RWM Feedback with Control Voltage Saturation and Sensor Noise in ITER

S. Wang[1], Y. Q. Liu[2,1], G. Y. Zheng[1], X. M. Song[1], G. Z. Hao[1], G. L. Xia[1,3], L. Li[4], B. Li[1], N. Zhang[1], G. Q. Dong[1], and X. Bai[1],

[1] *Southwestern Institute of Physics, P.O. Box 432 Chengdu 610041, China*

[2] *General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA*

[3] *CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK*

[4] *Donghua University, College of Science, Shanghai 201620, China*

This work studies active control of the $n = 1$ RWM in ITER, taking into account (i) recent design of the plasma equilibrium for the ITER 9 MA steady state scenario, and (ii) two important control aspects towards realistic modeling of the RWM feedback for ITER, namely the control power saturation issue and the presence of sensor signal noise. This is the first such attempt where both the aforementioned factors are included into investigation.

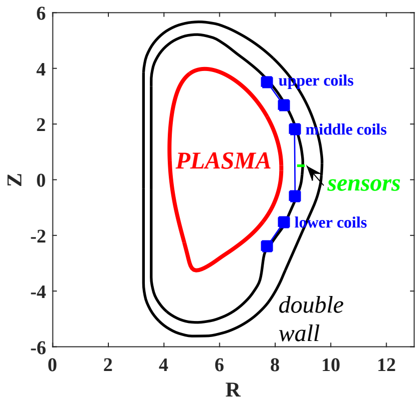

Figure 1: Geometry of the RWM feedback study for ITER, showing the plasma boundary shape, the double-wall vacuum vessel in complete thin-wall approximation, and the location of active and sensor coils.

We adopt the so-called flux-to-voltage control scheme, where the actuators are the ITER in-vessel magnetic coils driven by the control power voltage, and the sensor coils measure the poloidal component of the perturbed magnetic field just inside the vacuum vessel at the low field side outboard mid-plane. Three sets of magnetic coils, located in the gap between the ITER blanket modules and the inner vacuum vessel, are used as the active coils, which are shown in Fig. 1. The same sets of coils have also been designed to control the edge localized modes in ITER in a feedforward fashion. Gaussian noise, with the standard deviation level ranging between 0.1-1 G [1], is added to the sensor signal during initial value simulations by MARS-F[2]. The modeling results with both control power saturation and sensor signal noise are compared with those assuming more idealized conditions.

The flux-to-voltage control scheme takes into account the L/R response of the active coils. Following Ref. [3], we estimate that the L/R response time of the active coils in ITER is about one order of magnitude larger than the resistive wall field penetration time. This strong L/R response of active coils is beneficial for passive stabilization of the RWM stabilization. In fact, we can see from Fig. 2 that the open-loop growth rate of the RWM is substantially reduced, down close to the marginal stability level, for equilibria with C_β below 0.4. This passive L/R stabilization by active coils can be *quantitatively* re-produced by an analytic circuit model [4].

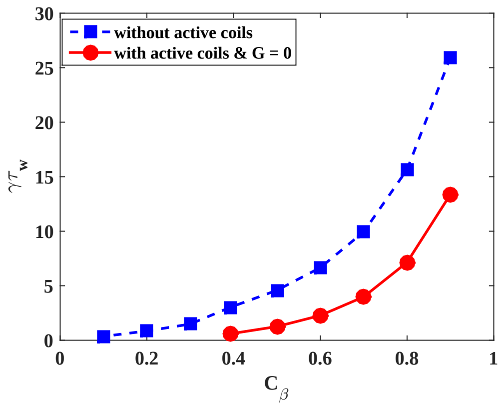

Figure 2: The open-loop growth rate of the $n = 1$ RWM, normalized by the wall time, versus the plasma pressure scaling factor C_β. Here $C_\beta = (\beta_N - \beta_N^{no-wall})/(\beta_N^{ideal-wall} - \beta_N^{no-wall})$. Compared are results with and without inclusion of the L/R response of active coils (as passive conductors). The L/R time of active coils is fixed at ten times larger than the wall time.

For a typical RWM in ITER, and in the presence of the L/R response of active coils, we find that linear closed loop eigenvalue (without voltage saturation and without sensor signal noise) becomes complex-valued *before* the mode is fully stabilized, as the feedback gain is increased. This behavior is again qualitatively explained in terms of a two-pole analytic plasma response model. Nevertheless, sufficiently large feedback gain does lead to full stabilization of the $n = 1$ RWM in ITER up to the ideal-wall beta limit, if we ignore the control voltage limitation as well as the sensor noise. Moreover, the mode stabilization can be further enhanced by adding the upper and lower sets of active coils and by tuning the toroidal phase of the feedback gains associated with the two sets of off-middle coils.

When the proportional controller is adopted in the feedback system, posing an upper limit on the control power voltage may result in loss of control of the RWM in ITER, for cases where the proportional feedback gain exceeds the critical gain value, i.e. the closed loop is linearly stable. In order to avoid the loss of control, the control power saturation limit, $V_f^{\rm limit}$, must be larger than a threshold value $V_f^{\rm min}$. Fortunately for ITER, this threshold value is rather small - in the order of ~ 1 V in the absence of sensor signal noise. Moreover, figure 3 shows that the $V_f^{\rm min}$ value decreases with increasing the feedback gain for ITER plasmas. This favorable tendency is solely related to the fact that the eigenvalue of the corresponding linear closed loop (in the absence of voltage limit) is complex-valued. Without the latter property, i.e. with real closed loop eigenvalue, $V_f^{\rm min}$ is analytically predicted [5] and numerically verified [6] to be independent of the feedback gain.

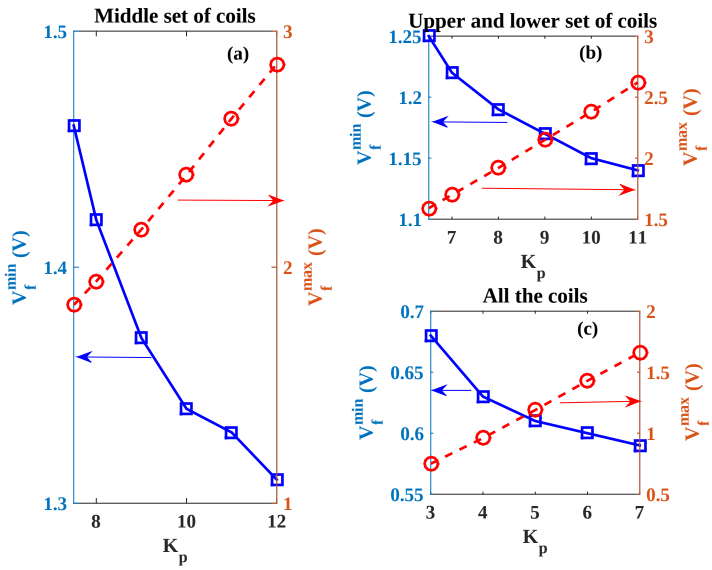

Figure 3: The MARS-F computed maximal control voltage $V_f^{\rm max}$ (dashed curves) and minimal voltage $V_f^{\rm min}$ (solid curves), as defined in the text, versus the feedback gain, for three active coil configurations: (a) single middle set, (b) upper and lower sets, and (c) all three sets. The phase of feedback gains are fixed at ($\phi_U = 150^{\rm o}$, $\phi_L = -150^{\rm o}$) for (b,c) .

The presence of the sensor signal noise, however, can significantly increase the tolerable level of the RWM control power saturation in ITER. For the feedback system with proportional controller only, the typical RWM at $C_\beta = 0.5$ (which is close to the ITER target plasma) with the feedback gain well beyond the critical value for the linear closed loop stability, can still be easily unstable if $V_f^{\rm limit}$ is below 4 V at the sensor signal noise level of $\sigma_{\rm noise} = 0.25$ G (Fig. 4), and $V_f^{\rm limit}$ below 40 V at $\sigma_{\rm noise} = 1$ G. Based on a statistical approach, where we run 20 initial value simulations with different noise samples for each fixed pair ($V_f^{\rm limit}$, $\sigma_{\rm noise}$), we evaluate that 90% of success rate for the mode control requires $V_f^{\rm limit}$ to be above 40 V for ITER, taking a conservative estimate of the high-frequency sensor signal noise level of $\sigma_{\rm noise} = 1$ G.

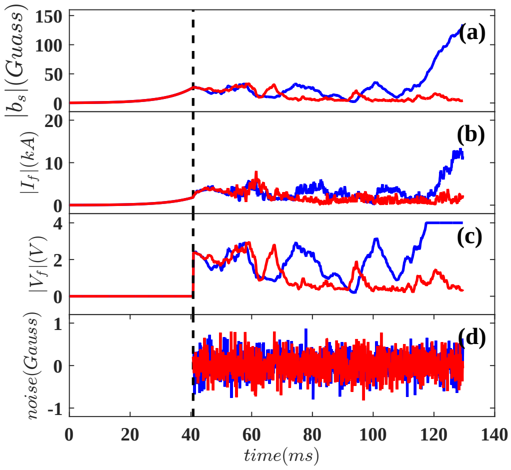

Figure 4: Two examples of initial value simulation of the $n = 1$ RWM feedback with control voltage saturation and sensor signal noise.Compared are (a) amplitude of the poloidal sensor signal, (b) the control coil current, (c) the control voltage, and (d) two samples of machine-generated noise sequence with Gaussian distribution and standard deviation of $\sigma_{\text{noise}} = 0.25$ G. The ITER plasma at $C_\beta = 0.5$ is considered. The middle set of active coils are used as the control actuator, with $\tau_f/\tau_w = 10$ and with feedback gain $K_p = 10$. The control voltage limit is set at $V_f^{\text{limit}} = 4$ V.

References

[1] Y. Q. Liu *et al.* 2017 *Fusion Sci. Technol.* **70** 387

[2] Y. Q. Liu *et al.* 2000 *Phys. Plasmas* **7** 3681

[3] E. F. Daly *et al.* 2013 *Fusion Sci. Technol.* **64** 168

[4] M. Okabayashi *et al.* 1998 *Nucl. Fusion* **38** 11

[5] L. Li *et al.* 2012 *Phys. Plasmas* **19** 012502

[6] S. Wang *et al.* 2018 *Fusion Sci. Technol.* **73** 519