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# Towards a better knowledge of the flow around rowing blade

Alban Leroyer, Sophie Barré, Jeroen Wackers, Patrick Queutey

18 juin 2012

## Résumé

Study of rowing involves hydrodynamics twice : for the hull and for the oar blades. However, describe the unsteady 3D flow around blades moving with 6 D.O.F. at the end of a flexible shaft and including violent free surface deformation, is the most challenging task. To gain knowledge about this flow, both experimental and numerical studies have been started for a decade at the Laboratory of Fluid Mechanics (LMF) of Ecole Centrale Nantes. The experimental activity involves in-situ measurements using instrumented boats and tests in towing tank at LMF using a dedicated device that reproduces simplified rowing strokes but giving accurate and repeatable measurements. The numerical studies are based on unsteady CFD simulations carried out using an in-house RANS solver with advanced methods such as automatic grid refinement to capture accurately the free surface evolution. The pursued objective is to use experimental results as a reference database to validate the numerical simulations. When validated, simulations become a useful and trusty tool to undertake parametric studies in real situations easier than with experimentation. They also permit to improve the parametric models used for the fluid forces in the simulators of rowing systems. So, empirical indications could be replaced by objective criteria for the choice of oars and settings and also, in the future, for optimization of the rowing style.

## 1 Introduction

Due to the growing power of the computational resources and the development of advanced numerical methods, CFD simulations become more and more popular and are used for many complex applications in naval hydrodynamics. During the last decade, free-surface capturing methods (volume of fluid, level-set formulation) have attracted an increasing interest because these approaches are more robust than those based on a free-surface fitting methodology since no regridding is necessary ([1, 2, 3]). Moreover, the merging or breakup of the interface is handled in a natural way. Here, the approach is used to compute the flow around a rowing blade, which is a far more violent test-case than usual. The blade moves with 6 D.O.F. close to the free sur-

face, leading to an unsteady flow with a very complex shape of free surface varying in time and including breakup. It also involves fluid-structure interaction through the flexibility of the shaft, considering the motion of the oar is imposed by the rower. In reality, the "boat-oar-rower" global system with the rower as a human actuator is even more complex, since the fluid force acting on the blade will be linked to the kinematics of the rower, since the latter activates a sensory motor control of its own motion in order to adapt it to the current position and external loads. The study of this global system is an issue which is currently addressed at the Laboratory as well ([4, 5]), but it will not be addressed here since it is outside the scope of the current communication.

To conduct properly this ongoing research work, the experimental approach is used to provide a reference database. Thus, the article describes both aspects of the research carried out at the LHEEA (ex-LMF) Laboratory of Centrale Nantes to study the flow around rowing blades. First the experimental approaches are presented, including both towing tank and on-board measurements. Then, the numerical methodology will be briefly described prior to the different steps of the validation process we have adopted. In the next section, the complementarity of experimental and numerical approaches when dealing with validation will be highlighted. To conclude, the next steps of this ongoing work will be revealed.

## 2 Experimental approach

The Laboratory has carried out experimental studies on rowing boats and oars using specific devices in the towing tank, as well as on-board measurements with an instrumented boat ([6, 7, 8]). Towing tank tests, on one hand, are focusing only on one part of the system (the boat or the oar), the settings are necessarily simplified with respect to the real case. The main advantage is that the environment and the parameters are well controlled, with good accuracy and repeatability. This technique permits the separation of the propulsive device (the oar) from the motor (the oarsman) and from the boat, as it is done for propellers. On the other hand, on-board measurement works directly on the real system (boat-oar-rower). However, the effective reali-

sation of the procedure involves numerous constraints :

- technological constraints : the instrumentation has to be light and as unintrusive as possible,
- environmental constraints : weather conditions (wind, wave,...) are hard to measure, impossible to control and non-repeatable,
- organizational and human constraints : elite rowers are not always free to spend time for such a test. It is also difficult to impose an experimental planning and to have a regular operation.

The real phenomena get closer, but the price to pay is a larger number of parameters, which are sometimes not precisely controlled. Furthermore, only a limited number of measured quantities can be recorded. A loss of accuracy is then expected compared with towing tank experiments.

## 2.1 Towing tank experiment

Given the intermittent and unsteady nature of the propulsion of rowing boats, it is difficult to plan trials of self-propulsion of the entire system as it is done for conventional vessels. However, it is possible to achieve separately testing on boats or on oars alone. Here, only the tests involving oars and using a specific device designed and build by the laboratory are described ([6]). This is a six-component dynamometer equipped with a servomotor and a mechanism which reproduces accurately and repeatably the rotation of the oar blade in the water (Fig. 1). Two arms can be fixed to the system. One of them is dedicated to receive 0.7 scale blades with a small rigid shaft (Fig. 1). Another has been designed to test real oars.

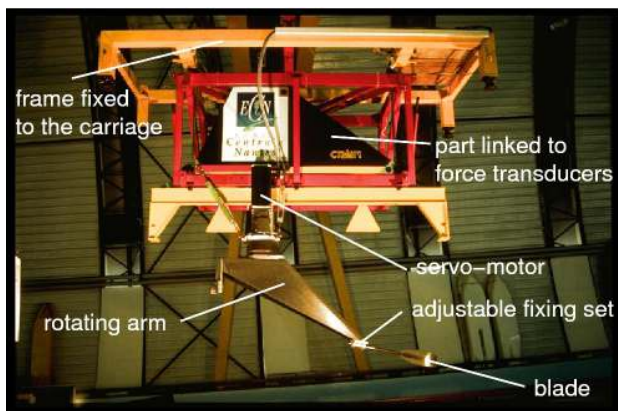


FIGURE 1 – Motion device fixed to the carriage of the towing tank for testing 0.7 scale blades.

The device is fixed to the carriage of the towing tank (long=140 m, width=4m, depth=3m) and the speed of translation is constant during the stroke. The variable rotation velocity combined with the forward velocity of the carriage allow us to reproduce a simplified motion, but one that is

representative of the physics of a real stroke (see the section 4.1 and [9] for more details). In any way, the generated flow reproduces more completely the reality than those obtained by [10], where a blade is only turning around its center in a uniform flow. However, this is still better than tests with constant incidence in uniform flow, where the crucial phenomenon of unsteadiness is not taken into account. Here, the forces acting on the blade are directly measured in the axes of the dynamometer without having to apply friction correction, since the rotation part and the motor are fixed on the sensitive part. Inertia and aerodynamic contributions are deduced from some specific tests. The measurement of the velocity of the carriage and the rotation of the blade complete the recorded data. With this system, uncertainties on the blade forces are estimated to be 0.5 N with a gap of repeatability less than 2 %. The uncertainty on the rotation velocity is 0.1 % and 0.3% on the translation velocity. This material enabled to carry out systematic campaign tests to deduce the influence of kinematic parameters on hydrodynamic forces. This database of reference is also very useful to validate CFD simulations on such a complex physics. More details about the experimental material and procedure can be found in [9].

## 2.2 On-board measurements

Measurements with instrumented boats allow the direct analysis of the rowing stroke and the boat behaviour. Their use by the coaching staff becomes more and more common due to the commercial availability of light and efficient equipment. We have such material, but the present goal is to describe specific tests carried out to validate CFD computations on rowing blades. Such tests can not be used on a daily basis. They need development of specific sensors and the adjustment of specific procedures to obtain enough accuracy to reach the objective.

### 2.2.1 Measuring the boat dynamics

Commercial sensors specifically designed for rowers give a rather accurate mean velocity. However, inertia and friction of the turbine bias the measure of the instantaneous velocity. In addition, accurate GPS receivers with high sampling rate and post-treatment or Real-Time-Kinematic (RTK) are too heavy devices and measure the velocity with respect to the Earth. All these observations lead us to develop a specific sensor to measure the velocity of the boat. This is done through a small Schiltnecht ducted turbine fixed below the fin of the skiff. The turbine contains a Baumer magnetic sensor, which counts the passing of each blade. The position ensures that the turbine is outside the boundary layer of the hull. It has been calibrated fixed on the boat in the towing tank : the resolution is 0.7 mm of displacement per pulse with an accuracy of 2 cm/s.

Acceleration is measured at the middle of the boat and vertically at the bow and the stern through three piezo-resistive  $\pm 5g$  ENTRAN EGCSY sensors. These sensors are calibrated with the gravity through a half-turn. Vertical acceleration is integrated twice to give the pitch and the heave, considering the pitch is small (about  $1^\circ$  of amplitude). To remove the drift after integration, we use the fact that displacements and their derivatives have zero averages for cyclic motions.

### 2.2.2 Measurements for the oars

To measure the trajectory of the blade, the oarlocks are equipped with three accurate potentiometers (Fig. 2) to measure the orientation of the oar : the horizontal sweep angle, the immersion angle and the spin angle (rotation around its own axis). Considering the dynamics of the oar, the following forces are involved : the action of the rower's hand on the handle, the reaction of the oarlock, the hydrodynamic and aerodynamic forces and the inertia and gravity forces. We do not know where the resultant of the hydrodynamic force is applied. To retrieve this information, all the forces and their moments should be measured, which is a arduous task. Considering the main objective which is to validate the numerical simulation, it is enough to measure bending and torsion moments in a section of the outside shaft and to compute the numerical results at the same location. If experiment and simulation match well, the numerical simulations can be used to obtain all the components of the hydrodynamic forces. For the measurements of these moments, the oars have been equipped with three strain gauges : two for the bending in orthogonal directions and the third one for the torsion. The pure hydrodynamic contribution is obtained by subtracting the inertia effects computed at the gauge positions. The inertial properties have been estimated from a model of the oar structure and the procedure has been globally checked for the position of the centre of mass, the global mass and the measure of inertia through the technique of bifilar pendulum. These dynamometric oars are calibrated in pair under static loads with a test bench specifically build for this procedure. This test bench is also used to measure the linear and angular deflection stiffness (Fig. 3), which are two essential parameters for the CFD simulations that take into account fluid-structure interaction.

### 2.2.3 Procedure to detect the contact of the blade with the water during the catch

The measure of the dynamic roll of the boat has not been integrated to the instrumented boat yet. The main reason is that this motion is neither of zero average over a cycle nor cyclic, but controlled by the rowers. Without this information, the position of the blade with respect to the water

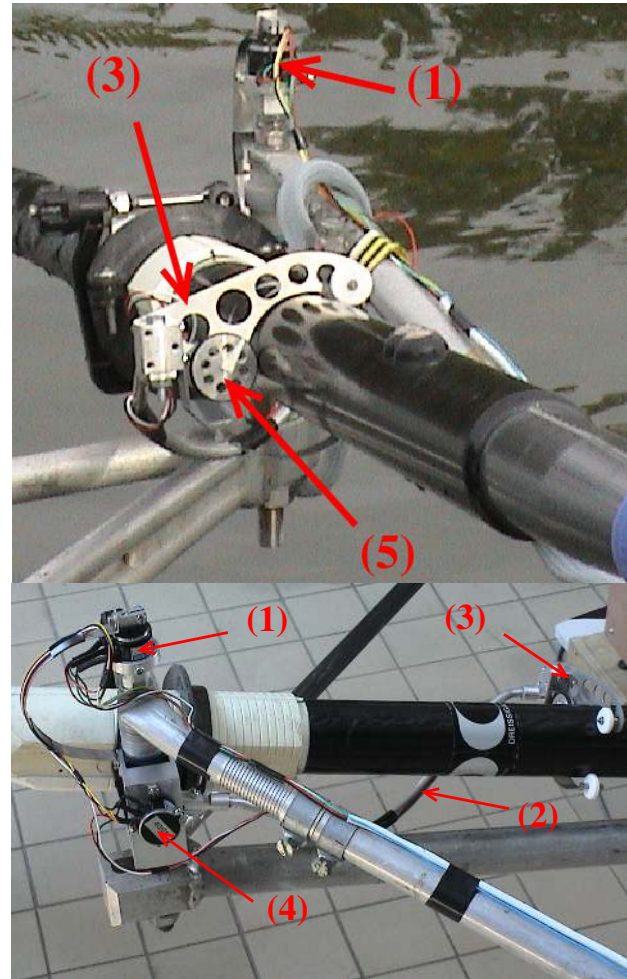


FIGURE 2 – Sensors to capture oar orientation : the horizontal sweep angle is directly measured with a potentiometer (1) fixed on the axis of the oarlock. An oscillating arm (2), with the head (3) clipped on the shaft, operates the potentiometer (4) which measures the immersion angle. The head is fitted with three small wheels, of which one is mounted on an elastic piece to tighten and maintain the no-slip roll of the wheels. The wheel (5) is linked to a potentiometer to measure the rotation of the shaft along its own axis.

is not accurately known. A procedure to detect the instant where the blade is touching the water is thus required, to trim the immersion angle. In addition to that, we have to assume that the trim remains valid during the whole drive phase, i.e that the roll does not change, which is not totally true. The procedure of blade/water contact detection is mainly based on the analysis of the Z-bending and X-torsion moment : both are approximatively null before the blade touches the water and increase suddenly when the contact is made. This detection can be checked by some kinematic signs : for elite rowers, the water entry is ob-

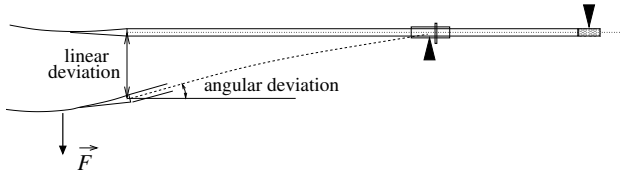


FIGURE 3 – Representation of the linear and angular deviation due to the flexible shaft.

tained after reaching the minimum sweep angle and when the spin rotation is stabilized. The analysis allows us to locate the sweep angle of the blade water entry with an accuracy of around  $1^\circ$  (for the sweep angle).

#### 2.2.4 Kinematic data to validate CFD simulations

Once the water entry of the blade is located, the angles of the oars and the motion of the boat are transformed into input data in a geometric rowing model used for the simulation of the global system ([4]). As an output, the model gives the motion of the blade with respect to the water frame of reference (Fig. 4). All the details of the real oar are taken into account, in particular the shift between the three axis of rotation at the oarlock. Up till now, the spin of the shaft is the only property which is not activated in the simulation since it is not crucial during the propulsive phase (where the blade remains vertical).

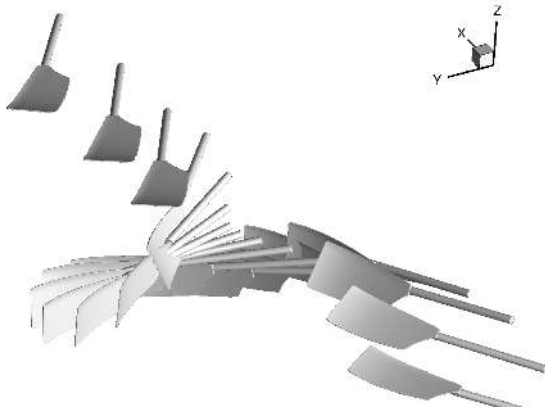


FIGURE 4 – Motion of the blade built through on-board measurement.

### 3 Numerical approach

The flow around a rowing blade presents two main features, i.e. unsteadiness and a very complex free surface deformation, which made it difficult to investigate for a long time. For performance analysis of rowing crews (even for optimization), rough models ([11, 12]) have been used to estimate the propulsive forces for lack of anything better, but with a limited accuracy. Under these conditions, the relevance of results is always debatable.

To investigate such a flow, only an experimental approach seemed possible around ten years ago. But nowadays, advances in computing power offer the possibility to investigate this flow using CFD. And the experimental investigations already available provide a useful and valuable reference database to validate CFD computations. In fact, CFD tools are no longer limited to simple physical problems and their field of applications has been significantly enlarged during the last years.

#### 3.1 Description of the RANS solver

The numerical tool used for these studies is the ISIS-CFD solver developed in the DSPM group of LHEEA. The solver is based on the Finite-Volume method to build a second-order accurate discretisation of the RANS equations. The flow equations are constructed face by face, which means that cells having an arbitrary number of arbitrarily shaped faces can be accepted. This enables the simulation of flows around complex geometries. The velocity field is obtained from the momentum conservation equations and the pressure field is extracted from the mass conservation constraint, or continuity equation, transformed into a pressure equation. In the case of turbulent flows, additional transport equations for modeled turbulent parameters are solved in a form similar to the momentum equations : they are discretised and solved using the same principles. Here, the two-equation  $k - \omega$  SST closure [13] is used to take into account the turbulence phenomena.

Free-surface flows are computed through an interface capturing method. The flow phases are modelled with a transport equation for the volume fraction of water  $c_w$  in each cell :  $c_w = 1$  means that the cell is completely filled with water,  $c_w = 0$  means that only air is present in the considered cell. The interface between air and water is represented by the numerical discontinuity in the solution for  $c_w$ . The effective flow physical properties (dynamic viscosity  $\mu$  and density  $\rho$ ) are obtained from the properties for each phase,  $(\mu_w, \mu_a)$  and  $(\rho_w, \rho_a)$  respectively for water and air, with the following constitutive relations :  $\mu = c_w \mu_w + (1 - c_w) \mu_a$  and  $\rho = c_w \rho_w + (1 - c_w) \rho_a$ .

Special attention has to be paid to preserving the sharpness of the interface, as well as the boundedness of the variable, when solving the transport equation for  $c_w$ . These requirements are fulfilled by introducing downwind differencing since compressive characteristics are required for an accurate interface capturing. This implies a constraint on the local Courant number (the Courant number is an adimensional parameter roughly defined by :  $\Delta t V / \Delta x$ , where  $V$  is the velocity through the considered cell,  $\Delta x$  the size of the cell, and  $\Delta t$  the global time step of the temporal discretisation). Here, the Blended Reconstructed Interface Capturing Scheme (BRICS) scheme is used ([14, 3]).

An Arbitrary Lagrangian Eulerian (ALE) approach is used to deal with moving bodies ([15, 16, 17]). All configurations of motion (up to 6 solved or imposed D.O.F.) can be applied. Analytical weighted deformation techniques have been developed to preserve a mesh fitted to the body during its motion [17, 18].

The temporal discretisation scheme is the second order implicit Euler scheme when dealing with unsteady configurations. For each time step, an inner loop (denoted by non-linear loop) associated to a Picard linearisation is used to solve the non-linearities of the system.

When the flexibility of the shaft is activated, the position of the blade is no longer fully imposed but depends on the fluid loads on the blade. Even if the position of the blade in the non-deformed configuration remains imposed, this fluid-structure interaction needs to be addressed with care. Since inertial effects of the oar are small compared to the fluid forces acting on the blade, the resolution of a static equilibrium of the structure is suitable. Due to the added mass effect, a part of the fluid loads on the blade depends on the acceleration and may lead to divergence of the numerical coupling ([19]). To keep a stable fluid-structure coupling, the position of the blade is updated at each non-linear iterations through a quasi-Newton method using a rough estimate of the added mass for the blade. It was evaluated from [20]).

For the computations reproducing the real rowing stroke, we also benefit from the automatic grid refinement included in the solver ISIS-CFD, which is described in more detail by [21] and [22], to capture accurately the evolution of the free surface. This technique enables to follow the free surface keeping always fine cells around it, and thus limiting the diffusion process of the volume fraction. This avoids to use a large area with fine cells surrounding all the region where the free surface takes place during the stroke.

## 4 Simulations and comparisons

### 4.1 Simulations of a planar 0.7 scale blade

This first validation reproduces one of the systematic tests carried out in the towing tank with a 0.7 scale oar (Fig. 1). In order to simplify as much as possible the first validations, we chose the reference blade, which is to say, a planar rectangular blade (Fig. 5) with a rigid shaft, which makes the meshing process very easy. Hence, it avoids a digitalization of a specific tested geometry and a fluid-structure coupling due to the interaction between the fluid force and the flexibility of the shaft. To define blade movements for systematic tests, the reproduction of real measured oar movements is not suitable because these are performed with oarsmen having different rowing styles and are not linked with reliable data to the instantaneous boat speed. Furthermore, the high number of parameters that define this kind

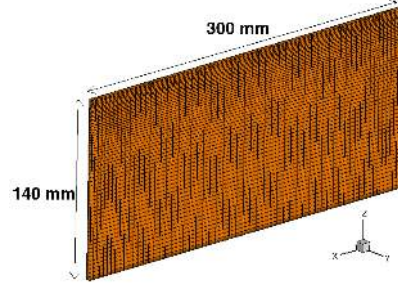


FIGURE 5 – Surface mesh of the planar rectangular blade (the shaft is not taken into account in the simulation).

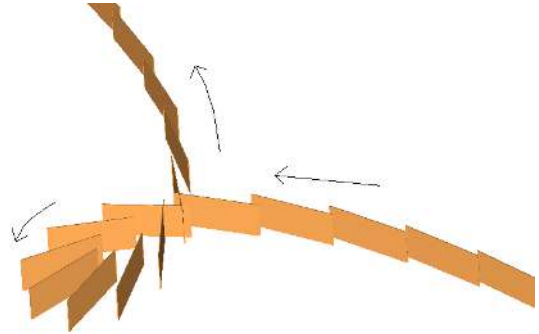


FIGURE 6 – Example of prescribed motion with the simplified kinematics used in the towing tank.

of movement makes the exploitation of test results difficult. However, even if simplified kinematics have to be used in a laboratory, it is crucial that the main physical phenomena of the real conditions are reproduced. Referring to kinematics and energy considerations ([9, 8]), systematic tests were performed by imposing a significant parameter  $\eta_0$  defined by equation (1) as a constant during the whole stroke.

$$\eta_0 = V_b \sin \theta / (L_e \dot{\theta}) , \quad (1)$$

with  $V_b$  velocity of the carriage,  $\theta$  angle between the forward direction of the carriage and the shaft and  $L_e$  the outer level (distance between the oar-lock and the middle of the blade). This parameter can be viewed as an advance parameter or a characteristic efficiency. To obtain a similar flow around the blade at reduced scale and around the blade at full scale, the advance parameter and the Froude number have therefore been respected.

Under these conditions, the imposed blade trajectory is shown in Fig. 6. We can remark that the typical "1" path of the real motion in Fig. 4 is reproduced.

Using this configuration, we demonstrate in [9] that unsteadiness and free surface effect were two crucial phenomenon to accurately capture the physics of such a flow. On the contrary, we also show that viscosity (and turbulence induced) has no critical physical features for application of that kind, at least in the central part of the rowing

stroke. For small  $\theta$  angle, the blade is nearly aligned with the forward direction, and in this situation, the friction drag becomes an important effect. But in a real stroke, this situation never happens since the angle of attack is about  $30^\circ$ .

## 4.2 Simulation of a real rowing stroke

From the experimental work described in section 2, a preliminary study has been launched to reproduce a real rowing stroke, including the fluid-structure interaction due to the flexible shaft. The only simplification is to keep the blade vertical (the rotation around its own axis has been removed). Except for that point, the 6 D.O.F. imposed kinematics is the one reproduced in Fig. 4, That was done to avoid resorting to sliding grids for the moment and starting with a simpler configuration, knowing that this motion is not crucial for the propulsive phase. A moderate adaptative grid refinement around the free surface has been activated too. A coarse mesh contains initially 240,000 cells (before refinement around the free surface) to reach about 1.6 million cells during the computation (Fig. 7). The first results,

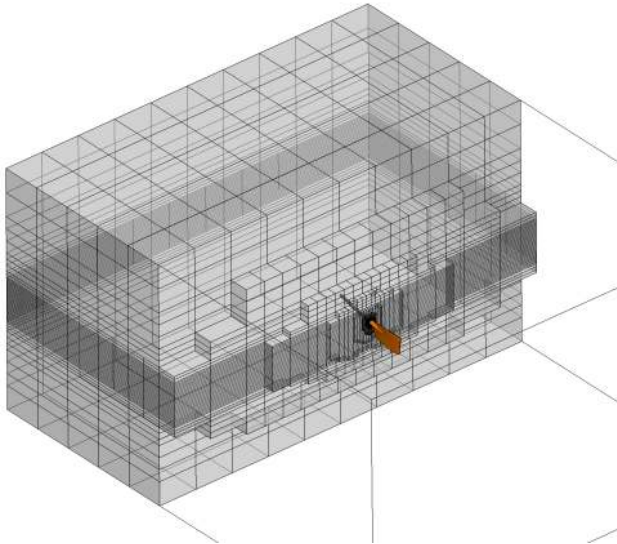


FIGURE 7 – Global view of the mesh.

in the absence of full validation, show the feasibility of such a configuration. On the one hand, the evolution of the free surface is realistic Fig. 8. On the other hand, the Z-axis moment, which is the highest load during the drive and where the flexibility of the shaft acts, is quite well reproduced with respect to the experimental data (Fig. 9), except a more oscillating signal. In this figure and in the two figures after (Fig. 10 and Fig. 11), the reference stroke corresponds to the stroke which was chosen to build the imposed kinematics among all the strokes of the recorded sequence (plotted with thin lines). The whole sequence highlights the variations obtained between different strokes of the sequence

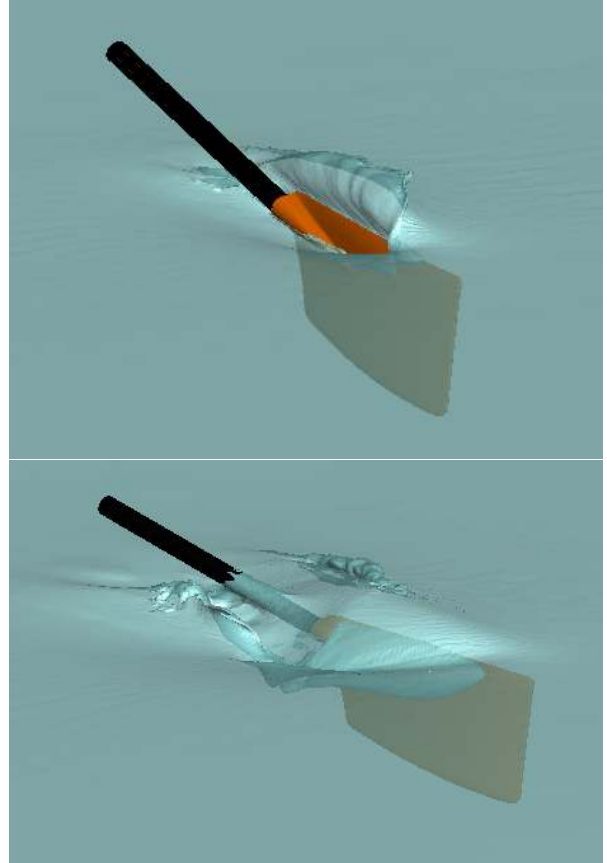


FIGURE 8 – Two views of the free surface at different time.

due to minor changes of the kinematics of the rower and of external parameters. It is an indicator of the reproducibility using on-board measurements. The other bending component (Y-Axis) matches quite well with the experiments too (Fig. 10). The observed gap before the blade enters the water (and where the simulation gives a value close to zero whereas the experimental signal is about  $-7\text{N.m}$ ) is due to the weight of the oar which is not caught by  $M_y$  where the blade is horizontal (the zero value of the sensor was calibrated with a vertical blade). As for the torsion component (Fig. 11), the evolution is quite well caught, even if the relative differences are much larger. Note that the order of magnitude for this component is quite weak compared to the others. A difference setting of the longitudinal pitch of the oarlock (which was not measured) may be the cause of this gap.

## 5 Conclusions

This article aims at reporting progress about the approach, both experimental and numerical, pursued at LHEEA to gain knowledge about the flow around rowing blades. In particular, it shows the complementarity of these two ap-

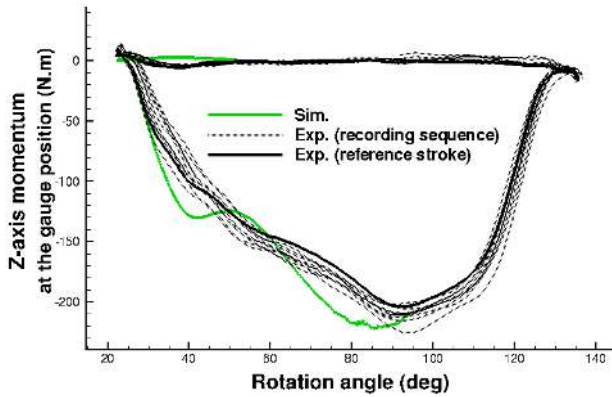


FIGURE 9 – Z-axis moment (oar frame of reference).

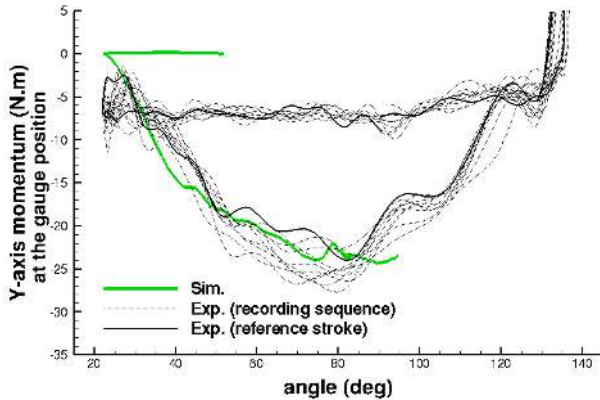


FIGURE 10 – Y-axis moment (oar frame of reference).

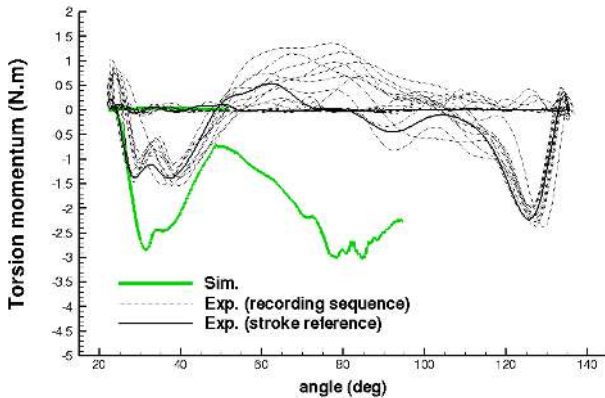


FIGURE 11 – X-axis moment (oar frame of reference).

proaches for this kind of research work. Accurate and well documented towing tank experiments dealing with simplified configurations, but reproducing the major physical features with respect to a real stroke are very useful because they enable to validate numerical models with care. This

step has been initiated using the simplest case. This case has also been used to quantify the influence of physical parameters. As it was done for swimming ([23]) and for insect flight ([24]), the crucial role of unsteadiness is demonstrated, invalidating works based on a series of "equivalent" steady flows to study such a configuration. And unsurprisingly, as the blade motion occurs just below the free surface, we show that this physical feature is also a sine qua non parameter to investigate such a flow.

Then, a preliminary study involving a real measured kinematic of a real oar has been started. Even if this work is at its first stage, it has reinforced the potential of the numerical methods which are used, especially the adaptive grid refinement to limit the diffusion of the interface, and the procedure to stabilize numerically the interaction between the flexible shaft and the fluid. However, experimental uncertainties, hard to estimate and resulting from non-measured parameters (such as the roll of the boat), make the validation task for this case difficult. As a consequence, we planned to come back to towing tank tests involving a full-scale oar to pursue the validation process with more controlled experimental data. As for the experimental part, a new on-board campaign should be considered. The objective will be to add a synchronized video acquisition as well as a measure of the roll of the boat to make up the missing data. This should improve the accuracy of the path of the blade with respect to the free surface and thus becomes reference data to validate a real configuration.

Once the validation process is fully completed, numerical investigations will be started to better understand the influence of some parameters, such as the flexibility of the shaft, the immersion of the blade, the setting of the oar (pitch of the oarlock, lever length, etc.). The final goal is to improve the simplified models which are used in the simulators of the global system boat-oar-rower (which corresponds to the Velocity Prediction Programs in sailing yachts).

## 6 Acknowledgments

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