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Effect of Partial-Slip on Unsteady Crossflow Vortices

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1 Introduction

We present an investigation aimed at determining the right sort of roughness which could provide a passive mechanism for delaying transition to turbulence in three-dimensional boundary layers. Specifically, we consider crossflow instabilities (co-rotating vortices) occurring in the boundary layer due to a rotating disc, which can be analysed using a linear stability analysis. The numerical study of Cooper *et al.* (2015) used a partial-slip boundary condition to model the effect of small-scale surface roughness compared to the boundary-layer thickness, and we follow this approach. Our focus is on the effect of roughness on travelling disturbances.

The asymptotic study of Hall (1986) for large Reynolds numbers, a smooth wall, and steady disturbances, revealed two neutrally stable modes: one governed by inviscid mechanisms (Type I) and the other by viscous mechanisms (Type II). The instability for both modes takes the form of co-rotating vortices, but they differ in terms of the values of the effective wavenumber and orientation of the vortices. They correspond, respectively, to the upper and lower branches of the neutral stability curve. The corresponding case for travelling Type I instabilities was investigated by Turkyilmazoglu & Gajjar (2001), determining the scale for the frequency of the disturbances. Cooper *et al.* (2015) found that the steady Type I instability was stabilised for both anisotropic and isotropic roughness. It was also found that the effect of roughness can be destabilising for steady Type II instabilities.

2 Approach

The current results extend the asymptotic investigations of Stephen (2016), Stephen (2017) into the effect of surface roughness on stationary Type I modes to consider non-stationary Type I disturbances. These studies showed that the asymptotic structure for partial-slip boundary conditions differs from that for a no-slip surface (Hall, 1986). It was determined that the effects of radially-anisotropic roughness (concentric grooves) and isotropic roughness were stabilising, in that the range of unstable wavenumbers was reduced as the level of roughness was increased. Excellent agreement was found with the numerical results of Garrett (2017) for large Reynolds numbers for the wavenumbers and wave angles of the stationary disturbances. The numerical study of Thomas *et al.* (2020) considered the effect of partial-slip on the local absolute and global linear stability of the flow due to a rotating disc.

3 Results

The asymptotic structure for non-stationary Type I crossflow instabilities will be detailed, and solutions will be presented for the effective wavenumber of the disturbances and the orientation of the vortices for a range of concentric roughness heights and disturbance frequencies. Comparisons will be made for large Reynolds numbers with our numerical solutions of the corresponding unsteady linear stability equations. Figure 1 shows the neutral stability curve from the numerical results for the case of stationary disturbances for the effective wavenumber $k_\delta = \sqrt{\alpha^2 + \beta^2}$ as a function of the Reynolds number R_δ for different roughness heights λ. Note that $\lambda = 0$ corresponds to the no-slip boundary condition. Figure 2 shows the asymptotic results for the Type I modes demonstating the effect of partial-slip on the stationary and non-stationary modes.

4 Conclusions

The asymptotic structure of unsteady Type I disturbances in rotating-disc flow has been deduced for partial-slip boundary conditions. The effect of positive and negative frequencies has been determined. Comparisons

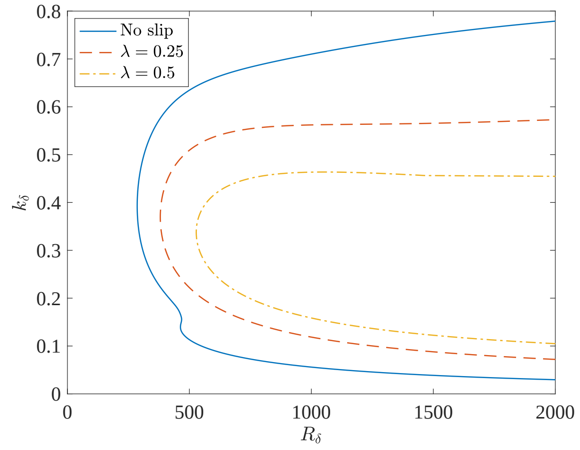

Figure 1. The neutral curve for the effective wavenumber k_δ for a range of roughness heights λ.

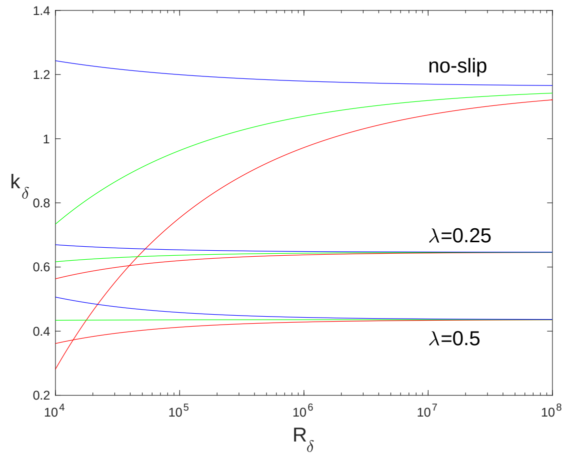

Figure 2. Asymptotic solutions for k_δ for a range of roughness heights λ and frequencies: green curves-stationary disturbances; red curves-negative frequency; blue curves-positive frequency.

are made with numerical solutions of the linear stability equations for large Reynolds numbers.

Previous numerical and asymptotic studies applied the slip boundary condition to the basic flow but the no-slip condition to the disturbances. A recent study by Thomas *et al.* (2023) demonstrated that when slip conditions are applied to both the undisturbed flow and linear disturbances, concentric roughness destabilises the flow. This issue should be addressed for unsteady disturbances.

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