RWM studies on RFX-mod with dynamical controllers: modelling and experimental results

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Introduction

Exploration of new and more efficient active MHD control techniques is mandatory for the continuous improvement of the magnetic confinement of thermonuclear plasmas. RFX-mod is a most suited test bed for experimental tests and precise benchmark of numerical models thanks to its powerful and flexible control system made up of 192 active saddle coils independently driven. The present paper deals with Resistive Wall Modes control in both experiments and simulations. A model of RFX-mod operation, as far as RWM control is concerned, has been developed as a joint effort of different associations [1]. It includes, in a fully consistent and integrated way, plasma response in toroidal geometry, 3D realistic description of passive and active conductors and a dynamic model of the control system. The plasma-3D conductor interaction is described by the CarMa model [2, 3]. Thus a full "flight simulator" for closed loop operations is now available. The assessment of the predictive capability of the flight simulator is a preliminary step in view of the model based design of prospective, more sophisticated control system of MHD modes. It is also worth while reminding that the highly linear dynamics of RWM's in RFP discharges is an ideal framework to perform these analyses.

After the encouraging results obtained with simple proportional controllers, the validation tests went on by implementing a proportional integral control both in the model and in the experiment. The possibility of performing extensive, independent scan in only two parameters (Kp and Ki) seemed particularly suitable to start the study of a dynamic controller effect on the closed loop response along with a straightforward experimental benchmark. In addition to the comparison of eigenvalue analysis results with those derived from experimental data, first full time domain simulations were run to further appreciate the simulator reliability.

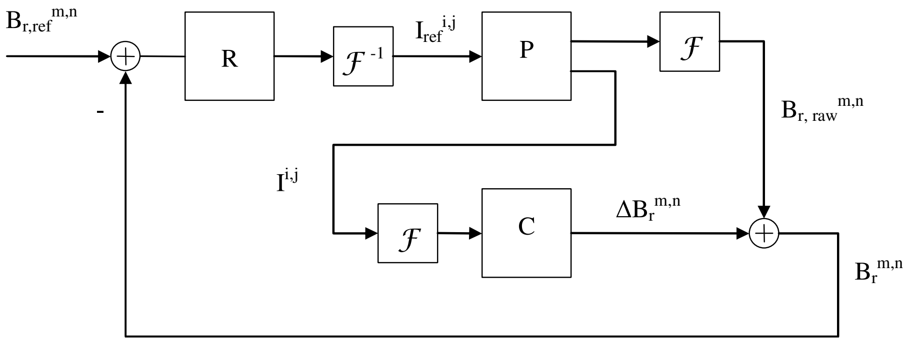

Fig. 1. Scheme of the control system with blocks representing the Plant (P), the Controller (R), the Mode Cleaner (C). Blocks performing DFT ($\mathcal{F}$) and inverse DFT ($\mathcal{F}^{-1}$) are also shown.

Closed loop control system

A block scheme of the control system, already described in more details in [1], is presented in fig. 1. The adopted control strategy was the so called Mode Control (MC), which consists in acting separately on each spatial harmonic component of the Discrete Fourier Transform (DFT) of the magnetic field radial component measured by the saddle probes mounted on the outer surface of the RFX-mod vacuum vessel. Though represented in the scheme for completeness, the Mode Cleaner block (C), which allows the removal of the aliasing error in the DFT of the magnetic field signal due to the effect of the discrete grid of active coils, was not used during the experiments and excluded in the model before performing both the eigenvalue analyses and the simulations. In the block scheme the plant (P) is a real variable linear system (CarMa model [2, 3]), whose outputs are the radial components (4x48) of the magnetic field at the saddle probe radius and the saddle coil currents (4x48) and whose inputs are the coil current references. The dynamics of the nested current control loop is taken into account by a single pole diagonal system with a time constant τ=2 ms. On the other hand, in the MC strategy, the error signal is a complex variable, whose real and imaginary parts are processed separately in the actual controller. Thus some algebraic manipulation work was carried out to embed the blocks performing the direct and inverse DFT into the controller and to obtain a minimum dimension real variable dynamic system in the standard state space representation.

Model-experiment comparisons

In the following we use the term "mode" and eigenvector in the meaning of the linear system theory, i.e. the eigenvector is an element of a basis which allows to express the general free evolution of a diagonalizable linear system. The "mode" is the time exponential function $e^{\lambda t}$ (or the couple $e^{\sigma t}\cos(\omega t)$, $e^{\sigma t}\sin(\omega t)$) characterized by the eigenvalue λ (or the couple $\sigma \pm i\omega$)

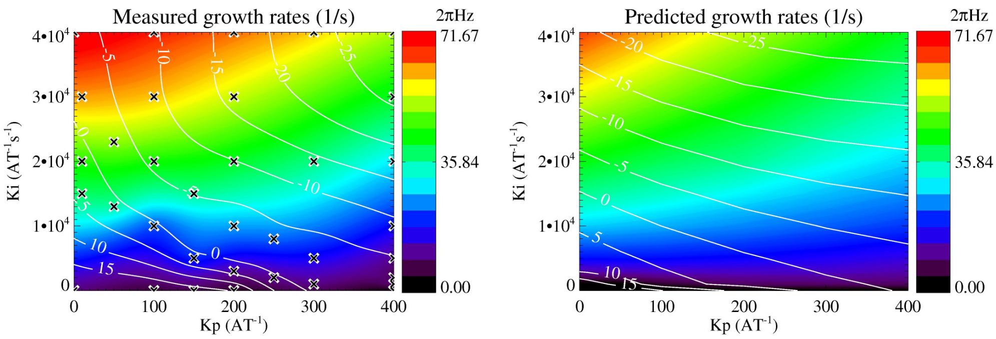

Fig. 2 Measured and predicted growth rates and oscillation angular frequencies in the presence of PI regulator of m=1, n=-6 harmonic component.

associated to each eigenvector. When a spatial interpretation of either the eigenvectors or the system output is possible, the "mode" provides the time evolution of the spatial pattern associated to the eigenvector itself or its output image. In our model one of the system outputs is the array of the magnetic field radial components and the corresponding (m, n) harmonic components are obtained by calculating its 2D spatial DFT. If we consider the output image of a single eigenvector and observe its spatial pattern, it is possible to have a rough but intuitive view of its dominant harmonic content. In a toroidal, and furthermore, non axisymmetric system, there is not a biunique correspondence between output harmonic components and system modes, as is the case of cylindrical axisymmetric geometry. Thus the following validation procedure was adopted. First the eigenvectors whose output images are characterized by the maximum relative content in the selected harmonic were found; then the corresponding growth rates and oscillation frequencies (in case of complex eigenvalues) were compared with growth rates and oscillating frequencies calculated by curve fitting on the DFT of the measured radial field components. In general the evolution of a harmonic component evidences the effect of different modes.

The analyses were focused on the most important RWM in RFX-mod, which is related to the m=1, n=-6 harmonic component. An extensive scan in the Kp-Ki plane was performed and the values for the onset of an oscillatory behaviour were derived. A significant subset of Kp-Ki gains were then tested in a series of dedicated pulses, aimed, in particular, at investigating the stability boundary curve predicted by the theoretical model.

The results are summarized in fig. 2, where growth rates are represented by contour lines and oscillation angular frequencies are represented by colour shading. A fairly good agreement is observed for Kp>50 and Ki<30000, while further investigations are on going for larger Ki and lower Kp. In particular, the stability boundary, dividing the stable and unstable experiments, is correctly predicted by the model in the above mentioned range of parameters.

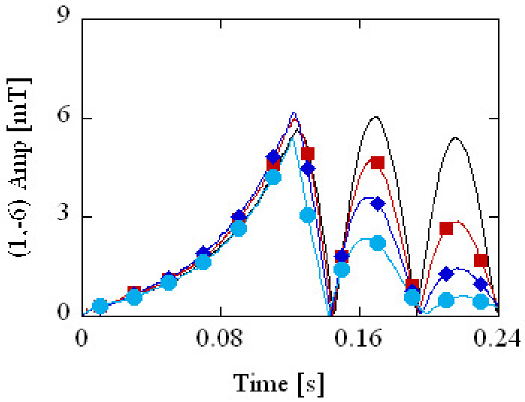

Fig. 3. Kp scan at constant Ki=40000. Kp=0 (black), 100 (red), 200 (blue), 400 (cyan).

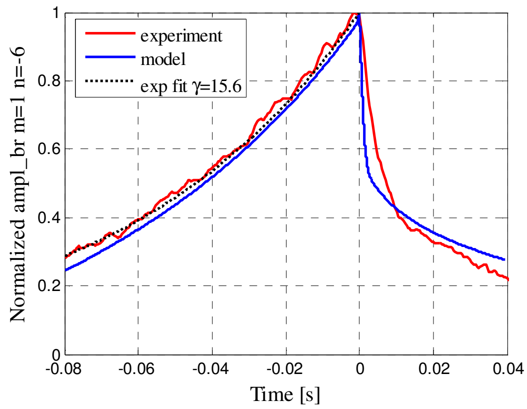

Fig. 4. Kp=100 (subcritical gain) for t*<0 s; Kp=800 for t*>0 s.

Separate scans in Kp and Ki allowed to ascertain how the former is more effective in changing the growth rate while the oscillation frequency is strongly dependent on the latter. An example of Kp scan at constant Ki is given in fig. 3. The first time domain simulations were run in the case of a proportional controller. Since the evolution depends on the initial condition, before being compared, the amplitudes were normalized with respect to their maximum value and the corresponding instant was assumed as t*=0 (t*=t-0.12 s). Fig. 4 shows the case of a shot where two proportional gains were used: the former is subcritical, the latter stabilizes the targeted harmonic component. The model correctly reproduces the actual system behaviour; in particular the presence of two different time constants in the second phase can be noticed.

Conclusions

Significant steps in the development and validation of a flight simulator of the active control system of RWM in RFX-mod have been accomplished. The predictive capability of the model in the presence of a dynamic controller has been tested both by eigenvalue analyses and time domain simulations. A satisfactory agreement was generally found; further investigations are in progress for the cases where the main differences have been observed.

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