### Acronyme

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### Titre du projet en français

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### Aide totale demandée

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1. Contexte et Positionnement du projet / Context and Positionning of the Proposal

Objects moving freely within a viscous fluid under the effect of buoyancy or gravity may display a large variety of paths. Well-known examples include the rise of small bubbles in water, which exhibit zigzagging or spiralling paths, and the falling of a paper card in air, which may lead to various motions such as fluttering, tumbling or chaotic oscillations. The central difficulty of such problems is tied to the intrinsic coupling between the fluid and body motions, the relative body displacement inducing a disturbance in the fluid which in turn imposes loads that govern the body motion. The aim of this project is to conduct fundamental research on this class of problems. Unlike many available studies which concern simpler two-dimensional situations, our focus is resolutely on three-dimensional objects. Specifically, we will focus on objects with axisymmetric geometry, such as spheres, disks, cylinders, or spheroids. This class of geometries provides generic models for objects as diverse as rising bubbles, sedimenting particles, leaves, seeds, or microscopic organisms.

Various theoretical models have been proposed for either bubbles (Shew & Pinton, 2006) or solid objects (Mahadevan 1996; Belmonte et al. 1998; Pesavento & Wang 2004; Ern et al). The starting point in all of these studies was the Kelvin-Kirchhoff equations governing the dynamics of the body, in which an empirical modelling of the forces and torques experienced by the moving body was introduced. However, none of these models is able to reproduce the whole diversity of observed behaviours.

The kind of modelling proposed here follows from a radically different approach. Here, the starting point is to consider as a whole the coupled fluid/body system, and to explain its dynamics as a superposition of a limited set of leading modes which interact nonlinearly. The relevant leading modes have to be selected from among the most amplified modes obtained from a linear stability analysis of the coupled system. The expected model resulting from this approach is a system of coupled equations governing the amplitude of the leading modes, and will therefore have a radically different form compared to existing models. A great advantage of the present approach is that the generic form of the resulting set of equations, called the normal form of the problem, can be determined a priori by a simple consideration of the properties of the linearly most amplified modes and the symmetries of the problem. Bifurcation theory (Golubitsky et al., 1988; Crawford & Knobloch, 1991) provides a systematic way to derive such normal forms. This approach proved to be fruitful in a wide variety of problems ranging from chemical reactions to plasmas and biological systems. The application of such methods to the problem of moving objects constitutes the main innovative idea of the present project. The power of this approach has been recently demonstrated in two simultaneous and independent studies conducted by two of the teams involved in the project (Fabre, Auguste & Magnaudet, 2008; Meliga, Sipp & Chomaz, 2008). The approach also extends ideas previously investigated by the third team involved in the project (Ghidersa & Dusek, 1999). These previous studies were conducted for the related problem of the wake behind fixed bodies. The ambition of the present project is to explore the potential of the approach for moving bodies in order to provide general models applicable to the whole class of problems represented here.

The project is structured around four generic problems characteristic of some field of application:

- The first problem is the fall (or rise) of a small object in a quiescent fluid, in an unbounded environment (“free-object problem”). This situation is the most generic one, and consequently will be the one deserving the larger number of activities in the project.
- The second problem concerns more specifically objects exchanging heat with the surrounding fluid (“hot-object-problem”). Compared to the previous one, added
complexity is expected due to the interference of natural convection with the intrinsic dynamics of the object.

- The third problem is that of an object falling (or rising) within a vertical or slightly tilted pipe ("object-in-pipe problem"). In this case added complexity results from the presence of the walls which affect the dynamics of the object.
- The fourth problem concerns the motion of an object suspended in a jet ("object-in-jet problem"). This entertaining and apparently simple situation, which can be easily demonstrated with a ping-pong ball and a hair dryer, hides a complex set of phenomena. Compared to the previous cases, the main complication is the inevitable presence of turbulence.

These reference cases embrace a large class of situations, with applications ranging from aerodynamics (Lugt, 1983) to biomechanics (Wang, 2005) and dispersed two-phase flows (Magnaudet & Eames, 2000). All of these cases are known to lead to a very rich variety of possible paths, ranging from rectilinear, zigzagging or helical, to cite the simplest, to tumbling, two-frequency motions, or chaotic ones, to cite a few of the most complicated ones. All these problems will be investigated using a common methodology, combining the following ways of investigation:

- A common theoretical approach based on the use of global stability analysis and weakly nonlinear expansions will be applied (Task 1). This approach allows one to reduce rigorously the full problem to a low-dimensional dynamical system describing the interaction of a limited set of leading modes. Such computations will be performed using a global stability code already in use in the ONERA team for the wake of fixed bodies. This code will be imported in the IMFT team and extended to incorporate the additional degrees of freedom necessary to apply it to moving objects.
- In parallel, a purely mathematical study of generic dynamical systems relevant to the present problem will be accomplished (Task 2), as well as a classification of the various solution types. This study is expected to provide useful guidelines for the remainder of the project.
- Direct numerical simulations will be carried out using four different numerical codes in possession of the different teams involved the project (Task 3). In a first stage, these numerical codes will be confronted with the objective of cross-validation and cross-fertilisation; in a second stage they will be used for extensive parametric studies.
- Experimental investigations will also be carried out (Task 4), in order to validate and extend previous investigations.

## 2. DESCRIPTION SCIENTIFIQUE ET TECHNIQUE / SCIENTIFIC AND TECHNICAL DESCRIPTION

### 2.1. ÉTAT DE L’ART / BACKGROUND, STATE OF THE ART

#### 2.1.1 State-of-the-art for “Free objects”
The motion of objects in free motion within an unbounded and quiescent fluid, which constitutes the first generic situation chosen in the present program, has become an active field of research in recent years. Numerous studies have considered the canonical cases of two-dimensional cards (Pesavento & Wang, 2004; Andersen et al., 2005; Mahadevan, 1996). The literature devoted to three-dimensional objects is comparatively poorer. Only two kinds of geometries, namely the sphere and the thin disk, have received significant interest. For the case of a sphere, a map of the possible states in a two-parameter plane spanned by the Reynolds number and the ratio of density between the body and the fluid was determined numerically by the IMFS team (Jenny et al., 2003 and 2004). However, this map is evidently far from exhaustive since new trajectory types were observed in recent experiments (Horowitz & Williamson, 2007). For thin circular disks a similar map has been constructed experimentally (Willmarch et al., 1964; Field, 1997). For the latter case, fluttering, tumbling or chaotic motions are observed (figure 2).

In an effort to fill the gap between these two extreme geometries, experimental (Fernandes, 2005; Fernandes et al., 2007; Ern et al., 2007) and numerical (Auguste, PhD 2009; Auguste et al., 2008) studies were conducted by the IMFT team using a family of oblate cylindrical bodies with aspect ratios ranging from 2 to 10, and density ratios close to unity. In this range of parameters, the most characteristic path is a periodic zigzag (see figure 2), however, with notable differences between the motion of thick bodies and thin ones. More complex paths were also observed. For instance, experiments revealed some cases with

![Figure 1: Examples of trajectories of a falling disk. (a): Rectilinear path (Willmarth et al., 1964). (b): Planar zig-zag path (Belmonte et al., 1998). (c): Tumbling path (Stringham et al., 1969). (d): Classification of trajectories as function of Reynolds number Re and dimensionless moment of inertia I*.

![Figure 1](image-url)
trajectories taking the form of elliptical zigzags, somehow intermediate between planar zigzags and helical paths. The numerical study (Auguste et al., 2008) also revealed the existence of new kinds of unsteady regimes existing below the critical Reynolds number corresponding to the onset of the zigzag path. In particular, a rectilinear nonvertical path was evidenced, as well several new unsteady regimes including two- and three-frequency motion, as well as weakly chaotic motion. These findings led us to reconsider the classification presented above for thin disks (figure 1d).

This rapid overview shows that despite existing work, the field of investigation is still largely open. Each new case of study seems to lead to the discovery a new type of dynamical behaviour. Since these problems are characterised by three independent parameters (aspect ratio, density ratio, and Reynolds number) a general understanding of the parameter dependence of the various path types is inconceivable in the absence of a guiding theory.

2.1.2 State-of-the-art for “hot objects”

In many applications, transport of solid particles in a fluid involves significant thermal effects. A typical example is the melting of an individual ice particle in water or the rise of a hot particle in air due to an inverse drag. Transition phenomena cannot be disregarded. A millimetric particle of ice in water can be expected to rise with limiting Reynolds numbers ranging roughly from 100 to almost 2000. The IMFS team recently focused on thermal effects (Kotouc 2008, PhD). In view of the high sensitivity of the transition scenario to secondary effects such as imperfections in the mass distribution of the sphere stated in Jenny et al. (2004), thermal effects were expected from the start to strongly affect the particle trajectories. The results obtained (Kotouc 2008, Kotouc et al. 2008 a,b) go, however, far beyond initial expectations and reveal the existence of numerous unsteady and non-axisymmetric states with exotic properties. Preliminary attempts have been made to model the problem as a nonlinear mode interaction, following the general idea of the project, and the potential of this idea appears promising.

With the notable exception of the 2D simulations of Gan et al. (2003) no numerical data are available on the trajectory types of sedimenting or ascending particles that take into account thermal convection. There exists, however, relatively abundant bibliography concerning thermal effects in flows past heated spheres. Pure free convection (Geoola & Cornish 1982 and Jia & Gogos 1996) is not relevant for spheres moving under the effect of gravity and buoyancy. The configuration of the latter corresponds to the mixed convection. If thermal effects accelerate the fluid in the wake (e.g. in the case of a falling hot sphere) the flow is called assisting; opposing flows correspond to the opposite situation. Mixed
convection past spheres has been investigated both experimentally (Yuge 1960, Klyachko 1963, Katoshevski et al. 2001, Mograbi et al. 2002) and numerically (Chen & Mucoglu 1977, Mograbi & Bar-Ziv 2005).

A common feature of available work on natural and mixed convection past a sphere (see Kotouc et al. (2008a) for a more exhaustive review) is the use of the Boussinesq approximation (Gray 1976) for the mathematical formulation of the coupling between the dynamics and the thermal field. The Boussinesq approximation assumes a uniform kinematic viscosity $\nu$ and thermal diffusivity $\kappa$, both constant throughout the flow; buoyancy effects are approximated using a linear thermal expansion law characterized by a small thermal expansion coefficient $\beta$. Combined with the sphere diameter $d$, the temperature difference $T_s-T_\infty$ between the sphere surface and the fluid (considering the sphere surface to be kept at a constant temperature $T_s$) and, in presence of the forced flow, with the asymptotic flow velocity $v_\infty$, these basic fluid properties lead to a characterization of the mixed convection flow regimes using three non-dimensional numbers: the Grashof number $Gr=\beta\kappa (T_s-T_\infty)d^3/\nu^2$, the Reynolds number $Re=v_\infty d/\nu$ and the Prandtl number $Pr=\nu/\kappa$. The Boussinesq approximation represents, nevertheless, a serious weakness in many practical applications.

The discussion of Gray 1976 shows that the Boussinesq approximation fits particularly badly to water. In the literature, a special attention has been paid to the anomalous thermal expansion of water. The latter affects free convection at temperatures close to $4^\circ$C (Schenk & Schenkel 1968). In contrast, viscosity variation is most often disregarded be it in water or in other fluids (see e.g. Mograbi & Bar-Ziv 2005) although it represents almost 50% between 0 and 20$^\circ$C for water and is of great importance in all other fluids once the temperature difference becomes large.

A second feature of virtually all of the available numerical work is that the simulations are axisymmetric. In the same way as in the wake of an unheated sphere, axisymmetry holds only within limits defined by the onset of three-dimensionality representing the first stage of the transition. The latter has been investigated in the parameter space of the Reynolds, Richardson ($Re=Gr/Re^2$) and Prandtl numbers in Kotouc et al. (2008b) for both assisting and opposing flow within the framework of the Boussinesq approximation. Prandtl numbers corresponding to air ($Pr=0.72$) and water ($Pr=7$) were considered and two $Re-Ri$ parameter planes were swept in the transition region much as done in Jenny et al. (2004) for the $G-\rho_u/\rho$ plane. As expected, convective effects considerably modify the transition scenario even for moderate Richardson numbers. They delay the onset of instabilities in assisting flows and advance it considerably in opposing flows.

2.1.3 State-of-the-art for “Objects-in-pipe”

There exist numerous examples in engineering and biomedical fields where bodies suspended in a fluid are transported through a tube, including flushing solid matter from a pipe or conduit, the complex flow through annular devices such as combustion chambers and turbomachinery, and the motion of red blood cells in narrow vessels. The description of the motion of immersed bodies in fluids is also present in several manufacturing processes, e.g. the feeding of converters in metallurgical industries, sedimentation procedures, fluidised beds, etc. All of them involve the description of the particle position as a function of time. L. Grinis (2008) studied the transport and the impact of particles in a pipe as a cleaner to remove wall sediments in heat exchanger pipes.

Migration and equilibrium of solid particles in shear flows have always been of great interest. Segré & Silberberg (1961, 1962) studied the migration of dilute suspensions of neutrally buoyant spheres in tube flows and found the particles migrate away from both the wall and the centreline and accumulate at a radial position of about 0.6 times the tube radius. This remarkable Segré-Silberberg effect (2002) has been verified by many experimental works on the same kind of problem (see Yang et al., 2005 for a review).

Among the large number of authors who numerically studied transport of rigid particles we have to mention the tremendous work of R. Glowinski (2002). He has developed the Lagrange multiplier-based fictitious domain method that he applied to study the
migration of multiple neutrally buoyant circular cylinders in plane Poiseuille flow of a Newtonian fluid where the Segré & Silberberg effect (2002) was found, to the motion of general shape particles in Newtonian fluids (Pan et al., 2002, Pan et al., 2005) where he showed that a settling ellipsoid in a narrow channel turns its broadside to the stream in the simulations. In a recent publication (Yang et al., 2005) he compared the ALE methodology based on a moving and adaptive grid and the Lagrange multiplier-based fictitious domain method on the cross-stream migration of a single neutrally buoyant rigid sphere in tube flow. The two methods showed good agreement.

Sheard and Ryan (2007) performed a computational investigation, supported by a theoretical analysis to investigate a pressure-driven flow around a line of equi-spaced spheres moving at a prescribed velocity along the axis of a circular tube. They studied the influence of the Reynolds number and showed that both the regular non-axisymmetric mode and the axisymmetric Hopf transition occur through a supercritical (non-hysteretic) bifurcation. Yu et al. (2004) studied the sedimentation of a sphere and its radial migration in Poiseuille flow in a vertical tube filled with a Newtonian fluid and showed that at relatively low Reynolds numbers, the sphere approaches the tube axis monotonically, whereas in high-Reynolds-number flow, where shedding of vortices takes place, the sphere takes up a spiral trajectory that is closer to the tube wall than the tube axis.

It is noteworthy that most available work actually corresponds to neutrally buoyant objects carried by an imposed flow. In this project, the focus will be rather on buoyant object moving on their own, and their motion will first be studied in the absence of a driving flow which will be introduced subsequently. Also, a theoretical modelling in the line of the general idea of the project has never been intended.

2.1.4 State-of-the-art for « objects-in-jet »

The “object-in-jet” problem has been partly studied by different authors, starting from Osbourne Reynolds himself who discussed, in his first paper, part of this amazing physics (Reynolds, 1870). Davoust and Jacquin (2009) recently conducted an experiment on that subject at ONERA-DAFE. The objective of this experiment is to explain and model the different regimes observed for the motion of the sphere. Rather large variations of the flow parameters (ball/fluid density ratio, ball/jet diameter ratio, Froude number and Reynolds numbers) have been considered to get sufficient data on the mean equilibrium position of the sphere, on the position variance and on the characteristic frequencies of the motion, see figure 3. These different variables have been successfully correlated using dimensional analyses and quasi-static models. But many fundamental aspects of this basic aerodynamic flow remain largely open. One of the most fascinating ones is the physics of the lift effect that maintains the sphere in the jet. Available results on spheres or cylinders in shear flows predict a force ejecting the sphere, indicating that the origin of the lift in the jet is not simply the mean shear (see e.g. Achenbach, 1972; Auton et al, 1988). Another challenge is to understand the physics of the observed sphere oscillation and its relation with the wake flow dynamics. This is our main objective in the present project.

Regarding theoretical modelling of the kind planned in the proposal, the ball-in-jet situation is free from any previous work. The sample trajectories presented in figure 3 are strongly appealing for a modelling as an interaction between modes of vertical and horizontal motions, and much can be expected from this approach.
Figure 3 – A sphere in a turbulent jet: (a) definitions, (b) smoke visualisation, (c) a sample trajectory, (d) horizontal and (e) vertical positions of the sphere corresponding to the trajectory (c) (from Davoust and Jacquin 2008).
2.2. OBJECTIFS ET CARACTÈRE AMBITIEUX/NOVATEUR DU PROJET / RATIONALE HIGHLIGHTING THE ORIGINALITY AND NOVELTY OF THE PROPOSAL

As explained in paragraph 1, the originality and novelty of the project is to formulate the motion of a free object in terms of the nonlinear interaction between several modes, and to study it using the methods of bifurcation theory. In order to illustrate the predictive power of this idea and to justify the proposed methodology, we will detail how this idea was recently able to explain what happens in the wakes of fixed objects, such as disks and spheres. In the case of the sphere two successive bifurcations occur, leading successively to a non-axisymmetric steady-state (SS) with planar symmetry, and a periodic, reflection-symmetry-preserving (RSP) mode (Johnson & Patel, 1999; Mittal, 1999; Ghidersa & Dusek, 1999; Bouchet et al., 2006). In contrast, in the case of a disk the second bifurcation leads to a periodic, reflection-symmetry-breaking (RSB) mode that is followed by a third bifurcation that produces a periodic mode in which the reflection symmetry is again restored. The latter is called a “standing-wave mode” (SW) (Fabre et al., 2008).

Formulating this problem as a nonlinear interaction problem between two modes, Fabre et al. (2008) used normal form theory to predict that the dynamics can be reduced to a low-dimensional dynamical system admitting the following form:

\[
\frac{da_0}{dt} = \lambda_0 a_0 + l_0 |a_0|^2 a_0 + l_1 (|a_1|^2 + |a_2|^2) a_0 + il_2 (|a_1|^2 - |a_2|^2) a_0 + il_3 \bar{a}_0 \bar{a}_2 a_1,
\]

\[
\frac{da_1}{dt} = (\lambda_1 + i\omega_0) a_1 + B(|a_1|^2 + |a_2|^2) a_1 + A|a_0|^2 a_1 + C|a_0|^2 a_2 + D a_0 a_2^2,
\]

\[
\frac{da_2}{dt} = (\lambda_2 + i\omega_0) a_2 + B(|a_1|^2 + |a_2|^2) a_2 + A|a_0|^2 a_2 + C|a_0|^2 a_2 + D \bar{a}_0 \bar{a}_2 a_1.
\]

where \(a_0, a_1, a_2\) are complex mode amplitudes, and the quantities \(l_0, l_1, l_2, l_3, A, B, C, D\) are coupling parameters. They were subsequently able to select values of these parameters which allow one to construct bifurcation diagrams compatible with their numerical results (see figure 4 a,b).

Simultaneously and independently, in the ONERA team, Meliga, Sipp & Chomaz (2008) have investigated the same problem using weakly nonlinear expansions. They obtained the same system as in Eq. (1) but were in addition able to perform a straightforward determination of the coupling parameters. The bifurcation diagram thus derived for the case of a disk is remarkably similar to that plotted in figure 4(b).

Very recently, a third kind of object, namely a cylindrical body of aspect ratio 3, was investigated using numerical simulations by the IMFT team (Auguste et al., 2008). An even
more complicated sequence of bifurcations was observed, containing a new bi-periodic mode occurring between the RSP and RSB modes. The corresponding bifurcation diagram, displayed in figure 4(c), could also be obtained from Eq. (1) using appropriate parameter values. In this case, the choice of parameters was strongly guided by a preliminary mathematical classification of the possible solutions of Eq. (1), started in collaboration with E. Knobloch (from the UC-B team).

The above discussion shows that the present theory can be applied in two complementary ways. First, qualitatively to explain numerical or experimental results (this approach requires a detailed mathematical understanding of the given dynamical system to be successful); second, quantitatively through the use of weakly nonlinear expansions. The ambition of the present project is to explore the potential of this approach (through its two ways of application) for problems of freely moving objects.

Having thus explained and justified the proposed methodology, we now detail the expected outcomes of this project, considering in succession the four generic situations identified in section 1.

- A detailed map of the various possible trajectories for the “free” object problem, considering a family of generic bodies as a function of the geometrical properties, density ratio and Archimedes number (i.e., nondimensional viscosity), obtained by means of numerical simulation (in a joint effort by two teams) and experiments.
- An understanding of the added effect of confinement, thermal effects and presence of turbulence (however, as in these cases the number of parameters is at least four, an exhaustive mapping is not realistic).
- A general model, in the form of a dynamical system involving a limited number of degrees of freedom, including the translation degrees of freedom, applicable to the whole class of problems constituted by moving axisymmetric bodies, and able to explain the diversity of behaviours observed for bubbles, disks, etc…
- A mathematical classification of all possible solutions of this dynamical system, which may in addition be useful for other physical problems admitting the same symmetries.
- For the “object-in-pipe” and “object-in-jet” problems, detailed experimental database that could be used as benchmarks for future numerical studies.
- Original results on the physics of these situations.
- On a different plane, another expected outcome is a general statement on the efficiency, predictive power, and limitations of the theory of mode interactions. The idea will be pushed to its limits and tested against difficult cases (in particular when considering its application to turbulent situations), and will necessarily reach its own limitations at some point. New ideas will then have to be found to go beyond the present conceptual framework.

It is noteworthy that the general ideas of the proposal have emerged simultaneously in the various teams of the project, coming from rather different backgrounds and motivations. In IMFT, the motivation originated from the study of multiphase flows, with a particular focus on the dynamics of bubbles. In the ONERA team the work presented above was motivated by an aeronautical application, namely the modelisation of unsteady loading experienced by afterbodies of spatial launchers. After exploration of the potential of the present theory on academic situations, a coming back to these applications is expected at the outcome of the project.

One of the main outcomes of the project is the delineation of the bounds of the theory of mode interaction. After two or three decades devoted to deep explorations in the field of the stability theory, supported by increasing capacities in CFD (which allows now for instance sounded investigations of global aspects of flow stability) there is a clear demand, coming from both the fundamental and the engineering sides of the community in Fluid Mechanics, for some statements about the potential of these approaches.
3. **Programme scientifique et technique, organisation du projet / Scientific and technical programme, project management**

3.1. **Programme scientifique et structuration du projet / Scientific programme, specific aims of the proposal**

The scientific programme and the methodology have been presented in the previous paragraphs. In this section we explain the organisation of the project.

The project is structured along two axes, according to the manner of investigation (global stability theory, mathematical analysis, numerical simulations, experiments), and according to the chosen generic situations (“free objects”, “hot objects”, “object-in-pipe”, “object-in-jet”). This leads to the “matrix” organisation illustrated in figure 5.

The horizontal structure corresponds to four main tasks which correspond to the four types of investigation cited above. Two additional tasks are devoted to coordination (task 0) and synthesis (task 5).

The vertical structure reproduces the four generic situations listed above, plus the additional situation of a fixed object, which is required as a preliminary validation case for some tasks.

Figure 6 positions the previous studies of the participants in the project, already described in section 2.1, in the same matrix diagram.
Figure 6: Matrix representation of previous work by the partners in the project.
3.2. COORDINATION DU PROJET / PROJECT MANAGEMENT  
(2 pages maximum)

Préciser les aspects organisationnels du projet et les modalités de coordination (si possible individualisation d’une tâche coordination : cf. tâche 0 du document de soumission A).

Owing to the matrix organisation of the project, coordination responsibilities are of two kinds. There will be both “horizontal coordinators” in charge of a given task, and “vertical coordinators” in charge of activities related to a given generic situation (GS), who will also be in charge of the overall synthesis of their case.

Task 1 (Weakly nonlinear theory) will be coordinated jointly by D. Fabre and D. Sipp. The main point of coordination will be to manage the transfer of competence from ONERA, which furnishes the numerical tool used for this task, to IMFT where this tool will be used and extended to include the additional degrees of freedom characteristic of the moving object problem.

Task 2 (Mathematical analysis) will be coordinated jointly by D. Fabre and E. Knobloch. This activity will be carried autonomously but is expected to benefit from the other tasks and provide direction to them for the duration of the whole project.

Task 3 (Numerical simulation) will be coordinated by G. Bouchet. His specific role will be first to manage the cross-fertilisation between the different numerical codes of the partners and possible transfer of technology between them, and secondly to define how the different cases to be studied will be distributed among the teams.

Task 3 (experiments) will be coordinated by P. Ern. Her specific role will be to manage the cross-fertilisation between the experimental competences existing in the IMFT and ONERA teams, particularly in trajectory mapping.

GS 1 (free objects) will be coordinated by D. Fabre. He will gather the results of all activities to prepare the synthesis, which in this case is expected to be rather exhaustive.

GS 2 (hot objects) will be coordinated by G. Bouchet, as activities planned on this case are mostly of numerical nature and will be carried out at IMFS.

GS 3 (objects-in-pipe) will be coordinated by P. Ern. A specific point requiring coordination is the confrontation of experimental activities (IMFT) with the numerical computations and modelling (IMFS) of this case.

GS 4 (objects-in-jet) will be coordinated by L. Jacquin. Here the main aspect which requires coordination is the introduction of turbulence, which will have to be introduced in a convenient and coherent way in the theoretical and numerical activities, guided by the experimental results.

To ensure a good coordination between the different tasks and partners, progress meetings will be organised each year.

3.3. DESCRIPTION DES TRAVAUX PAR TÂCHE / DETAILED DESCRIPTION OF THE WORK ORGANISED BY TASKS

The proposed project spans four years divided into eight semesters numbered S1 to S8, with a start date expected in September, 2009. A proposed schedule of each subtask is given in terms of these semesters.
3.3.0 Task 0 : Coordination
As explained in the previous paragraph, the coordination task is divided into four “horizontal subtasks” (0-H1 to 0-H4) and four “vertical subtasks” (0-V1 to 0-V4)

Subtask 0-H1 : Weakly nonlinear theory (D.Fabre/D. Sipp)
Subtask 0-H2 : Mathematical analysis (D.Fabre/E. Knobloch)
Subtask 0-H3 : Numerical simulations (G. Bouchet)
Subtask 0-H4 : Experiments (P.Ern)
Subtask 0-V1 : Free objects (D.Fabre)
Subtask 0-V2 : Free hot objects (G. Bouchet)
Subtask 0-V3 : Objects-in-pipe (P. Ern)
Subtask 0-V4 : Objects-in-jet (L. Jacquin)

3.3.1 Task1 : Linear and weakly nonlinear global stability theory

Coordinators : D. Fabre / D. Sipp
Participants : IMFT (post-doc), ONERA, IMFS

This task is the central part of the proposal. The goal is to develop a weakly nonlinear global stability approach applicable to the whole class of problems considered in the project, namely axisymmetric bodies moving freely in a viscous fluid. As stated above, a global stability code allowing this kind of computations for fixed bodies has already been developed in the ONERA team. This existing numerical tool will form the starting point for this task. A post-doc with specific competences in global stability and asymptotic methods will be recruited for the first year of the project. He will be based in the IMFT team but will also spend a part of his time in the ONERA team. The activity will then be continued by a PhD student (also involved in task 3).

The task is composed of four subtasks.

Subtask 1-1 : Linear and weakly nonlinear global stability for fixed objects (S1-S3).
The first activity (1.1a, S1) will be to assimilate the existing ONERA code and import it to IMFT. As a first application, the code will be applied to the wakes of cylindrical and spheroidal bodies which have been studied previously at IMFT by numerical means. The continuation of this subtask (activity 1.1b, S2-S3) concerns the extension to heated or cooled fixed bodies. Technically, this requires the introduction of an additional equation governing heat convection to the basic equations of the problem (Navier-Stokes). This step will be done in interaction with the IMFS team whose numerical code can also be used to perform linear global stability calculations.

Subtask 1-2 : Global stability for free objects (S1-S3).
This subtask will be divided into two activities. First (activity 1-2a, S1), the study will be restricted to the linear part of the problem, in the case of motion in a quiescent and unbounded fluid. This step is necessary to identify the linearly most amplified modes. Technically, the linear problem for moving bodies is similar to the related problem for fixed bodies, except for additional terms arising from the degrees of freedom of the body and their coupling with the wake dynamics. Incorporation of these additional terms will result in a generalised eigenvalue problem which will be solved in the same way as for the fixed body problem. The expected outcome of this subtask is the identification of a set of leading eigenmodes which will constitute the “kernel” or “central variety” of the nonlinear problem.

The next step (activity 1-2b, S2-S3) is to investigate the weakly nonlinear coupling effects between the leading modes previously identified, still in the case of motion in a quiescent and unbounded fluid. The objective is to arrive to a nonlinear system similar to the one governing the fixed body problem where all coupling terms are entirely determined as
function of the body characteristics. Such a computation is already tedious for the fixed body problem, and can be expected to be even more complex for the moving body problem, especially if the central variety for the moving body turns out to contain a larger number of modes than for the fixed object.

Subtask 1-3 : Global stability for free objects, extensions (S3-S6)

The objective of this subtask is to extend the analyses of the previous ones to treat the next generic situations targeted by the program. Three activities, concerning the application to “hot objects” (1-3a), “object-in-tube” (1-3b) and “object-in-jet” (1-3c) (restricted in the latter two cases to laminar flow) are planned. A final planned activity (1.3d), which is relevant to the last two generic problems, concerns the extension to the case where the jet (or pipe) is slightly tilted. Assuming the inclination angle to be small and developing the base flow as a function of this small parameter should make the problem tractable within the weakly nonlinear framework. This task is a rather straightforward extension of the previous subtask. No precise agenda is given for this extension which will be undertaken depending on the degree of progress on the corresponding primary tasks.

Subtask 1-4 : Global stability for moving objects in a turbulent flow (S5-S6)

The next subtask is devoted to the application of the global stability approach to situations characterised by the presence of turbulence. This extension is necessary when one wants to address problems characterised by large Reynolds numbers, such as the object-in-pipe problem in presence of a strong counterflow, or the object-in-jet problem. There are conceptual problems related to the use of linear stability concepts for turbulent flow as one may object that the unstable eigenmodes revealed by the theory are in some way already present in the “turbulent” part of the flow. As a consequence, this task is intended as exploratory, and the objective is simply to test the potential of the approach for such problems. A crucial point is the selection of a relevant base flow to introduce in the code for such developments. This point is the object of another subtask (3.5) whose accomplishment is a precondition for the start of the present one.

3.3.2 Task 2 : Mathematical analysis of model dynamical systems

Contributors : D. Fabre (IMFT), E. Knobloch (UC-Berkeley)

The work proposed in this task consists of a purely mathematical study of systems of dynamical equations describing mode interactions for fixed and moving objects. These resemble Eq. (1) in the first task but include additional modes corresponding to translational and rotational degrees of freedom of a free body. However, here the purpose is not to derive such systems for a given object and compute the precise values of the coupling constants from a weakly nonlinear analysis, but rather to consider these systems in general, with arbitrary coefficients, to provide a general classification of the possible solutions, independent of specific application, using the tools of the mathematical theory of dynamical systems with symmetry (Golubitsky et al., 1988; Crawford & Knobloch, 1991). This task is strongly linked with the preceding one. However, to start the mathematical analysis planned here, the only mandatory result is the knowledge of the most amplified linear modes (activity 1-2a), as the generic form of the corresponding nonlinear systems can be deduced a priori from symmetry considerations.

The results of this task should provide useful guidelines for the interpretation of the results obtained in the other tasks, and to indicate ranges of coefficient values for which interesting dynamics can be expected.

This task is divided into three subtasks.

Subtask 2-1 : Mathematical analysis of dynamical systems for fixed bodies
In the first subtask, we will concentrate on the normal form of the fixed body problem, as given in Eq. (1). A classification of the simplest solutions (steady or periodic) of this system is already available (Golubitsky et al., 1988). Preliminary investigations have shown that this dynamical system also admits more exotic solutions, such as 2-frequency solutions, chaotic solutions, heteroclinic cycles, etc... Interestingly, the mathematical structure of the system (Eq. 1) shows close resemblance with a system studied in Hirshberg & Knobloch (1993; 1998) initially derived for a chemical reaction-diffusion problem. This activity is already well advanced, so that a first publication can be expected within the first months of the project.

Subtask 2-2 : Mathematical analysis of dynamical systems for moving bodies

In this subtask, the same kind of analysis will be performed for systems governing the motion of free bodies in the four principal cases of interest. Compared to the case of a fixed body, the mathematical models expected here will include additional modes associated with the translational and rotational degrees of freedom of the body. As the first case we will consider motion in a quiescent, unbounded fluid (activity 2.2a). In this case at least one additional mode is expected: the translational mode associated with changes in the mean velocity. This translational mode is expected to be weakly damped but strongly coupled with the other ones. Spontaneous symmetry-breaking may lead to the excitation of horizontal translation modes, involved in tumbling and zigzagging. The next activity (2.2b) is the extension to motion in an inhomogeneous environment (which is relevant to both the “object-in-pipe” and “object-in-jet” situations). Here, additional modes associated to the breaking of the invariance under horizontal translation are expected to intervene.

Subtask 2-3 : Strongly nonlinear models.

The last subtask (2.3), which is more exploratory, is an extension of the previous models into the strongly nonlinear regime. The aim is to derive, using symmetry considerations, models applicable to strongly nonlinear motions, such as the large-amplitude oscillations of the object observed in the object-in-jet problem, or tumbling motions of free flat objects.

It is important to stress that results obtained in this task may be useful for completely different applications than the ones considered in the project. Indeed, normal form theory guarantees that dynamical systems of the kind considered here are generic to all problems sharing the same symmetry group. For example, the system (Eq. 1) relevant to fixed objects was initially derived for the Taylor-Couette system (flow between two concentric rotating cylinders). As a consequence, the results obtained here will be disseminated independently of the remainder of the project, for example, by publication in mathematical journals.

3.3.3 Task 3 : numerical simulations

Coordinator : G. Bouchet
Participants : IMFT (PhD), IMFS, ONERA

The IMFT team will provide their numerical code (called JADIM). This code, developed for about 15 years in the team, is devoted to the study of multiphase flows and allows one to treat a very large range of situations, including volume tracking of deformable interfaces (through the VOF method), tracking of Lagrangian particles, and Large Eddy Simulations of turbulent flows, for a variety of geometries. The particular version of the code used in the project solves simultaneously the Navier-Stokes equations governing the flow in the reference frame of the body, and the Kelvin-Kirchhoff Equations governing the trajectory of the body. This version of the code, initially developed for the case of a rising bubble (Mougin & Magnaudet, 2002), was adapted for the case of cylindrical objects during the PhD of F. Auguste, and successfully validated against experimental data.

The IMFS team will provide two numerical codes.
The Spectral Element – Fourier IMplicit - EXplicit solver SEFIMEX has been developed with a special focus on the simulation of transient flows in axisymmetric geometries. The incompressible Navier-Stokes and scalar transport equations are solved in cylindrical coordinates. The spatial discretization combines a spectral element discretization in the radial-axial plane with a Fourier expansion in the azimuthal direction. A fully implicit numerical method has been specially designed to accommodate the coupling with the degrees of freedom of a freely moving sphere at very limited extra costs and without robustness tradeoffs whatever the sphere density.

The Navier-Stokes Multi-Block (NSMB) code is a multi-purpose industrial code to the development of which the team contributes thanks to Yannick Hoarau (member of the IMFS team). The source code is thus fully available as well as the necessary expertise to tailor the code to the team’s needs. At its origin, the code is a compressible Navier-Stokes control volume solver applied mainly to aerodynamic simulations in complex geometries. The code performs well in the low Mach limit and is being reformulated for fully incompressible Navier-Stokes equations. The project will take advantage of the geometrical flexibility, parallelization and of the implementation of the chimera method for the treatment of moving geometries.

The numerical activity planned at ONERA will use the same numerical tool as used in task 1 based on finite element discretisation and written using the free-fem++ toolbox.

**Subtask 3.1 : Optimisation and cross-fertilisation of the numerical codes (S1-S2)**

The code of the IMFT team (JADIM) suffers from two main drawbacks which do not affect its precision but impose the use of a very small time step, resulting in very long computation times. The aim of this task is to optimise the existing code in order to overcome these drawbacks. The expected outcome is a gain in computational time of about a factor 10.

The first limitation of the code is due to the nature of the computational mesh. The requirements of a fine resolution in the vicinity of the body and of a sufficiently large computational domain result in the presence of very coarse mesh cells located far away from the body. This property does not pose any particular problem for fixed objects placed within a uniform flow. On the other hand, when computing the flow around a moving body, the mesh is moving along with the body, and relative velocities with respect to the mesh can attain much higher values, especially if the body is experiencing strong rotations. Owing to the classical CFL stability condition (which imposes the time step to be everywhere smaller than the grid step divided by the velocity), the computations require very small time steps. The first activity (3.1a) aims at avoiding this difficulty by using other kinds of meshes with a more uniform grid step distribution away from the body. Meshes based on a conformal mapping are expected to be adapted to this purpose.

The second limitation of the code arises from the strategy employed for the coupling between the motion of the body and the flow around it. In the present state of the code, the velocity of the body is assumed to be constant during each time step. At the end of a time step, the flow field is updated, the forces exerted on the body are computed, and the velocity of the body is impulsively modified to a new value which is held constant during the next time step. This impulsive variation of the velocity affects the production of vorticity at the surface of the body by the occurrence of a Stokes layer. This difficulty was analysed in detail in Mougin & Magnaudet (2002b). They showed that, although the temporal schemes used for the Navier-Stokes solver and the Kelvin–Kirchhoff equations are both of second order of accuracy, the coupled scheme is only accurate up to order $\frac{1}{2}$ in case of no-slip conditions (i.e. for solid bodies) and 1 for no-stress conditions (i.e. for bubble). The proposed solution is to modify the code in order to introduce an implicit treatment of the viscous force exerted at the surface of the body (3.1b). This solution has already been put into practise by Jenny et al. (2004) for the case of a moving sphere and the IMFS team will put its experience at disposal to help in implementing its method within the JADIM code.
The principal limitation of the code of the IMFS team, in its current formulation, is to be able to treat efficiently only the movements (free falls or free rise) of spherical objects. The reasons are basically the same as those stated by the IMFT team. In the framework of the project, an implicit version the code will provide a choice between a mostly explicit and a mostly implicit formulation to circumvent, if necessary, the restrictive CFL criterion. This is expected to make it possible to accommodate, at low costs, the domain rotation (3.1c).

Once implemented in the codes, all these improvements will have to be validated extensively (activity 3.1d).

Subtask 3.2: intensive simulations for free objects (S3-S7)

The aim of this task is to perform numerical simulations of the flow around moving bodies using the numerical codes already in use in IMFT and IMFS. Concerning IMFT, this task will constitute the main part of the work of a PhD student who will be recruited within the project and is expected to join the team in September of the first year (m0). He or she will first work in close collaboration with F. Auguste (who is expected to leave the team after the first year of the project) to take in hand the existing code.

The first activity consists of an extensive investigation of the dynamics of free moving objects by numerical means. The beginning of this subtask is delayed to S3 in order to benefit from the optimised code that will be developed in task 3. The expected outcome of this task is a general classification of the various kinds of motions (zig-zag, helix, tumbling, chaotic motions etc...) as a function of the three dimensionless parameters of the problem (Archimedes number, density ratio and aspect ratio of the body), as well as a fine characterisation of the flow for each kind of motion. Because of the three free parameters, a systematic study will be very consuming in terms of computational costs, and output for the theoretical activities of tasks 1, 2 and 5 will be very useful in order to identify the ranges of parameters leading to interesting behaviours.

A complementarity of both available codes, JADIM and SEFIMEX, is expected. In the first stage, the comparison of results will help in validating the numerical algorithms in absence of reliable and sufficiently fine experimental data. Further on, depending on the code performance in individual configurations the work load will be shared between both teams. Objects with sharp edges are likely to be better suited for simulation with JADIM whereas spheroids can better benefit from the pseudospectral discretization of SEFIMEX.

Subtask 3.3: Simulations of moving objects with thermal effects (S3-S7)

The aim of this part of the present project is to complete the investigation of trajectography of single particles by taking account of thermal effects to enlarge the scope of practical applications of the proposed research. Simulations will be performed using the spectral element numerical code developed at IMFS and presented above. As can be extrapolated from results of Jenny et al. 2004 and of Kotouc et al. 2008 b, the dynamics of the flow and of the particle in early stages of transition obeys a weakly non-linear theory whatever the complexity of the configuration. Even in the simplifying framework of Boussinesq approximation, addition of the free sphere movement to the flow and temperature fields brings the number of parameters to four (Galileo, Grashof, Prandtl numbers and solid/fluid density ratio). Covering all possible cases by sweeping the whole 4-parameter space becomes an interesting challenge for the sweeping strategy and for the mobilization of computing resources. The theoretical tasks of the project will be especially helpful to guide the numerical investigation planned in this subtask. Two activities are planned, first restricting to Boussinesq approximation (activity 3.3a, S3-S5), and then focusing on the problem of movement of an ice particule within water, which requires the use of a more realistic state equation (activity 3.3b, S6-S7).
Subtask 3.4 : Simulations of “objects-in-pipe” (S1-S6)

The numerical study of a fall near a wall is not a trivial task: it involves fluid-structure interaction (the movement of the sphere derives from the pressure and viscous forces of the fluid on its surface), moving-grid, turbulence or transition to turbulence, which implies high grid density namely in the boundary layers. To be able to solve these problems we have decided to implement the chimera methodology in our Navier-Stokes solver.

The chimera overset scheme provides a simple solution for simulations of flow past complex geometries or moving geometries. This method was developed by Benek et al. and there are many studies using this technique. The chimera method consists in solving the equations on overlapping grids. The main difficulty is the communication between the overset blocks. We have implemented an interpolation technique based on the inverse distance and an arbitrary stencil of points to improve the accuracy. Setting up these interpolated values on the overlapped block can be done in two ways: in the first method, called “switch method”, the interpolated values are simply imposed whereas in the second method, they are combined to the local values coming from the resolution of the Navier-Stokes equation (Fujii). These two methods have been implemented in the NSMB code which solves the Navier-Stokes equations for steady or unsteady compressible and incompressible flows.

We have used the chimera method to simulate the flow past a 2D cylinder and two cylinder in tandem and compared our results to that in literature. The first results are consistent with the previous work and validate the implementation of the chimera method. The implementation of the chimera methodology has been done in the first year of the PhD thesis of Thibaut Deloze (Numerical simulation of the flow around a sphere falling in a tube). In the second year of this thesis, which corresponds to the first year of this project, we will improve the interpolation technique to enable the parallelization of the chimera methodology and we will modify the implementation to handle moving chimera grids. In the same time we start to study the flow around a fixed sphere placed near a wall. In the second year of the project we plan to implement the fluid-structure interaction of the moving sphere and to compute the numerical solution of a sphere falling in a tube under gravity. In the two last years we will study the transition to turbulence of this kind of flows depending on the sphere to tube diameter ratio.

Subtask 3.5 : Generation of an axisymmetric turbulent base-flow (S5-S6)

The aim of this subtask is to generate numerically an axisymmetric “base-flow” solution for the object-in-jet problem and object-in-tube, which will serve as a starting point for the weakly nonlinear modelisation planned in task 1-4. The solution will be computed using the FreeFem-based-software developed at ONERA-DAFE, which also constitutes the basis of the weakly nonlinear developments of task 1. The difference between base-flows and mean-flows has been addressed by Sipp & Lebedev (2007) and is crucial for both the success and physical relevance of the linear and weakly non linear analysis. Different strategies will be tested in order to obtain relevant steady base flows. One will try to get closer as possible from the experiments. This could necessitate the use of a turbulence model.

3.3.4 Task 4 : Experimental studies (S1-S6)

Coordinator : P. Ern
Participants : IMFT (PhD), ONERA

This task contains three different experimental activities, devoted to three of the generic situations described in section 1, namely the free object, the object-in-pipe, and the object-in-jet. Two PhD students will be involved in these activities, one at IMFT, the other at ONERA.
Subtask 4.1 : Experiments for free objects (S1-S3)

The aim of this task is to perform experimental measurements of the motion of free objects in order to validate the numerical/theoretical calculations and to extend the range of situations explored. The experimental set-up already in use in the IMFT team allows us to measure the three-dimensional path of one or several bodies rising or falling freely under the effect of buoyancy in a fluid at rest. The body is followed by two travelling cameras. The evolution in time of the body’s position and orientation is then retrieved by image processing. Such experiments have already been successfully carried out during the PhD thesis of P. C. Fernandes (2002-2005) and of N. Brosse (2007-2010).

The activity planned here is a continuation of these researches, with a particular focus on a specific range of parameters corresponding to thin bodies (thin disks of diameter-to-thickness ratio larger than 6) moving at Reynolds numbers about $130 < \text{Re} < 200$. As described in section 2.1, recent numerical simulations suggest the existence in this range of Reynolds numbers of new kinds of behaviour, including the controversial rectilinear nonvertical paths, two-period and three-period motions, as well as weakly chaotic paths. Detailed experiments will be carried out in this regime for bodies of various density ratios. The experimental difficulty is that the fluctuations in the body motion due to the intrinsic dynamics of the fluid-body system are of the same order of magnitude as the surrounding perturbations in the liquid (e.g. due to density or temperature fluctuations). The input of the numerical and theoretical results will help us to process the experimental measurements and in particular to separate the characteristics of the intrinsic dynamics from the background perturbations.

Subtask 4.2 : Moving objects in a vertical pipe (S1-S8)

The scope of the second experimental task is to investigate the effect of confinement on freely moving bodies. As presented in §2-1, the confinement is expected to affect the transition from the rectilinear to the periodic path as well as the nature and characteristics of the selected paths. In the case of unconfined freely moving bodies, for a large range of parameters the path can be considered in a first approximation to be contained in a vertical plane : the path is a helix of low eccentricity, nearly a zigzag path. As a first stage (activity 4.2a), the effect of breaking the symmetry of the path with respect to the vertical will be explored by introducing a single wall in the experiment. Several behaviors of the body can then be expected: a lateral migration, the body moving away from the wall, or on the contrary a vertical sliding of the body along the wall. This experiment is in line with the experiments on the motion of two freely moving bodies interacting through the flow induced by their motion, which are currently performed by N. Brosse in his PhD Thesis.

A PhD thesis, spanning the three last years of the project, will be subsequently devoted to strongly confined motions, focusing on disks (of diameter $d$) falling/rising in circular ducts of diameter $D < 3d$. Since the liquid flow field induced by the body motion is strongly altered with respect to the unconfined case, the transition from a rectilinear path to a periodic path is expected to occur at different Reynolds numbers than in the unconfined case, depending also on the degree of confinement $d/D$. Also, different periodic motions may appear. In particular, helical motions may be preferred either to the rectilinear path or to the zigzag path. After considering the case of a body confined in a pipe filled with quiescent liquid (activity 4.2b), a counterflow will be added, first (activity 4.2c) as a weak and laminar flow (i.e., a flow of mean velocity smaller or of the order of magnitude as the gravitational velocity of the body) and second, stronger and turbulent flow (activity 4.2d). Concerning the latter aspect, the analysis of the measurements will be performed in close interaction with the work developed in subtask 4.3. This task requires a specific experimental configuration to be set up (the details are given in § 6.1).

As in subtask 4.1, the experiments will consist in following the body motion with two cameras and image processing will allow us to obtain the position and orientation of the body as a function of time. In several specific configurations, such as the helical motion in a
confined channel, the velocity field induced by the body could also be measured by Particle Image Velocimetry in a horizontal plane (i.e. in a section of the duct).

**Subtask 4.3 : Experiment on the object-in-jet (S3-S8)**

The objective of this subtask is to provide novel experimental data on the sphere/jet flow. These data will be based on the simultaneous applications of two measurement techniques: the PIV, that provides snapshots of the velocity field around the sphere, and model deformation measurements (MDM), a stereoscopic CCD imaging technique developed at ONERA-DAFE that will allow thanks to the tracking of reference markers the localisation of the instantaneous position and rotation of the sphere in the flow (Le Sant et al 2005, 2007). Such a database coupling simultaneous information on large 3D movements of an object with the flow velocity around it has never been accomplished.

These experiments will be performed in the ONERA team. A close interaction with the numerical (3.3) and theoretical (1.3) activities on the same problem is expected.

A PhD, spanning the three last years of the project, will be devoted to this subtask.

**3.3.5 Task 5 : Synthesis**

Coordinator : David Fabre
Participants : all.

This task will occupy the last year of the project. At this time, the theoretical parts of the project (tasks 1 and 2) should be mostly completed. The first goal of the year (subtask 5-1) will be to prepare a general synthesis on the fundamental aspects of the project. The expected outcome is to provide generic models which potentially contains the whole diversity of observed behaviours, and are able to predict the possible bifurcations between all of these states. The synthesis is also expected to provide a systematic cartography of all possible states for a given family of generic bodies, such as spheroids or cylinders. Such a systematic study can be expected to be helpful for a large range of applications.

The second goal of the synthesis will be to reorient the numerical and experimental activities of the project towards situations less academicals and closer to potential applications. Although no precise anticipation about the directions that will be explored at this stage can be made, three domains of applications are particularly suspected:

- The first potential application is the modelling of dispersed two-phase flows, such as clouds of rising bubbles, sedimenting particles, etc... This field of application constitutes the core of the activity of the INTERFACE research group. The ideas explored in this proposal may result as
- The second potential application is towards aeronautical flows characterised by much higher Reynolds numbers. One example of such flow is that in the wake a launcher after-body, a configuration actively studied in the associated ONERA team. This flow is characterized by a massive separated area that generates strong low frequency wall-pressure fluctuations and induces aerodynamic excitation, resulting in high dynamic loads and intense oscillations that can be critical during the transonic phase of flight.
- The last expected field of application is the dynamics of small organisms, such as plankton, seeds, etc... This application may lead to the extension toward different geometries, including flexible objects and structures (in connection with subtask 5-c).
- Regarding the “hot-object” and “object-in-pipe” problems, the obvious applications are industrial ones,

The synthesis task will occupy the last year of the project. It will be divided in four subtasks according to the generic situations investigated in the project. Each subtask will be managed by the corresponding “vertical coordinator”, as defined in section 3.2. The expected outcomes of this synthesis have already been described in section 2.2.
Subtask 5-1: Synthesis on free objects (D. Fabre)
Subtask 5-2: Synthesis on hot objects (G. Bouchet)
Subtask 5-3: Synthesis on Objects-in-pipe (P. Ern)
Subtask 5-4: Synthesis on Objects-in-jet (L. Jacquin)

3.4. CALENDRIER DES TACHES, LIVRABLES ET JALONS / PLANNING OF TASKS, DELIVERABLES AND MILESTONES

Here is presented the expected planning of the tasks, indicating relations and deliverables (with stars). The list of deliverables of the project is given below.

<table>
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<tr>
<th>Tâche / Task</th>
<th>Intitulé et nature des livrables et des jalons / Title and substance of the deliverables and milestones</th>
<th>Date de fourniture / Delivery date, in months starting from T0</th>
<th>Partenaire responsable du livrable / Partner in charge of the deliverable</th>
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<td>Work Package 1: Weakly nonlinear global stability analysis</td>
<td>D1. Weakly nonlinear stability analysis for fixed objects</td>
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<td>IMFT, ONERA</td>
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• TABLEAU des LIVRABLES / Deliverables
2. Weakly nonlinear stability analysis for free moving objects

D3. Mathematical study of dynamical systems for fixed objects

D4. Dynamical systems for free moving objects

D5. State-of-the-art on numerical tools and definition of strategy for next numerical activities

D6. Numerical cartography of the free-object problem

D7. Numerical cartography of the free-heated-object problem

D8. Numerical database for objects-in-pipe

D9. Generation of turbulent base flows for global stability

D10. Experimental results for free objects

D11. Experimental database for objects-in-pipe

D12. Experimental database for objects-in-jet

D13. General synthesis

Completion of task 1.1a (importation of the ONERA global stability code to IMFT) at m6 is mandatory for next activities but should not pose any problem. The complete outcome of task 1.1 (including thermal effects) will be presented in deliverable D1 at m18.

Subtask 1.2 is expected to provide a global stability code for moving objects which is of central importance in the project. The achievement is expected at m24 and will be presented in deliverable D2. Delay in this subtask may strongly affect the progress of the project.

Subtask 1.4 starts at 36 and is conditioned by subtask 3.5.

The output of subtask 2.1 is expected at m12 and presented in deliverable D3. This output, as well as the identification of the linear kernel for the moving object problem (activity 1.2a), are mandatory to start the next subtasks (2.2, 2.3) whose outcome will be synthesised at m42 in deliverable D4.

Subtask 3.1 will occupy the first year of the project, resulting in a deliverable (D4) presenting the State-of-the-art on available numerical tools and the definition of a common strategy for the intensive simulations on free objects planned in the next subtask (3.2). The outcome of this intensive parametric study will be delivered at m42 in D5.

Tasks 3.2 will start at m12 and will benefit from the optimised codes performed in the former subtasks. The corresponding results will be delivered, respectively, at m42 (D6) and m48 (D7). Task 3.3 will be accomplished in the two first years of the project and the outcome will be delivered at m30 (D8)

The outcome of subtask 3.5 will be delivered at m36 (D9). As already stated it is mandatory for the starting of Subtask 1.4.

The outcome of the experimental activities are expected at m24 for subtask 4.1 (D10), and at m42 for the two next ones (4.2 : D11).

The final year of the project will be devoted to the preparation of the synthesis. Numerous deliverables previously mentioned are due at m42, and will help for the preparation of the final report at m48 (D13).

4. STRATEGIE DE VALORISATION DES RESULTATS ET MODE DE PROTECTION ET D’EXPLOITATION DES RESULTATS / DATA MANAGEMENT, DATA SHARING, INTELLECTUAL PROPERTY AND RESULTS EXPLOITATION
As the kind of research planned here is of fundamental nature, the privilegiated means of dissemination will be publication in scientific journals and participation in international congress.

During the last year of the project, the participants wish to organise an international symposium to share the results of the project with the academic community. Support for such a symposium could be demanded, for example, to the Euromech or IUTAM societies.

Communication to a wider public will also be intended. The obvious relation of the present problems to day-life situations (falling leaves and seeds, rising bubbles, etc...) as well as their entertaining aspect, in particular for the sphere-in-jet problem, offer a good potential for vulgarisation. Publications in scientific journals of large audience (La recherche, Scientific American, etc...) is envisaged. Participation to local and national events (journées portes-ouvertes, journée de la science, etc...) is also planned.

5. ORGANISATION DU PARTENARIAT / CONSORTIUM ORGANISATION AND DESCRIPTION

5.1. DESCRIPTION, ADÉQUATION ET COMPLÉMENTARITÉ DES PARTENAIRES / RELEVANCE AND COMPLEMENTARITY OF THE PARTNERS WITHIN THE CONSORTIUM

5.1.1. IMFT

IMFT (Institut de Mécanique des Fluides de Toulouse) is one of the largest fluid mechanics laboratories in France. The INTERFACE group (15 permanent researchers) , to which belong the participants of the present project, gathers one of the strongest research potential in Europe on the topic of multiphase flows, in particular through the combination of modelisation, numerical simulation and experimentation. The international radiation of researches carried in this group is attested by numerous high-level publications and plenary lectures.

The IMFT team is composed of two junior researchers (D. Fabre and P. Ern), one senior researcher (J. Magnaudet), two research engineers (A. Pedrono and S. Cazin) and two PhD students already in position (F. Auguste and N. Brosse). The team will be completed by a post-doc (in the first year) who will be mostly involved in the theoretical part (task 1) and a PhD student who will continue these activities, and will also take in charge the numerical part of the project (task 3).

Patricia Ern has carried out several experimental and theoretical investigations on hydrodynamical instabilities. She has supervised with F. Risso and J. Magnaudet the PhD thesis of P. C. Fernandes (2005) and is now supervising the PhD thesis of N. Brosse, both devoted to the experimental study of freely moving bodies.

Jacques Magnaudet is a senior researcher and one of the leading figures of the INTERFACE research group in IMFT. He has been at the origin of the studies on moving objects now conducted in IMFT, in particular as advisor of the PhD of G. Mougin on rising bubbles. He is also one of the creators of the JADIM numerical code used in task 3, and his expertise will be especially useful for these activities.

F. Auguste is supposed to defend his PhD in March 2009, and will be still present in the team, in with ATER position (temporary associate teacher and researcher), during the first months of the project. N. Brosse started his PHD in 2007 an will be present in the team for first year.

A. Pedrono is member of the “COSINUS” service of IMFT, devoted to support on numerical resource and code development. S. Cazin is member of the “Signaux-Image” service devoted to support on measurement and visualisations.
5.1.2 IMFS

The institute of mechanics of the fluids and solids (IMFS) is a laboratory associated for its scientific activity both to the National center of scientific research (CNRS) to the University of Strasbourg.

The team involved in this project is Instabilities, Turbulence, Two-phase flows (ITD). One of the most noteworthy contributions of the ITD group at IMFS in recent years consists in a series of numerical and theoretical results on the breaking of axisymmetry by hydrodynamic instabilities. A primary fully non-linear theoretical analysis of axisymmetry breaking allowed us to develop an original, efficient and accurate Navier-Stokes solver combining the spectral element discretization and the azimuthal Fourier decomposition. The participants in the project are G. Bouchet (CNRS research scientist), Y. Hoarau (Associated professor), a PhD student (T. Deloze) and J. Dusek (Professor). The PhD student started in 2007 and will be present in the team for the two first years of the project schedule. A post-doc financed by ANR will reinforce the team.

Gilles Bouchet has carried out several experimental and numerical investigations on hydrodynamic instabilities. He has supervised, with J. Dusek, the PhD theses of M. Jenny and M. Kotouc devoted, respectively, to the theoretical, numerical and experimental investigation of a free sphere and of a heated sphere.

Yannick Hoarau is one of major contributors of the NSMB control volume compressible Navier-Stokes code. In the framework of the present PhD thesis of T. Deloze he has implemented an incompressible version of the solver and introduced a chimera method of treatment of moving geometry. These improvements will be applied to simulation of a freely moving sphere in a circular channel (task 2).

Jan Dusek heads the ITD research team at IMFS. He was at the origin of the theoretical study of the axisymmetry breaking as supervisor of the PhD of B. Ghidersa. He is also the creator of the numerical code used in tasks 3.2 and 3.3. During the project he will provide expertise for the numerical and theoretical activities and support of the spectral-element – Fourier numerical code.

5.1.2. ONERA

ONERA (8 sites, 1700 employees) is a multidisciplinary scientific and technical establishment with industrial and commercial status, supervised by the French Ministry of Defence. ONERA conducts and orients research programs in field of aeronautics and space, targeting on industrial applications. The Department of Fundamental and Experimental Aerodynamics (DAFE, 50 persons) belongs to the Fluid Mechanics & Energetics Branch of ONERA. DAFE concentrates its activities on the comprehension of complex flows (turbulence, vortex shedding, shocks interactions,...) and the development of new flow control theories. DAFE has also developed a long experience concerning flow metrology and it can propose in particular a new technology concerning Model Deformation Measurement (MDM) to be used with the time resolved version of PIV for the study of moving objects.

Laurent Jacquin is leading the Department of Fundamental and Experimental Aerodynamics (DAFE) since 2003 where he advises theoretical and experimental works of different kinds on aerodynamics. The ‘ball in jet’ problem was one of his a favourite pedagogic support during his laboratory courses on Aerodynamics at Ecole Polytechnique where he used such a bench to illustrate as much basic aerodynamic rules as the space which is let for research in this domain. Two centuries after the pioneering works by O. Reynolds, one of the pioneering explorer of the turbulence enigma, recent developments on flow stability, on CFD and on metrology offer today an opportunity to revisit this fascinating problem with a novel ambition. An experiment has been launched in 2008 in the framework of Samuel Davoust’s master internship.
Denis Sipp is working at ONERA/DAFE where he is mainly involved in stability and control of detached flows. He is at the origin of the global stability code that will be used in task 1. His participation to the project will be crucial for the transfer of this tool to the IFMT team. He has been in contact with D. Fabre since 1998, when D. Fabre was a PhD student in ONERA/DAFE. L. Jacquin was the advisor of the thesis works of D. Sipp and D. Fabre, and these three contributors have already collaborated in various projects on vortex stability and they have already published several common papers on this subject.

Samuel Davoust has started a PhD on a different subject but his expertise in the experimental aspects will be required in the project.

Yves Le Sant is a research engineer in charge of the experimental facilities and measurement methods.

5.1.4 UC-Berkeley

University of California at Berbeley is represented in the project by Edgar Knobloch. E.K. is a reputed expert on the theory of dynamical systems. He is a regular visitor to IMFT and already collaborates with other teams of the laboratory. He got involved in the present problem during one of his visits in 2007, and will be contributing to the mathematical part of the proposal (task 2). His implication as an applied mathematician provides an indication of the broad interdisciplinary nature of this project.

5.2. Qualification du coordinateur du projet / Qualification of the project coordinator

David Fabre, the leader of the project, is an expert in hydrodynamic stability, asymptotic methods and numerical simulation. In the former years he has mostly worked on the stability of vortex flows, with application to trailing vortex wakes. Since his recruitment in IMFT, he got involved in the problem of moving objects and is supervising the PhD of Franck Auguste on this topic.

David Fabre has already been involved in 5 national and international research projects. In particular, he is the scientific manager of the IMFT team for two ongoing projects on vortex stability, namely the “FAR-WAKE” European project and the ANR project “VORTEX”. Both these projects will be finished by the end of 2008, before the expected beginning of the present project.

D.F. is a former member of the ONERA team where he did his PhD from 1998 to 2002, and has since maintained an active collaboration with this team. He has also started a collaboration with E. Knobloch in 2007 on the mathematical aspects on the present proposal.

D. Fabre has obtained for 2008/2009 a partial delegation to CNRS, implying relief of half of his current teaching load.
## 5.3. Qualification, rôle et implication des participants / Contribution and qualification of each project participant

<table>
<thead>
<tr>
<th>Partenaire 1 : IMFT</th>
<th>Nom</th>
<th>Prénom</th>
<th>Emploi actuel</th>
<th>Personne mois</th>
<th>Rôle / Responsabilité dans le projet 4 lignes max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinateur</td>
<td>Fabre</td>
<td>David</td>
<td>Maître de Conférences</td>
<td>48</td>
<td>General coordination ; Coordination of task 1, 2 and VA 1 ; Expertise in linear stability and bifurcation theory.</td>
</tr>
<tr>
<td>Ern</td>
<td></td>
<td></td>
<td>Chargée de recherche</td>
<td>24</td>
<td>Coordination of task 4 and VA 3 ; Expertise on experimentation</td>
</tr>
<tr>
<td>Magnaudet</td>
<td></td>
<td></td>
<td>Directeur de recherche</td>
<td>12</td>
<td>Expertise on numerical analysis, turbulence modelling and multiphase flows.</td>
</tr>
<tr>
<td>Auguste</td>
<td></td>
<td></td>
<td>ATER (?)</td>
<td>12</td>
<td>Numerical code optimisation and intensive simulations</td>
</tr>
<tr>
<td>Brosse</td>
<td></td>
<td></td>
<td>PhD</td>
<td>12</td>
<td>Experiments on falling bodies.</td>
</tr>
<tr>
<td>Post-doc 1</td>
<td></td>
<td></td>
<td>Post-doc</td>
<td>24</td>
<td>Weakly nonlinear global stability theory (task 1).</td>
</tr>
<tr>
<td>PhD 1</td>
<td></td>
<td></td>
<td>PhD</td>
<td>36</td>
<td>Weakly nonlinear stability (task 1) and Numerical simulations (tasks 3.1 and 3.2).</td>
</tr>
<tr>
<td>PhD 2</td>
<td></td>
<td></td>
<td>PhD</td>
<td>36</td>
<td>Experimentation on free objects (4.1) and objects –in-pipe (4.2)</td>
</tr>
<tr>
<td>Cazin</td>
<td>Emmanu</td>
<td></td>
<td>Ingénieur de recherches</td>
<td>12</td>
<td>Technical support on visualisation and PIV.</td>
</tr>
<tr>
<td>Pedrono</td>
<td>Emmanu</td>
<td></td>
<td>Ingénieur de recherches</td>
<td>12</td>
<td>Technical support on numerical analysis and code development</td>
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</table>

<table>
<thead>
<tr>
<th>Partenaire 2 : IMFS</th>
<th>Nom</th>
<th>Prénom</th>
<th>Emploi actuel</th>
<th>Personne mois</th>
<th>Rôle / Responsabilité dans le projet 4 lignes max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinateur</td>
<td>Bouchet</td>
<td>Gilles</td>
<td>CR CNRS</td>
<td>24</td>
<td>Coordination of task 3 ; Expertise on numerical analysis.</td>
</tr>
<tr>
<td>Dusek</td>
<td>Ian</td>
<td></td>
<td>Professeur</td>
<td>18</td>
<td>Expertise on numerical analysis and bifurcation theory</td>
</tr>
<tr>
<td>Hoarau</td>
<td>Yannick</td>
<td></td>
<td>Maître de Conférences</td>
<td>12</td>
<td>Expertise on numerical scheme, moving grid</td>
</tr>
<tr>
<td>Deloze</td>
<td>Thibault</td>
<td></td>
<td>PhD Student</td>
<td>12</td>
<td>Numerical simulations (task 3.4)</td>
</tr>
<tr>
<td>Post-doc 2</td>
<td></td>
<td></td>
<td>PhD</td>
<td>12</td>
<td>Numerical simulations (tasks 3.2 and 3.3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Partenaire 3 : ONERA/DAFE</th>
<th>Nom</th>
<th>Prénom</th>
<th>Emploi actuel</th>
<th>Personne mois</th>
<th>Rôle / Responsabilité dans le projet 4 lignes max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinator</td>
<td>Jacquin</td>
<td>Laurent</td>
<td>Directeur de Recherche</td>
<td>12</td>
<td>Coordination of VA4 “object-in-jet” ; Expertise on turbulence modelling,</td>
</tr>
<tr>
<td>Sipp</td>
<td>Denis</td>
<td></td>
<td>Maître de Recherche</td>
<td>8</td>
<td>Coordination of task 1 ; Expertise on global stability theory and Weakly nonlinear methods</td>
</tr>
</tbody>
</table>
A one-page CV of all members of the team is given in the appendix.

6. JUSTIFICATION SCIENTIFIQUE DES MOYENS DEMANDES / SCIENTIFIC JUSTIFICATION OF REQUESTED BUDGET

On présentera ici pour chaque partenaire, la justification scientifique et technique des moyens demandés dans le document de soumission A. Ces moyens sont synthétisés à l’échelle du projet dans la fiche «Tableaux récapitulatifs » dans ce document de soumission A.

Chaque partenaire justifiera les moyens qu’il demande en distinguant les différents postes de dépenses selon le canevas suivant :

6.1. PARTENAIRE 1 / PARTNER 1 : IMFT

- **Équipement / Equipment**

Préciser la nature des équipements* et justifier le choix des équipements

Si nécessaire, préciser la part de financement demandé sur le projet et si les achats envisagés doivent être complétés par d’autres sources de financement. Si tel est le cas, indiquer le montant et l’origine de ces financements complémentaires.

*Un devis sera demandé si le projet est retenu pour financement.

The experimental investigation planned in section 3 (Task 4) requires the purchase of a high-resolution camera (2000x2000 pixels). This equipment will substantially improve the accuracy of the path measurements that can be performed, which is necessary in several particular regimes. Two such cameras are needed for the reconstruction of the full 3D paths, however an identical camera is already available in the laboratory and could be used simultaneously. The price of this camera is about 30k€, including the required optics and the acquisition computer. The experiments for freely moving bodies in a confined channel, possibly in the presence of a counterflow, require to build up a new experimental set-up. The IMFT laboratory hall permits to set up a vertical channel about 10-meter long, the measurements being then performed about mid-height. The advantage of such a long channel is to ensure that the paths observed are those corresponding to the steady-state. The experimental set-up will consist in transparent pipes of various diameters in which the bodies are released and retrieved through two lock-chamber systems. The motion of the bodies will be followed by two cameras mounted on a cart translating on a guiding track. The cart will be move manually to follow the body's motion, its position in time being recorded by a magnetic encoder. The cost of this experimental set-up is estimated to 15k€. The equipment needed to perform the Particle Image Velocimetry measurements is not asked from the ANR since this system will be used punctually and can be shared with other activities within the laboratory.
The financial support for the PhD Student to be involved in the experiments is also not asked from the ANR. Other expected expenses of the IMFT team include three personal computers for the post-doc, the PhD and the project leader. Global stability computations require an extended RAM (up to 32 Go) for storage of very large matrices; thus each of these computers is estimated to 4000 €.

In summary, regarding the experimental and numerical tasks at IMFT, the funding requested is estimated to 57 k€.

• Personnel / Staff

The project requires the recruitment of a post-doc for one year (S1-S2), who will be in charge of the theoretical aspects (task 1), and of two PhD students, the first one for numerical work (task 3; S1 to S6), the second one for experimental work (task 4; S3 to S8). The profiles of the corresponding positions are given in appendix.

The corresponding cost amounts to 49 000 € for the pot-doc plus 6 x 33000 € for the PhDs, leading to a total of 247 000 €. The funding for the post-doc and the first PhD is demanded to ANR, while the second one will be funded by other means (MESR, DGA, or industrial contract).

In summary, the total cost for nonpermanent staff is 247 k€, and the demanded contribution is 148 k€.

The manpower cost corresponding to the permanent staff, needed for the computation of the total cost of the project, has been estimated as follows:

<table>
<thead>
<tr>
<th>Staff/Position</th>
<th>Contract</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Fabre (MdC, 48 months)</td>
<td>4 x 1.8 x 45 000 €</td>
<td>324 000 €</td>
</tr>
<tr>
<td>P. Ern (CR1, 16 months)</td>
<td>2 x 1.8 x 66 000 €</td>
<td>237 600 €</td>
</tr>
<tr>
<td>J. Magnaudet (DR2, 8 months)</td>
<td>0.66 x 1.8 x 82 000 €</td>
<td>98 400 €</td>
</tr>
<tr>
<td>S. Cazin (IR, 12 months)</td>
<td>1 x 1.8 x 53 000 €</td>
<td>95 400 €</td>
</tr>
<tr>
<td>A. Pedrono (IE, 12 months)</td>
<td>1 x 1.8 x 53 000 €</td>
<td>95 400 €</td>
</tr>
<tr>
<td>Total for permanent staff</td>
<td></td>
<td>860 800 €</td>
</tr>
<tr>
<td>F. Auguste (ATER, 1year)</td>
<td>1 x 1.8 x 49 000 € x 50 %</td>
<td>44 100 €</td>
</tr>
<tr>
<td>N. Brosse (Doctorant, 1year)</td>
<td>1 x 1.8 x 33 000 €</td>
<td>59 400 €</td>
</tr>
<tr>
<td>Total for nonpermanent staff not financiered by ANR</td>
<td></td>
<td>103 500 €</td>
</tr>
</tbody>
</table>

Total manpower cost = 964 300 €

• Prestation de service externe / Subcontracting

• Missions / Missions

The travel expenses needed for the members of the IMFT team include the participation to national and international congresses, as well as visits to the other collaborators involved in the project.

The cost estimation is based on one international mission (estimated to 2000 €) and two national missions (estimated to 500 €) for each of the six researchers member of the IMFT (disregarding the students who will only be present in the first year).

For the post-doc, the transfer of competence for the global stability code of the ONERA team will also require a one-month stay in Paris, estimated to 2000 €.

The total mission cost therefore amounts to 6x2000 + 12x500+2000 = 20 000 €. Adding the mission costs of partner 4 (se above), the total mission cost demanded to ANR is 250000 k€.
Other expenses

A contribution to the common resources and technical services of the laboratory, estimated for 10000€, is also demanded to ANR.

Total de l’aide demandée / Total demanded sum

The cost of the project funded by ANR therefore amounts to:

\[
148\,000 + 50\,000 + 15\,000 + 22\,000 = 240\,000 \text{ €}
\]

Adding the administrative fees (estimated to 4% of the this latter sum, i.e. 9600 €), leads to the total sum demanded to ANR : 249 600 €

6.2 Partenaire 2 / partner 2 : IMFS

Équipement / Equipment

The project assumes very large parametric studies. Our team can be considered as reference in this field because our papers Jenny et al. 2004 and Kotouc et al. 2008B, represent, to our knowledge, the most complete parametric investigations in the domain of transition to turbulence ever published. The mentioned parametric investigations necessitated two essential ingredients: very rapid and efficient algorithms and a large number of available processors for running a large number of independent simulations. Parallelization appeared to be rather counter-productive owing to losses in communications if several simultaneously running independent simulation were replaced by the same number of parallel runs executed one after another. For this reason we, so far, postponed the code parallelization and focused on the sequential optimization by balancing the rapidity and memory requirements depending on available computing material. At some stages of work we ran typically up to 50 simultaneous runs, which is easily explainable by the fact that the last published parametric study involved several thousands of independent simulations.

Such very specific needs require a resource management not provided on large national clusters of IDRIS and CINES and force us to seek acquisition of a dedicated, specifically tailored equipment. The algorithmic structure of the code SEFIMEX allows, due an increasing implementation of direct sparse algorithms, large acceleration of computations by using ever increasing memory. The balance is given practically exclusively by economic criteria. At present, the clock frequency of processors tends to saturate between 3 and 4 Ghz for processors available within reasonable price limits while the RAM limitations virtually exploded since the introduction of 64 bit architectures accompanied, in parallel, by a significant decrease of memory prices. As a result, our present strategy consists in purchasing medium performance processors with maximum available cache and RAM. The reduction of overhead costs, advantages in sharing memory and peripherals and in minimizing investment in additional cooling and networking makes us prefer multicore multiprocessor machines.

A rapid inspection of the present market seems to be in favor of the following configuration easily available ready to deliver:

- 4 processor motherboard, with 4 quads running at about 3 Ghz,
- 64 GB RAM
- 300 GB of rapid disk memory
- 1TB of standard disk

Delivered in standard housing (with standard peripherals, good video card, Gigabit network card) such a configuration is available roughly at EURO 8000.
In this demand we seek to acquire 4 machines of this type at total cost: **EURO 32 000**.

**Personnel / Staff**

The project requires the recruitment of a post-doc for one years (S5-S6), who will be in charge of the numerical aspects (task 3). The profile of the position is given in appendix.

The corresponding cost amounts to **49 000 €** for the post-doc. The funding for the post-doc is demanded to ANR.

The total cost for nonpermanent staff is **49 k€**, and the demanded contribution is **49 k€**.

The manpower cost corresponding to the permanent staff, needed for the computation of the total cost of the project, has been estimated as follows:

- G. Bouchet (CR1, 24 months): \(2 \times 1.8 \times 66 000€ = 237 600€\)
- Y. Hoarau (MdC, 12 months): \(1 \times 1.8 \times 45 000€ = 81 000€\)
- J. Dusek (PR1, 18 months): \(1.5 \times 1.8 \times 85 000€ = 229 500€\)

Total for permanent staff = **548 100€**

- T. Deloze (Doctorant, 1year): \(1 \times 1.8 \times 33 000€ = 59 400€\)

Total for nonpermanent staff not financiered by ANR = **59 400€**

**Total manpower cost** = **607 500€**

**Prestation de service externe / Subcontracting**

**Missions / Missions**

The travel expenses needed for the members of the IMFS team include the participation to national and international congresses, as well as visits to the other collaborators involved in the project.

The cost estimation is based on one international mission (estimated to 2000 €) and one national mission (estimated to 500 €) for each of the four researchers members of the IMFS over the duration of the project.

The total mission cost therefore amounts to **4x2000 + 4x500 = 10 000 €**.

In summary, the total mission cost is **10 k€** and is the part demanded to ANR is **10 k€**.

**Dépenses justifiées sur une procédure de facturation interne / Internal expenses**

**Autres dépenses de fonctionnement / Other expenses**

A contribution to the common resources and technical services of the laboratory, estimated for **10 000 €**, is also demanded to ANR.

In summary, the total cost of other expenses is **10 k€**, and the demanded contribution is **10 k€**.

**Total de l’aide demandée / Total demanded sum**

The cost of the project funded by ANR therefore amounts to:

\[32 000 + 49 000 + 10 000 + 10 000 = 101 000 €\]
Adding the administrative fees (estimated to 4% of the this latter sum, i.e. 4040 €), leads to the total sum demanded to ANR:

Total sum for partner 2: 105 040 €
6.3. Partenaire 3 / partner 3 : ONERA/DAFE

The project requires the recruitment of a PhD student (S3-S9), who will be in charge of the experimental work on the “object-in-jet” problem. The corresponding cost amounts to 104,976 € which is demanded to ANR. The cost of the experimental set-up and of the measurement devices are supported by ONERA.

The travel expenses needed for the members of the ONERA team include the participation to national and international congresses, as well as visits to the other collaborators involved in the project. The estimated mission cost is 4000 € and demanded to ANR.

The total request from ANR is thus 108,976 €

6.4. Partenaire 4 / partner 4 : UC-Berkeley

The last partner of the project is an international one, and therefore cannot apply for ANR fundings. As a consequence the expenses listed in this section have actually been credited to partner 1.

Mission expenses correspond to four one-month visits of E. Knobloch to Toulouse, estimated to 5000€ per month (total: 20000 €). Financing of one of these visits is demanded to ANR and has been credited to partner 1; the other ones will be covered partly by UC Berkeley, and partly by other resources such as invited professor positions from UPS.

7. Annexes

7.1. References bibliographiques / references


Davoust S. & Jacquin L. 2009 The suspension of a sphere in a turbulent jet, *the 7th Symposium on Turbulent Shear Flow Phenomenae*, TSFP7 (accepted).


Horowitz M. & Williamson C. 2007 Dynamics and wake patterns of freely rising and falling spheres at Re = 500, In *the 60th Annual Meeting of the Division of Fluid Dynamics November 18–20, 2007, Salt Lake City, Utah, USA*.


Klyachko L. 1963 Heat transfer between a gas and a spherical surface with the combined action of free and forced convection, *J. Heat Transfer* 85, 355-357.


Le Sant Y., Durand A., Merienne M.C., Image Processing Tools Used for PSP and Model Deformation Measurements, 35th AIAA Fluid Dynamics Conference and Exhibit, paper AIAA 2005-5007, Toronto, CN, 6-9 June 2005


### 7.2. Biographies / CV, Resume

*(une page maximum par personne)* Cf. § Erreur ! Source du renvoi introuvable.
David FABRE

Age : 33 ans.
Situation familiale : vie maritale, 1 enfant.
Adresse : 2 impasse André Broussin, 31100 Toulouse
Tél. : 06 68 87 41 61 ; Fax : 05 61 28 59 91 ; E-mail : David.Fabre@imft.fr

Emploi actuel :
Maître de conférences, Université Paul Sabatier (UPS) / Institut de Mécanique des fluides de Toulouse (IMFT).
Délégation à mi-temps au CNRS (impliquant une dispense d’enseignement) demandée pour 2008.
Habilitation à diriger les recherches envisagée pour 2009.

Cursus :
1995 DEA mécanique des fluides, ONERA Meudon / Université Paris VI.
1998-2002 Thèse en mécanique des fluides, ONERA Meudon / Université Paris VI.
2002-2003 Post-doc à l’ONERA Meudon
2004 ATER à l’Université Paul Sabatier

Encadrement de thèses et post-docs :

Contrats de recherche :

Publications :
Articles dans des journaux internationaux : 16 (7 JFM, 5 Physics of Fluids).
Sélection de 5 articles :

Patricia ERN

39 ans

Acronyme XXX

Chargée de Recherche de 1ère Classe au CNRS, Institut de Mécanique des Fluides de Toulouse (IMFT), depuis octobre 1999.

### Emplois précédents


### Cursus

1994 : Ingénieur Ecole Nationale des Ponts et Chaussées, Paris; D.E.A. Dynamique des Fluides et des Transferts, Université Paris XI.

### Implication dans d’autres projets

* Co-encadrement de 3 thèses de Doctorat (dont 1 bourse CIFRE et dont 1 soutenue).

### Publications

Articles dans des journaux internationaux : 13, dans des journaux nationaux : 2

Sélection de 5 références :


Jacques Magnaudet
Né le 22 mars 1959 à Bayonne, marié, 2 enfants

Formation

Parcours professionnel

Thèmes de recherche
Hydrodynamique, Ecoulements diphasiques, Turbulence, Méthodes numériques

Production scientifique
65 publications dans des revues à comité de lecture, 9 chapitres d'ouvrages, 22 conférences plénières, 48 participations à des colloques internationaux, 18 participations à des colloques nationaux, 26 séminaires invités

Activité contractuelle : 17 contrats de recherche (Air Liquide, Arcelor, CEA, CEE, CNES, EADS, EDF, IFP, St Gobain, Total…)

Management de la recherche :
04/2006 → Directeur de l'Institut de Mécanique des Fluides de Toulouse (UMR 5502)

Contribution à la formation par la recherche
17 thèses de doctorat soutenues, 3 en cours ; Membre d’environ 120 jurys de thèse et d'HDR, dont 45 en tant que rapporteur ; 1999 –2004 Responsable du DEA de Dynamique des Fluides de Toulouse ;2004 –2007 Directeur de l'Ecole Doctorale TYFEP (devenue MEGeP en 2007)

Activités d’enseignement

Activité éditoriale
2002 → Editeur Associé de International Journal of Multiphase Flow

Animation nationale et internationale de la recherche

Activités d’expertise et d’évaluation

Distinctions

Sélection de 5 publications récentes
Franck AUGUSTE
Age : 28 ans.
Situation familiale : célibataire.
Adresse : 48 Rue Henri Bergson, 31400 Toulouse
Tél. : 05 61 28 58 17 ; Fax : 05 61 28 59 91 ; E-mail : franck.auguste@imft.fr

EMPLOI ACTUEL
Doctorant, Institut de Mécanique des fluides de Toulouse (IMFT), jusqu’au 31/09/2008.
Moniteur, Université Paul Sabatier (UPS).

EMPLOIS PRECEDENTS

EMPLOI SUPPOSE EN 2009
ATER, Institut de Mécanique des fluides de Toulouse (IMFT) et Université Paul Sabatier (UPS).

CURSUS
2005 Master Dynamique, Énergétique et transferts, INP / Université Paul Sabatier.
2004 Licence-Maîtrise de mécanique, Université Paul Sabatier

PUBLICATIONS
Articles dans des journaux internationaux : 2.
Conférences avec actes : 1, sans actes : 3


Fabre D., Auguste F. & Magnaudet J., Bifurcations and symmetry breaking in the wake of a disk, 60th meeting of the APS Division of Fluid Dynamics, novembre 2007, Salt Lake City, USA.
Nicolas BROSSE
29 rue Gaston Phoebus
31300 Toulouse
Tél : 06 73 99 44 31
E-mail : Nicolas.Brosse@imft.fr

EMPLOI ACTUEL

Sujet :   « Mouvement et sillage de deux corps mobiles en interaction, libres ou couplés mécaniquement »

CURSUS

EXPERIENCE PROFESSIONNELLE
Eté 2007   Stage Master Recherche à l’IMFT de cinq mois. Étude expérimentale sur l’interaction de deux corps en chute libre dans un liquide au repos (Sillage, trajectoire, interaction)
Eté 2006   Stage au Bureau Central d’Etude pour les équipements d’Outre Mer (BCEOM) de cinq mois. Réalisation d’études d’aléa inondation. (Hydrologie et hydraulique fluviale)
Denis SIPP
35 ans.
Né le 13 mars 1972,
Nationalité française, marié, un enfant.

Adresse :
ONERA / DAFE, 8 rue des Vertugadins, 92190 Meudon. Tel : 01 46 23 51 55. Fax : 01 46 23 51 58
Mail : sipp@onera.fr


Thème de recherche : Instabilités en aérodynamique et leur contrôle.

Formation :

Encadrement de thèses :

Nombre de publications : 17 (dont 5 Journal of Fluid Mechanics, 10 Physics of Fluids)

Liste des publications significatives sur les 5 dernières années :
Laurent JACQUIN

Birth
• 24 February 1959 in Aix-en-Provence – France

Position
• Research Director ONERA
• Director of the Fundamental and Experimental Aerodynamics Dpt – ONERA
• Associated Professor in Mechanical Engineering at Ecole Polytechnique – Palaiseau

Background
• Master Degree in Mechanical Engineering from University of Marseilles in 1981
• PhD from University of Marseilles in 1983
• Research Habilitation (thèse d’état) from University of Lyon in 1987
• Joined ONERA in 1987.

Research topics:
Turbulence - hydrodynamic stability - vortex dynamics - compressible flows- aerodynamics, experimental methods

Scientific leadership
• Advised 15 PhD, 5 post-doc and 20 Master theses
• Referee in 44 PhD
• Leader task in three European projects on wake vortices (EuroWake,C-Wake, Farwake)

Publication activity
• 42 articles and 52 symposia

Honours
• Prize ” Sciences/Engineering ” EADS Foundation and Académie des Sciences – 2007

Recent selected publications
• Jacquin L. : « Aircraft trailing vortices » : an introduction », CR physique, 6, 2005
• Jacquin L., Fabre D., Sipp D. & Coustols E. : “Unsteadiness, instability and turbulence in trailing vortices”, CR physique, 6, 2005

Samuel Davoust

Né le 6 septembre 1984 à Heidelberg, Allemagne
PROGRAMME BLANC

Acronyme XXX

EDITION 2009

DOCUMENT DE SOUMISSION B

Coordonnées :
32, rue Anne Barratin
78100 Saint Germain-en-Laye
+33 6 32 55 53 95
samuel.davoust@polytechnique.org

Fonctions :
2008 : Début de Doctorat
ONERA, Département d’Aérodynamique Fondamentale et
Expérimentale, Meudon.
Etude Théorique et Expérimentale d’un Jet Tournant Turbulent

2008 : Stage de Master Recherche
ONERA, Département d’Aérodynamique Fondamentale et
Expérimentale, Meudon.
Etude Expérimentale d’une Sphère Suspendue dans un Jet

2007 : Ingénieur Stagiaire
EADS Astrium, Département Modélisation Outils Systèmes,
Toulouse.
Calcul Conductifs et Radiatifs Couplés pour les Satellites

2004 – 2005 : Service Militaire, Officier
8ème Régiment Parachutiste d’Infanterie de Marine, Castres.

Formation :
2002 : Baccalauréat Scientifique Option International Mention Bien

Congrès et Publications:

Motion of a Sphere Suspended in a Turbulent Jet, S. Davoust & L. Jacquin, Sixth International

Gilles BOUCHET

40 ans.
Né le 10 juin 1968,
Nationalité française, vie maritale, trois enfants.

Adresse :
IMFS, 2 rue Boussingault, 67000 Strasbourg. Tél. : 03 90 24 28 95. Fax : 03 88 61 43 00
Mail : bouchet@imfs.u-strasbg.fr

Position administrative : Chargé de recherche CNRS (CR1).
Thème de recherche : Instabilités et transition à la turbulence.

Formation :
1993-1996 : Doctorat, Université Paris VI, Bourse Docteur Ingénieur CNRS / Schlumberger, Laboratoire de Physique et Mécanique des Milieux Hétérogènes, ESPCI, Paris «Etupe expérimentale et numérique des auto-oscillations d’un jet confiné ».

1989-1992 : Diplôme d’ingénieur, ENSIMEV.

Encadrement de thèses :

3. Miroslav KOTOUČ (bourse MENRT) Transition au chaos d’une particule froide en fusion se déplaçant librement dans un fluide Newtonien (2005-2008) – 50 %
5. Cyril LOUX (bourse de la Région Alsace) Mélange dispersif de polymères (2007-) – 50 %
6. Tanvir AKBAR (bourse du gouvernement pakistanaïs) Etude et modélisation du décrochage dynamique (2007-) – 33 %

Nombre de publications : 11 articles dans des journaux internationaux, 15 conférences avec actes

Liste des publications significatives sur les 5 dernières années :

Jan DUSEK
57 ans.
Né le 30 août 1951,
Nationalité tchèque, marié, deux enfants.

Adresse :
IMFS, 2 rue Boussingault, 67000 Strasbourg. Tél. : 03 90 24 28 93. Fax : 03 88 61 43 00
Mail : dusek@imfs.u-strasbg.fr

Position administrative : Professeur des Universités (PR1).
Thème de recherche : Instabilités et transition à la turbulence.

Formation
Master de Physique Théorique, Faculté de Mathématiques et Physique de l’Université Charles de Prague (1975); 
Doctorat de 3ème cycle, Faculté de Mathématiques et Physique de l’Université Charles de Prague (1977); 

Expérience professionnelle
1976-1977 : Assistant, Département de Mathématiques, Ecole Supérieure de Génie Mécanique et Electrique (actuellement Université de Bohême de l’Ouest) à Plzen, République Tchèque;
1977-1980 : doctorant et enseignant vacataire au Département de Physique Mathématique, Faculté de Mathématiques et Physique de l’Université Charles de Prague;
1980-1988 : Maître de Conférences, Département de Physique, Ecole Supérieure de Génie Mécanique et Electrique à Plzen;
1988-1991 : Chercheur, Département de Mécanique des Fluides de l’Institut Central de Recherche Skoda à Plzen;
1991-1992 : Poste rouge de DR2 au CNRS à l’IMST Marseille;
1992-1995 : Professeur 2e cl. à l’Université de Bohême de l’Ouest, nombreux séjours en tant que professeur invité à l’Institut de Mécanique de Marseille, recherche : IMST, Marseille;
1995-2003 : Professeur 2e classe, ULP Strasbourg I;
2003- : Professeur 1ère classe.

Nombre de publications : 37 (dont 6 Journal of Fluid Mechanics, 4 Physics of Fluids)

Liste des publications significatives sur les 5 dernières années :
Yannick HOARAU

Maître de conférences à l’Université Louis Pasteur de Strasbourg depuis 2005
Institut de Mécanique des Fluides et des Solides de Strasbourg
Groupe « Instabilité, Diphasique, Turbulence »
2 rue Boussingault, 67000 Strasbourg
hoarau@imfs.u-strasbg.fr
Tel: 0 390 242 894
35 ans, Masculin

Cursus


06/06/2002 : Thèse de doctorat de Mécanique des Fluides à l’Institut de Mécanique des Fluides de Toulouse.
Sujet : Analyse physique par simulation numérique et modélisation des écoulements décollés instationnaires autour de surfaces portantes.


Sujet : Contrôle actif des ondes de Tollmien-Schlichting par aspiration - soufflage (sujet expérimental effectué à l’ONERA-Toulouse).


Publications : 13 articles et 25 actes de congrès avec à comité de lecture


Thibaud Deloze
IMFS
2 rue Boussingault
67000 Strasbourg
Tél : 0390.242.892
Email : deloze@imfs.u-strasbg.fr
Né le 15 mars 1981 (27 ans)
Emploi actuel :

Depuis octobre 2007 :

**Doctorant** en Mécanique des Fluides sur le couplage fluide-solide appliqué à l’étude de mouvement d’une sphère libre dans un tube, sous la direction du Professeur Jan Dusek et avec la participation de Yannick Hoarau dans le groupe Instabilité, Diphasique et turbulence de l’Institut de Mécanique des Fluides et des Solides de Strasbourg (UMR 7507, ULP-CNRS).

**Moniteur** à l’Université Louis Pasteur et encadrement de travaux pratiques de mécaniques des fluides, analyse des huiles et analyse vibratoire pour des étudiants en IUT 2ème année.

Cursus :

2006/07 : Master Physique, option Modélisation Numérique en Science Physique option mécanique des fluides
2005/06 : Maîtrise de Physique, option Modélisation Numérique
   - 2004/05 : Licence de Mécanique à l’Université Louis Pasteur de Strasbourg
   - 2001/04 : DEUG mention Physique à l’Université Louis Pasteur de Strasbourg
   - 2000 : Obtention du Baccalauréat mention Assez-Bien

Expériences professionnelles et stages :

- 2007 : stage de fin d’étude de 6 mois sur l’implémentation d’une méthode de gestion de maillages superposées dans un solveur parallèle multi-blocs des équations de Navier-Stokes (Navier Stokes Multi Blocks, NSMB).

Communications :

- **Septembre 2008** : présentation de l’étude d’une sphère fixe puis translatante uniformément à différentes distances d’une paroi plane à la « 7th EUROMECH Fluid Mechanics Conference » à Manchester (orateur : T. Deloze).
- **Juin 2008** : présentation et validation de la méthode chimère et son application dans l’étude de l’écoulement autour d’une sphère fixe proche paroi plane au « 5th European Congress on Computational Methods in Applied Sciences and Engineering » (ECCOMAS 2008), (orateur : Y. Hoarau)
- **Octobre 2007** : réunion des utilisateurs du code NSMB à Toulouse, présentation de la méthode chimère implémentée au meeting NSMB.
Edgar KNOBLOCH
Professor in Physics, University of California at Berkeley
Age : 54. Married, one child.

Education
Edgar Knobloch received his B.A. and M.A. in Mathematics in 1974 and 1978 from the University of Cambridge, UK. He received his A.M. and Ph.D. degrees in Astronomy from Harvard University in 1975 and 1978, and an Sc.D. from the University of Cambridge, UK, in 1994. He was an Alfred P Sloan Research Fellow (1980-84) and is a Fellow of the American Physical Society. In 1992 he was a Rosenbaum Fellow at the Isaac Newton Institute, Cambridge, and in 1996 he was a Visiting Fellow for one year at JILA, University of Colorado, Boulder. In 1999 he spent an extended period at the Institute for Theoretical Physics at UC Santa Barbara. In the fall of 2004 and again in the fall of 2005 he was a long term participant at the Newton Institute for Mathematical Sciences at the University of Cambridge. He has held visiting positions at Kyoto University, Université Paul Sabatier (Toulouse), Institut de Mécanique des Fluides de Toulouse (IMFT), Polytechnic University of Catalunya (Barcelona) and the University of Auckland, New Zealand.

Professional Appointments
Junior Fellow, Harvard Society of Fellows (1978-80)
Research Fellow, St John's College, Cambridge (1978-80)
Assistant Professor of Physics, University of California, Berkeley (1978-1984)
Associate Professor of Physics, University of California, Berkeley (1984-1987)
Professor of Physics, University of California, Berkeley (1987-present)
Professor of Applied Mathematics, University of Leeds, UK (2000-2004)

Current Research Interests
Fluid Dynamics, Nonlinear Dynamics, Reaction-diffusion systems.


Professional service
Societies: Elected to the advisory board of the SIAM Dynamical Systems Activity Group; past member and chair of the J D Crawford Prize Committee; current member of J D Crawford Prize Committee. Elected vice-president of the SIAM Nonlinear Waves Activity Group.
Member: American Physical Society (Fellow), Society for Industrial and Applied Mathematics.

Research supervision:
Students : 7 ; post-docs : 3

Scientific production:
Edgar Knobloch is the author or coauthor of approximately 250 refereed publications.
7.3. Implication des personnels dans d'autres contrats / involvement of project participants to other grants, contracts, etc ...

Table of projects already evaluated:

<table>
<thead>
<tr>
<th>Part.</th>
<th>Nom de la personne participant au projet</th>
<th>Personne. mois</th>
<th>Intitulé de l'appel à projets</th>
<th>Source de financement Montant attribué</th>
<th>Titre du projet</th>
<th>Nom du coordinateur</th>
<th>Date début &amp; Date fin</th>
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<tr>
<td>N° 1</td>
<td>J. Magnaudet</td>
<td>9</td>
<td>ANR Blanche 61 k€ (part IMFT)</td>
<td>GIMIC (Gravity-induced mixing in confined geometries)</td>
<td>J-P. Hulin (FAST)</td>
<td>2007 - 2010</td>
<td></td>
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<tr>
<td>N° 1</td>
<td>J. Magnaudet</td>
<td>6</td>
<td>Air Liquide 119.4 k€</td>
<td>Simulation de l’hydrodynamique des contacteurs à film</td>
<td>J. Magnaudet</td>
<td>2007 - 2009</td>
<td></td>
</tr>
<tr>
<td>N° 3</td>
<td>L. Jacquin D. Sipp</td>
<td>8 8</td>
<td>ANR Blanche 104 k€</td>
<td>ENTOMOPTERE</td>
<td>R. Godoy-Diana (ESPCI)</td>
<td>2008-2011</td>
<td></td>
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Table of projects under evaluation:

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<th>N° 1</th>
<th>J. Magnaudet</th>
<th>12</th>
<th>ANR blanche (IMFT : 119 k€)</th>
<th>TrapCell</th>
<th>Annie Viallat</th>
<th>2009 - 2012</th>
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<tr>
<td>N° 3</td>
<td>Sipp</td>
<td>18</td>
<td>ANR Blanche (ONERA : 134 k€)</td>
<td>SHOCK-BUFFET</td>
<td>Peter Schmid</td>
<td>2009 - 2013</td>
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