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ABSTRACT

A model-based multivariable controller for plasma shape control has been successfully tested on the DIII–D tokamak. Good steady-state control of plasma boundary shape and X–point position was demonstrated in lower single-null ohmic plasmas. Quality of control for rapid plasma shape variation was mixed, but was robustly stable for all degrees of freedom explored. The control design was based on a linear plasma response model derived from fundamental physics assumptions, which was extensively validated against DIII–D experimental data. A linear controller produced with robust control design methods was tested and improved using results of closed loop simulations prior to experimental tests. A modification of the linear controller which addressed one of several practical DIII–D nonlinear constraints was tested during the experimental discharges.

1. INTRODUCTION

The history of DIII–D plasma control is one of synergism between improvements in plasma control and advances in experimental physics. Improved control has increased experimental capability; more ambitious experiments have fueled desires for better control. Installation of the digital plasma control system (PCS) in 1992 [1] provided significant impetus to advances in control because of the ease with which new controls could be implemented. Starting in 1996, operational use of the realtime EFIT equilibrium reconstruction algorithm [2] provided unprecedented accuracy in real time estimation of the plasma boundary position. These capabilities contributed to an increased ease in accurately and reproduceably achieving a variety of plasma shapes and consequently to improved experimental productivity. Concurrent with improvements in control were additions of new in-vessel hardware which increased the difficulty of control. This created the need for more operator tuning to obtain effective control. A fundamental improvement on the present empirical control design methodology is now required. Near term objectives are to reduce experimental time spent on control related issues and to improve control of the plasma shape. Approximately 20 to 25 percent of experimental time is spent dealing with control issues because of the increasing diversity of DIII–D plasmas. Control solutions are needed to reduce control oscillations, improve robustness to shape changes, obtain and control more difficult shapes, and incorporate operational constaints such as power supply limitations. Longer term, new methods are needed to improve the process of new shape development, and for simultaneous shape and current profile control needed for Advanced Tokamak operation.

This paper describes the successful experimental implementation of a model-based multiple-input-multiple-output (MIMO) algorithm for control of plasma shape and position on DIII–D. Model-based control requires developing and maintaining dynamic models of plasma evolution and interaction with control coils. Relatively little use has been made of modern multivariable control design methods in operating tokamak experiments. The most extensive implementation on a tokamak was achieved by a collaboration between the TCV device team and the CREATE consortium, employing a controller design based on a high-order, linear model of the deformable-plasma response which regulated five shape and position quantities [3]. In contrast with [3], the DIII–D controller is based on a “minimal” semi-rigid plasma response model [4] and regulates a large number of shape and position quantities (~15), comparable to the number of independent control coils (~17).

2. PRESENT DIII–D PLASMA SHAPE CONTROL

The isoflux control method [2], now in routine use on DIII–D, exploits the capability of the real-time EFIT plasma equilibrium reconstruction algorithm to accurately calculate total magnetic flux at specified locations within the tokamak vacuum vessel. Controlled parameters are values of flux at prespecified control points on the plasma boundary along with the X–point R and Z position. By requiring that the flux at each control point be the same value, the control forces the same flux contour to pass through all of these control points. By choosing this value equal to the flux at the X–point, this contour must be the last closed flux surface or separatrix. Present DIII–D operations use the isoflux control method with proportional, integral, and derivative (PID) operations on the control point flux and X–point R and Z errors. The resulting PID signals are multiplied by a gain matrix to produce commands to the pulse width-modulated (chopper) power supplies on each plasma shaping coil.

3. MIMO CONTROLLER DESIGN AND SIMULATION

The controller design was derived from a linear model of the system to be controlled (plasma, conductors, power supplies) and incorporates knowledge of the time response of all outputs (flux and X–point errors) due to each input (chopper voltages). A linearized plasma response model was developed and extensively validated [4,5] in order to enable the use of mature linear multivariable design techniques.

The system of plasma, shaping coils, and passive structure can be described using circuit equations derived from Faraday's Law. Radial and vertical force balance relations, assumption of rigid radial and vertical displacement of the equilibrium current distribution, and specification of a resistive plasma circuit equation close this set of equations [4]:

$$\left(M_{ss}+X_{ss}\right)\frac{dI_s}{dt}+R_{ss}I_s+\left(M_{sp}+X_{sp}\right)\frac{dI_p}{dt}+X_{s\beta}\frac{d\beta_p}{dt}+X_{s\ell}\frac{d\ell_i}{dt}=V_s \quad , \tag{1}$$

where the subscript "s" refers to stabilizing conductors (active and passive), I_s and I_p are the (perturbed) conductor and plasma currents, z_c is the plasma current centroid vertical position, R_m is the magnetic axis major radial position, X_{ss}, X_{sp}, $X_{s\beta}$, and $X_{s\ell}$ model variation of conductor flux due to plasma motion in response to variations in conductor current, plasma current, β_p, and ℓ_i, respectively, and M_{ss} and M_{sp} are the mutual inductances between conductors and between plasma and conductors. Circuit connections in DIII–D cause individual matrices to be modified from values calculated from independent coil currents, but the equation form remains the same. The system states are perturbed conductor and plasma currents (I_s, I_p), while perturbations of β_p and ℓ_i from equilibrium values are treated as disturbances. Plasma current dynamic response is modeled by a similar circuit equation which treats the plasma as a single circuit consisting of a distributed array of conducting elements. The shape of the current distribution was fixed while total current (I_p) was allowed to vary.

The normalized coprime factorization (NCF) design technique [6] was used to derive controllers from the linearized system. In this method, input and output weighting matrices specify relative importance among the controlled parameters, applied voltages, and control coil current variations. For the experimental implementation, a single controller based on a system linearized around a LSN ohmic plasma equilibrium was used to control the entire discharge.

Figure 1 shows an overview block diagram of isoflux plasma shape control using a MIMO controller. Magnetic diagnostic signals are used by the realtime EFIT algorithm to reconstruct the plasma equilibrium shape and current distribution, from which the X–point location and control point flux errors are calculated. These errors are processed by the MIMO shape control algorithm to produce demand voltages for choppers on each shaping coil. A set of chopper voltage controllers provides closed loop control of the choppers to produce the demanded voltages. This approach avoids having to include the highly nonlinear set of chopper models in the system to be controlled. A fast vertical stability control algorithm is also executed within the PCS to reduce the growth rate sufficiently that the slower shape control can stabilize the plasma.

Testing of controller designs was performed using a detailed simulation of the system response ("DIII–D and Plasma" and "Shaping Power Supplies" blocks in Fig. 1), connected directly to the PCS implementation of the MIMO controller [7]. The simulator includes both linearized plasma-conductor models and nonlinear power supply models. The simulation receives commands from the PCS and outputs magnetic diagnostic values corresponding to simulated conductor current variation and plasma motion. This allows testing of the PCS implementation, as well as iterative improvement of the controller, without the need for experimental machine time.

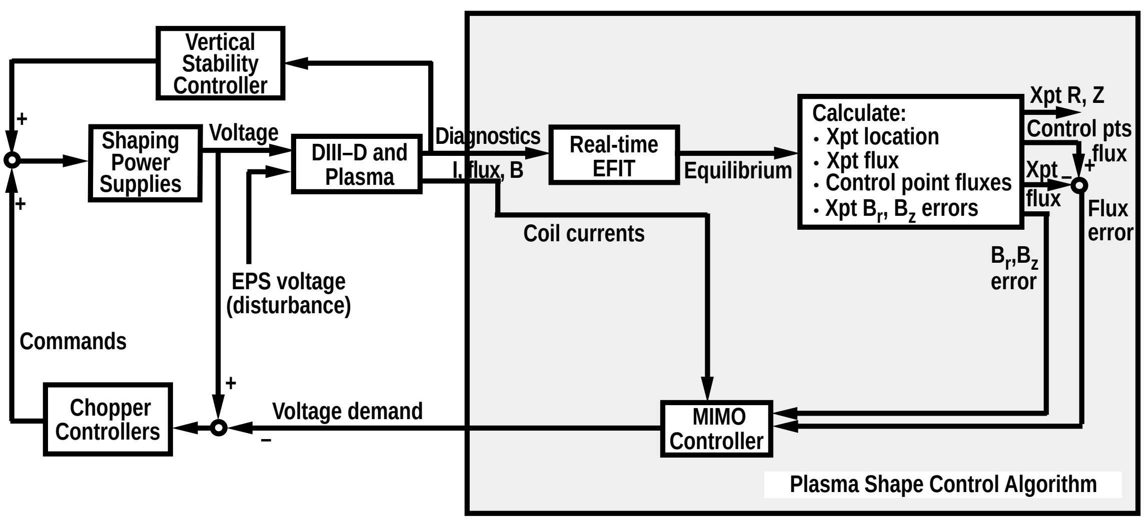

Fig. 1. Overview of MIMO isoflux control scheme.

4. CONTROLLER IMPLEMENTATION ON DIII–D

During testing, MIMO control was first introduced in the middle of several ohmic discharges, then extended to include plasma current rampup, flattop, and rampdown phases in later discharges. Steady state plasma shape control was quite good in general, although accuracy of the upper isoflux control points was somewhat worse than the lower control points and the X–point, reflecting the greater weight given to X–point control in the controller design. Quality of control during dynamic variation of plasma shape was mixed, but the control was always stable.

Figure 2 shows two shots in which the requested plasma shape changed with time. Control of the X–point vertical and radial position (Z_X,R_X) was generally very good, but flux at the upper control points followed their requests relatively slowly. In shot 99350, an approximately rigid vertical plasma motion was programmed between 1.5 s and 4.2 s. In shot 99351, an approximately rigid radial plasma motion was programmed. The radial motion was better behaved than the vertical motion, even during the sudden steps starting at 3.5 s. The large ringing on X–point vertical position following the requested step change also coupled to the radial control to produce poor control of the inner wall to plasma gap (gapin). This problem was found to be due to inaccuracies in the model of the closed-loop vertical stability control used in the control design (see Fig. 1). These inaccuracies have been corrected since this implementation, and closed-loop simulations can now reproduce the behavior observed in the experiment.

Performance of the MIMO controller was also affected by plasma internal inductance (ℓ_i). Internal inductance naturally increases throughout an ohmic discharge as the profile evolves toward steady state. The accuracy of X–point and top gap control varied from about 0.5 cm to 1.5 cm with control accuracy depending on ℓ_i. This is likely the result of controller optimization for a relatively high ℓ_i equilibrium, corresponding to the plasma state in the interval $3.2 < t < 3.5$ s in discharge 99350.

The MIMO controller also operated on coil current "errors" in order to prevent coil current limit faults from ending plasma shots. Reference vectors were constructed as heavily filtered versions of coil currents whenever currents were not near limits. A reference signal was modified to produce a large error if the corresponding current approached a limit. In at least three cases in the shots shown, F-coils came close to limiting values, at which point the algorithm increased the coil current error and prevented those currents from causing faults.

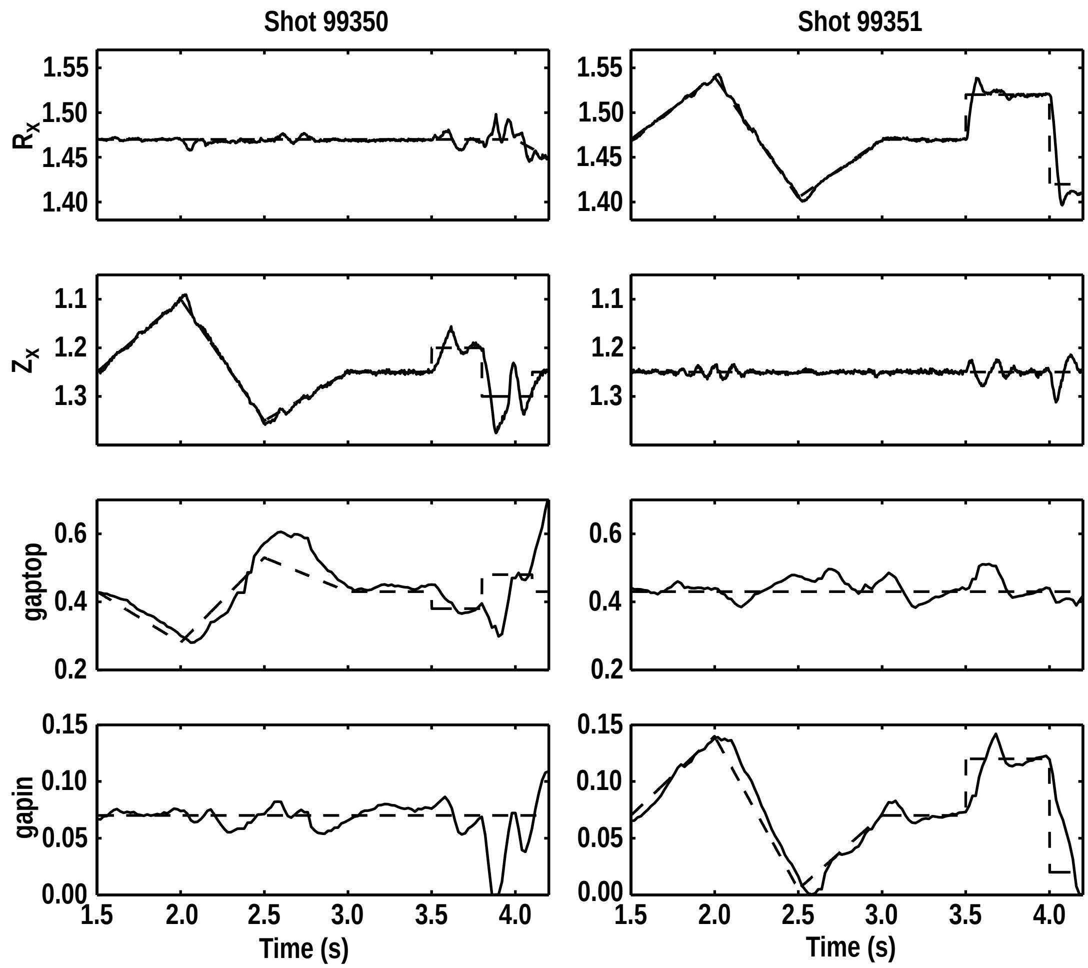

Fig. 2. Control of two shots with requested plasma shape changing over time (units in meters). Solid lines indicate achieved values, while dashed lines denote target values.

5. SUMMARY

A model-based multivariable controller was successfully tested on the DIII–D tokamak. Steady state control was quite good in general, with control accuracy of upper portions of the plasma somewhat worse than lower portions and the X–point. Better X–point control was consistent with much higher weighting given to its regulation in the design process. Quality of control in tracking of changing plasma shape requests was mixed; X–point control remained very good while some upper plasma-to-wall gaps in some shots were not well controlled. The plasma was successfully controlled throughout all phases of the discharge, including plasma current rampup, flattop, and rampdown. The control was always stable despite the wide range in ℓ_i and relatively high ℓ_i of the controller design point. A modification of the linear controller which addressed the nonlinear constraint of coil current limiting was successfully tested. Some control inaccuracies which occurred were not unexpected, since there were known inadequacies in accuracy of some models, especially the closed-loop vertical control. Controller modifications which provide more balance between X–point and gap control and which correctly address the interaction between shape and vertical position control should significantly improve performance.

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