Turbulent bands in a planar shear flow without walls

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Regular patterns of turbulent and laminar flow are a robust feature found at transitional Reynolds numbers. Studied first in Taylor-Couette flow [2,4] (but also in plane Couette flow [5] and plane Poiseuille flow [6]) these patterns are not aligned with the shear direction but tilted into the spanwise direction. Bands have been computationally studied in minimal domains which are tilted with an angle θ against the streamwise direction to align with the pattern and thereby require a computational domain with only a single large dimension, denoted z, which is aligned with the wavevector of the pattern [7,8]. Averaging over time and the band-aligned direction, which we denote by x, reveals coherent structures of rolls and streaks which are maintained by time-dependent Reynolds stresses. It has been proposed that the bands emerge in a linear instability from the time averaged uniform turbulence [7]. Attempts to model this behaviour have thus far been limited and not found the success of modelling localized turbulence in pipe flow [1]. There still remains much work to understand the mechanisms involved in maintaining these patterns which motivates this work.

To understand the mechanisms involved in turbulence in small domains, Waleffe [10] studied the sinusoidal shear flow created by a sinusoidal body forcing with periodic boundary conditions in (x, z) and stress-free conditions at $y = \pm 1$, where y is the "wall"-normal direction. The Reynolds number is defined using the same non-dimensionalization as plane Couette flow. This forcing invokes a laminar flow $U(y) = \sin\left(\frac{\pi}{2}y\right)$, which is linearly stable [9]. This flow is clearly related to Kolmogorov flow, however the imposition of stress-free boundary conditions removes the instabilities associated with that flow.

To study bands in this flow we use `ChannelFlow` [3] to simulate a domain tilted at $\theta = 24°$ and of size $L_x \times L_y \times L_z = 10 \times 2 \times 40$, which matches those used in studies of Couette and Poiseuille flow [7,8]. We find turbulent bands over a wide range of Reynolds numbers $Re \in [125, 350]$. These bands qualitatively match those found in plane Couette flow but differ in the near-wall regions due to the differing boundary conditions. In Waleffe flow, the sinusoidal laminar flow and stress-free boundary conditions induce dynamics which can be captured with a small number of Fourier modes in the "wall"-normal direction. Utilizing this and motivated by Waleffe's self-sustaining process [10] we attempt to model the development of bands from the time-averaged uniform turbulent state found at higher Reynolds numbers.

References

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