Shape reconstruction and eddy currents estimation via Kalman Filter at the EAST tokamak

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Introduction

The real-time reconstruction of the poloidal flux map in a tokamak is usually carried out by means of iterative solvers of the Grad-Shafranov equation (e.g. RT-EFIT [6] and LIUQE [8]). These methods, however, suffer from two main disadvantages. First they have to forgo some accuracy to achieve the desired execution speed. Moreover, the effects of the currents induced in the passive structures (which are not directly measurable) are usually neglected. This last issue has already been addressed at the DIII-D tokamak, where Kalman filtering theory has been successfully used in order to estimate the eddy currents and include them in the real-time equilibrium reconstruction [9].

A possible extension to this approach is proposed in this paper. Exploiting the linearized models obtained by means of the CREATE equilibrium codes [1], which have been experimentally validated on several machines over the past years (e.g. JET [2], TCV [4], EAST [3]), a state observer can be designed. Once the state is known, a fast and accurate reconstruction of the plasma shape can be achieved exploiting the estimated static relation between the currents (including plasma and passive structures) and the flux map.

The CREATE equilibrium codes

The CREATE 2D equilibrium codes are FEM codes designed to solve numerically the Grad-Shafranov equation with a high degree of accuracy. Furthermore, they are able to generate linearized models of the plasma-circuits dynamical behavior in a neighborhood of the considered equilibrium configuration in a standard *state-space* form

$$\delta\dot{x}(t) = A\delta x(t) + B\delta u(t)\,, \tag{1a}$$

$$\delta y(t) = C\delta x(t) + D\delta u(t)\,, \tag{1b}$$

where $\delta u(t) = [\delta I_{PF}(t)\ \delta I_{IC}(t)\ \delta I_p(t)]^T$ is the input vector containing the current variations in the Poloidal Field Coils (PFCs in the following) and the Internal Coils (IC in the following), and the plasma current variation, while $\delta x(t)$ is the vector containing the variations in the poloidal fluxes linked to the input currents [5].

Recursive Kalman filter

The Kalman filter [7] is an algorithm which is used to estimate the state of a dynamical system starting from known inputs to the system and output measurements affected by uncertainty. In this work, its recursive formulation is considered. Given a linear dynamical discrete-time system[1]

$$x(k+1) = Ax(k) + Bu(k) + v_x(k)\,, \tag{2a}$$

$$y(k) = Cx(k) + v_y(k)\,, \tag{2b}$$

where the additive noise signals $v_x(k)$ and $v_y(k)$ are assumed to be gaussian, uncorrelated and with zero average, if we let[2]

$$Q = \mathrm{var}\left[v_x\right], \quad R = \mathrm{var}\left[v_y\right], \quad N = \mathrm{var}\left[v_x, v_y\right], \tag{3}$$

then the optimal bayesian linear estimator of the state variables is given by

$$L(k) = P(k|k-1)C^T \left[CP(k|k-1)C^T + R\right]^{-} 1\,, \tag{4a}$$

$$\hat{x}(k|k) = \hat{x}(k|k-1) + L(k)\left[y(k) - C\hat{x}(k|k-1)\right], \tag{4b}$$

$$P(k|k) = \left[I - L(k)C\right]P(k|k-1)\,, \tag{4c}$$

$$\hat{x}(k+1|k) = A\hat{x}(k|k) + Bu(k+1)\,, \tag{4d}$$

$$P(k+1|k) = AP(k|k)A^T + BQB^T\,. \tag{4e}$$

It is important to remark that a tokamak plasma is far from being a linear system. Nevertheless, in the neighborhood of a given equilibrium, the results proved to be good even when the plasma behavior is approximated by a linearized model.

Application to the EAST tokamak

To test the proposed algorithm, a collection of 10 upper null pulses done at EAST has been used [10]. The considered pulse set includes pulses #7130, #71308, #71309, #71372, #71375, #71379, #71380, #71381, #71382, #71464. A single linearized model was generated using the data related to pulse #71307 at 4 s and then used for all the other pulses, in order to verify that

[1] Model (1) can be recast in a discrete-time formulation via standard discretization methods.

[2] With var$[\cdot]$ we denote the covariance matrix of a signal vector.

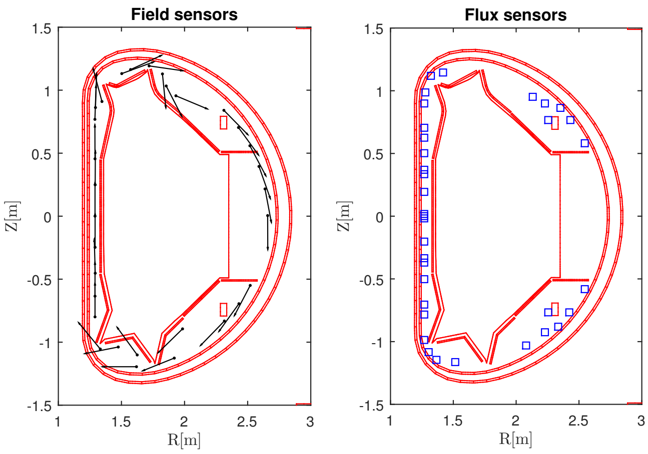

Figure 1: *Field and Flux sensors used for the simulations.*

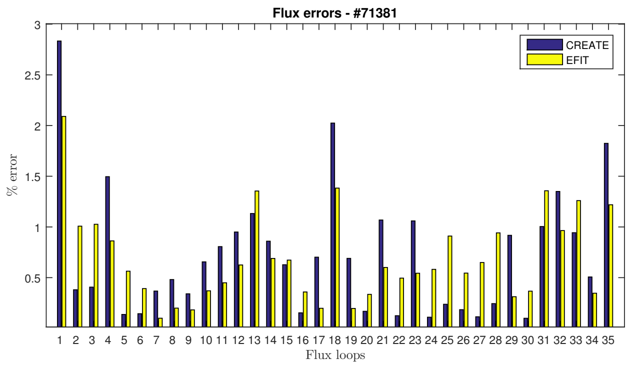

Figure 2: *Mean error in the flux probes traces for EFIT and the approach proposed in this paper (labeled as CREATE in the figure). The errors are comparable and always under the 3% of the total poloidal flux.*

the same model provides a good response even for different plasma discharges. In this way, in a realistic control-room scenario, the linearized model obtained using data from the designed scenario (or from a similar discharge done in a previous experimental session) should work also for a new experiment, provided that the controller succeeds in keeping the plasma parameters near to the desired values.

On the EAST tokamak, 43 field measurements and 35 poloidal flux probes are available. Of these, the ones used for the simulation are shown in Fig. 1 (some of the sensors were removed because their measurements were judged unreliable). The filter received as inputs the output vector of the system (magnetic probes and plasma current) and the measured PFC and IC currents. The covariance matrices R, Q were estimated exploiting the experimental data of pulse #73107.

Conclusions and future work

In this paper a preliminary step towards the application of the Kalman filtering theory to plasma shape reconstruction in tokamak devices was presented. To achieve better performances in a real-time implementation, the matrices of the linearized model used by the filter could be updated during the pulse (e.g. pairing the observer with a slower cycle that linearizes the plasma response, which may take advantage of the eddy currents estimation provided by the Kalman filter for an increased accuracy in solving of the Grad-Shafranov equation). Furthermore, an extended Kalman filter could be used to take into account some nonlinear effects. Finally, the effect of β_p and l_i variations was neglected in this paper. However, an estimate of these quantities could be used to further increase the amount of information available to the observer.

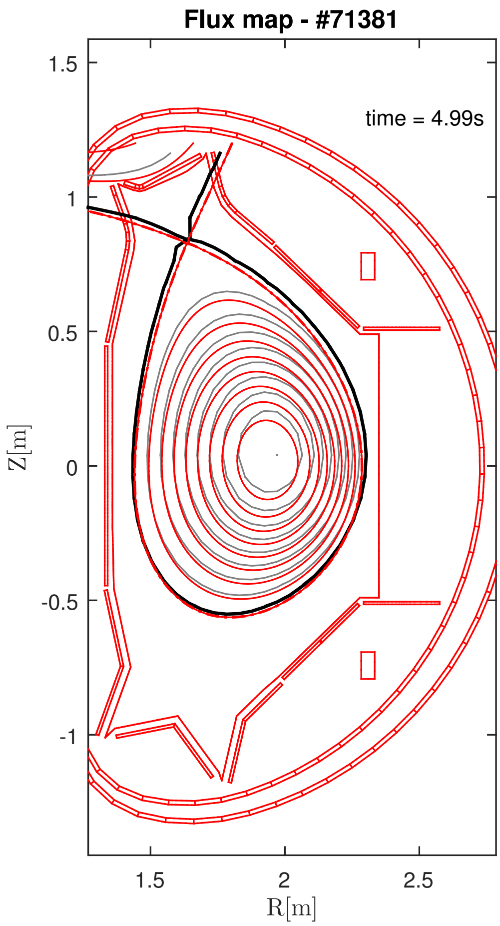

Figure 3: *Comparison between the obtained flux map (in gray) and the one computed by EFIT (in red).*

References

[1] R. Albanese, R. Ambrosino, and M. Mattei. CREATE-NL+: A robust control-oriented free boundary dynamic plasma equilibrium solver. *Fus. Eng. Des.*, 96–97:664–667, Oct. 2015.

[2] R. Albanese et al. Overview of modelling activities for Plasma Control Upgrade in JET. *Fus. Eng. Des.*, 86(6–8):1030–1033, 2011.

[3] R. Albanese et al. ITER-like Vertical Stabilization System for the EAST Tokamak. *Nucl. Fus.*, 57(8):086039, Aug. 2017.

[4] M. Ariola et al. A modern plasma controller tested on the tcv tokamak. *Fusion Technology*, 36:126–138, 1999.

[5] A. Castaldo et al. Simulation Suite for plasma magnetic control at EAST tokamak. *Fus. Eng. Des.*, 2018.

[6] J. R. Ferron et al. Real time equilibrium reconstruction for tokamak discharge control. *Nucl. Fusion*, 38:1055, 1998.

[7] R. E. Kalman. A new approach to linear filtering and prediction problems. *Transactions of the ASMEâĂŞJournal of Basic Engineering*, 82(Series D), 1960.

[8] J. M. Moret, B. P. Duval, H. B. Le, S. Coda, F. Felici, and H. Reimerdes. Tokamak equilibrium reconstruction code LIUQE and its real time implementation. *Fus. Eng. Des.*, 91:1–15, 2015.

[9] Y. Ou, M. L. Walker, E. Schuster, and J. R. Ferron. Equilibrium reconstruction improvement via Kalman-filter-based vessel current estimation at DIII-D. *Fus. Eng. Des.*, 82:1144 – 1152, 2007.

[10] B. J. Xiao et al. Integrated plasma control for long pulse advanced plasma discharges on EAST. *Fus. Eng. Des.*, 128:90–94, 2018.