Plasma Boundary Flux Control at JET

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Motivations

Advanced Tokamak Scenarios

AT plasmas

An Advanced Tokamak (AT) plasma is a plasma with:

- high plasma kinetic pressure;
- a large fraction of self-induced current;
- a good particle and energy confinement.

- AT scenarios are aimed at allowing steady-state operation without a large amount of externally driven current.
- AT scenarios are aimed to increase the efficiency of a tokamak reactor.
To achieve AT plasma performance, accurate shape control is needed:

- to obtain the shapes required to achieve high $\beta$;
- to optimize the coupling with the additional heating systems;
- to optimize divertor shape for pumping;
- ....
Control of the plasma internal pressure and current profiles in AT regimes is needed:

- to improve the energy confinement;
- to increase the noninductive current fraction (*bootstrap current*).

One way to increase the bootstrap fraction is to generate an *internal transport barrier* (ITB), which also causes a reduction of turbulence and therefore an increase of confinement.

ITB triggering strongly depends from the current density profile.
Plasma boundary flux control

- Steady-state scenarios should in principle be fully noninductive, and zero loop voltage should be maintained at the plasma boundary.
- Obtaining effective and routine boundary flux control is an essential step in AT regime.
- An integrated approach for the control of the plasma shape and boundary flux has been developed at JET, and it has been tested on ITER-relevant plasmas.
The JET Tokamak

A simplified plasma linearized model relates the variations of the currents in the *poloidal field* (PF) coils to the variations of the geometrical descriptors around a given equilibrium:

\[
\delta \dot{x}(t) = A \delta x(t) + B \delta u(t), \\
I_{peq} \delta g(t) = C \delta I_{PF}(t),
\]

where:

- \( \delta x(t) = [\delta I_{PF}^T(t) \ \delta I_p(t)]^T \) includes the currents in the eight PF circuits available for shape control, and the plasma current \( I_p \);
- \( \delta u(t) = [\delta V_{PF}^T(t) \ 0]^T \) is the input voltages vector;
- \( \delta g(t) \) are the shape descriptors variations;
- \( I_{peq} \) is the equilibrium value of the plasma current.
The **eXtreme Shape Controller (XSC)** controls the whole plasma shape, specified as a set of 32 geometrical descriptors, calculating the PF coil current references.

Let \( I_{PF_N}(t) \) be the PF currents normalized to the equilibrium plasma current, it follows that

\[
\delta g(t) = C \delta I_{PF_N}(t).
\]

It follows that the plasma boundary descriptors have the same dynamic response of the PF currents.

The XSC design has been based on the \( C \) matrix. Since the number of independent control variables is less than the number of outputs to regulate, it is not possible to track a generic set of references with zero steady-state error.
The XSC has then been implemented introducing weight matrices both for the geometrical descriptors and for the PF coil currents.

The determination of the controller gains is based on the SVD of the following weighted output matrix:

$$\tilde{C} = \tilde{Q} C \tilde{R}^{-1} = \tilde{U} \tilde{S} \tilde{V}^T,$$

where $\tilde{Q}$ and $\tilde{R}$ are two diagonal matrices. The XSC minimizes the cost function

$$\tilde{J}_1 = \lim_{t \to +\infty} (\delta g_{\text{ref}} - \delta g(t))^T \tilde{Q} (\delta g_{\text{ref}} - \delta g(t)),$$

using $\bar{n} < 8$ degrees of freedom, while the remaining $8 - \bar{n}$ degrees of freedom are exploited to minimize

$$\tilde{J}_2 = \lim_{t \to +\infty} \delta I_{PFN}(t)^T \tilde{R} \delta I_{PFN}(t).$$
XSC - control scheme
XSC - experimental results

(a) JET pulse 68953 - plasma shape at $t = 46.5s$.

(b) JET Pulse 68953 - plasma shape descriptors time traces.

Figure: JET pulse 68953.
The boundary flux controller for the JET tokamak has been implemented using the XSC architecture.

The actuator that has been chosen to control the plasma boundary flux $\psi_b$ is the current in the $P1$ circuit. The other circuits are much less efficient and therefore it is much worth to use them for the shape control.

When controlling $\psi_b$, the control of the $P1$ current is released to the XSC. A new actuator is then available to the XSC and it is used to control $\psi_b$, with negligible influence on the shape.

When the XSC controls $\psi_b$ the plasma current is not controlled, and it is left floating between given bounds.
Plant model

In order to design the plasma boundary flux controller, a SISO model in the form

$$\delta \psi_b(s) = W(s) \delta I_{P_1}(s),$$

is needed.

To obtain a model in the form (1):

1. the loop consisting of the XSC and the plant model has been considered.

2. a model order reduction has been performed so that a low-order model is obtained. (A balanced model reduction has been performed, arriving to a model of the fourth order).
XSC with boundary flux control
Constant $v_{loop}$
**v_{loop} modulation**

**Experimental Results**

- **Pulse 67840 – plasma boundary flux v_{b}**
- **Pulse 67840 – relative control error ε_{bc}**
- **Pulse 67840 – plasma current I_p**
- **Pulse 67840 – plasma loop voltage V_{l}**
Experimental Results

Simulation vs. experiment

Figure: Simulation of the plasma loop voltage modulation experiment.
Experimental Results

$V_{\text{loop}}$ modulation - plasma shape

**Pulse 67840 – radial inner gap (RIG)**

**Pulse 67840 – outer strike point (RSO)**

**Pulse 67840 – top gap (TOG3)**

**Pulse 67840 – inner strike point (ZSI)**
Future works

- In the future, the XSC with boundary flux control will be integrated in a more general scheme with the objective of obtaining a centralized controller for the plasma shape, boundary flux, current and pressure profiles.

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