Extended characterization of RWM active control system in RFX-mod

G.Marchiori[1], M. Baruzzo[1], T. Bolzonella[1], Y.Q. Liu[2], A.Soppelsa[1], F. Villone[3]

[1]*Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, Padova, Italy*

[2]*Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, UK*

[3]*Ass. Euratom/ENEA/CREATE, DAEIMI, Università di Cassino, Italy*

Introduction

In the last years the capability of stabilizing RWMs by means of an active system of saddle coils covering the whole toroidal surface of the RFX-mod load assembly has been widely tested. An integrated dynamic model of such a system has been developed and validated including the plasma response of the most unstable mode, which is the internally non resonant m=1, n=-6 in RFX-mod [1]. The interest for the study of the effectiveness of reduced set of coils in stabilizing the RWMs is now acknowledged in the fusion community for its reactor relevancy. The flexibility of the RFX-mod active control system suggested to perform a series of experiments where different configurations of coils were tested in both the virtual shell scheme and the mode control scheme [2]. A basic advantage of the latter is the possibility of applying a reduced set of coils to control only selected RWMs, while maintaining the full set for the control of other modes. This allowed focusing the experiment on the phenomenon to be investigated, ruling out the undesired effect of tearing modes and making much more consistent the comparison with models which include only a limited part of the plasma response spectrum. Recently an enriched version of the dynamic model has been developed featuring the plasma response of RWMs with abs(n)=1, 2, 3, 4, 5, 6. This is important to analyse the effect of a reduced set of coils since it allows the simultaneous study of modes which could be amplified by the low n order sidebands produced by the coils (Resonant Field Amplification). To investigate the reliability range of the model, dedicated experiments were also run destabilizing marginally stable modes by means of negative proportional gains in the control loop.

The multimodal plasma response model and the destabilization of modes by positive feedback

The new multimodal plasma response model has been developed for the same reference equilibrium assumed in the previous analyses (Θ=1.4 and F=-0.06).

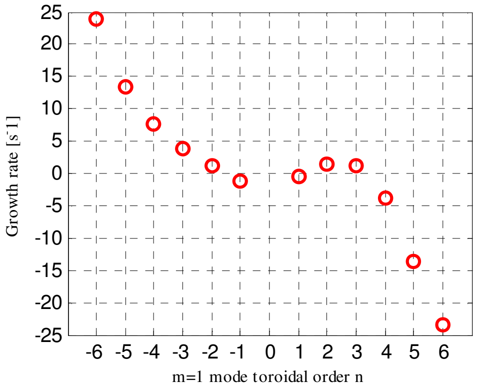

Fig. 1. Open loop largest eigenvalues of multimodal plasma response model.

This allowed an immediate consistency check between the results provided by the previous single mode (abs(n)=6) plasma response model and the new extended version. The open loop model is a dynamic system whose inputs are the saddle coil currents and whose outputs are the radial components of the magnetic field measured by the saddle probes mounted on the RFX vacuum vessel outer surface. The same approach exposed in previous papers [1] has been followed for model validation tests: that is to say, we calculate the Fourier transform of the outputs associated to the main eigenvectors and then look for the one which exhibits the higher relative content in the selected (m, n) harmonic. Under this assumption it is possible to correlate harmonic components and eigenvalues and to perform a direct comparison with the results of Fourier analyses on the arrays of measured magnetic field radial components. In fig.1 an example of the eigenvalue spectrum of internally (n<0) and externally (n>0) non resonant resistive wall modes is presented. The model predicts an unstable behaviour for the internally non resonant harmonic components, while a stable response is expected for most of externally non resonant harmonics. The agreement with the experimental growth rates reported in [3] is satisfactory, even if a wider dispersion of experimental estimates is observed for n=4 and 5. Generally, the dynamic characteristics of marginally stable/unstable modes (|n|≤2) are not easily observable due to the duration of the shots (≤400 ms). Thus in the following we will focus on the |n|≥3 modes, whose dynamic characteristics can be calculated

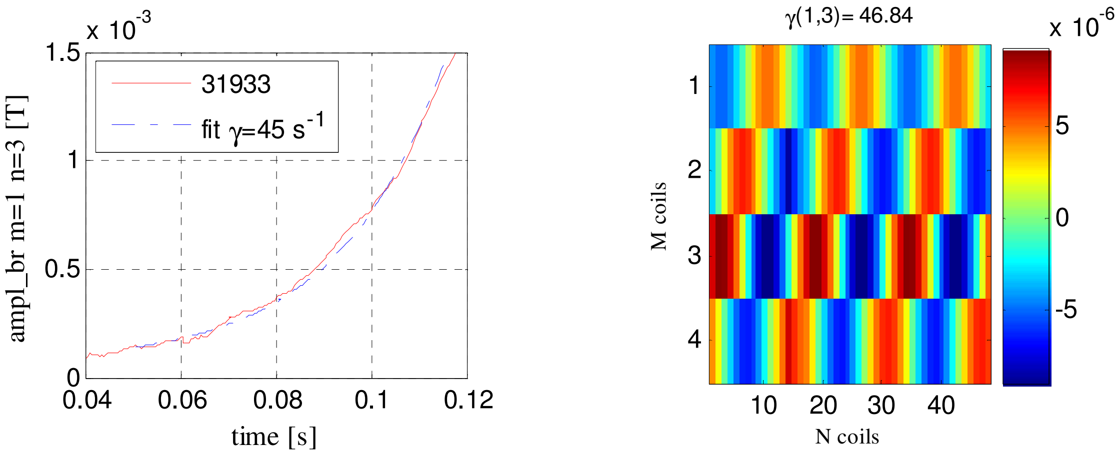

Fig. 2. Destabilization experiments: in the left plot time evolution of (1, 3) harmonic component and exponential fit; in the right plot output associated to the most unstable mode exhibiting a clear (1, 3) pattern.

with higher confidence by processing the experimental data. In order to extend the assessment range of the predictive capability of the dynamic model, some experiments were carried out applying a negative proportional gain in the feedback control loop of otherwise stable harmonic components m=1, n>0. In fig. 2 is presented the result of an experiment where a proportional gain Kp=-500 was used to destabilize the harmonic component (1,3). An exponential curve is observed (left) with an estimated growth rate γ=45 s^{-1}, in good agreement with the model prediction of two unstable modes (γ=46.3 s^{-1} and 46.8 s^{-1}). An example of the output associated with one of them, exhibiting a clear (1,3) pattern, is given in the right plot.

Control of RWMs with reduced sets of active coils

Different configurations have been tested to find the minimum set of active coils capable of stabilizing the whole group of RWMs, in particular to investigate the rigidity of the plasma response, i.e. the possibility of controlling a single mode even by a reduced set of coils without triggering the growth of other modes originally stable. Instead, the mode rigidity is simply the possibility of controlling a single mode by applying a local control action, ruling out the equispaced configurations whose periodicity allows the mode to choose “nodes” where it can grows freely. In the first series of experiments here presented (shots 31968 and 31971) a set of 4x3 adjacent coils (3 full poloidal arrays, adjacent along the toroidal direction, each consisting of 4 coils) was applied to the control of harmonic components m=1, n= -4, -5, -6. This configuration did not prove capable of stabilizing the modes in both cases, although the proportional gains were one order of magnitude higher than in the standard control case in 31968 and further doubled in 31971. The result was correctly predicted by the model, as visible by the position of the closed loop eigenvalues in the left plot of fig. 3. In shot 31971

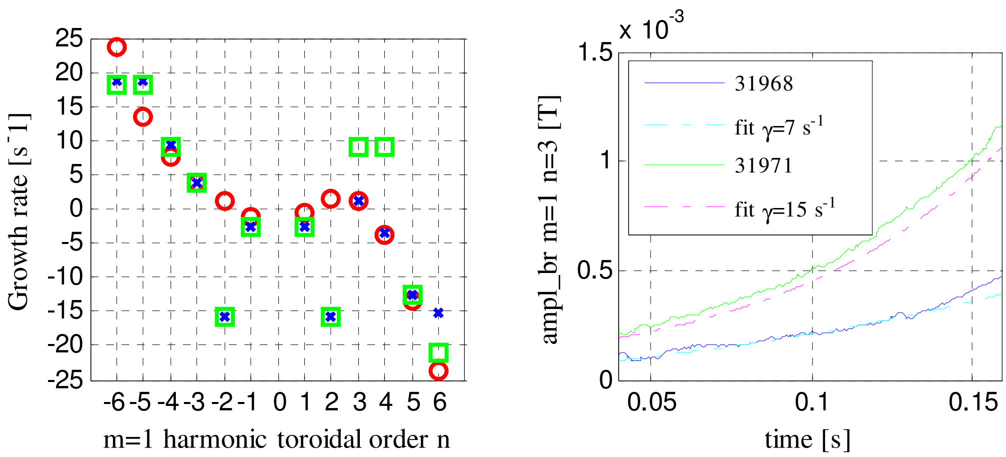

Fig. 3 Reconfiguration of active coils: 4x3 adjacent coils. In the left plot, model largest eigenvalues: open loop (red o), closed loop 31968 configuration (blue x), closed loop 31971 configuration (green sq). In the right plot, time evolution and exponential fit of harmonic component (1, 3) in shots 31968 and 31971.

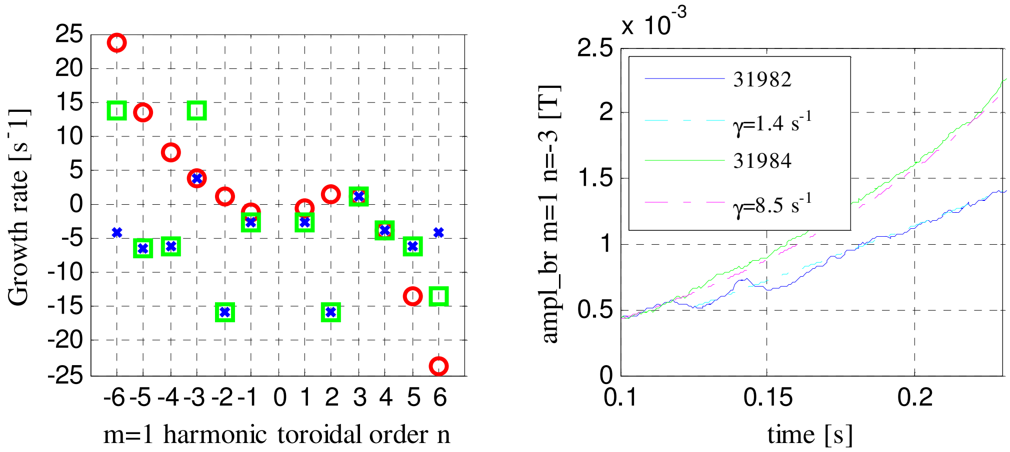

Fig. 4 Reconfiguration of active coils: 4x3 equispaced coils. In the left plot, model largest eigenvalues: open loop (red o), closed loop 31982 configuration (blue x), closed loop 31984 configuration (green sq). In the right plot time evolution and exponential fit of harmonic component (1, -3) in shots 31982 and 31984.

the harmonic components n=3 and n=4 are characterized by even amplified unstable growth rates (see time evolution of (1,3) harmonic in the right plot of fig. 3), which are calculated by the model with sufficient accuracy. In the second case (shots 31982 and 31984) a configuration with 4x3 equispaced coils (again 3 full poloidal arrays equispaced along the toroidal direction) was applied on the same set of harmonics, the only difference was the additional feedback control of (1,-3) in shot 31984. This configuration allowed mode stabilization in shot 31982, but when the control of (1,-3) was activated, the mutual effect of the sidebands caused a larger growth rate of the same (1,-3) harmonic (fig. 4 right plot) along with a destabilization of n=-6, notwithstanding its own feedback control loop. As it can be seen from the closed loop eigenvalues shown in fig. 4 (left), the model again correctly predicts these effects providing a fairly accurate estimate of the growth rates of the unstable modes.

Conclusions

The multimodal version of the dynamic model for the study of RWMs in RFX-mod is now available and validation tests performed up to now are encouraging about the possibility of its use as a predictive tool to assist the experimental investigations on the control of RWMs by means of a limited number of active coils.

References

[1] G. Marchiori et al., *Nuclear Fusion* **52** (2012) 023020.
[2] L. Marrelli et al., *Plasma Physics and Contr. Fusion* **49** (2007) 083037.
[3] M. Baruzzo et al., *Nuclear Fusion* **51** (2011) 083037.