Model based feedback control system of plasma shape in RFX-mod Tokamak discharges

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Introduction

The RFX-mod experiment (R/a = 2.0/0.46 m), originally designed to produce high current Reversed Pinch Field plasmas (plasma current up to 2 MA), is currently operated also as a low current circular low-q Tokamak (Bt ~ 0.55 T, Ip ~150 kA @ qa≈2). The MHD active control system allowed obtaining Tokamak discharges at 1.3≤qa≤2 through the feedback stabilization of m=2, n=1 mode. In order to extend the significance of these studies, the achievement of X-point divertor like configurations and possibly ohmic H-mode discharges was planned. As a preliminary step, stable D-shaped plasma discharges were obtained in the past years with a feedforward generation of the 8 Field Shaping Coil (FSC) current references and an effective feedback control system of the vertical position. This was implemented by acting on the m=1, n=0 current component of the outer and inner array of saddle coils of the MHD active control system. A feedback control system of plasma ellipticity was then designed following a Single-Input-Single-Output approach and successfully operated to gain experience in plasma shaping [1]. The design of a full model based Multiple-Input-Multiple-Output (MIMO) control of the plasma shape [2] has now been accomplished after the development of a new linearized plasma response model obtained by CREATE_L code [3]. In order to generate reliable feedback signals, a new plasma boundary reconstruction algorithm was developed providing estimates of 8 plasma boundary distances from the first wall (gaps) and the 2 X-point positions. The algorithm is capable of removing the spatial aliasing errors in the magnetic flux and field measures due to the Field Shaping Coils [4]. The control system including a Kalman Filter and a LQ regulator along with the boundary reconstruction algorithm were fully implemented in the RFX-mod MARTe framework. A recent experimental campaign allowed successful testing of the new shape control system performance and robustness in the presence of plasma disturbances.

Linearized plasma response model

Equilibrium data of an open loop Double Null (DN) discharge (34572) were used to derive the linearized plasma response model by means of CREATE_L code. The dynamic model is characterized by 193 states corresponding to the currents of the active circuits (8 FSC, 4 magnetizing winding (M) sectors, 1 outer-inner array and 1 up-down array of saddle coils (SC), respectively), the passive structures (60 Inconel vessel, 59 copper shell and 59 stainless steel support structure) and the plasma. The presence of poloidal cuts in the shell and the support structure is also implicitly taken into account imposing that their total current be null. One nearly vertical unstable mode is exhibited by the model with a growth time of about 35 ms, consistent with the characteristics of the RFX-mod passive structures. The equilibrium reconstruction by CREATE_L code is shown in fig.1. Before using the model for the design of the control system, the degrees of freedom were further reduced to take into account the topology of the real RFX-mod poloidal field system, made up of four equal sections where two FS coils are connected in parallel with a sector of the magnetizing winding. A proper reconnection matrix was added to express each M current as a function of two FSC currents. The final model with 188 states was obtained after removing the state corresponding to the current of the up-down SC array, whose control is performed independently of the equilibrium field configuration. The model outputs include both the direct estimate of the gaps and the magnetic measurements (8 poloidal fluxes and 8 poloidal field components), all the quantities being expressed in terms of variations with respect to the equilibrium values. The input signals are the 8 voltages of the FS coils and the voltage applied to the outer-inner array of saddle coils.

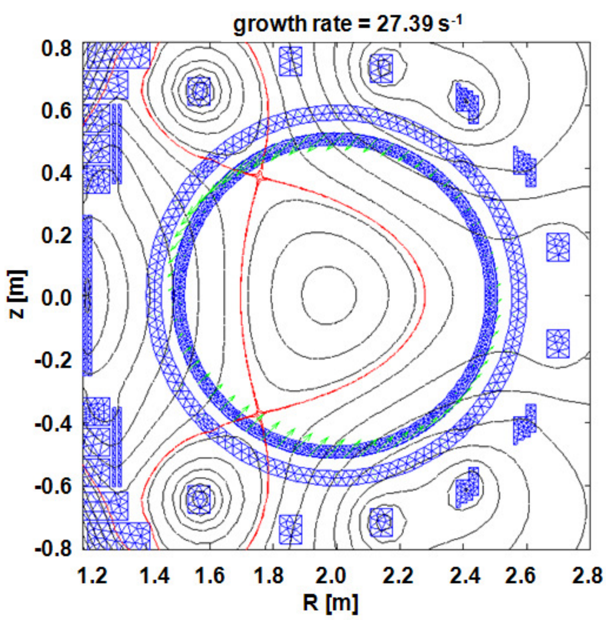

Fig. 1. Shot 34572: equilibrium reconstruction by Create_L code

Control system design

Both the theoretical estimates of the growth rate and the experimental tests showed that the feedback stabilization of the vertical position was not a major concern in RFX-mod. A simple proportional controller of the vertical position can assure the vertical stability of the plasma discharge. Once obtained a stable model, input signals were reduced to the 8 FSC voltages, while the

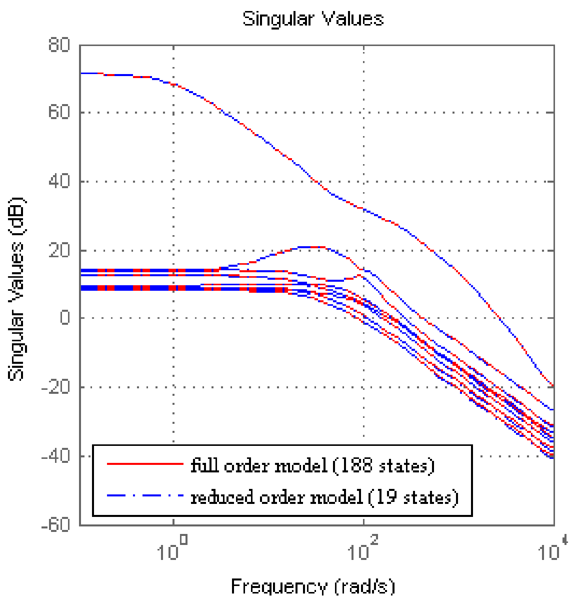

Fig. 2. Singular value Bode plot of full and reduced order model

output matrix was rearranged to extend the output vector with quantities needed by the shape control system such as the FSC and plasma currents. A reduction of the model order was the following step in view of the control system design and on-line implementation. A technique based on Hankel singular values was adopted which allowed a satisfactory reproduction of the system dynamics with only 19 states, even if it must be reminded they lose any direct physical meaning. In fig. 2 the singular values of the frequency response of the full (188 states) and the reduced order model (19 states) are compared: they are nearly indistinguishable even beyond the frequency range of interest (0-1000 rad/s). The control system consists of a Kalman Filter as an estimator of the states of the reduced order model and a linear-quadratic (LQ) regulator. Measurement noise covariance data were used for the design of the Kalman filter, while the LQ optimal gain matrix was obtained minimizing a cost function where quadratic forms of states and inputs are included. Maximum gap and FS current deviations are converted into a state weighting matrix and maximum deviations of FS coils voltages are converted into input weighting matrix. Different combinations were tested according to the desired control performances. Dominant time constants were typically within 5-10 ms for the estimator and 25-40 ms for the shape controller.

Experimental results

Implementation and testing of both the new shape control system and the on-line reconstruction algorithm were sped up by the availability of a full real time system simulator replicating the whole flow of signals within MARTe framework. Initially the control system was operated as a regulator, verifying its capability to maintain the amplitude of the gaps at the values of the control insertion time. In particular, the robustness of the control in the presence of disturbances was assessed by applying a β_ϑ variation obtained by injection of new gas in a short time window of the discharge. In fig. 3 the evolutions of the four outer (1, 2, 7, 8) gaps are compared with (shot 36380, insertion time at 0.45 s) and without control (shot

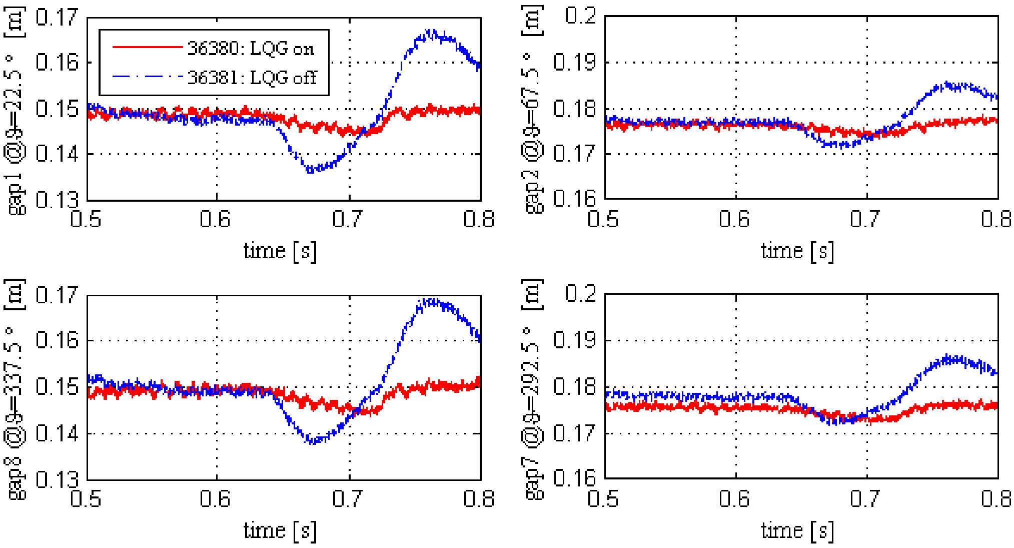

Fig. 3. Outer (1, 2, 7, 8) gap evolution in the presence of β_ϑ variation. Feedback control inserted at t=0.45 s, gas injection in the interval [0.63-0.71] s.

36381). As shown in the figure, the controller proved capable of coping with this kind of perturbations. The possibility of applying gap reference inputs was then added to the system and first tests confirmed its capability to track small variations of the shape during the discharge.

Conclusions

A completely new model-based plasma shape feedback control system has been designed and implemented in RFX-mod with the aim of obtaining reproducible double null discharges in Tokamak configuration. The multivariable controller allows exploiting better the available degrees of freedom of the FSC power supplies. It was successfully operated both as a regulator to keep the desired plasma shape in the presence of disturbances and to track small variations of the boundary. Further improvements of its performances could be achieved by testing different weighting matrices in the controller design and tuning feed-forward inputs on the basis of experimental data.

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