable levels for feedback controller design, a simplified description of the conducting structures has been used, as described in [5]. The active coils, the plasma configuration and the position of output sensors are the same as in the previous section.
First of all, the Best Achievable Performances (BAP) [2] have been computed, i.e. the maximum allowable initial (i.e. at t = 0) perturbations of the magnetic fields measured by the sensors, which is recoverable by any closed-loop feedback controller with currents and voltages inside the saturation limits of the power supplies. To this purpose, we have scanned the maximum available voltage, keeping the same maximum current, as depicted in Table 1. The in-vessel coils are supposed to have 6 turns, and a resistance of 2.6 mΩ each. The results of the BAP analysis are reported in Table 2. Evidently, for voltage saturation levels higher than 36 V, the current saturation provides the most stringent limitation. This conclusion is valid for the configuration under exam, but it may not necessarily be true for plasmas with

higher growth rates, for which a higher available voltage may be advantageous.

In addition, a LQG feedback controller has been designed, with the same technique described in [2]. Each power supply has been modeled as a first order filter with a time constant of 7.5ms, plus an additional delay of 2.5ms. The maximum voltage and current are 144V and 16kA, respectively. The feedback controller is supposed to be based on the vertical field measurement. The performances of this controller are reported in Table 3 and Fig. 4.

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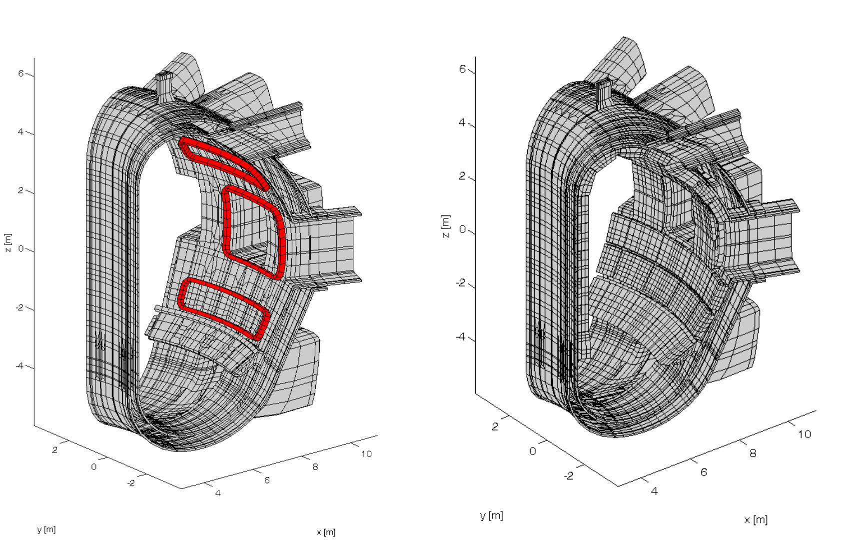

(a) (b)

Fig. 1. Reference ITER geometry (cutaway): (a) vessel with ports: (b) vessel + blanket modules

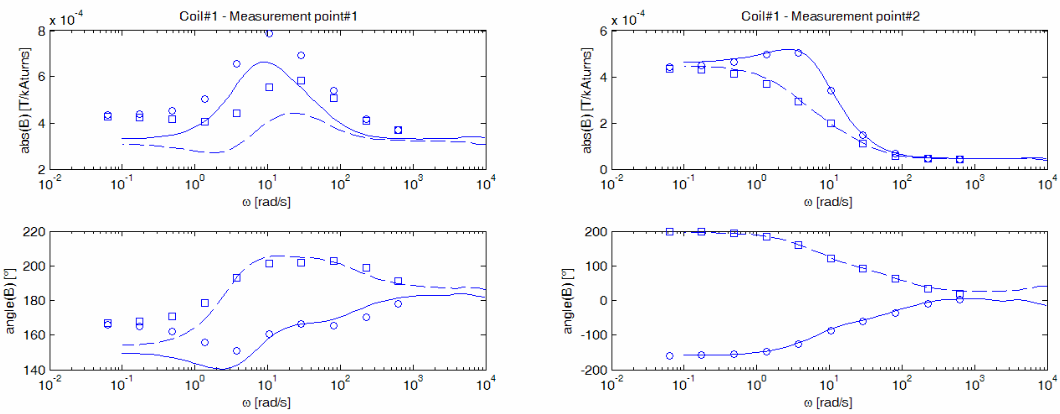

Fig. 2. Transfer function for 2D test case (solid, dashed: MARS-F; circles, squares: CarMa): (a) point close to coil, (b) point far from coil. Both positive and negative frequencies are reported.

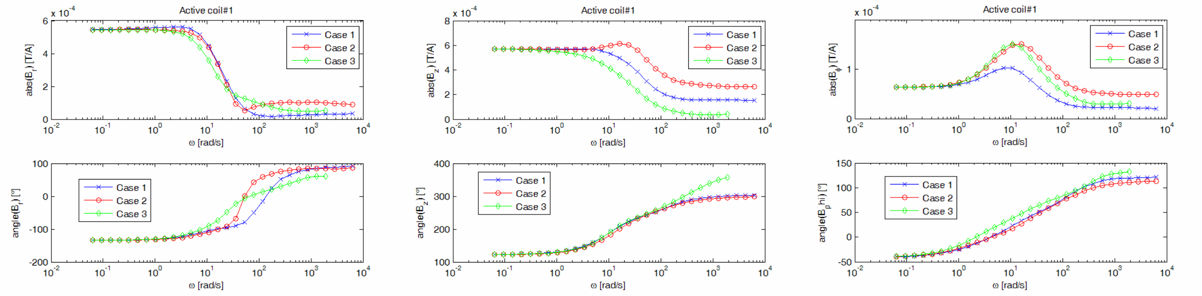

Fig. 3. Transfer function for 3D meshes (only positive frequencies are reported).

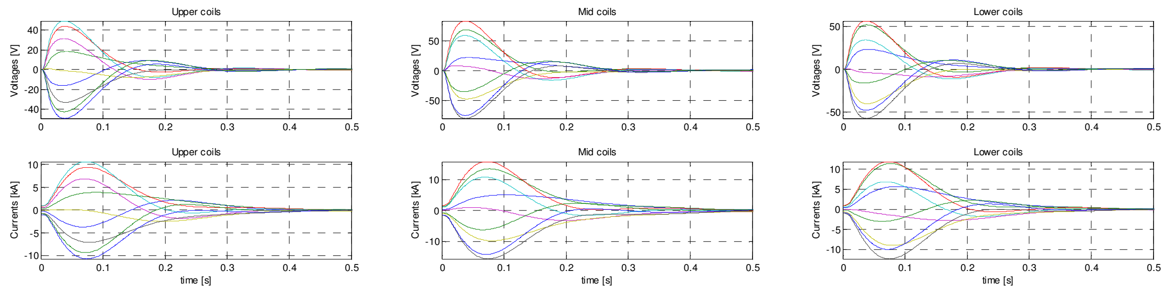

Fig. 4. Currents and voltages in the active in-vessel coils during feedback control of RWM

	V_M (V)	I_M (kA)
Case 1	36	16
Case 2	72	16
Case 3	144	16
Case 4	216	16

Table 1. Cases considered for the evaluation of the BAP.

	Initial Magnetic field perturbation			Maximum field pertubation			Maximum	Maximum
	B_φ (mT)	B_r (mT)	B_z (mT)	B_φ (mT)	B_r (mT)	B_z (mT)	Voltage (V)	current(kA)
Case 1	6.43	22.44	35.92	18.47	56.56	46.92	36.00	13.05
Case 2	7.28	25.41	40.67	28.19	52.75	43.45	72.00	16.00
Case 3	7.54	26.33	42.16	45.33	56.16	43.36	144.00	16.00
Case 4	7.54	26.33	42.16	45.33	56.16	43.36	216.00	16.00

Table 2. Results of the BAP analysis

Initial Magnetic field perturbation			Maximum field pertubation			Maximum	Maximum
B_φ (mT)	B_r (mT)	B_z (mT)	B_φ (mT)	B_r (mT)	B_z (mT)	Voltage (V)	current(kA)
5.34	18.88	27.41	28.43	58.53	36.52	82.63	15.87

Table 3. Results of the closed-loop analysis with a LQG feedback controller