Three-dimensional waves inside an open cavity and interactions with the impinging shear layer

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1 Motivations

A separated flow over an open cavity (Fig.1) is primarily characterised by the enhancement of self-sustained oscillations [12]. *Kelvin-Helmholtz* travelling waves arise in the shear layer and *lock on* to the cavity length L due to an acoustic feedback loop [11, 13]. This leads to locked-on modes of oscillations often referred to as *Rossiter* frequencies in the compressible regime. When the external velocity is small with regards to sound speed ($U_0 \ll c$), the corresponding frequencies f_n typically verify

$$f_n L/U_0 \approx n/2, \tag{1}$$

where $n = \{1,2,3\}$ is the number of periods (or wavelengths) over L. Self-sustained oscillations represent highly energetic fluctuations, generating noise and drag and fluid-structure interactions. However, the envelope of those self-sustained oscillations is often disregarded, although drastic amplitude modulation is generally ob-

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served [6, 10]. An example of *very low* frequency modulations is shown in Fig.2. The shear layer locked-on mode constitutes the carrier while the envelope evolves over 20 times larger time-scales (about 40 D/U_0 time-steps).

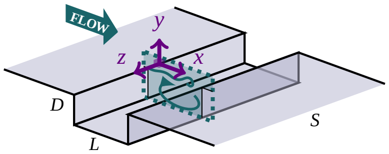

Fig. 1 Sketch of the geometry under study. Flow features are illustrated in the *xy*-plane (normal to the bottom of the cavity).

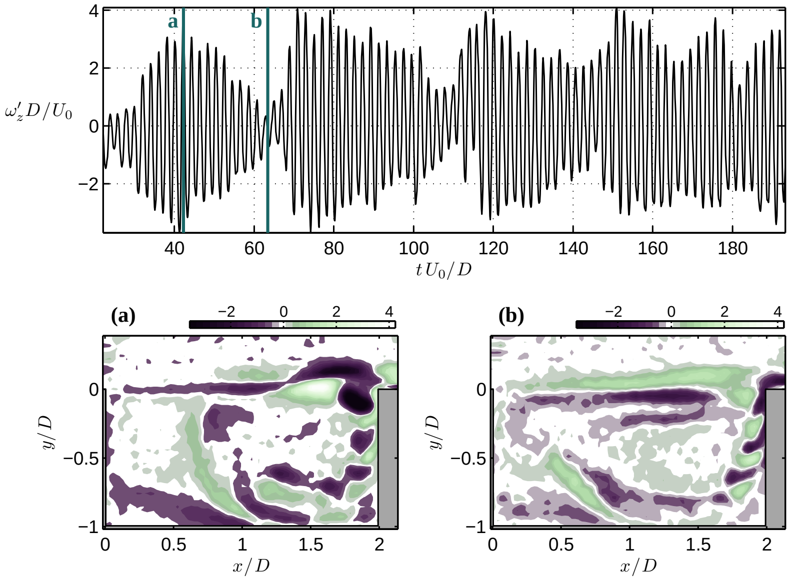

Fig. 2 Vorticity fluctuations $\omega'_z D/U_0$ out of Time-Resolved Particle Image Velocimetry data in a *xy*-plane, for $L/D = 2.0$ and $L/\theta_0 = 82$ ($U_0 = 1.38$ m/s). **Top** Time-series extracted near the impingement $(x,y) = (1.5D, 0)$ and **bottom** picked-up snapshots.

This contribution aims at identifying the flow dynamics responsible for such low frequencies. The three-dimensional (3D) organisation of the flow is believed to be the source of the amplitude modulation [10]. In particular, the extensive literature on the recirculating flow inside the cavity has shown how *centrifugal instabilities* lead to slow 3D waves. In both lid-driven [1, 16] and shear-driven cavity flows [7, 8, 9], vortical structures are observed along the span of the cavity. They are typically associated with low frequencies f_{ci} such that

$$f_{ci}D/U_0 \leqslant 0.05, \tag{2}$$

consistent with the time scales of the envelope observed in Fig.2. Furthermore, Brès & Colonius [5] have already pointed out such low frequencies co-existing with *Rossiter* oscillations of the shear layer, in direct numerical simulations (DNS) of compressible open cavity flows.

2 Experiments

The present study deals with an experimental cavity flow in the incompressible regime. Consider a laminar incoming flow, for which θ_0 is the momentum thickness of the Blasius boundary layer at separation. The dimensionless cavity length L/θ_0 and the Reynolds number $\mathrm{Re}_D = U_0 D/\nu$ are primary control parameters. Two campaigns have been conducted to encompass a wide range of the parameter space: $1500 \leqslant \mathrm{Re}_D \leqslant 9000$ and $23 \leqslant L/\theta_0 \leqslant 104$. The space-time evolution of the 3D flow dynamics is investigated through Time-Resolved Particle Image Velocimetry (TRPIV) measurements performed in two planes. On one hand, wind-tunnel experiments at LIMSI focus on the shear layer waves and the primary dynamics. High-speed PIV measurements (500Hz) are performed in a *xy*-plane, streamwise normal to the bottom of the cavity [2, 3, 4]. On the other hand, the water-tunnel campaign at LTRAC is concerned with the spanwise extension of the flow [2]. It consists of high-resolution PIV data out of a *zx*-plane, parallel to the bottom of the cavity at $y/D = -0.1$. Velocity fields are obtained from particle images recorded by three synchronised cameras and processed using a cross-correlation algorithm [15]. Cavity span is larger at LTRAC ($S = 10D$) than at LIMSI ($S = 6D$) so as to better identify spanwise wavelengths. Note that the spanwise extension is large enough in both cases to ensure that influence of the end-walls remains secondary to intrinsic stability properties of the recirculating inner-flow.

3 Slow dynamics inside the cavity

Since PIV data are time-resolved, spectral filtering can be performed to separate the low frequency range from the dominant locked-on frequency and its harmonics. Such a decomposition is illustrated in Fig.3. The locked-on frequency of the shear layer f_a is such that $\mathrm{St}_a = f_a D/U_0 = 0.49$, while the local maximum of the low frequency range is observed at $\mathrm{St}_\Delta = f_\Delta D/U_0 = 0.024$.

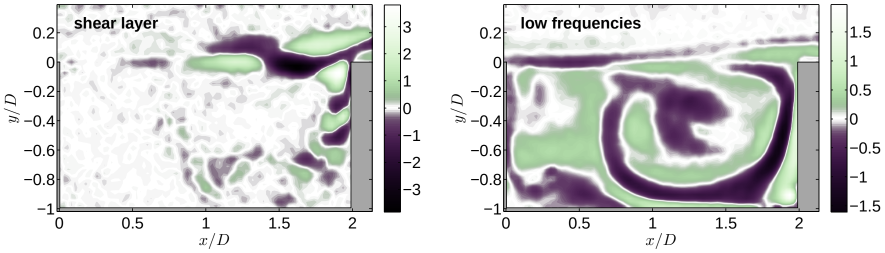

Fig. 3 Filtered vorticity fluctuations in a *xy*-plane (LIMSI), for $L/D = 2.0$ & $L/\theta_0 = 82$. Examples of filtered snapshots, **left**, around shear layer frequencies, **right**, for low frequencies only.

As expected, the dynamics corresponding to f_a is restricted to the shear layer and to inflows along the downstream wall of the cavity. On the contrary, low frequency dynamics encompasses the entire inner-flow. More particularly, slow dynamics organises as large-scale fluctuations winding up around the main recirculation and implying outflows near the impingement. Such a spatial structure associated with frequencies matching Eq. 2 suggests 3D waves resulting from centrifugal instabilities, as observed in numerical studies by [5, 9]. The identification of those waves requires an investigation of the spanwise extension of the flow.

4 Spanwise travelling waves

The spanwise extension of the inner-flow is investigated through PIV measurements in a *zx*-plane at $y/D = -0.1$. Since recordings are time-resolved, Fourier transform can be applied to the time-series at each point of the velocity fields [14, 4]. Spatial structures associated with a single frequency are hence identified. They are referred to as *global Fourier modes* in the following.

The most energetic global Fourier modes are always associated with Strouhal numbers matching $\mathrm{St}_\Delta = f_\Delta D/U_0 \approx 0.02$, as shown in Fig.4. The salient dynamics of the inner-flow organise as planar spanwise-travelling waves. Highly coherent spanwise oscillations appear for large areas of the *zx*-plane, yielding a unique spanwise wavelength $\lambda \approx D$. In other words, the dominant 3D dynamics of the inner-flow can be represented by *monochromatic spanwise travelling waves*. Such space-time feature typically come by pair of counter-propagating waves, which may exclude each other or partially overlap. In the latter case, interference leads locally to a (quasi) *standing wave* [2].

With increasing control parameters, shear layer disturbances get stronger and make the inner-flow more unsteady. However, the most salient modes connected to slow dynamics persist as monochromatic spanwise travelling waves. This is shown in [3], for $L/\theta_0 = 76$, $\mathrm{Re}_D = 6800$. Hence, it is reasonable to assume that 3D dynamics corresponding to frequency St_Δ can write in the (dimensionless) form

$$\psi_\Delta(x,y,z,t) = \zeta_\Delta(x,y) \times \exp\left[i\left(\beta z - 2\pi \mathrm{St}_\Delta\, t\right)\right], \tag{3}$$

where β is the spanwise wavenumber and $\zeta_\Delta(x,y)$ stands for the global Fourier mode associated with St_Δ in a *xy*-plane. With that assumption, the spanwise dynamics of ψ_Δ is equivalent to the temporal dynamics in a single *xy*-plane. Through a simple dispersion relationship, it comes

$$\frac{\partial \psi_\Delta}{\partial z} \propto \frac{\partial \psi_\Delta}{\partial t} \qquad \left(\frac{\partial \psi_\Delta}{\partial z} = \beta\, \psi_\Delta = \frac{2\pi \mathrm{St}_\Delta}{c_\Delta}\, \psi_\Delta = -\frac{1}{c_\Delta}\frac{\partial \psi_\Delta}{\partial t}\right), \tag{4}$$

with c_Δ the (constant) spanwise phase velocity of the wave. Three-dimensional dynamics associated with frequency St_Δ can therefore be estimated through a reconstruction in the space-time volume (x,y,t) using the *xy*-plane Fourier mode $\zeta_\Delta(x,y)$ (Fig.5). Time-wise axis here stands for the spanwise extension of the flow.

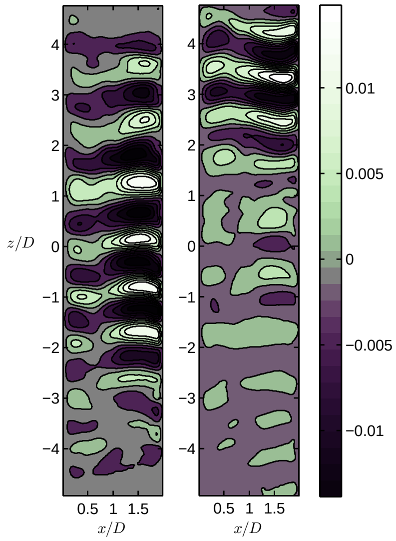

Fig. 4 Example of global Fourier modes in the *zx*-plane (LTRAC) for $L/D = 2.0$, $L/\theta_0 = 59.2$, $\mathrm{Re}_D = 2400$. Using streamwise velocity fluctuations $u'_x D/U_0$, real parts of the Fourier modes associated with **left**, $\mathrm{St} = 0.019$, **right**, $\mathrm{St} = 0.013$, corresponding to two counter-travelling waves.

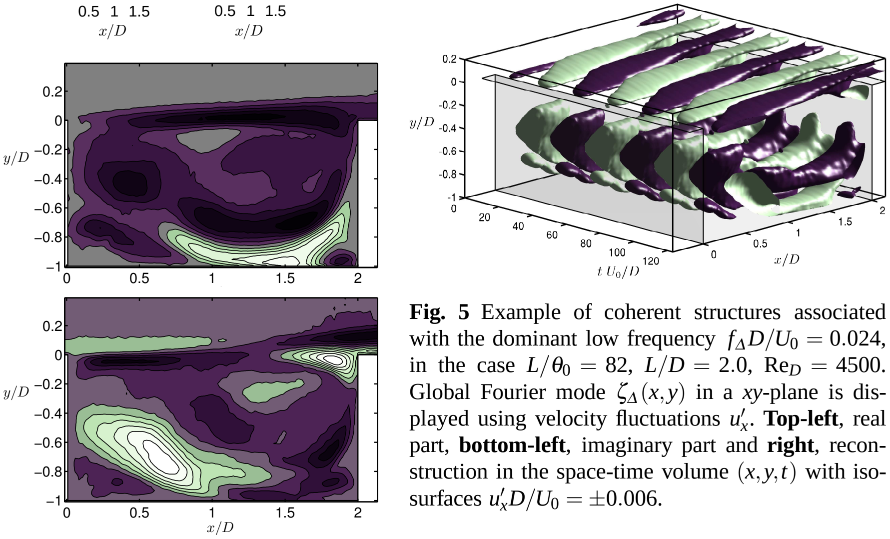

Fig. 5 Example of coherent structures associated with the dominant low frequency $f_\Delta D/U_0 = 0.024$, in the case $L/\theta_0 = 82$, $L/D = 2.0$, $\mathrm{Re}_D = 4500$. Global Fourier mode $\zeta_\Delta(x,y)$ in a *xy*-plane is displayed using velocity fluctuations u'_x. **Top-left**, real part, **bottom-left**, imaginary part and **right**, reconstruction in the space-time volume (x,y,t) with isosurfaces $u'_x D/U_0 = \pm 0.006$.

5 Conclusion and outlook

We have shown that the lowest amplitude modulations of the shear layer waves are related to centrifugal instabilities inside the cavity. In fact, inner-flow fluctuations can be primarily modelled as monochromatic spanwise travelling waves of frequency $f_\Delta D/U_0 \approx 0.02$. Such a model implies spanwise derivatives become proportional to temporal derivatives. As a result, 3D structures associated with f_Δ can be estimated out of the two-dimensional space-time dynamics at a given position *z*. Future works will aim to characterise more precisely the non-linear interactions between shear layer waves and 3D slow dynamics inside the cavity.

References

[1] Albensoeder, S., Kuhlmann, H.C., Rath, H.J.: Three-dimensional centrifugal-flow instabilities in the lid-driven-cavity problem. Phys. Fluids **13**, 121–135 (2001)

[2] Basley, J.: An experimental investigation on waves and coherent structures in a three-dimensional open cavity flow. Ph.D. thesis, Université Paris-Sud (Orsay, France) & Monash University (Melbourne, Australia) (2012)

[3] Basley, J., Pastur, L.R., Delprat, N., Lusseyran, F.: Space-time aspects of a three-dimensional multi-modulated open cavity flow. Phys. Fluids **25**(6), 064,105 (2013). DOI 10.1063/1.4811692

[4] Basley, J., Pastur, L.R., Lusseyran, F., Faure, T.M., Delprat, N.: Experimental investigation of global structures in an incompressible cavity flow using time-resolved piv. Experiments in Fluids **50**, 905–918 (2011). DOI 10.1007/s00348-010-0942-9

[5] Brès, G.A., Colonius, T.: Three-dimensional instabilities in compressible flow over open cavities. J. Fluid Mech. **599**, 309–339 (2008). DOI 10.1017/S0022112007009925

[6] Delprat, N.: Low-frequency components and modulation processes in compressible cavity flows. J. Sound Vibrat. **329**(22), 4797–4809 (2010)

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

[8] Koseff, J.R., Street, R.L.: Visualization studies of a shear driven three-dimensional recirculating flow. Trans. ASME: J. Fluids Eng. **106**, 21–29 (1984)

[9] Meseguer-Garrido, F., de Vicente, J., Valero, E., Theofilis, V.: Effect of aspect ratio on the three-dimensional global instability analysis of incompressible open cavity flows. AIAA Paper (3605) (2011). DOI 10.2514/6.2011-3605

[10] Neary, M.D., Stephanoff, K.D.: Shear-layer-driven transition in a rectangular cavity. Phys. Fluids **30**(10), 2936–2946 (1987)

[11] Powell, A.: On edge tones and associated phenomena. Acustica **3**, 233–243 (1953)

[12] Rockwell, D., Naudascher, E.: Review — self-sustaining oscillations of flow past cavities. J. Fluids Eng. **100**, 152–165 (1978)

[13] Rossiter, J.: Wind-tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds. Aeronautical Research Council **Report No. 3438** (1964)

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

[15] Soria, J.: Multigrid approach to cross-correlation digital piv and hpiv analysis. 13th Australasian Fluid Mechanics Conference, Sydney (1998)

[16] Theofilis, V.: Advances in global linear instability of nonparallel and three-dimensional flows. Prog. Aerosp. Sci. **39**(4), 249–315 (2003)