RECONSTRUCTION OF WAVELIKE THREE-DIMENSIONAL COHERENT STRUCTURES THROUGH TIME-RESOLVED PLANAR MEASUREMENTS

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Abstract This work aims to reconstruct three-dimensional coherent structures associated with centrifugal instabilities by making use of the dynamics in a space-time volume (x, y, t) and the spanwise-travelling wave assumption.

CONTEXT

Open cavity flows are often studied with regard to the self-sustained oscillations of the shear layer impinging onto the downstream corner of the cavity. However, the recirculating inner-flow is also known to be linearly unstable with respect to continuous families of spanwise-travelling waves, interpreted as the result of centrifugal instabilities. In a saturated state, centrifugal instabilities lead to highly energetic broad-banded three-dimensional dynamics, which can be decomposed as spanwise-distributed wavelike structures organising along the main recirculation. Those coherent structures are often referred to as Taylor-Görtler vortices [8, 1, 5, 6]. They are associated with frequencies at least one order of magnitude smaller than those of the self-sustained oscillations. Identifying such slow dynamics in the permanent regime is of particular interest since it influences drastically the vortices shed within the shear layer.

DATA AND METHODOLOGY

In the volume (x, y, z), consider a rectangular cavity flow such that x is the streamwise coordinate and y is the crosswise coordinate, normal to cavity bottom, and z is the spanwise coordinate, parallel to cavity bottom. The three-dimensional organisation of the inner-flow has been investigated using multiple time-resolved planar PIV measurements from two distinct experimental campaigns. Through time-Fourier transform over such space-extended data, we can obtain *global Fourier modes* associated with a given frequency [9, 3]. This process can be performed either in a zx-plane, parallel to the bottom of the cavity (Figure 1), or in a xy-plane (Figure 2).

The space-time dynamics observed in a zx-plane typically depicts spanwise-travelling waves, whose characteristics match results from the literature [4]. When considering the overall broad-banded dynamics deriving from the centrifugal instabilities, Strouhal numbers are such that

$$\mathrm{St} = \frac{fD}{U_0} = \frac{\omega D}{2\pi U_0} \leqslant 0.04.$$

with D the cavity depth and U_0 the incoming velocity. As for the spanwise wavenumbers, they generally scale as

$$3 \leqslant \beta = \frac{2\pi D}{\lambda} = k\,D \leqslant 15,$$

as reported in [2].

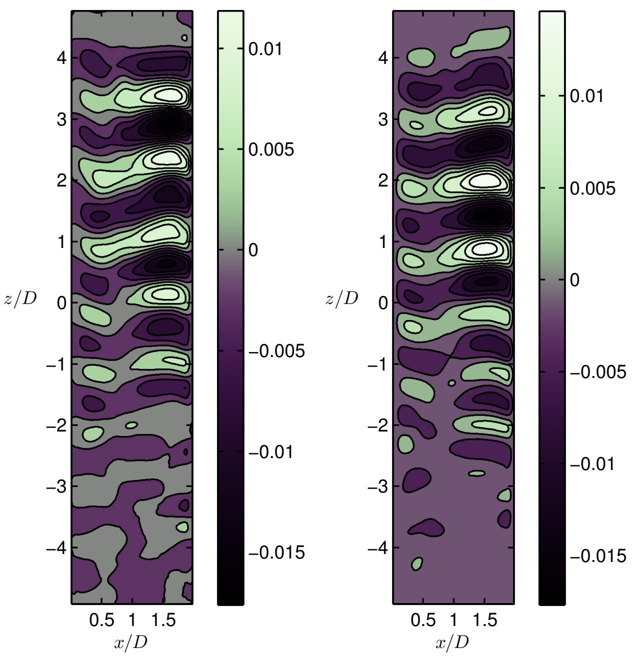

Figure 1. Example of global Fourier mode in a zx-plane at $y/D = -0.1$, associated with frequency $f\,D/U_0 = 0.018$, for $\mathrm{Re}_D = 2400$. Real part (*left*) and imaginary part (*right*) are depicted with contours of the streamwise velocity component u', normalised by incoming velocity U_0.

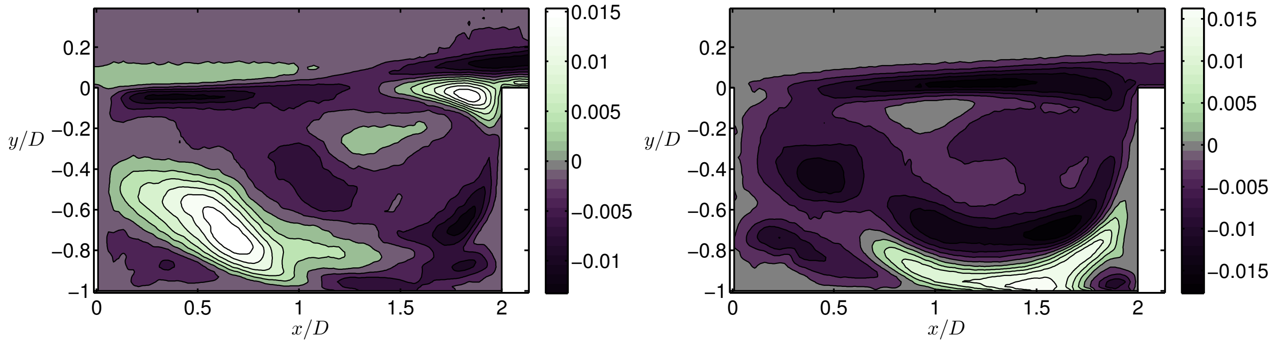

Figure 2. Example of global Fourier mode in a xy-plane, associated with frequency $f\,D/U_0 = 0.024$, for $\mathrm{Re}_D = 4570$. Real part (*left*) and imaginary part (*right*) are depicted with contours of the streamwise velocity u', normalised by incoming velocity U_0.

Relying on such results, we argue that, at the first order, the assumption of periodic spanwise-travelling waves can apply to the permanent regime, similarly to what is considered for (linear) Bi-Global stability analyses. The three-dimensional flow then rewrites

$$\boldsymbol{U}(x,y,z,t) = \sum_{\omega} \ \boldsymbol{\Psi}(x,y,\omega)\ \mathrm{e}^{i(\omega t - kz)} \ + \ \text{c.c.},$$

where $\boldsymbol{\Psi}(x,y,\omega)$ is the (complex) global Fourier mode, associated with the pulsation ω in a xy-plane. It comes that the temporal evolution of the wavelike structure in a given xy-plane is equivalent to its spanwise evolution at a given time. For each frequency corresponding to a spanwise-travelling wave, we can therefore reconstruct the associated coherent structures in the three-dimensional space (x,y,z) through the space-time volume (x,y,t), as shown in Figure 3. Using that methodology, we intend to identify the three-dimensional organisation of the broad-banded dynamics of the inner-flow, with respect to periodic eigenfunctions provided by linear stability analyses from the literature [4, 7].

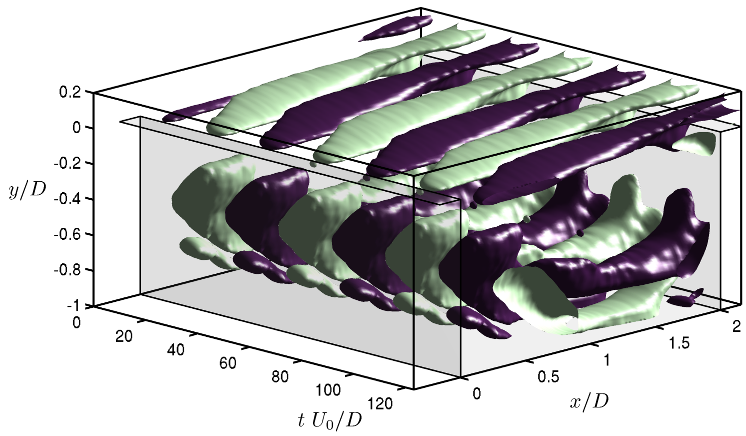

Figure 3. Reconstruction of a spanwise-travelling three-dimensional wave in the space-time volume (x,y,t), performed from the global Fourier mode shown in Figure 2. Iso-surfaces of streamwise velocity are displayed for two levels ($u'/U_0 = \pm 0.0055$).

References

[1] S. Albensoeder and H. C. Kuhlmann. Nonlinear three-dimensional flow in the lid-driven square cavity. *J. Fluid Mech.*, **569**:465–480, 2006.

[2] J. Basley. *An Experimental Investigation on Waves and Coherent Structures in a Three-Dimensional Open Cavity Flow*. PhD thesis, Université Paris-Sud – Monash University, 2012.

[3] J Basley, L. R. Pastur, F. Lusseyran, T. M. Faure, and N. Delprat. Experimental investigation of global structures in an incompressible cavity flow using time-resolved piv. *Experiments in Fluids*, April 2011. DOI: 10.1007/s00348-010-0942-9.

[4] G. A. Brès and T. Colonius. Three-dimensional instabilities in compressible flow over open cavities. *J. Fluid Mech.*, **599**:309–339, 2008.

[5] T. M. Faure, P. Adrianos, F. Lusseyran, and L. R. Pastur. Visualizations of the flow inside an open cavity at medium range reynolds numbers. *Experiments in Fluids*, **42**(2):169–184, 2007.

[6] T. M. Faure, L. R. Pastur, F. Lusseyran, Y. Fraigneau, and D. Bisch. Three-dimensional centrifugal instabilities development inside a parallelepipedic open cavity of various shape. *Experiments in Fluids*, **47**(3):395–410, 2009.

[7] F. Meseguer-Garrido, J. de Vicente, E. Valero, and V. Theofilis. Effect of aspect ratio on the three-dimensional global instability analysis of incompressible open cavity flows. *AIAA Paper*, (3605), 2011.

[8] C. Migeon, G. Pineau, and A. Texier. Three-dimensionality development inside standard parallelepipedic lid-driven cavities at re=1000. *J. Fluids Struct.*, **17**:717–738, 2003.

[9] C. W. Rowley, T. Colonius, and A. J. Basu. On self-sustained oscillations in two-dimensional compressible flow over rectangular cavities. *J. Fluid Mech.*, **455**:315–346, 2002.