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Response theory for non-equilibrium systems: theory and applications (Outstanding Young Scientist Lecture)

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We consider the general response theory recently proposed by Ruelle for describing the impact of small perturbations to the non-equilibrium steady states resulting from Axiom A dynamical systems. We show that the causality of the response functions entails the possibility of writing a set of Kramers-Kronig (K-K) relations for the corresponding susceptibilities at all orders of nonlinearity, and specific results are provided for the case of arbitrary order harmonic response. These results shed light on the very general impact of considering the principle of causality for testing self-consistency: the described dispersion relations constitute unavoidable benchmarks that any experimental and model generated dataset must obey. These results, taking into account the chaotic hypothesis by Gallavotti and Cohen, might be relevant in several fields, including climate research. In particular, whereas the fluctuation-dissipation theorem does not work for non-equilibrium systems, because of the non-equivalence between internal and external fluctuations, K-K relations might be robust tools for the definition of a self-consistent theory of climate change. Along these lines, we present here the first evidence of the validity of these integral relations for the linear and the second harmonic response for the perturbed Lorenz 63 system, by showing that numerical simulations agree up to high degree of accuracy with the theoretical predictions. The numerical results confirm the conceptual validity of the nonlinear response theory, suggest that the theory can be extended for more general non equilibrium steady state systems, and shed new light on the applicability of very general tools, based only upon the principle of causality, for diagnosing the behavior of perturbed chaotic systems and reconstructing their output signals.