Sloshing Interfaces and Contact Line Energy Dissipation

Ballottements, dissipation et lignes de contact

I. Pre-proposal's context, positioning and objectives


Figure 1 : sloshing in a glass of red wine.

Sloshing of liquid in a shaking container is a common situation which can be observed in everyday life (see figure 1 for a cheering example). This problem has also practical implications. For instance, oscillations of fuel in a partially filled tank occur in vehicles of all kinds (ships, spatial launchers and satellites), and are potentially dangerous for manoeuvrability and structure resistance. Partially filled tanks are also used as vibration dampers in applications such as offshore wind turbines or seismic design of building structures. The modelling of sloshing has of course a long history [1], but most of the studies still rely on the potential approach, neglecting friction at the boundaries. Most of them also neglect capillary effects. Such approaches are sufficient to predict the oscillation frequencies for large tanks but are unable to predict dissipation effects, such as damping rate of free oscillations or the amplitude response at resonance for forced oscillations.

Both viscosity and surface tension are dominant at the contact lines where the free surface meets the wall surface. Investigation of what happens in the vicinity of such contact lines reveals a glaring paradox. In effect, in the corpus of continuum mechanics, the almost universally accepted adherence condition tells us that the velocity of the fluid along a surface should vanish. Therefore, a contact line should not be allowed to move. This paradox is considered by many as one of the most important open questions in fluid mechanics since it calls into doubt the validity of continuum mechanics in the vicinity of the contact line and requires an understanding of the underlying microscopic physics. The simplest physical models [2] lead to predictions of the damping rate containing terms proportional to $log(L/a)$ where L is the macroscopic scale and a is a microscopic length-scale, generally modelled in an ad-hoc way. This logarithmic term symbolizes the unavoidable meeting of microscopic and macroscopic worlds, and gives a flavour of the mathematical difficulty of the problem.

The objectives of the project are twofold. First our ambition is to provide important contributions, both theoretically and experimentally, to the "slip paradox" presented above. The second objective is to provide practical answers and convenient numerical tools (DNS codes and/or modal solvers) potentially usable by industrials to have reliable predictions of the characteristics of sloshing, especially damping rates, in a variety of situations.

II. Project organisation and means implemented

Presentation of the consortium and general organization of the project

The project involves three French laboratories and two external European partners.

IMFT, the coordinating partner, is a joint research laboratory between CNRS, INPT and Toulouse 3 University. With a staff of around 200 persons, it represents one of the major concentrations in France and even in Europe in terms of research and advanced training in fluid dynamics, both by its size and by the wide spectrum of scientific topics and applicative fields it addresses.

ONERA (Office National d'Etudes et Recherches en Aérospatial) is a public institution acting at the interface between academic research and industrial world in aeronautics. The Department of Aerodynamics, Aeroelasticity and Acoustics (DAAA) gathers around 200 research engineers working on the development of innovative scientific and technological solutions for improving the aerodynamics, the aeroelasticity and the acoustics of the next generation of airplanes.

The **LFCR**, a joint industry-academic research unit (TOTAL, CNRS, UPPA), is a quite unique structure in the French research landscape. It embodies about 90 peoples coming from chemical

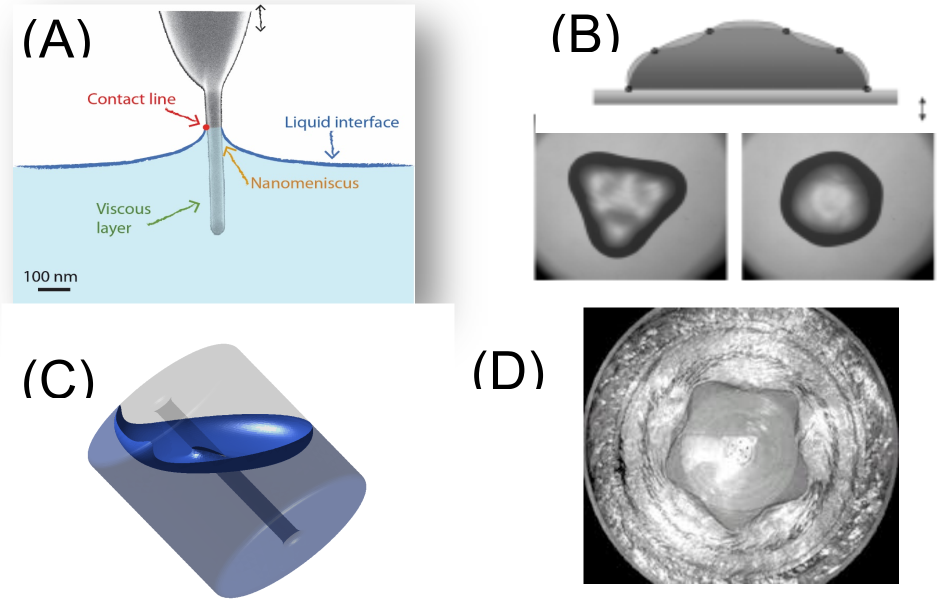

Figure 2 : Illustration of the four generic "sloshing" situations considered in the project.

engineering, fluids physics, geomechanics, geophysics and geology and is so truly multiscale. Its researches are largely application-oriented, in particular in relation with fluid flows at the nanoscale.

Within **EPFL** (Lausanne), the **LMFI** investigates fluid dynamics on the basis of simplified models. This enables to unravel basic mechanisms and governing parameters. The team focusses on hydrodynamic instability applied to separated flows, coaxial jets and droplet formation, as well as droplet based microfluidics.

Finally, **DTU** (Denmark) has a broad research effort and expertise on fluid dynamics across several departments. The FLUIDS section at the department of Physics investigates fluid dynamics over a wide range of scales, spanning from macroscopic fluid flows dominated by vortices, through microfluidic flows in lab-on-a-chip systems down to flows around swimming microorganisms and in the vasculature of plants.

The participants of the consortium have complementary skills and have already collaborated under several European, national or regional projects. In the present project, a close collaboration will be maintained by regular meetings and exchange of students. More specifically, it is planned to start two co-advised PhDs (IMFT-EPFL and ONERA-DTU) and two shared post-docs (IMFT-LCFR and ONERA-IMFT). These recruitment will represent the largest part of the budget requested from ANR.

The sloshing problem (defined in the broad sense as the forced or free oscillations of a liquid with a free surface) is considered in the present project as a generic situation offering a well-defined scope for fundamental studies on contact-line motion problems. In practise, we will consider four generic configurations at different scales (as illustrated in figure 2), which allow focusing on specific aspects of the problem. The project will also be structured in five tasks corresponding to different investigation methods. This organisational matrix will be developed in the next paragraphs and the role of the various participants will be explained.

Four generic situations

The **first configuration (A**) consists of an **oscillating needle** of a hundred of nanometers diameter traversing a free surface. This setup allows to focus on viscous and capillary effects at submicron scales, approaching the limits of continuum mechanics. Among the participants, **T. Ondarçuhu (IMFT)** has recently demonstrated in the frame of the ANR project Nanofluidyn, that Atomic Force Microscopy (AFM) combined with the nanofabrication of dedicated cylindrical probes, allows the quantitative monitoring of dissipation in the viscous layer or in a pinned oscillating nano-meniscus [3]. In the present project, we will extend these studies to the case of the moving contact line by measuring the associated dissipation, including the contribution of nanometric defects responsible for contact angle hysteresis [4].

The **second configuration (B)** consists of a **liquid drop mounted on an oscillating plate**. In the past decade, Noblin [5] has conducted a number of experiments of this kind and observed a number of interesting phenomena, such as oscillation modes with multiple nodal lines (figure 2B, top) and non-axisymmetric oscillation modes called "triplons" (figure 2B, bottom). Although the link with the other "sloshing" situations considered in the project may seem tenuous, this case actually provides a configuration of choice to focus on contact line dynamics, thanks to the simplicity of the setup and the ease of performing flow measurement and shape visualisation. This configuration will thus be the favoured one in the starting of the project for the theoretical and numerical tasks. A series of detailed experiment will also be undertaken, under the supervision of **J. Sebilleau.**

The **third configuration (C)** consists of a **tilted cylindrical tank traversed by a rod**. This configuration was selected in the team of **J-S. Schotté** [6] as a representative of the 3D geometries of interest for industrials in the field of transport, and the sloshing modes are already well documented in the potential case. This configuration will serve as a benchmark for the development of the 3D, viscous modal analysis (task 1), as well as for the nonlinear parts of the project (tasks 3 and 5).

Finally**, the fourth configuration (D)** consists of a **cylindrical tank with rapidly rotating bottom**. This configuration is known to give rise to spectacular patterns in the form of rotating polygons along the free surface. **T. Bohr**, **D. Fabre** and **J. Mougel** have previously collaborated on this configuration. They have given the first credible explanation of these patterns as resulting from a resonance between different families of surface waves [7]. The role of viscosity, turbulence, and, in particular, the moving contact line on the rotating bottom for stabilizing the polygons remains challenging and will be addressed with the tools developed in this project.

Five investigation methods

Linear modal analysis (task 1) is the natural framework for sloshing analysis. The two main partners of the project have a long experience in linearized approaches and have developed complementary tools. In the **ONERA** team, **J-S. Schotté** has developed methods based on energy minimization to compute the equilibrium shape of the free surface, and on linearized Euler equations (potential theory) to compute the properties of sloshing modes [6]. Such methods are able to treat 3D containers with arbitrary geometries (see fig. 2C), but do not include a mean flow or viscosity. In the **IMFT** Team**, D. Fabre** is a specialist and promoter of global stability approaches. His team has recently applied such methods to free surface problems such as the sloshing of a viscous liquid in a rotating tank [8], the oscillations of a liquid bridge [9], and path instability of a rising bubble. These developments are currently limited to 2D or axisymmetric geometries but fully include viscosity and a possible mean flow. Efficient parallel numerical tools are currently developed by **O. Marquet** in the ERC-StG14 project AEROFLEX, to investigate three-dimensional linear instabilities emerging in elastic material when immersed in a viscous fluid. An important milestone of the project will be to combine these tools into a common solver allowing the solution of 3D viscous sloshing problems.

Incorporating contact line dynamics into this approach will necessitate a reflection on **Physical modelling (task 2),** in order to introduce microscopic effects into the macroscopic equations. For the slip paradox evoked above, the simplest idea consists of replacing the no-slip condition by a slip-length model [10]. Other ways to incorporate microscopic effets, such as disjunction pressure, may be incorporated as well. Among the participants of the project, **D. Legendre (IMFT) and F. Gallaire (EPFL)** have notable expertise on these questions and will be particularly involved in this task.

The reflection on physical modelling will be alimented by **numerical simulations** (task 3). Two simulation strategies are planed. First, simulation at the microscopic scale using **Molecular Dynamics** is a convenient way to get insight into microscopic effects. Among the participants, **G. Galliero** has a reckoned expertise on this approach [11]. Secondly, macroscopic simulations using front-tracking methods (Volume-Of-Fluid of LevelSet) are planned, with the involvement of **D. Legendre.** Such methods are customarily used for contact line motions but the dissipation is not correctly estimated. Ideas to correct these methods using a subscale dissipation modelling will be tested, guided by the results of the previous tasks.

To check the validity of the results form the theoretical and numerical tasks, the project will be completed by a series of **experiments** (task 4) for chosen representative situations. This task will particularly benefit from the presence of three experienced participants. **T. Ondarçuhu** (IMFT) is familiar with experiments at nano to micro scale, and has used Atomic Force Microscopy (AFM) to scrutinize dissipation in the vicinity of free surfaces. **J. Sebilleau** (IMFT) has expertise on experiments on capillary effects at millimeter and centimeter scale [11]. Finally, **T. Bohr** (DTU) is well-known for designing and conducting simple model experiments giving rise to surprising structures, and has expertize with free-surface flows such as hydraulic jumps and sloshing induced by rotation.

Finally, a last exploratory but challenging task is to introduce **Nonlinear** effects into the **modal analysis** formalism (task 5)**.** Nonlinear global approaches are recent methods in fast development in the stability community, and project participants **F. Gallaire**, **D. Fabre** and **O. Marquet** are important actors in this development. In the present problem, nonlinearity appears in the geometry itself and original ideas to incorporate this in a nonlinear modal formalism will have to be developed.

Qualification of the scientific coordinator

D. Fabre, the coordinator of the project, is a leading expert in the field of hydrodynamic instabilities. He has developed original stability tools on an open-source basis [13] and applied them to many problems including aircraft trailing vortices, wake instabilities over oscillating wings [14], free surface swirling flows [7-8], capillary oscillations [9], acoustic instabilities of whistling jets, or path instabilities of falling bodies and rising bubbles. On this later subject, he has conducted an ANR-funded project "OBLIC" [15] which also involved the ONERA partner. This project used a methodology similar to that of the present project, combining theoretical modeling, simulations and experiments around a central task consisting of global stability analysis (equivalent to the modal approach employed here).

III. Impact and benefits of the project

One of the main objectives of this project is to provide a better understanding of the dissipation near a moving contact line. This problem remains a challenge at the crossroads of **fluids dynamics** and **atomic/molecular physics,** and asks for theoretical and numerical methods from the fields of **non-linear physics** and **instabilities**. From scientific point of view, the "slip paradox" at the contact line remains an open fundamental question, and important advances on this problem are expected to reach a large audience. As for potential economic impact, the IMFT, ONERA and LFCR teams already have contractual activities with industrial partners of the aeronautic sector (Thales, Airbus, Astrium, CNES) on related questions, and this will facilitate knowledge and technology transfers.

IV. References related to the project

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