Experimental Measurement of Nonlinear Energy Transfer in PANTA

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Nonlinear interactions among plasma waves are central to understanding plasma turbulence. The development of methods for estimating nonlinear energy transfer began with the work of [1] and has since been widely pursued by numerous researchers in various experiments. However, direct analysis of nonlinear energy transfer in wavenumber (k) space has remained a challenge due to inherent limitations in the spatial resolution of experimental measurement.

Plasma Assembly for Nonlinear Turbulence Study (PANTA) is a linear plasma device equipped with poloidal 64-channel probe array. This Langmuir probes array provides high spatial/temporal resolution measurements of ion saturation current fluctuations, which can be interpreted as electron density fluctuations.

Unlike the Fourier components in frequency (f) space, which exhibit conjugate symmetry for a real signal (making negative frequency components redundant), the components in wavenumber (k) space generally lack this symmetry. In k-space, waves propagating in both the electron and ion diamagnetic drift directions are distinct and equally important phenomena in turbulence physics. Motivated by this issue, we constructed, for the first time, the analytic signal by adding the Hilbert transformed signal to remove conjugate symmetry as $\phi(t) + i\mathcal{H}\left(\phi(t)\right) = \sum_k X_k^a(t) e^{ik\theta}$. Time evolution of $X_k^a(t)$ can be described as

$$\frac{\partial X_k^a}{\partial t} = L_k X_k^a + \sum_{\substack{k_1 \geq k_2 \\ k = k_1 + k_2}} Q_k^{k_1,k_2} \left(X_{k_1}^a X_{k_2}^a + \mathcal{H}\left(X_{k_1}\right)\mathcal{H}\left(X_{k_2}\right) \right)$$

where L_k and $Q_k^{k_1,k_2}$ represent linear and quadratic (nonlinear) transfer functions [1], and superscript 'a' denotes the analytic signal. Following the methodology of Ritz (1989) [2] and Kim (1996) [3], the linear (L_k) and nonlinear ($Q_k^{k_1,k_2}$) energy transfer functions can be experimentally determined. These functions provide a quantitative measure of the energy transferred by three-wave coupling and linear evolution of the waves.

We then applied this analysis method for a deeper investigation of the solitary wave and streamer phenomena observed in PANTA [4]. Experiments to reproduce two kinds of phenomena were conducted under neutral gas pressure at 0.42 Pa and 0.23 Pa. Figure 1 shows analysis results on two conditions. The results of the nonlinear energy transfer analysis provide a further detailed information of the energy exchange.

Analysis of nonlinear energy transfer in wavenumber (k) space using data from PANTA shows linear/nonlinear energy change. We expect this analysis to enhance our insight into plasma turbulence and we plan to extend the analysis to the onset of turbulent events.

References

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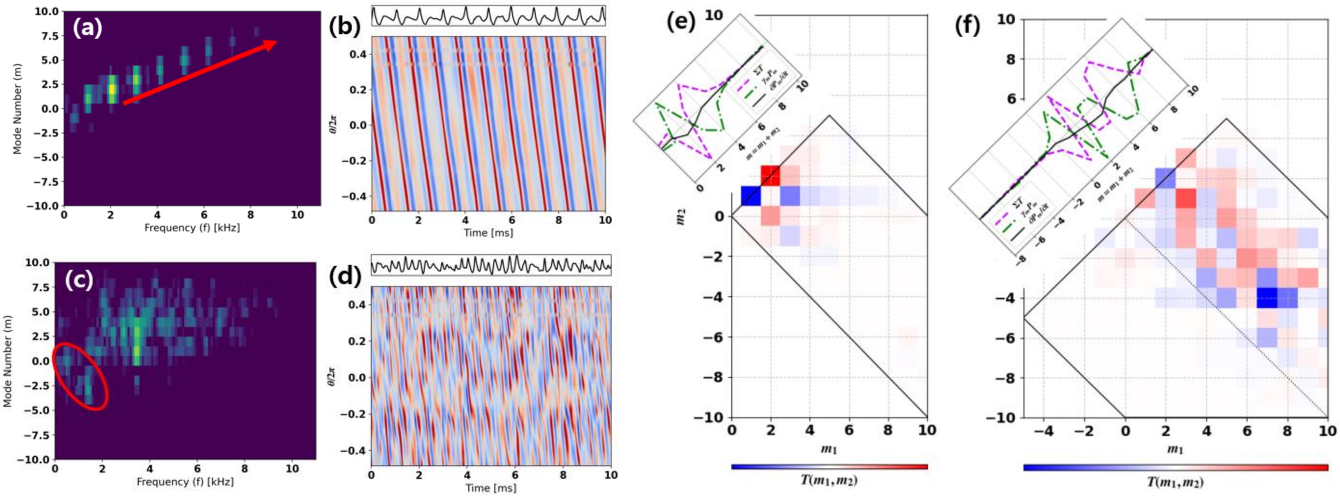

Figure 1. Frequency – mode number spectrum, raw signal evolution, and nonlinear energy transfer analysis results of (a)(b)(e) solitary wave (p_n =420 mPa) case and (c)(d)(f) streamer (p_n =230 mPa) case.