Modelling multi-modal Resistive Wall Mode feedback control in JT-60SA perspective high β scenarios

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Introduction The superconducting tokamak JT-60SA is being built in Naka (Japan) and has an important supporting mission for the development of fusion energy: designed to achieve long pulses (100 s) and break-even equivalent plasmas, it will help in both the exploitation of ITER and in solving key issues for the future DEMO devices [1][2]. JT-60SA will be able to explore plasma configurations with shape factor up to $S=q_{95}I_p/(aB_\varphi)$ ~ 7 (where B_φ is the toroidal field, I_p the plasma current in MA, a is the minor radius, q_{95} the safety factor at 95% of the toroidal flux) and aspect ratio down to A ~ 2.5. Additional heating and current drive systems will provide up to 41 MW for 100s, divided between 34 MW neutral beam injection and 7 MW of ECRF. The off-axis Negative-NBI at 0.5 MeV beam energy in particular, allows current profile tailoring for Advanced Tokamak scenarios with fully non-inductive current drive. In the present work the focus is set on high β_N scenarios, in which one or more Resistive Wall Modes are potentially unstable [3]. It is foreseen that synergic contributions from passive (i.e. drift-kinetic resonances) and active means shall be exploited for RWM stabilization. In JT-60SA feedback control of RWMs will be possible thanks to a set of 18 active coils located on the inner side (i.e. the plasma facing side) of the Stabilizing Plate (SP). A plasma response model provided by the CarMa code [4] is being implemented for simulations of RWM feedback control with the most unstable n=1 and n=2 modes, where n is the toroidal mode number. This model includes a realistic description of the active coils, with both RWM Control Coils (RWMCCs) and Error Field Correction Coils (EFCCs) represented as single turn conductors. The stabilizing plate is also described with all its 3D features, while an axisymmetric vacuum vessel is assumed. Ongoing work is aiming at developing a multimodal simulator for RWM control [5].

The pressure driven n=1 and n=2 kink instabilities have been studied with the MARS-F code. The target plasma for feedback stabilization studies is an Advanced Tokamak scenario with $\beta_N \simeq 3.6$. This lies beyond both the n=1 and n=2 no-wall limits, which are $\beta_N^{nw} \simeq 1.9$ and $\beta_N^{nw} \simeq 2.3$ respectively, as shown in Fig. 1. This suggests that at least two RWM modes will require simultaneous feedback during operation of similar scenarios. In order to simulate simultaneous feedback on both n=1,2 RWMs, the CarMa code has been used to obtain a state-space representation of the system. This step, which is the first towards a complete time simulation of RWM feedback, is described in the following sections.

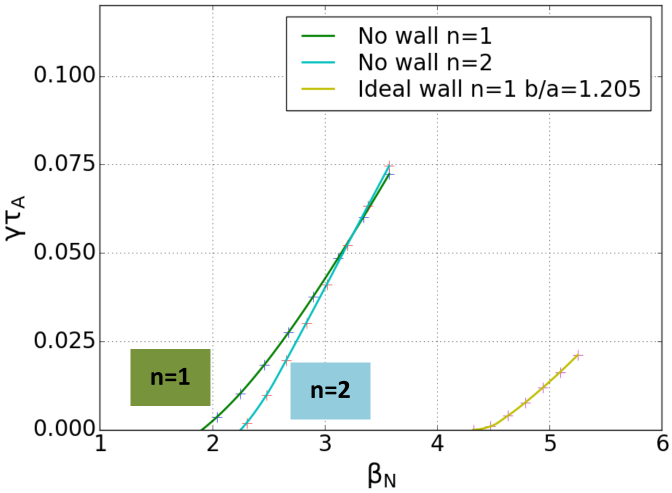

Figure 1 - Pressure scan for ideal kink mode. No-wall limits are shown for n=1 and n=2. Ideal-wall limit is calculated for n=1 and stabilizing plate position.

Description of the open-loop multimodal CarMa system From the point of view of passive and active structures surrounding the plasma, as represented in Fig. 2, the implemented model contains a realistic 3D description of the Stabilizing Plate, Resistive Wall Mode Coils and Error Field Correction Coils. While we will only use the former set of coils in the following, the latter allows modelling of vacuum fields for Error Field correction, ELM control and Resonant Magnetic Perturbation studies in general.

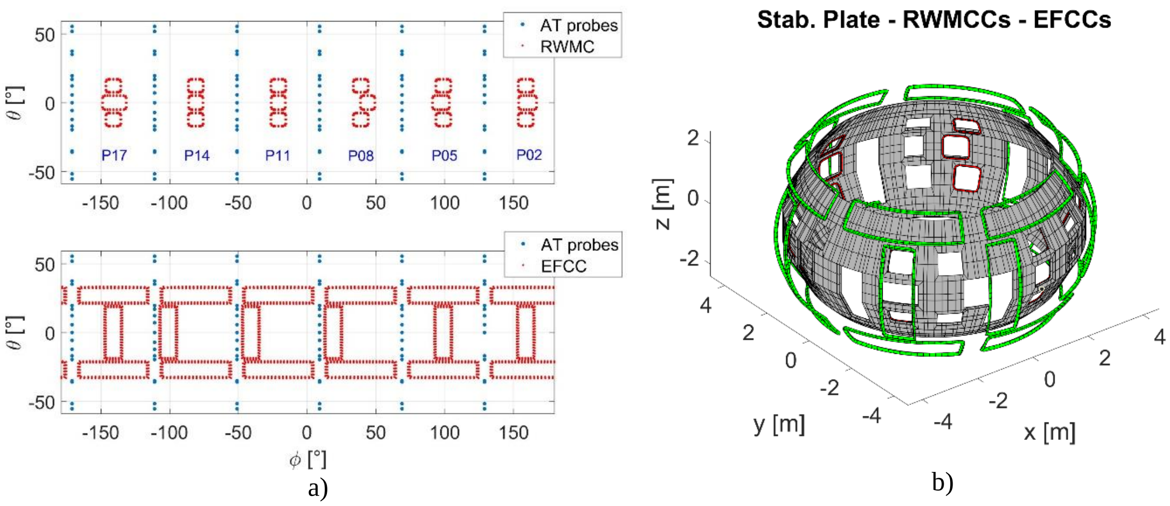

Figure 2 – a) 2D representation of RWM Coils (upper plot) along with magnetic probes, and EFCCs (lower plot). b) 3D representation of both active coils and Stabilizing Plate meshes as represented in the model.

The growth rates of most unstable n=1,2 modes have been compared between MARS-F and axisymmetric version of the CarMa model. The relative difference between eigenvalues is 8.4% for n=1 and about 10% for n=2. This depends on the number of Fourier harmonics used for poloidal reconstruction of the eigenfunctions, which compromises with conditioning of plasma response matrices. For the same reason a spurious imaginary part is found in the eigenvalues, which is however $< 5\%$ of the real part. Eigenvalues calculated by MARS-F and axisymmetric CarMa are compared in Table 1 for both mode numbers.

	$\gamma\tau_w$ **MARS-F**	$\gamma\tau_w$ **CarMa**
n=1	12.48	11.43
n=2	10.57	9.50

Table 1 – Comparison of eigenvalues for n=1 and n=2 modes between MARS-F and axisymmetric CarMa

When the 3D stabilizing plate is introduced, with both partial poloidal coverage and ports, four unstable modes are found for the open-loop system. This is due to a splitting of the two modes found in the 2D case. The same behavior was found in previous versions of the model [3] and, although under investigation, can find a possible explanation in the partial poloidal coverage of the stabilizing plate. Fourier analysis of the unstable eigenvectors reveals either n=1 or n=2 dominant components. Eventually two modes have dominant n=1 content and two show

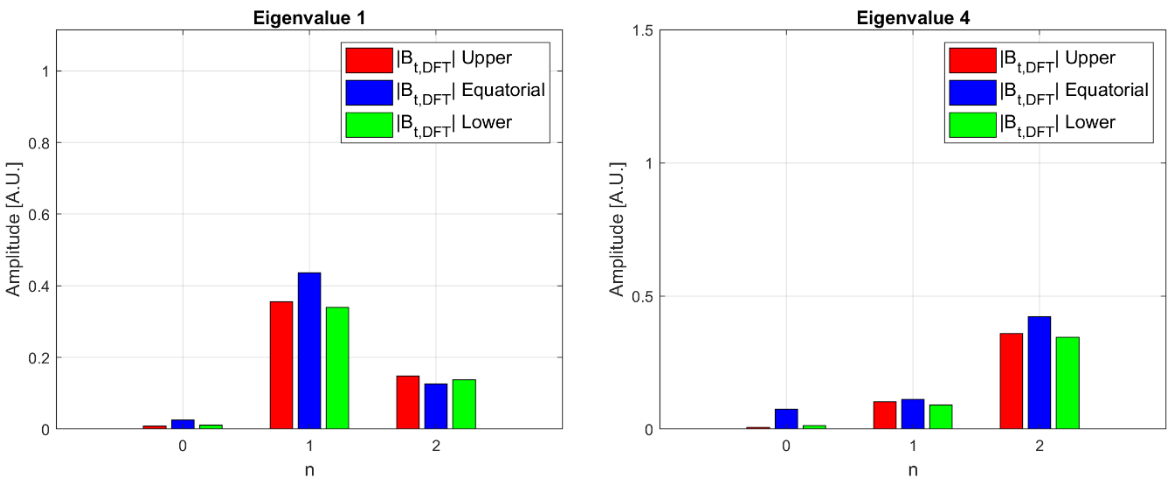

Figure 3 – Fourier components of two unstable modes of the open-loop system. The image of the first eigenvector on selected probes shows dominant n=1 component (left) while the image of the fourth eigenvector on the same probes shows dominant n=2 (right).

dominant n=2 pattern. Fig. 3 shows the dominant harmonic components of two modes, representatives of n=1 (left) and n=2 (right). These are calculated using the image of system outputs on three arrays of magnetic probes corresponding to the three toroidal arrays of active coils. Each output of the system provides a magnetic measurement on three axes, this is converted to a local coordinate system for each probe and the tangential component (B_t at constant toroidal angle) is selected as the feedback variable for the closed-loop study. B_t has mainly a poloidal component. **Eigenvalue study of the closed-loop system** A proportional controller is implemented in the closed loop system, feedback is carried out simultaneously on n=1 and n=2 harmonics using the tangential field component. Preliminary studies of single mode control have shown that they can be stabilized separately. Eigenvalue study of the closed-loop system suggests that the four unstable modes might be simultaneously stabilized as well.

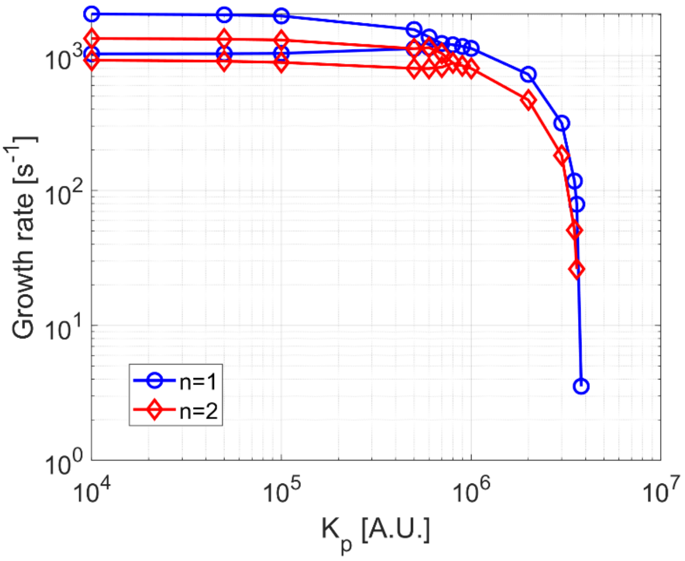

Figure 4 – Scan of proportional gain on both n=1 and n=2 harmonics

While scanning the proportional gain, modes change their structure and harmonic components are mixed. The couples of unstable modes with n=1 and n=2 dominant components respectively, turn into couples of complex conjugates, which have the same growth rate. This behavior is shown in Fig. 4 where the trajectories of the mode growth rates are plotted as a function of the proportional gain. Here the modes of the system are identified with their main harmonic content. This identification is not always clear or unique. The system unstable modes change for different gain values, and the harmonic is varied by the controller action in the Fourier space, i.e. feedback is carried out on the Fourier components rather than on the single modes. **Conclusions and Outlook** This work has described the development and first analyses of a tool for multi-modal RWM control modeling. If on one hand this has the limitation of a purely fluid RWM description that does not allow non-ideal effects such as drift-kinetic damping, on the other it allows relatively simple feedback studies with realistic 3D structures. Simultaneous stabilization of n=1 and n=2 has been achieved with a proportional controller. Ongoing work aim at developing a time simulation and comparing the presented results with a model that includes RWM drift-kinetic damping.

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.