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MODEL-BASED FULL SIMULATOR OF RWM CONTROL SYSTEM IN RFX-Mod

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Introduction

The regular operation of the active control system of MHD modes in RFX-mod has allowed dramatic improvements of the device experimental performances [1]. Up to now Proportional-Integral-Derivative (PID) regulators have been used whose parameters have been mainly fine tuned during the experimental sessions. A model based design approach has been recently developed since it is considered an important step to achieve further progress of the system performances, as well as a key demonstration of ITER-relevant controller design techniques. To accomplish that task, two fundamental advances were found to be necessary: the first was the adaptation of the CarMa code [2] to RFX-mod in order to have a model coupling the relevant MHD physics to a three-dimensional (3D) description of passive and active boundary, and the second was the development of dynamic models of the control system cast in the more convenient state variable representation. As first, non-trivial application of the new integrated tool, closed-loop RWM stability analyses have been benchmarked against experimental data provided ad hoc.

The CarMa model of RFX-mod

A surface S is chosen, in between the plasma and the conducting structures. Neglecting plasma mass, the plasma response to a given magnetic flux density perturbation on S is computed as a plasma response matrix. The currents induced in the 3D structures are described using a volumetric time-domain integral formulation of the eddy currents equations, requiring a finite elements discretization of the conducting structures only. The effect of 3D structures on plasma is evaluated by computing the magnetic flux density on S due to 3D currents. The induced currents are computed via an equivalent surface current distribution on

S providing the same magnetic field as plasma outside *S*. A realistic description of the RFX-mod conducting structures is given by a finite elements mesh: the conducting shell with cuts and overlaps is considered, along with a detailed geometrical representation of the 192 active coils and 192 flux measurement sensors. The correctness of such modelling has been validated against experimental measurement of the open-loop RWM growth rates [3] and of the vacuum mutual inductance matrix [4]. The overall plasma response model can be recast as:

$$\begin{aligned} \underline{\underline{L}}_{SS} \frac{d\underline{I}_S}{dt} + \underline{\underline{L}}_{SC} \frac{d\underline{I}_C}{dt} + \underline{\underline{R}}_S \underline{I}_S &= 0 \\ \underline{\Phi}_M &= \underline{\underline{L}}_{MS} \underline{I}_S + \underline{\underline{L}}_{MC} \underline{I}_C \end{aligned} \quad (1)$$

where $\underline{I}_S$ are the currents in the passive structure, $\underline{I}_C$ are the active control currents (assumed as known inputs), $\underline{\Phi}_M$ are the simulated magnetic fluxes. The induction matrices $\underline{\underline{L}}_{XY}$ are different from the vacuum values due to the presence of the plasma.

Integration of CarMa Model and Control System

The highly flexible digital control system of RFX-mod allowed to implement different control strategies [5]; one of them, named Mode Control, consists in acting separately on each harmonic component of the Discrete Fourier Transform (DFT) of the magnetic field measured by the sensors. In the present version the control system consists of 192 PID controllers, whose parameters can be independently set. Since the error signal is a complex quantity, it must be split into real and imaginary part before being processed by the control algorithm. In particular, as a further degree of freedom in the control action, the possibility of using complex proportional gains to introduce phase shift between input and output signal is also provided. The outputs of the two control blocks are then recomposed into a complex array, which is converted into 192 saddle coil current references by inverse DFT. A couple of dynamic models cast in the more convenient state variable representation along with blocks performing DFT and inverse DFT were developed and connected to the CarMa model of the plasma response for a thorough simulation of the control system operation. In RFX-mod the best experimental results were obtained after removing the aliasing error in the measurement of the magnetic field harmonic components due to the high poloidal and toroidal order sidebands produced by the discrete grid of 4x48 saddle coils. This approach, named Clean Mode Control [6], turned out particularly effective in the case of the Tearing Mode control, while less apparent results were noticed acting on RWM's. Since the sensors are inside the RFX-mod copper shell, the algorithm for the correction of the aliasing error is based on the

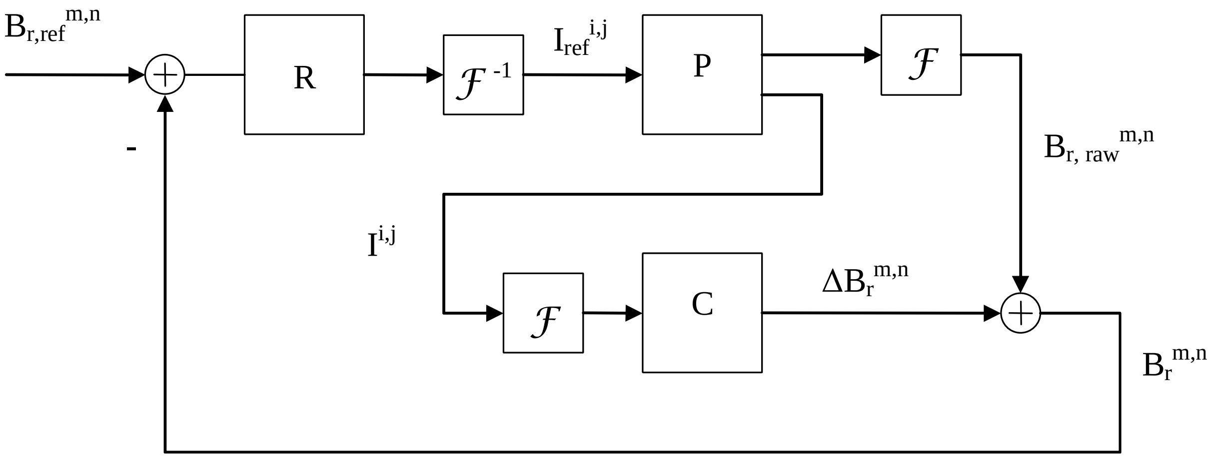

Fig. 1. Scheme of the control system with blocks representing the Plant (P), the Controller (R), the Mode Cleaner (C). Blocks performing DFT and inverse DFT are also shown.

diffusion equation of the different magnetic field harmonic components. Thus it can be represented as a dynamic system whose inputs and outputs are the coil current harmonics and the field harmonic corrections evaluated at the sensor radius, respectively. In order to obtain the "cleaned" magnetic field harmonic component this correction must be subtracted from the homologue component produced as an output of the CarMa Model. The simulation tool was supplemented by a specific state space system to perform these calculations, too. A general view of the block scheme is given in fig. 1. For a first benchmark against experimental data we considered shots at plasma current Ip=600-700 kA and fixed equilibrium parameters ($\Theta=B_\vartheta(a)/<B_\Phi>=1.4$, $F=B_\Phi(a)/<B_\Phi>=-0.06$), where two different control actions were applied in sequence to the most unstable RWM for that equilibrium (the internal non resonant m=1, n=-6). In the first time window (0-120 ms) the gain of a pure proportional controller was progressively increased from zero (free passive evolution) to the marginal value to achieve stabilization, in the second a much higher value was used to suppress the mode and prevent the fast termination of the discharge itself. The other accessible modes were always

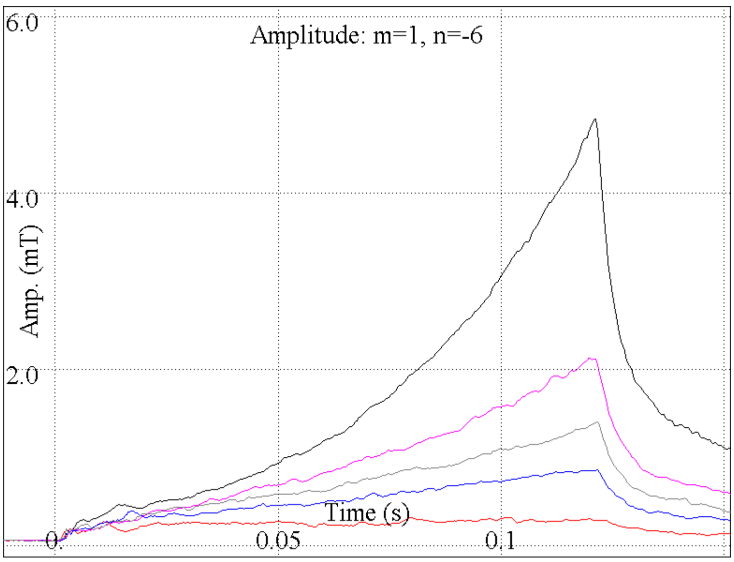

Fig. 2. Effect on the (1,-6) RWM growth rate of increasing proportional gains. From the top: Gp=0 (black), Gp=100 (purple), Gp=150 (gray), Gp=200 (blue), Gp=400 (red).

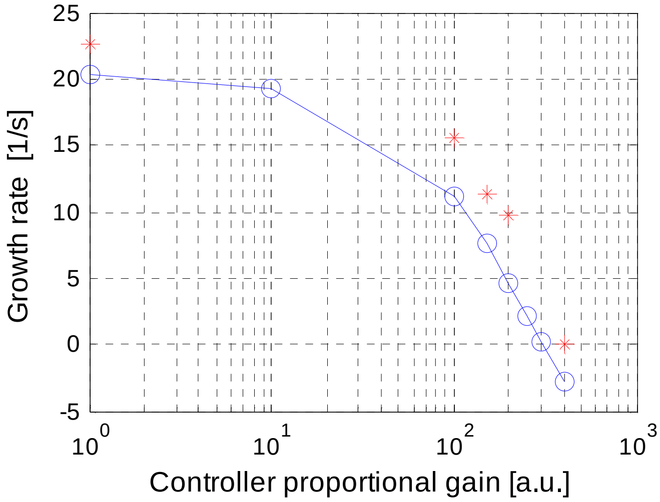

Fig. 3. Experimental (red asterisk) vs. model (blue circles) growth rates as a function of the controller proportional gain.

feedback controlled. The corresponding growth rate of the m=1, n=-6 was calculated as a function of the controller gain. In fig. 2 the different experimental time evolutions are shown. The eigenvalues of the closed loop model were also calculated for the same values of the proportional gain and a 2D Fourier analysis of the corresponding eigenmodes was performed to highlight the associated harmonic components. A dominant m=1, n=-6 component was identified so as to allow a direct comparison between the experimental growth rate and the inverse eigenvalues. The results are presented in fig. 3: the trend is correctly reproduced by the model, even if a general underestimation of the growth rate as well as of the critical gain providing stabilization can be noticed. It can be shown that, within a single-pole model, such critical gain depends only on the active coil and sensor geometry and not on the model of the passive structures. Consequently, the discrepancy between experimental data and calculated critical gain is probably caused by inexact equilibrium reproduction.

Conclusions

An integration between CarMa model and the RFX-mod control system was accomplished and full closed loop analyses of dynamic and stability properties of the MHD control system as a function of the regulator parameters can be already carried out. Benchmarking against experimental data is in progress and first results supports the expectation to obtain useful directions for the experimental activity.

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