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RESPONSE TO LOCALIZED FORCING OF THE BOUNDARY LAYER ON A ROTATING DISK

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1 Introduction

The boundary layer that develops over a disk rotating in an otherwise still fluid undergoes an abrupt transition to turbulence at a non-dimensional radius of $R \simeq 500$, and has long served as a canonical configuration for the study of three-dimensional boundary layers [1]. Based on a fully nonlinear analysis and a secondary stability analysis [2], Pier [3] showed that it was possible to delay the onset of secondary perturbations, and hence the transition, by replacing the natural flow state with the response to an appropriate harmonic forcing.

As a first step towards implementing this control strategy, the experiments reported here study the response to a localized forcing applied with a prescribed frequency relative to the disk.

2 Experiments

2.1 Experimental setup

The experimental setup consists of a 50 cm diameter glass disk that is rotated at a constant angular speed Ω_d . The boundary layer on a rotating disk is of constant thickness, with the boundary layer unit given by $\delta = \sqrt{\nu/\Omega_d}$ (a typical value here is $\delta \simeq 550 \mu\text{m}$), where ν is the kinematic viscosity. In the entire study, coordinates are nondimensionalized based on δ and Ω_d .

The forcing assembly consists of a hollow circular cylinder placed above, and concentric with, the disk. The cylinder, whose angular speed may be varied independently of the disk, has provisions for holding pins or forcing elements that extend down into the disk boundary layer and force the flow. In this study, we consider the response to forcing by an isolated forcing element, corresponding to a radially localized perturbation. Two different forcing elements (spherical and cylindrical) were used to see the influence on the flow dynamics.

The azimuthal velocities are measured by a hot-wire anemometer, which is positioned by a high-precision two-axes traversing mechanism.

2.2 Response to forcing

The rotation rate of the disk was chosen such that the non-dimensional forcing radius was just below the theoretical onset of convective instability. The forcing elements were rotated at various frequencies ω_f in the range $0 \leq \omega_f \leq 1.0$, with $\omega_f = 1$ corresponding to forcing that is stationary with respect to the disk surface.

Time-series of azimuthal velocity are recorded at different radial and axial locations for a large number of forcing revolutions. To extract those components that are periodic with respect to the forcing, phase-locked averages are computed, which can be interpreted as the mean perturbed flow in the frame of reference of the forcing device.

Figure 2 shows how a forcing at $R_f = 250$ produces perturbation ‘humps’ that propagate radially outwards, along a trajectory with a nearly constant slope in the (R, θ) -plane. These slopes κ are found to increase with ω_f and to agree extremely well with predictions based on linear theory, as described in the next section.

3 Theoretical analysis

At the radial values of interest, the assumption of weak radial development is legitimate, and small-amplitude perturbations are then written in normal-mode form as $\mathbf{u}(z) \exp i(\alpha r + \beta \theta - \omega t)$, where the radial wavenumber α , the azimuthal mode number β and the frequency ω are governed by the local dispersion relation

$$\omega = \Omega(\alpha, \beta; R),$$

obtained at each radial location R by solving the associated eigenvalue problem.

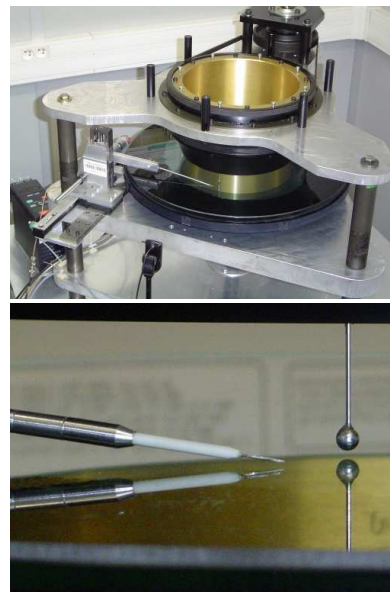


Figure 1: Experimental apparatus and close up of the hot-wire probe and spherical forcing element.

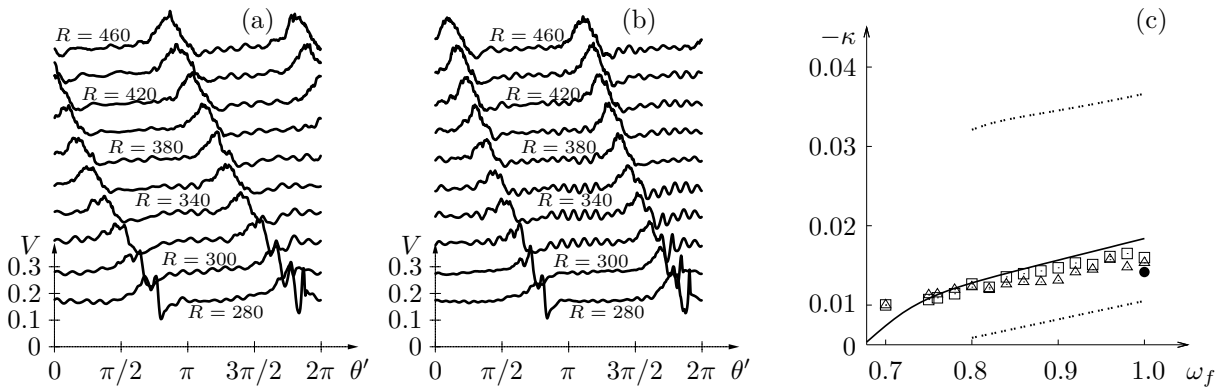


Figure 2: Response to rotating forcing applied at $R_f = 250$ using two forcing elements located at $\theta' = 0$ and π . (a,b) Phase-locked average of azimuthal velocity time series for $\omega_f = 1.0$ (a) and 0.8 (b). Measurements at $R = 280, 300, \dots, 460$ are each shifted vertically by $\Delta V = 0.1$. (c) Experimentally determined slopes $\kappa = \Delta\theta'/\Delta R$ of the trajectories of perturbation maximum (open symbols) plotted together with the theoretical predictions of the maximum (solid line) and leading and trailing edges (dotted lines). Also shown is the result from experiments [4] with a roughness element fixed to the disk surface (filled circle).

Solving the dispersion relation for complex α with given real values of β and ω yields two spatial branches $\alpha^\pm(\beta, \omega; R)$, with the α^+ branch corresponding to a response developing radially outwards from the forcing.

Now, consider a localized forcing element at radial position r_f rotating at a constant angular frequency ω_f . For simplicity, we consider a local linear theory at $R = r_f$, and assume that the perturbation due to the forcing is steady in the frame of reference of the forcing element. Then, for $r > r_f$, the full spatial response is given by

$$\mathbf{u}(r, \theta, z, t) \simeq \int_{\beta} d\beta \mathbf{u}(z; \beta) \exp i[\alpha(\beta)(r - r_f) + \beta_f \theta'],$$

where $\alpha(\beta) \equiv \alpha^+(\beta, \omega = \beta\omega_f; R = r_f)$ and $\theta' = \theta - \omega_f t$ is the azimuthal coordinate in the forcing frame; \mathbf{u} represents the associated spatial eigenmode. For $r \gg r_f$, the integral may be evaluated by the classical method of stationary phase, and the maximum of the forced response is then expected to follow the ray $\theta'/r = \kappa_{max}$ where the slope κ_{max} is given by

$$\kappa_{max} = -\frac{d\alpha}{d\beta}(\beta_{max}) \quad \text{with} \quad \frac{d\alpha_i}{d\beta}(\beta_{max}) = 0.$$

The leading and trailing edges of the localized perturbation may be similarly computed.

4 Discussion

Figure 2(c) shows the experimentally measured and theoretically calculated trajectories as a function of the forcing frequency. Despite significant nonlinear effects in the experiment, the trajectory of the maximum of the forced perturbation is found to be in good agreement with the predictions of the local linear theory, over the range of ω_f for which theory predicts an amplified response. The perturbation trajectory for $\omega_f = 1$ also compares well with the results of experiments with a single roughness elements fixed to the disk surface [4]. Measurements using smaller forcing elements, expected to produce a linear response, will also be presented.

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