RWM control modelling in RFX-mod Tokamak plasmas

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Introduction
An integrated model of the control system of RWMs in the RFP experiment RFX-mod was developed and has already been validated [1]. It includes a refined model of the plasma response based on the toroidal MHD stability code MARS-F [2]. Eigenvalue analysis of the closed loop system performed in the presence of different kind of dynamic regulators allows characterizing the time response of selected modes with satisfactory accuracy. Time simulations can be run including realistic details of the active system such as saturation of the power supplies and delays of the digital control. The agreement with the experimental data confirmed the reliability of the model as a prediction and optimization tool. In order to fully exploit the unique active coil system present in RFX-mod some experiments were executed in the past operating RFX-mod as a low current Tokamak in which, by lowering $q$ at the plasma edge to values slightly below 2, a growing $m=2$, $n=1$ mode was observed [3]. The capability of the active control system to stabilize this mode suggested performing new experiments in this configuration and producing a new version of the integrated model for the Tokamak configuration. First, relevant equilibrium quantities were reconstructed trying to match the available experimental data. Then, in order to obtain the CarMa [4] model of the system, the modal plasma response was evaluated and integrated into a realistic description of the active saddle coils and the 3D passive structures surrounding the plasma. Finally, the real time control system was also thoroughly represented, including the on-line correction of the aliasing error in the field raw harmonics due to the sidebands produced by the finite number of coils. The experimental results highlighted the importance of the sidebands issue in the stabilization capability of the system and suggested investigating further this aspect by applying the model. A gain scan was performed to compare the effectiveness of the Mode Control (MC) and the Clean Mode Control (CMC) strategy [5] in allocating the closed loop eigenvalues.
Equilibrium reconstruction

The 2D finite elements equilibrium code MAXFEA [6] was used to determine the q profile needed as an input to the toroidal stability code MARS-F for the calculation of the plasma response. MAXFEA assumes a parameterized description of the plasma current toroidal density according to the equation: 

$$J_\psi = \frac{R}{R_0} \beta + \frac{R_0}{R} (1-\beta) (1-\psi^\alpha),$$

where $\alpha$ and $\beta$ are parameters related to the plasma internal inductance and pressure, respectively; $\psi$ is the normalized poloidal flux defined as $\psi = \frac{\psi_b - \psi_a}{\psi_b - \psi_a}$, where $\psi_a$ and $\psi_b$ are the poloidal flux at the magnetic axis and the plasma edge, respectively. Some shots both in open and closed loop control of $m=2$, $n=1$ harmonic were analysed to derive the plasma response and the linearized model. Figure 1 shows the time evolutions of plasma current, raw and clean amplitude of $(2,1)$ controlled harmonic and safety factor at the plasma edge for shot #29806. Since in RFX-mod no diagnostics is available to reconstruct the plasma current density profile, we validated the choice of $\alpha$ and $\beta$ parameters trying to match the magnetic measures and other equilibrium macroscopic quantities such as plasma shift and poloidal field asymmetry coefficient $\Lambda$. For shot #29806 the equilibrium was reconstructed at $t=0.4$ s, the estimated $q$ at $\psi = 0.95$ is also represented in the bottom plot of fig. 1, a bit lower than the experimental value at the graphite radius. In figure 2 the resulting q profile is shown. By assuming $\alpha=2$ (normalized internal inductance $l_i=0.85$) it was possible to highlight the $(2,1)$ external kink mode feedback stabilized in this pulse while matching the edge q value ($q_a$). The dependence of the unstable mode growth rate $\gamma$ on $q_a$ and $\alpha$.

Fig. 1. Shot #29806: time evolution of plasma current, $(2,1)$ mode amplitude and safety factor at the edge.
was studied by means of MARS-F with a 2D resistive wall located at 1.1 the plasma radius using data of two RFX-mod shots. The values of $\gamma$ evaluated by MARS-F are multiplied by a correction factor to take into account of 3D features of the conducting structures. The curves plotted in fig. 3 show how sensitive is the growth rate to both $\alpha$ and $q_a$: the experimental growth rates are somewhat below the minima of the calculated ones, probably because a more refined parametrization would be necessary to fully describe the plasma current density profile. It should also be pointed out that the correction factor, derived by calculations performed on the CarMa model, resulted to increase with the growth rate itself so further enhancing the difference from the experiment. Notwithstanding that we decided to keep the experimental values of $q_a$ and plasma current and to start closed loop analyses in the case of shot #29806, considering the resulting high value of $\gamma=118$ s$^{-1}$ a more conservative “worst case”.

**Closed loop analyses**

First experiments run adopting the MC strategy, i.e. aimed at cancelling the targeted harmonics of the radial field component, proved that it was only possible to slow the mode $m=2$, $n=1$ without stabilizing it with a simple proportional controller. Note that similar experiments of RWMs control in RFP discharges were successfully carried out allowing a full stabilization of the modes. The results were completely different applying the CMC strategy, which already played a key–role in the dramatic improvement of RFP discharges making it possible the active control of tearing modes [7]. This strategy consists in the removal of the aliasing error in the measurement of the radial magnetic field harmonic components due to the poloidal and toroidal order sidebands produced by the discrete grid of 4x48 saddle coils. The dynamic block performing the calculation of the
sidebands can be easily switched on or off in the model and a proportional gain scan was carried out comparing the two strategies. According to a procedure followed in the past [1], first the eigenvalues associated to the eigenvectors whose output images exhibit the largest relative content in the \( m=2, n=1 \) harmonic component were singled out, then either the fastest unstable one or the slowest stable one was considered for each gain. The growth rates obtained in this way are plotted against the corresponding proportional gain in fig. 4. In qualitative agreement with the experimental results, the MC scheme turns out unable to stabilize the \( m=2, n=1 \) mode, the growth rate appearing very soon substantially independent of the applied gain. A similar result was obtained with a different model, where a root locus analysis showed the presence of a positive zero, which asymptotically attracts the unstable pole of the closed loop system [8]. On the contrary, the CMC approach confirms the possibility of actively stabilizing the mode by correctly measuring the targeted harmonics of the magnetic field radial component.

At the moment we observe an experimental critical gain (3000) equal to about 30\% of the calculated one, but this can be attributed to the exceedingly high estimate of the growth rate. We expect that a refined tuning of the equilibrium should yield a closer quantitative agreement between experiment and model.

Conclusions

The CarMa model of the RWM control system of RFX-mod operating as a Tokamak has been developed and its predictive capability tested on recent experimental results. A qualitative agreement was already reached and the first analyses also provided information for a further tuning of the input equilibrium, considered necessary to achieve the same predictive accuracy of the model as observed in the case of the RFP discharges.