Frequency-domain fluctuation–response relation as a diagnostic tool for nonequilibrium spectra

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Fluctuation–response relations provide a central route to connecting spontaneous fluctuations, external responses, and dissipation in nonequilibrium systems. While conventional formulations often focus on time-domain observables or zero-frequency limits [1,2], many experiments and simulations naturally characterize dynamics through power spectra. This raises a simple question: can a fluctuation spectrum be decomposed into physically meaningful response channels?

In this talk, I will present a frequency-domain fluctuation–response relation for Markov jump and overdamped Langevin systems [3]. For Markov jump networks, the relation decomposes the power spectrum of an observable into contributions from individual transition edges. For Langevin systems, it gives a spatial decomposition in terms of local force-response contributions. These decompositions turn a global spectrum into a diagnostic map of the underlying dynamics.

I will illustrate the theory with two examples. First, in a two-conformation Markov motor with hidden substeps, the edge-resolved decomposition identifies which transition channels dominate different frequency regimes and reveals a finite-frequency window where the thermodynamic uncertainty relation becomes tight. Second, in a tilted periodic potential, the spatial decomposition shows which regions of the state space contribute to the velocity spectrum and how finite-band perturbations can reconstruct the main spectral features. The same information can guide the choice of perturbations entering response uncertainty bounds.

These results show that the frequency-domain fluctuation–response relation is not only a formal identity, but also a practical tool for diagnosing nonequilibrium spectra and identifying relevant channels, spatial regions, and frequency windows for fluctuation–response and thermodynamic bounds.

[1] E. Kwon, H.-M. Chun, H. Park, and J. S. Lee. Phys. Rev. Lett. 135 (9), 097101
[2] H.-M. Chun, E. Kwon, H. Park, and J. S. Lee. arXiv:2601.16387
[3] E. Kwon, H.-M. Chun, H. Park, and J. S. Lee. arXiv:2605.05038