Preliminary Study of the Control Algorithm for Advanced Divertor Configuration

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1. ***Introduction.*** The advanced configurations (snowflake and tripod) have been designed with EFIT and CORSICA based on current poloidal field (PF) coils system of HL-2M to study the advanced divertor physics and support the high performance plasma operation [1]. The characteristic parameters of the advanced configuration (the distance between two X-points, magnetic flux expansion[2] and weak field area and so on), are the key factor for the advanced divertor studies. So the active magnetic control (especially X-points control) of the advanced configuration is essential for the operation and the study on physical mechanism of the advanced divertor. In this paper, a control algorithm for the advanced divertor configuration has been developed. The preliminary simulation results with this algorithm have also been introduced.

2. ***Control model.*** The control algorithm for the advanced divertor configuration is derived from the snowflake, but also applies to the tripod configuration.

Firstly, the magnetic flux, ψ ,is expanded around the snowflake center (r_0, z_0) in the new coordinates $(x, y), r = r_0 + x, z = z_0 + y$ up to the third order to achieve[3]:

$$\psi_{\exp} = c_0 + c_1 x + c_2 y + c_3 x^2 + c_4 xy + c_5 y^2 + c_6 x^3 + c_7 x^2 y + c_8 xy^2 + c_9 y^3 \quad (1)$$

As the poloidal magnetic field components can described by flux function $\psi_{\exp}\left(C_{\exp}, x, y\right)$ as follow : $B_r = -\partial\psi_{\exp}/(r\partial y)$, $B_z = \partial\psi_{\exp}/(r\partial x)$ (2).

The magnetic field nulls are solved by setting $B_r\left(C_{\exp}, x, y\right)=0$, $B_z\left(C_{\exp}, x, y\right)=0$. This results in the location of the two X-points $x_1\left(C_{\exp}\right), y_1\left(C_{\exp}\right), x_2\left(C_{\exp}\right), y_2\left(C_{\exp}\right)$. In addition , the derivative, $P = \delta C_{\exp}/\delta B$ (3), has also been obtained. In other hand, these unknowns $C_{\exp}$ are solved with the magnetic field, $B = \left\{B_{r0}, B_{z0}, B_{r1}, B_{z1}, B_{r2}, B_{z2}, B_{r3}, B_{z3}\right\}^T$, from the real-time equilibrium reconstruction

(RTEFIT) at the first choosing four points around the snowflake center.

Once the locations of the two X-points are obtained, poloidal field (PF) coils are used to control the relative locations to obtain the desired Snowflake (exact, minus, plus). For precise control, the effect of the change in PF coil currents, δI_{PF}, on the X-point locations is calculated. This is achieved by applying the chain rule on the snowflake parameters:

$$\frac{\partial \delta x1}{\partial \delta I_{PF}} = \frac{\partial \delta x1}{\partial C_{\exp}} \frac{\partial C_{\exp}}{\partial B} \frac{\partial B}{\partial \delta I_{PF}} \qquad (4)$$

Here, $\delta x1$ is the radial motion of the first X-point due to the δI_{PF}. It can replace by $\delta x2, \delta y1, \delta y2$ in equation (4). The three terms at the right hand of equation (4) will be explained as following:

Firstly, define the derivative $X_1 = \left\{ \frac{\partial x_1}{\partial C_{\exp}} \right\}$, $X_2 = \left\{ \frac{\partial x_2}{\partial C_{\exp}} \right\}$, $Y_1 = \left\{ \frac{\partial y_1}{\partial C_{\exp}} \right\}$, $Y_2 = \left\{ \frac{\partial y_2}{\partial C_{\exp}} \right\}$ for each expansion coefficients at the two X-points and calculate them from the equations (2). So the $X \equiv \{X_1, Y_1, X_2, Y_2\}^T$ is obtained. And then, according the equation (3), we get the second term. The third term $\frac{\partial B}{\partial I_{PF}} = \frac{\partial B_{PF}}{\partial I_{PF}} = G_{PF}$ is found from the Green's Function of the G-S problem. However, consider the plasma rigid motion [4], the third term should be $\frac{\partial B}{\partial \delta I_{PF}} = \frac{\partial B_{PF}}{\partial I_{PF}} + \frac{\partial B_{pl}}{\partial r_c}\frac{\partial r_c}{\partial I_{PF}} + \frac{\partial B_{pl}}{\partial z_c}\frac{\partial z_c}{\partial I_{PF}} = G_{PF} + G_R + G_Z = G_x$. G_R, G_Z are the response matrixes of the magnetic as the plasma rigid motion in radial or vertical direction at four sample points.

For remain the plasma main parameters, the isoflux control will be used in the snowflake configuration control. As the same as the x-points control, consider plasma rigid motion, the flux change as the δI_{PF} can write as :

$$\delta\psi_{iso} = \left(\frac{\partial \psi_{iso}}{\partial I_{PF}} + \frac{\partial \psi_{iso}}{\partial r_c}\frac{\partial r_c}{\partial I_{PF}} + \frac{\partial \psi_{iso}}{\partial z_c}\frac{\partial z_c}{\partial I_{PF}} \right) \delta I_{PF} = G_{iso}\delta I_{PF} \qquad (5)$$

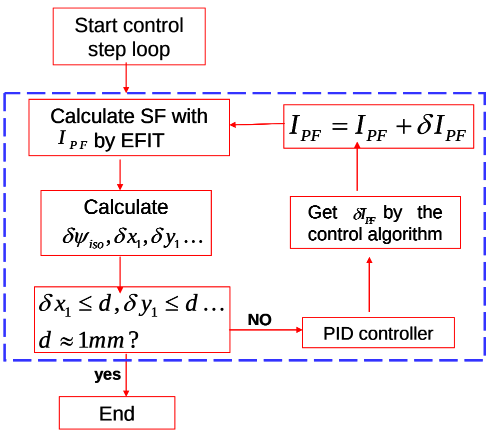

Fig. 1, The iteration loop for the SF control.

Finally, we get the expression as :

$$D = A \cdot \delta I_{PF} \qquad (6)$$

Where, $D = [\delta\psi_{iso}, \delta x_1, \delta y_1, \delta x_2, \delta y_2]^T$, $A = \begin{bmatrix} G_{iso} \\ X \cdot P \cdot G_x \end{bmatrix}$,.

Then, the control needed to achieve the requested snowflake configuration is obtained by taking the pseudo-inverse of this equation and multiplying it by a weighting function, W,

$$\delta I_{PF} = (A^T A)^{-1} \cdot A^T \cdot W \cdot D \qquad (7)$$

3. *Simulation scheme*

The preliminary simulation will be run based on the control algorithm for snowflake configuration with EFIT. EFIT will be used to calculating the equilibrium configuration for the given PF current I_{PF}, and providing the magnetic filed signal at the four sample points(this function will be replaced by RTEFIT in the real-time control system). The X-points location can obtain from the snowflake identification algorithm. The differences (such as $\delta x_1, \delta y_1, \ldots$) of the X-points location which compared to the user-requested values are filtered with a Proportional-Integral-Derivative controller and then fed to the control algorithm. Therefore the change of PF current δI_{PF} will be achieved by the control algorithm. The update PF currents , $I_{PF} = I_{PF} + \delta I_{PF}$,will feedback to the EFIT to calculate the new equilibrium configuration and provide the magnetic filed signal for the control algorithm. Repeating these steps until the differences of X-points location between the current values and the user-requested values are less than the convergence conditions. It's mean that the accurately controls for the X-points location are achieved, and then end of these loop. The detail simulation steps have described as in figure 1.

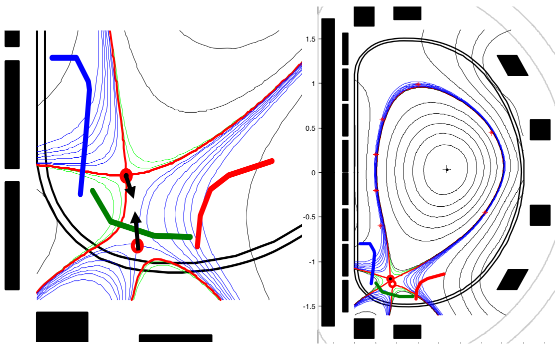

Fig. 2. The advanced divertor configuration control from tripod (left) to quasi-exact Snowflake configuration (right)

4. *Preliminary simulation results.*

Since the snowflake and tripod configurations have been designed and will be operation on HL-2M to study the advanced divertor physics. The desired snowflake (exact, minus, plus), even the transition between the snowflake and tripod configurations can be obtain by control the relative locations of the two X-points with the control methods as describe above.

As an example, the quasi-exact snowflake with the distance between the two X-points (rho) less then 3cm (Fig 2, right) has been obtained from the initial tripod configuration which the rho more then 25cm (Fig 2, left) by control of the location of two X-points with the snowflake control algorithm. During these control process, the differences between the current values and the user-requested values of X-points location are also shown in figure 3. In addition, the changes of PF currents for each control step are shown in figure 4.

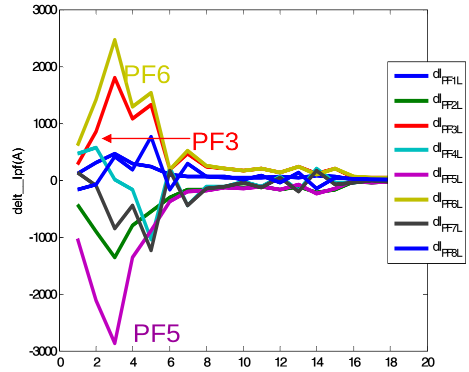

Fig. 4.The difference of PF currents compared to their initial values

5. ***Summary.*** A control algorithm for the advanced divertor configuration has been developed. The relationship between the X-point location and the PF coils current has been created by this algorithm with the magnetic filed of four control points near the divertor area. With this algorithm, the location of the X-points, can be accurately tuned by regulating the current in PF coils (especial in divertor coils), meanwhile remain the plasma main parameters.

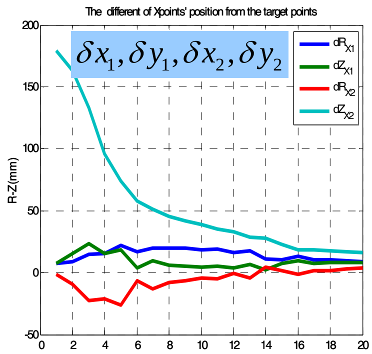

Fig.3 The differences of the X-points location compared to the user-requested values

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