9th International Symposium on Bifurcations and Instabilities in Fluid Dynamics

Tuesday 16–Friday 19 August 2022
University of Groningen
The Netherlands

Local organising committee

- Fred Wubs
- Alef Sterk
- Martin Sanders
- Sarah van Wouwe

Advisory committee

- Zvi Pinhas Bar-Yoseph (Technion)
- Morten Brøns (Technical University of Denmark)
- Alexander Gelfgat (Tel Aviv University)
- Alexander Oron (Technion)

Sponsors

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- Dutch Research Council (NWO)
- Maritime Research Institute Netherlands (MARIN)
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Conference venue

Important: the venue on Wednesday differs from Tuesday, Thursday, and Friday!

Tuesday, Thursday, Friday

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Street address:
University of Groningen
Harmonie building
Oude Kijk in Het Jatstraat 26
9712 EK Groningen

Rooms:
1314.0026 and 1314.0014

The rooms can be found by turning left when underneath the three arches.

Wednesday

Street address:
University of Groningen
Academy building
Broerstraat 5
9712 CP Groningen

Rooms:
Heymanszaal and room A2

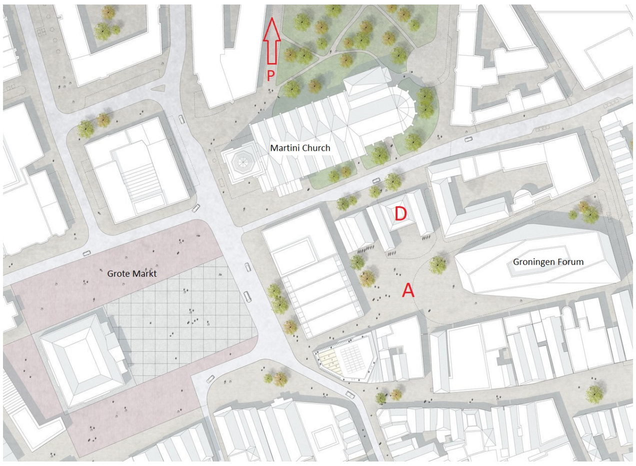
The rooms can be found by turning right after entering the building via the front steps.

Location of welcome reception

Street address:
Prinsenhof
Martinikerkhof 23
9712 JH Groningen

The location can be found by following the arrow which is marked by a "P" on the map.

Location of conference dinner



Street address:
Restaurant "Feithhuis"
Martinikerkhof 10
9712 JG Groningen

The address refers to the *backside* of the restaurant. The restaurant is marked by a "D" on the map. You can enter the restaurant via the square marked "A" (between The Market Hotel and Groningen Forum).

Assembly point city walk

The walk will start at 17.00h. Please gather around 16.50h at the assembly point marked "A" above. The tour guides are wearing green jackets. Each tour guide will take a group of approximately 20 people. The walk finishes at the same location.

Birds eye view of the programme

	Tue 16 August		Wed 17 August		Thu 18 August		Fri 19 August	
	Harmonie building, room 1314.0026	Harmonie building, room 1314.0014	Academy building, Heymanszaal	Academy building, room A2	Harmonie building, room 1314.0026	Harmonie building, room 1314.0014	Harmonie building, room 1314.0026	Harmonie building, room 1314.0014
8:40	Badge pickup							
9:00			P4	P3	Keynote lecture:		Keynote lecture:	
9:20	Opening		P4	P3	Andrew Hazel		Henk Dijkstra	
9:40	Keynote lecture:		P4	P9				
10:00	Karin Jacobs		P4	P7	Poster pitches		P8	
10:20			P4	P8			P8	
10:40	Coffee break		Coffee break		Coffee break		Coffee break	
11:00						Poster session		
11:20	P5	P1	P4				P8	
11:40	P5	P1	P4				P8	
12:00	P5	P1	P4		P6		P8	
12:20	P5	P1	Next edition		P6		P8	
12:40	P5	P1			P6		Closing	
13:00	Lunch break		Lunch break		Lunch break			
13:20								
13:40								
14:00								
14:20								
14:40	P5	P1	Time for collaborations		P6	P2		
15:00	P5	P1			P6	P2		
15:20	P5	P1			P6	P2		
15:40	P5	P1			P6	P2		
16:00	Coffee break				Coffee break			
16:20								
16:40	P5	P1			P6	P2		
17:00	P5	P1	City walk		P6	P2		
17:20		P1			P6			
17:40		P1			P6			
18:00		P1						
18:20								
18:40	Welcome reception		Dinner					
19:00								
19:20								
19:40								
20:00								
20:20								
20:40								
21:00								

Key:

- P1: Films, drops and liquid bridges
- P2: Magneto- and electrohydrodynamics
- P3: Active fluids: biophysical fluids, reacting flows, crystal growth
- P4: Computational, numerical and analytical methods
- P5: Flows driven by buoyancy, density gradients and/or Marangoni effect
- P6: Mechanically-driven flows
- P7: Bifurcating flows in labs and applications, experimental methods
- P8: Control of instabilities and parametric excitations
- P9: Miscellaneous

Tuesday 16 August

	Harmonie building, room 1314.0026	Harmonie building, room 1314.0014
8:40-9:20	**Badge pickup**	
9:20-9:40	**Opening**	
9:40-10:40	**Karin Jacobs** — Instabilities and bifurcations: the good, the bad and the beauty	
10:40-11:20	**Coffee break**	
	P5 (chair: Henk Dijkstra)	P1 (chair: Michael Grinfeld)
11:20-11:40	**Fred Feudel** — The influence of a differential rotation on bifurcations of buoyancy driven spherical shell convection	**Eugene Benilov** — Dynamics of a drop floating in vapor of the same fluid
11:40-12:00	**Julian Koellermeier** — Equilibrium manifolds and stability analysis of extended shallow water models	**Alexander Oron** — Buoyancy instabilities in a liquid layer subjected to an oblique temperature gradient
12:00-12:20	**Jonathan Demaeyer** — Global bifurcation of Shilnikov type in a low-order coupled ocean-atmosphere model	**Michael Bestehorn** — Hopf instability of a Rayleigh-Taylor unstable thin film heated from the gas side
12:20-12:40	**Oisin Hamilton** — Investigating the impacts of non-linearised temperature equations in a low-order quasi-geostrophic model	**Alexander Nepomnyashchy** — Dynamics and instabilities of non-isothermal floating droplet
12:40-13:00	**Katia Ali Amar** — Combined effects of viscous dissipation and Soret effect on mixed convection of Poiseuille flows of binary fluid mixtures	**Stephen Wilson** — Rivulet flow over and through a permeable membrane
13:00-14:40	**Lunch break**	
	P5 (chair: Fred Feudel)	P1 (chair: Eugene Benilov)
14:40-15:00	**Alexander Mikishev** — Modulated patterns in Marangoni convection with deformable surface covered by surfactant	**Michael Grinfeld** — Perfectly wetting pendent steady rivulets on an inclined plane
15:00-15:20	**Ilias Sibgatullin** — Wave attractors in large aspect ratio domains	**Thomas Corbin** — Effect of a deep periodic corrugated wall on Faraday instability of an interface
15:20-15:40	**Antoine Meyer** — Stability of a dielectric liquid confined in a differentially heated vertical Taylor-Couette system with applied radial electric field	**Lennon Ó Náraigh** — A cross-validation study of computational methods for droplet impact
15:40-16:00	**Giuseppe Arnone** — Density inversion phenomenon in porous penetrative convection	**Patricia Pfeiffer** — Merging of bubbles in Newtonian and non-Newtonian liquids
16:00-16:40	**Coffee break**	
	P5 (chair: Julian Koellermeier)	P1 (chair: Michael Bestehorn)
16:40-17:00	**Jacopo Alfonso Gianfrani** — The weakly nonlinear Sutton problem: the transition between the Darcy-Bénard problem and the Wooding problem	**Eugene Benilov** — Condensation of vapour in a corner formed by two walls
17:00-17:20	**Lekha Sharma** — Effect of horizontal aspect ratio on magnetoconvective instabilities in liquid metals	**Khang Ee Pang** — A mathematical model and mesh-free numerical method for contact-line motion in lubrication theory
17:20-17:40		**Luca Biancofiore** — Spatiotemporal evolution of evaporating liquid films sheared by a gas
17:40-18:00		**Rodica Borcia** — Phase field modelling in liquid binary mixtures: isothermal and non-isothermal problems
18:00-18:20		**Teng Dong** — Partial coalescence of aqueous droplets on liquid-liquid interfaces
18:30-20:30	**Welcome reception**	

Wednesday 17 August

	Academy building, Heymanszaal	Academy building, room A2
	P4 (chair: Yuri Feldman)	P3, P9, P7, P8 (chair: Uwe Thiele)
9:00-9:20	**Lou Kondic** — Instabilities and dewetting of nematic liquid crystal films	**Alexander Morozov** — Strong correlations and the origin of collective motion in dilute microswimmer suspensions
9:20-9:40	**Yakov Nezhihovski** — Experimental measurements versus linear stability analysis for primary instability of stratified two-phase flows in a square rectangular duct	**Uwe Thiele** — Homoclinic snaking and emergence of oscillations in Cahn-Hilliard and phase-field-crystal systems with nonreciprocal coupling
9:40-10:00	**Patrick Farrell** — Computing disconnected bifurcation diagrams with deflation	**Ganlin Lyu** — Studies of disturbance growth in transonic boundary layers over complex geometries using embedded DG simulations
10:00-10:20	**Nicolas Boullé** — Optimal control of bifurcation structures	**Didzis Berenis** — Numerical simulations on bifurcations and experiments on bi-stability in forced transparent electrolyte flow in a ring-shaped container
10:20-10:40	**Sven Baars** — FVM: a parallel Python package for bifurcation problems in incompressible flows	**Johann Herault** — Parametric instability of a snake-like robot on the water surface
10:40-11:20	**Coffee break**	
	P4 (chair: Alexander Gelfgat)	
11:20-11:40	**Yuri Feldman** — Fully-implicit direct forcing immersed boundary method: SIMPLE-Schur complement approach	
11:40-12:00	**Darío Martínez Martínez** — A Schwarz domain decomposition method applied to the Rayleigh-Bénard convection problem	
12:00-12:20	**Ilya Barmak** — Instability of two-phase stratified pipe flows	
12:20-12:40	**Stephen Wilson** — Announcement next BIFD conference	
13:00-14:40	**Lunch break**	
14:40-16:40	**Time for collaborations and networking**	
17:00-18:30	**City walk**	
18:30-21:00	**Dinner**	

Thursday 18 August

	Harmonie building, room 1314.0026	Harmonie building, room 1314.0014
9:00-10:00	**Andrew Hazel** — Bubbly bifurcations	
10:00-10:40	**Poster pitches**	
10:40-11:20	**Coffee break**	
11:20-12:00		**Poster session** **Ajay Chatterjee** — A three-dimensional branching flow with a surface perturbation **Jakub Fabisiak** — Low-Reynolds number mixing and hydrodynamic instability in the presence of non-symmetric wall corrugation **Lou Kondic** — Dielectrowetting of a thin nematic liquid crystal layer **Vivaswat Kumar** — Experimental investigation of the nutation angle's effect on the flow inside a precessing cylinder **Michele Pellegrino** — Molecular simulations of shear-induced critical transitions for confined nanodroplets **Ilias Sibgatullin** — Dynamics of $(n, 1)$ wave attractors **Teke Xu** — Lax-Wendroff scheme on Saint-Venant equation with dynamical boundary conditions and non-linearity
	P6 (chair: Fred Wubs)	
12:00-12:20	**Marine Aulnette** — Non-linear wind waves over a highly viscous liquid	
12:20-12:40	**Miguel Bustamante** — On the role of continuous symmetries in the solution of the 3D Euler fluid equations and related models	
12:40-13:00	**Yohann Duguet** — The concept of edge state in the presence of a linear instability	
13:00-14:40	**Lunch break**	
	P6 (chair: Andrew Hazel)	P2 (chair: Alfaisal Hasan)
14:40-15:00	**Paolo Falsaperla** — Stability of Bingham flow in an inclined channel	**Mattias Brynjell-Rahkola** — Edge states in ducts subject to transversal magnetic fields
15:00-15:20	**Daniel Andrés Mora Paiba** — Three-dimensionality of the triadic resonance instability of a plane inertial wave	**Cyril Courtessole** — Relaminarization of magneto-convective flow around a pair of submerged differentially heated cylinders
15:20-15:40	**Alexander Morozov** — Time-dependent 3D dynamics in viscoelastic pressure-driven channel flow	**Ilke Kaykanat** — Thermocapillary and electrohydrodynamic instability of trilayer flow in a microchannel
15:40-16:00	**Péter Tamás Nagy** — The investigation of the enstrophy growth at the energy stability limit in the plane channel flow	**Ashish Mishra** — Nonlinear simulations of magnetorotational instability: scaling properties and their importance in upcoming DRESDYN-MRI experiment
16:00-16:40	**Coffee break**	
	P6 (chair: Miguel Bustamante)	P2 (chair: Mattias Brynjell-Rahkola)
16:40-17:00	**Juan Pimienta** — Characterization and evolution of the recirculation bubble of a backward-facing step flow through different Reynolds number	**Alfaisal Hasan** — Electrogravitational stability of an oscillating streaming fluid cylinder
17:00-17:20	**Lohengrin Van Belle** — Structures of non-buoyant round jets subjected to background rotation	**Bernard Knaepen** — Onset of instability in the magnetohydrodynamic pipe flow subject to a transverse magnetic field
17:20-17:40	**Michael Zaks** — Transport anomalies in steady plane flow patterns with degenerate stagnation points	
17:40-18:00	**Akankshya Majhi** — Coupling flow directions in emulsions with wall roughness	

Friday 19 August

	Harmonie building, room 1314.0026	Harmonie building, room 1314.0014
9:00-10:00	**Henk Dijkstra** — Bifurcation analysis of ocean flows	
	P8 (chair: Oz Oshri)	
10:00-10:20	**Ion Dan Borcia** — Resonance on surface waves in a circular channel	
10:20-10:40	**Juan Marin** — Drift instabilities in localised Faraday patterns	
10:40-11:20	**Coffee break**	
	P8 (chair: Ion Dan Borcia)	
11:20-11:40	**Oz Oshri** — Dynamic response of a laterally compressed sheet in a closed fluid contained chamber	
11:40-12:00	**Sebastian Richter** — Direct numerical simulation of liquid films on a non-planar substrate under external vibration	
12:00-12:20	**Julien Sablon** — Modal and nonmodal stability of variable-density trailing vortices	
12:20-12:40	**Jishen Zhang** — Wind wave growth over a viscous liquid	
12:40-12:50	**Closing**	

Key note lectures

Instabilities and bifurcations: the good, the bad and the beauty

Karin Jacobs — Saarland University

“What are you researching?” – “Instabilities and bifurcations!” – “Instabilities? You mean risk analyses?” Small talk like this is something many of us may have had before. Dealing with “instabilities” sounds weak, fragile, and a bit pessimistic, too. “Bifurcations,” on contrast, sounds stronger, more promising (because unknown?), and more optimistic. Yet in our research work, neither of these attributes are there.

As an experimentalist, I come more in contact with “instabilities”, and having been in this “business” for more than two decades, I suffer from a “déformation professionelle” and see instabilities everywhere. Is that a good thing or a bad thing? Depends on to whom you are talking...

However, instabilities in experiments or simulations often carry an irresistible beauty. That’s what happened to me when I saw “my first instability”: a dewetting thin polymer film. The analysis took some time, but the result is still important to my research today! Multiple instabilities are for instance also involved in bacterial adhesion, which in my group is characterized by atomic force microscopy in single-cell force spectroscopy mode. So I’ll take you on a journey through the good, the bad, and the beauty of instabilities!

Bubbly bifurcations

Andrew Hazel — University of Manchester
(Co-authors: Anne Juel, Alice Thompson, Andres Franco-Gomez, Antoine Gaillard, Jack Keeler, Jack Lawless, Gregoire Lemoult)

The behaviour of fluids is beautiful, complex and difficult to predict. If a viscous liquid containing gas bubbles is driven through a confined geometry, it exhibits complex nonlinear behaviour, even in the absence of fluid inertia. The behaviour is driven by interaction between the geometry, capillary forces at the liquid-gas interface, and viscous forces within the bulk liquid. The system is relatively simple, yet it exhibits a remarkable variety of nonlinear phenomena, making it ideally suited to studies of bifurcations and instabilities in fluid dynamics.

At the Manchester Centre for Nonlinear Dynamics, we use a combined experimental and theoretical approach to study such flows through Hele-Shaw channels with small axially-uniform variations in channel depth. From a theoretical point of view, the system is attractive because it can be accurately described by depth-averaged equations. Moreover, the state of the system is characterised by the bubbles’ shapes and relative locations within the channel, which are easy to access experimentally. An unusual feature of the system is its frequent topology changes as bubbles break up into smaller bubbles that can later recombine or not. Topology changes alter the entire solution structure, meaning that a single bifurcation diagram cannot capture the system’s dynamics. For a fixed set of control parameters (e.g. flow rate and total bubble volume) the solution structure can change several times over the course of an experiment. In addition, the system shows heightened sensitivity to perturbations in regimes where the bubble is likely to break up. We find multiple steadily propagating and oscillatory states, regions of multi-stability and practical unpredictability, where the final outcome is extremely sensitive to minor perturbations.

We use numerical bifurcation techniques to determine the structures that organise the dynamics of the system, including key roles played by unstable periodic orbits and weakly unstable steadily propagating solutions. We find a strong correspondence between single and multiple bubble solutions which allows us to predict and construct non-trivial stable multi-bubble states. Although our interest in these systems is motivated by the desire to understand complex nonlinear dynamics, there are applications to microfluidics. In this talk, I will present a survey of what we know about the system so far, it’s connection to other interfacial flows and present some of the open challenges.

Bifurcation analysis of ocean flows

Henk Dijkstra — Utrecht University

The global ocean circulation is a complex three-dimensional flow, but it can roughly be described by a mostly wind-driven surface flow and a density affected overturning flow. Each of these components is susceptible to large-scale instabilities due to the existence of several feedbacks.

In this talk, I will give an overview of these instability phenomena and the numerical techniques to determine the associated bifurcations, with a focus on the western boundary currents (e.g. the Gulf Stream) and the Atlantic Meridional Overturning Circulation.

P1 Films, drops and liquid bridges

Dynamics of a drop floating in vapor of the same fluid

Eugene Benilov — University of Limerick

Evaporation of a liquid drop surrounded by either vapor of the same fluid, or vapor and air, is usually attributed to vapor diffusion – which, however, does not apply to the former setting, as pure fluids do not diffuse. The present paper puts forward an additional mechanism, one that applies to both settings. It is shown that disparities between the drop and vapor in terms of their pressure and chemical potential give rise to a flow. Its direction depends on the vapor density and the drop's size. In undersaturated and saturated vapor, all drops evaporate – but in oversaturated (yet subspinodal) one, there exists a critical radius: smaller drops evaporate, larger drops act as centers of condensation and grow. The developed model is used to estimate the evaporation time of a drop floating in saturated vapor. It is shown that, if the vapor-to-liquid density ratio is small, so is the evaporative flux – as a result, millimeter-sized water drops at temperatures lower than 70°C survive for days. If, however, the temperature is comparable (but not necessarily close) to its critical value, such drops evaporate within minutes. Micron-sized drops, in turn, evaporate within seconds for all temperatures between the triple and critical points.

Condensation of vapour in a corner formed by two walls

Eugene Benilov — University of Limerick

The dynamics of saturated vapour between two intersecting walls is examined. It is shown that, if the angle φ between the walls is sufficiently small, the vapour becomes unstable, and spontaneous condensation occurs in the corner, similar to the so-called capillary condensation of vapour into a porous medium. As a result, an ever-growing liquid meniscus develops near the corner. The diffuse-interface model and the lubrication approximation are used to demonstrate that the meniscus grows if and only if $\varphi + 2\theta < \pi$, where θ is the contact angle corresponding to the fluid/solid combination under consideration. This criterion has a simple physical explanation: if it holds, the meniscus surface is concave—hence, the so-called Kelvin effect causes condensation. If the near-vertex region of the corner is smoothed, the instability can be triggered off only by finite-size perturbations, including enough liquid to cover the smoothed aria by a microscopically-thin liquid film.

Hopf instability of a Rayleigh-Taylor unstable thin film heated from the gas side

Michael Bestehorn — BTU Cottbus-Senftenberg
(Co-authors: Alex Oron)

A thin liquid film located on the underside of a horizontal solid substrate can be stabilized by the Marangoni effect if the liquid is heated from the free surface. Applying long wave approximation and projecting the velocity and temperature fields onto low-order polynomials, we derive a dimension-reduced set of three coupled model equations where nonlinearities in both the Navier-Stokes and the heat equation are considered. We have found that in a certain range of fluid parameters and layer depths the first instability is oscillatory and sets in with a finite but small wave number. The oscillatory branch is computed by a linear stability analysis of the long wave model but also by solving the linearized hydrodynamic original equations. Finally, numerical solutions in three spatial dimensions of the reduced nonlinear model equations are presented.

Spatiotemporal evolution of evaporating liquid films sheared by a gas

Luca Biancofiore — Bilkent University
(Co-authors: Omair A.A. Mohamed, Michael C. Dallaston)

Evaporating liquid films have many important technological applications across a wide range of industries e.g., in distillation, combustion, and chemical synthesis, among many others. The evolution of the liquid film's interface is tied directly to the performance and efficiency of these systems, which, if enhanced, can result in large economic and environmental gains. The spatiotemporal evolution of an evaporating liquid film subjected to a shearing gas was investigated, where both thermal and inertial instability modes were considered where the shearing gas's role was modeled by prescribing a constant shear stress along the liquid interface. Following Joo et al. (JFM, 1991), long-wave theory was applied to derive a "Benney-like" equation governing the evolution of the liquid interface under the effects of inertia, hydrostatic pressure, surface tension, thermocapillarity, evaporation, and gas shear. Linear stability theory was used to investigate the temporal and spatiotemporal properties of the flow, where it was found that the evaporation of the film can cause convective/absolute transitions in the nature of the perturbations. It was also found that a strong enough counter-flowing shearing gas can suppress the inertial instability mode, confirming similar results found by previous studies for a strongly confined film (Lavalle et al., JFM, 2019). In the nonlinear regime, the liquid interface's governing equation was solved numerically to simulate the film's evolution subject to finite perturbations. This was followed by a nonlinear numerical spatiotemporal analysis where we found the wave-front dynamics to be dictated nonlinearly (linearly) for weak (strong) thermal instabilities. Finally, we investigated the role of the dimensionless shear stress, among other parameters, on the film's rupture mechanism through an analytical self-similarity analysis, which was subsequently validated by comparison to rescaled numerical evolution interface data.

Phase field modelling in liquid binary mixtures: isothermal and non-isothermal problems

Rodica Borcia — BTU Cottbus-Senftenberg
(Co-authors: Ion Dan Borcia, Michael Bestehorn, Deewakar Sharma, Sakir Amiroudine)

Based on the conservative phase field model developed by Lowengrub and Truskinovsky [Proc. R. Soc. Lond A 454, 2617 (1998)] for almost incompressible liquid binary mixtures, we propose an extended scheme for studying immiscible/miscible liquids. Below a critical temperature T_c, the liquids are immiscible with separating interfaces. Above T_c, the interfacial effects vanish and the liquids become perfectly miscible. The free energy density of the system depends not only on the phase field variable (which describes the system composition) but also on the reduced temperature $r = (T_c - T)/T_c$ which measures the distance to the critical point described by T_c. The free energy suffers transformations through Tc in a way to permit a two-phase system in the subcritical (immiscible) regime and a mono phase in the supercritical (miscible) regime. Numerical simulations in two spatial dimensions have been performed for isothermal problems (with r as control parameter) as well as for non-isothermal problems with the energy equation describing the temperature distribution. These simulations reveal the behavior of liquid mixtures and droplet coalescence placed in temperature gradients with temperatures continuously varying from $T < T_c$ to $T > T_c$, problems that could be of large interest in phase transitions in micro- and nanofluidics.

Partial coalescence of aqueous droplets on liquid-liquid interfaces

Teng Dong — University College London
(Co-authors: Qianyi Chen, Panagiota Angeli)

Often, when a droplet approaches and contacts a liquid-liquid interface it does not completely merge with its homophase, but leaves secondary droplets behind, resulting in partial coalescence. The phenomenon can repeat itself several times producing different sizes of daughter droplets and extending the whole coalesce time, which brings challenges in processes such as the separation of oil/water dispersions in liquid/liquid coalescers. There has been a lot of studies on this topic but the mechanism of coalescence is still not well understood. In this work, a 2 dimensional high-speed PIV study was carried out on the coalescence of mm size aqueous droplets at the interface of liquid/liquid systems. To match the refractive index, a 0.65 cst Silicone oil was chosen as organic liquids while the aqueous phase was a glycerol/water mixture at a volume concentration of 33%. By analysing the velocity fields as well as the morphology of the coalescing droplet, a hypothesis was suggested to explain the partial coalescence phenomenon. The pressure fields, the strain rate field, and the shear field were extracted from the original PIV velocity data to further discover the mechanism of partial coalescence. It was found that the horizontal stress due to the Laplace pressure that acts on the droplet liquid favours the generation of a liquid cylinder, while the subsequent pinch-off is promoted by the pressure distribution in the droplets. Simulations were conducted on the same liquid system as the experiments using the VOF model. The initial shapes of the deformed droplet and the phase interface from the experiments were used to initialize the simulation. The advantages and shortcomings of applying 2D PIV in the study of 3-dimensional coalescence were discussed.

Perfectly wetting pendent steady rivulets on an inclined plane

Michael Grinfeld — University of Strathclyde

We consider the existence of perfectly wetting pendent steady rivulets of Newtonian fluid flowing down an inclined plane. We work in the lubrication approximation framework without neglecting curvature effects. We use classical differential equations analysis techniques such as the Liapunov-Schmidt reduction and time maps, and compare our results to those obtained by using linearized equations. We will also briefly consider the non-perfectly wetting case.

Effect of a deep periodic corrugated wall on Faraday instability of an interface

Thomas Corbin — University of Florida
(Co-authors: Ranga Narayanan, B. Dinesh)

The natural frequency of a bilayer of liquids is known to depend primarily on the density difference of the fluids, the interfacial tension between them and the wave number of the disturbances that cause flow oscillations. In addition to these, the morphology of the walls bounding the bilayer can also be expected to influence the natural frequency. In this study, computations arising from a reduced-order model are used to show that a deep corrugated wall lowers the natural frequency. These theoretical findings are qualitatively validated by physical experiments that use parametric excitation over frequency ranges to obtain different interfacial modes. As a consequence of the shift of the natural frequency, theoretical calculations also show a shift in the instability regions when fluid layers are subject to Faraday excitation, suggesting that wavy walls can either raise or lower the Faraday instability threshold compared to the flat-wall case, depending on the parametric excitation frequency.

Dynamics and instabilities of non-isothermal floating droplet

Alexander Nepomnyashchy — Technion – Israel Institute of Technology
(Co-authors: Ilya Simanovskii)

Droplets on a liquid substrate ("liquid lenses") play an important role in various branches of engineering, including microfluidics, chemical engineering, environment protection, etc. In applications, it can be necessary to change the shape of floating droplets or move them in a controllable way. The simplest way to influence a liquid droplet is heating which creates Marangoni convection in the droplet and in the liquid substrate. In the present talk, we consider a droplet of a liquid that floats on the layer of another liquid when being in contact with the gas phase. Assuming that the liquid droplet is slender because of a small (negative) spreading coefficient or because of the action of gravity, we apply the long-wave approximation that allows to reduce the problem to a closed system of equations that govern the evolution of the shapes of interfaces. In the region of the droplet, the top layer has a macroscopic thickness, and it is described by standard thin-film equations. In the precursor, the equations are amended by corresponding disjoining pressures. If the temperature of the substrate is different from that of the gas and the droplet is axisymmetric, a stationary radially symmetric thermocapillary flow, both inside the droplet and in the liquid substrate, is generated. That flow changes the shape of the interfaces, especially that of the interface between the droplet and the substrate. With the enhancement of heating, instabilities are developed. By heating from below, the droplet acts as a seed for the development of the monotonic deformational Marangoni instability of the substrate layer leading to its rupture. Cooling from below can lead to an oscillatory instability of the droplet. That instability manifests itself as a time-periodic or irregular change of the droplet shape. The spatially nonhomogeneous cooling creates a disbalance of thermocapillary stresses that leads to the redistribution of the liquids in the droplet and in the substrate: they become thicker in the colder region and thinner in the hotter region. The temporal modulation of heating also changes the droplet's shape. The internal oscillations are either synchronized to the oscillations caused by the Marangoni number modulation or coexist with them creating quasiperiodic oscillations. The research was supported by the Israel Science Foundation (grant No. 843/18).

A cross-validation study of computational methods for droplet impact

Lennon Ó Náraigh — University College Dublin
(Co-authors: Juan Mairal)

We simulate the impact of millimetre-scale droplets impinging on a surface. The purpose of the simulations is twofold. We aim to confirm if OpenFOAM, an open-source toolbox for the solution of continuum mechanics problems, can be used to simulate droplet impact in the low-Ohnesorge-number (Oh) limit, this is done by cross-validation with respect to the Diffuse Interface Method. Secondly, we aim to validate existing correlations in the literature for the maximum spread of a droplet impacting on a surface, as a function of surface wettability. Overall we find that, in the parameter regime studied ($\mathrm{Oh} \ll 1$ and Weber number $\mathrm{We} = O(1)$), traditional correlations underestimate the importance of viscous dissipation, and new correlations need to be found. We provide such correlations, and validate them for the case of idealized cylindrical droplets and more realistic axisymmetric droplets.

Buoyancy instabilities in a liquid layer subjected to an oblique temperature gradient

Alexander Oron — Technion – Israel Institute of Technology
(Co-authors: Ramkarn Patne)

We investigate the temporal and spatiotemporal buoyancy instabilities in a horizontal liquid layer supported by a poorly conducting substrate and subjected to an oblique temperature gradient (OTG) with horizontal and vertical components, denoted as HTG and VTG, respectively. General linear stability analysis (GLSA) reveals a strong stabilizing effect of the HTG on the instabilities introduced by the VTG for Prandtl numbers $Pr > 1$ via inducing an extra vertical temperature gradient opposing the VTG through energy convection. For $Pr < 1$, a new mode of instability arises as a result of a velocity jump in the liquid layer caused by cellular circulation. A long-wave weakly nonlinear evolution equation governing the spatiotemporal dynamics of the temperature perturbations is derived. Spatiotemporal stability analysis reveals the existence of a convectively unstable long-wave regime due to the HTG. Weakly nonlinear stability analysis reveals the supercritical type of bifurcation changing from pitchfork in the presence of a pure VTG to Hopf in the presence of the OTG. Numerical investigation of the spatiotemporal dynamics of the temperature disturbances in the layer in the weakly nonlinear regime reveals the emergence of travelling wave regimes propagating against the direction of the HTG and whose phase speed depends on Pr. In the case of a small but non-zero Biot number, the wavelength of these travelling waves is larger than that of the fastest-growing mode obtained from GLSA.

A mathematical model and mesh-free numerical method for contact-line motion in lubrication theory

Khang Ee Pang — University College Dublin
(Co-authors: Lennon Ó Náraigh)

We introduce a mathematical model with a mesh-free numerical method to describe contact-line motion in lubrication theory. We show how the model resolves the singularity at the contact line, and generates smooth profiles for an evolving, spreading droplet. The model describes well the physics of droplet spreading–including Tanner's Law for the evolution of the contact line. The model can be configured to describe complete wetting or partial wetting, and we explore both cases numerically. In the case of partial wetting, the model also admits analytical solutions for the droplet profile, which we present here.

Merging of bubbles in Newtonian and non-Newtonian liquids

Patricia Pfeiffer — Otto-von-Guericke Universität Magdeburg
(Co-authors: Claus-Dieter Ohl)

Soap bubbles fascinate children and adults alike due to their beauty and fragility. Furthermore, they play an important role in many industrial applications such as waste water treatment and separation of different liquids. Although soap bubbles are studied for centuries, their coalescence is not very well understood by now. The coalescence of centimeter-sized bubbles in a soap solution is studied with varying soap concentrations. The soap solutions are either Newtonian or non-Newtonian (shear thinning) by adding a polymer to the solution. One bubble is induced from the top and the other from the bottom in a Hele-Shaw cell via a thin capillary. Typically, bubbles form a dimple when they approach each other. This occurs either in case of coalescing soap bubbles in air, entrapping a tiny volume of air, or when bubbles coalesce in a liquid solution, entrapping a tiny volume of the liquid. Due to illumination with monochromatic light in a top/bottom view, interference rings become visible and the thickness of the entrapped volume can be determined. Here, we try to visualize the dimple from the side in a Hele-Shaw cell using diffuse illumination of the bubbles to allow light passing through the whole bubble interface in combination with high-speed imaging of the bubble coalescence. The collision time of the bubbles is analyzed with varying surfactant concentration and their collision velocity. The latter is determined via the optical flow method.

Rivulet flow over and through a permeable membrane

Stephen Wilson — University of Strathclyde
(Co-authors: Abdulwahed S. Alshaikhi, Brian R. Duffy)

Motivated by small-scale natural and industrial processes involving flow over and/or through a layer of a porous medium, a mathematical model for the steady gravity-driven flow of a thin rivulet of fluid with finite width over and through an even thinner permeable membrane is formulated and analysed. The three dimensional shape of the free surface of a rivulet with either fixed semi-width or fixed contact angle is determined, and it is shown how the length, base area and volume of the rivulet on the permeable part of the membrane depend on the physical properties of the system. In particular, whereas there is a physically realisable pendant rivulet solution only if the semi-width does not exceed a critical value, there are physically realisable sessile and vertical rivulet solutions for all values of the semi-width; moreover, a sessile rivulet with fixed semi-width has a finite maximum possible length which is attained in the limit of a wide rivulet.

Alshaikhi, A.S., Wilson, S.K., Duffy, B.R. Phys. Rev. Fluids 6 (10) 104003 (2021) doi: 10.1103/PhysRevFluids.6.104003

P2 Magneto- and electrohydrodynamics

Edge states in ducts subject to transversal magnetic fields

Mattias Brynjell-Rahkola — Technische Universität Ilmenau
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The study of laminar-turbulent transition from a dynamical systems perspective has significantly advanced our understanding of subcritical transition in common hydrodynamic (HD) shear flows such as pipes and channels. In spite of this success, little attention has been paid to these developments in the magnetohydrodynamic (MHD) community, where subcritical transition can be expected in both applications involving liquid metals and astrophysical contexts. In a duct subject to a transverse magnetic field, electromagnetic induction leads to the formation of Hartmann and Shercliff layers on the walls orthogonal and parallel to the field direction, respectively. Traditionally, transition to turbulence in such flows has been characterized by a critical Reynolds number R based on the Hartmann layer thickness, which is the ratio between the Reynolds and the Hartmann number based on the bulk velocity and the duct half width. On the contrary, modern direct numerical simulations (DNS) suggest that transition first takes place in the Shercliff, instead of in the Hartmann layers. Motivated by this slight contradiction in literature, we will revisit the classical MHD duct flow using high-order DNS and concepts originally developed within the HD community. Emphasis is placed on different possible transition routes, as well as the interaction between the different boundary layers, whose relative importance for the flow dynamics may be changed by varying the aspect ratio of the duct, or modifying the Hartmann number (keeping the variable R constant). Since edge states correspond to unstable states that are attracting along the edge manifold, initial conditions that reside close to the edge are expected to resemble edge states during transient times. To address these, the quasi-static MHD approximation (assuming low magnetic Reynolds number) is invoked, wherein a one-way coupling exists between the velocity and the magnetic flux density. The governing electromagnetic equations (i.e. Ohm's law with charge conservation) have been incorporated into the spectral element solver Nek5000, and for edge state calculations, the bisection algorithm is employed. In our contribution, numerical aspects of the quasi-static MHD implementation will be outlined together with the results of the edge tracking. Specifically, edge states in periodic square ducts will be discussed along with their dependence on the magnetic field strength, and domain length.

Relaminarization of magneto-convective flow around a pair of submerged differentially heated cylinders

Cyril Courtessole — Karlsruhe Institute of Technology
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Magnetoconvection is of great interest for engineering applications, in particular in the field of nuclear fusion technology. It has applications in liquid metal breeding blankets such as the water-cooled lead-lithium (WCLL) blanket, which was recently selected as a European candidate for a future DEMO reactor [1]. In this concept, heat conversion is ensured by the eutectic lead-lithium alloy that serves both as breeder material and heat transfer fluid. Power extraction is achieved by water-cooled pipes immersed into the liquid metal, resulting in large temperature gradients driving thermal convection. The latter is opposed by the strong magnetic field that confines the fusion plasma. Blanket engineering requires a good understanding of the combined effects of buoyant and electromagnetic forces on the flow when internal obstacles (pipes) are present. Within this scope, a generic geometry has been selected for studying magneto-convective heat transfer between two differentially heated isothermal horizontal cylinders submerged in the model fluid GaInSn. The experimental volume is confined to a thermally and electrically insulated rectangular box and placed in the gap of a large dipole magnet in the MEKKA laboratory at KIT. The test section is instrumented with a large number of thermocouples on walls and inside the fluid [2]. A parametric study was performed over a range of Grashof numbers $1E6 < Gr < 5E7$ and Hartmann numbers $0 < Ha < 3000$. The former one is a nondimensional measure for the driving temperature difference and the latter for the strength of the applied magnetic field. Results demonstrate braking of convective motion by the electromagnetic force. Depending on the strengths of buoyant and electromagnetic forces, several flow regimes were observed from recorded temperature data. The present work focuses on the relaminarization of buoyant flow by the magnetic field. The analysis of the time-dependent signals indicates that, in the absence of a magnetic field, convection between the pipes is turbulent. By increasing the magnetic field, it is possible to determine the critical Hartmann number beyond which the core flow becomes laminar. [1] Federici et al. "An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort," Fus. Eng. Des., vol. 141, pp. 30-42, 2019. [2] Koehly et al. "Design of a test section to analyze magneto-convection effects in WCLL blankets," Fus. Sci. Tech., vol. 75, pp. 1010-1015, 2019.

Electrogravitational stability of an oscillating streaming fluid cylinder

Alfaisal Hasan — Arab Academy for Science

The electrogravitational instability of an oscillating streaming fluid cylinder surrounded by a selfgravitating tenuous medium pervaded by transverse varying electric field is discussed under the action of selfgravitating, capillary and electro dynamic forces. This has been done for all modes of perturbation. A second order integro-differentialequation of Mathieu type has been derived. Several published works are obtained as limiting cases from the present general one. The model is stable due to the stabilizing effect of the transverse electric field in all modes of perturbation. The capillary force has a strong destabilizing influence on the selfgravitating instability of the model. The streaming has a strong destabilizing effect in all kinds of perturbation.

Thermocapillary and electrohydrodynamic instability of trilayer flow in a microchannel

Ilke Kaykanat — Bogazici University
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Microdroplets can be used as microreactors to reduce the contamination and the use of large amounts of chemical. Microdroplets can also be used for better mixing of reactants. When an electric field is applied to a system of two or more immiscible fluids, the interface(s) may be deflected. This process is known as electrohydrodynamic (EHD) instability. When the system consists of leaky dielectric fluids and the electric field is applied normal to the flat interface between these fluids, the electric field has either a stabilizing or a destabilizing effect depending on the electrical properties of the fluids. The droplet volume is a function of the applied voltage, the flow rates and the physical properties of the fluids, and the interfacial tension, which depends on temperature. The interfacial tension gradients due to temperature fluctuations may cause thermocapillary (TC) instability. Having three immiscible fluids instead of two, provides many advantages. A major application for the third fluid could be to separate plugs of different reagents with different viscosities in channels. The microfluidic plugs dispersed in an immiscible carrier fluid are used in protein crystallization, synthesis of microparticles and double emulsions, enzymatic assays, protein expression, and screening reaction conditions. Thus, the flexibility of controlling the droplet volume plays a crucial role, which can be achieved by combining the TC and EHD effects. In addition, applying electric field and thermal field simultaneously, would reduce the strengths of the fields. In this work, the physical system includes three immiscible, leaky dielectrics, incompressible Newtonian fluids subjected to a pressure-driven base flow in a microchannel. These interfaces can be destabilized in the presence of an externally applied electric field. The walls are kept at constant temperatures. A linear stability analysis is performed. A surface coupled model is used. The important parameters that are analysed are the electric and the Marangoni numbers, the flow rates, the thicknesses, the viscosities and the electrical properties of the fluids.

Onset of instability in the magnetohydrodynamic pipe flow subject to a transverse magnetic field

Bernard Knaepen — Université Libre de Bruxelles
(Co-authors: Y. Velizhanina)

Numerous studies suggest that the hydrodynamic pipe flow is linearly stable, although it has been known since the experiments of O. Reynolds that it may transition to turbulence at finite Reynolds numbers. This apparent contradiction has been resolved using non-modal linear stability analysis and the observation that disturbances of small amplitude can exhibit large transient growth before nonlinear effects induce the flow transition. Classical linear stability and transient growth analyses have been conducted for the magnetohydrodynamic (MHD) pipe flow in the presence of an axial magnetic field by Akerstedt [1]. In that case the magnetic field does not modify the mean velocity profile, but it induces electric currents that lead to Joule dissipation and magnetic damping. For those reasons the magnetic field has a stabilizing effect for this flow configuration. Here we address the stability of the MHD pipe flow subject to a transverse magnetic field. In contrast with the previous case, the mean flow is modified and primarily becomes elongated in the direction of the magnetic field. Moreover, when the pipe's wall is electrically conducting and the magnetic field exceeds a critical value, regions of velocity overspeed arise in the Roberts layers. In the case of the MHD square duct flow, Priede et al. [2] have shown that such mean flow modifications can lead to exponentially growing infinitesimal perturbations. In this work we demonstrate that despite the magnetic damping, this is also the case for the MHD pipe flow with an electrically conductive wall in the presence of a transverse magnetic field. To perform the linear stability analysis we have developed a two-dimensional spectral solver based on Chebyshev and Fourier decompositions. Using this solver, we perform a parametric study by varying the Hartmann number - a measure of the strength of the applied magnetic field - and the pipe's wall electrical conductivity to determine under which conditions the flow becomes linearly unstable. We also present some results concerning the transient growth of perturbations at subcritical Reynolds numbers, and discuss for which values of the parameters it can play a role in the transition.

[1] H. O. Akerstedt, Fluid Dyn. Res., 15 295 (1995).

[2] J. Priede, S. Aleksandrova, and S. Molokov, J. Fluid Mech., 708, 111 (2012).

Nonlinear simulations of magnetorotational instability: scaling properties and their importance in upcoming DRESDYN-MRI experiment

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Magnetorotational instability (MRI) is considered as the most likely mechanism driving angular momentum transport in astrophysical disks. However, despite many efforts, the direct and conclusive experimental evidence of MRI in lab is still elusive. Recently, performing 1D linear analysis of the standard version of MRI (SMRI) between two rotating coaxial cylinders with imposed axial magnetic field, we showed that SMRI can be detected in the context of upcoming new DRESDYN-MRI experiments based on cylindrical MHD Taylor-Couette flow with liquid sodium (Mishra et al. 2022, Phys. Rev. Fluids, submitted). Here, we study the nonlinear evolution and saturation properties of SMRI and analyse its scaling behaviour with respect to various system parameters using the pseudo-spectral code. We did a detailed analysis for the extensive ranges of magnetic Reynolds number $Rm \in (8.5, 33)$, Lundquist number $Lu \in [1.5, 15.5]$ and Reynolds number, $Re \in [10^3, 10^5]$. For fixed Rm, we investigated the nonlinear dynamics of SMRI to very small magnetic Prandtl numbers down to $Pm \sim O(10^{-5})$ typical of liquid metals. For all sets of (Lu, Rm), the time evolution of magnetic energy shows that the exponential growth rate in the simulations coincides reasonably well with the growth rate obtained in our 1D linear stability analysis. Since the magnetic energy of SMRI depends on Rm, the exponential growth rate and saturation energy is smaller for smaller Rm. However, the torque exerted on the cylinders, characterizing angular momentum transport, increases substantially for larger Rm both in exponential growth and saturated state. Normalised turbulent torque in the saturated state, for fixed Rm, increases with increasing Re. We also studied the scaling of magnetic energy and turbulent torque in the saturate state as a function Re and conduct a power law fit of the form aRe^b. For all sets of (Lu, Rm), magnetic energy in the saturated state and normalised turbulent torque appear to form a family of parallel lines for $Re > 1000$ with averaged $b \approx -0.5$ and $b \approx 0.5$, respectively. We also explored the dependence on Lundquist number and magnetic Reynolds number. The scaling laws derived here will be instrumental in subsequent analysis and comparison of numerical results with that obtained from upcoming DRESDYN-MRI experiments for conclusively and unambiguously identifying SMRI in laboratory.

P3 Active fluids: biophysical fluids, reacting flows, crystal growth

Strong correlations and the origin of collective motion in dilute microswimmer suspensions

Alexander Morozov — University of Edinburgh
(Co-authors: Viktor Skultety, Cesare Nardini, Joachim Stenhammar, Davide Marenduzzo)

Recent years witnessed a significant interest in physical, biological and engineering properties of self-propelled particles, such as bacteria or synthetic microswimmers. The main distinction of this 'active matter' from its passive counterpart is the ability to extract energy from the environment and convert it into directed motion. One of the most striking consequences of this distinction is the appearance of collective motion in self-propelled particles suspended in a fluid observed in recent experiments and simulations: at low densities particles move around in an uncorrelated fashion, while at higher densities they organise into jets and vortices comprising many individual swimmers. Here, we present a novel kinetic theory [1] that predicts the existence of strong correlations even below the transition to collective motion. We calculate the velocity-velocity correlation functions and the effective diffusivity of passive tracers, and reveal their non-trivial density dependence. The theory is in quantitative agreement with our recent Lattice-Boltzmann simulations [2] and captures the asymmetry between pusher and puller swimmers below the transition to collective motion. We finish by discussing the influence of strong correlations on the origin of the transition to collective motion.

[1] V Skultety et al., Phys. Rev. X 10, 031059 (2020)

[2] J. Stenhammar et al., Phys. Rev. Lett. 119, 028005 (2017)

Homoclinic snaking and emergence of oscillations in Cahn-Hilliard and phase-field-crystal systems with nonreciprocal coupling

Uwe Thiele — Institut für Theoretische Physik, Universität Münster
(Co-authors: Tobias Frohoff-Hülsmann, Max Holl)

We consider nonreciprocal coupling between the species of a mixture (as a particular type of active media) as modelled by continuum models namely (i) a generic two-field Cahn-Hilliard (CH) model and (ii) a two-field phase-field-crystal (PFC) model. First, we briefly consider the stability and bifurcation behaviour of the CH model in the passive limiting case (only reciprocal coupling). Then we show that in the active case its linear stability can be mapped onto the one of the classical Turing system, i.e., we show that activity not only allows for the usual large-scale stationary (CH) instability of the well-known passive case but also for small-scale stationary (Turing) and large-scale oscillatory (Hopf) instabilities. In consequence of the Turing instability, activity may completely suppress the usual CH coarsening dynamics and result in the emergence of localized patterns. This is supported by a number of bifurcation diagrams that also allow us to discuss the emergence of drifting and oscillatory states. In the second part we show that also for PFC models nonreciprocal coupling may strongly change the bifurcation behaviour of periodic (crystalline) and localized states and can result in the occurrence time-periodic states.

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[2] T. Frohoff-Hülsmann and U. Thiele, Localised States in Coupled Cahn-Hilliard Equations, IMA J. Appl. Math. 86, 924 (2021).

[3] M. P. Holl, A. J. Archer, S. V. Gurevich, E. Knobloch, L. Ophaus, and U. Thiele, Localized States in Passive and Active Phase-Field-Crystal Models, IMA J. Appl. Math. 86, 896 (2021).

P4 Computational, numerical and analytical methods

FVM: a parallel Python package for bifurcation problems in incompressible flows

Sven Baars — University of Groningen
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We will present the Python package FVM (https://github.com/BIMAU/fvm), which contains a continuation code and a set of standard bifurcation problems in fluid dynamics in 2 and 3D, among others lid-driven cavity, Rayleigh-Benard, Taylor-Couette, and differentially heated cavity. These problems are discretized using the finite volume method. FVM can be used as a standalone package, in which case solvers available in scipy will be used, or as an interface with MPI parallel solvers available through Trilinos, such as HYMLS (https://github.com/nlesc-smcm/hymls) and FROSch (https://shylu-frosch.github.io/). These methods allow us to solve 3D problems on fine grids. Both solvers, written in C++, have several design concepts in common: they are based on a domain decomposition approach and make use of parallel linear algebra packages from Trilinos. Moreover, FROSch allows for acceleration by performing local solves on GPUs. Whereas FROSch implements multilevel Schwarz solvers for general linear systems arising from PDEs, HYMLS is a special purpose multilevel solver for finite volume methods on structured grids for solving the incompressible Navier-Stokes equation extended with transport equations. Alongside FVM we also built the Python package JaDaPy (https://github.com/BIMAU/jadapy), which enables us to perform stability analysis during the continuation process by computing eigenvalues with the Jacobi-Davidson method. HYMLS and FROSch can again be used for solving the occurring linear systems. During the presentation, we will discuss the packages and show the results on a number of the above-mentioned problems, including novel results for the differentially heated cavity.

[1] Heinlein, Hochmuth, and Klawonn. Reduced dimension GDSW coarse spaces for Monolithic Schwarz domain decomposition methods for incompressible fluid flow problems, International Journal for Numerical Methods in Engineering, 121(6), 2020, https://doi.org/10.1002/nme.6258.

[2] Baars, van der Klok, Thies and Wubs. A staggered-grid multilevel incomplete LU for steady incompressible flows, International Journal for Numerical Methods in Fluids, 93(4), 2021, https://doi.org/10.1002/fld.4913.

[3] Wubs and Dijkstra, Bifurcation Analysis for Fluid Flows, forthcoming.

Instability of two-phase stratified pipe flows

Ilya Barmak — Tel Aviv University
(Co-authors: Alexander Gelfgat, Neima Brauner)

In this work, we study the instability of two-phase stratified flow in a circular pipe geometry. For this purpose, we formulate and solve numerically in bipolar coordinates the linearized 3D governing equations in each phase, combined with the linearized boundary conditions at the pipe walls and the fluid-fluid interface. To the best of our knowledge, this problem has never been solved before. Previous studies were formulated either in the framework of the simplified mechanistic Two-Fluid models or in the simpler two-plate geometry. However, due to those simplifications, the implications of circular pipe geometry on stability characteristics are still unknown. Only recently, a rigorous stability analysis of two-phase stratified flow in a rectangular duct was reported (Gelfgat et al., 2021). Bipolar coordinates are used since they are convenient for analysing two-phase stratified pipe flows. In these coordinates the pipe walls and a fluid-fluid interface of constant curvature coincide with the coordinate lines. The base flow of the stability analysis is laminar, steady and fully developed, for which there exists an exact closed-form analytical solution (Goldstein et al., 2015). The base flow and the fluid-fluid interface are subject to perturbations of all wavenumbers propagating in the axial direction. The linearized governing equations and boundary conditions for the 3D perturbed flow are formulated as an eigenvalue problem, discretized on a staggered grid using a finite-volume method that we developed for the bipolar coordinate system. The eigenvalue problem is solved by the Arnoldi iteration in the shift-and-invert mode. The numerical solution for the base flow was validated by comparison with the analytical solution. The stability characteristics calculated in bipolar coordinates are validated by comparison with those we obtain independently using the well-established Immersed Boundary Method in Cartesian coordinates. The resulting stability boundaries, the critical perturbations that trigger flow instability and their patterns in the pipe cross section will be reported and discussed for gas-liquid and liquid-liquid stratified pipe flows of particular practical importance.

Optimal control of bifurcation structures

Nicolas Boullé — University of Oxford
(Co-authors: Patrick Farrell, Alberto Paganini, Marie Rognes)

Many problems in engineering can be understood as controlling the bifurcation structure of a given device. For example, one may wish to delay the onset of instability, or bring forward a bifurcation to enable rapid switching between states. In this talk, we will describe a numerical technique for controlling the bifurcation diagram of a nonlinear partial differential equation by varying the shape of the domain or a parameter in the equation. Our aim is to delay or advance a given branch point to a target parameter value. The algorithm consists of solving an optimization problem constrained by an augmented system of equations that characterize the location of the branch points. The flexibility and robustness of the method also allows us to advance or delay a Hopf bifurcation to a target value of the bifurcation parameter, as well as controlling the oscillation frequency. We will apply this technique on systems arising from biology, fluid dynamics, and engineering, such as the FitzHugh–Nagumo model, Navier–Stokes, and hyperelasticity equations.

Computing disconnected bifurcation diagrams with deflation

Patrick Farrell — University of Oxford
(Co-authors: Nicolas Boullé)

The combination of pseudo-arclength continuation with branch switching is very powerful for exploring the bifurcation diagrams of partial differential equations. However, this combination does not detect branches that are disconnected from the initial data, and can thereby miss important solutions. In this work we propose a complementary numerical technique, referred to as deflation, for detecting disconnected branches and computing more complete bifurcation diagrams. In particular, deflation allows for the discovery of disconnected branches without modifying secondary parameters to restore symmetries. Deflation works by modifying the residual of a problem to prevent the convergence of Newton's method to known roots (under mild assumptions). By preventing convergence to known roots, deflation enables the discovery of unknown ones, even from the same initial guess for Newton's method. By combining deflation with continuation methods disconnected branches of bifurcation diagrams may be discovered robustly. We verify the utility of deflation by using it to discover disconnected branches for PDE systems arising in Rayleigh-Bénard convection, Allen-Cahn phase separation, and liquid crystals.

Fully-implicit direct forcing immersed boundary method: SIMPLE-Schur complement approach

Yuri Feldman — Ben Gurion University

A novel formulation of immersed boundary method utilizing a fully implicit direct forcing approach incorporated within the SIMPLE method is presented for the simulation of incompressible flows. Both the incompressibility and the no-slip kinematic constraints are treated implicitly as distributed Lagrange multipliers and are fully coupled with each other by incorporating them into a Karush-Kuhn-Tucker (KKT) system of equations. The system is solved by utilizing the Schur complement approach which allows one to decompose the regularization, interpolation and Helmholtz operators, constituting the KKT system and take advantage of any existing solvers developed for the solution incompressible flows governed by the Helmholtz operator. The capabilities of the developed methodology are demonstrated by applying it to the simulation of representative 2D and 3D flows driven by pressure gradient, shear and buoyancy forces.

Experimental measurements versus linear stability analysis for primary instability of stratified two-phase flows in a square rectangular duct

Yakov Nezihovski — Tel Aviv University
(Co-authors: Alexander Gelfgat, Amos Ullmann, and Neima Brauner)

The onset of the primary instability of two-phase air-water stratified flow in a square duct was studied experimentally. Measurements were carried out by a specially designed non-intrusive technique. Critical values of the air and water superficial velocities corresponding to the primary instability were measured and successfully compared with the computationally predicted stability diagram. The experimentally measured stable and unstable flow regimes, separated by a numerically calculated linear stability boundary, are presented in a plane of the air and water superficial velocities, as commonly used in flow pattern maps. Good quantitative agreement is obtained between the experimentally measured and numerically predicted critical superficial velocities. We observed that instability may set in due to short or long waves. The long wave mode is characterized by streamwise wavenumber and oscillation frequency values tending to zero. Nevertheless, this mode preserves a finite value of the phase velocity. On the other hand, a short wave mode is characterized by finite values of the streamwise wavenumber and of the oscillation frequency. A comparison of the measured and calculated oscillation frequencies is more difficult than that of the critical superficial velocities, and can be done only for the short-wave modes. The qualitative agreement obtained between predicted and measured frequencies of the critical perturbations indicates that the numerically predicted frequencies are in the range of the experimentally observed ones. At low superficial air velocities, long wave instability is predicted. Based on the experimentally obtained spectra of the interface oscillations, we offer some arguments favoring a conjecture that the long-wave instability is indeed encountered at low superficial air velocities.

Instabilities and dewetting of nematic liquid crystal films

Lou Kondic — New Jersey Institute of Technology
(Co-authors: Linda Cummings)

Partially wetting nematic liquid crystal (NLC) films on substrates are unstable to dewetting-type instabilities due to destablizing solid/NLC interaction forces. These instabilities are modified by the nematic nature of the films, which influences the effective solid/NLC interaction. In this work, we focus on the influence of imposed substrate anchoring on the instability development. The analysis is carried out within a long-wave formulation based on the Leslie-Ericksen description of NLC films. Linear stability analysis of the resulting equations shows that some features of the instability, such as emerging wavelengths may not be influenced by the imposed substrate anchoring. Going further into the nonlinear regime, considered via large-scale GPU-based simulations, shows however that nonlinear effects may play an important role, in particular in the case of strong substrate anchoring anisotropy. Our simulations show that instability of the film develops in two stages: the first stage involves formation of ridges that are perpendicular to the local anchoring direction; and the second involves breakup of these ridges. Acknowledgements: This work was funded by National Science Foundation, Grant No. DMS-1815613.

A Schwarz domain decomposition method applied to the Rayleigh-Bénard convection problem

Darío Martínez Martínez — Universidad de Castilla la Mancha
(Co-authors: Henar Herrero Sanz, Francisco Pla Martos)

A Schwarz domain decomposition (DD) method applied to the Rayleig-Bénard problem is presented in this work. The problem is modeled using the incompressible Navier-Stokes equations alongside the heat equation in a rectangular domain (2D). The Boussinesq approximation and infinite Prandtl are considered. As this problem has non-linear terms, a Newton method is used first. In each iteration of the Newton method, a Legendre collocation discretization is applied. However, the collocation methods are ill-conditioned. This means that if the problem is too complex or big, the method will have problems to find a real solution. The Schwarz DD method is then used with these two methods to avoid this issue. The Schwarz DD method splits the domain in several rectangular subdomains, making partitions in both the vertical and horizontal axis. Then, the problem is re-arranged and solved in each subdomain independently using the Newton and Legendre collocation methods as before. Although each subdomain has the same problem of ill-conditioning, the mesh used for the whole domain is bigger than without the DD method, and therefore, better conditioned. The numerical convergence of this method is theoretically proved if there is an overlapping area between adjacent subdomains. Thanks to the Schwarz DD method it is possible to use a Legendre-Gauss-Lobatto mesh with high order and small computational cost. Moreover, the aspect ratio and the Rayleigh number of the problem can be increased in order to reach turbulence.

P5 Flows driven by buoyancy, density gradients and/or Marangoni effect

Combined effects of viscous dissipation and Soret effect on mixed convection of Poiseuille flows of binary fluid mixtures

Katia Ali Amar — University of Lille
(Co-authors: Silvia Hirata, Mohamed Najib Ouarzazi)

Linear stability analysis of a binary fluid mixture heated from below or from above in the presence of Poiseuille flow is performed analytically and numerically. Both vis- cous dissipation and Soret effects are taken into account. No external temperature difference is imposed on the layer: the upper wall is isothermal and the lower bound- ary is adiabatic. Thus, the sole cause of thermal instability is the flow rate, through the volumetric heating induced by the viscous dissipation. A linear stability analysis suggests that the most unstable perturbations are in the form of longitudinal rolls. The nature of their bifurcation depends on the separation ratio ψ, which measures the impact of Soret effect on the stability of the system. It is found that there exists a particular value ψ_c at the codimension two bifurcation point such that for $\psi > \psi_c$, the system undergoes a pitchfork bifurcation at the onset leading to monocellular flow when $\psi > \psi_{mono}$. On the other hand, when $\psi < \psi_c$, a Hopf bifurcation may set up leading to oscillatory convection. The critical Reynolds number and the frequency determined at the onset of convection are proposed as criteria to determine the separation ratio of binary mixtures used in experiments.

Density inversion phenomenon in porous penetrative convection

Giuseppe Arnone — University of Naples Federico II
(Co-authors: Florinda Capone)

Penetrative convection occurs in many natural phenomena where an unstable stratified fluid moves into a stable one. This topic is of interest in many research field like, for example, in geophysics and astrophysics [1, 2]. In the preset talk, the onset of penetrative convection in a horizontal porous layer saturated with water is investigated, on taking into account for VERONIS' quadratic density law [2]: $\rho = \rho_0(1 - \alpha(T - T_0)^2)$ (1) motivated by the anomalous density-temperature relation of water, sometimes called density-inversion phenomenon [3]. For the problem at stake, the strong form of the principle of exchange of stabilities has been proved and hence the convection can occur only through a steady motion. The critical RAYLEIGH numbers for the onset of stationary convection have been found via the linear instability analysis of the conduction solution. Moreover, the nonlinear stability of the motionless state has been investigated with the energy method [4] and suitable LYAPUNOV functions have been introduced to this aim. Numerical simulations have been performed through CHEBYSHEV-tau spectral method, from which codes on MatLab software have been developed in order to solve the generalized eigenvalue problems arising from the linear and nonlinear analysis.

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Global bifurcation of Shilnikov type in a low-order coupled ocean-atmosphere Model

Jonathan Demaeyer — Royal Meteorological Institute of Belgium

Low-order double-gyre ocean models are known to exhibit global bifurcation scenarios like the Shilnikov phenomenon (Nadiga and Luce, 2001). We show here that this type of bifurcation is also present in a low-order coupled ocean-atmosphere model (Vannitsem et al., 2015) which is known to possess coupled modes of low-frequency variability. The model solutions near the bifurcation are computed and studied in more detail to analyze how they structure the regimes of the system. In addition, the impact of these bifurcations on the predictability of the model's coupled modes of variability is considered. References Nadiga, B. T., & Luce, B. P. (2001). Global bifurcation of Shilnikov type in a double-gyre ocean model. Journal of physical oceanography, 31(9), 2669-2690. Vannitsem, S., Demaeyer, J., De Cruz, L., & Ghil, M. (2015). Low-frequency variability and heat transport in a low-order nonlinear coupled ocean–atmosphere model. Physica D: Nonlinear Phenomena, 309, 71-85.

The influence of a differential rotation on bifurcations of buoyancy driven spherical shell convection

Fred Feudel — University of Potsdam
(Co-authors: Ulrike Feudel)

We investigate numerically the bifurcation phenomena of buoyancy driven convection in a rotating spherical shell which is heated by imposing a constant temperature difference between the inner and outer spheres, and is subject to a radially directed gravity force. Along with the overall rotation of the fluid shell the influence of a shear generated by a differential rotation between both spheres on the convection pattern is the focus of this work. This configuration is an appropriate model of convection flows in geophysical and astrophysical applications, as e.g. in the outer cores of terrestrial planets. Due to the imposed differential rotation of both spheres the dynamics for small Rayleigh numbers generates a nonzero basic flow which possesses features of the spherical Couette flow. Increasing the Rayleigh number the axisymmetry of the flow is broken in successive Hopf bifurcations generating new stable branches of rotating waves (RWs) and modulated rotating waves (MRWs), respectively, with an azimuthal mode number $m = 3$. However in comparison to the configuration without differential rotation, now in addition, a new RW branch with no symmetry, $m = 1$, bifurcates in a saddle node bifurcation, separated from the other branches. The stable $m = 3$ MRWs and the arising stable $m = 1$ RWs are coexisting along a certain interval of the Rayleigh numbers creating a region of bistability. We demonstrate that finally the stable $m = 3$ MRW branch collides with an unstable RW branch in an homoclinic bifurcation, and the $m = 1$ MRW branch remains in this scenario the only stable branch for larger Rayleigh numbers. In summary, in contrast to the situation with no differential rotation in this configuration a saddle node bifurcation generates a branch with no axial subsymmetry which also enhances the heat transfer in comparison to the other branches and which forms the final attractor after the homoclinic bifurcation.

The weakly nonlinear Sutton problem: the transition between the Darcy-Bénard problem and the Wooding problem

Jacopo Alfonso Gianfrani — University of Naples Federico II
(Co-authors: F. Capone, G. Massa, D.A.S. Rees)

The Sutton problem [1] involves the thermoconvective instability which is induced by heating a uniform porous layer from below, but it differs from the classical Darcy-Bénard problem by allowing for a constant fluid suction through the upper and lower boundaries. The throughflow velocity is characterised by the Péclet number, Pe, and the strength of buoyancy forces by the Darcy-Rayleigh number, Ra. The Darcy-Bénard problem is recovered by taking the $Pe \to 0$ limit and, after some minor rescaling, the Wooding problem [2] is obtained in the $Pe \to \infty$ limit. For all values of Pe, the linear stability curve is unimodal with a well-defined minimum when the wavenumber is $k = k_c(Pe)$. However, the two limiting cases are well-known to have different stability characteristics: the onset of convection is supercritical for the Darcy-Bénard problem, while it is subcritical for the Wooding problem. The general aim of this talk is to use weakly nonlinear theory to obtain a Landau equation for the amplitude of convection and from this to identify the nature of the onset of convection. We find that onset of convection is supercritical when Pe is less than 3.1617, but it is then subcritical for larger values. The loss of symmetry in the basic temperature field, which is brought about by the suction velocity, gives rise to a resonance phenomenon at those points on the neutral curve where the wavenumbers, k and $2k$, correspond to the same critical Darcy-Rayleigh number. We modify the weakly nonlinear analysis to investigate the mutual interaction between these modes for those cases when $Pe << 1$. A coupled pair of Landau equations result from this and these are analysed.

Investigating the impacts of non-linearised temperature equations in a low-order quasi-geostrophic model

Oisin Hamilton — Royal Meteorological Institute of Belgium
(Co-authors: Jonathan Demaeyer, Stéphane Vannitsem, Michel Crucifix)

Reduced order quasi-geostrophic ocean-atmosphere coupled models provide a platform that preserve key atmosphere behaviours, while still being simple enough to allow for analysis of the system dynamics. For example, these models produce typical atmospheric dynamical features like atmospheric blocking and other low-frequency variability. For this reason, these models are well suited to investigating tipping points or bifurcations in the Earth's climate due to their simplified but insightful dynamics. In our present work, we compare the dynamics of an ocean-atmosphere coupled model, previously implemented with linearised temperature equations (Vannitsem et al., 2015), against the same model but now including the non-linear Stefan-Boltzmann law in the radiative temperature term. When compared with the linearised temperature model, this modified version of the model is found to produce different dynamics and to change the stability of the solutions, leading to an increase in the number of stable attractors for certain model parameter values. The comparison between the dynamics of both models is further investigated using Lyapunov exponents and by analysing the unstable periodic orbits (UPOs).

Vannitsem, S., Demaeyer, J., De Cruz, L., & Ghil, M. (2015). Low-frequency variability and heat transport in a low-order nonlinear coupled ocean–atmosphere model. Physica D: Nonlinear Phenomena, 309, 71-85.
Jonathan Demaeyer, Stéphane Vannitsem, Michel Crucifix

Equilibrium manifolds and stability analysis of extended shallow water models

Julian Koellermeier — University of Groningen
(Co-authors: Qian Huang, Wen-An Yong)

We present the stability analysis of equilibrium manifolds of hyperbolic shallow water moment equations. Shallow water moment equations describe shallow flows for complex velocity profiles which vary in vertical direction and the models can be seen as extensions of the standard shallow water equations. Equilibrium stability is an important property of balance laws that determines the linear stability of solutions in the vicinity of equilibrium manifolds and it is seen as a necessary condition for stable numerical solutions. After an analysis of the hyperbolic structure of the models, we identify three different stability manifolds based on three different limits of the right-hand side friction term, which physically correspond to water-at-rest, constant-velocity, and bottom-at-rest velocity profiles. The stability analysis shows that the structural stability conditions are fulfilled for the water-at-rest equilibrium and the constant-velocity equilibrium. However, the bottom-at-rest equilibrium can lead to instable modes depending on the velocity profile. Relaxation towards the respective equilibrium manifolds is investigated numerically for different models.

Stability of a dielectric liquid confined in a differentially heated vertical Taylor-Couette system with applied radial electric field

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(Co-authors: Martin Meier, Peter Szabo, Yaraslau Sliavin, Vasyl Motuz, Philipp Gerstner, Jonas Roller, Vincent Heuveline, Christoph Egbers)

A dielectric fluid is subjected to the dielectrophoretic (DEP) force when an inhomogeneous a.c. electric field is applied to it. The DEP force results from the differential polarization of fluid particles, which is due in the present study, to a temperature stratification. The dielectric fluid is confined in a gap formed by two concentric vertical cylinders. The inner cylinder is heated and rotates while the outer one is cooled and is at rest. Finally, the two cylinders are maintained at different electric potential, so that a radial alternating electric field is created. The DEP force can be seen as natural buoyancy generated by an effective centripetal electric gravity. The thermoelectric buoyancy is able to destabilize the flow depending on the values of the temperature difference and of the electric tension applied. In the studied system two additional buoyancies are considered. Indeed both the Earth's gravity and the centrifugal acceleration produced by the inner cylinder rotation act on the density stratification. Those two buoyancies complement the DEP force and lead to a complex dynamic behavior of the system. The combined effects of those mechanisms are evaluated using a linear stability analysis. Stability diagrams spanned by the dimensionless electric potential and by the Taylor number are calculated for different fluid properties. Those results serve for the parameterization of a laboratory experiment which is in preparation.

Modulated patterns in Marangoni convection with deformable surface covered by surfactant

Alexander Mikishev — Sam Houston State University
(Co-authors: Alexander Nepomnyashchy)

In the vicinity of the threshold of a pattern-forming instability, the perturbation theory can be applied for description of the basic periodic solutions and their longwave modulation. That theory leads to the amplitude equations of the Ginzburg-Landau (GL) type with real coefficients. Here we investigate the nonlinear dynamics of the large-scale patterns formed by monotonic Marangoni convection in a liquid layer with the deformable free surface covered by insoluble surfactant (interval of wave numbers $k = O(Bi^{1/2})$, $Bi << 1$, Bi is the Biot number). The problem is characterized by two conservation laws, those of the liquid volume and amount of the surfactant. They create two additional slowly evolving modes corresponding to the surface deformation and surfactant redistribution. Coupling of the GL-type equations with equations governing those modes influences the pattern stability significantly. Our previous research shows that the typical stationary patterns in this problem can be rolls, squares and hexagons. The dependence of roll stability on the heat transfer from the deformable surface of the liquid characterized by Biot number and the gravity effects described by Galileo number at different values of surfactant concentration is studied. The interaction of long-wave disturbances near the bifurcation point produces a modulational instability of the patterns. The linear analysis of this type of instability is performed. Longitudinal as well as two types of tranverse modulations of the rolls are considered. Different regions of supercritical rolls representing the boundary of the monotonic Eckhaus instability and their dependence on insoluble surfactant concentration are found. The zigzag instability condition does not depend on the existence of the surfactant. Additionaly, we studied the modulation of the hexagonal pattern. Here the deformability of the free surface generates new non-gradient quadratic terms with the spatial derivatives within the GL-system and produces the non-equilateral hexagons based on the resonance of the wave vectors with slightly different lengths. Systematic investigation of these deformed hexagons in the framework of a self-consistent non-potential model is performed. Also, the influence of insoluble surfactant's concentration on the modulational instability is considered. Acknowledgments. A.A.N. acknowledges the support by Israel Science Foundation (grant No.843/18).

Effect of horizontal aspect ratio on magnetoconvective instabilities in liquid metals

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Three-dimensional direct numerical simulations (DNS) are performed to uncover the effect of horizontal aspect ratio ($\Gamma = k_y/k_x$, k_x and k_y being the wave numbers along the x and y directions, respectively) on magnetoconvective instabilities using plane layer Rayleigh-Bénard geometry in presence of an external uniform horizontal magnetic field. The fluid under consideration is an electrically conducting, Newtonian fluid (liquid metal) having a very small Prandtl number ($\mathrm{Pr} \sim 10^{-2}$) and vanishingly small magnetic Prandtl number ($\mathrm{Pm} \sim 10^{-6}$). Extensive DNS are conducted to explore the dynamics of the system by varying the control parameters, namely, the Chandrasekhar number (Q, strength of the magnetic field) and the Rayleigh number (Ra, vigor of the buoyancy) together with Γ in the ranges of $0 < \mathrm{Q} \leq 10^3$, $0 < \mathrm{Ra} \leq 7 \times 10^3$ and $1/2 \leq \Gamma \leq 6$. It is found that both Q and Γ have a similar effect on the system dynamics in the sense that increment in either of them delays the oscillatory instability and enhances the stability regime of two-dimensional rolls. The onset of oscillatory instability is found to scale as Q^{α}. Two different scaling exponents have been identified depending on the strength of the magnetic field and Γ. For weak and moderate magnetic field ($\mathrm{Q} < 100$), the exponent α is found to be much higher compared to that of a stronger magnetic field ($\mathrm{Q} \geq 100$) and gradually decreases with the increment in Γ. Different routes to chaos are also observed depending on Γ and Q including the well-known period doubling and quasiperiodic routes to chaos. The appearance of transient chaos (TC) in the system due to the presence of chaotic saddles is found to be a remarkable finding of the present study. It is found that TC eventually leads to persistent chaos and can be considered as a possible route to chaos in magnetoconvection. Chaotic flow reversals induced by attractor-merging crisis are also observed for $\Gamma \leq 3$. Interestingly, we notice transient chaotic flow reversals in a wide parameter space which may be attributed to the presence of a merged chaotic saddle there. It is found that transient chaotic flow reversals also lead to persistent chaotic flow reversals as the Rayleigh number increases.

Wave attractors in large aspect ratio domains

Ilias Sibgatullin —
(Co-authors: Stepan Elistratov, Evgeny Ermanyuk, Thierry Dauxois)

Dynamics of internal and inertial waves in closed domains possess a remarkable property of focusing on the geometrical limit cycles called wave attractors. The significant growth of amplitude at wave attractors results in instabilities in case of viscous fluids. The scenarios of transition to turbulence and description of fully turbulent regimes differ substantially from the cases observed in closed domains in absence of wave attractors. The previous studies demonstrated the key role of a cascade of triadic resonances as the route to fully developed wave turbulence, either with overturning events or not. In the present report we show that in a shallow elongated domain with small aspect (depth-to-length) ratio, the frequency spectrum of wave motion exhibits significant peaks at integer and half-integer multiples of the forcing frequency. For the aspect ratio of about one tenth the temporal average of total kinetic energy grows monotonically with amplitude and have a bend at a particular amplitude. Below this amplitude the cascade transferring energy to superharmonic components prevails, while above this amplitude the amplitudes of subharmonic and superharmonic waves are comparable. The spatial spectra of waves in the domains of the aspect ratio varying from small values to the values close to unity are compared. It is shown that in the former case (i.e. for elongated shallow domains) the spectrum has two zones (at small and high wave numbers) characterized by different slopes. The fully turbulent regimes show the trend toward long-term evolution leading to new regimes with complex resonant dynamics of large-scale coherent structures.

P6 Mechanically-driven flows

Non-linear wind waves over a highly viscous liquid

Marine Aulnette — PMMH, CNRS, ESPCI Paris, Université PSL, Sorbonne Université, Université de Paris (Co-authors: Marc Rabaud, Frédéric Moisy)

When the wind blows over a liquid of low viscosity, small disorganized deformations first appear. These structures are the random wakes generated by the turbulent pressure fluctuations in the air flow. When the wind velocity is increased above a threshold, these wrinkles evolve into almost periodic waves propagating in the direction of the wind. If we strongly increase the viscosity of the liquid over which wind blows, the picture changes. The initial wave-packet becomes unstable and generates large isolated fluid bumps pushed by the wind. We call these non-linear objects, first observed by J. R. D. Francis (1954), viscous solitons. Their shape and dynamics result from a balance between wind drag, surface tension and viscous dissipation in the liquid. We present here an experimental study of their generation and propagation using a wind tunnel blowing wind over a liquid bath. We show that, above a critical viscosity, an unstable wave train appears at small fetch, where the shear stress is larger. This wave train generates a soliton that can propagate at larger fetch, where the stress is lower, indicating that the instability is subcritical. We show that the wave packet is the result of the Kelvin-Helmholtz instability of a highly viscous fluid sheared by a turbulent airflow: The critical friction velocity and critical wavelength are independent of the liquid viscosity ν_l, whereas the phase velocity decreases as $1/\nu_l$ [1,2], in agreement with Miles' prediction (1959). The subcritical nature of the transition to viscous solitons is demonstrated by mechanically triggering them using a wave maker for a wind velocity under their natural threshold. Using PIV visualizations, we also show that the flow field induced by a viscous soliton is well described by a two-dimensional Stokeslet singularity. The resulting viscous drag, and therefore the soliton's propagation velocity, is found to depend on the liquid depth, in good agreement with our measurements. [1] Aulnette, M., Rabaud, M., & Moisy, F. (2019). Wind-sustained viscous solitons. Physical Review Fluids, 4(8), 084003. [2] Aulnette, M., Zhang, J., Rabaud, M., & Moisy, F. (2022). Kelvin-Helmholtz instability and formation of viscous solitons on highly viscous liquids. Physical Review Fluids, 7(1), 014003.

On the role of continuous symmetries in the solution of the 3D Euler fluid equations and related models

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We review the continuous symmetry approach based on Sophus Lie's transformation theory, and apply it to find the solution of the 3D Euler fluid equations in several instances of interest, via the construction of constants of motion and infinitesimal symmetries, without recourse to Noether's theorem, in a setup that allows for unsteady flows as well as unsteady infinitesimal symmetries. Roughly speaking, an infinitesimal symmetry is a vector field that is continuously transported along the flow. When the flow admits two linearly independent infinitesimal symmetries, we obtain a number of general results: (i) If these symmetries commute, then we construct a constant of motion for the flow. (ii) If these symmetries do not commute, then we construct a new infinitesimal symmetry and can repeat the search (i) with a new pair of symmetries, or repeat the search (ii) to find a complete Lie algebra of infinitesimal symmetries. Another general result, of remarkable geometrical and dynamical importance for both steady and unsteady flows, is that the vorticity field is an infinitesimal symmetry of the flow. Therefore, if the flow admits another infinitesimal symmetry other than the vorticity, then by points (i) and (ii) above one can construct new constants of motion and/or a Lie algebra of new symmetries. For steady Euler flows this leads directly to the distinction of (non-)Beltrami flows: an example is given where the topology of the spatial manifold determines whether extra infinitesimal symmetries can be constructed. As for unsteady flows, we study the stagnation-point-type exact solution of the 3D Euler fluid equations introduced by (Gibbon et al., Physica D, vol. 132, 1999, pp. 497-510) along with a one-parameter generalisation of it introduced by (Mulungye et al., J. Fluid Mech., vol. 771, 2015, pp.468-502). Applying the continuous symmetry approach to these models allows for the explicit construction of constants of motion and the subsequent integration of the fields (vorticity, its stretching rate, and the back-to-labels map) along pathlines, revealing a fine structure of blowup, depending on the value of the free parameter and on the initial conditions. A remarkable formula for the blowup time is obtained, which shows how the flow's regularity depends on the initial conditions. We produce explicit blowup exponents and prefactors for a generic type of initial conditions. This work will appear in Philosophical Transactions A (doi 10.1098/rsta.2021.0050).

The concept of edge state in the presence of a linear instability

Yohann Duguet — LISN-CNRS
(Co-authors: Miguel Beneitez, Dan S. Henningson)

The transition to turbulence in many shear flows proceeds along two competing routes : the bypass route is linked with finite-amplitude disturbances while the classical route originates from a linear instability. This phenomenon is notorious in the Blasius boundary layer flow as well as in plane channel flow as will be shown based on unsteady spectral numerical simulations. The dynamical systems concept of an edge manifold has been suggested in the subcritical case to explain the partition of the state space of the system. This investigation is devoted to the evolution of the edge manifold when linear stability is added in such subcritical systems, a situation poorly studied despite its prevalence in realistic fluid flows. In particular, the fate of the edge state as a mediator of transition is unclear. A deterministic three-dimensional model is suggested, parametrized by the linear instability growth rate. The edge manifold evolves topologically, via a global saddle-loop bifurcation of the underlying invariant sets, from the separatrix between two attraction basins to the mediator between two transition routes. For larger instability rates, the stable manifold of the saddle point increases in codimension from 1 to 2 after an additional local pitchfork bifurcation, causing the collapse of the edge manifold. As the growth rate is increased, three different regimes of this model are identified, each one associated with a flow case from the recent hydrodynamic literature. A simple non-autonomous generalization of the model is also suggested in order to capture the complexity of spatially developing flows such as the Blasius boundary layer.

Stability of Bingham flow in an inclined channel

Paolo Falsaperla — Università degli Studi di Catania
(Co-authors: Andrea Giacobbe, Giuseppe Mulone)

We consider the flow of a Bingham fluid in an inclined open channel. We apply to this problem recent results of Falsaperla et al. for laminar Couette and Poiseuille flows of Newtonian fluids in inclined channels. In this article, we prove a stabilizing effect of the Bingham parameter B. We also study the stability of the linear system with an energy method (Lyapunov functions) solving a generalised Orr equation. We prove that the streamwise perturbations are always stable, while the spanwise perturbations are energy-stable below a critical Reynolds number. This system has geophysical applications to the evolution of landslides.

Coupling flow directions in emulsions with wall roughness

Akankshya Majhi — Wageningen University & Research
(Co-authors: Lars Kool, Raquel Serial, Joshua Dijksman, Jasper van der Gucht)

Dense emulsions behave as a yield stress fluid, that has a critical stress above which the material starts to flow. Typically, the yield stress behaviour is captured in the Herschel-Bulkley model, which assumes a constant yield stress as material parameter. The microscopic origin of the yield stress is still under debate. It can be argued that flow in orthogonal directions simultaneously affect the yield stress and will make the yield stress either flow rate or field dependent. Therefore, it is important to understand how two orthogonal flows affect each other and how the Herschel-Bulkley equation can be generalised to explain such orthogonal flow situations. In this work, we show that wall patterning can be used to generate flow in two orthogonal directions that affect each other significantly. We induce secondary flows via shearing a common yield stress fluid in a rheometer using a concentric cylinder geometry with angled ridges. We image the flow fields by employing rheoMRI methods to show that flow directions in yield stress fluids are indeed significantly decoupled. This work is funded by the Dutch Research Council (NWO) and TKI-E&I.

Three-dimensionality of the triadic resonance instability of a plane inertial wave

Daniel Andrés Mora Paiba — FAST / CNRS / Université Paris Saclay
(Co-authors: Eduardo Monsalve, Maxime Brunet, Thierry Dauxois, Pierre-Philippe Cortet)

We analyze theoretically and experimentally the triadic resonance instability (TRI) of a plane inertial wave in a rotating fluid. Building on the classical triadic interaction equations between helical modes, we show by numerical integration that the maximum growth rate of the TRI is found for secondary waves that do not propagate in the same vertical plane as the primary wave (the rotation axis is parallel to the vertical). In the inviscid limit, we prove this result analytically, in which case the change in the horizontal propagation direction induced by the TRI evolves from 60 to 90 degrees depending on the frequency of the primary wave. Thanks to a wave generator with a large spatial extension in the horizontal direction of invariance of the forced wave, we are able to report experimental evidence that the TRI of a plane inertial wave is three-dimensional. The wave vectors of the secondary waves produced by the TRI are shown to match the theoretical predictions based on the maximum growth rate criterion. These results reveal that the triadic resonant interactions between inertial waves are very efficient at redistributing energy in the horizontal plane, normal to the rotation axis.

Time-dependent 3D dynamics in viscoelastic pressure-driven channel flow

Alexander Morozov — University of Edinburgh
(Co-authors: Martin Lellep, Moritz Linkmann)

Dilute polymer solutions do not flow like Newtonian fluids. Their flows exhibit instabilities at very low Reynolds numbers that are driven not by inertia, but rather by anisotropic elastic stresses. Further increase of the flow rate results in a chaotic flow, often referred to as purely elastic turbulence. The mechanism of this new type of chaotic motion is poorly understood. In this talk we present the first coherent state in purely elastic parallel shear flows. We consider a model shear-thinning viscoelastic fluid driven by an applied pressure gradient through two- and three-dimensional channels. By starting from a linearly unstable mode recently discovered by Khalid et al.[1] at very large flow rates and very low polymer concentrations, we demonstrate the existence of 2D travelling-wave solutions in such flows. We show that this state sub-critically connects to significantly higher values of polymer concentration and lower flow rates [2], rendering travelling-wave solutions experimentally relevant. Upon embedding the 2D coherent states in a 3D domain, we observe the emergence of a time-dependent, turbulent-like state, see Fig.1 for an instantaneous snapshot. We perform extensive characterisation of the ensuing dynamics and demonstrate its strong connection to purely elastic turbulence.

[1] M. Khalid et al., Phys. Rev. Lett. 127, 134502 (2021)

[2] A. Morozov, arXiv:2201.01274 (2022)

The investigation of the enstrophy growth at the energy stability limit in the plane channel flow

Péter Tamás Nagy — Budapest University of Technology and Economics

The laminar-turbulent transition in a channel flow is subcritical. It usually occurs at a much lower Reynolds number in experiments than the predicted Reynolds number using the eigenvalues of linear stability analysis. However, it can be shown that the non-linear term in the incompressible Navier-Stokes equation is energetically conservative. This problem is also known as the Sommerfeld paradox which can be partially explained with the non-orthogonality of the eigenvectors of the linearised Navier-Stokes equations or with its pseudo spectrum. In practice, the estimation of the transition Reynolds number is the desired aim, but the previously mentioned linear method fails in this case. A promising candidate is the energy or Reynolds-Orr method. In that case, the stability limit can be determined using a variational problem. The perturbation velocity field is varied to minimise the Reynolds number, where the temporal derivative of the energy is zero. Below this Reynolds number, the kinetic energy change must be negative, and the energy of any perturbation decays exponentially. Since the non-linear term has no direct effect on the energy change and the result is independent of the perturbation amplitude, this method is called the non-linear energy method. Unfortunately, the predicted Reynolds number is very conservative and not practical in many cases. An attempt is made to improve the method using the enstrophy, which is the volume integral of the squared vorticity. Previously published results showed that the enstrophy stability limit is significantly larger than the kinetic energy limit. However, it can be used only in two-dimension since in three dimensions, the non-linear terms in the vorticity equation affect the enstrophy change. Here, the enstrophy change of the solution (the critical perturbation) of the Reynolds-Orr equation is evaluated. Since the equation is linear, the solution is assumed in a waveform, whose tilt angle and wavelength are varied. The significant result of the study is that the kinetic energy change and enstrophy change are zero in the case of critical perturbation with a long wavelength and with a tilt angle of 45°. A recently published paper found that the travelling wave solution at the lowest Reynolds number has a tilt angle of 45° by using edge tracking direct numerical simulation. This result can explain that. Furthermore, the wavelength of the most critical perturbation wave is close to that of the critical travelling wave.

Photon Lines

Juan Pimienta — PMMH laboratory
(Co-authors: Jean-Luc Aider)

Characterization and evolution of the recirculation bubble of a backward-facing step flow through different Reynolds number The Backward-Facing Step (BFS) flow is considered and used as a relevant benchmark case for shear flows and separated flows [1]. Its relevance lies in its simple geometry, a downward step of height "h", with a sharp edge, producing very complex fluid structures such as a shear layer, vortex rolling/paring/shedding, formation of coherent structures, superimposed to a large recirculation bubble. In this study we characterize [2] the BFS flow in a gravity-driven hydrodynamic tunnel for Reynolds numbers ranging from 100 to 3200 with a Reynolds step $Re_h = 100$. For each Reynolds number, the flow is measured using PIV (Particle Image Velocimetry) in 11 horizontal planes distributed along the height of the BFS. It allowed us to perform a full 3D reconstruction of the volume of the time-averaged recirculation bubble at each Reynolds, and to observe the variation of the average recirculation area at each plane of measurement. We could also study the variation of the dynamics and frequencies of the flow throughout the different heights and Reynolds numbers by observing the fluctuations of turbulent kinetic energy on the instantaneous velocity fields, the power spectra of the flow, as well as modal analysis. Analysis of the instantaneous velocity fields allowed us to observe the occurrence of turbulent spots close to the frontier of the instantaneous recirculation bubble through different Reynolds numbers, which seems to be a key phenomenon in the transition process towards turbulent flow. The 2D2C PIV measurements were performed using an Optical-Flow based code developed in collaboration with Photon Lines. It allows a higher resolution of the velocity fields and a better characterization of the natural BFS flow than in previous studies, leading to the first observation of turbulent spots in the instantaneous velocity fields. References: [1] Jean-Luc Aider, Alexandra Danet, Marcel Lesieur, Large-eddy simulation applied to study the influence of upstream conditions on the time-dependant and averaged characteristics of a backward-facing step flow, Journal of Turbulence, 8, N51, 2007 [2] Gautier N. and Aider J.-L. 2013 Control of the separated flow downstream of a backward-facing step using visual feedback Proc. R. Soc. A. 469 : 20130404

Structures of non-buoyant round jets subjected to background rotation

Lohengrin Van Belle — KU Leuven
(Co-authors: Sam Booth, Maarten Vanierschot, Peter Thomas)

In this work, the flow structures in a non-buoyant round jet, subjected to a rotating environment are investigated. Direct Numerical Simulation (DNS) is performed at Re 200 in a standstill and rotating environment. The simulation in the standstill environment resulted in a laminar, self-similar solution further downstream. When the jet is subjected to background rotation, an anticyclonic precession around the central axis develops with well-defined time-periodic structures. The precessing frequency is directly proportional to the environment's background frequency. The jet precesses at St 0.016 and St 0.038 for a Rossby number of 5.5 and 2.75, respectively. Besides the precession motion, the background itself shows oscillatory behavior. Flow patterns are analyzed using Fourier analysis and are evaluated for inertial waves. The instability criterion of Nagarathinam, Sameen & Mathur (J. Fluid Mech. (2015), vol. 769, pp. 26-45) is applied and suggests that axisymmetric centrifugal instabilities are present. To corroborate on the flow structures, a Particle Image Velocimetry (PIV) analysis is initiated.

Transport anomalies in steady plane flow patterns with degenerate stagnation points

Michael Zaks — Humboldt University of Berlin

We consider time-independent flow patterns in plane layers of viscous incompressible fluids. Arrays of steady vortices in such flows can be excited e.g. by the action of spatially periodic forces. If the velocity field features periodicity with respect to both spatial coordinates, Lagrangian dynamics of a drifting particle turns into a flow on a two-torus. When the rotation number of this flow is irrational, the streamlines outside the vortices are not closed: each of them comes arbitrarily close to stagnation points of the velocity field. Although in absence of molecular diffusion the motion of passive tracers stays deterministic, cumulative effect of repeated passages through the stagnation zones results in transport anomalies. The time within which a tracer traverses the elementary cell of the flow, diverges near the stable separatrix of a stagnation point. The character of divergence predetermines the kind of transport anomaly. Near hyperbolic stagnation points, singularities of passage times are logarithmic, causing weak subdiffusion: logarithmic time growth for the variance in ensembles of advected tracers. In absence of hyperbolicity, singularities of passage times are stronger; accordingly, time growth for the variance obeys power laws. At the saddle-center bifurcation that creates new stagnation points in the flow pattern, transport of tracers is subdiffusive. For degeneracies of the higher order the transport becomes superdiffusive, as we demonstrate with an explicit example of the velocity field. We also discuss the role that the barriers, formed by the streamlines, heteroclinic to the stagnation points, play in the transport.

P7 Bifurcating flows in labs and applications, experimental methods

Numerical simulations on bifurcations and experiments on bi-stability in forced transparent electrolyte flow in a ring-shaped container

Didzis Berenis — University of Latvia
(Co-authors: Ilmārs Grants)

We study stability of an electrically conducting liquid flow, generated by a transversely magnetized permanent magnet rotating inside the bore of a cylindrical ring. In the dimensionless approach, the half-height and the inner radius of the ring are set to unity and R, the outer radius of the ring, controls the flow type. A previous study has already established that width of the ring is responsible for the change in flow regimes. In a thin ring configuration ($R < 2$), which resembles a centrifugal pump, the core of the flow exhibits almost solid body rotation. It is a well-known solution for the uniformly rotating magnetic field generated flows. On the contrary, in wide ring configurations ($R > 2$) the flow stability decreases because of a distinctive outward radial jet that develops at the mid-plane. The previous parametric study [Grants & Berenis2020] investigated ring configuration up to $R = 3$. The findings of the current research with a wider ring configuration are that the critical Taylor number (Ta) as well as the critical Reynolds number (Re) drops noticeably at $R = 3.2$. For instance, increasing outer radius from 3 to 4 leads to critical Re drop from 190 to 60. To investigate the instabilities in more detail we set $R = 4$ and only vary the Ta. We find that the first instability occurs at $Ta = 2.7e4$ and is axially symmetric and monotonic. Consequently, a new stationary solution manifests which can take one of two mirror-symmetric possibilities − the jet facing upwards or downwards. The secondary instability, which is cyclic and path dependent, develops at $Ta = 5.5e4$. Increasing EM force further leads to the flow becoming aperiodic at around $Ta = 1.2e5$ and transitioning to bi-stable turbulence, in which the jet is no longer settled in one of the positions but is switching between facing upwards or downwards, at $Ta > 2e5$. The time interval between two consecutive switching events is stochastic and can exceed the characteristic diffusion time of the momentum. When EM force is increased further yet, the turbulence starts to dominate and the bi-stability disappears. Numerical results suggest that bi-stability persists after reasonable deviations from the symmetry and, thus, should be observable experimentally. A time-lapse photography will be performed to observe the direction change of the radial flow over a period of several hours. Injected dye at several points around the azimuth will serve as a flow direction indicator.

P8 Control of instabilities and parametric excitations

Resonance on surface waves in a circular channel

Ion Dan Borcia — Brandenburgische Technische Universität
(Co-authors: Rodica Borcia, Wenchao Xu, Michael Bestehorn, Sebastian Richter, Uwe Harlander, Leo R.M. Maas)

We excite surface waves in a ring channel placed on a rotating table [1,2]. The tank can rotate with constant velocity and/or can librate. The experiment works in two parameter regimes: high libration amplitudes and small frequencies are used for the generation of traveling surface waves, while smaller amplitudes and higher frequencies are necessary for studying the patterns generated by horizontally excited Faraday waves. For the horizontal Faraday instability only high viscosity liquids (glycerin-water solutions) can be excited by the mean shear. For the resonance, low viscosity liquids (pure water) can be used. For an efficient excitation, a barrier should be placed in the channel. A proper comparison between experimental and numerical data demands a reconstruction of the whole space-time series for the experimental data. The concept will start from the fact that the waves usually change their shape very slowly during propagation with the exception of the region where they meet (collide) or reflect. In the following we will use a geometrical method for identifying the resonance windows. The method is very similar with that used for inertia-gravity waves. The method was successfully used in finding attractor windows in water waves in (usually 2D but also 3D) basins governed by a canonical, second-order, hyperbolic equation on a closed domain. Although the model is linear, it gives information about the nonlinearities [3]. [1] I. D. Borcia, R. Borcia, W. Xu, M. Bestehorn, S. Richter, and U. Harlander, Undular bores in a large circular channel," Eur. J. Mech. B Fluids 79, 2020 [2] I. D. Borcia, R. Borcia, S. Richter, W. Xu, M. Bestehorn, and U. Harlander, Horizontal faraday instability in a circular channel", PAMM 19, 2019 [3] Maas, LRM, "Wave attractors: Linear yet nonlinear", Int. J. of Bifurcation and Chaos, 15, 2005.

Parametric instability of a snake-like robot on the water surface

Johann Herault — IMT Atlantique Nantes
(Co-authors: Xiao Xie, Max Roccuzzo, Vincent Lebastard, Frédéric Boyer)

The diversity and beauty of animal locomotion have always been a source of inspiration and fascination for biologists, physicists, and engineers. For twenty years, a new generation of marine robots inspired by eels and aquatic snakes has emerged in academic contexts. These hyper-redundant serial robots (HR) are compact and highly maneuverable, and are now deployed in industrial context. Despite the great potential of these bio-inspired robots, their stability on the water surface remains too precarious at low speed or during extreme conditions (swell, wind, current). Furthermore, their slender morphology, which accounts for their performances, becomes a handicap on the water surface at low speed. Indeed, they are susceptible to the roll motion due to their low axial moment of inertia and the destabilizing buoyancy forces. Here, we want to address the questions: What causes this instability? How to stabilize the roll instability? To address these questions, we perform experimental, numerical, and theoretical investigations of the instability mechanisms during undulatory swimming. To do so, we explore the robot's response as a function of the gait features given by the frequency and the amplitude of the bending wave running along its backbone. We observe the presence of an unstable region describing an "Arnold tongue" in-between two areas of beating oscillations. This is the unmistakable signature of a parametric resonance, which accounts for the solid roll motion. However, our results show that this resonance does not follow the standard framework of the Mathieu equation. Indeed, the resonance occurs at frequencies significantly much smaller than the eigenfrequency of the robot, while unstable frequency bands are larger than expected. We instead show that a Mathieu-Duffing equation finally describes this instability. Besides, we have also the unique opportunity to investigate experimentally the role played by the hydrodynamics effects (wave-drag, added mass..etc) thanks to our snake-like robot. Finally, we address the mechanisms of stabilization and the implications of this instability on the swimming performances.

Drift instabilities in localised Faraday patterns

Juan Marin — University of Santiago
(Co-authors: Rafael Avila, Saliya Coulibaly, Majid Taki, Leonardo Gordillo, Monica Garcia-Ñustes)

Nature is intrinsically heterogeneous, and remarkable phenomena can only be observed in the presence of intrinsically nonlinear heterogeneities. Spontaneous pattern formation in nature has fascinated humankind for centuries, and understanding underlying symmetry-breaking instabilities has been of longstanding scientific interest. In this talk, I will summarize theoretical and experimental evidence that heterogeneities can generate convection (drift instabilities) in the amplitude of localized patterns. We derive a minimal theoretical model describing the growth of localized Faraday patterns under heterogeneous parametric drive, unveiling the presence of symmetry-breaking nonlinear gradients. Furthermore, the model reveals new dynamics in the phase of the underlying patterns, exhibiting convective instabilities when the system crosses a secondary bifurcation point. Finally, we discuss the impact of our results in understanding convective instabilities induced by heterogeneities in generic nonlinear extended systems far from equilibrium.

Dynamic response of a laterally compressed sheet in a closed fluid contained chamber

Oz Oshri — Ben-Gurion University

Mechanical instabilities that emerge from the interaction between thin elastic sheets and a fluid medium is of interest in the design of many technological applications including, for example, soft mechanical switches and energy harvesting devices. Motivated by these applications, we study the dynamic response of a thin sheet that is compressed between the two sides of a closed rectangular chamber. The two parts of the chamber, above and below the sheet, are filled with an ideal fluid. We show that the system is governed by three dimensionless numbers. One is the lateral compression of the sheet, second is the density ratio between the sheet and the fluid multiplied by the slenderness of the sheet, and third is the vertical dimension of the chamber. Given a small dynamic perturbation on a static equilibrium configuration of the sheet, we derive an analytical model that can predict the largest growth rate, and its corresponding flow field, at the onset of the instability. Approximated analytical solutions to these growth rates are derived under the assumption that the amplitude of the sheet remains small. Our theoretical results agree well with the numerical solution of the nonlinear equations. In addition, we investigate the system's behavior slightly beyond the linear instability regime and discuss how the potential energy stored initially in the sheet is subsequently transferred to the fluid.

Direct numerical simulation of liquid films on a non-planar substrate under external vibration

Sebastian Richter — BTU Cottbus-Senftenberg
(Co-authors: Michael Bestehorn)

We study the dynamics of a two-dimensional liquid layer subjected to an external time-periodic force. The layer is bounded by a solid and non-planar substrate on the bottom side and by its free surface on the top side. Based on direct numerical simulations, a finite difference method on staggered grids for the full incompressible Navier-Stokes equations is presented allowing the investigation of the formation of surface instabilities. Surface tracking and interpolations are avoided by employing the nonlinear coordinate transformation $z = (h(x,t) - s(x))z'$, which maps the layer on a constant rectangular region. A sparse linear system for the pressure satisfying momentum and mass conservation can be obtained from the discretized Navier-Stokes equations taking into account the continuity equation. Vertical excitations produce classic Faraday waves, and in the case of lateral forces and low thickness of the liquid film, we observe coarsening droplets. With lateral excitation breaking the horizontal mirror symmetry $x \to -x$, a preferred direction of motion of the drops and a non-vanishing mean flow rate are found. The results are compared with those of systems with planar substrate.

Modal and nonmodal stability of variable-density trailing vortices

Julien Sablon — ISAE-SUPAERO, Université de Toulouse
(Co-authors: Jérôme Fontane, Laurent Joly)

The stability of trailing vortices has been studied for years and remains an active research subject nowadays. These vortices, unavoidable by-product of lift-generating finite wings, can be hazardous for aircrafts following each other especially in take-off and landing phases. This led to the imposition of security standards that limit airports capacity. Besides, these trailing vortices interact with engine effluents at cruise level and, in some specific atmospheric conditions, are very persistent and can induce artificial cirrus clouds which have a significant impact on the radiative forcing. Therefore, the mitigation of contrails is a subject of active research and one strategy relies on the control of natural instabilities. The understanding of the destabilisation mechanisms stands as a prerequisite before developing control techniques that could be tested and implemented on aircraft. Therefore, this study consists in conducting a stability analysis of an isolated variable density trailing vortex which is well approximated by the analytical q-vortex model, where q is the swirl number measuring the ratio between azimuthal and axial velocity scales. First, a linear modal stability analysis is performed on this baseflow and shows that the presence of a density distribution within the vortex core yields an extension of the unstable domain up to infinite swirl numbers. A complete parameter study has been conducted to consider the influence of the swirl number, the Atwood number, the Reynolds number, the velocity-to-density radius ratio and both the azimuthal and axial wavenumbers of the modes. These different parameters do not have independent influence on the stability of the flow and the main effects are outlined. As the modal stability analysis only deals with long term behaviours, a non-modal stability analysis has also been conducted to unveil possible transient energy growth and associated unstable physical mechanisms. Due to the non-normality of Navier–Stokes operator, short term perturbations that develop quickly are likely to trigger early vortex destabilisation and lead to rapid vortex mitigation via phenomenon such as vortex breakdown, even when the flow is asymptotically stable.

Wind wave growth over a viscous liquid

Jishen Zhang — Université Paris-Saclay, CNRS, FAST
(Co-authors: Marc Rabaud, Frédéric Moisy)

Theoretical and laboratory studies of wind-wave generation have focused primarily on the air-water interface, with weak effects of viscosity. Here we are interested in the growth rate of wind waves with strong viscous effects close to the onset velocity. In our experiment, wind is blowing over a layer of silicon oil, of viscosity 20 times more viscous than water, and waves are excited by an immersed wave-maker. At low wind velocity, all frequencies are attenuated, whereas beyond a critical wind velocity, waves are amplified in a certain range of frequencies, that widens as the velocity is increased. We measure the spatial evolution of the wave field using Free-Surface synthetic Schlieren, a refraction-based optical method with micrometer accuracy. Using band-pass filtering of the surface elevation, we can selectively measure the growth rate for each excitation frequency, even if the excited wave is attenuated while amplified waves are present at other frequencies. We measure systematically the spatial growth rates for all wind velocities and wave frequencies, from which we deduce the marginal stability curve. By subtracting the viscous damping rate from the measured growth rates, we show that our results compare well with the classical Miles' prediction.

P9 Miscellaneous

Studies of disturbance growth in transonic boundary layers over complex geometries using embedded DG simulations

Ganlin Lyu — Imperial College London
(Co-authors: Chao Chen, Shahid Mughal, Xi Du, Spencer J. Sherwin)

Laminar boundary layer natural transition for external flows is of particular interest in both the aeronautical industry and academia. The transitional process is dominated by the linear growth of disturbances, e.g., Tollmien–Schlichting waves and crossflow waves, and therefore a correct prediction on the development of the disturbances is necessary for a successful transitional analysis. Most conventional studies focused on the disturbances developing based on incompressible boundary layer flows over ideal, clean geometries. However, the physical settings for the real conditions are different for the flow compressibility and geometrical complexity. The compressibility stems from the transonic operational conditions, and for the real geometries the main source of the complexity is the existence of surface imperfections, which typically take the form of steps and gaps whose sizes are comparable with the boundary layer thickness. In the current work we therefore further extend the physical settings to transonic laminar boundary layer at realistic Reynolds numbers, and over wing sections with surface imperfections. The validation of the method will be demonstrated by analyzing a 2D transonic flow over flat plates at Mach 0.8. Both clean geometry and the geometry with a forward-facing step are studied. The zero-pressure gradient is adopted for the clean case while for the stepped case pressure gradient is generated due to the existence of the step although the same boundary conditions are enforced. Good agreements in comparisons of N-factors obtained by others verify the approach. Moreover, it is worth mentioning that the reflected wave at the step is dominated by acoustics since the pressure component has the largest amplitude while the velocity components also have a comparable amplitude. We then study the disturbance development over wing sections with surface imperfections. High fidelity DG simulations are carried out in a near-wall, reduced domain which is embedded in a full 3D RANS solution. The boundary data of the reduced domain is interpolated from the outer solution, and pressure compatibility is achieved through the entropy-pressure compatible Riemann inflow. After the computation for the disturbance fields, the N-factor on this wing section is subsequently generated. In the conference we will demonstrate the simulation results of the disturbances' growth with the existence of a step as well as cover the following analysis.

Poster presentations

A three-dimensional branching flow with a surface perturbation

Ajay Chatterjee — San Francisco State University
(Co-authors: Jorn Sesterhenn)

Bifurcations in laminar flow of a Newtonian fluid are seen in many flow configurations, a classical example being the two-dimensional flow through a sudden expansion. We consider a three-dmensional model flow in a Cartesian T-junction branching configuration with a geometrical perturbation of the impinging surface. The perturbation represents a local surface bulge in the neighborhood of the T-junction, and it is located symmetrically about the mid-plane of the geometry. Its height is less than half the width of the inlet channel for the flow, and due to its symmetrical placement the steady flow stagnation point is at the center of the perturbation. Such a perturbation feature models flow into a shallow cavity, and in a physiological context may represent an idealization of an aneurysm structure in a branching arterial flow. Within the domain of the perturbation the steady flow at low Reynolds numbers 100-150 possesses symmetry in both planes perpendicular to any axial plane, such as the plane z=0 which locates the T-junction. However, this flow is asymptotically unstable, the first instability being a pitchfork bifurcation. The bifurcation leads to a flow which exhibits asymmetry in any plane perpendicular to the plane of the corresponding two-dimensional branching flow. We present numerical linear stability results for the critical Reynolds number and describe the characteristics of the two asymmetric stable flows which emerge beyond the bifurcation point. Since wall shear stress is an important consideration in arterial flows we depict its distribution on the walls of the perturbation structure and observe a three-fold variation due to the flow asymmetry. The streamlines of the flow also are considerably modified, with those originating from points near the geometrical axis acquiring a helical character such that neighboring streamlines wrap around the central streamline as they traverse towards the arms of the T-junction from the interior of the perturbation region. Although a symmetry breaking instability is expected to occur in this flow, its appearance at such a low Reynolds number is interesting and important for relevant applications. We also briefly comment on experimental work underway to characterize the bifurcation flow, and continuing detailed numerical calculations to analyze exhaustively the features of the instability.

Low-Reynolds number mixing and hydrodynamic instability in the presence of non-symmetric wall corrugation

Jakub Fabisiak — Warsaw University of Technology
(Co-authors: Stanisław Gepner)

Mixing is a phenomenon observed throughout nature, science and technology. Processes, such as flows through heat exchangers, both in micro- and macro-scale, polymer and metal processing, extrusion or injection or systems handling fragile, biological flows to a large extend employ principles of mixing. Improving mixing efficiency is a way to improve performance of numerous devices. A common approach is flow turbulisation, but however effective, this approach is not always desirable or realizable. Processing of highly viscous fluids, microfluidic applications or biological flows containing sheer-sensitive molecules calls for laminar mixing to be applied. Mixing in the laminar regime is particularly difficult since flows remain dominated by viscous effects and lacks strong advection and stirring. Another challenge is the choice of an appropriate mixing quantification method. Commonly used variance is able to catch concentration decrease caused by both advection and diffusion. However time derivative of variance excludes advection and explicitly depends on diffusivity only, which is problematic in cases featuring weak diffusion or where improved stirring is the objective. To overcome shortcomings of variance a class of 'mix-norms', defined as Sobolev norms of negative index are currently being researched. Basing on operator, that can be interpreted as an inverse gradient, they are smoothing concentration gradients and emphasizing the role of advection in the formation of small scales, at the same time downplaying the diffusive action. It is known that channel corrugation might result in the onset of hydrodynamic instabilities, leading to complex flow patterns and consequently improved mixing via principles of chaotic advection. In this work we perform Direct Numerical Simulation (DNS) of low Reynolds number, pressure driven flow in a doubly-periodic, one-side-corrugated channel to analyse mixing inspired by hydrodynamic instabilities. We investigate impact of symmetry breaking of the geometry and its influence on stirring and mixing efficiency. We use a mixing measure based on a negative index Sobolev mix-norm. The DNS is performed utilizing Nektar++ Spectral/hp Element framework. Flows of varying Reynolds and Schmidt numbers are simulated to analyse mixing in different advective and diffusive conditions. We compare obtained asymmetric channel results with results in symmetry preserving corrugated channel considered in previous works of co-author.

Dielectrowetting of a thin nematic liquid crystal layer

Lou Kondic — New Jersey Institute of Technology
(Co-authors: Linda Cummings)

We consider a mathematical model that describes the flow of a Nematic Liquid Crystal (NLC) film placed on a flat substrate, across which a spatially-varying electric potential is applied. Due to their polar nature, NLC molecules interact with the (nonuniform) electric field generated, leading to instability of a flat film. Implementation of the long wave scaling leads to a partial differential equation that predicts the subsequent time evolution of the thin film. This equation is coupled to a boundary value problem that describes the interaction between the local molecular orientation of the NLC (the director field) and the electric potential. We investigate numerically the behavior of an initially flat film for a range of film heights and surface anchoring conditions. (Work funded by NSF Grant No. DMS-1815613.)

Experimental investigation of the nutation angle's effect on the flow inside a precessing cylinder

Vivaswat Kumar — Helmholtz-Zentrum Dresden Rossendorf
(Co-authors: Federico Pizzi, Andre Giesecke, Thomas Gundrum, Matthias Ratajczak, Sten Anders, Frank Stefani)

Precession-driven flows are considered as potential sources of dynamo action on Earth, ancient moon, and some asteroids. At the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), a precession-driven dynamo experiment is now being constructed as part of the DRESDYN project. It is a cylinder filled with liquid sodium with a radius of 1 m and a height of 2 m. The cylinder rotates at a frequency of up to 10 Hz and precesses around the second axis at a rate of up to 1 Hz. To gain a better understanding of the hydrodynamics of a precessing cylinder, a downscaled 1:6 water mockup with the same aspect ratio, rotation, and precession frequency was built. The typical non-axisymmetric Kelvin mode, which initially increases as the precession ratio increases, is alone not suitable for dynamo action in the experiment. However, a secondary axisymmetric mode that appears in a narrow region of the precession ratio was demonstrated to be particularly promising for dynamo action in the sodium experiment. To predict dynamo behavior for different precession ratios and precession angles, a thorough understanding of the flow structure in the precessing cylindrical vessel is required. For that purpose, we performed a series of precession measurements on the downscaled water experiment with Ultrasonic Doppler velocimetry (UDV) at various precession angles of 60 degree, 75 degree, and 90 degree. We present the effect of precession angle and rotation direction (i.e. prograde or retrograde) on the dominant flow modes, and quantify this behaviour in dependence on the rotation rate, which is parameterized by the Reynolds number $Re = \Omega_c R^2/\nu$, and the precession ratio $Po = \Omega_p/\Omega_c$, where ν is the viscosity and $\Omega_p = 2\pi f_p$ is the angular frequency of the precession. The experimental results are compared with numerical simulations.

Molecular simulations of shear-induced critical transitions for confined nanodroplets

Michele Pellegrino — KTH
(Co-authors: Berk Hess)

Understanding droplet breakage, film deposition and liquid bridge formation in micro-/nano-scale flows is of the utmost importance for the control of many industrial processes, such as printing or coating. In many cases, these critical transitions are connected to the motion of a fluid-vapour interface over surfaces; hence, an effective mathematical modelling of three-phases contact line dynamics confers predictive power and allows for the quantification of critical parameters. We perform Molecular Dynamics simulations of SPC/E water nanodroplets confined between silica-like walls which are moved in opposite directions in order to induce a fluid flow [1]. Depending on the speed of the moving walls the resulting flow may be steady (sub-critical wall speed) or unsteady (super-critical wall speed). In the latter case, depending on the liquid-solid interaction energy we observe either the formation and the consecutive breakage of a liquid bridge (hydrophobic surfaces), or the development of a liquid film at the receding contact line while the advancing contact line is not affected significantly (hydrophilic substrates). We observe that the critical transition on hydrophobic substrates is anticipated by a node-saddle bifurcation of the flow streamlines. Large oscillations in the motion of contact lines emerge for sub-critical wall velocities close to the critical value, which we hypothesize are the product of both a molecular stick-slip process and of the coupling between the inertia of the surrounding flow field and the moving contact line fluctuations. In the case of hydrophilic surfaces, the asymmetry between advancing and receding contact lines upon critical transition can be explained by considering a contact line friction model based on energy barriers in molecular jumping and rolling motion [2], which predicts the maximum velocity attainable by receding contact lines being different than the one of advancing contact lines, and can thus explain the onset of film deposition. This work constitutes a stepping stone towards demystifying dynamic wetting on high-friction hydrophilic substrates. It also aims to build an openly accessible database of NEMD benchmarks, available for the validation of contact line motion models. References: [1] Lācis et al, arXiv:2112.09682 [physics.flu-dyn] (2021) [2] Johansson and Hess, Phys. Rev. Fluids 3, 07420 (2008)

Dynamics of $(n, 1)$ wave attractors

Ilias Sibgatullin —
(Co-authors: Alexandr Petrov, Xiulin Xu, Leo Maas)

The simplest geometry of the domain, for which internal wave attractors were for the first time investigated both experimentally and numerically, has the shape of a trapezium with one vertical wall and one inclined lateral wall, characterized by two parameters. Using the symmetries of such a geometry we give an exact solution for the coordinates of the wave attractors with one reflection from each of the lateral boundaries and an integer amount n of reflections from each of the horizontal boundaries. The area of existence for each $(n, 1)$ attractor has the form of a triangle in the (d, τ) parameter plane, and the shape of this triangle is explicitly given with the help of inequalities or vertices. The expression for the Lyapunov exponents and their connection to the focusing parameters is given analytically. The corresponding direct numerical simulations with low viscosity fully support the analytical results and demonstrate that in bounded domains $(n, 1)$ wave attractors can be effective transformers of the global forcing into travelling waves. The saturation time from the state of rest to the final wave regime depends almost linearly on the number of cells.

Lax-Wendroff scheme on Saint-Venant equation with dynamical boundary conditions and non-linearity

Teke Xu — University of Groningen
(Co-authors: Hugo Carrillo, Alden Waters)

In water supply systems, water hammer or hydraulic shock is inevitable and sometimes causes the bursting of the pipes if the pressure is too high. It is important to predict the water flow and the pressure in the pipes especially during the transient due to the sudden closure of the valve. The classical Euler equations or otherwise known as Saint-Venant equations in one dimension case have been widely used to describe the fluid flow in the pipeline models. However, specific solutions of these nonlinear hyperbolic equations are hard to obtain and we therefore try to look for possible numerical approximations. Several numerical methods have been used to model the Saint-Venant equations, such as the Upwind Scheme and Galerkin methods, but they did not take into account an extra nonlinear friction term. To this end, we study the nonlinear Saint-Venant equations with dynamical boundary conditions and non-linearity by using the Lax-Wendroff scheme, which is more general. Our result is new by taking into account both the moving boundary conditions and giving convergence for the numerical approximations to the solution to the semi-linear hyperbolic system, and these numerical techniques will be applicable to more general (conservative) systems of the form. A long range future application of the research is to expand the results to multiple valves opening and closing-modelling the human circulatory system or blood flow in the human body.