Identification of multiple eigenmode growth rates towards real time detection in DIII-D and KSTAR tokamak plasmas

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Abstract
The successful application of three-dimensional (3D) magnetohydrodynamic (MHD) spectroscopy enables us to identify the multi-mode eigenvalues in DIII-D and KSTAR tokamak experiments with stable plasmas. The temporal evolution of the multi-modes’ stabilities have been detected. The new method is numerically efficient allowing the real time detection of MHD modes’ stabilities during the discharge. The method performs active detection of the plasma stability by utilizing the upper and lower rows of internal non-axisymmetric coils to apply a wide variety of 3D fields. Multi-mode eigenvalues are extracted using subspace system identification of the plasma response measured by 3D-field magnetic sensors distributed at different poloidal locations. The equivalence of this new method with the one introduced by Wang (2019 Nucl. Fusion 59 024001) has been numerically corroborated. The more robust and efficient calculation developed here will enable real time monitoring of the plasma stability based on the extracted eigenvalues of stable modes.

Keywords: 3D MHD spectroscopy, multi-mode stability, real time detection

(Some figures may appear in colour only in the online journal)

1. Introduction

Global magnetohydrodynamic (MHD) instabilities, such as kink modes [1] and tearing modes [2, 3], can be extremely dangerous to advanced tokamak operation, such as ITER-like tokamaks and future high power fusion reactors [4, 5], where the unstable global MHD modes can disrupt the plasma and lead to severe damage of tokamak devices. Therefore, it is essential to develop a technique dedicated to the real time stability detection of these MHD modes with quantitative stability measurements to track and avoid instabilities that lead to disruptions.

Tokamak plasmas can be sensitive to a low level of non-axisymmetric magnetic perturbations applied by external coils [6], and the response of plasmas contains information related to the stability of various MHD modes. For instance, the resonant field amplification of plasma response, indicating the
\[ \beta \text{ limit of ideal kink instability, has been extensively investigated in various experiments [7–10]. Such responses are often modelled using linear MHD theory [11–16], since the magnitude of magnetic perturbation (}\delta B)\text{ is often several orders smaller than the equilibrium magnetic field (}B). Many previous works [17–19] assume one single dominant stable eigenmode in the plasma response. However, the plasma response can contain multiple significant stable MHD eigenmodes, which is not only indicated by theoretical studies [20–26] but also observed in the EAST [27] and DIII-D experiments [28–30]. Therefore, the plasma response is the linear combination of multiple stable eigenmodes in the linear system [29, 30].

Theoretically, the active detection of dominant eigenmodes in plasma can be achieved by varying the external perturbations, which was first developed in [6] called MHD spectroscopy, to identify the damping rate and the mode rotating frequency of the stable resistive wall mode. In the method, the single-mode assumption is adopted as done in many previous works [17–19]. Since the multi-mode plasma response has been detected in DIII-D experiments [28], it motivates us to develop multi-mode three-dimensional (3D) MHD spectroscopy based on the multi-pole transfer function for more reliable detection of plasma stability [31]. Since the transfer function needs to be extracted by fitting the measured magnetic response and perturbed coil currents in the frequency domain, this method is referred to as the frequency domain method (FDM) in this work. The FDM method is not efficient for experimental real time detection. A new time domain method (TDM), working in time domain directly, is developed by employing the subspace system identification (SSI) theory [32], which has previously been utilized to understand MHD stabilities in reversed field pinch and tokamak plasmas through offline analysis, respectively [33, 34]. The TDM analysis does not require complicated frequency analysis and nonlinear fitting in the FDM analysis. In the TDM, the linear least square fitting, without requiring the initial guess, not only guarantees the numerical convergence of extracted eigenmodes, but also achieves impressive numerical efficiency. Previous real time spectroscopy [35] used a single-mode model approximation. In this work, it shows for the first time the feasibility of quantitatively detecting the multiple MHD modes’ stabilities in real time, based on the active detection and the TDM analysis, which is so-called real time 3D MHD spectroscopy. The technique can be important to monitor the evolution of plasma stability and to avoid the severe plasma disruption in the advanced operation of a fusion reactor.

2. Real time 3D MHD spectroscopy

Real time 3D MHD spectroscopy is approached by involving SSI theory [32, 34]. Compared with the FDM, which requires the nonlinear fitting to extract the transfer function, SSI improves the numerical efficiency dramatically while extracting the mode stabilities with linear least square fitting. SSI solves the following linear state-space response model (1), which can represent the plasma response modelled by linear...
The modes, and equation (1b) represents the measurements of the plasma response. Here, the eigenmodes are less stable individual modes [31] and can be resonant with the external perturbation due to the small eigenvalues [17]. Matrix $B$, representing the impact of the applied 3D coil current $\delta J_k$, has $N$ by $M$ dimensions. The $l$ by $N$ matrix $C$, with $l$ being the number of employed sensor arrays, describes the contribution of eigenmodes’ response to the measurements $\delta B_k$. Matrix $D$, having $l$ by $M$ dimensions, represents the response of vacuum vessel and other components to the applied 3D perturbation. Since this model can also be directly derived from MHD equations, the eigenmodes extracted from this model should be the same as those extracted from the multi-mode transfer function [31]. In other words, these two methods are theoretically equivalent. Evidence of the equivalence between these two methods will be shown later in this work.

Although this work will not focus on the algorithm itself, here the process of the eigenmodes extraction is briefly introduced as follows. The input and output data can be obtained by conducting a dedicated set of system identification experiments. Different from FDM, TDM estimates the system state $x_k$ sequence by making a series of mathematical operations on input and output data. Therefore, one can identify the system matrices $A$, $B$, $C$, and $D$ by linear least square fitting, which is the major advantage of this TDM to greatly improve the fitting efficiency and convergence. Finally, the eigenvalues of the eigenmodes, as the stability index of mode, can be computed by the eigenvalue decomposition of the matrix $A$ in TDM analysis. Note that a finite number of $x_k$ is used to determine matrix $A$, which evolves on a longer time scale than the $k$ step.

3. Experimental application and validation

3.1. Experimental analysis in DIII-D tokamak

The TDM has been used to detect the time evolution of the growth rate for multiple stable MHD modes in DIII-D plasmas. In these experiments, the upper and lower rows of internal 3D coils [9] are applied to generate $n = 1$ 3D magnetic perturbations. The number of system input, the coil current $\delta J_k$, is thus $M = 2$. Both the coil current phasing $\Delta \phi$ and rotation frequency $f$ are scanned to measure the variation of the plasma response. This provides more information of system output $\delta B_k$ for better fitting equation (1). Here, the coil phasing $\Delta \phi = \phi_{up} - \phi_{low}$ is the difference between the upper coil current phase, $\phi_{up}$, and the lower coil current phase, $\phi_{low}$. In addition, both the square wave and travelling wave coil oscillations were applied to assess any difference in the reliability between the two which can help to optimize the coil waveform in the future development of real time 3D MHD spectroscopy. In this paper, the plasma response is denoted as the total magnetic perturbations measured by the toroidally distributed 3D magnetic sensor arrays located at the middle plane on both the low field side (LFS) and high field side (HFS) to observe more aspects of plasma response. The configuration of magnetic probes are described in [25, 36].
Figure 4. Phasing dependence of magnetic response with 10 Hz rotating frequency is based on the transfer function obtained from a synthetic experiment utilizing the MARS-F simulation. (a), (b) The amplitude of simulated magnetic response measured by radial sensor located at LFS and HFS, respectively. The solid black curve represents the total transfer function. The least stable and secondary modes of that transfer function are presented by dot-dashed curves in blue and dashed curves in red, respectively.

A wave packet, applied in the experiment, is designed to involve multiple travelling waveform simultaneously with the different combination of $(\Delta \phi, f)$, where $f \in \{ -110 \text{ Hz}, -60 \text{ Hz}, -35 \text{ Hz}, -10 \text{ Hz}, 10 \text{ Hz}, 35 \text{ Hz}, 60 \text{ Hz}, 110 \text{ Hz} \}$ and $\Delta \phi \in \{ 0 \text{ deg}, 90 \text{ deg}, 180 \text{ deg}, 270 \text{ deg} \}$. Random length square waves with $\Delta \phi \in \{ 0 \text{ deg}, 45 \text{ deg}, 90 \text{ deg}, 135 \text{ deg}, 180 \text{ deg}, 225 \text{ deg}, 270 \text{ deg}, 315 \text{ deg} \}$ are also tested. The maximum current amplitude in both the upper $(I_{\text{up}})$ and lower $(I_{\text{low}})$ coils is 2 kA. Since the ratio of the magnetic response to the equilibrium toroidal field is less than 0.1%, figure 1(a) indicates the equilibrium with little variation is hardly perturbed by the applied 3D fields. Therefore, the plasma response is in the linear regime in the DIII-D experiments, which has already been validated in [31]. In the stable discharge 178583, the coil current, illustrated in figure 1(b), is applied to generate $n = 1$ perturbed fields in the flattop phase, where figure 1(a) shows plasma current ($I_p$), safety factor ($q_9$) and normalized beta ($\beta_n$) have little variation. Figures 1(c) and (d) present the time evolution of $n = 1$ magnetic response measured by the radial sensors located at the middle plane of LFS and HFS, respectively.

With the input of coil current ($\delta I_l$) and the output of measured 3D magnetic response ($\delta B_\phi$), TDM analysis is made by fitting equation (1) with SSI method [32, 34]. Figures 1(c) and (d) report a good agreement between the fitting results and DIII-D experimental data for both HFS and LFS magnetic response. By fitting the time interval from 1.1 s to 2 s, TDM finds two dominant stable eigenmodes, where the least stable mode has the eigenvalue $\gamma_1 = -9.54 + 1.88i \text{ Hz}$ and the secondary mode has $\gamma_2 = -73.24 + 0.85i \text{ Hz}$. It is noted that the real part of the eigenvalue, $\text{Re}(\gamma)$, is identified as the damping rate of mode, where the more negative damping rate indicates the mode is more stable. The imaginary part of eigenvalue represents the natural mode rotating frequency. Though there are only stable modes found in this stable plasma, it is important to note that the SSI method, employed by TDM analysis, is theoretically capable for the detection of unstable modes.

For the purpose of developing real time 3D MHD spectroscopy to detect the eigenmodes’ stabilities in real time, equation (1) needs to be fit using a time sequence of experimental data within a short time window. In figure 2, equation (1) is fit in a short time window $\sim 100 \text{ ms}$ at both the beginning of the travelling and square waves covered by the shade respectively. The predictions, made by the travelling wave fit model and the square wave fit model, are represented by the dash-dotted curves in yellow and dashed curves in red in figures 2(a) and (b). The results show that both fit models can provide good predictions agreeing with the experimental measurements. Here, the prediction errors $E_p = \frac{1}{2 \sum_{i=1}^{N} |y_p(i) - y_\text{exp}(i)|}$, with $y_p$ being predicted data and $y_\text{exp}$ being experiment data, have been evaluated as the fitting tolerance. Defining a good prediction as $E_p < 5\%$, it is found that the minimum time window is about 40 ms in the presence of the square wave perturbations. The minimum time window is 60 ms when the travelling wave is applied.

Here, the feasibility of extracting the dominant eigenmodes with a short time window is verified. The streaming analysis can be carried out to trace the evolution of eigenmodes’ stabilities. The temporal evolution of the extracted stable eigenmodes is shown in figure 3, where the slipping time window size is $\Delta t = 150 \text{ ms}$, and the window moving step, which is the actual updating time of eigenvalues, is $\delta = 10 \text{ ms}$. Note that, in the experiment, $\delta$ depends on the performance of the fitting process in the plasma control system (PCS). A DIII-D PCS test indicates that TDM analysis can achieve high efficiency and update the eigenvalues every $\delta = 4 \text{ ms}$, which is sufficient for real time detection. It is noted that, due to the existence of the resistive wall, the high frequency magnetic signal could be shielded, which implies the eigenmodes with very stable eigenvalues and high nature frequencies can be hardly resonant with the applied 3D fields. Thus, real time 3D MHD spectroscopy mainly focuses on the detection of low frequency global MHD modes. In figure 3, zero is the marginal stability boundary of each eigenmode. $\text{Re}(\gamma) > 0$ indicates the eigenmode is unstable. During the discharge, the two dominant eigenmodes have negative $\text{Re}(\gamma)$ fluctuating with little change, since the equilibrium parameters in the flattop remain almost constant.

The MARS-F code [37, 38] is employed to simulate the ideal plasma response for better understanding the extracted eigenmodes in the experiment. Figure 1 shows the equilibrium has little variation in the flattop phase. The equilibrium, reconstructed at $t = 2200 \text{ ms}$ of discharge 178583 for the MARS-F simulation, is preferred since there is a quiet plasma and no
externally applied 3D fields to ensure a reliable equilibrium reconstruction. Here, the MARS-F code performs the linear simulation of plasma response with different combination of \((\Delta \phi, f)\). The simulated plasma response can be easily transformed from the frequency domain into the time domain for the TDM analysis. The FDM and TDM are applied to fit the simulation data in the frequency domain and the time domain respectively. Both methods find the two dominant eigenmodes. The FDM analysis finds the eigenvalues of two modes are \(\gamma_1 = -10.20 + 0.058i\) Hz and \(\gamma_2 = -42.29 - 4.88i\) Hz. The TDM analysis reports \(\gamma_1 = -9.96 + 0.16i\) Hz and \(\gamma_2 = -47.73 - 0.040i\) Hz. The similar eigenvalues, comparing the FDM and TDM analysis, further confirm the reliability of TDM analysis. In particular, the simulated eigenvalue of the least stable mode is close to the experimental measurement. The eigenvalue of the secondary mode is slightly different from experimental one, which could be due to the sensitivity of equilibrium reconstruction and the impact of other physics such as plasma rotation and resistivity which are not included in the simulation. By decomposing the contribution of each dominant mode in the plasma response based on FDM analysis [31], figure 4 shows the least stable mode is dominant at the HFS and the second mode is dominant at LFS. This result illustrates how necessary it is to measure the plasma response at multiple locations, which greatly help to better extract the multiple eigenmodes, as shown in [28–30]. Moreover, the MARS-F code can also solve eigenvalue problem of MHD equations with driving terms turned off in the simulation [39, 40]. Note that it is challenging to solve the individual MHD mode when the mode is stable due to the existence of Alfvén continuum spectra. Alternatively, using the eigenvalue, extracted by real time 3D MHD spectroscopy, as the initial guess greatly helps to find the dominant eigenmodes. Figure 5 shows the different structures of two stable dominant \(n = 1\) eigenmodes calculated by MARS-F. The least stable mode shows the core dominant structure in the radial displacement. The mode, with a kink like structure, shows a single dominant poloidal mode triggered in plasma regions with strong gradients of the plasma current. Although the \(m = 1, -1\) poloidal Fourier harmonics of the radial displacement have big amplitudes near the magnetic axis, the large magnetic perturbation is observed at the plasma boundary in radial magnetic perturbations in figure 5(a), since \(B_r \sim (m - nq)\xi_r\) is amplified while increasing the safety factor \(q\). The secondary mode has more edge perturbations, and the toroidal coupling between poloidal harmonics indicates this eigenmode could be the seed of a peeling or a ballooning mode.

3.2. Experimental analysis in KSTAR tokamak

TDM analysis is also applied in KSTAR experiments for cross-device validation. In this experiment, an \(n = 1\) travelling wave is generated by the upper, middle and lower rows of internal 3D coils. The magnetic perturbations are measured by the toroidally distributed magnetic pick-up sensor arrays located at the middle plane of the LFS, where the configuration of magnetic probes are described in [41]. Despite the smaller number of sensors and a lower signal to noise ratio in the KSTAR data, a reliable TDM analysis is still possible by using a larger time window of 250 ms. Figures 6(c) and (d) present the applied
current field and the measured magnetic perturbation, respectively. The TDM fitting marked by dashed curves in red shows good agreement with the experimental data marked by solid curves in black underneath. Fitting equation (1) with current and plasma response, TDM analysis finds two dominant eigenmodes. The time evolution of the stability index $\text{Re}(\gamma)$ of each mode is presented in figure 6(b). $\text{Re}(\gamma_1) \sim -18.26$ Hz of the least stable mode and $\text{Re}(\gamma_2) \sim -32.88$ Hz of the secondary mode remain fairly constant during the steady KSTAR equilibrium as shown in figure 6(a). The $\text{Re}(\gamma)$ curves have higher variance (with prediction error $E_p \sim 15\%$) than the case in figure 3, despite the steady KSTAR equilibrium parameters. A main reason is the higher noise level of magnetic measurements, since the sensor arrays are not dedicated to the 3D magnetic measurement in KSTAR. However, the general tendency of modes’ stabilities is almost constant. One may eliminate the variance by averaging the eigenvalue within a short time window. To improve quantitative accuracy of the extracted eigenvalues, more sensors and/or better wave-filtering techniques are needed for the high quality of signals. Nevertheless, the strong anti-noise feature of the TDM guarantees the qualitative correctness of stability as long as the noise is incomparable to the plasma response.

4. Conclusion

In this paper, 3D MHD spectroscopy towards real time detection of multi-mode plasma stabilities is successfully developed and applied in both DIII-D and K-STAR stable plasmas. A new TDM has been applied to experimentally extracted the eigenvalues of multiple dominant eigenmodes by fitting the magnetic response measured on 3D sensors in a short time window (about 50 ms). In this work, the post-processing TDM analysis proves the feasibility of tracing the evolution of multi-mode instability. As with FDM analysis [31], the TDM is capable of quantifying the number of dominant modes and the corresponding eigenvalues. Meanwhile, the TDM shows great numerical efficiency towards the real time detection. Successful cross-machine application of TDM in both DIII-D and KSTAR tokamak indicates the technique can be transferred to multiple machines equipped with 3D coils and magnetic sensors. In comparison with the DIII-D case, the extracted multiple eigenvalues from KSTAR experimental data having higher variance shows how clean 3D magnetic measurements at multiple poloidal locations can greatly reduce the fitting time window of TDM and improve the reliability of eigenmode extraction. A short time window is critical for real time
detection in the future to facilitate the stability monitoring to avoid plasma disruption. The updating time window relies on the system hardware, which in ITER would not have much difference with in DIII-D (less than 4 ms). The fitting time window is generally determined by the lowest frequency of applied perturbation, such as 10 Hz in DIII-D experiment. Provided the quality of response signal in ITER should be no worse than that in DIII-D, it is expected that the fitting time window should not be quite different from DIII-D one. The efficiency of the TDM will be investigated for ITER in the future.

Besides the great convergence and efficiency for real time detection, the TDM, as real time 3D MHD spectroscopy, can be combined with FDM to understand the contribution of the each dominant mode in the 3D plasma response by using the TDM extracted eigenmodes as the initial guess to reduce the nonlinear fitting uncertainty in the FDM analysis. Real time 3D MHD spectroscopy can also provide the reliable initial guess for the simulation of stable individual MHD modes and reveal the structure of modes. For instance, MARS-F simulation indicates that the secondary mode in figure 5 has more edge perturbation. Here, one may consider an application to find the optimal frequency and phasing to amplify this mode, which may help with the suppression of the edge localized mode. One key feature of TDM analysis is to identify the MHD stability quantitatively through the real parts of extracted eigenvalues. This work suggests using the square wave in the real time detection, since the shortest fitting time window of the square wave is shorter than that of the travelling wave. But, a more comprehensive comparison between the two waveform should be further investigated. TDM has been implemented in DIII-D PCS for testing the real time detection of plasma stability in live experiments. This form of real time 3D MHD spectroscopy detection of plasma stability could be significant for the prediction of MHD stabilities and therefore the avoidance of the severe disruptions in ITER and future fusion reactors.

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