Computational Fluid Dynamics as a performance aid tool in rowing: utopia or reality

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ABSTRACT

The massive growth in computational power and advances in numerical modeling have made it feasible to use numerical simulations for analyzing and enhancing sports performance. This practice has already become standard for many years to design and optimize Formula 1 cars or racing sailboats. In water sports, this remains a challenging task due to the complexity and coupled physical phenomena typically involved, particularly when human interaction comes into play. Moreover, elite athletes already operate near the boundaries of optimal performance, leaving little room for improvement. Consequently, the modeling of all relevant phenomena must be sufficiently accurate to yield meaningful insights. This is essential for analyzing interactions and providing reliable trends when varying certain parameters. The case of rowing is presented here. After outlining the specific fluid mechanics aspects of this sport, it will be shown that Computation Fluid Dynamics (CFD) is now capable of addressing such complexity. Then, the main features of the high-fidelity Simulator of Performance in Rowing (SPRing) will be described. The remaining elements to be addressed in the simulator to be used in production will eventually be presented.

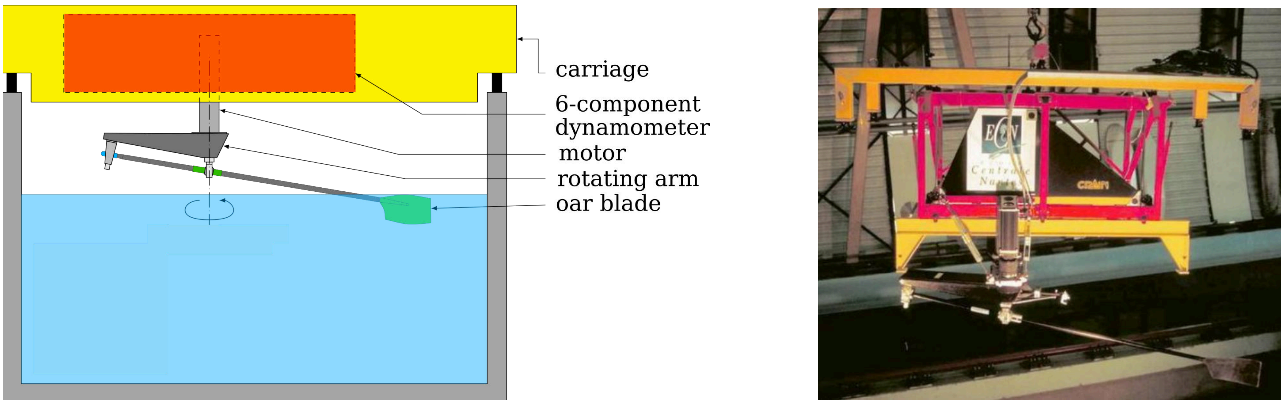
Keywords: Computational Fluid Dynamics (CFD); Fluid-Structure Interaction (FSI); high-fidelity Computational Fluid Dynamics approach; multiphysics; rowing; biomechanics; High Performance Computing (HPC).

1 INTRODUCTION

Numerical simulation is an increasingly useful and widely used tool across all branches of industry for designing and improving product performance. The same trend can be observed in sports, particularly in those that involve equipment. Thus, local weather forecasts are conducted to estimate the quality of ski slope snow and choose the most suitable waxing. In Formula 1, the entire car design undergoes extensive research, for mechanical parts as well as aerodynamics. Water sports are no exception, particularly in sailing. For example, the design process of new IMOCA class sailing boats involves more and more CFD simulations, especially to drive classical Velocity Performance Program (VPP) and also dynamics ones (Robin et al. (2024)). This is also especially true for America's Cup teams, which have the financial resources to make intensively use of CFD.
Does a sport like rowing deviate from the rule ? What is the current status, the future prospects, and the technological barriers to overcome ? After describing the specificities of fluid mechanics in rowing that generate complexity, it will be shown that CFD is now able to handle it (Robert et al. (2018)). Then, the crucial role of the interactions between the boat, the athletes and the oars will be described as well as the features and status of the high-fidelity Simulator of Performance in Rowing (SPRing), which fully couples the dynamic of the whole mechanical system Boat-Oars-Rower(s) (BOR) with fluid forces on hull and blades computed by the ISIS-CFD solver (Leroyer and Barré (2022)). The barriers that remain to be overcome in term of modeling and automation of data input will be analysed.

2 FLUID MECHANICS IN ROWING

Two complex flows are involved in rowing: the one around the boat and those around the blades. While the flow around these streamlined and elongated hulls might seem easy to model, it's actually complicated by large surge and pronounced secondary movements in heave and pitch. It results from a highly unsteady propulsion system driven by the forces generated by the athletes on the oar blades, as well as by the athletes' own motion relative to the hull. These features are quite unique in the field of ship resistance in calm water and little work can be found in the literature.
Some experimental work have been done in the towing tank of the LHEEA Lab., which has been used to validate the CFD simulation. In particular, it has been shown that the ISIS-CFD solver is able to reproduce the shifting phase between the oscillationg velocity signal and the resistance force (Robert et al. (2018)) for frequencies relevant to rowing.
In terms of complexity, the highly unsteady and violent flow around the blades, occurring close to the free surface, is no exception! In this situation, simplifying the problem by neglecting the presence of the free surface or by adopting a quasi-static approach doesn't really make sense, even though a few such attempts can be found in the literature (Caplan and Gardner (2007a); Coppel et al. (2008); Norstrud and Meese (2012); Yusof et al. (2017)). The unsteadiness and the proximity of the free surface makes modeling particularly challenging and requires the use of advanced simulation tools and computational resources to achieve a level of accuracy consistent with the objectives (Leroyer et al. (2008, 2010); Robert et al. (2018)). An extensive validation effort was carried out to ensure high fidelity and accurate numerical reproduction of these flow characteristics in the CFD simulations. For this purpose, a prior experimental campaign was employed, utilizing a custom-built apparatus in the LHEEA towing tank to replicate the key physical features of an actual rowing stroke with a real oar, see Fig. 1 and Barré (1998) for more details. Originally conducted to enhance the understanding of the flow physics and to support simplified modeling efforts, this experimental campaign — unique in its kind to the best of the author's knowledge — was later used as a reference database for CFD validation, see Fig. 2 for illustrative purposes and Robert (2017); Robert et al. (2018) for the complete description of the validation.

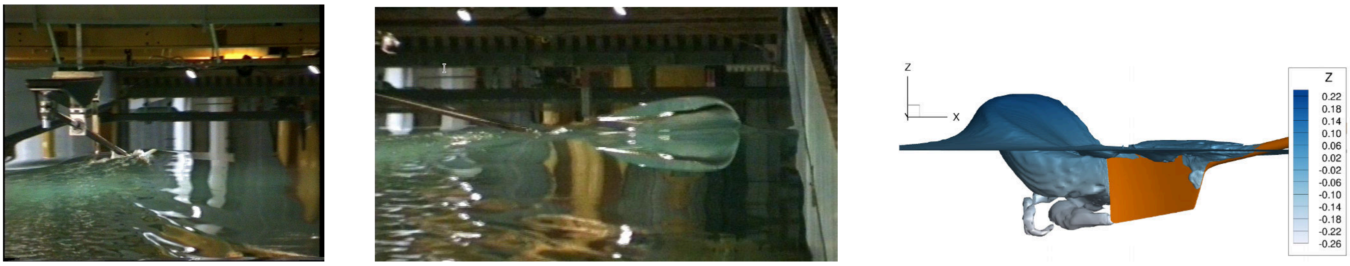


(a) Sketch of the specific device mounted on the carriage (dimensions are not respected).

(b) Device being mounted onto the carriage during lifting in the LHEEA Lab. towing tank.

Figure 1: Custom-built apparatus to reproduce a simplified rowing stroke using real oar.

While it was found that the simplified models could not meet the accuracy requirements for the intended application (Barré and Kobus (2010)), this reference dataset proved to be extremely valuable for validating the CFD tool (Robert et al. (2018)). In particular, it was shown that we were able to reproduce, within the measurement uncertainty, the different components of the hydrodynamic forces on the blade, as well as the sensitivities to various settings (blade immersion depth, blade pitch, oar flexibility, etc.).
Validating the flow fields was a crucial step that allowed to confidently start the mechanical model's development.



(a) Begin of the imposed rotation of the oar.

(b) Closest view during the propulsive phase.

(c) Simulation of the test n°154 at sweep angle=135°.

Figure 2: Experimental campaign used for CFD tool validation.

3 ROWING AS A MECHANICAL SYSTEM

Mastery of flow modeling, which was the result of this previous work, isn't enough on its own to provide a performance-enhancing tool. It's essential to be able to integrate and couple these numerical simulations with a mechanical model of the complete BOR system. This model, in turn, needs to be precise enough to accurately reproduce and differentiate the technical signatures of various rowers and the numerous adjustale parameters (rowing rigging).

3.1 Specificities

The substantial mass and inertia difference between the boat and the rower means the rower's movement profoundly affects boat dynamics. The rower's distinctive gestural signature (including the temporal evolution of hand height, particularly in the catch and release phases and muscle group sequencing, see Fig. 3) subsequently dictates how propulsive force is generated at the blades. In addition to that, this hydrodynamic force is coupled to the flexibility of the oar shaft.
To provide a valuable performance-support tool, all these complex interactions need to be reproducible. That's clearly a very ambitious project.

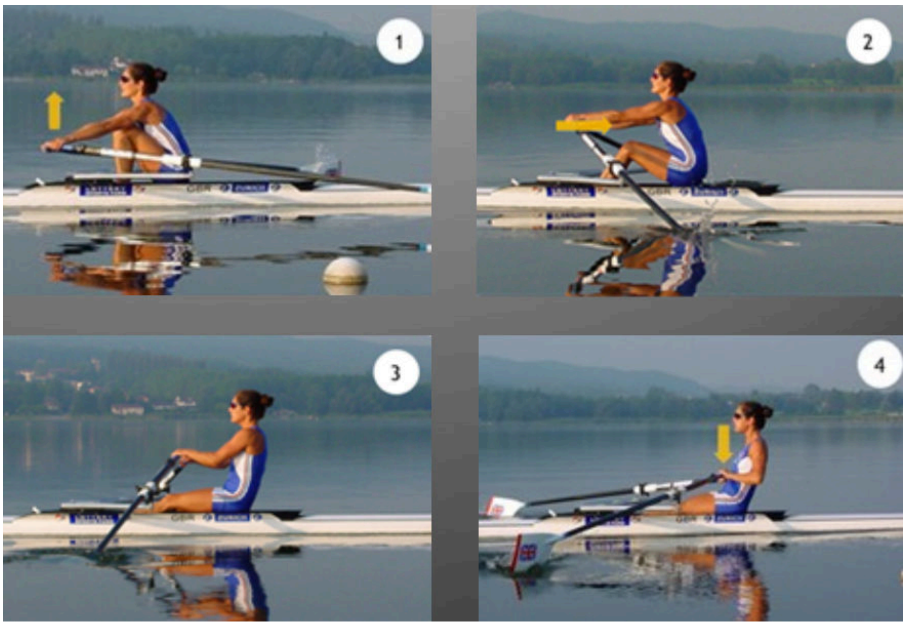


Figure 3: Some snapshots of the driving phase of a rowing stroke, including the catch (1) and the release (4). Source: http://britishrowing.org/rowing-stroke.

3.2 Literature review

Several studies aiming to model the global BOR system are reported in the literature. Many of them consider the rower as a point mass whose motion is prescribed relative to the boat (Pope (1973); Sanderson and Martindale (1986); Brearley et al. (1998); Cabrera et al. (2006); Caplan and Gardner (2007b); Sliasas and Tullis (2009, 2010); Pettersson et al. (2014)). Among these, a multibody model is sometimes used, but only to refine the kinematics of the rower and thus the evolution of the center of mass position: the dynamics remain based on a point mass, with varying levels of refinement (Cabrera et al. (2006); Caplan and Gardner (2007b); Pettersson et al. (2014)). The analysis is then limited to the interaction with the surge motion of the hull, without any consideration of pitch or heave motions, and using a simplified model for the fluid forces acting on the hull and blades.

Only Sliasas and Tullis (2009) and Sliasas and Tullis (2010) use a CFD model to evaluate the fluid force acting on the blade within a point mass framework, but without any vertical motion of the blade. Furthermore, the shaft flexibility considered in Sliasas and Tullis (2009) leads to rather questionable results, with a negative propulsive force at the end of the drive phase ! The modeling of shaft deformation is simplified and performed via a weak coupling approach, by recalculating the same stroke multiple times using the deformation obtained from fluid forces of the previous stroke (Sliasas and Tullis (2011)), which is far from optimal in terms of computational cost.

In contrast, Serveto et al. (2009); Formaggia et al. (2009a,b); Rongère et al. (2011) and Rongère (2011) have used more advanced multibody models that account for the evolution of both the center of mass and the system's inertia. A more realistic system dynamics can then be resolved, by coupling the yaw, surge, and pitch motions. However, the fluid models remain limited to simplified representations of the fluid force acting on the blade, and most often, on the hull as well. Nonetheless, more refined models have been employed to study the flow around the hull: Formaggia et al. (2009a) describes a method based on potential flow to assess the fluid force on the hull. Formaggia et al. (2009b) also use this model and compare the results with a RANS model.

4 SPRing project

High-fidelity modeling can be likened to high performance in sport — in this case, rowing. To reach the asymptote of what is possible, that is, the full potential, no aspect can be neglected without risking becoming the weak link. The levers of each component must be pushed to their limits.

For the SPRing simulator, this requires not only evaluating hydrodynamic loads through CFD calculations, but also tightly coupling them with a detailed deformation model of the oar shaft, not to mention the athletes themselves — an integral part of the mechanical system and dominant in terms of inertia as exposed in section 3.1: for reference, in a single scull, the rower typically weighs between 70 and 90 kg, while the boat itself weighs only about 14 kg! Modeling them is particularly challenging, as it involves capturing the full subtleties of their motion patterns, which influence both the generation of hydrodynamic forces and the overall hull dynamics.

4.1 Overview of the model and the chosen approach

The BOR system is mechanically considered as a system composed of a set of rigid bodies. The mass is conserved over time, while its inertial properties — namely the position of the center of gravity and the inertia matrix — vary according to the internal degrees of freedom defined by the position of the oars and the rower(s) relative to the boat. Once the floating reference frame attached to the boat is defined, the resolution of the BOR system dynamics reduces to applying the Newton's laws to a system subjected to external forces, but whose inertial properties vary over time (Leroyer and Visonneau (2005)). The hull's kinematics is therefore the outcome of the resolution process. Except for gravity, most of the external forces — strongly coupled to the BOR system — originate from hydrodynamic forces acting on the hull and the blades. To achieve a high-fidelity model, these forces are computed using CFD (Robert et al. (2018)). The coupling, based on an internal implicit algorithm, must be stabilized through an appropriate procedure (Yvin et al. (2018)). Aerodynamic forces, exhibiting limited contributions, are represented by simplified analytical models.

In addition to that, a mechanical model describing shaft deformation, based on an evolution law of the bending stiffness, is achieved. It is calibrated through a specific portable bench to measure the deformation of the oar shaft and the position/orientation modification of the blade. This flexibility bench is based on the use of lasers and targets, which makes it possible to derive a law of linear and angular deflection of the oar blade relative to the reference plane defined by the collar's contact surface on the oarlock, see Fig. 4.
The deformation of the oar shaft is also solved simultaneously with the other variables using a quasi-static approach stabilized by an added mass operator which does not alter the converged solution.

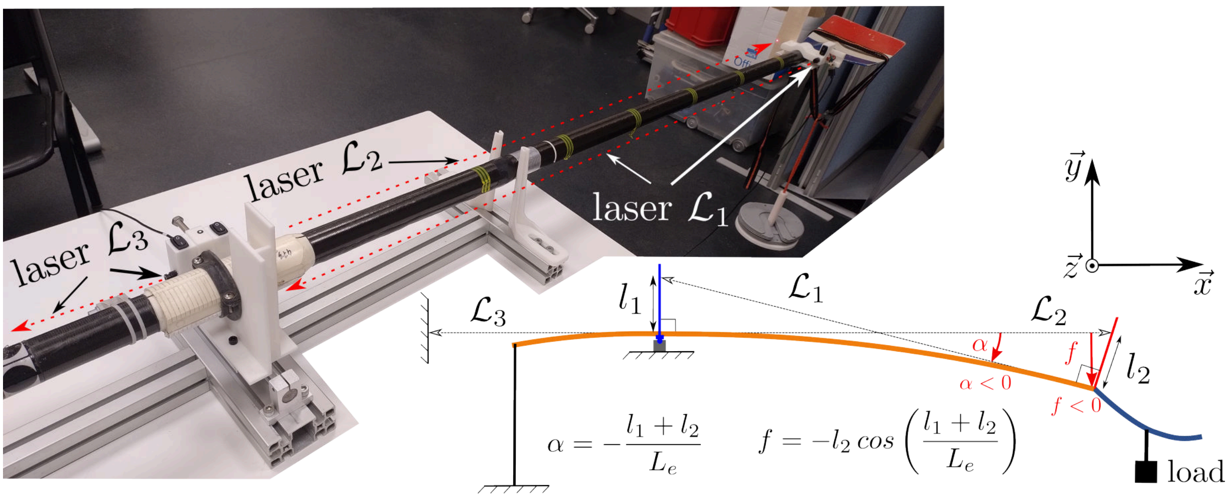


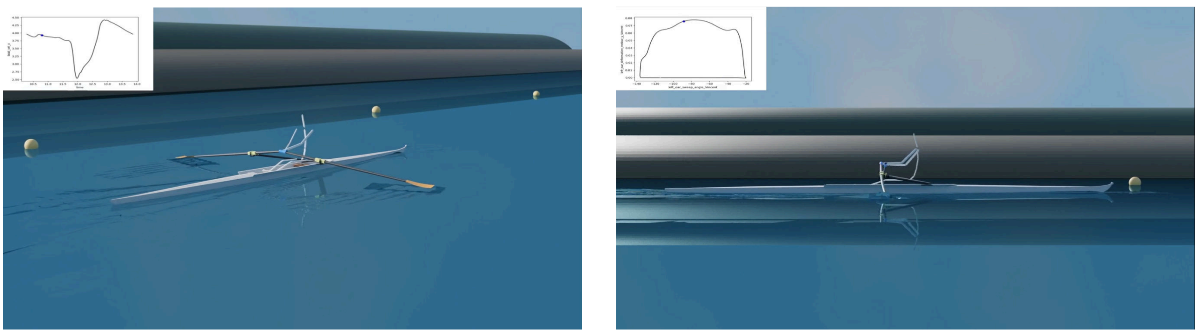
Figure 4: Photo of the flexibility bench and diagram of the laser-based deformation measurement method. Laser $\mathcal{L}_3$, aligned horizontally, measures the shaft deformation. Model calibration uses this data while enforcing displacement (f) and angular (α) constraints at the blade root via lasers $\mathcal{L}_1$ and $\mathcal{L}_2$ (L_e refers to the distance between the two targets).

For the control-command of the athletes themselves, the approach based on directly actuating joint torques to produce the rower's motion was not retained. While this strategy may appear to best reflect the functioning of the athlete's neuromuscular system, it is particularly challenging to implement when attempting to reproduce a given motion signature, due to the strong dependency of the resulting kinematics on system interactions. As a result, an imposed-kinematics approach was preferred, in which each rower is explicitly driven. Although not yet been implemented, the joint torques required to achieve the imposed kinematics could subsequently be inferred for biomechanical analysis. While this approach does not resolve all challenges, it greatly simplifies the control problem. Moreover, it aligns with the coach's perspective, which is primarily grounded in the observation of the rowers' movements — readily accessible during on-water training — rather than in the forces that produced them.
Thus, the control of each rower relies, on the one hand, on an imposed kinematic trajectory of the oar, which determines the position of the rower's hands over time (with the feet being fixed to the foot stretcher attached to the boat), and on the other hand, on the parameterization of a gesture signature that incrementally defines the sequencing of the main muscle groups (legs, back, and arms) throughout the two phases (drive and recovery) of the rowing stroke.

4.2 Input data

Aside from equipment-related data (such as the CAD geometry of the boat and blades, oar settings, etc.), an anatomical description of each rower is required. Currently, this is performed through manual measurement of the various segment lengths. An inertial model of each limb is then derived using the work and anthropometric model proposed by Leva (1996).
As described previously, the oar kinematics is imposed. It is divided into two distinct components: the angular sweep as a function of time, and the vertical position of the blade relative to the water. The sweep angle can be modeled based on experimental data, as this is part of the standard set of measurements collected in situ. However, the recorded data must be processed to average the signals and ensure they are perfectly periodic. For that, a kind of phase average is applied to keep average value of extrema. Additional work was carried out to synthesize the discrete periodic angular signal into parametric curves, enabling easy modification of this kinematic signature, and allowing the study of its influence on the boat's dynamics. The durations of the drive and recovery phases, as well as their shapes, can thus be easily adjusted by modifying the control points. Regarding the vertical position of the blade relative to the water, a parametric model was developed in the absence of direct measurements. For now, the calibration of the various parameters is performed visually using a dedicated interface, supported by video observations and analysis of experimental measurements (Leroyer and Barré (2022)). This parameterization is expected to evolve, as its descriptive capability presents certain limitations.
Regarding the gesture signature of the rower, even though the position of the oar (and thus the handles) is known over time, this does not uniquely define the rower's posture: there are infinitely many combinations of joint angles that allow the rower's feet and hands to be correctly positioned (with the feet on the foot stretcher and the hands on the handles). Moreover, the rower's motion relative to the boat must be sufficiently smooth (at least of $\mathcal{C}^2$ class) so that the boat's dynamic response is also smooth. To address these challenges, when a new position of the handles is imposed, the adopted method distributes the contributions of each muscle group (leg, trunc, arms) according to their relative range of motion percentage, rather than the ratio of angular sweep. Thus, this strategy follows an incremental formulation: the rower's posture is explicitly defined only at execution time. Nevertheless, the specification of muscular contributions remains both intuitive and readily interpretable in terms of its influence on the resulting motion signature. The asymmetry between port and starboard movement patterns is accounted for both by a rotation of the torso around an axis aligned with the spine, and by an asymmetric behavior of the arms, following a distribution law that forms part of the overall parameterization of the gesture signature. To further refine this signature, additional motion-related parameters have been incorporated or are currently under development. These include the curvature of the spine, the minimum ankle angle prior to foot lift-off from the foot stretcher, and a predefined shoulder extension law during the catch phase. These refinements aim to capture more subtle biomechanical characteristics of the rowing motion.

All these combined elements result in high-fidelity simulations, as demonstrated in Fig. 5.



(a) 3D view (inset: forward speed profile).   (b) Side view (inset: linear deflection profile).

Figure 5: Realistic Blender rendering. Oar deformation is clearly visible in the side view.

5 CONCLUSION

This scientific challenge seeks to position numerical simulation as a powerful tool for analyzing and optimizing performance in rowing.
While no remaining scientific lock appear to block the achievement of the targeted objective, some aspects still need to be reviewed, such as the modeling of blade height and, most importantly, the automation of anthropometric features (including the creation of athlete avatars and the generation of associated input files).
Not an utopia but not yet ready to be used in production as a digital twin of the complete system boat-oars-rower(s), this high-fidelity tool SPRing has equipped itself to match its ambitions and provide reliable trends for limited variations in the settings, thus eventually supporting the inquiries of coaches, whose answers have so far been largely empirical.

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