Enhancements of the real-time magnetic equilibrium on ASDEX Upgrade

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Introduction

Pre-emptive stabilisation of a neoclassical tearing mode, NTM, and disruption avoidance using real-time magnetic equilibria to feedback control a launching mirror for electron cyclotron current drive (ECCD) have been demonstrated in ASDEX Upgrade [1, 2, 3]. Real-time magnetic equilibria are calculated by a Grad-Shafranov solver constrained to fit 40 magnetic probes and 18 flux loop differences. The 33x65 poloidal flux matrix is available on the reflective memory network with a 2 ms cycle time. Four enhancements of the real-time magnetic equilibrium solver (JANET) [2] on ASDEX Upgrade have been implemented.

Basis functions

The magnetic equilibrium for a tokamak is described by the Grad–Shafranov equation :

$$\frac{\partial^2 \psi}{\partial R^2} - \frac{1}{R}\frac{\partial \psi}{\partial R} + \frac{\partial^2 \psi}{\partial Z^2} = -\mu_0 R j_\phi(R,Z) \tag{1}$$

$$j_\phi(R,Z) = R\frac{\partial p}{\partial R} + \mu_0 \frac{F}{R}\frac{\partial F}{\partial R} \tag{2}$$

where ψ is the poloidal flux per steradian, j_ϕ is the current density, and R, Z and ϕ are the cylindrical coordinates. The plasma pressure, p, and poloidal plasma current, F , are functions of ψ. The number of current density basis functions for the solver has been increased to 6 splines for the p' terms and 6 splines for the FF' terms. The coefficients of the basis functions (α_i for the p' terms and β_i for the FF' terms) giving the best fit to the magnetic probe and flux loop measurements are obtained with a least squares solver using second order regularisation. To achieve a cycle time of 2 ms, it was necessary to use look up tables of pre-calculated values as a function of normalised poloidal flux for generating the current density basis functions on the poloidal flux matrix and for the integrals for the evaluation of F.

Transfer function

The amplitude and phase response of the magnetic probes to the currents in the poloidal field coils used for fast vertical plasma position control were measured at four frequencies (10, 20, 40 and 80 Hz). This experimentally determined transfer function can be expressed as a set of

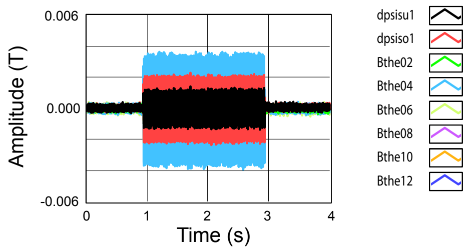

Figure 1: *Difference of measured and calculated magnetic probe signal when supplying an 80 Hz current to the upper fast control coil without compensation for the transfer function due to the vacuum vessel between the control coil and probe.*

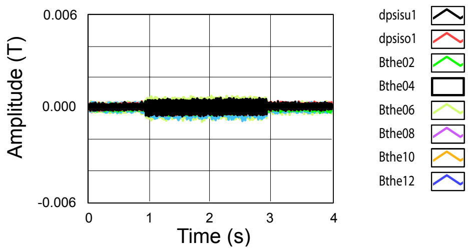

Figure 2: *Difference of measured and calculated magnetic probe signal when supplying an 80 Hz current to the upper fast control coil with compensation for the transfer function due to the vacuum vessel between the control coil and probe.*

filter coefficients operating on the coil currents and thus simulate the low pass filter effect of the vacuum vessel. The ability to calculate the magnetic field produced by these control coils and measured by the probes is demonstrated in Figs. 1 and 2. The 80 Hz current is excited for the time between 0.9 s and 2.9 s. The amplitude and phase response of the magnetic probes to the coil currents is now successfully taken into account as the difference of measured and calculated probe signal can be reduced to a value of smaller than 0.5 mT. This value is smaller than the 1 mT difference of measured and fitted signals required for real-time magnetic equilibrium reconstruction. This is particularly important for the current oscillations in the control coils resulting from the control system reaction to the presence of edge localised modes. Magnetic equilibria with vertical oscillations were produced when the low pass filtering effect of the vacuum vessel on the magnetic probe response was ignored.

Internal constraint

Without internal constraints for the magnetic equilibrium reconstruction from the Motional Stark Effect or polarimeter, it is advantageous to introduce a physically motivated safety factor constraint on the magnetic axis, q(0). This relates the coefficient of the spline basis functions at the magnetic axis (α_o and β_o) to q(0) [4] :

$$\alpha_o R_M^2 + \beta_o = \frac{2\pi}{\mu o} \frac{R_o B_o}{R_M} \frac{\kappa^2+1}{\kappa} \frac{1}{q(0)} \tag{3}$$

where κ is the plasma elongation, R_M is the radius of the magnetic axis, R_o is the radius of the vacuum vessel axis and B_o is the value of toroidal field at R_o. The safety factor profile, *q(r)*, is calculated from the flux surface contour integrals at ten values of normalised poloidal flux. Rational surfaces are located as a function of normalised radius by spline interpolation. For pre-emptive NTM stabilisation or disruption avoidance experiments it is necessary to choose a value of q(0) close to 1 in order to predict the location of the rational surface to within 0.05 of normalised radius. A launcher mirror is positioned to deposit ECCD on this rational surface.

Ferromagnetic tiles

The introduction of two rows of ferromagnetic tiles in ASDEX Upgrade to the inner heat shield requires that the perturbation of the probe measurements and the equilibrium near these tiles be calculated in real-time. The perturbations of the probe measurements and equilibrium can be calculated by a surface current model of ferromagnetic material in a tokamak [5, 6]. The magnetic probes for poloidal field measurements, with length 13 cm in the poloidal direction and 4.5 cm in the radial direction, are situated about 5 cm away from ferromagnetic tiles. The tile dimensions are 8 cm in the poloidal direction and 1.4 cm in the radial direction. A volume average of the calculated probe response is required for those probes close to the ferromagnetic tiles. For real-time calculation, this is reformulated into an average over the mutual inductances between points inside the probe volume and the ferromagnetic tile surface currents.

Shown in Fig. 3, are the calculated probe responses to the l surface current elements, i_s^l, flowing on the ferromagnetic tiles generated by the excitation of individual poloidal field coils that produce magnetic field at the tile surface, B_{ext}. The surface currents on the tile are calculated from the solution of a matrix equation relating B_{ext} and i_s^l and the requirement that the tangential components of magnetic field internal, $B_{\tau i}$ and external, $B_{\tau e}$, to the tile are related by the equation $B_{\tau i}/\mu_{eff} = B_{\tau e}$, where μ_{eff} is the effective magnetic permeability. The magnitude of the magnetic field at the tile surface is known for each poloidal field coil excitation. Therefore, a μ_{eff} can be predetermined for each current flat top in these calibration discharges without toroidal field. The small difference of calculated and measured probe response in the period of current flat top, shown in Fig. 4, indicates that the contribution due to ferromagnetic tiles has been modelled successfully. The magnetic probe signal due to the poloidal field coil current is 80 mT for the largest calculated perturbation of 13 mT. This calculation must reduce the flat top difference of calculated and measured signal to values smaller than 1 mT for magnetic equilibrium reconstruction.

For real-time calculations in plasma discharges with toroidal field, B_o, the matrix for calculating the surface currents for 24 elements is calculated prior to the discharge. The matrix for calculating the magnetic probe perturbation and perturbation of ψ on the grid due to the surface currents are also calculated prior to the discharge. The magnitude of perturbations of the magnetic probe measurements is typically a factor of 5 smaller than shown in Fig. 4, as μ_{eff} is much smaller for typical values of B_o = 2.5 T. To determine the current density distribution, j_ϕ(R,Z), flowing in the plasma, these ferromagnetic tile perturbations and the value of magnetic field due

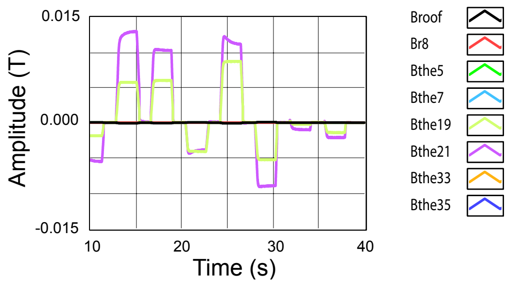

Figure 3: *Calculated magnetic probe response generated by the surface currents of ferromagnetic tiles when exciting currents in individual poloidal field coils in the absence of toroidal field.*

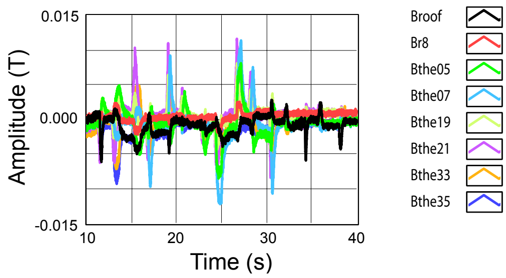

Figure 4: *The small difference of calculated and measured probe response produced by currents in poloidal field coils in the absence of toroidal field indicates that the contribution due to ferromagnetic tiles is successfully modelled.*

to the currents flowing in the poloidal field coil are subtracted from the magnetic probe measurements. The least squares solver then calculates the coefficients of the spline current basis functions giving the best fit of these corrected measurements.

Conclusion

Real-time magnetic equilibria are routinely available for feedback control of NTM's and disruption avoidance. The presence of two rows of ferromagnetic tiles and the modified probe response owing to the transfer function of the fast control coils caused by the vacuum vessel have been included in the real-time equilibrium calculation. The imposition of a constraint on q(0) is necessary to predict the location of the NTM to within 0.05 of normalised radius, as internal constraints by MSE or polarimeter measurements for the real-time equilibrium solver are not available. The equilibrium solver now uses 6 spline functions to represent the p' and FF' terms of the Grad-Shafranov equation and second order regularisation to obtain the fit coefficients.

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