Symmetry-breaking Hopf bifurcations to 1-, 2-, and 3-tori in small-aspect-ratio counter-rotating Taylor-Couette flow

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The nonlinear dynamics of Taylor-Couette flow in a small aspect-ratio wide-gap annulus in the counter-rotating regime is investigated by solving the full three-dimensional Navier-Stokes equations [1]. The system is invariant under arbitrary rotations about the axis, reflection about the annulus mid-plane, and time translations. A systematic investigation is presented, both in terms of the flow physics elucidated from the numerical simulations as well as from a dynamical systems perspective provided by equivariant normal form theory. The dynamics are primarily associated with the behavior of the jet of angular momentum that emerges from the inner cylinder boundary layer at about the mid-plane. The sequence of bifurcations as the differential rotation is increased consists of an axisymmetric Hopf bifurcation breaking the reflection symmetry of the basic state leading to an axisymmetric limit cycle associated to an invariant one-torus manifold with a half-period-flip spatio-temporal symmetry. This undergoes a Hopf bifurcation breaking axisymmetry, leading to quasi-periodic solutions evolving on a 2-torus that is only setwise half-period-flip symmetric due to precession. These undergo a further Hopf bifurcation introducing a third incommensurate frequency leading to a 3-torus that is also setwise half-period-flip symmetric and the solution maintains its quasi-periodicity. On the 3-torus, as the differential rotation is further increased, a saddle-node-on-an-invariant-circle (SNIC) bifurcation takes, destroying the 3-torus and leaving a pair of symmetrically-related 2-tori states on which all symmetries of the system have been broken.

[1] S. Altmeyer, Y. Do, F. Marques, and J. M. Lopez. *Symmetry-breaking Hopf bifurcations to 1-, 2-, and 3-tori in small-aspect-ratio counter-rotating Taylor-Couette flow.* Phys. Rev. E. **86**:046316 (2012).