

## DYNAMICS OF LOW REYNOLDS IMPINGING JET FLOWS.

Javier Sierra-Ausin<sup>1,2</sup>, Flavio Giannetti<sup>2</sup>, David Fabre<sup>1</sup>

<sup>1</sup>*Institut de Mécanique des fluides de Toulouse (IMFT), Toulouse 31400, France*

<sup>2</sup>*Dipartimento di Ingegneria (DIIN), Università degli Studi di Salerno, Fisciano 84084, Italy*

We present a summary of comprehensive results for the dynamics of the unconfined (respectively, confined) laminar rounded compressible [2, 11, 12] impinging jet and the confined plane incompressible impinging jet. We study these flow configurations from a dynamical system perspective, which aims to characterize the main underlying physical mechanisms responsible for the instabilities [8, 9], see Fig. 1. Herein,

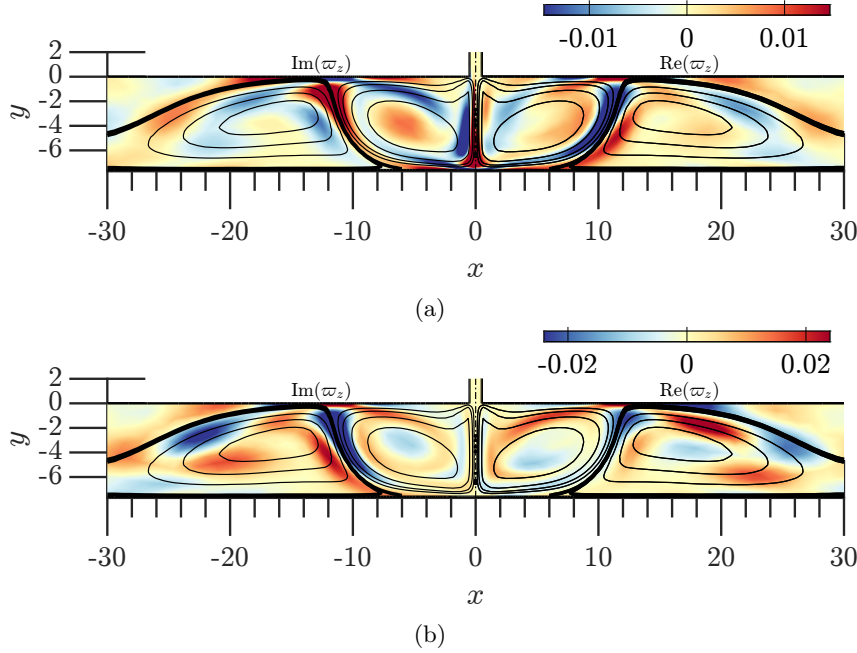


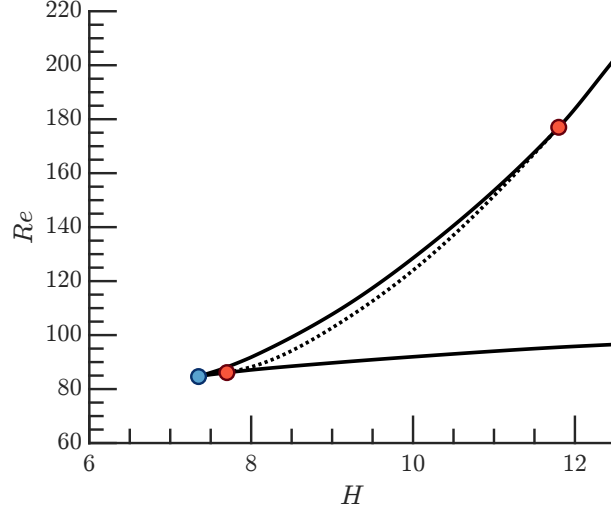
Figure 1: Spatial distribution of the vorticity field for the (a) symmetric and (b) antisymmetric spanwise symmetry breaking modes.

we perform a complete characterisation of the bifurcation scenario in the parameter space:  $(H, Re, M)$ , with  $H$  the nozzle to impinging wall distance,  $Re$  the Reynolds number, and  $M$  the Mach number. The identification of the fundamental fluid instabilities responsible for transition allows the construction of a low-dimensional system that governs the evolution of the flow [5, 6]. We show that for sufficiently large values of  $H$ , the confined plane (2D) low Reynolds impinging jet flow displays intermittent dynamics. Such a feature is the result of the interaction between two physical mechanisms with a clear separation of scales, the slow convection in the recirculation region and the fast motion of the jet flapping. Such a mode-interaction is dynamically revealed by a Cusp-Hopf organizing centre, see Fig. 2.

Table 1: Coefficients of the normal form eq. 1 evaluated at  $H = 7.7$ ,  $Re_{ZF} = 86.05$ .

Coefficient (Z)	Value	Coefficient (H)	Value
$\beta_Z(H, Re)$	$1.98\varepsilon_\nu$	-	-
$\lambda_Z(H, Re)$	$0.195\varepsilon_\nu$	$\lambda_F(H, Re)$	$(10.5 + 9.1i)\varepsilon_\nu$
$\gamma_{Z^2}$	$-8 \cdot 10^{-4}$	-	-
$\gamma_F$	$-1.3 \cdot 10^{-2}$	$\zeta_Z$	$(7.35 - 12.7i) \cdot 10^{-3}$
$\gamma_{Z^3}$	$-4 \cdot 10^{-4}$	$\zeta_F$	$(3.83 - 3.72i) \cdot 10^{-2}$
$\gamma_{ZF}$	$1.8 \cdot 10^{-3}$	$\zeta_{Z^2}$	$(-8.35 - 0.4i) \cdot 10^{-3}$

The slow-fast dynamics prevails also in the three-dimensional case, thus confirming that it is a robust mechanism, nonetheless with the presence of transversal travelling/standing waves. The dynamics of the two-dimensional impinging jet within a range of Reynolds numbers where primary instabilities occur (



(a)

Figure 2: Region of steady flow hysteresis bounded by two saddle nodes. (●) Cusp point. (●) Zero Hopf points. The dashed curve is the Hopf line tangentially intersecting the fold at the two zero Hopf points.

$50 < Re < 500$ ) can be understood as a low dimensional manifold.

$$\begin{aligned}\partial_T A_Z &= \beta_Z + \lambda_Z A_Z + \gamma_{Z^2} A_Z^2 + \gamma_{Z^3} A_Z^3 + \gamma_F |A_F|^2 + \gamma_{ZF} A_Z |A_F|^2 \\ \partial_T A_F &= A_F \left( \lambda_F + \zeta_Z A_Z + \zeta_F |A_F|^2 + \zeta_{Z^2} A_Z^2 \right)\end{aligned}\quad (1)$$

On the other hand, the rounded impinging jet flow also exhibits flapping jet motion associated to a feedback loop, evidenced by the evolution of the frequency spectra with respect Mach number as Rossiter frequencies. However, in this flow configuration, the convective motion within the recirculation region is somehow secondary. In the confined configuration, the primary bifurcation is associated to the same feedback loop for all Mach numbers, to avoid reflection from boundaries we use the complex mapping technique [7, 10], yet with distinct quantization, which is evidenced by its frequency. We also show results from Harmonic Balance computations [8, 1]. Further connections will be made with the unconfined configuration and strong tonal noise observed in experiments at large subsonic Mach numbers. These results have implications for a variety of impinging flows such as those in jet-flap devices, jet past a hole[3, 4], cooling applications, fluidic oscillators and membrane systems.

## References

- [1] Sierra-Ausin, Javier and Citro, Vincenzo and Giannetti, Flavio and Fabre, David *Efficient computation of time-periodic compressible flows with spectral techniques* Computer Methods in Applied Mechanics and Engineering, 393 (2022), p. 114736.
- [2] Citro, Vincenzo and Giannetti, Flavio and Sierra, Javier *Optimal explicit Runge-Kutta methods for compressible Navier-Stokes equations* Applied Numerical Mathematics, 152 (2020), pp. 511–526.
- [3] Sierra-Ausin, Javier, and Fabre, David and Citro, Vincenzo and Giannetti, Flavio. *Acoustic instability prediction of the flow through a circular aperture in a thick plate via an impedance criterion* Journal of Fluid Mechanics, 943 (2022), A48.
- [4] Hirschberg, Lionel and Guzman Inigo, Juan G and Aulitto, Alessia and Sierra, Javier and Fabre, David and Morgans, Aimee and Hirschberg, A *Linear theory and experiments for laminar bias flow impedance: Orifice shape effect* 28th AIAA/CEAS Aeroacoustics 2022 Conference, p. 2887.
- [5] Sierra, J and Fabre, D and Citro, V and Giannetti, F *Bifurcation scenario in the two-dimensional laminar flow past a rotating cylinder* Journal of Fluid Mechanics, 905 (2020) A2.
- [6] Sierra-Ausin, J and and Lorite-Diez, M and Jimenez-Gonzalez, JI and Citro, V and Fabre, D *Unveiling the competitive role of global modes in the pattern formation of rotating sphere flows* Journal of Fluid Mechanics 942 (2022).
- [7] Sierra-Ausin, Javier and Fabre, David and Citro, Vincenzo *Efficient stability analysis of fluid flows using complex mapping techniques* Computer Physics Communications, 251 (2020), p. 107100.
- [8] Sierra-Ausin, Javier and Jolivet, Pierre and Giannetti, Flavio and Citro, Vincenzo *Adjoint-based sensitivity analysis of periodic orbits by the Fourier–Galerkin method* Journal of Computational Physics, 440 (2021), p. 110403.
- [9] Sierra-Ausin, Javier and Bonnefis, Paul and Tirri, Antonia and Fabre, David and Magnaudet, Jacques *Dynamics of a gas bubble in a straining flow: Deformation, oscillations, self-propulsion* Physical Review Fluids, 7.11 (2022), p. 113603.
- [10] Sierra-Ausin, Javier and Fabre, David and Citro, Vincenzo *On boundary conditions for compressible flow simulations* Symposium on Fluid-Structure-Sound Interactions and Control 2019, 335–340.

- [11] Saez-Mischlich, Mischlich and Sierra-Ausin, Javier and Gressier, Jeremie *The Spectral Difference Raviart–Thomas Method for Two and Three-Dimensional Elements and Its Connection with the Flux Reconstruction Formulation* Journal of Scientific Computing, 93, 1–54.
- [12] Saez-Mischlich, Mischlich and Sierra-Ausin, Javier and Gressier, Jeremie *On the properties of high-order least-squares finite-volume schemes* Journal of Computational Physics, 457, 111043.