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Development of adaptive equilibrium controller in JT-60SA

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Precise shape control, such as control of elongation (κ) and triangularity (δ), is essential not only to achieve high fusion output in tokamak devices but also for plasma physics exploration. Especially in superconducting tokamaks, we should achieve control of κ and δ control, as well as of plasma vertical/horizontal position and plasma current (I_p) within limited power supply voltages and coil number. We developed the Adaptive Voltage Allocation scheme [1], which adaptively adjusts balance between the shape control and the $I_p$control. In this paper, we extend our research to control highly shaped plasmas, where our controller adaptively changes control matrix to follows targeted input shape parameters, such as κ and δ. For control of highly shaped plasmas, Singular Value Decomposition (SVD)-based method (eXtreme Shape Controller) has been developed and validated in JET and in JT-60SA (numerically) during steady states [2]. On the other hand, it is not straightforward to obtain the many reference points before experiments since we do not know the precise shape of plasmas before experiments. Notably, the precise shape is not necessarily required to control κ and δ, for which we have developed adaptive search scheme of control points. Figure 1 shows device conditions of JT-60SA used in the MECS (MHD Equilibrium Control Simulator) simulation. Schematic view of the adaptive search scheme is also shown for the uppermost control point. Our Cauchy Condition Surface (CCS) scheme detects the uppermost point on the Last Closed Flux Surface (LCFS), and calculates the intersections of LCFS and a circle, whose origin is the uppermost point. ISO-FLUX control is applied against the shifted intersecting points of the circle, whose shift is calculated from the reference of the uppermost point. The position of the uppermost point is explicitly determined to satisfy references of κ and δ. Other feature points such as for the lowermost, the innermost, and the outermost, are also calculated via the same procedures. ISO-FLUX control scheme is adopted in our controller, and control equations are $\boldsymbol{M}\delta\boldsymbol{I} = \delta\boldsymbol{\psi}$, where $\delta\boldsymbol{\psi}$ is the residual flux between the control points and the LCFS, and the $\delta\boldsymbol{I}$ is the required currents for compensation. $\boldsymbol{M}$ is calculated from the green matrix between each control point and each coil current. Since the element of the $\delta\boldsymbol{I}$ differs from that of $\delta\boldsymbol{\psi}$, pseudo-inverse matrix of $\boldsymbol{M}$ is used to determine $\delta\boldsymbol{I}$ from $\delta\boldsymbol{\psi}$. The solution is determined to minimize $||\boldsymbol{M}\delta\boldsymbol{I} - \delta\boldsymbol{\psi}||^2 + \lambda||\boldsymbol{S}\delta\boldsymbol{I}||^2$. We newly developed optimization scheme of λ via evaluating the voltage saturation rate of power supply. Here we set the $\boldsymbol{S}$ by the diagonal component of $\boldsymbol{M}$.

In figure 2, the effect of this Adaptive Thikhonov Regularization (ATR) scheme is explored. Control with 8 reference points specifies all the uppermost, the lowermost, the innermost, and the outermost control points. In the case with 6 points, the Z position of inner/outermost control points are freed, which is suitable for substantial change of shape. As shown in the figure, in the absence of the ATR scheme, the control of plasma fails and moves vertically, which is due to the saturation of the power supply voltages (e.g., see CS4 voltage in figure 2). The two ATR cases successfully control κ from 1.5 to 1.8, where voltage saturation is avoided by the regularization of control matrix.

References
[1] S. Inoue *et al*., Nucl. Fusion 61, 096009 (2021).
[2] D. Corona *et al*., Fusion Eng. Des 146, 1773 (2019).

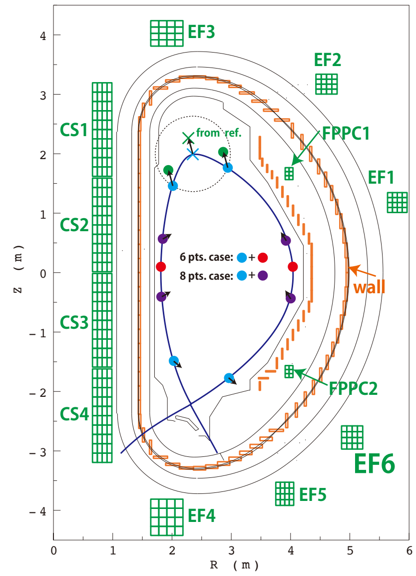

Figure 1 device conditions of JT-60SA used in the MECS and schematic view of adaptive control point setting.

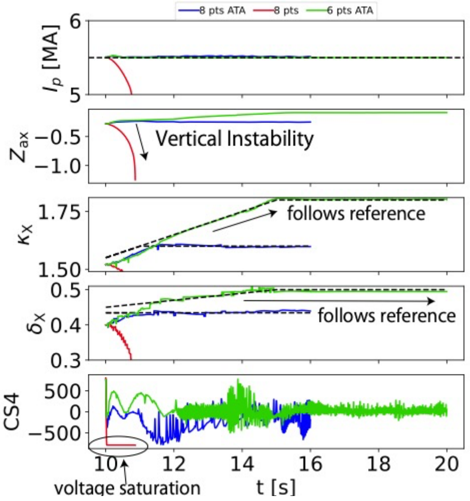

Figure 2 temporal evolution of the plasma current, the vertical position, the elongation, and the triangularity.