Validation of Plasma Equilibrium Simulator: MECS code in JT-60SA

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Introduction

The plasma equilibrium control for a large tokamak device must be designed based on simulations due to the limited number of plasma discharges available for experimentation. Simulation-based approaches are essential for several critical aspects of plasma control, including the development of control logic, the creation of plasma operation scenarios (such as ramp-up and ramp-down), and the fine-tuning of control gains. In the broader context of tokamak research, simulation codes like TokSys [1] and CREATE-L/NL [2] have been developed and widely used in large tokamak devices. These tools have been instrumental in demonstrating the estimation of controllability, control gain tuning, and control logic development. Similarly, the Magneto-hydrodynamic (MHD) equilibrium control simulator (MECS) code has been developed since 2009 to serve as a reliable simulator for the JT-60SA tokamak [3], [4] , [5] . This simulator aims to accurately model the behavior of plasma, enabling researchers to optimize control strategies before implementing them in real experiments. From October to December 2023, integrated commissioning was successfully conducted on the JT-60SA using the control logic developed within the MECS framework. The control gains determined by the MECS were directly applied in real operations, performing as expected and validating the simulator's accuracy in replicating actual plasma behavior. This study focuses on validating the controllability of the MECS code by comparing its performance against experimental data. Specifically, the research examines the time and phase space of feedback control for plasma current and plasma shape. Additionally, the study demonstrates the MECS code's capability for fine gain tuning, further enhancing the precision and stability of plasma operations. In this study, we validated the time evaluation of control on MECS and experiment for different frequency fluctuation and the controllability for closed-loop (feedback control) using Bode plots. By comparing the time evolution of control, we could confirmed the reproduction of overshooting. By comparing the frequency transfer function, we assessed the cut-off frequency, gain and phase margins. By demonstrating these capabilities, the study underscores the importance of simulation-based design in plasma control and highlights the MECS code as a useful for optimizing control strategies. This work contributes to the broader goal of achieving reliable and efficient plasma operation.

Control Logic Based on the ISO-FLUX Scheme

In the plasma equilibrium control using the ISO-FLUX scheme, superconducting coils are employed to control the plasma current, position, and shape. The ISO-FLUX scheme aims to minimize the flux gaps between the measured fluxes and their reference values. The plasma current control reduces the gap between the reference plasma current, I_{p_ref}, and the measured plasma current, I_{p_mes}. This difference is defined as: $\delta I_p = I_{p\_ref} - I_{p\_mes}$. The controlled fluxes for plasma current can be calculated using the internal inductance, L_p, as $\delta\psi_X = -L_p \delta I_p$. The plasma shape and position control reduces the gap between the fluxes at the X-points and those touching the limiter with the fluxes at the control points. This difference is defined as: $\delta\psi_{S\_SC} = \psi_{surf.} - \psi_{cont.}$ Here, $\psi_{surf.}$ represents the fluxes on the plasma surface, and $\psi_{cont.}$ represents the fluxes at the control points. By minimizing these gaps, the ISO-FLUX scheme ensures the plasma current remains in the desired value, maintaining the required shape and position. The deviation of controlled flux by superconducting poloidal field coils using proportional, integral, and derivative (PID) control can be defined as:

$$\delta\psi_{SC} = G_{X,AVA}\left(G_{PX}\delta\psi_X + G_{IX}\int\delta\psi_X\,dt + G_{DX}\frac{d\delta\psi_X}{dt}\right) + G_{S,AVA}\left(G_{PS}\delta\psi_{S\_SC} + G_{IS}\int\delta\psi_{S\_SC}\,dt + G_{DS}\frac{d\delta\psi_{S\_SC}}{dt}\right) \quad (1)$$

where $G_{X,AVA}$ and $G_{S,AVA}$ are adaptive allocation gains for plasma current and plasma shape controls, respectively. Coil current changes are derived using the pseudo-inverse matrix of the Green function $M_c^{\dagger}$ between coils and control points as $dI_{coil\_con} = M_c^{\dagger}\delta\psi_{SC}$. The coil voltage command is implemented by replacing the deviation element of flux with the deviation element of coil current change as $V_{com} = M_c\frac{dI_{coil\_con}}{dt} + \frac{d(M_{pl\_con}I_{pl\_mes})}{dt}$. This ensures the control system can adjust the coil currents to maintain the desired plasma equilibrium.

Evaluation of Controllability

To evaluate the controllability of the experiment, the frequency transfer function was obtained by introducing fluctuations to the reference values. We applied fluctuations to the references at 25, 12.5, 8.3, 5, and 2.08 Hz in one plasma discharge and observed the plasma axis or plasma current. Vertical direction fluctuations had a 3 cm amplitude, and plasma current (I_p) fluctuations had a 10 kA amplitude. The time delay between the peak of the reference fluctuation and the peak of the controlled fluctuation at a certain frequency indicates the phase at that frequency. The ratio between the amplitude of the peak of the controlled fluctuation and the amplitude of the peak of the reference fluctuation indicates the magnitude of the frequency transfer function. Using these procedures, we could obtain the Bode plot for the plasma position and shape control in the vertical direction, as shown in Fig. 1.

The comparison of the time evolution of the fluctuations reveals specific controllability characteristics, such as overshooting, in both the MECS code and experiments. The Bode plot analysis can be used to evaluate the feedback control system's gain and phase margins, as well as the frequency transfer func-

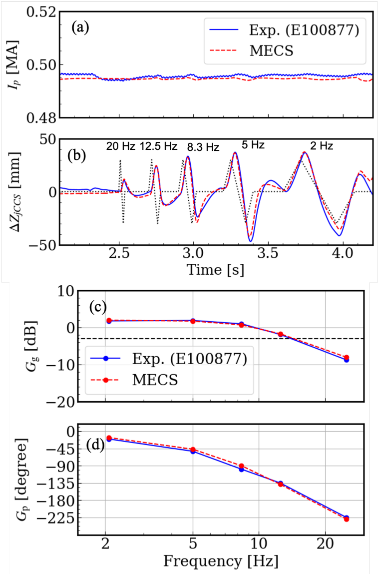

Figure 1: The time evolution of (a) plasma current and (b) plasma current centroid in the experiment. The frequency transfer function of the vertical direction. (c) Magnitude, (d) Phase of frequency transfer function.