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Phase tracking with Hilbert transform and nonlinear wave-wave coupling analysis on the HL-2A tokamak

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Nonlinear couplings among three coherent modes have been recently noticed in magnetically confined plasma research. On NSTX, nonlinear interactions among low-frequency energetic particle modes (EPMs) and high-frequency toroidal Alfvén modes (TAEs) have been reported [1, 2]. On JET, an m/n = 3/2 neoclassical tearing mode (NTM) is stabilized through the nonlinear coupling among m/n = 3/2, 4/3 and 7/5 modes [3]. Routinely, bi-spectral analysis is applied to detect the nonlinear interaction [4]. However, a number of statistical ensembles are necessary for the bi-spectral analysis. The Hilbert transform [5] analysis does not need ensembles. It has already been applied for nonlinear mode coupling analysis on the camera data in the linear magnetized device PANTA [6]. A phase tracking method based on Hilbert transform algorithm is applied to the nonlinear wave-wave coupling analysis on HL-2A tokamak. Synthetic signal analysis shows the principle of phase analysis for the detection of nonlinear coupling. If the phase difference between two coherent modes is synchronized with the phase of a third mode, the three modes are nonlinearly coupled, vice versa. The time evolution of the phase of a coherent mode could be computed with Hilbert transform for experimental data.

On HL-2A tokamak, in discharge number 26121 the 136-141 kHz Alfvén modes AM1, 126-132 kHz Alfvén modes AM2 and 7-12 kHz tearing mode TM are observed. The nonlinear coupling among AM1, AM2 and TM has been confirmed with FFT bicoherence analysis.

The instantaneous phases of AM1, AM2 and TM - θ_{AM1}, θ_{AM2} and θ_{TM} are calculated with Hilbert transform. In figure 1(a), the blue curve is the phase delay between AM1 and AM2, i.e. $\Delta\theta_{12} = \theta_{AM1}-\theta_{AM2}$, and the red curve is θ_{TM}. We could observe that $\Delta\theta_{12}$ and θ_{TM} are roughly synchronized with each other, and the maximum value of cross-correlation coefficient between $\Delta\theta_{12}$ and θ_{TM} $r(\Delta\theta_{12}, \theta_{TM})$ reaches 0.82, as shown in figure 1(b). An alternative to the cross-correlation method to check the synchronization is to observe the time evolution of the difference between $\Delta\theta_{12}$ and θ_{TM}, i.e. $\Delta\theta_{12}-\theta_{TM}$. If $\Delta\theta_{12}-\theta_{TM}$ varies smoothly and stays in a small range, $\Delta\theta_{12}$ and θ_{TM} are locked and nonlinear coupling exists among the three modes. If the time evolution of $\Delta\theta_{12}-\theta_{TM}$ is not a simple steady process but a kind of intermittent one, the phases are unlocked and nonlinear coupling does not exist among the three modes. Figure 1(c) shows the time evolution of $\Delta\theta_{12}-\theta_{TM}$ for the case when nonlinear coupling exists. $\Delta\theta_{12}-\theta_{TM}$ varies smoothly for the case that nonlinear coupling exists, and the histogram in figure 1(d) is peaking near $(\Delta\theta_{12}-\theta_{TM})/\pi = 1/2$. These all mean that $\Delta\theta_{12}$ and θ_{TM} are locked together, and thus nonlinear coupling exists among AM1, AM2 and TM.

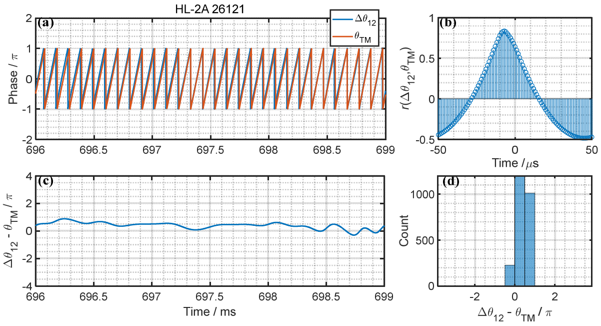

Figure 1. (a) The time evolution of $\Delta\theta_{12}$ and θ_{TM}. (b) The time evolution of $r(\Delta\theta_{12}, \theta_{TM})$ during [-50μs, 50μs]. (c) The time evolution of $\Delta\theta_{12}-\theta_{TM}$ for the case when nonlinear coupling exists. (d) The histogram of time evolution data.

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