SELF-SUSTAINED OSCILLATIONS OF OPEN CAVITY FLOWS: WHEN THE INNER FLOW DYNAMICS COUPLE TO THE SHEAR-LAYER OSCILLATIONS

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ABSTRACT

Open cavity flows are known to develop energetic self-sustaining shear-layer oscillations. Such oscillations are strongly modulated in time, as the result of nonlinear feedback mechanisms and coupling with the dynamics of inner-flow patterns. The latter result from centrifugal instabilities that develop well-before the shear-layer start oscillating. Depending on the cavity aspect ratio and its span to depth ratio, a family of quasi-steady modes is selected at threshold for small aspect ratio while a family of left and right traveling modes is selected at large aspect ratio, as predicted by linear stability analyses.

NOMENCLATURE

$x, y, z$ Streamwise, vertical and spanwise coordinates.  
$u, v, w$ Streamwise, vertical and spanwise velocity components.  
$U_0$ Free stream velocity at $x = 0$.  
$L, D, S$ Cavity length, depth, span.  
$Re_{L,D}$ Reynolds number based on $L,D$.  
$St_{L,D}$ Strouhal number based on $L,D$.  
$\lambda$ Wavelength of inner-flow patterns.  
$t_{conv}$ Convective time $L/U_0$.  
$LDV$ Laser Doppler Velocimetry.  
$PIV$ Particle Image Velocimetry.
INTRODUCTION

Shear-layer driven cavity flows are known to develop powerful self-sustained shear-layer oscillations, beyond some critical values of the control parameters, as a result of pressure feedback at impingement at the cavity trailing corner [1–3] and hydrodynamical feedback through the inner-flow recirculation [4]. As a result, shear-layer dynamics is not broad-banded anymore and power spectra of the flow field exhibit discrete peaks rising from the background noise [5, 6]. At such flow regimes, acoustic modes are not excited within the cavity depth. Yet, the primary instability of the steady base flow develops against centrifugal instabilities of the cavity inner-flow [7], far before the energetically dominant self-sustained oscillations of the shear-layer be activated, at larger Reynolds numbers. In this paper, both the shear-layer Kelvin-Helmholtz and centrifugal inner-flow instabilities are reviewed, together with their dynamical coupling, based on the thorough work of [6–15].

EXPERIMENTAL SETUP

The wind-tunnel is composed of a centrifugal fan providing stationary volume flow upstream of the wind-tunnel, a settling chamber that equalizes the flow and a honey-comb panel, placed at the inlet of the contraction, which contributes to laminarise the flow. The wind-tunnel is open in the room. The boundary layer develops above a 300 mm-long plate with profiled leading edge, upstream of the cavity leading edge. The wind-tunnel span S is 300 mm-long. The distance between the top of the channel and the top of the cavity is 75 mm, large enough to avoid perturbation from the top boundary layer. The cavity height can be fixed to either D = 25 or 50 mm, providing as span to depth ratio S/D = 12 or 6, respectively. Complete optical access is made available using reflection-treated glass walls. A cartesian coordinate system (e_x, e_y, e_z) is set mid-span at the cavity leading corner. Various cases of streamwise shape ratio L/D are investigated, by modifying the cavity length L. Reynolds numbers \( Re_L = U_0 L / \nu \) can go up to 70,000, where \( U_0 \) is the velocity outside of the boundary layer at the cavity leading edge (\( x = 0 \)). Mach numbers are smaller than \( 8 \times 10^{-3} \) and the cavity is not at acoustic resonance. At such very low Mach numbers, the flow can be considered as incompressible. Background turbulence is less than 1%.

VELOCIMETRIES

A dual-head New Wave PEGASUS laser is used for PIV measurement in the \((x, y)\) plane. The camera is a Photron FASTCAM-APX RS. The time step between images is \( dt = 2\) ms, optimised for the inside and shear flow particle displacements. The sampling rate for the velocity fields is \( f_s = 250 \) Hz, high enough to resolve all frequency components in power spectra. Displacement fields are computed using an optical flow algorithm based on an orthogonal dynamical programming [16]. PIV plane is set to \( z/S = 0.07 \) to avoid any symmetry plane of the flow. PIV in the \((x, z)\)-plane is conducted at \( y/D = -0.30 \) based on twin-pulsed 200 mJ Quantel YAG lasers and a single-frame AVT Marlin camera with frame rate 20 Hz. Seeding particles are liquid droplets of mineral oil DEHS (diameter \( \simeq 1 \mu m \)) sprayed at the fan entrance. Measurements only start after the seeding particle distribution is uniform inside the cavity. An electronic delay-generator is used to synchronise flash lamps and Q-switches of lasers together with the camera chronogram and, when required, LDV recordings, with a precision of 0.5 \( \mu s \).

LDV measurements are carried out with a DANTEC BSA system using a 35 mW continuous laser at 660 nm with a front lens of focal length 300 mm and a Bragg cell modulated at 80 MHz. When dealing with shear-layer features, the LDV measurement point is set slightly above and upstream of the impinging corner (\( y \gtrsim 0, x/L \lesssim 1 \)), where the amplitudes of shear-layer oscillations are the largest. When dealing with the inner-flow features, the measurement point is set inside the cavity, typically somewhere between \( y/D \simeq -1/3 \) and \(-1/2 \) in the upstream half of the cavity (\( x/L < 0.5 \)).

SHEAR-LAYER SELF-SUSTAINED OSCILLATIONS

Beyond some critical value of the Reynolds number and boundary layer thickness, the steady base flow loses stability with respect to shear-layer self-sustained oscillations, in a supercritical Hopf bifurcation. As a result, discrete harmonic families of peaks are selected by the cavity length, whose fundamental frequencies \( f_n \) roughly satisfy the semi-empirical Rossiter’s formula [17, 18]:

\[
\frac{f_n L}{U_0} = \frac{n - \alpha}{\Ma + U_0/c}, \quad n \in \mathbb{N}^*,
\]

in the limit of Mach number \( \Ma \to 0 \), where \( \alpha \neq 0 \) is a phase shift not strictly constant and \( c \) the celerity of shear-
FIGURE 1: Mean flow field (arrow) colored by the velocity strength, in configuration $L/D = 2$, $Re_L \simeq 14000$ ($D = 50$ mm).

FIGURE 2: Power spectral density (psd) from local LDV measurement close to the impinging corner, in configuration $L/D = 2$, $Re_L \simeq 14000$ ($D = 50$ mm).

layer waves, $U_0/c \simeq 2$ [11].

Driven by the outflow, the inner-flow is put into motion, generating a main fluid recirculation inside the cavity, as shown in the mean flow field of Fig. 1, for the case $L/D = 2$, $Re_L = 14000$. Because of the shear-layer oscillations, fluid from the out-flow is periodically injected inside the cavity at the impinging corner, at the frequency of the shear-layer oscillations (Strouhal number $St_L = f_2L/U_0$ in Fig. 2).

The main inner flow recirculation provides a secondary delayed feedback mechanism, carrying the injected momentum and vorticity back to the shear layer. This feedback mechanism has been recently described in the form of the so-called “carousel” wheel, in idealised two-dimensional numerical simulations of double cavity flows [4]. In the power spectral distribution of Fig. 2, this feedback mechanism has its signature at Strouhal number $St_L$. In time, mass fluxes are cyclically exchanged between the inner and the outer flows. Nonlinear effects strongly influence the impinging region, resulting into amplitude and frequency modulations [19–21].

FIGURE 3: Mode competition in configuration $Re_L = 14000$, $L/D = 2$ ($D = 50$ mm). Time is expressed in units of $t_{conv} = L/U_0$.

As the Reynolds number is increased, secondary peaks rise in the spectrum ($St_3 = St_2 + St_-$ in Fig. 2), whose amplitude increases as the Reynolds number is increased, until two dominant modes of equal amplitude be present in the spectrum, namely at $St_2$ and $St_3$. In such a configuration, two modes of oscillations compete in time in the shear-layer, as illustrated in the spectrogram of Fig. 3 [8, 9, 22]. Further on, the primary dominant peak $St_2$ progressively dies out, letting the secondary peak $St_3 \simeq 1.5$ as the unique dominant component in the spectrum, together with its harmonics.

VERY LOW-FREQUENCY MODULATIONS

In Fig. 4 is shown a typical LDV (centered) signal with its envelope (black thick line on the top of it) and its low-frequency component (thick gray line at the bottom of it). The dominant mode in the power spectrum, associated with the shear-layer self-sustained oscillations, is strongly modulated in amplitude over frequency ranges smaller than $St_L = 0.4$. The envelope (thick black line) follows the low-frequency component of the signal (thick gray line), indicating a common origin of both phenomenon, while such very low-frequency features are absent from two-dimensional simulations of the flow, where only the faster time scales of non-linear couplings between shear-layer modes remain in the power
FIGURE 4: LDV signal close to the impinging cavity corner (velocity vertical component measured), at \( Re_L = 14700 \), \( L/D = 1.75 \) \((D = 50\text{ mm})\). Black thick line at the top of the signal: envelope of the signal extracted by complex demodulation, as described in [23]. Thick gray line at the bottom of the signal: low-frequency component extracted by low-pass filtering the signal at the cutoff frequency \( St_L \approx 0.4 \).

spectrum [4]. This typically three-dimensional feature actually results from the coupling between the inner-flow slow dynamics with the shear-layer oscillations [13].

CENTRIFUGAL INSTABILITIES

FIGURE 5: Smoke visualization of Taylor-Görtler-like vortical structures in the plane located at \( y/D = -0.1 \), cavity depth \( D = 50\text{ mm} \) (topview).

The primary instability of the fully three-dimensional steady base-flow is not two-dimensional with respect to Kelvin-Helmholtz modes, but results from centrifugal instabilities of the inner-flow and to the formation of a spanwise alley of counter-rotating vortical structures winding around the main inner-flow recirculation, the so-called Taylor-Görtler vortices shown in Fig. 5 from smoke visualization [7, 14, 24–27]. The bifurcation is supercritical, though experimentally imperfect [14, 27]. Onsets of pattern formation are shown in Fig. 6 for both cavity depths. Square cavities are the most stable, as also predicted by [25].

FAMILIES OF MODES

FIGURE 6: Onset of centrifugal instabilities, determined by the rising of a peak in the LDV power spectrum, for cavity depths \( D = 25\text{ mm} \) (circles) and \( D = 50\text{ mm} \) (+). Open circles: onset of left traveling wave, filled circles: onset of the right traveling wave.

FIGURE 7: Strouhal number \( St_D \) as a function of \( L/D \) for cavity depth \( D = 25\text{ mm} \) (open circles) and \( D = 50\text{ mm} \) (filled circles).

At threshold, the Taylor-Görtler vortices slightly drift toward the cavity spanwise walls [10], generating a rising peak in LDV power spectra of the inner-flow. For cavity depth \( D = 50\text{ mm} \), the associated Strouhal numbers, based on \( D \), are of the order of \( St_D \approx 5 \times 10^{-3} \) for any ratio \( L/D \), as shown in Fig. 7 (filled circles) and wavelengths are about \( \lambda/D = 0.68 \pm 0.08 \), as shown in Fig. 8 (filled circles). For cavity depth \( D = 25\text{ mm} \), evo-
FIGURE 8: Wavelength $\lambda/D$ as a function of $L/D$ for cavity depth $D = 25$ mm (open circles) and $D = 50$ mm (filled circles).

FIGURE 9: Space-time diagram based on a topview of the vorticity inner-flow field, at $Re_D = 2000$, $L/D = 1.75$ ($D = 25$ mm).

olutions of both the Strouhal number and the wavelength break at $L/D$ between 1.3 and 1.4 (open circles in Fig. 7 and Fig. 8, respectively) [14, 15]. For smaller aspect ratios $L/D < 1.4$, $St_D \approx 4 \times 10^{-3}$ — similar to the Strouhal numbers found for the cavity depth $D = 50$ mm —, while for larger aspect ratios $L/D > 1.3$, $St_D \approx 1.2 \times 10^{-2}$, indicating that the pattern drifts faster toward the walls in the latter case. Similarly, the wavelength of the inner flow pattern changes from $\lambda/D \approx 0.7$ for small aspect ratios to $\lambda/D \geq 1$ for larger aspect ratios. It is worthwhile noticing that a quasi-symmetric traveling wave rises above, though close to, the primary onset, for cavity of large aspect ratio $L/D > 1.3$, see the filled circles in Fig. 6. When both right and left traveling patterns overlap, a pattern of quasi-standing wave is formed, as shown in the space-time diagram of Fig. 9.

As a result, two different families of modes are selected at threshold depending on the cavity aspect ratio $L/D$: a quasi-steady family of modes for small aspect ratio, a family of right and left traveling modes for large aspect ratio, as expected from linear stability analyses on a two-dimensional steady base-flow [25, 26].

DISCUSSION AND CONCLUSION

It is worthwhile noticing that at high enough Reynolds numbers in the incompressible flow regime, power spectra do not exhibit salient features anymore, while non-harmonic families of the so-called Rossiter’s modes rise again at non vanishing Mach numbers. Such a breakdown in the evolution of power spectra suggests that Rossiter spectra may not be in the continuation of power spectra at vanishing Mach number. Other question of interest is the route undergone by the inner-flow to space-time chaos and wave turbulence [14], and the role played by the shear-layer oscillations in the complexity of the inner-flow dynamics. Such questions are left to further investigations.

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