EMS Annual Meeting Abstracts
Vol. 14, EMS2017-585, 2017

Optimal excitation of asymmetric disturbances on a cylindrical vortex sheet

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A tornado is one of the most dangerous meteorological phenomena and it is recognized that the most severe one often take asymmetric structure know as the "multiple vortex structure" where the several secondary vortices emerge and revolve around the eye of their parent vortex. To reveal the optimal excitation and non-normal growth of such secondary vortices, a singular-value analysis, in addition to an eigenvalue analysis, is carried out for a cylindrical vortex sheet, i.e. one of the simplest models of a tornado.
The analysis is carried out based on Bernoulli's principle under the assumption of linearity. Different from an eigenvalue analysis, it is necessary to assign a norm, i.e. an index to measure the growth, for conducting a singular-value analysis. Here, three norms are adopted: Energy norm, L2 norm and Sobolev norm, Then, the singular-value analysis is performed analytically for each norm respectively. Analytical solutions enable us to know the growth of the secondary asymmetric disturbances as a function of prescribed target time.
The results indicate that non-normal growth occurs absolutely so that the amplitude of the secondary disturbances, regardless of the norm, more or less becomes larger than that of the corresponding normal mode, which grows exponentially with time. However the detail of the non-normal growth is different both qualitatively and quantitatively in accordance with the norm adopted for the analysis. The energy norm gives the mildest growth and the non-normal growth is insignificant except for disturbances with low vertical wave numbers. Sobolev norm, defined as the distance on the space consisting of dimensionless length and velocity, gives a little larger amplification than the case with the energy norm. There, the non-normal growth is seen in most parts of the wavenumber space. In contrast, the L2 norm exhibits extremely large amplification and its sharp changes with the vertical wavenumber of the disturbances. Target time dependence of the amplification factor against the normal mode growth indicates that in most cases, the non-normal growth is nearly saturated before the unit target time has passed.