Model-based frequency decoupled control of plasma shape and position in the TCV tokamak

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Introduction

Shaping the plasma to an elongated cross section leads to improved performance in tokamaks and requires feedback control of the vertical instability. The TCV tokamak is designed for extreme plasma shaping and features 16 independently powered poloidal field coils and a pair of antiseries coils internal to the vacuum vessel dedicated to vertical stabilization. An isoflux real time shape controller [1] relying on LIUQE [2] magnetic equilibrium reconstruction had previously been tested using the SCD digital distributed control system [3]. However, shaping of high performance elongated plasmas in TCV remains challenging as vertical stabilization shares the same actuators (PF coils) with the shape controller and is not yet routinely used.

In this work, we propose an improvement to the legacy shape controller allowing independent shape and position control design acting on different time scales, thus achieving frequency decoupling. Firstly, the vertical controller is optimized including the plasma dynamics as part of the design and the performance improvement is measured in dedicated experiments. Subsequently, the shape controller is designed on the basis of an improved model for the plasma deformation, which includes the plasma contribution to the magnetic flux perturbation.

Optimized vertical control in TCV

The vertical instability in TCV plasma discharges is stabilized using a feedback controller for the voltage applied to the PF coils. This voltage is a function of the displacement in the plasma reference position observed with linear combinations of magnetic diagnostics. In this work, vertical control in TCV is optimized by applying modern control theory to models for the plasma dynamics coupled with the vessel and the coil currents' evolution, separating optimal coil selection and controller synthesis.

The optimal coil combinations or actuation directions for vertical control are different on long and short time scales. On time scales longer than the vertical instability growth time but shorter than the plasma discharge, directions for position control (T_{zI} and T_{rI}) are derived to minimize the PF coil currents for plasma positioning and to be orthogonal to the remaining coil combinations used for shape control. On fast time scales, vertical control is performed using
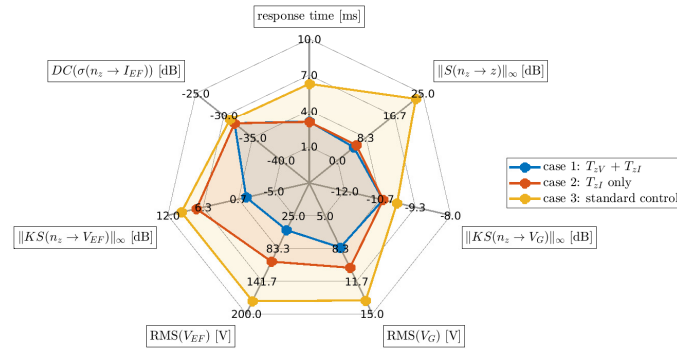
Figure 1: Vertical control performance summarized in a star plot. Several figures of merit are represented for the three schemes for vertical control that were tested experimentally. The best performance is defined by the smallest shaded area, which corresponds to the vertical controller combining T_{zV} and T_{zI}.

an actuation direction T_{zV} computed for optimal input selection by aligning it with the input pole vector of the dynamical model corresponding to the vertical unstable mode. This allows the minimization of the peak of the control sensitivity for the stabilization of an unstable system [4] which in practical terms leads to a reduction of the voltage request to the power supplies for vertical control. Instead of including the internal coil in the input pole vector, it is kept as an extra degree of freedom T_G in the optimization due to the different nature of its fast-switching power supply that does not tolerate DC currents for extended periods of time.

Subsequently, structured H_∞ [5] is applied for synthesizing a stabilizing vertical controller featuring a desired structure (proportional control along T_{zI}, derivative control along T_{zV} and separate derivative control along T_G). This provides an optimized controller for the vertical position with a structure analogous to the legacy analog controller of TCV, allowing quantitative performance comparison. The model-based controller synthesis is constrained to respect a set of performance requests defined as closed loop frequency response functions. This allows obtaining a desired controller bandwidth (response time) and minimizing the input usage in terms of peaks in transfer functions from noise on the vertical position to coil currents and voltage requests to the power supplies. A general set of performance filters is used such that the requirement for tuning is minimized for different equilibria that can be realized in TCV.

Results are provided in terms of simulations of the RZIp model [6] in closed loop with the optimized vertical controller and the magnetic control system of TCV, as well as in terms of experimental runs during plasma discharges. The plasma equilibrium used for validation is characterized by a relatively large vertical instability linear growth rate of 1 kHz. The results
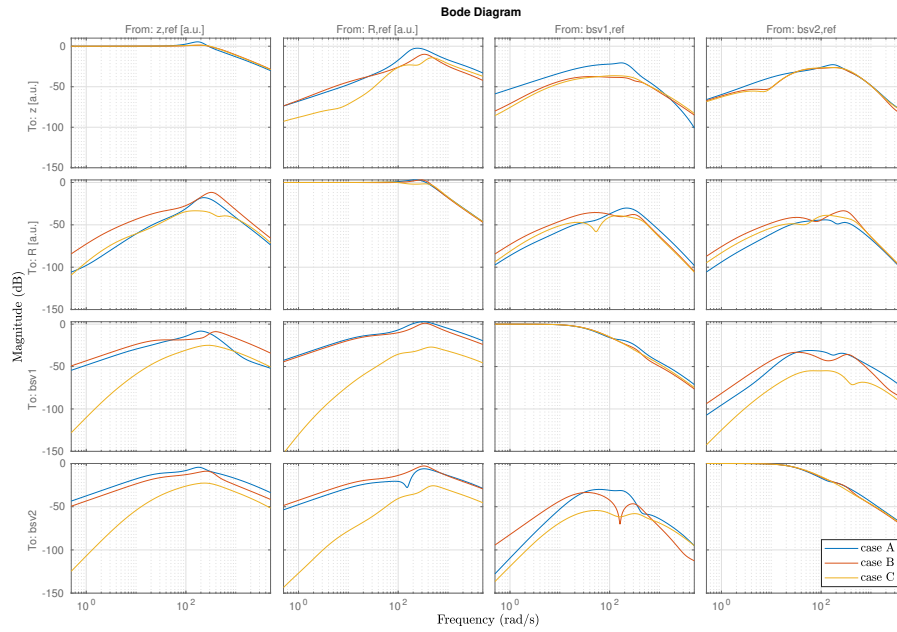
Figure 2: Bode plots for the closed loop for shape and position control coupling RZIp and G_0. The transfer functions on the diagonal show exact tracking of the reference up to the bandwidth, the off-diagonal terms show no residual coupling in steady state.

show a reduction in the amplitude of the vertical position oscillations, indicating larger stability margins. The performance improvement is quantified using a set of figures of merit, which are scalar performance parameters for the closed loop model and for the experimental power supply usage. The best performance is obtained combining T_{zI} and T_{zV}, confirming the validity of the approach for vertical controller synthesis.

Decoupled shape and position control

The shape controller is designed to respond only to shape deformation and is integrated in the magnetic control loop to modify the pre-programmed coil current references in real time.

In order to have a position control loop consistent with shape control, the position estimator is corrected at low frequency with the radial and vertical displacement of the last closed flux surface. This displacement is obtained using a matrix O_{zr} acting on fluxes and fields on a set of control points, estimated by the LIUQE real-time equilibrium reconstruction code [2]. The shape controller design is based on a static plant for the plasma deformation where the low frequency plasma response is modeled as $G_0 = \partial \psi / \partial I_a$ which is a perturbed Grad-Shafranov equilibrium following a variation in the PF coil currents. Shape observers O_{sh} combine the outputs of G_0 to controlled quantities and shape actuation directions T_{sh} define the coil combinations for shape control such that $O_{sh}G_0T_{sh}$ is diagonal and $O_{zr}G_0T_{sh} = 0$.

The plasma vertical dynamics is included taking as an input for the static model G_0 the state I_a of the RZIp model (PF coil currents) including the position controller in closed loop. Fig. 2 shows the frequency response to variations of the references for vertical and radial plasma position and the first two shape variables. The frequency separation of shape and position control is obtained by appropriately tuning the shape controller that acts on a stable dynamical system and is observed in the different bandwidths of the transfer functions along the diagonal. Three schemes are studied for decoupling shape and position control. In case A, the standard position controller is used, relying on the tuning provided by the tokamak operator. In case B, the low frequency actuation directions for plasma position are derived to minimize the coil currents used for plasma displacement, but only in case C is exact decoupling obtained in the sense that $O_{sh}G_0T_{zr} = 0$ using a weighted singular value decomposition. Case C shows the lowest coupling at most frequencies, pointing to the best performance. Both cases B and C require tuning of the vertical controller that can be obtained with the optimized scheme described earlier. Further analysis will be performed to show the trade-offs of the MIMO system, in particular in terms of power supplies requirements.

Conclusions and outlook

The presented extension of the legacy shape controller to a frequency decoupled scheme featuring optimized vertical control aims to simplify its usage in standard TCV operations. Future work will determine the best scheme for shape control in terms of several trade-offs given by closed loop frequency responses, integrating linear and nonlinear free-boundary model simulations [7] and testing the shape controller in experimental runs.

Acknowledgements

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