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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT

The JET Shape Controller (SC) uses nine distinct circuits, powering the JET poloidal field coils, to control in real time the coil currents, and the plasma shape, current and position. The control scheme presently used [1] is based on a Multiple Input Multiple Output (MIMO) controller, which is designed to decouple the inductive coupling of the different coils. Achieving such a decoupling, the SC allows the user to tune independently the time response of each circuit. As a matter of fact the intended decoupling algorithm has been incorrectly coded in the JET SC system. This paper describes the modelling and experimental activities performed to correct the code error, and to improve the performance on a subset of the controlled parameters.

1. INTRODUCTION

In a tokamak device it is fundamental to precisely control the distance of the plasma last closed surface from the plasma facing components. In this way it is possible to control the thermal loads on the plasma facing components and the pollution of the plasma due to material melting, to shape the plasma to best fit the vacuum chamber, and to exploit the influence of shape parameters, such as the area, the triangulatiry, the elongation, etc., on the plasma performance. The problem of controlling the plasma current and shape is achieved at JET by the Shape Controller (SC), which is part of the Plasma Position and Current Control system (PPCC), which powers a set of eight Poloidal Field coils (PF) using nine distinct circuits. The control scheme presently used [1, 2] is based on a Multiple Input Multiple Output (MIMO) controller, which is designed to decouple the inductive coupling of the different coils. As a matter of fact the intended decoupling algorithm has been incorrectly coded in the SC plant system. However, the controller exhibits a good overall performance due to the extensive tuning of the parameters performed in the first commissioning phase, back in 1997.

This paper describes the modelling and experimental activities performed to correct the code error, and to improve the performance on a subset of the controlled plasma parameters. All these activities have been carried out by using the CREATE models [3, 4]. The use of these models permitted to perform simulations aimed at optimizing the behaviour of the SC when controlling specific plasma parameters. This paper is structured as follows: a brief description of the JET SC is given in section 2, which also introduces the coding error in the plant system and the strategy that has been adopted to correct the problem. Section 3 introduces the modelling tools that gave the opportunity to reduce at the minimum the time needed for the commissioning of the corrected controller on the plant. Once it has been proved that these modelling tools were able to reproduce the experiments, they have been used to improve the performance of the SC, as shown in section 4, where some preliminary experimental results are presented. Conclusive remarks are given in section 5.

2. THE JET SHAPE CONTROLLER

This section briefly introduces the control algorithm of the JET SC. The details of the algorithm and the JET implementation are given in [1, 2]. The JET SC is conceived as a solution to the shape control problem for the entire discharge; in the different phases of a discharge the SC can control a combination of currents in the PF circuits and geometrical descriptors of the plasma last closed surface, as decided by the Session Leader. The control scheme implemented by the SC is based on a MIMO controller, which is designed to decouple the strong mutual inductive coupling present between some of the different coils. Using this approach, the SC achieves a complete decoupling of the controlled variables, leading to a set of single-input single-output (SISO) loops. A simplified scheme of the controller is reported in Figure 1. The linearised equations of the plant are hereafter reported:

$$\begin{cases} M_s \dot{I} + R_s I = V \\ Y = TI \end{cases} \tag{1}$$

where M_s represents the inductance matrix, R_s the coils resistance matrix, I the PF circuits and plasma currents, $\dot{I}$ the time derivative of the same quantity, V is the vector of control voltages to be applied to the circuits, Y the controlled variables measurements, (*i.e.* a combination of plasma current and boundary geometrical descriptors with PF currents), and T is the linearized relation between I and Y.

The feedback loop is:

$$V = RI + K(Y_{ref} - Y) \tag{2}$$

where, R is the estimation of the resistance matrix, Y_{ref} is the reference value of the variables to be controlled, and K is the control matrix, defined as:

$$K = MT^{-1}C \tag{3}$$

where M represents the matrix containing the estimated mutual inductance of the system, while C is a diagonal matrix that specifies the desired time constants for each SISO control loop. By substituting (1) and (3) in (2), if the plant (M_s, R_s) and the controller model (M, R) are similar, after some cancellations the feedback becomes:

$$\dot{Y} = C(Y_{ref} - Y). \tag{4}$$

It follows that the user can independently tune the time response of each control loop by simply specifying the elements of the diagonal matrix C.

As a matter of fact the intended decoupling algorithm has been incorrectly coded in the JET SC plant system by using the relation $K = CMT^{-1}$ [5]. Nonetheless, the SC exhibits a good control performance due to the tuning of the parameters that has been done during an extensive commissioning phase in 1997. The tuning included the manipulation of the mutual inductance matrix M, with several entries of this matrix set to zero. Moreover, a cancellation matrix H, whose entries are 1 or 0, has been introduced to switch off undesired off- diagonal coupling terms (more details can be found in [2]). The cancellation matrix H was originally introduced to avoid high voltage requests during fast variations, which may lead to saturations, in the case of coupled circuits with too large differences in terms of inductances and amplifier voltage capabilities. It is now believed that some of the entries both in M and H matrices may have been set to zero to adjust the decoupling after the wrong matrix algebra. Although it was recognized that the fixing of the SC was an important issue for the JET PPCC system, this activity had to fulfill a number of requirements. The most important was to avoid any delay in the JET experimental campaigns with the ITER-like wall. This requirement naturally calls for the adoption of a model- based approach (see section 3), in order to minimize the time needed for the commissioning of the corrected controller on the real plant.

Another set of requirements was related to the capability of reproducing the past JET experiments in terms of control performances, also when using the corrected version of the SC. In particular:

- If needed, it should be always possible to switch back to the original SC algorithm, i.e. the one with the wrong matrix algebra; this requirement is automatically fulfilled thanks to the JET Level 1 [6], which stores the different SC gains in different scenarios.
- A first set of gains for the corrected version should be designed in such a way to keep the dynamic response on each SISO channel unchanged. Once the same performance has been achieved also with the correct matrix algebra, it will be allowed to make some improvements.

Finally, the two following requirements have been also considered:

- Use of a more realistic mutual inductance matrix M taken from CREATE models. These models have been extensively validated at JET, in different pulse phases with [7] and without plasma [8], and present significant differences in some of the mutual and also in the self-inductance terms comparing with the one used for the original design of the SC. The main reason of this choice is to use a realistic electromagnetic model in the controller, while allowing the tuning of each control channel solely changing the terms of C, as a good control practice.
- Preserve the zeros present in the entries of both the M and H matrices. This requirement is essential to reduce to the minimum the commissioning time to a couple of restart shifts, avoiding, for the time being, the lengthy re-tuning exercise of the H matrix that was carried out in 1997. Furthermore, this partially conservative approach was judged to be important because it would contribute to minimize the commissioning time needed but at the same time to have a correct SC algorithm.

The list of the described requirements were considered to be adequate to deliver a robust working system, with the correct matrix algebra and a realistic model, which would represent a better starting point for future upgrades and improvements, as it will be shown in section 4.

3. MODELLING OF THE JET SC SYSTEM

As anticipated in section 1, the main requirement for the improvement of the SC system was to minimize the impact of this activity on the JET experimental campaigns. For this reason a set of modeling and simulation tools have been developed. A closed-loop simulation scheme of the JET plasma with the SC has been implemented in MatLab Simulink, as a first step for the redesign of the SC gains. This scheme utilizes the CREATE plasma models [3, 4], that link the voltages applied to the PF coils to the controlled variables (plasma current, PF currents, distance of plasma last closed surface to first wall, power exhaust position, etc.), as in (1).

Two different models of the SC have been implemented. The first one aimed at reproducing the experiments, hence it included the coding error. This model has been used to validate the closed-loop scheme against various past JET shots. With this model it has been possible to reproduce with high accuracy the behavior of the various controlled variables. In Figure 2 we show the simulation results reproducing the JET Pulse Number 86107; during this shot the tracking of a step on the vertical position of the plasma centroid, named Zc, has been requested at t = 20*s*. The figure shows on the top the tracking results, which are poor, and the control effort in terms of requested voltage (middle) and current (bottom) of the imbalance circuit. The Imbalance circuit produces radial magnetic field and is the main circuit used for the control of the plasma vertical position. Once the closed-loop scheme has been validated using the wrongly coded SC, a new algorithm with the correct matrix algebra has been used to test the impact of different gains on the control performance. The availability of the reliable simulation tools developed allowed to take one step forward and design a control system with increased bandwidth for specific controlled variable of interest, which were known to exhibit poor tracking performances. A large number of simulations were run to tune the gain of the specific variable to be controlled, changing only the relative term of the diagonal gain matrix C, until the system exhibited a satisfactory behavior. The optimization criteria chosen where both the tracking performances of the desired control variable and the limitation of the control action. The latter criterion is important to avoid the saturation of the voltage in the amplifiers, and to avoid tracking overshoot behaviors on the same variable. This may also lead to less effective decoupling with other variables, in cases where the relative amplifier has a lower voltage capability. A series of new gains were finally proposed to be used on the real plant to achieve the enhanced performances of the required control variables.

4. EXPERIMENTAL RESULTS

The new designed control algorithm was commissioned during the restart phase of JET campaign in July and December 2013. A series of test were carried out in different condition, tracking currents in the PF coils or plasma boundary geometrical descriptors.

In the Figure 3 are represented the enhanced results achieved in terms of mutual inductance decoupling control, with the new algorithm, with the correct algebra and modified matrices M and C designed to preserve the bandwidth of the old system, versus the old algorithm. While the performance of the ramping circuit is kept unchanged, as per design, the better decoupling of the new controller allows an improved decoupling of the inductive coupled circuits and thus a better tracking of the desired variables during the fast transients. This is particularly important in the phases where fast current changes are expected, which represents the cases where the inductive coupling is higher, as fast plasma current ramp-up/down, emergency plasma shutdown, etc. The better decoupling performances achieved in the plant with the new algorithm, together with the availability of a reliable simulation tool, allowed to take one step forward and design a control system with increased bandwidth for specific controlled variable of interest by the JET operator.

Figure 4 shows the enhanced tracking control of a step reference given to the vertical position of the plasma current centroid Zc.

The improvement is evident if compared with the results presented in Figure 2, where the variable never really reached the desired value. By using the new gain, designed in simulation, such enhancement was achieved while keeping the voltage of the imbalance amplifier well within its limits and minimizing the impact on the other controlled geometrical descriptors, which remain constant as required.

5. CONCLUSIONS

The modelling and experimental activities described in this paper allowed to develop a reliable simulation tool able to reproduce with a good accuracy the behavior of the JET plant in term of plasma shape and current control and PF coil current control. This new tool permitted to design in simulation a new SC control algorithm with the corrected matrix algebra, removing the coding error present at JET since 1997 [5], and a more realistic internal model of the JET plant, by using the CREATE model [3-4]. This allowed to minimize the impact of the commissioning time of the experimental campaign, which was an essential requirements, being the time constrain the main reason for preventing the resolution of this problem in the past. The new proposed algorithm was tested in the JET campaign restart in July and December 2013, in a limited number of JET plasmaless and plasma pulses. The first experimental result presented in the paper shows a better decoupling of the different controlled variable of the system, while keeping the same bandwidth of the old system. This allowed a further step which permitted to design in simulation a series of new control gains able to enhance the control performances for a series of plasma parameters which where previously exhibiting poor performances. The experimental result presented shows the achievement of the desired control enhancement with better variable tracking control, while keeping all the other plasma parameters decoupled. The new SC system overall improved performances, together with the correction of the matrix algebra in the algorithm and a more realistic decoupling model, represents a good starting point for future upgrades and improvements. Since June 2014 the new SC systems is now routinely used at JET for the majority of the pulses.

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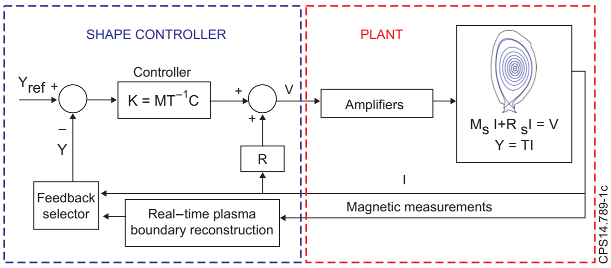

Figure 1: Block diagram of the JET Shape Controller feedback loop. The feedback selector permits to change among the available control modes.

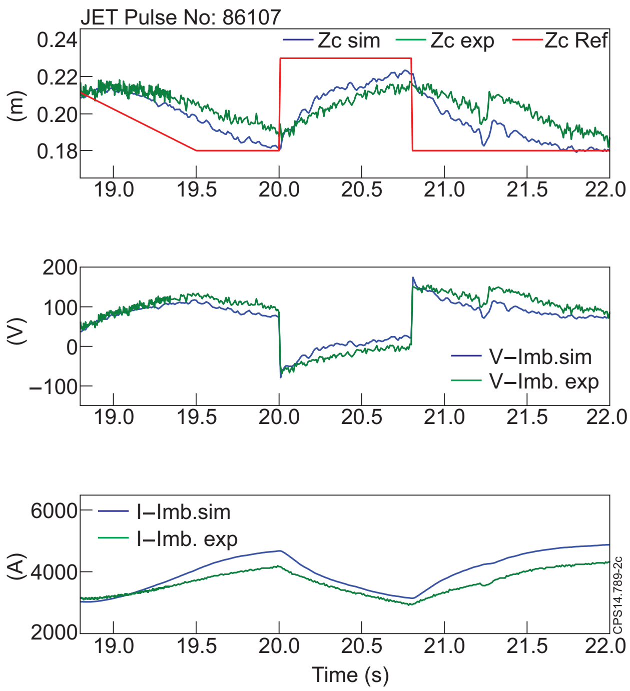

Figure 2: JET Pulse Number 86107: SC with the bug. The simulation results (blue traces) show a good agreement with the experiment (green traces). The control of the plasma vertical centroid position Zc is poor, with the variable never reaching the set value (red trace). The behavior of the voltage and current of the Imbalance is reproduced in simulation with a good agreement.

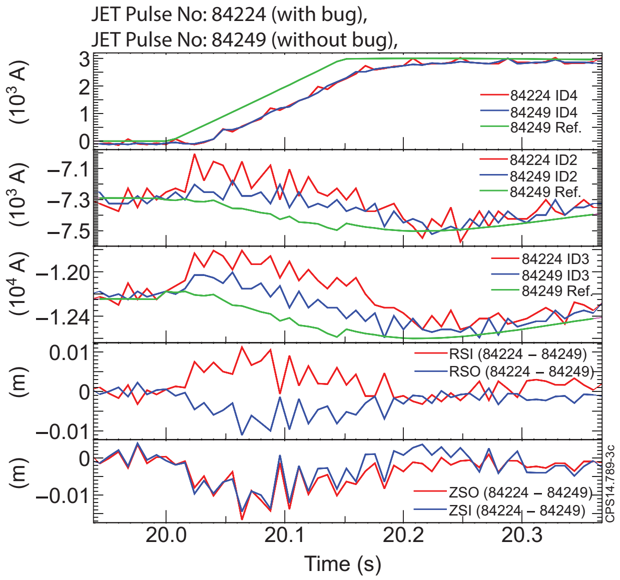

*Figure 3: JET Pulses Number 84224 (old algorithm with the "bug"), and number 84249 (new algorithm but the same bandwidth). Same performances achieved for ID4 circuit current step reference tracking (top picture), as per design, while better decoupling is achieved with the new algorithm for the inductively coupled circuits ID2 and ID3. The improvement is in this case is of ≈ 200A in both circuits, which results in 1.5cm on the vertical (**Z**), and 1cm in the radial (**R**) inner (**I**) and outer (**O**) power exhaust position, named **ZSI/ZSO** and **RSI/RSO**.*

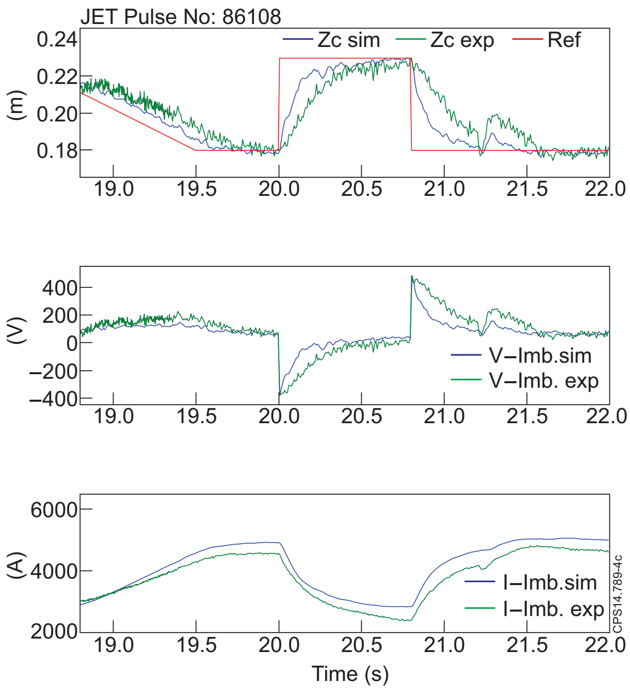

Figure 4: JET Pulse Number 86108: SC without bug and with increased gains. The simulation results (blue traces) show a good agreement with the experimental results (green traces). The plasma vertical centroid position Zc control is improved, while keeping the requested current and voltage within the amplifier limits.