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Inertial manifold dimensionality & finite-time instabilities in stochastic dynamical systems with applications to 2D Navier-Stokes equations

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We examine the geometry of the inertial manifold associated with fluid flows described by Navier-Stokes equations and we relate its nonlinear dimensionality to energy exchanges between the mean flow and stochastic modes of the flow. Specifically, we employ a stochastic framework based on the dynamically orthogonal field equations to perform efficient order-reduction in terms of time-dependent modes and describe the inertial manifold in the reduced-order phase space in terms of the associated probability measure. We introduce the notion of local fractal dimensionality and we establish a connection with the finite-time Lyapunov exponents of the reduced-order dynamics. Based on this tool we illustrate in 2D Navier-Stokes equations that the underlying mechanism responsible for the finite dimensionality of the inertial manifold is, apart from the viscous dissipation, the reverse flow of energy from the stochastic fluctuations (containing in general smaller lengthscales) back to the mean flow (which is characterized by larger spatial scales).