Effective three-dimensional transition in bluff plate boundary layers

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ABSTRACT

Experiments (Sasaki & Kiya, 1991) have shown that the transition in the boundary layer flow over a long rectangular plate is via a two-stage process. For $320 < Re < 380$, the separating and reattaching shear layer forming the recirculation zone develops Kelvin-Helmholtz instability waves which grow sufficiently to shed as discrete vortex structures. In turn these appear immediately unstable three-dimensionally, forming lambda-shaped loops which align from one row to the next. They describe this as *Pattern A* shedding. For $Re > 380$ the KH waves merge into larger-scale vortical structures that shed directly from the recirculation zone. These vortices are apparently also immediately unstable three-dimensionally resulting in a 3D mode in the form of hairpins which are 180° offset from one row to the next. This is called Pattern B. Pattern A has a spanwise wavelength of about $2H$ and Pattern B 3-$4H$, where H is the plate thickness. In contrast, global stability analysis predicts the initial transition is a regular bifurcation from steady 2D flow to steady 3D flow at $Re = 393$ for a wavelength of $15H$. The global transition to unsteady flow occurs at a much higher Reynolds number of approximately 500. Transient growth analysis indicates the most-amplified mode is 3D with a wavelength of $12H$. Thus, the experimental results appear at odds with the theoretical stability analysis. It appears that the two 3D instabilities are associated with an elliptical instability of the shed vortex cores. Floquet analysis of the weakly forced flow predicts both instability modes and, in particular, the downstream symmetry and the observed wavelengths. The calculated perturbation vorticity field distribution has the characteristic lobes within the vortex cores aligned with the strain field characteristic of elliptic instability. In addition, the predicted wavelength from the finite eccentricity theory of Landman and Saffman (1987) is consistent with the observed wavelength, and the estimate of the growth rate shows strong amplification as the cores convect downstream. Finally, 3D direct numerical simulations under the assumption of weak cross-stream forcing, show the characteristics of the observed hairpins and lambda vortices of Patterns A and B.

REFERENCES

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