Model-based design of multi-mode feedback control in high-current RFX-mod regimes

L. Piron, F. Bonomo, L. Marrelli, P. Piovesan, P. Zanca, B.Zaniol

Consorzio RFX, Euratom-ENEA Association, Padova, Italy

The RFX-mod machine is equipped with the most advanced magnetic feedback system realized in a fusion device. With its 192 active coils, independently driven and fully covering the torus surface, RFX-mod is ideally suited to investigate different schemes for multi-mode feedback control of MHD modes and error fields. A great advance in the RFX-mod performance was recently obtained through the so-called Clean Mode Control (C.M.C.), which allows operations up to 1.8MA for the first time in a reversed-field pinch [1,2]. To improve the overall plasma performance and, in particular, to control the plasma-wall interaction, the edge radial magnetic field of Tearing Modes (TMs), associated with the dynamo mechanism, must be kept at a low value and the modes must be maintained into rotation.

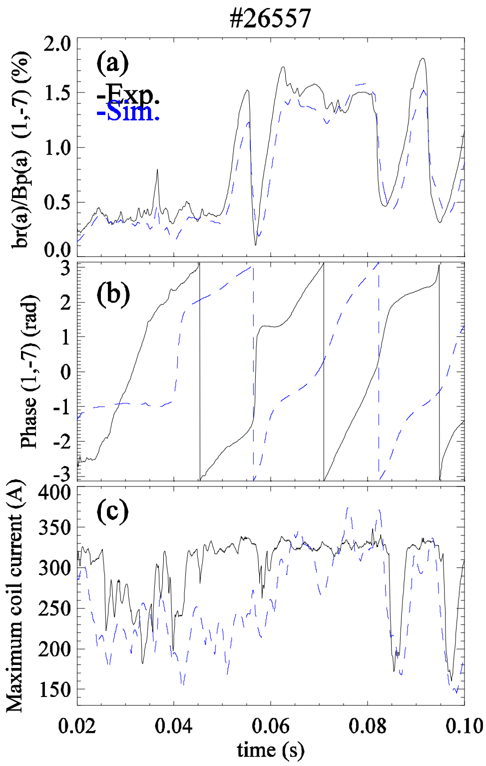

Figure 1. Normalized edge radial magnetic field (a), phase (b) of the (1,-7) mode and maximum coil current of the feedback system (c) in a 1.7 MA discharge and from the simulation.

A model of the non-linear dynamics of multiple interacting TMs, including their feedback control, has been developed [3]. The model solves the single-fluid motion equation including the viscous torque due to the fluid motion and the electromagnetic torques produced by external currents (i.e. feedback ones and eddy currents on the vacuum vessel and resistive shell) and by the non-linear interaction between different TMs.

The model can be run in an interpretative way giving the amplitudes of the magnetic field at the resonant surface, calculated from the experimental measurements [4], while the edge TM amplitudes and phases are computed by the model. In this work the model has been used to optimize the C.M.C. controller in RFX-mod, looking for a set of proportional (K_p) and derivative gains

(K_d) on each TM that reduces the edge radial magnetic field to the lowest value predicted by the model and maintains the mode into rotation.

The model reproduces well several aspects of the mode dynamics. In Fig.1 the time evolution of the edge radial magnetic field and phase of the innermost resonant TM (m=1, n=-7) and the maximum current into the active coils are compared with the results of the simulation for one of the highest current discharges obtained up to now (#26557, Ip=1.7MA).

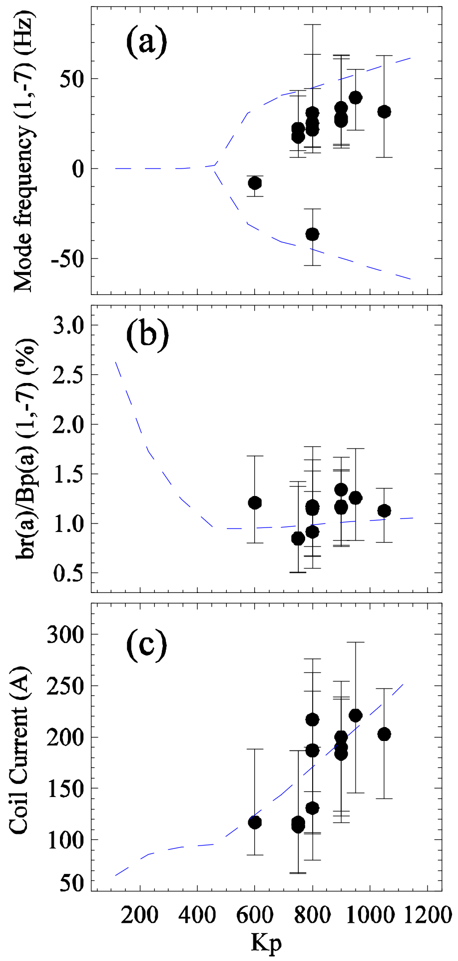

Figure2. Effect of the proportional gain on the median of the mode rotation frequency (a), normalized radial amplitude (b), coil current (c) for the m = 1, n = -7 mode (error bars represent the 25th and the 75th percentile) estimated during the flat top of reproducible discharge at 1.4 MA. The blue curve represents the trend predicted by the model.

The model describes the TM dynamics also when varying the control parameters, such as the proportional gain (K_p). The effect of K_p on the mode rotation frequency, normalized radial magnetic field and coil current for the m=1, n=-7 mode is shown in Fig.2. The experimental data are compared with the trends predicted by the model, obtained with a K_p scan. Note that, both in the model and in the experiment, positive and negative frequency solutions are obtained, even if the former is found more often in the experiment. The simulations of the K_p scan suggests the existence of a broad minimum in the dependence of the edge radial field on the proportional gain.

The strategy employed to optimize the mode controller is to simulate the dynamics of each TM scanning the proportional (K_p) and derivative gains (K_d) over a 2D grid searching for a minimum of the edge radial magnetic field. Since the number of variables involved in the optimization is high (ten modes with m=1, n= -7 to -16 and different gain values), the 2D scan has been applied on each single mode one at a time, neglecting the non-linear interaction among modes. In fact it has been verified that the non-linear interaction modifies TMs rotation frequencies, while it has no significant impact on TMs edge amplitudes [3]. 2D scans reveal the existence of a minimum of the edge radial field as shown in Fig. 3(a) for the (1, -7) mode.

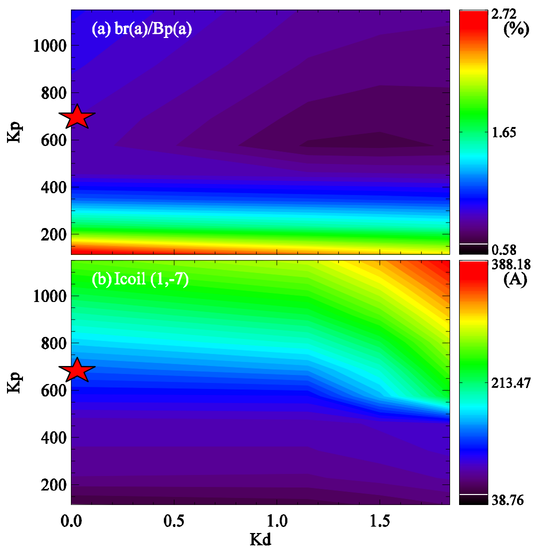

Figure 3. 2D scan of the normalized edge radial magnetic field (a) and the coil current requested by the feedback system (b) for the (1, -7) mode.

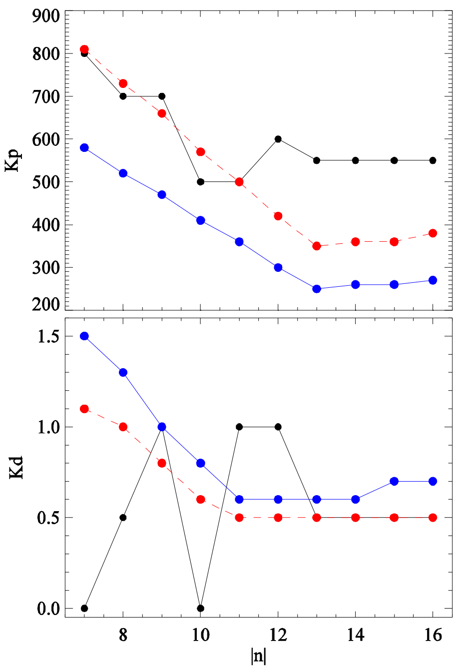

Figure 4. Values of K_p and K_d gains applied to TMs (m=1, n=-16,-7). The black dots correspond to the empirical set, the blue dots, the optimal set suggested by the model, the red dots, the optimal experimental set.

The minimum of the edge radial field corresponds to the values of K_p=580 and K_d=1.5, which are different from the ones normally used in the experiment on this mode, that are indicated with a red star. Note that the coil current requested by the feedback system for the (1, -7) mode, shown in Fig. 3(b), increases with K_d and K_p, and this has to be taken into account in the optimization as a constraint, since the possibility of a saturation of the coils currents has to be avoided.

In Fig.4 the set of K_p and K_d suggested by the model (blue line) is compared with the values empirically found (in black) by varying the gains of each mode on a subset of possible values, given the limited experimental time. Note that, the values of K_p of the optimized set are lower than those normally used in RFX-mod, while the values of K_d are significantly higher for some modes, such as (m = 1, n = -7, -8, -10).

The effective existence of a minimum in the edge radial field in the K_p-K_d space has been tested in an experimental campaign and the following results have been obtained from a statistical analysis of a set of reproducible discharges (#20) in the range of plasma current I_p = (0.8, 1.1) MA and with similar magnetic equilibria defined by the reversal parameter

$F = B_t(a)/\langle B_t(a)\rangle = (-0.05,-0.02)$.

Since the model reproduces the behavior of the RFX-mod feedback chain only approximately, we cannot expect the predicted and experimental (K_p, K_d) minimum to coincide. Moreover it is impossible for the limited experimental time to perform a complete 2D scan on each mode. Therefore the leading criterion for the experimental optimization was to maintain the trends of

K_p and K_d suggested by the model, and to multiply the red curves shown in Fig.4 by the constants α_Kp and α_Kd respectively, looking for a minimum in the edge radial magnetic field. α_Kd has been varied in the range α_Kd = (0.25-0.75), while α_Kp in the range α_Kp = (1.3-1.5). The range of gain values is limited in the experiment both by hardware limits, such as current saturation at high gains, and by the fact that at low gains the mode rotation stops and the discharge performance degrades.

The existence of a minimum of the edge radial field has been confirmed experimentally, as shown in the contour plot of the total radial magnetic field, defined by $b_r^{tot} = \frac{\sqrt{\left(\sum_{m=1,n=-16}^{-7} b_r^n(a)\right)^2}}{Bp(a)}$ in Fig.5 (a). The optimal result corresponds to value of α_kp=1.4 and α_kd=0.75, and the set of K_p and K_d are plotted in Fig.4 with red dots. In Fig.5 (b) the simulated total edge radial magnetic field is shown, where each point is the average on several simulations performed on the set of discharges used in the analysis. Note the coincidence of the minimum for the two 2D scan for the same value of α_Kp and α_Kd.

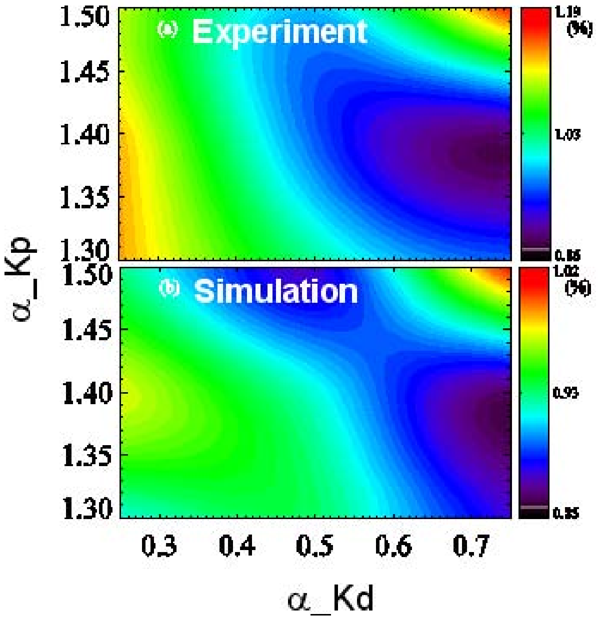

Figure 5. Experimental (a) and simulated (b) contour plot of the total radial magnetic field

Conclusion: In this work a model-based optimisation for the P.I.D. controller of RFX-mod has been performed. The set of K_p and K_d gains obtained in this way allows a reduction of the edge radial field of about 12% and of the plasma surface distortion of the order of 5% with respect to discharges in which the feedback gains were optimized following an empirical procedure. The model is thus a powerful tool to design and to optimize offline the P.I.D. controller of the CMC, taking into account the TMs dynamics, and it allows a better control of the magnetic boundary.

References:

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