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Simulation of neoclassical tearing mode stabilization via minimum seeking method on ITER

M. H. Park [a], M. Kim [b], K. Kim [a], D. H. Na [a], C. S. Byun [a] and Y. S. Na [a*]
[a] *Dept. of nuclear engineering, Seoul National Univ., 1 Gwanak-ro, Gwanak-gu, Seoul 08826*
[b] *FNC Technology Co. Ltd*
[*] *Corresponding author: ysna@snu.ac.kr*

1. Introduction

Neoclassical tearing modes (NTMs) are well known resistive magnetohydrodynamic (MHD) instabilities. These instabilities are sustained by a helically perturbed bootstrap current. NTMs produce magnetic islands in tokamak plasmas that can degrade confinement and lead to plasma disruption [1]. Because of this, the stabilization of NTMs is one of the key issues for tokamaks that achieve high fusion performance such as ITER. Compensating for the lack of bootstrap current by an Electron Cyclotron Current Drive (ECCD) has been proved experimentally as an effective method to stabilize NTMs [2]. In order to stabilize NTMs, it is important to reduce misalignment. So that even ECCD can destabilize the NTMs when misalignment is large [1]. Therefore, feedback control studies have started to reduce misalignment. Feedback control method that does not fully require delicate and accurate real-time measurements and calculations, such as equilibrium reconstruction and EC ray-tracing, has also been proposed [3]. One of the feedback control methods is minimum seeking method. This control method minimizes the island width by tuning the misalignment, assuming that the magnetic island width is a function of the misalignment [2].

2. Methods and Results

In this section some of the control methods and numerical methodologies are described. The control method includes a Finite Difference Method (FDM) based minimum seeking method and sinusoidal perturbation based minimum seeking method.

2.1 Modified Rutherford Equation for description of the NTM evolution

The temporal behavior of the NTM is governed by the Modified Rutherford Equation (MRE) [4]. There are different forms of MRE. In this paper, we used a simplified form of the MRE with the effect of ECH as follows [5]:

$$\frac{\tau_R}{r_s}\frac{dW}{dt} = r_s\Delta_0' + r_s\delta\Delta_0' + a_2\frac{j_{bs}}{j_p}\frac{L_q}{W}\left[1 - \frac{W_{marg}^2}{3W^2} - K1\frac{j_{EC}}{j_{bs}} - \alpha_H F_H\frac{W}{W_{dep}}\frac{P_{EC}\eta_{EC}}{I_{EC}}\right] \tag{1}$$

2.2 Minimum island width growth rate seeking controller

There are two types of controller in minimum island width growth rate seeking controller. One is FDM based controller, the other is sinusoidal perturbed based controller.

Input parameters of each controller are ‘island width’ and ‘island width growth rate’. When a controller finds minimum point with ‘island width’, there are both ways to increase misalignment and decrease misalignment. But if a controller finds minimum point with “growth rate’, there is only way to decrease misalignment [3].

2.3 Integrated numerical modelling of NTM

In order to perform a feedback control simulation, a system of the simulation is required. The system is an ITER plasma with 2/1 NTM. This system consists of transport solver, equilibrium solver, heating source module, MRE solver and diagnostic converter [3].

ASTRA (Automated System for Transport Analysis [6]) is transport solver. ESC (Equilibrium and Stability Code [7]) is equilibrium solver. TORAY (Tokamak ECH/CD RAY-tracing code [8]) is used for calculation of the ECH/CD. ISLAND calculates saturation island width [9].

In particular, the diagnostic data is selected as the Mirnov coil. It is well known that the measurement is noisy in various experiments and noise level is approximately 10% of the signal amplitude [10]. So, when diagnostic converter converts island width to Mirnov signal, noise is taken into account. Noisy environment makes the controller to the wrong judgement.

2.4 NTM full suppression time with EC power and beam width scan when EC perfect aligned

Prior to the test for each control method, Scan of the beam width and the beam power is performed in EC perfect alignment condition (see figure 1). As shown in figure 1, the smaller the beam width, the larger the beam power, suppression time is reduced. But, beam power and beam width are limited in ITER. In addition, beam width is small, it is difficult to reduce the relative misalignment of ECCD [11]. In this work, absorption beam power set to about 20 MW, and beam width set to about 0.07 m. was applied to each control method.

2.5 Results with FDM based minimum seeking method

Feedback stabilization of the NTM is simulated using FDM based minimum seeking method for the two cases of initial poloidal angle. And there are two input parameters. One is the island width, the other is the island width growth rate. As mentioned above, 'island width growth rate' is much more effective input parameter than 'island width' to suppress NTM. The resulting island width evolutions are shown as the green curves in figure 2 for the two different initial poloidal angle and input parameter.

As shown in figure 2, full stabilization of the NTM is achieved with both input parameters. But 'island width growth rate seeking method' is much faster than 'island width seeking method' with both initial poloidal angles. First controller takes about 17 seconds to achieve full stabilization of the NTM, and Second controller takes about 30 seconds.

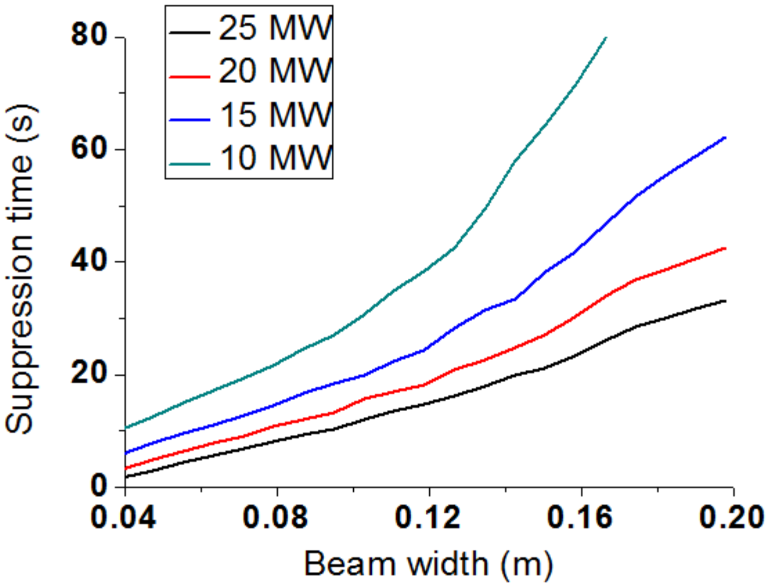

Fig 1. NTM full suppression time scan with EC beam power and width. This result was obtained on the assumption that the EC beam is perfect aligned.

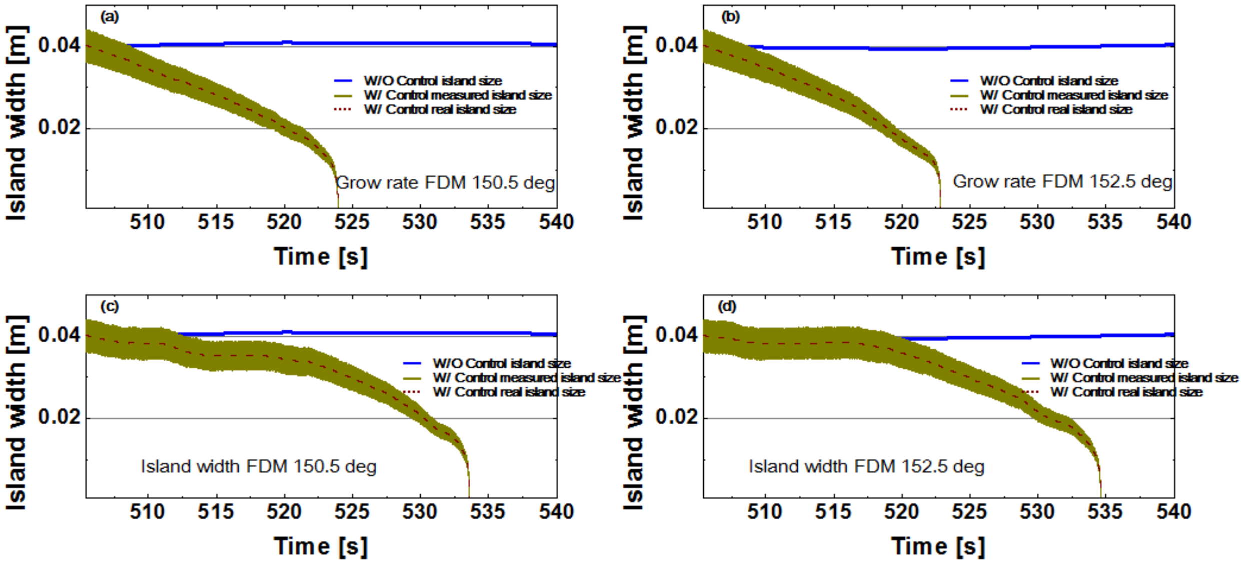

Fig 2.The simulated island width behavior using FDM based minimum seeking controller. (a) and (b) using island width growth rate seeking method, (c) and (d) using island width seeking controller. Each initial angle is 150.5˚ and 152.5˚. Blue line is island width without feedback control. Green line is measured island width with feedback control at noisy environment. Red dot line is real island width with feedback control.

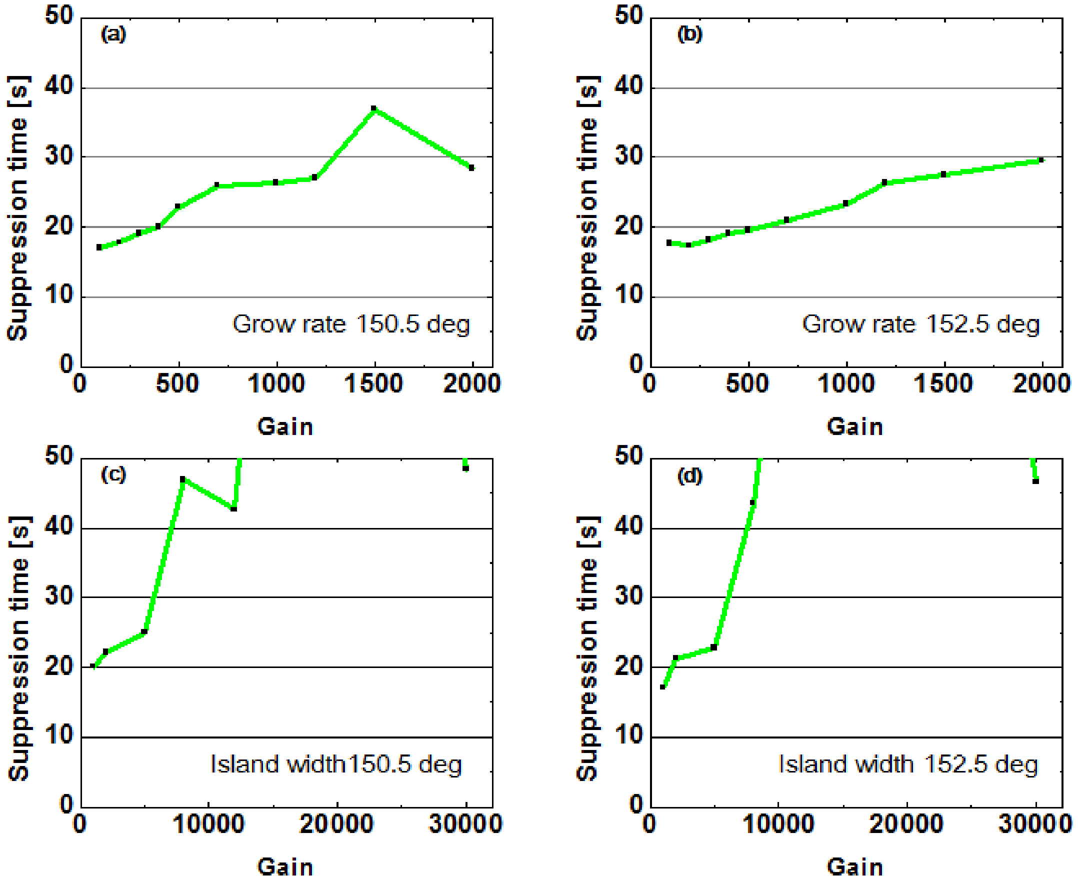

Fig 3. The full suppression time in the adaptive gain scan for the sinusoidal perturbation based extremum seeking method. Each graph represents sinusoidal perturbation based minimum ‘island width growth rate’ seeking controller with initial angle 150.5° (a) and 152.5° (b), and the sinusoidal perturbation based minimum ‘island width’ seeking controller with initial angle 150.5° (c) and 152.5° (d).

2.6 Results with sinusoidal perturbation based minimum seeking method

The sinusoidal perturbation based extremum seeking control is tested. In this controller, adaptive gain multiplies by the sinusoidal perturbation. Since the scale of the island width growth rate (order of 0.1) is larger than that of the island width (order of 0.01), the adaptive gain of the controller is different from two input parameters. In conclusion, it is found to succeed to fully suppressing the mode at most of minimum ‘island width growth rate’ seeking controller. But some case of minimum ‘island width’ seeking controller cannot suppress the mode.

As shown in Figure 3, suppression times of the sinusoidal perturbation based minimum ‘island with growth rate’ seeking controller are about 20 ~30 seconds with both initial poloidal angles. But many cases of sinusoidal perturbation based minimum ‘island width’ seeking method failed in full stabilization of NTM.

3. Conclusions

As a robust and simple method of controlling NTM, minimum ‘island width growth rate’ seeking control is purposed and compared with performance of minimum’ island width’ seeking control. At the integrated numerical system, simulations of the NTM suppression are performed with two types of minimum seeking controllers; one is a FDM based minimum seeking controller and the other is a sinusoidal perturbation based minimum seeking method. The full suppression is achieved both types of controller. The controllers adjust poloidal angle of EC beam and reduce misalignment to zero. The sinusoidal perturbation based minimum seeking control need to modify the adaptive gain. But, the FDM based minimum seeking control does not need modifying adaptive gain. And it is found that the FDM based minimum ‘island width growth rate’ seeking controller is much more efficient than FDM based 'island width' seeking controller at noisy signal environment. But the sinusoidal perturbation based minimum seeking method need to find appropriate adaptive gain and some cases cannot reach a full suppression of NTM.

FDM based minimum 'island width growth rate seeking method is thought to be more effective in NTM suppression compared with other control methods such as FDM based minimum 'island width' seeking control and sinusoidal perturbation based minimum seeking control in terms of speed and robustness. Noisy environment makes the controller to the wrong judgement. In such an environment, FDM based minimum 'island width growth rate' seeking controller produces fewer mistakes than any other controller. This minimum seeking control with island width growth rate as input parameter and EC poloidal angle as output parameter can be a new control scheme at ITER. It just requires a rough position of mode.

Nevertheless, furthermore studies such as the case of different beam width are necessary in future. The narrower the beam width, the more rapidly NTM is stabilized. But, since relative of misalignment of ECCD is increased, in order to use the extremum seeking control, beam should be more close to the island center.

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