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Identification of the dynamic plasma response for integrated profile control in advanced scenarios on JET

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1. Introduction

During the 2003-2004 experimental campaigns on JET, real-time control of radially distributed parameters, such as the current and electron temperature gradient profiles, was achieved for the first time [1]. This was the initial step of an ongoing long-term research program which aims to ultimately develop integrated control of steady state advanced tokamak scenarios and internal transport barriers (ITB). At this stage, and for the sake of simplicity, the controller was based on the static plasma response only and on an algorithm that minimises a weighted sum of least square integral errors between requested magnetic and kinetic profiles (known to be strongly coupled) and measured ones. Such an integrated strategy is particularly relevant to future fusion devices such as ITER where the heating and current drive (H&CD) actuators will be limited while more controls will be needed for burning plasmas. In addition, some actuators will be less versatile than in present-day tokamaks, due to simple physics and/or technology considerations (antenna design, wave propagation, etc..). The approach newly developed at JET therefore aims to use the combination of H&CD/PF (poloidal field) systems and the experimentally deduced plasma couplings in the most efficient dynamic way to achieve a set of simultaneous tasks. The controller based on the static plasma response was successful in achieving the various targets that were aimed at, thus demonstrating the relevance of the coupled profiles approach [1]. However, the control was not robust enough to rapid plasma events such as the spontaneous emergence of transient ITBs or MHD instabilities.

2. Structure of the dynamic plasma model and appropriate state variables

In order to address this issue and to use optimal control theory to better regulate the plasma evolution in advanced tokamak scenarios, a physics-based technique has been developed to experimentally identify a dynamic, one-fluid plasma model valid in some broad vicinity of an equilibrium state. The structure of the model stems from a set of transport equations,

$$\mu_0 \frac{\partial j}{\partial t} = -\nabla \mathrm{x} \nabla \mathrm{x} E, \qquad \frac{\partial n}{\partial t} = -\nabla . \Gamma + S_n, \qquad \frac{3}{2}\frac{\partial (nT)}{\partial t} = -\nabla . Q + S_T \qquad (1)$$

in which couplings are retained with no loss of generality. The system (1) is linearized around an equilibrium reference state (which need not be known explicitly) so that it can ultimately be cast in the generic form of a state space model, a form commonly used in control engineering. In doing so, the state variables appear naturally to be the variations of the internal poloidal magnetic flux, Ψ, and of the temperature, T, and the state space model reads:

$$\partial\Psi/\partial t = A_{11}\Psi(t) + A_{12}T(t) + B_{11}P(t) + B_{12}n(t) + U.V_{ext}(t) \qquad (2a)$$

$$\varepsilon\,\partial T/\partial t = A_{21}\Psi(t) + A_{22}T(t) + B_{21}P(t) + B_{22}n(t) \qquad (2b)$$

with inputs P = [P_{LH}, P_{NBI}, P_{ICRH}], the heating and current drive input powers, and V_{ext}, the surface loop voltage. The distributed variables Ψ(x) and T(x), where x is a radial coordinate, are projected onto a finite set of trial functions using a Galerkin approximation so that the original partial differential system of equations reduces to an ordinary linear differential system where U is known and $A_{i,j}$, $B_{i,j}$ are matrices of appropriate dimensions which are to be identified from experimental data. The small (constant) parameter, ε, represents the ratio between the energy confinement time and the characteristic resistive diffusion time ($\varepsilon \ll 1$), and is introduced here to scale matrices A and B so that their coefficients have similar magnitudes. In the forthcoming JET experiments, the density profile will not be controlled in real time yet, so the variations of the plasma density, n, will be considered as a disturbance (n is therefore treated here as an additional input). The main assumptions leading to (2) are that

i) we consider a one-fluid model with temperature T(x) (the same methodology could be used later to seek a model with $Te \neq Ti$, and eventually momentum transport and plasma flows),

ii) the particle and heat fluxes, Γ(x) and Q(x), depend only on the current density j(x) and on the density n(x) and temperature T(x) through differential operators,

iii) the electrical conductivity depends only on T(x) (variations of the effective charge, Z_{eff}, could otherwise be introduced as another disturbance)

iv) gas or pellet injection are negligible compared to beam fuelling so that the particle source, $S_n(x)$, depends only on the neutral beam power, P_{NBI},

v) the heat and particle deposition profiles $S_T(x)$ and $S_n(x)$ depend on P, n(x), T(x) and j(x),

vi) the non-inductive current density depends on P, and on n(x), T(x) and j(x).

3. Two-time-scale approximation and practical model identification

The high dimensionality of the state space and the large ratio between the various time scales involved (resistive and thermal diffusions with strong interactions between fast and slow dynamic modes) call for an appropriate model identification procedure and control algorithm. The technique proposed in this paper makes use of a multiple-time-scale approximation

(ε<<1) and is based upon the theory of singularly perturbed systems [2]. We therefore seek two models of reduced orders, a slow model,

$$\partial\Psi/\partial t = A_s\Psi + B_s u_s \qquad \text{together with} \qquad T_s = C_s\Psi + D_s u_s \tag{3}$$

and a fast model ($\tau = t/\varepsilon$),

$$\partial T_f/\partial\tau = A_f T_f + B_f u_f \tag{4}$$

where $T=T_s+T_f$, and where u_s and u_f are the slow and fast components, respectively, of a vector, $u=u_s+u_f$, containing all the inputs (P, n and V_{ext}). A stepwise, interactive identification procedure was set-up using system identification algorithms described in [3], and data (poloidal flux, electron temperature, etc ...) obtained from the semi-empirical transport model implemented in the JETTO code. Whenever possible, matrices obtained at one step are either fixed or used to initialize the following step of the identification procedure. The first step is an identification of the fast model matrices A_f and B_f and is carried out by considering discharges where each one and then all of the input powers have been modulated randomly with different high frequency spectra (≈10 Hz). The slow component (f < 2.5Hz) of both the inputs and outputs are filtered out so that the fast response can be isolated. An example of the fast modulated input for the NBI power is shown on Fig. 1 (red trace). A comparison between the original data obtained from the JETTO simulation and the data reconstructed from the identified state space model is shown on Fig. 2 for a simulation where all the inputs have been

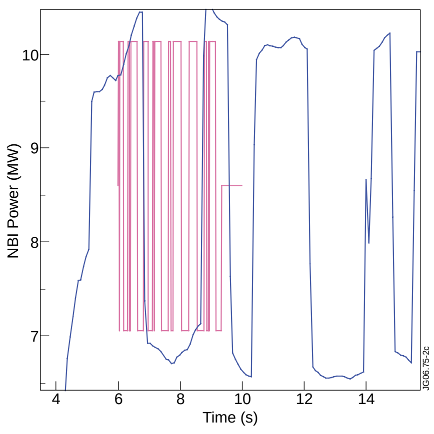

Fig. 1 Examples of a fast (red) and of a slow (blue) modulation of the NBI power used for the identification of a two-time-scale state space model.

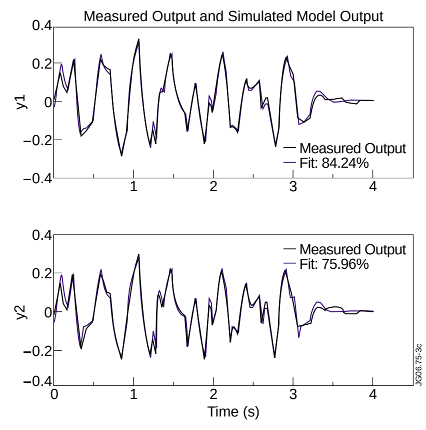

Fig. 2 Comparison between the data from JETTO and from the identified state space (fast) model for two elements of the electron temperature vector.

modulated. The second step provides an approximation for the A_s matrix by considering the free dynamics (i. e. with constant heating and current drive powers) of the system on the resistive time scale (Fig. 3). The smallest eigenvalue of the A_s matrix corresponds to a resistive time constant τ_R = 6.9 s. In a further step, B_s is then identified while keeping A_s fixed, using various pulses with slow modulations of the inputs (Fig. 1, blue trace). Finally, the identification of C_s and D_s provide a slow model governing the coupled evolution of the slow variables, Ψ, and the slow component of the kinetic variables, T_s (Fig. 4).

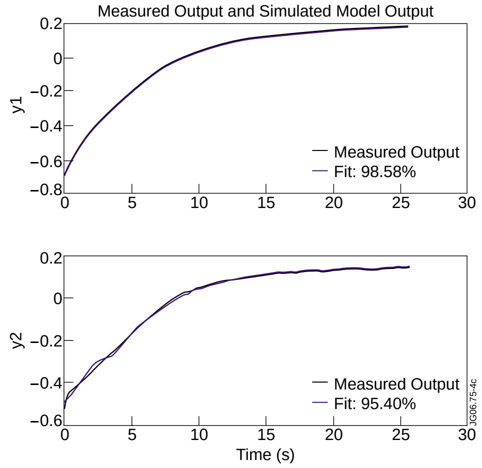

Fig. 3 Comparison between the free dynamics data from JETTO and from the identified state space (slow) model for two elements of the poloidal flux vector.

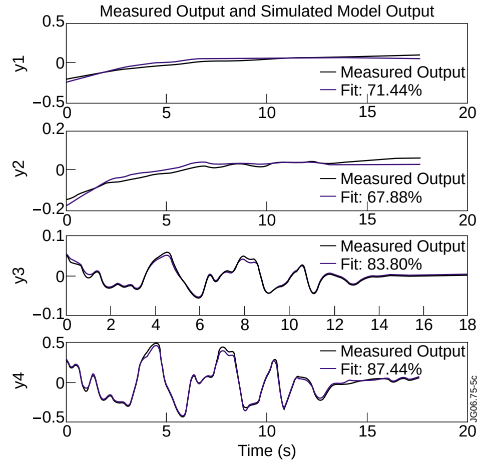

Fig. 4 Comparison between the data from JETTO and from the identified state space (slow) model for two elements of the poloidal flux vector and two elements of the electron temperature vector.

Starting from these approximate reduced-order systems, a full-order comprehensive model can also be found when using data obtained from JETTO. This however proves difficult (ill-conditioned) and may not be practical when using noisy experimental data. The optimal profile control scheme which is to be tested in the near future on JET (but cannot be described here) is therefore based on the two-time-scale reduced-order models and on the use of singular perturbation methods.

4. Conclusion

The aim of the work reported in this paper was to develop a system identification strategy which can be applied to experimental data in order to use optimal control to possibly regulate the dynamics of advanced scenarios on JET. It was shown that fairly accurate theory-based models could be found from simulated data using the two-time scale approximation. The strategy will be applied to real data during the coming experimental campaign on JET, and closed-loop experiments will assess whether the response models are accurate enough for the real time control of magnetic and kinetic profiles in advanced tokamak scenarios.

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