Real-time Control of Neoclassical Tearing Mode in Time-dependent Simulations

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1. Introduction

As a resistive instability, neoclassical tearing mode (NTM) produces magnetic islands in magnetized plasma that can significantly degrade confinement and even lead to plasma disruption. Real-time feedback control of NTMs is essential to achieve the high performance steady state operation of a fusion reactor. The electron cyclotron current drive (ECCD) is one of the most effective methods for the stabilization of the NTMs when ECCD deposition is well-localized at islands. However, it is difficult to find and align the optimum position for complete island suppression by ECCD because of modification of island and ECCD deposition location according to the plasma transport.

In this paper, NTM control simulation using a transport code, ASTRA, combined with the modified Rutherford equation has been performed in KSTAR. By NTM controller, ECCD launcher parameters are changed with time-varying plasma conditions considering the different time scale, i.e. plasma transport, the NTM growth rate, controller response. Based on the results, the NTM control system is expected to be obtimized for efficient NTM suppression in preparation for KSTAR experiments.

2. Simulation of Neoclassical Tearing Modes and Their Control using ECCD

NTMs are characterized by the magnetic islands in which the bootstrap current has been lost. To simulate NTMs using ASTRA package (ASTRA, TORAY and the MRE solver), we assume that the heat conductivity of electron and ion is increased inside the islands.
The time evolution of island size is calculated by the modified Rutherford equation (MRE) as following [1]: $\frac{\tau_R}{r_s}\frac{d\omega}{dt} = \Delta'_0 r_s + \delta\Delta' r_s + a_2 \frac{j_{bs}}{j_\parallel}\frac{L_q}{\omega}\left[1 - \frac{\omega^2_{marg}}{3\omega^2} - K_1 \frac{j_{ec}}{j_{bs}}\right]$

All variables of the MRE are calculated by ASTRA self-consistently, except the geometric constant a_2 which is inferred from the saturated island width from ISLAND [2].

Simulation performed for hybrid scenarios in KSTAR with NTM's and the plasma current and toroidal field are assumed to be 1 MA and 2.65 T, respectively. They are adjusted for ECCD setting as 170 GHz X2 mode. The predictive modeling of hybrid modes is performed with the ASTRA code employing the Weiland model for transport calculations. In this work, (2, 1) NTM is only considered because (2, 1) mode NTM is more dangerous than (3, 2) NTM. The simulation starts at 3.8 s and (2, 1) NTM is occurring at 4.1 when β_N is above 3 high enough trigger NTM.

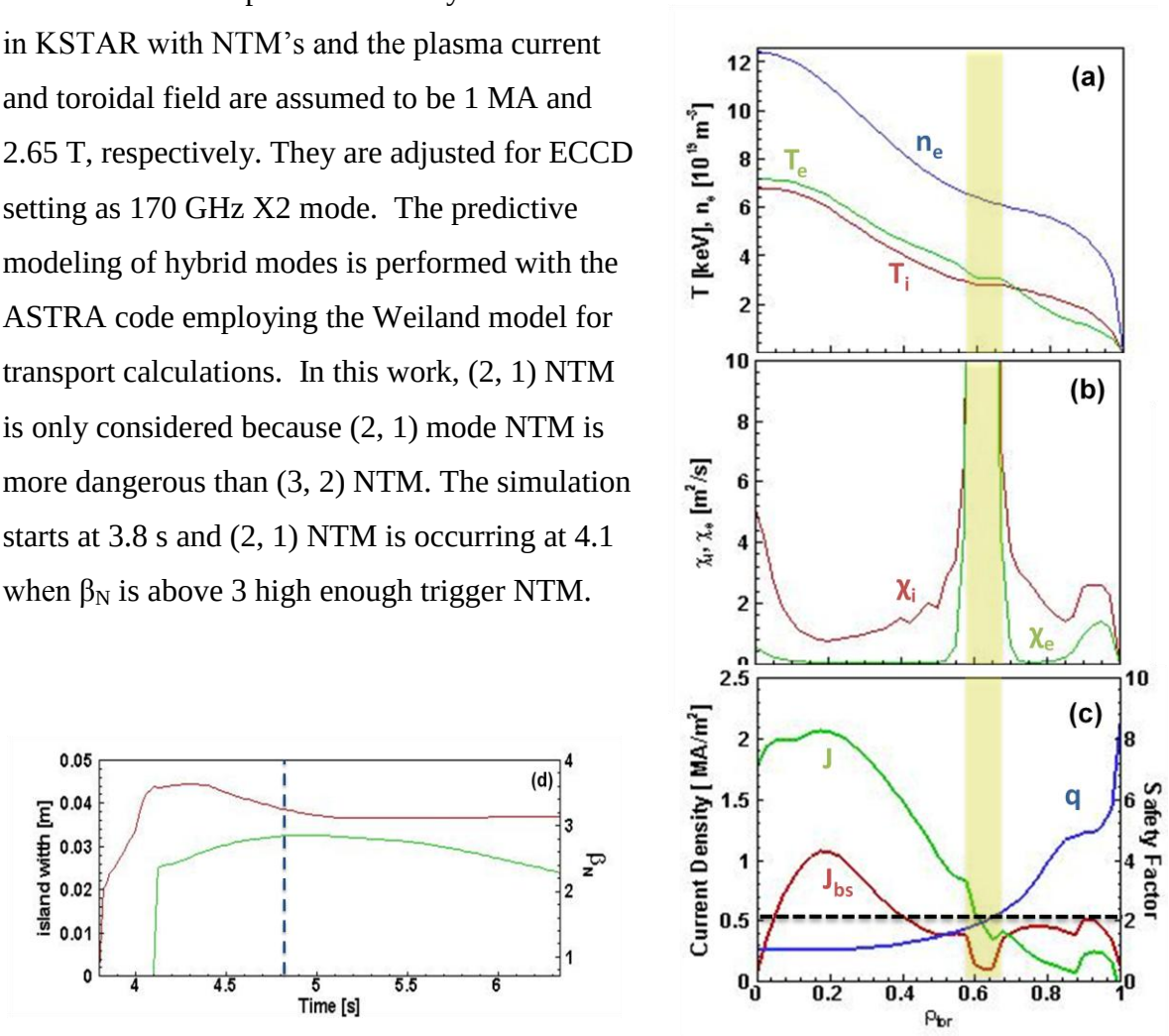

Figure 1 NTM Simulation using ASTRA package at 4.12s. Ion, electron temperature and the electron density (a), ion and electron heat conductivity (b), total, bootstrap current and q profile (c), time evolution of island width and β_N

3. Method for the system identification

For system modeling, the input and output parameter is defined. It is possible to choose the input parameter as the ECCD launch angles (poloidal or toroidal) and power. In this paper among them, we defined the input parameter as poloidal launch angle because ECCD launch actuator usually cannot change the poloidal and toroidal angle at the same time during a discharge. We defined the output parameter as the NTM island width because the ECCD alignment can affect the island width directly.

For system identification tool, the modulation of the input parameter is needed and the frequency of the modulation waveform is considered the various time scale including heat and

current diffusion, energy confinement, and actuator. The modulation data sampling of the poloidal angle is made with 10 ms time scale as shown in figure 2 (a). We define Δ in this paper as the difference between modulated and reference (not- modulated) values. The island width is saturated at about 4.7 s in the reference simulation without ECCD (see figure 1). The initial poloidal and toroidal angle are assumed 98 ° and 190 °, respectively. The ASTRA simulation with modulation of the poloidal angle will inject ECCD at about 4.7 s and the modulation starts after 1 s. The island width decreases rapidly when localized deposition of ECCD current is at the resonant surface where NTM occurs.

Using the system identification toolbox, we estimate the linear mathematical model of a dynamic system from the simulated data. As computing the given input and output with the various parametric models, we can choose the best estimated model for the NTM controller. The iv441 method as a ARX model and the n4s7 method as a state-space model represent with high accuracies of about 81.76 % and 88.76 %, respectively (see figure 2 (b)).

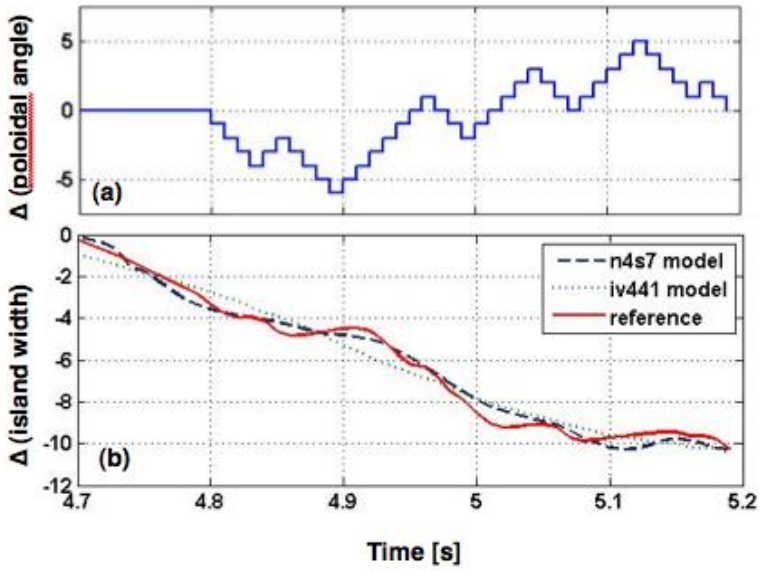

Figure 2 The method of system identification. The modulation form of the input parameter (a), the results of estimated the linear mathematical model (b)

4. Validation of the identification

To validate the system model in Section 3, the database with other modulation form is made by simulating ASTRA. The modulation form is used the minimum time scale 10 ms and the time duration is different each other. The modulation form is different from the shape used in section 3 (see figure 3 (a)). As result, the iv441 method as a ARX model is matched 77.27 % and the n4s7 method as a state-space model is matched 71.39 % as shown figure 3 (b). It shows a different trend that is estimated in previous section.

This result is caused by the less fluctuation of the given output parameter for testing the model than that for constructing the model. Although the iv441 method has high accuracy than the n4s7 method, the n4s7 method tends to the reference better than the iv441 method after 4.85 s when the modulation is started. In the range which is started from 4.85 s, the n4s7 method has 71.6 % accuracy and the iv441 method has 59.12 % accuracy. It is the same trend as shown in section 3.

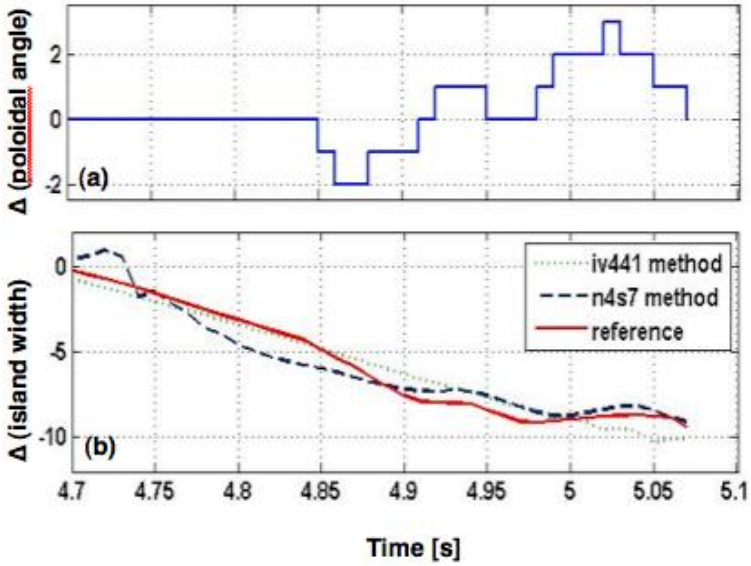

Figure 3 The method of system identification. The different modulation form of the input parameter (a), the test results of estimated the linear mathematical model (b)

5. Summary and Future work

To identify system for NTM controller, the NTM effects are taken into account by coupling the solver of MRE to ASTRA for computing time evolution of widths of islands, self-consistently. The saturated island is established in simulation without ECCD. As simulating with the modulation of the poloidal launcher angle as the input parameter, we calculated the island width data as the output parameter for the system identification. The various parametric models are calculated for the best model estimated. The iv441 method and the n4s7 method represent with high accuracies of about 81.76 % and 88.76 %, respectively. It is the same trend at the range of modulation in the calculation for validation the model.

In this work, the performed system identification is very simplified using single input and single output. The realistic NTM control using ECCD must be considered the plasma response as well as the island width because ECCD affects the plasma temperature and density profile.

References

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[2] Nguyen C N, Bateman G and Kritz A H 2004 *Phys. Plasmas* **11** 3460