Determination of multi-variable control gain based on response characteristics and control tests in JA-DEMO plasma

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The design of fusion DEMO reactors is progressing. Among the challenges, the control of core plasma is a significant issue. In the control of fusion plasmas, a single manipulated variable affects many controlled variables. In addition, there is a mixture of phenomena with different time scales. Therefore, it is necessary to construct a control logic for such a complex system[1]. Additionally, real-time simulation using measured data is required to predict physical quantities that are difficult to measure. This requires the development of integrated codes that simulate the core plasma. The integrated code TOTAL[2] performs 1D particle and thermal transport analysis and 2D magnetic equilibrium analysis. The purpose of this study is to develop the method determining the PID control gain using the multi-variable feedback control function of TOTAL, toward establishment of an appropriate control logic for DEMO plasmas.

In multi-variable PID control, the j-th manipulated variable X_j is determined by

$$X_j(t) = X_j^{\mathrm{pre}}(t) + X_j^{\mathrm{base}} + \sum_k C_j^k(t) \qquad (1)$$

where X^{pre}, X^{base} are the pre-provisioned and steady-state (base) values. C_j^k is obtained by the PID control equation shown in

$$C_j^k(t) = G_{\mathrm{p},j}^k \left(e_k(t) + \frac{1}{\tau_{\mathrm{i},j}^k} \int e_k(t)\,dt + \tau_{\mathrm{d},j}^k \frac{de_k(t)}{dt} \right) \qquad (2)$$

$$e_k(t) = Y_k^{\mathrm{target}} - Y_k(t) \qquad (3)$$

where e_k is the deviation at the k-th controlled variable Y_k. In this study, manipulated variable X_1, X_2 and controlled variable Y_1, Y_2 are defined as follows:

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} = \begin{pmatrix} P_{\mathrm{NB}} \\ f_{\mathrm{pel}} \end{pmatrix}, \begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = \begin{pmatrix} P_{\mathrm{fus}} \\ \overline{n_e} \end{pmatrix}.$$

Here, P_{NB} is NB injection power, f_{pel} is pellet fueling rate, P_{fus} is fusion power, and $\overline{n_e}$ is electron density. The proportional control gain matrix $\boldsymbol{G}_{\mathbf{p}}$ was calculated based on the response due to the step change in X_1, X_2, assuming a linear relationship between the manipulated variable vector and the controlled variable vector.

$$\boldsymbol{G}_{\mathbf{p}} = \begin{pmatrix} 0.2582\ [-] & -1.024 \times 10^{-17}\ [\mathrm{MW \cdot m^3}] \\ 3.126 \times 10^{17}\ [\mathrm{s^{-1} \cdot MW^{-1}}] & 7.388 \times 10^{1}\ [\mathrm{s^{-1} \cdot m^3}] \end{pmatrix} \qquad (4)$$

To evaluate the validity of the control gain calculated based on the step response, 2 types of control tests were carried out. One is decreasing $\overline{n_e}$ while keeping the P_{fus} constant (test 1), and the other is decreasing P_{fus} while keeping the $\overline{n_e}$ constant (test 2). The results of each control test were shown in Fig.1 and Fig.2.

To evaluate the influence of off-diagonal term of $\boldsymbol{G}_{\mathbf{p}}$, two cases were compared in each test. Comparison of the calculation with and without G_{12} in test 1, and comparison of the calculation with and without G_{21} in test 2. In test 1, a significant difference was observed in the result of P_{fus}. The off-diagonal term, which gives correction to P_{NB} (increase) from the deviation of $\overline{n_e}$ (decrease), has a large influence on the P_{fus} control, and a negative correction was made by the diagonal term to return P_{fus} to the target value. In test 2, there was no remarkable difference. These results show that the off-diagonal element G_{12}, which adjusts P_{NB} based on deviation of $\overline{n_e}$, has a large influence, and the off-diagonal element G_{21}, which adjusts f_{pel} based on deviation of P_{fus}, has a small influence.

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References
[1] Working group report on Diagnostics & Control for fusion DEMO, Joint Special Design Team for Fusion DEMO, Sep. 2023, QST-M-43.(in Japanese)
[2] K. Yamazaki, *et al.*, Nucl. Fusion **32** (1992) 633.

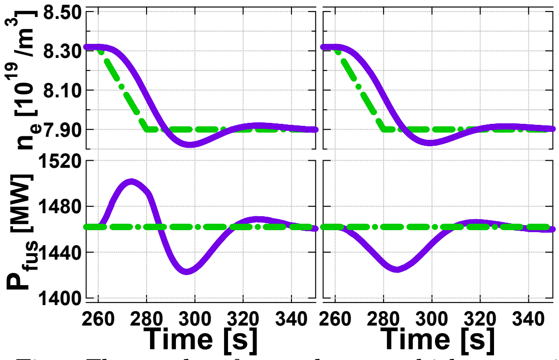

Fig.1. The results of control test 1 which comparing the calculation with (left) and without (right) off-diagonal term G_{12} in $\boldsymbol{G}_{\mathbf{p}}$. The green line represents the target value and purple line represents the calculation result.

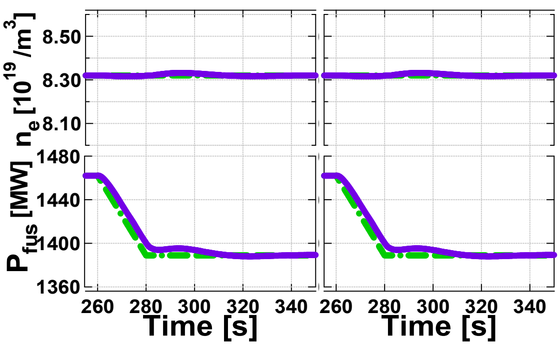

Fig.2. The results of control test 2 which comparing the calculation with (left) and without (right) off-diagonal term G_{21} in $\boldsymbol{G}_{\mathbf{p}}$. The green line represents the target value and purple line represents the calculation result.