NUMERICAL INVESTIGATION OF THE LAMINAR-TURBULENT TRANSITION OF THE FLOW IN A ROTOR-STATOR CAVITY

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Summary Incompressible fluid flow in a rotor-stator configurations has been numerically investigated for cylindrical and annular cavity. The numerical computations are based on a pseudo spectral Chebyshev-Fourier method for solving 3D Navier-Stokes equations. The nature of the transition to unsteadiness is investigated as well as the influence of the shaft and shroud boundary layers on the transitional process. A linear stability analysis is also performed in order to enlighten the DNS results with respect to type I and type II instability. Moreover, the absolute instability regions are theoretically identified.

INTRODUCTION

Flow in rotting disks systems is not only a subject of fundamental interest but is also a topic of practical importance. Typical configurations are cavities between compressors and turbines disks. Numerous works have been recently devoted to the investigation of the instabilities associated to a single disk flow [1] and to a differentially rotating disks flow. [2-5] Identification and characterization of mechanisms related to this process should improve the prediction methods and lead to new more efficient control strategies. In the present work the incompressible fluid flow in a stator/rotor cavity (cylindrical and annular) is numerically investigated using direct numerical simulation (DNS) and theoretical method (LSA). The nature of the transition to unsteadiness as well as the influence of the end-walls boundary conditions (the influence of the attachment of the shroud and shaft to the rotor or to the stator and the influence of the approximation of the end-walls azimuthal profiles) on the stability of the flow have been investigated.

MATHEMATICAL MODEL AND NUMERICAL METHOD (DNS)

The geometrical configuration consists of a closed cylindrical and annular cavity (Fig.1a). The rotor rotates at uniform angular velocity $\Omega = \Omega\, e_z$, e_z being the unit vector. The flow is controlled by three physical parameters which are the Reynolds number based on the outer radius $Re_R = R_1^2\Omega/\nu$, the aspect ratio $L=(R_1-R_0)/2h$ (R_0 is the inner radius) and the curvature parameter $R_m = (R_1+R_0)/(R_1-R_0)$.The governing equations are 3D Navier-Stokes equations. The numerical solution is based on a pseudospectral collocation Chebyshev-Fourier Galerkin approximation. The approximation of the flow variables Ψ = (u, w, v, p) is given by a development in truncated series:

$$\Psi_{NMK}(r,z,\varphi,t) = \sum_{p=-K/2}^{K/2-1}\sum_{n=0}^{N}\sum_{m=0}^{M}\hat{\Psi}_{nmp}(t)T_n(r)T_m(z)e^{ip\varphi} \quad \text{for} \quad \begin{matrix} -1 \le r,z \le 1 \\ 0 \le \varphi \le 2\pi \end{matrix}$$

The time scheme is semi-implicit and second-order accurate. It corresponds to a combination of the second-order backward differentiation formula for the viscous diffusion term and the Adams-Bashforth scheme for the non-linear terms. The method uses a projection scheme to maintain the incompressibility constrain. No slip boundary conditions apply at all rigid walls, then u = w = 0. For the azimuthal velocity component, the boundary conditions are v=0 on the stator and v = (1+r)/2 on the top rotating disk. For the cylindrical cavity the end-wall cylinder is also at rest, then v=0. However, in order to eliminate singularity the of the azimuthal velocity at the junction between the stationary end-wall and the rotating disk, this boundary condition is smoothed using an exponential azimuthal velocity profile v = exp((z-1)/0.006) which approximates well the thin gap between the edge of the rotating disk and the stationary end-wall. For the annular geometry we considered the following cases: a) the linear profiles for the shaft and shroud, b) the exponential profiles with the both end-walls attached to the stator, c) the exponential profiles with the shaft attached to the rotor and with the shroud attached to the stator. The initial condition is as follows: u=0, v = (1+r)(z+1)/4, w=0.

RESULTS AND DISCUSSION

In the case of cylindrical geometry computations have been performed using the LSA method for a two disk flow and using the DNS method for a rotor-stator cavity of aspect ratio L=5 in order to accurately investigate the transition to unsteadiness. Surprisingly, no transition from a steady Batchelor state to an unstable oscillatory flow has been numerically emphasized till now, except in cavities of small aspect ratio L≤2. Starting from a base state at Re_R=3000 and increasing very slowly the disk rotation, this study has emphasized a supercritical Hopf bifurcation to an oscillatory solution of frequency $\sigma \approx 1.1$, and at a critical Reynolds number estimated between $11500 \le Re_R \le 12300$. As expected, for the cylindrical cavity the unsteadiness first develops in the stator boundary layer while the rotor boundary has remained stable for the rotation rates considered in this work. Three-dimensional structures related to the stationary disk boundary layer instabilities have been accurately emphasized by DNS and studied using LSA results.

Spiral arms with positive and negative angles have been observed in the stationary disk layer flow(Fig.1b) in good agreement with the LSA results. Taylor-Görtler-like vortices have been also observed at the junction between the stationary shroud and the stator expanding in near end-wall flow region under the form of large spiral arms. Computations have been repeated for the flow additionally disturbed by superimposing on the initial condition for every consecutive Re_R the disturbance of the form $\eta \sin(\pi\varphi/2)$ $(0.0 \le \eta \le 3.5)$. For the cylindrical cavity the absolute/convective character of the instability of the both boundary layer has been also investigated using LSA. The computations performed for the annular geometry have shown the dramatic influence of the end-walls boundary conditions on the stability of the stationary and rotating disk boundary layers. Figs.2a, b and c show the exemplary iso-lines of the fluctuations of the azimuthal velocity component obtained for Re_R =60000, L=5 and R_m =4 for three different end-walls boundary conditions. Calculations have shown that the most unstable is the case with the shroud attached to the stator and the shaft attached to the rotor. For the annular geometry as well as for cylindrical geometry the nature of the transition to unsteadiness has been investigated.

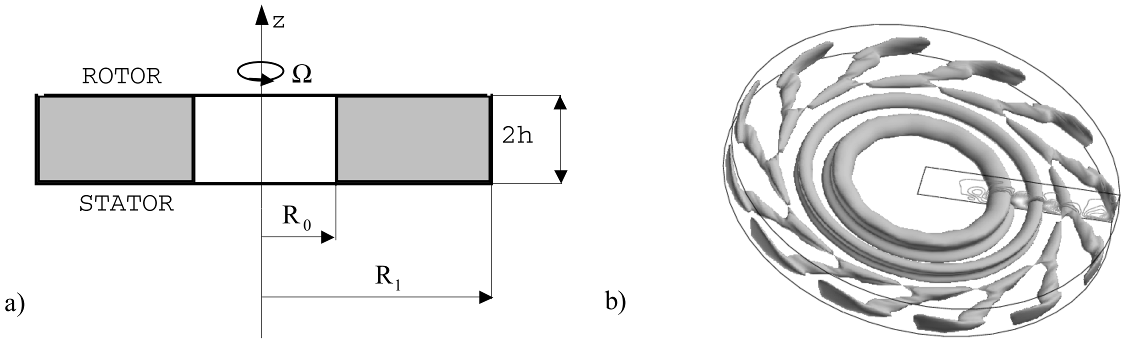

Fig. 1. a) Schematic picture of the rotating annular cavity (in the case of the cylindrical cavity $R_0 = 0$). b) Iso surface of the fluctuations of the axial component of the velocity at Re_R= 13200. Coexistence of annular and spiral structures related to stationary disk layer instability during the transient time t=60.

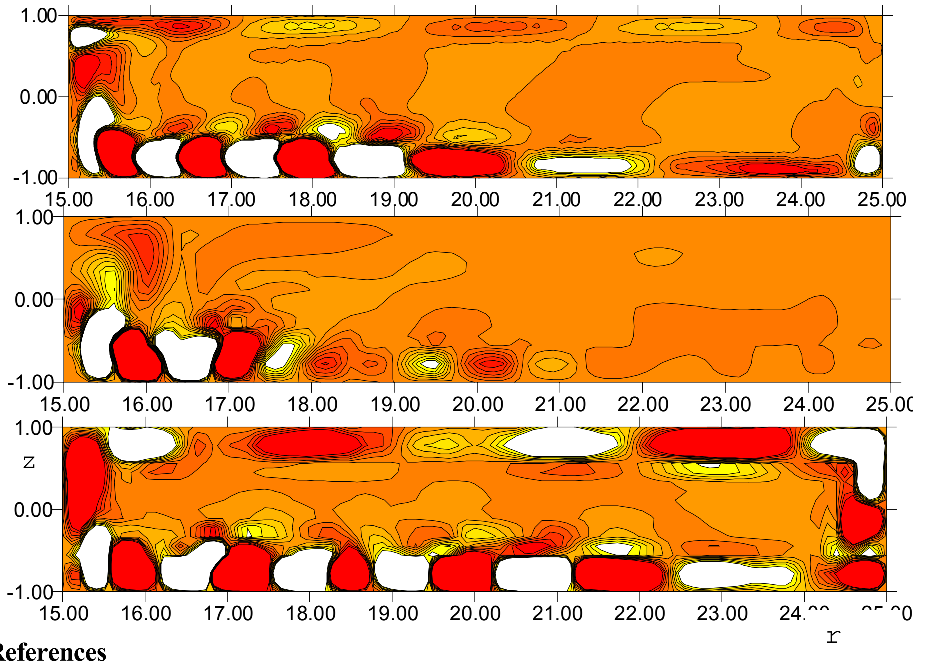

Fig.2 Time dependent axisymmetric instability at Re_R =60000, L=5, R_m =4. Iso-lines of the azimuthar velocity component in the (r,z) plane obtained for the different end-walls boundary conditions. From the top to the bottom: a) the linear profiles for the shaft and shroud, b) the exponential profiles with the both end-walls attached to the stator, c) the exponential profiles with the shaft attached to the rotor and with the shroud attached to the stator.

References

[1] Lingwood R.: Absolute instability of the boundary layer on a rotating disk,J. Fluid. Mech. **299**, 1, 1995
[2] Tuliszka-Sznitko E., Soong C.Y.: Instability of non-isothermal flow between coaxial rotating disks, Proceedings of European Congress on Computational Methods in Applied Sciences and Engineering, Barcelona, 2000.
[3] Serre E., Bontoux P.:Vortex breakdown in a three-dimensional swirling flow, J. Fluid Mech. **459**, 347, 2002.
[4] Serre E., Tuliszka-Sznitko E., and Bontoux P., 2004, ‘’Coupled numerical and theoretical study of the flow transition between a rotating and a stationary disk’’, Phys. of Fluids (in print).
[5] Tuliszka-Sznitko E., Serre E. and Bontoux P., 2002, “On the nature of the boundary layers instabilities in a flow between a rotating and a stationary disc”, C.R. Mecanique **30**, 90.