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Research for core plasma profile control

核融合炉心プラズマ分布制御に向けた研究

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For the future reactor, how to control the plasma is one of the most important issues. The plasma in the future reactor is Multi-Input Multi-Output (MIMO) system, thus, the controller has to be designed to be able to apply such a system. Additionally, in future plasma, the plasma profile control will be needed, and in such a situation, the number of output will be larger than that of input. Generally, in such a case, the actuators can't control all parameters, thus, the parameters are controlled to minimize some evaluation that, for example, the summation of reference error. In this research, the method of model based profile controller design and the profile control simulation is demonstrated.

1. Introduction

The controller for the future reactor have to be designed to be able to control the multiple plasma parameters (e.g. the fusion power, plasma current and so on) with multiple actuators (e.g. NBI, gas-puff and so on), and they are not one-to-one correspondence (e.g. NBI has the influence both of the fusion power and the plasma current). The controller design considering such a coupling effect is necessary [1]. Additionally, the actuators and the diagnostics which can be installed into the reactor will be limited because of high heat and neutron flux, and the discussion about what devices can be installed have been done [2].

For these reasons, the construction of controller design method which have broad utility (i.e. which can handle any set of controlled objects, actuators and diagnostics) will be needed. In our previous research, one example of plasma MIMO control simulation is demonstrated and the model based controller design method is shown [3]. In this previous research, the plasma current, the fusion power, and the plasma density are controlled by the ohomic current, the NBI and the gas-puff injection. This is 3 inputs 3 outputs control, i.e. the number of output equals that of input, and in this situation, the plasma profile is not considered. For the plasma stability, however, the plasma profile control will be necessary and in this situation, the number of controlled parameters will be larger than that of actuators. For example, the 5 points q profile is controlled by 3 actuators in JET experiment [4].

To do the profile control, the controller will be designed from the physical model and to minimize some evaluation such as the summation of reference error. In this research the example of profile controller design and the profile control simulation is demonstrated.

2. The concept of controller design

In ref [3], the controller is designed from the 0-dimensional plasma differential equation shown as eqs. (1) to (3). These equations are nonlinear equations, and they can be linearized to eqs. (4) and (5). Doing this linearization, the control problem is changed to the linear algebra problem.

$$\frac{d}{dt}\begin{pmatrix} I \\ N \\ W \end{pmatrix} = \begin{pmatrix} -\frac{I}{\tau_j}+\frac{1}{\tau_j}\left(C_{bs}\varepsilon^{0.5}\beta_p I+\frac{\gamma}{n_{20}R}P_{NBI}\right)+\dot{I}_{ind} \\ -\frac{N}{\tau_p}-\frac{n^2}{2}<\sigma v>V+N_{puff} \\ -\frac{W}{\tau_e}+\frac{E_\alpha}{4}n^2<\sigma v>V-C_B n_{20}^2 T_{10}^{1/2}V+P_{NBI} \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} I_p \\ P_{fus} \\ n_e \end{pmatrix} = \begin{pmatrix} I_p \\ \frac{E_\alpha N^2}{V}<\sigma v> \\ \frac{N}{V} \end{pmatrix} \tag{2}$$

$$\boldsymbol{u} = \begin{pmatrix} \dot{I}_{ind} \\ P_{NBI} \\ N_{puff} \end{pmatrix} \tag{3}$$

$$\frac{\mathrm{d}}{\mathrm{dt}}\mathbf{x} = \mathbf{Ax} + \mathbf{Bu} \tag{4}$$

$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du} \tag{5}$$

Equation (4) and (5) are called linear state equation, and the controller design method from this state equation is greatly typical method in control engineering [5].

3. Modeling for the current profile control

To use the state equation method, the plasma differential equation which depends on only time is needed. For the profile control, however, the basic plasma equation for the profile controller depends on time and space as eq. (6).

$$\frac{\partial \Phi_p}{\partial t} = -2\pi R\eta(j - j_{bs} - j_{RF} - j_{bs}) - \dot{\Phi}_{CS} \tag{6}$$

This is the plasma circuit equation. Using some profile assumption, this equation can be changed analytically. For example, the typical negative shear current profile can be written as 4th order equation as eq. (7),

$$\mathrm{j}(\rho) = \mathrm{j}_0(\mathrm{t})(\mathrm{c}_{\mathrm{j}1}(\mathrm{t})\rho^4 + \mathrm{c}_{\mathrm{j}2}(\mathrm{t})\rho^3 + \mathrm{c}_{\mathrm{j}3}(\mathrm{t})\rho^2 + 1), \tag{7}$$

where ρ is r/a and j_0 is current density at the center of plasma. With the assumption of the deposition of NBI and RF, and that of the profile of the plasma temperature and the density like eq (7), equation (6) can be changed to the form of eq. (8).

$$F_1(\dot{j_0}, \dot{c_{j1}},, \dot{c_{j2}}, \dot{c_{j3}}, \rho) \simeq G_1(\rho, t) \tag{8}$$

From equation (8), the time differential of each profile parameter (i.e.j_0, c_{j1}, c_{j2}, c_{j3}) should be gotten.

There are two way to get the time differential of profile parameters from eq. (8). The first is to assume c_{j1}, c_{j2} and c_{j3} are constants, and get the time differential of j_0 and write the controlled value (e.g. q_{min}) as the function of j_0. This method is simple and easy, but this method can control only one parameter. For example, this method can't control the q_{min} and this position simultaneously. The second is to divide eq. (8) with basis function. If equation (8) can be divided some basis function as eq. (9),

$$\sum_{k=1}^{n} \frac{d}{dt}\phi_k(t) f_k(\rho) = \sum_{k=1}^{n} g_k(t) f_k(\rho) \tag{9}$$

n time differential of profile parameters can be gotten. These n parameters control equals profile control. In this case, however, the number of controlled parameters will be much larger than that of actuators, thus, all parameters can't follow the reference value with no error. To tackle this problem, the controller should be designed to minimize some evaluation as the function of each reference error.

4. Profile control simulation

In this section, the simulation that the first method is used and the minimum value of safety factor, the fusion power and the plasma density are controlled by NBI, RF and gas-puff is shown. Also in this case, the time differential equations can be liniarized and written as the form of eqs. (4) and (5), and then, the number of components of $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{u}$ is 3. To design the controller, equation (4) and (5) can be changed as the form of eq. (10).

$$\frac{d}{dt}\begin{pmatrix} \boldsymbol{y} \\ \int_0^t \boldsymbol{y}\, d\tau \end{pmatrix} = \begin{pmatrix} \boldsymbol{A}' & \boldsymbol{0} \\ \boldsymbol{I} & \boldsymbol{0} \end{pmatrix}\begin{pmatrix} \boldsymbol{y} \\ \int_0^t \boldsymbol{y}\, d\tau \end{pmatrix} + \begin{pmatrix} \boldsymbol{B}' \\ \boldsymbol{0} \end{pmatrix}\boldsymbol{u} \tag{10}$$

Assuming the PI control, $\boldsymbol{u}$ can be written as follows,

$$\boldsymbol{u} = (-\boldsymbol{K_p} \quad -\boldsymbol{K_i})\begin{pmatrix} \boldsymbol{y} \\ \int_0^t \boldsymbol{y}\, d\tau \end{pmatrix} \tag{11}$$

From equation (10) and (11), equation (12) can be written.

$$\frac{d}{dt}\begin{pmatrix} \boldsymbol{y} \\ \int_0^t \boldsymbol{y}\, d\tau \end{pmatrix} = \begin{pmatrix} \boldsymbol{A}' - \boldsymbol{B}'\boldsymbol{K_p} & -\boldsymbol{B}'\boldsymbol{K_i} \\ \boldsymbol{I} & \boldsymbol{0} \end{pmatrix}\begin{pmatrix} \boldsymbol{y} \\ \int_0^t \boldsymbol{y}\, d\tau \end{pmatrix} \tag{12}$$

The answer of eq. (12) is linear combination of exponential functions, and each time constant equals to the eigenvalue of the coefficient matrix of eq. (12). Thus, from the time constant which satisfy the control request, the gain matrix $\boldsymbol{K_p}$ and $\boldsymbol{K_i}$ can be gotten. The simulation result with this PI controller is shown in fig.1. In this simulation, the reference value of minimum q value is changed from 1.6 to 1.7 at 500 sec, and at the same time, the reference value of the fusion power and the plasma density are kept constant. Figure.1 shows that to control the minimum q value, the ratio of the NBI power and the RF power is changed, and then gas-puff changed to keep the fusion power and the plasma density constant. The safety factor, the fusion power and the plasma density have large coupling, but the controller can control the parameters independently.

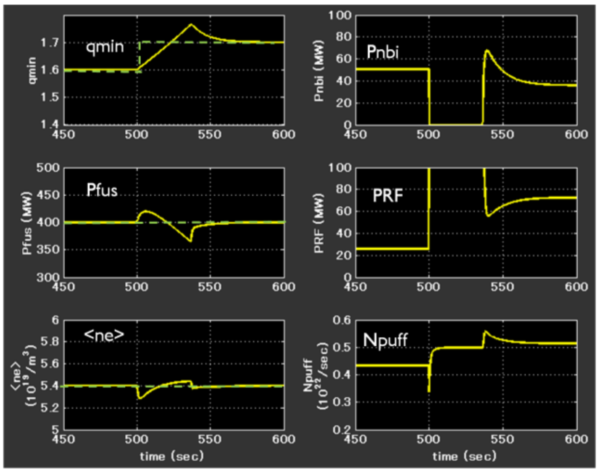

Fig.1 PI profile simulation result. Each yellow line shows each parameter, and each green dash line shows each reference value.

5. Summary

For the future reactor, the multiple parameter control, including the profile control will be needed, and the devices which can be installed into the reactor are limited because of high heat and neutron flux. Thus, to realize the fusion reactor, the construction of controller design method that can apply any controlled parameter, actuator and diagnostics set.

Our research suggested the plasma MIMO controller design method using the control engineering, and benchmarked the method through the simulation.

In this conference, the plasma profile control method and simulation will be demonstrated.

References

[1] T.Suzuki, J.Plasma Fusion Res. Vol**86**, No9 530–535 (2010) (in Japanese).

[2] Alan E Costley, IEEE TRANSACTION ON PLASMA SCIENCE vol**38**, No10, 2934–2943 OCTOBER (2010)

[3] Y.Miyoshi et al, Plasma Fusion Res vol **9** 1405015 (2014)

[4] D.Moreau *et al*, Nucl Fusion **43** 870-882 (2003)

[5] Graham C.Goodwin *et al*., 'Control System Design', Prentice Hall (2000)