Nyquist analysis of kinetic effects on the plasma response in NSTX and DIII-D experiments*

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Externally applied, nonaxisymmetric magnetic perturbations can strongly modify tokamak plasmas, leading to the plasma response. Plasma response often closely related to the resonant field amplification and to the ELM control using magnetic coils, has been systematically observed in tokamaks. In particular, the importance of drift kinetic effects on modifying the plasma response has been demonstrated via quantitative modeling of NSTX and DIII-D high beta experiments [1, 2]. Nyquist analysis, as a powerful tool in stability theory, has been used to study the RWM stability [3]. Recently, this method is extended to analyze the response of intrinsically stable plasmas, where the technique, combined with Padé approximation, provides the deep physics understanding of the plasma behavior. As one important example, based on the idea that the plasma response to externally applied 3D fields is often due to certain stable eigenmodes' response in linear combination, the method can be used to investigate how the kinetic effects can change the damping rate of these stable eigenmodes in the plasma, without resorting to direct stability computations. The Nyquist technique also provides a direct tool of analyzing the so-called multi-mode response, a phenomenon currently under extensive discussions [4].

In order to carry out the Nyquist analysis, the finite field rotating frequency, f, in terms of the external magnetic perturbation, is scanned from -∞ to +∞, where '+' and '-' define the co-current and counter-current directions. The real and imaginary parts of the total perturbed field δB^{tot} measured on the magnetic sensor can be plotted in the complex plane to form the Nyquist contour. In this work, the simulation of Nyquist contour is performed by MARS-K code, which employs the hybrid drift kinetic-MHD model including the resistive wall and the external coils. The Nyquist contour has been simulated for the NSTX plasma, where the external coil at the low field side (LFS) of middle plan is used to generate the n=1 magnetic perturbation. The Nyquist contour of δB^{tot}, measured by upper sensor at LFS, is plotted in Fig. 1. The contours predicted by the kinetic-MHD model show the significant difference comparing with the one calculated by ideal MHD model with no rotation. This difference clearly shows the impact of kinetic effects on the plasma response. The ideal MHD with flow has the similar contour to the kinetic-MHD, since the kinetic resonance of passing ions, corresponding to the ion acoustic damping included in the ideal MHD while existing the rotation, is dominant due to the high rotation in NSTX experiments. The Nyquist contour, associated with the Padé approximation, can also infer the mode stability. Fitting the Nyquist contour by Padé approximation can infer the plasma stability. In the Padé approximation, the plasma transfer function, $P = \sum_{j=1}^{N} \frac{n_i}{i2\pi f-\gamma_i}$, is used to fit the contour, where n_i is the coefficient of each term. Each term in the transfer function corresponds to one eigenmode, where the real part of the eigenvalue γ_i is the growth/damping rate of each eigenmode. Applying the transfer function P to fit the contours in Fig. 1, the ideal MHD with no rotation gives the positive γ_i=13.66 Hz, which is consistent that $\beta_N > \beta_N^{nw}$ in this

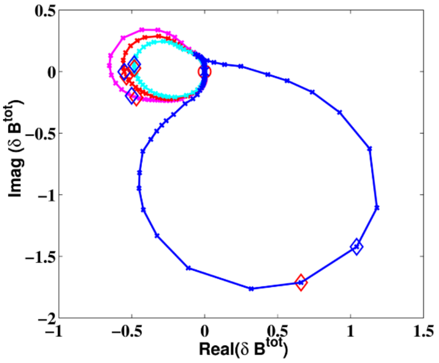

Figure 1. n=1 Nyquist contours in NSTX plasma with β_N=4.9. The ideal MHD without plasma flow (blue), with flow (red) and kinetic-MHD without plasma flow (magenta) and with flow (cyan) are used to simulate Nyquist contour, respectively.

NSTX case, where β_N^{nw}=4.75 is the no-wall beta limit predict by ideal MHD. The kinetic-MHD with rotation predicts γ_i=-13.2 Hz which means the kinetic effects stabilize the NSTX plasma.

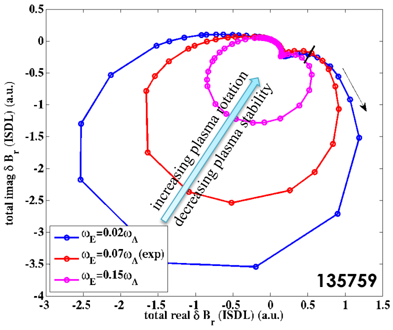

Figure 2. n=1 Nyquist contours in DIII-D plasma for discharge 135759, β_N/β_N^{nw}=1.06. The Nyquist contours are simulated by the kinetic-MHD with different EXB rotation. EXB rotation frequency $\omega_E$is normalized by Alfvén frequency ω_A at plasma center.

Nyquist analysis is also applied to study DIII-D experiments for the discharge 135759 [1]. The similar result has been found that the plasma is stabilized by the kinetic effects with $\beta_N > \beta_N^{nw}$, where the n=1 Nyquist contour in DIII-D case is formed by scanning the I-coil frequency with I-240 configuration. The plasma response is measured by ISDL sensor located at the middle plane of LFS. Figure 2 shows the size of Nyquist contour simulated by kinetic-MHD is decreased while increasing the EXB rotation. The Padé approximation indicates that the smaller rotation can further stabilize the plasma due to stronger kinetic damping. It is noted that the higher rotation causes the smaller contour, which is less close to a circle. It implies the plasma response is not dominant by one single eigenmode. Figure 3 presents to use the Padé approximation to extract the eigenmodes for the case with $\omega_E = 0.15\omega_A$ in Fig. 2. It can yield the corresponding damping rate and the transfer function for each eigenmode. Figure 3 shows the three eigenmodes contribute to the Nyquist contour, but the third mode has a small contribution. The result directly shows the existence of multi-mode response and the relation among each eigenmode. It is interesting that instead of least stable mode (blue), the contribution from second least stable mode (red) can dominate the plasma response generally. If we look into the details of the contour, at the zero frequency point (marked as 'o' in Fig. 3), the 1st mode and the 2nd mode have the comparable contribution to kinetic plasma response. When the coil frequency is 10Hz (marked as '⋄'), the amplitude of 1st mode decreases. The 2nd mode contribution becomes more significant. Further increasing the coil frequency, it should be able to enhance the 2nd mode to be dominant in the plasma response. It is possible to use this method to amplify the preferred the eigenmode which probably leads to the ELM suppression as presented in [4].

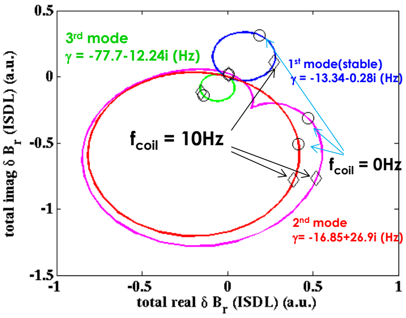

Figure 3. Decomposition of Nyqust contours (magenta) for the case with $\omega_E = 0.15\omega_A$ in Fig. 2 by Padé approximation. Three dominant poles (three circles) contributed to the Nyquist contour are plotted respectively.

This work shows that the Nyquist analysis, as a very powerful tool, helps to reveal a range of underlying physics associated with 3D fields, including the drift kinetic modification of the plasma response, inferring plasma stability for potential ELM mitigation or suppression, direct observation of multi-mode response and identification of amplification associated with the preferred eigenmode. The aforementioned analysis will be applied to 3D experiments, by direct measurements of the Nyquist contours, as well as by quantitative comparison between toroidal computations and experiments. The plasma transfer function extracted from the experimental Nyquist contour can be very useful to design the MHD control system and to better predict plasma behavior in future experiments.

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