Mode interactions in external flows

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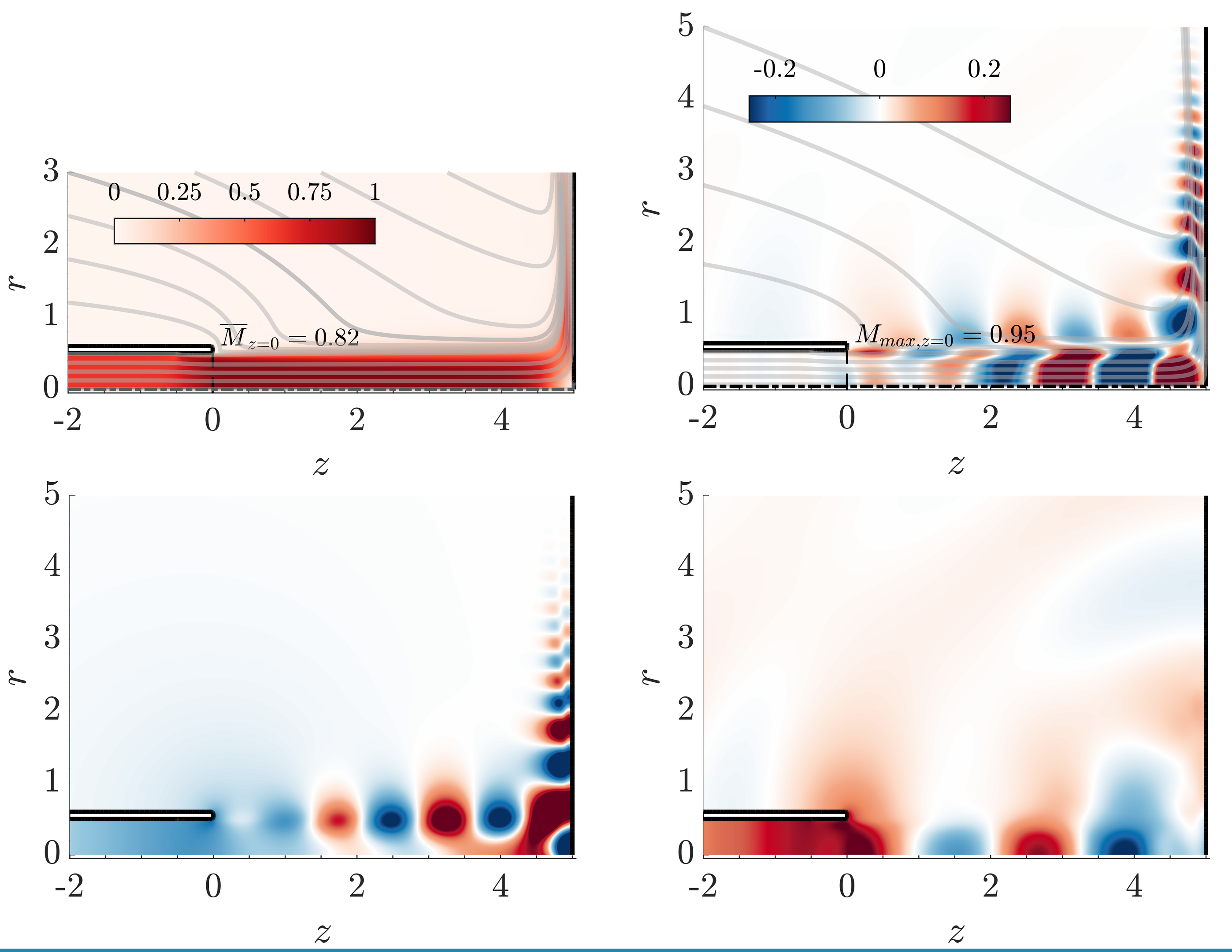
Brief summary

In this thesis, we study the formation of coherent structures in the early stages of transition from a laminar state towards a turbulent regime. A profound understanding of the transition and the underlying physical mechanisms provides valuable information to design passive control strategies in engineering practices. In particular, we analyse the formation of large coherent structures that emerge under the competition of multiple global instabilities. The study of such problems is an active field of research which requires a number of mathematical tools (bifurcation, normal forms, adjoint methods, sensitivity, . . .) and numerical techniques (fixed point and continuation methods, . . .). In this thesis all these techniques are applied, and often extended beyond the existing state-of-the-art, to several physical problems including acoustics, wake and jet flows, and problems with moving interfaces, each of them detailed below.

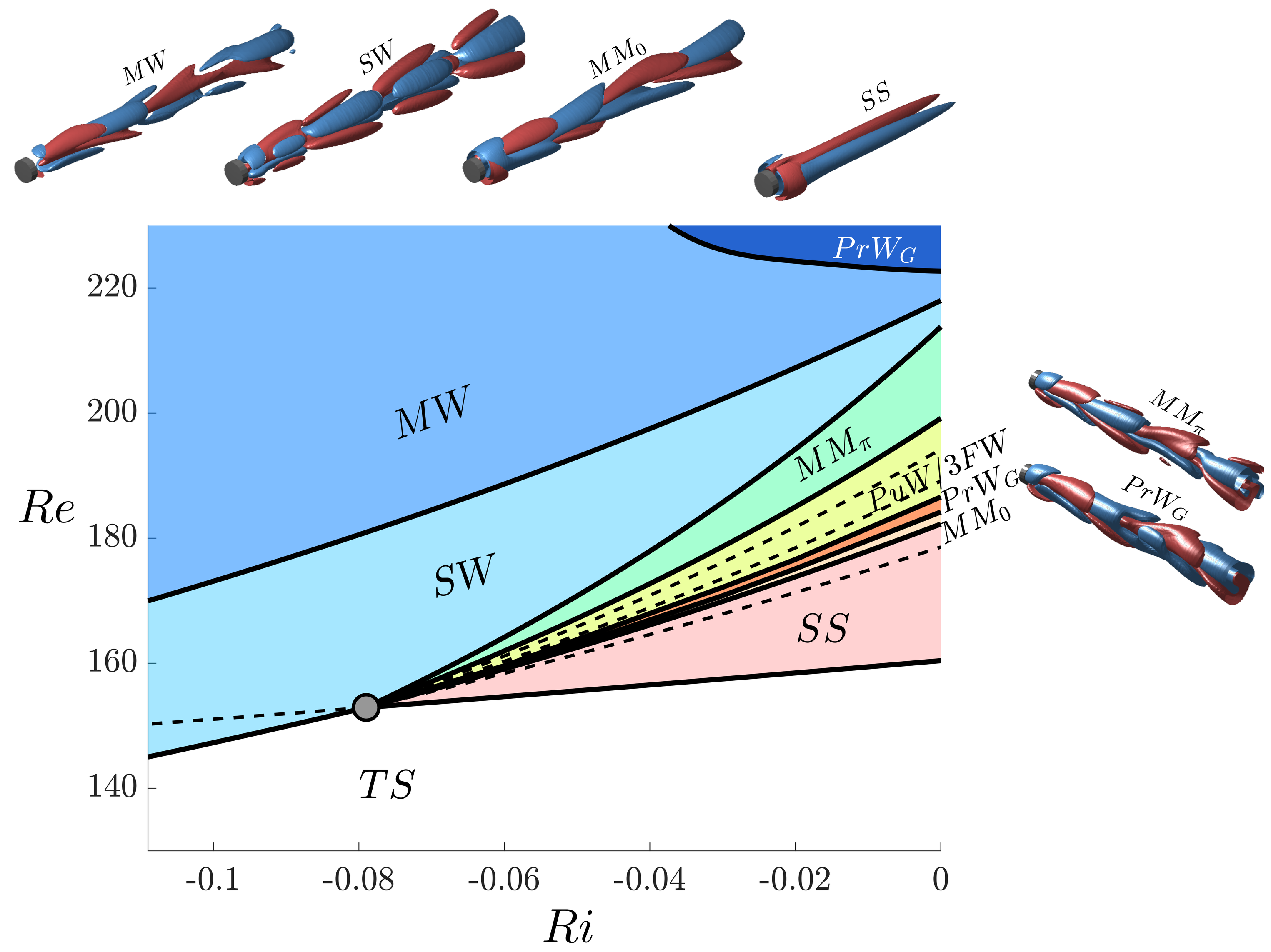
Acoustics

Our focus is to understand how fluid dynamics instabilities generate sound. We study two flow configurations. In the first case, we analyse the flow past a circular aperture, which serves as a minimal flow configuration to mimic human phonation. In this case, we provide a criterion for the existence of the flow instability: the frequency of the instability is determined as a zero of the transfer function, the impedance. The continuation of the emerging limit cycle from the self-sustained instability is carried out following a fixed-point method for limit cycles, which also provides information about the sensitivity of the cycle characteristics to localised variations in the flow-field. The second configuration we analyse is the subsonic rounded impinging jet, an important flow configuration in many industrial applications such as the cooling of devices, and for vertical take-off and landing (VTOL) aircraft. Here, we would like to understand which are the fundamental physical mechanisms leading to tonal or broadband sound emissions. For the study of these long-range instabilities (arising due to the interaction of hydrodynamic and acoustic waves), we propose a novel concept for the identification of the flow regions where the feedback loop is initiated and closed. In addition, by analysing how these interactions take place, we can propose a model that faithfully represent the fundamental properties of the sound emissions. Below, we show an example of the flow instability responsible for the sound generation, at a large subsonic Mach number. The instability is supported by two waves, a vortical instability of the shear layer (bottom left figure) and an acoustic wave that lies within the jet (bottom right figure).



Wake and jet flows

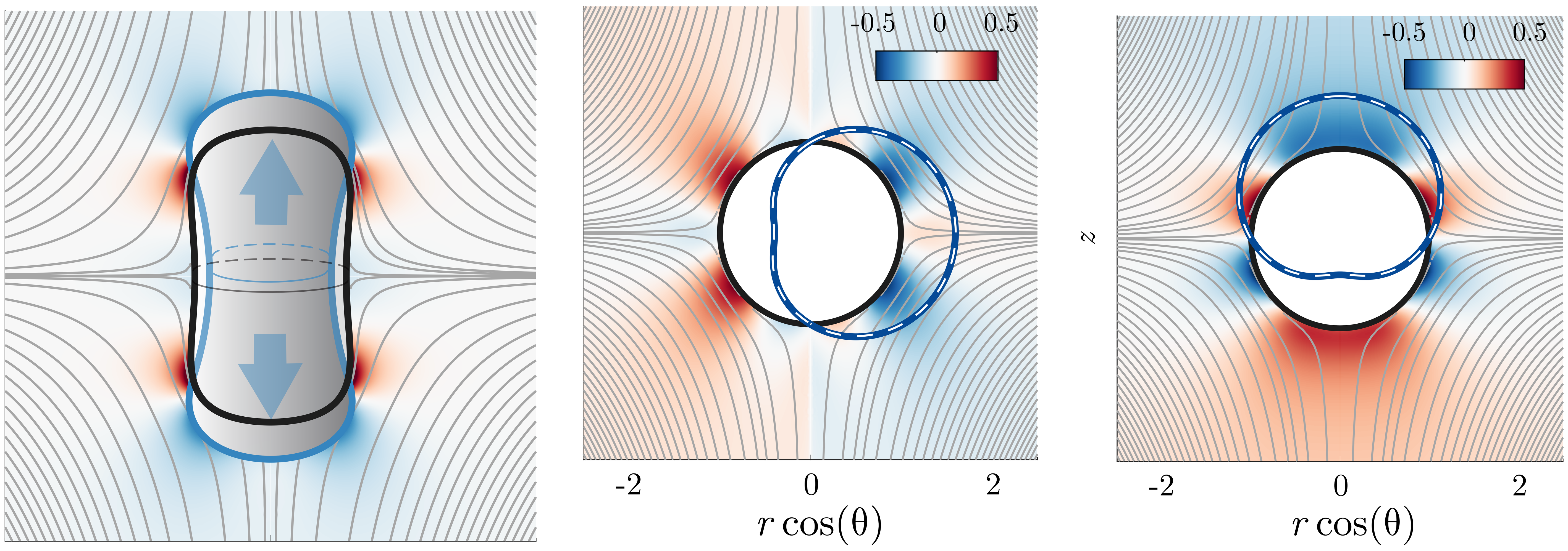
We analyse in four configurations the formation of the coherent structures under the competition/cooperation of multiple flow instabilities, thereby covering most of the conceivable pattern formation scenarios. First, in the flow past a spinning cylinder, which is a canonical configuration of flow control of the vortex-shedding instability, we highlight the existence of an organising centre[a] that rationalises the existence of hysteresis and self-sustained instabilities. Second, we study a flow configuration of two co-axial jets. This flow system exhibits a particular type of symmetry-breaking bifurcation, a steady-steady bifurcation with 1:2 resonance condition[b], which leads to the existence of robust heteroclinic cycles[c]. This is the first time that such solutions have been observed in external flows. Third, we analyse the pattern formation in the wake flow behind a rotating particle, which finds applications in particle-driven flows or fluidized bed combustion. Fourth, we analyse the (bouyancy-driven) wake flow past axisymmetric bodies, whose transition is driven by a steady-Hopf bifurcation, that is, the interaction between a symmetry-breaking instability and an unsteady instability. Below, we provide a classification of the flow patterns for the (bouyant) flow past a disk



[a]A region in the space of parameters, where it is possible to derive a minimal reduced model that mimics the fundamental dynamical properties observed in the system.
[b]Interaction between two flow patterns with wavenumber $m = 1$ and $m = 2$.
[c]Aperiodic solutions which intermittently switch between two attractors.

Moving interfaces

We study two flow problems with moving interfaces: the dynamics of a bubble in a straining flow, and a fluid-structure-interaction (FSI) problem displaying Vortex-Induced-Vibrations (VIV). These problems are challenging from a methodological standpoint. Herein, we explore two numerical methods. The technique of a linearised diffusive Immersed Boundary Method (IBM) for the VIV case, and the linearised Arbitrary Lagrangian Eulerian (L-ALE) technique for the dynamics of the bubble in a straining flow. In particular, we show a novel self-propelled instability of the bubble in this problem (right panel).



Methodology

We employ a set of numerical & theoretical methods to get a fine insight into the physical mechanisms leading to particular dynamical features of the system. These theoretical methods belong to dynamical systems theory and, in particular, to equivariant bifurcation theory, which comprises a series of techniques that allows us to derive reduced equations to study the formation of emergent flow patterns under the competition of several flow instabilities. In the following, a list of the methods employed is presented, altogether with the relevant works that used those techniques. Most of the numerical codes are available in the `StabFem` open-source project.

- Numerical & theoretical methods

1. Global linear stability
   (a) Linear stability from a transfer function [12, 0]
   (b) Sensitivity analysis [5, 3, 6]
   (c) Novel identification of the active flow regions of long-range instabilities based on a decomposed structural sensitivity [1].
2. Harmonic balance & Floquet–Hill Method for the computation and continuation of limit-cycle solutions and the Floquet analysis of incompressible and compressible flow solutions [4, 11].
3. Equivariant normal form theory of the following organizing centres [5, 3, 6, 7, 1].
4. Methods for moving interfaces: Arbitrary Lagrangian Eulerian (ALE) method for the coupling of the incompressible Navier–Stokes equations & interface with a bubble [2]. Immersed Boundary Method (IBM) for the Fluid-Structure-Interaction (FSI) problem involving the coupling of the incompressible Navier–Stokes equations & solid bodies for Vortex-Induced-Vibrations (VIV) [8].

Selected publications

[1] **Sierra-Ausin, J.** and F. Giannetti. "On the linear and nonlinear mechanisms for the tonal and broadband noise of subsonic rounded impinging jets". In: *Journal of Fluid Mechanics (submitted)* (2023).

[2] **Sierra-Ausin, J.**, Paul Bonnefis, Antonia Tirri, David Fabre, and Jacques Magnaudet. "Dynamics of a gas bubble in a straining flow: Deformation, oscillations, self-propulsion". In: *Physical Review Fluids* 7.11 (2022), p. 113603.

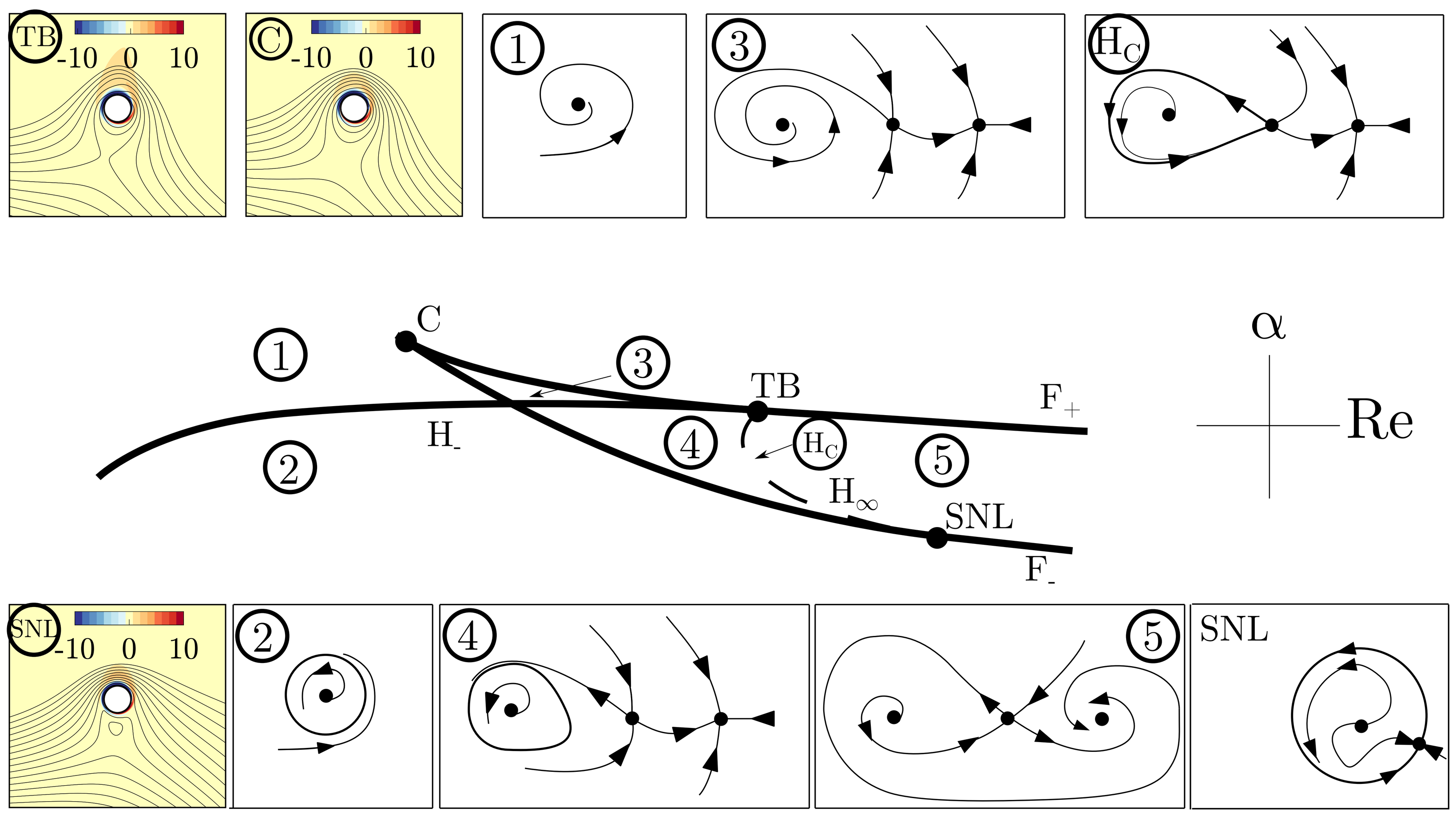
[3] **Sierra-Ausin, J.**, M Lorite-Diez, JI Jimenez-Gonzalez, V Citro, and D Fabre. "Unveiling the competitive role of global modes in the pattern formation of rotating sphere flows". In: *Journal of Fluid Mechanics* 942 (2022).

[4] **Sierra-Ausin, J.**, Pierre Jolivet, Flavio Giannetti, and Vincenzo Citro. "Adjoint-based sensitivity analysis of periodic orbits by the Fourier–Galerkin method". In: *Journal of Computational Physics* 440 (2021), p. 110403.

[5] **Sierra-Ausin, J.**, David Fabre, Vincenzo Citro, and Flavio Giannetti. "Bifurcation scenario in the two-dimensional laminar flow past a rotating cylinder". In: *Journal of Fluid Mechanics* 905 (2020). **Highlighted in Focus of Fluids by** Brøns, Morten. The organizing centre for the flow around rapidly spinning cylinders. *Journal of Fluid Mechanics* 906 (2021): F1.

Main results and achievements

The first case, a degenerate Takens–Bogdanov bifurcation, is actually a codimension-three bifurcation, with an illustration of the parametric portrait showing rich dynamics just below.



Surprisingly, when varying two parameters, we (almost) find numerically a codimension-three bifurcation. The reason behind this anomaly might be the regularity of the Navier–Stokes equation when the Reynolds number tends to zero. The uniqueness of the steady-state solution at this limit constraints the number of steady solutions in the parameter space to be odd; at least when considering the laminar bifurcation problem. This suggests that this kind of degenerate Takens-Bogdanov bifurcation might be more general than it seems for the Navier–Stokes equations. Sierra-Ausin et al. [5][a] provides a rationalisation for the existence of multiple steady states for the flow past a spinning cylinder, a canonical flow configuration conceived for the control of bluff-body instabilities, which are ubiquitous in engineering.
In [3, 1] we study the interaction between three oscillating instabilities, a triple Hopf bifurcation: this case is of relevance for fluid flows interacting with rotating particles, which has applications in multiple practical and natural phenomena like particle-driven flows, fluidized bed combustion, sports aerodynamics or seeds' flight. In, [3] we provide a bifurcation and a parametric portrait of the wake flow behind a rotating sphere. This is an example of the non-resonant case, which arises naturally in fluid flows depending on several parameters and displaying multiple interacting self-sustained instabilities, where the core of the instability or wavemaker of the global modes is localised in space. The resonant case, instead, is relevant for the study of the non-linear interaction between a family of global modes associated to a long-range instability underpinned by a hydro-acoustic feedback-loop. In this case, the core of the instability is not localised in space, and the frequency of the global modes is nearly a multiple of a fundamental pulsation $\Delta\omega$. In [1] we analyse the dynamics of a laminar rounded impinging jet, which exemplifies the resonant-case. Therein, in addition to studying the resonant mode interaction, we propose an acoustic-hydrodynamic decomposition of the structural sensitivity, which serves to identify the spatial localisation of the feedback-loop, which, for instance, could motivate passive control techniques for the noise-reduction of vertical take-off devices.
In [4] we develop a numerical suite based on the Harmonic Balance method for the continuation of the limit cycle of incompressible Navier–Stokes equations. The resulting linear system is subsequently solved with a Newton–Krylov method. The evaluation of the linear stability of the periodic solution is evaluated with the Floquet–Hill method. The sensitivity with respect to frequency variations of the limit cycle and its structural sensitivity is then evaluated. This novel numerical strategy greatly simplifies the numerical burden required for an efficient evaluation of the wavemaker of the instability with respect to time-stepping approaches.
Finally, in the work [2] we analyse the linear stability of a bubble suspended in an axisymmetric uniaxial straining flow using a recently developed Linearized Arbitrary Lagrangian-Eulerian (L-ALE) approach. We compute the steady equilibrium states and associated bubble shapes. And we subsequently evaluate the stability of the bubble-flow configuration, which lead us to the finding of a novel physical result, the existence of an instability leading to a self-propelled motion of the bubble.

[a] This work was highlighted in Focus of Fluids by Brøns (2021).

Other publications

[6] A. Corrochano, **Sierra-Ausin, J.** ., J. A. Martin, D. Fabre, and S. Le Clainche. "Mode selection in concentric jets with resonance 1:2". In: *Journal of Fluid Mechanics (accepted)* (2023).

[7] **Sierra-Ausin, J.**, D. Fabre, and E. Knobloch. "A Note on the steady-state mode and Hopf mode interaction in the presence of O(2)-symmetry". In: *Phys. Rev. E (submitted)* (2023).

[8] Antonia Tirri, Alessandro Nitti, **Sierra-Ausin, J.**, Flavio Giannetti, and Marco D de Tullio. "Linear stability analysis of fluid–structure interaction problems with an immersed boundary method". In: *Journal of Fluids and Structures* 117 (2023), p. 103830.

[9] Gonzalo Sáez-Mischlich, **Sierra-Ausin, J.**, and Jérémie Gressier. "The Spectral Difference Raviart–Thomas Method for Two and Three-Dimensional Elements and Its Connection with the Flux Reconstruction Formulation". In: *Journal of Scientific Computing* 93.2 (2022).

[10] Gonzalo Sáez-Mischlich, **Sierra-Ausin, J.**, Gilles Grondin, and Jérémie Gressier. "On the properties of high-order least-squares finite-volume schemes". In: *Journal of Computational Physics* 457 (2022), p. 111043.

[11] **Sierra-Ausin, J.**, Vincenzo Citro, Flavio Giannetti, and David Fabre. "Efficient computation of time-periodic compressible flows with spectral techniques". In: *Computer Methods in Applied Mechanics and Engineering* 393 (2022), p. 114736.

[12] **Sierra-Ausin, J.**, D Fabre, V Citro, and F Giannetti. "Acoustic instability prediction of the flow through a circular aperture in a thick plate via an impedance criterion". In: *Journal of Fluid Mechanics* 943 (2022).

[13] V Citro, F Giannetti, and **Sierra-Ausin, J.** "Optimal explicit Runge-Kutta methods for compressible Navier-Stokes equations". In: *Applied Numerical Mathematics* 152 (2020), pp. 511–526.

[14] **Sierra-Ausin, J.**, David Fabre, and Vincenzo Citro. "Efficient stability analysis of fluid flows using complex mapping techniques". In: *Computer Physics Communications* 251 (2020), p. 107100.

[15] D. Fabre, V. Citro, D. Ferreira Sabino, P. Bonnefis, **Sierra-Ausin, J.**, F Giannetti, and M Pigou. "A practical review on linear and nonlinear global approaches to flow instabilities". In: *Applied Mechanics Reviews* 70.6 (2018).