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Assessment of Accuracy of Plasma Shape Reconstruction by Cauchy Condition Surface Method in JT-60SA

JT-60SAにおけるコーシー条件面法を用いたプラズマ形状再構築精度の評価

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It is essential for a stable plasma operation and analysis to reconstruct an accurate plasma boundary on the poloidal cross section in tokamak devices. Cauchy Condition Surface (CCS) method is a numerical approach to calculate the spatial distribution of the magnetic flux outside a hypothetical surface and reconstruct the plasma boundary from the magnetic measurements outside the plasma. An accuracy of the plasma shape reconstruction has been assessed by comparing the CCS method and an equilibrium calculation in JT-60SA, which has a high elongation and triangularity of the plasma shape.

1. Introduction

An efficient and safe operation of magnetic confinement fusion devices requires an accurate feedback control of many of discharge parameters. Especially, the accurate feedback control of the plasma shape is essential for an operation objective and device protection in tokamak devices, and the plasma shape must be accurately estimated. Cauchy Condition Surface (CCS) method which calculates the spatial distribution of the magnetic flux around the plasma boundary from the magnetic measurements has been established originally in Japan Atomic Energy Agency [1, 2]. Once the spatial distribution of the magnetic flux is calculated, it is possible to reconstruct the plasma boundary. The CCS, where both Dirichlet (ϕ, poloidal flux function) and Neumann (B_θ, poloidal magnetic field tangent to the CCS) conditions are unknown, is defined as a hypothetical surface located inside the real plasma region. It was shown that the accuracy of the plasma shape reconstruction is less sensitive to the CCS free parameters such as the position and shape of the CCS in JT-60U, and they were determined empirically based on the JT-60U experiments [1]. However, there is a possibility that the accuracy of the plasma shape reconstruction is sensitive to the CCS free parameters in the configuration which has high elongation and triangularity of the plasma. Since the elongation and triangularity of the plasma shape in JT-60SA are larger than those in JT-60U, the sensitivity of the accuracy of the plasma shape reconstruction to the CCS free parameters has been investigated in JT-60SA.

2. Investigation of dependence of condition number

The CCS method is a numerical approach to reconstruct the plasma boundary on the poloidal cross section from the observation values of the magnetic measurements outside the plasma. Figure 1 shows an axisymmetric model of the central solenoid (CS) modules, equilibrium field (EF) coils, flux loops (FLs), magnetic probes (MPs) and the definition of the CCS in JT-60SA. M is the number of CCS nodes on the CCS. The vertical and horizontal diameters of the CCS are defined as the CCS height h_{ccs} and width d_{ccs}. Assuming that the CCS encloses all the plasma current and there are no plasma current outside the CCS, it plays the same role as the plasma current in causing the

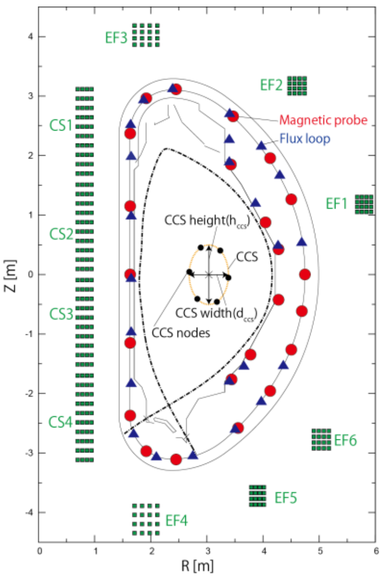

Fig. 1 Locations of 4 CS modules, 6 EF coils, 24 FLs, 23 tangential MPs and definition of CCS in JT-60SA.

magnetic flux. The three types of boundary integral equations for the vacuum field are given using the magnetic measurement signals to determine the ϕ and B_θ at the several nodes along the CCS, and they are coupled and expressed in a matrix form. After the ϕ and B_θ is determined by solving the matrix equation in a least square sense, the spatial distribution of magnetic flux outside the CCS for any points is provided by the ϕ and B_θ. The plasma boundary can be reconstructed by plotting the contour of spatial distribution of magnetic flux, which passes through the X-point or limiter point on the first wall.

The CCS method can be categorized as an inverse problem for Maxwell's equation, and the solution is oscillated if the property of a constitutive matrix is ill-conditioned. The condition number is a numerical index for evaluating the property of the constitutive matrix. Since it is known that the measurement errors affect the solution errors in proportion to square of the condition number, the condition number should be reduced for avoiding the ill-posed problem. It has been shown that the condition number strongly depends on the magnetic sensor arrangement, CCS shape and *M* in the JT-60SA configuration. Therefore, it has been found that the ill-posed problem can be avoided by changing the magnetic sensor arrangement, CCS shape and *M*.

3. Assessment of Accuracy of Plasma Shape Reconstruction in JT-60SA

It is expected that there is the optimum CCS shape and *M* for the accurate plasma shape reconstruction without the ill-posed problem in JT-60SA. For investigating the optimum CCS shape and *M*, the reconstructed plasma shape is compared with the reference one by changing the CCS shape and *M*. The reference plasma shape and magnetic sensor signals for the plasma shape reconstruction are provided by the equilibrium calculation [3]. There are 4 types of discharge scenarios, which have different plasma current and profile, as follows: (1) I_P is 5.5 MA with normal internal inductance l_i (l_i = 0.75). (2) I_P is 4.6 MA with normal l_i. (3) I_P is 5.5 MA with low l_i (l_i = 0.50). (4) I_P is 4.6 MA with low l_i. The plasma with low l_i has a broad plasma current profile than that with normal l_i. It has been found that the optimum CCS size and *M* for the accurate plasma shape reconstruction are in proportion to the plasma size, and it is independent of the plasma discharges.

For assessing the accuracy of the plasma shape reconstruction using the optimum CCS shape and *M* in JT-60SA, the reconstruction errors in plasma shape and locations of the strike points are compared under several CCS settings. It is essential to maintain the minimized reconstruction errors in the plasma shape and locations of strike points for the stable control and device protection in whole plasma discharge, and the reachable reconstruction errors are defined as the maximum ones among the above 4 types of discharge scenarios. Figure 2 shows the reachable reconstruction errors in plasma shape, locations of the inner and outer strike points for 3 CCS settings. The CCS settings are as follows: (Setting I) Half of d_{ccs} and h_{ccs} are 0.4 and 0.6 m for M = 6. (Setting II) Optimum CCS shape for M = 6. (Setting III) Optimum CCS shape and *M*. It has been found that the reachable reconstruction errors in plasma shape and locations of the strike points under low l_i scenario are substantially larger than those under normal l_i scenario due to the broad plasma current profile. In Setting III, the reachable reconstruction errors in the plasma shape and locations of the strike points under the normal l_i scenario are 3 and 2 mm, and ones under the low l_i scenario are 8 and 6 mm, respectively. It has been found that the accuracy of the plasma shape reconstruction greatly improves by using the optimum CCS shape and *M* in JT-60SA.

An applicability assessment of the optimum CCS shape and *M* and the dependence of the accuracy of the plasma shape reconstruction on the arrangement and the number of the magnetic sensors are also reported.

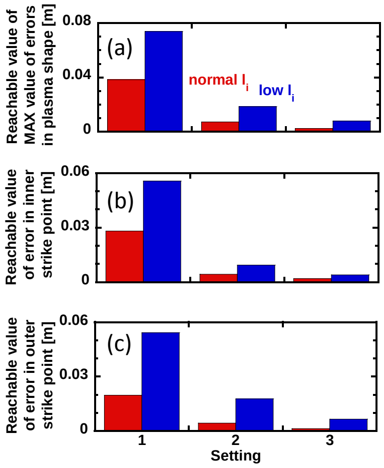

Fig. 2 Reachable values of reconstruction errors in (a) plasma shape, locations of (b) inner and (c) outer strike points for 3 CCS settings.

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