Slow Phases, Fast Waves: Nonlinear Dynamics of Pendulum-Based Wave Energy Converters

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Abstract:
Wave energy converters are traditionally designed and analyzed within a linear, resonance-based framework, in which performance is tied to oscillatory response amplitudes at the dominant wave frequency. Nonlinear dynamics offers additional mechanisms for energy conversion in systems whose long-time behavior is governed by phase evolution rather than oscillation amplitude. This presentation focuses on the nonlinear rotational dynamics of pendulum-based wave energy converters as a pathway to robust energy conversion.
Experimental measurements and analysis of these converters demonstrate that efficient energy extraction is associated with phase-locked rotational states rather than large oscillation amplitudes, illustrating how nonlinearities can be deliberately exploited to enhance energy generation. The underlying mechanisms by which geometric asymmetry, parametric excitation, and dissipation combine to produce directionally biased energy transfer are described, revealing a response that is inherently robust to variations in wave frequency and amplitude. These insights provide a natural framework for control and power-take-off design, in which PTO damping and control actions can be managed to stabilize and maintain phase-locked rotational states. Together, these findings illustrate how deliberately exploiting nonlinearities expands the design space for wave energy converters operating in realistic, broadband sea states.