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ABSTRACT.

New algorithms using a truncated singular value decomposition of a linearised model have been implemented in the JET control system.Using three heating and current drive actuators (LHCD,NBI,ICRH),successful control of the safety factor profile has been achieved in quasi steady state conditions where the loop voltage was small and a large fraction of the plasma current was carried by the bootstrap current.

1. INTRODUCTION

In order to control the current and pressure profiles in high performance tokamak plasmas with Internal Transport Barriers (ITB),a multi-variable model-based technique has been proposed which offers the potentiality of retaining the distributed character of the current and heat diffusion (distributed-parameter system)[1,2].

Here,we describe first experiments using the simplest,lumped-parameter,version of this technique.In section 3 only one actuator (LHCD) is used.In section 4,the first experiments using a multiple-input-multiple-output controller to control the q-profile with 3 heating and current drive actuators (LHCD,NBI,and ICRH)are reported.

2. TRUNCATED SINGULAR VALUE DECOMPOSITION

Let Q (s)be the linearized Laplace response around the target equilibrium:

$$\mathbf{Q}(s)=\mathbf{K}(s)\,.\,\mathbf{P}(s) \tag{1}$$

where **Q** represents a safety factor difference vector and **P** an input power difference vector.The kernel **K**(s) can be identified from power modulation experiments around the target steady state,or by simulations using a predictive transport code.

For the experiments described below,the steady state gain matrix **K** (0)was sufficient.A singular value decomposition is performed, yielding :

$$\mathbf{K}(s) = \mathbf{W(s)}\,\Sigma\mathbf{(s)V(s)}^{+} \tag{2}$$

and this defines decoupled modal inputs and modal outputs :

$$\alpha(s) = \mathbf{V(s)}+ \,.\, \mathbf{P}(s) \text{ and } \beta(s) =\mathbf{W}(s)+ \,.\mathbf{Q}(s) \tag{3}$$

related by :

$$\beta(s) = \Sigma(s)\mathbf{.}\alpha(s) \tag{4}$$

Pseudo-modal control techniques can be used by taking the steady state limits,$\mathbf{V}_0$, Σ_0,$\mathbf{W}_0$,of **V** (s), Σ(s), W(s),and by inverting the diagonal steady state gain matrix,Σ_0, where $[\Sigma_0]_{i,j} = \sigma_i.\delta_{i,j}$.In order to obtain a simple PI feedback control with minimum (least square)steady state offset,we choose the controller **G** (s)as (Fig.1)

$$\alpha(s) = \mathbf{G}(s)\,.\,\beta(s) = g_c\,[1 + 1/(\tau_i.s)]\,\Sigma_0^{(-1)}\,\beta(s) \tag{5}$$

where g_c is the proportional gain and $(g_c/\tau_i)$is the integral gain.

The SVD expansion of $\mathbf{K}$ is truncated to retain the most significant singular values. In the example below (Fig.2),3 actuators are used (LHCD,NBI,ICRH),but σ_3 is small which indicates that the family of accessible profiles is only a 2-parameter family spanned by the first two singular vectors, $\mathbf{W}_{0,1}$ and $\mathbf{W}_{0,2}$.We then use the truncated operator with only σ_1 and σ_2 : $\mathbf{K}_{0,T} = \sigma_1 \mathbf{W}_{0,1}.\mathbf{V}_{0,1}{}^{+} + \sigma_2 \mathbf{W}_{0,2}.\mathbf{V}_{0,2}{}^{+}$.

3. CONTROL OF THE SAFETY FACTOR PROFILE WITH LHCD

The first,simplest -and in some sense trivial -application of the lumped parameter SVD control scheme was to reach a predefined q-profile with only one actuator, namely LHCD,but 5 q-setpoints.The accessible targets are restricted to a one- parameter family of profiles and must therefore be chosen reasonably.Applying an SVD technique with 5 points,rather than only one,can be an advantage if the q-profile "rotates"when varying the power.It may not allow to reach any one of the setpoints exactly,but minimizes the error on the profile shape (e.g.weak or reversed shear), contrary to a control of li.Such an experiment was performed during an extended LHCD preheat phase [3],a usual prelude to the formation of ITB's in JET.The central line-integrated density was 2.7×10^{19} m $^{-2}$ to allow for efficient LHCD.The toroidal field was 3T and the plasma current was 1.3 MA so as to approach a full non-inductive regime.A linearized model which links the values of q(r)at r/a = 0.2, 0.4, 0.5, 0.6, 0.8 to the input LH power was identified from simple step power changes.The q-profile reconstruction uses the real-time data from the magnetic measurements and from the interfero-polarimetry,and a parameterization of the magnetic flux surface geometry [4, 5].The output signals are available every 50ms.

The effectiveness of the controller in achieving,and maintaining in steady state, various q-profiles can be seen on Fig.3.

4. CONTROL OF THE Q-PROFILE WITH LHCD,NBI AND ICRH

The second set of experiments conducted so far and using the proposed SVD technique (Fig.3) was a first attempt at using the 3 available heating and current drive systems to control the q-profile during a strong heating phase,in an ITB scenario with moderate bootstrap current.The toroidal magnetic field was 3T and the scenario started with a reversed shear 2.5MW LHCD preheat phase during which the plasma current was ramped up to 1.8MA,at a line-integrated plasma density around 3×10^{19} m $^{-2}$ At 4.3s, 12.5MW of NBI and 3MW of ICRH power were applied resulting in the triggering of an ITB and,starting at 7s,the plasma current was ramped down to a final 2-second-long 1.5MA plateau.The determination of the steady state responses to variations of the heating and current drive powers was made from the analysis of four dedicated discharges,including the reference discharge around which the system is to be linearized.The result is shown on Fig.4.

CONCLUSION

A successful control of the safety factor profile was obtained with a lumped- parameter SVD algorithm.This provides an interesting starting basis for a future experimental programme at

JET,aiming at the sustainement and control of ITB’s (q(r) and ρT* criterion)in fully non-inductive plasmas with a large bootstrap current.

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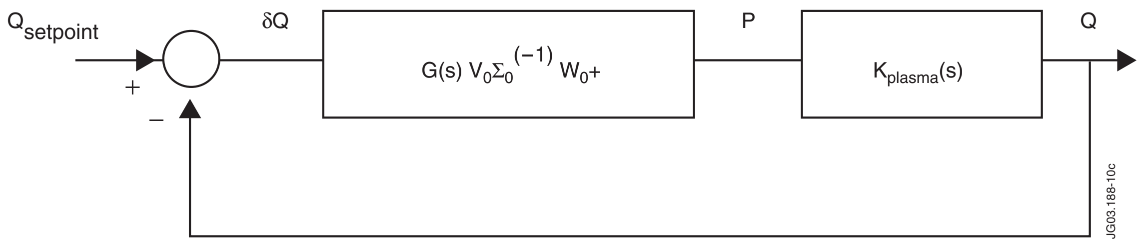

Figure 1.Control diagram used for the feedback control of the safety factor.

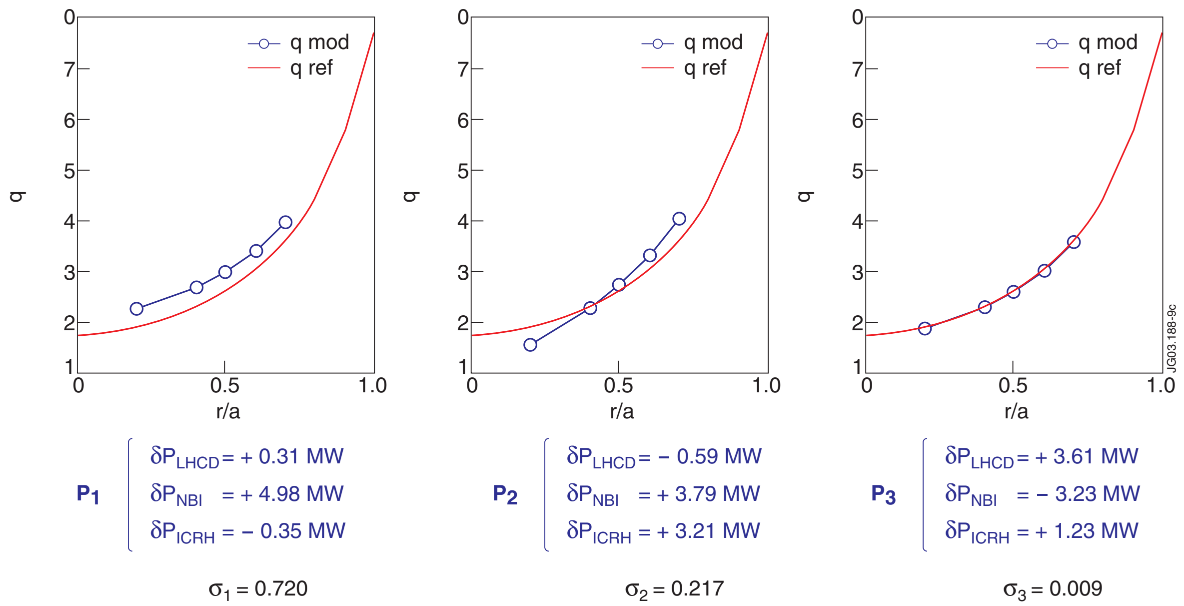

Figure 2: Respective influence of the 3 identified singular input vectors on the q-profile when using simultaneously LHCD, NBI and ICRH as actuators. The full profile which appears in all frames corresponds to the reference equilibrium obtained with P_{LHCD} =3MW,P_{NBI} =7MW,P_{ICRH} =3MW, around which the system is linearized. The open circles on the left, central, and right frames show the q-profiles estimated from the model when adding the power combinations P1,P2, and P3, respectively,to the reference case powers. P_1,P_2, and P_3, are proportionnal to the singular vectors, V_1, V_2, and V_3, but normalized to 5MW. σ_1, σ_2, and σ_3 are the corresponding singular values.

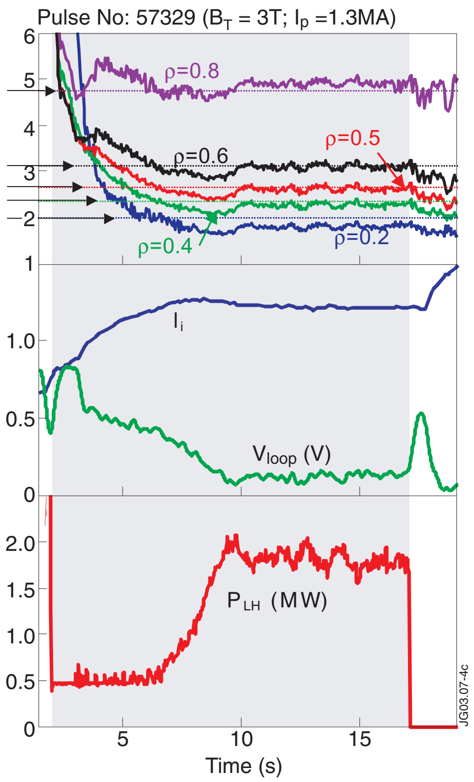

Figure 3(a): Real-time control experiment with LHCD only (Pulse No: 57329, B_T=3T, I_p = 1.3MA).Top :Safety factor at r/a =[0.2 0.4 0.5 0.6 0.8].Centre :Internal inductance parameter, l_i, and loop voltage, V_{loop}.(Volts). Bottom: LHCD power (MW).

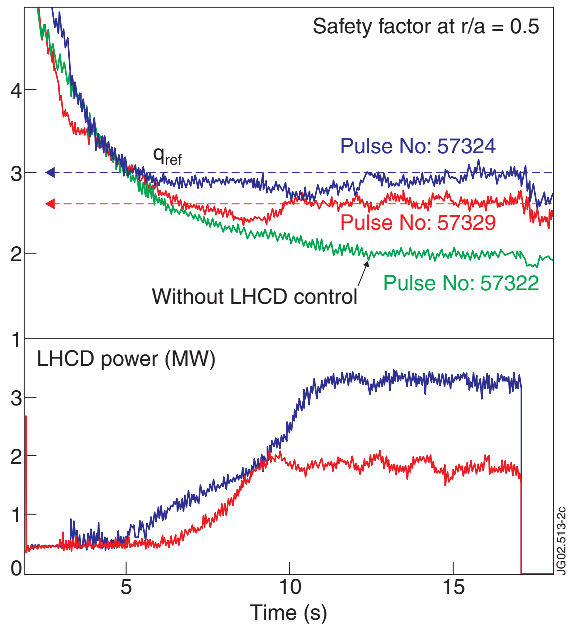

Figure 3)b)Measured and requested q-values at a r/a =0.5,and LHCD power for 2 controlled pulses (Pulse No: 57329 and Pulse No: 57324 B_T=3_T, I_p=1.3MA).A pulse without control is shown for comparison (Pulse No: 57322).Control

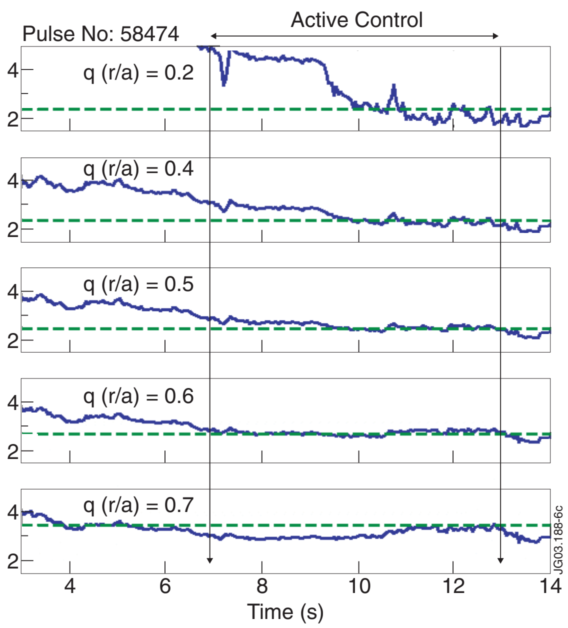

Figure 4(a):Measured and requested time traces of q(r/a) at the 5 radii selected for the control experiment with LHCD, NBI and ICRH (Pulse No: 58474, B_T=3T, I_p=1.5 MA).

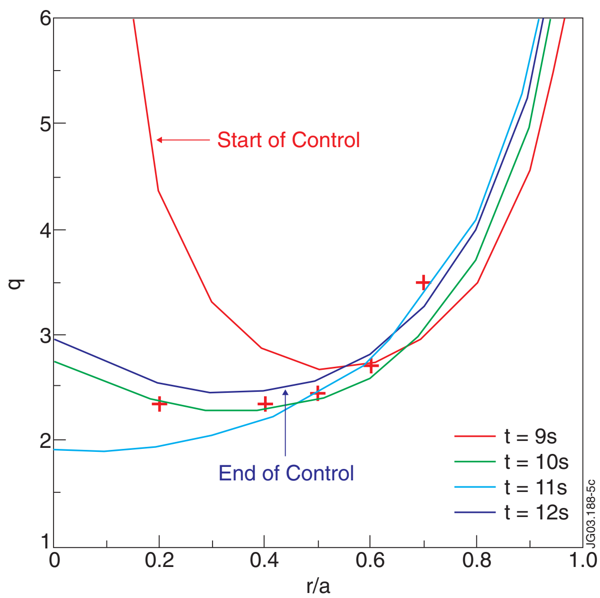

Figure 4(b)Same as in Fig.4a (Pulse No: 58474, B_T=3T, I_p=1.5MA):q-profiles at four times between 7s and 12s. Pluses represent the 5 setpoints.