36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-1.165 (2009)

Physical description of external circuitry for Resistive Wall Mode control in ASDEX Upgrade

W. Suttrop[1], D. Hahn[1], J. Hartmann[1], A. Herrmann[1], M. Rott[1], B. Streibl[1], W. Treutterer[1], T. Vierle[1], D. Yadikin[1], I. Zammuto[1], E. Gaio[2], V. Toigo[2], P. Brunsell[3], E. Olofsson[3], and the ASDEX Upgrade Team

[1]Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85740 Garching, Germany
[2]Consorzio RFX, Associazione EURATOM-ENEA, I-35127 Padova,
[3]Royal Institute of Technology KTH, Association EURATOM-VR, SE-10044 Stockholm

Introduction

A set of in-vessel saddle coils has been developed for ASDEX Upgrade [1, 2] that is intended for ELM suppression, locked-mode avoidance for disruption control and feed-back Resistive Wall Mode (RWM) control [3, 4]. In conjunction with a realistic 3D copper wall structure (thickness: 5 mm), unstable RWM growth rates up to 84.2 s^{-1} are predicted [5] for a realistic plasma scenario with normalised plasma beta $\beta_N = 2.62$. However, depending on β_N and plasma wall distance, the RWM growth rate can vary significantly. The RWM can be stabilised if an external field is produced (by the non-axisymmetric saddle coils as actuators) that compensates the RWM perturbation field. It is useful to combine magnetic sensor signals to form a controller input signal representative of a one or more unstable modes ("mode control") which can be controlled simultaneously. The various components of the active feedback loop, sensors, controller, power amplifier, actuator coils, all have frequency dependent gain and phase delays. Other parameters, such as controller gain and maximum tolerable dead time, can be specified for optimum closed loop performance. In this contribution, we consider optimum loop parameters of the planned RWM control system for ASDEX Upgrade that maximise the range of RWM growth rates that can be stabilised.

Control loop model

A simple scalar model is used to describe independent unstable plasma modes and an individual control loop for each mode. For a linear instability, the reaction of the plasma perturbation field $B_k(t)$ (time domain) or $B_k(s)$ (Laplace space) to an external field associated with an eigenmode k may be written as [6]

$$\dot{B}_k(t) - \gamma_k \cdot \left[B_k(t) + \frac{1}{\gamma_k \tau_k} B_k^{ext}(t) \right] = 0, \qquad \text{or} \qquad G_k \equiv \frac{B_k(s)}{B_k^{ext}(s)} = \frac{\gamma_k}{s - \gamma_k} \cdot \frac{1}{\gamma_k \tau_k} \tag{1}$$

where s is the complex Laplace coordinate, γ_k is the growth rate of the resistive wall mode instability (kth eigenmode), B_k^{ext} is the amplitude component corresponding to mode k of the field produced by external control coils, τ_k is the decay time constant for the current distribution associated with mode k in the resistive wall, and G_k is the plasma transfer function for this mode. Without specifying the wall geometry and without calculating $\gamma_k \tau_k$ for each individual plasma configuration, we assume $\gamma_k \tau_k = 1$, noting that it enters only as a frequency-independent factor in the loop gain which can be accounted for *a posteriori*. A magnetic sensor signal $U_k = n_s A_s \int \dot{B}_k \mathrm{d}t = n_s A_s B_k$ is formed as the time-integrated voltage induced in one sensor coil winding (cross section A_s, n_s turns; here: $A = 1$ cm^2, $n_s = 1000$) or, in practice, as a suitable linear combination of signals of spatially distributed sensors to

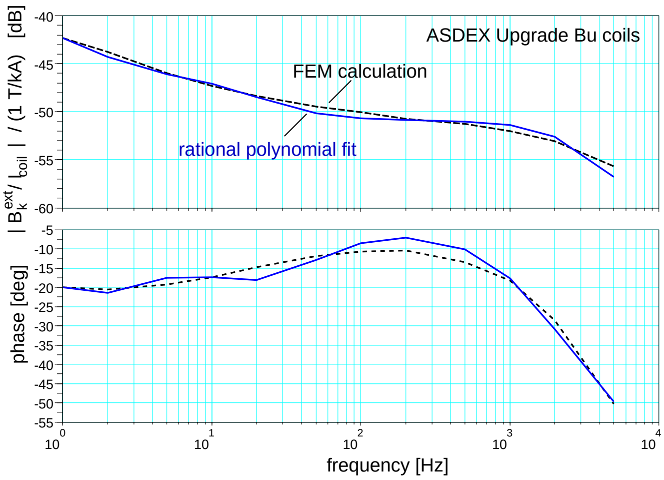

Figure 1: Bode plot of the coils response as calculated in Ref.[2] with finite elements (dashed curve) and rational polynomial fit (solid curve).

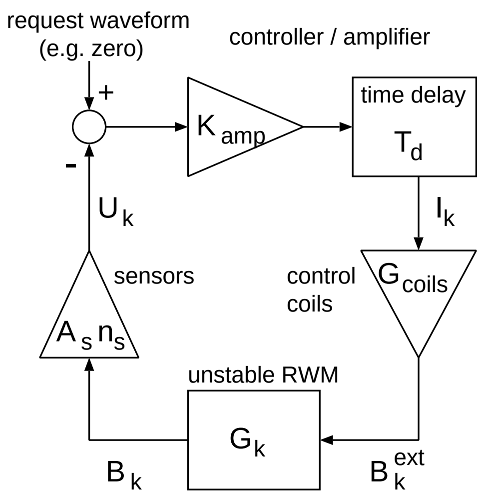

Figure 2: Schematic of the RWM control loop.

suppress false modes' contributions. U_k may be complex to reflect the spatial orientation of a mode, however only the amplitude is considered here as the sensor input to the controller. The controller requests the coil current, or best fitting coil current combination I_k, to produce the external field B_k^{ext} necessary to stabilise the mode. In general, the amplifier and coils response is frequency dependent with two main effects playing a role: (a) the attenuation and phase shift of the produced field B_k^{ext} due to image currents in conducting structures surrounding the control coils, (b) a time delay ("dead time") introduced by digital data transfer, the computing time of the controller, and the modulation scheme of a switched power amplifier. The magnetic field produced by the ASDEX Upgrade upper and lower in-vessel coils is assessed by finite-element calculations [2]. We concentrate on the upper ("Bu") coils that have the slowest response (worst case) and fit a rational polynomial to assess the normal field amplitude per unit current:

$$G_{coils} = \frac{B_k^{ext}}{I_k} = \frac{0.0102975 + 8.686794 \cdot 10^{-4}\, s + 4.6592 \cdot 10^{-6}\, s^2 + 2.727 \cdot 10^{-11}\, s^3}{1.0647639 + 0.1783119\, s + 0.0016405\, s^2 + 8.978 \cdot 10^{-8}\, s^3} \mathrm{T/kA} \tag{2}$$

A Bode plot of this function, compared to the original FEM data, is shown in Fig. 1.

For proportional control, the amplifier (gain K_{amp}, dead time T_d) is described as:

$$G_{amp} = \frac{I_k}{U_k} = K_{\mathrm{amp}}\, e^{-T_d \cdot s} \approx K_{\mathrm{amp}} \left(1 + \frac{T_d \cdot s}{n}\right)^{-n}; \quad n = 8 \tag{3}$$

The complete model of the control loop is depicted as a schematic diagram in Fig. 2.

Open loop response

The open loop response (magnitude and phase) is shown in the Bode plots Figs. 3 and 4 for a slow unstable RWM ($\gamma_k = 84.2\ \mathrm{s}^{-1}$ as in Ref. [5], gain $K_{\mathrm{amp}} = 3.55 \cdot 10^6$ A/Vs) and a hypothetical fast growing mode ($\gamma_k = 3000\ \mathrm{s}^{-1}$, $K_{\mathrm{amp}} = 3.76 \cdot 10^6$ A/Vs), respectively. The dead time is varied between $T_d = 10\ \mu$s and 100 ms and the gain is chosen for maximum dead time in a stable loop. This maximum dead time is $T_d \leq 5.6$ ms for the slow and $T_d \leq 0.2$ ms for the fast mode; however, for these marginal cases the phase margin (phase value above

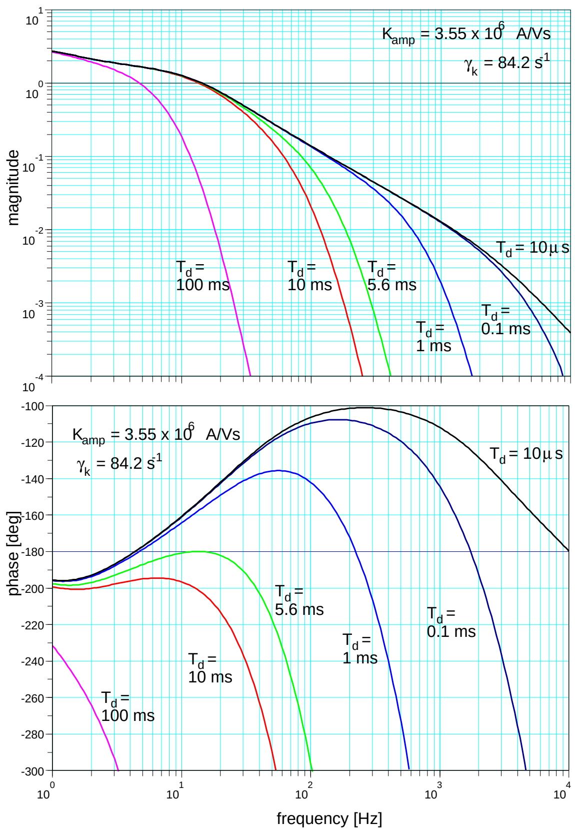

Figure 3: Bode plot (open loop gain magnitude and phase) for $\gamma = 84.2$ s^{-1} ($K_{\rm amp} = 3.55 \cdot 10^6$ A/Vs).

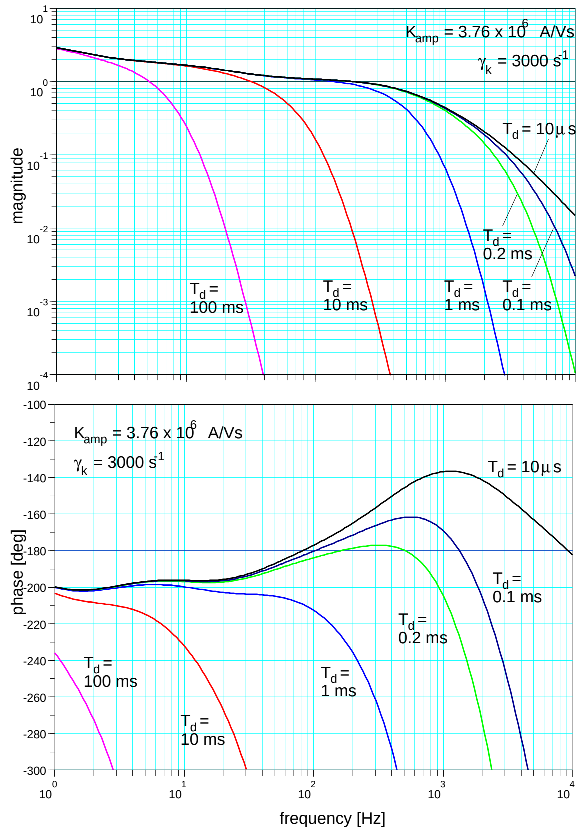

Figure 4: Bode plot (open loop gain magnitude and phase) for $\gamma = 3000$ s^{-1} ($K_{\rm amp} = 3.76 \cdot 10^6$ A/Vs).

-180 degrees at unity gain) vanishes. With a somewhat reduced dead time, $T_d = 1$ ms for the slow RWM and $T_d = 10$ μs for the fast RWM, a phase margin of about 20° can be recovered in both cases. Up to $f = 200$ Hz, the phase lag introduced by the control coils decreases with frequency (Fig. 1). Therefore, for fixed growth rate, a larger phase margin is obtained by increasing the amplifier gain, provided the dead time is kept sufficiently small. With $T_d = 10$ μs, the maximum phase margin is 80° (slow RWM, transit frequency $f_T = 300$ Hz, $K_{\rm amp}$ increased $\times 20$), and 42° (fast RWM, $f_T = 1.2$ kHz, $K_{\rm amp}$ increased $\times 3$).

Stable closed loop operation range

A more comprehensive picture of the stable operation range is given by the minimum and maximum values of $K_{\rm amp}$ as a function of the variable parameters γ_k and T_d (Fig. 5). In addition, the “optimum gain” (gain for minimum closed loop growth rate) is indicated. Fig. 6 shows the closed loop damping rate (stable loop) or growth rate (unstable loop) for optimum gain. The damping rate at optimum gain depends only weakly on γ_k or T_d for a stable loop. Stabilisation of the highest accessible γ_k requires gain values around $K_{\rm amp} \approx 4 \times 10^6$ A/Vs, almost independently of the dead time, however, the accessible values of γ_k depend strongly on T_d. At high γ_k, the optimum gain is close to the minimum gain and the phase margin remains small. Therefore, it is useful to increase the gain, even at the cost of a slight reduction of the maximum γ_k that can be stabilised.

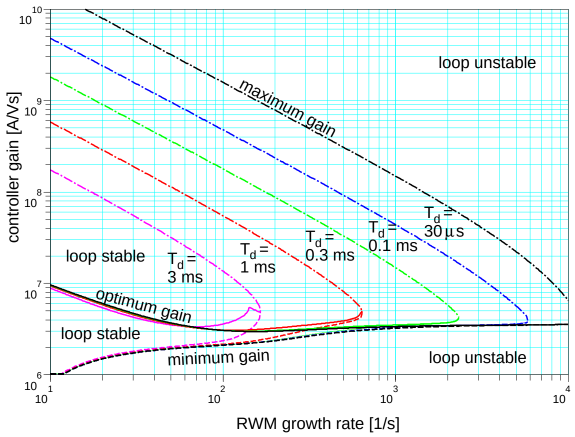

Figure 5: Stable range (minimum and maximum) of amplifier gain K_{amp} and optimum gain for varying RWM growth rate γ_k and various values of dead time T_d.

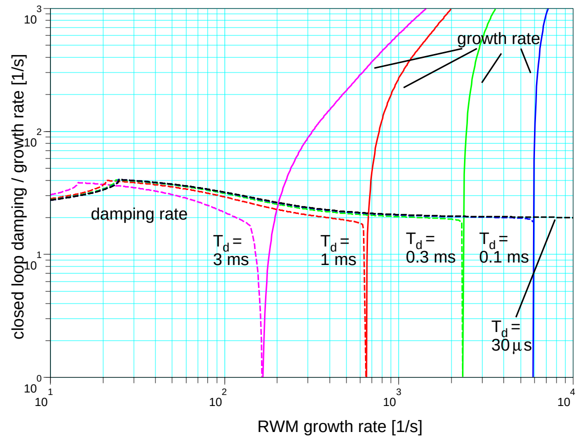

Figure 6: Closed loop growth rate (solid lines, stable loop) or damping rate (dashed lines, unstable loop) for optimum gain as shown in Fig. 5.

Conclusions

A simple scalar model of the control loop planned for ASDEX Upgrade shows that a proportional controller is sufficient to stabilise the RWM. Furthermore, with fixed controller gain (control coil current vs. sensor flux) a wide range of RWM growth rates is covered, a convenient feature for practical operations. With realistic loop parameters, total delay time $T_d = 0.1$ ms, and controller gain $K_{\mathrm{amp}} = 2 \times 10^7$ A/Vs $\times \gamma_k \tau_k$, RWMs with $\gamma_k \leq 3000$ s^{-1} can be stabilised. This γ_k range is much larger than needed for the case of Ref. [5] and provides flexibility for variations of β_N and the plasma-wall distance. However it is important to note that a sufficiently short dead time of the control loop is crucial to maintain the favourable phase response of the control coils. In the present study the frequency response of the sensor coils is neglected. In the mode control scheme, there is some flexibility to mount sensors at a distance from passive structures, and oriented to measure the field component tangential to the conductor surfaces to minimise the phase lag introduced by eddy currents. If all sensors behave similarly, treatment of their common transfer function is straightforward.

References

[1] T. Vierle *et al*, Fusion Eng. Design 84 (2009) 1928

[2] M. Rott *et al*, Fusion Eng. Design 84 (2009) 1653,

[3] W. Suttrop *et al*, in *Europhysics Conference Abstracts (CD-ROM, Proc. of the 35th EPS Conference on Plasma Physics, Hersonissos, Crete, 2008)*, volume 32D, P4.075

[4] W. Suttrop *et al*, Fusion Eng. Design 84 (2009) 290

[5] S. Günter *et al*, Plasma Phys. Controlled Fusion 50 (2008) 124004.

[6] P. R. Brunsell *et al*, Phys. Plasmas 14 (2007) 102505.