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## Toward optimization using unsteady CFD simulation around kayak hull

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### Abstract

The aim of this research work is to develop a procedure including experimental measurements and advanced numerical simulations of fluid flow to address optimization problems in kayaking. The different steps preparatory to the optimization task are described: the use of experimental data on the hull kinematics to create a simplified, periodic but realistic kinematic model, the numerical simulation using this kinematics as an imposed hull motion, the *a posteriori* computation of the loads of the athlete acting on the hull. Finally, a verification of the whole chain is carried out, by solving the flow around the hull, which is now free to move according to the computed loads of the athlete. Some preliminary results of this on-going work are finally shown.

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### 1. Introduction

Fluid mechanics is a scientific field that plays a key role in nautical sports, often in complex situations. Due to the growing power of computational resources and the development of advanced numerical methods, Computational Fluid Dynamics (CFD) becomes more and more popular and is now daily used for industrial applications in naval hydrodynamics (design, prediction of performance, etc). Nautical sports start also to be impacted by such tools. If sailing remains pionnier in this field, due to a large financial support as for the America's Cup, some works can also be found in kayaking ([1? ]). However, most of them does not take into account for the unsteadiness of the hull motion and only uses the time-averaged forward velocity as an input. The action of the athlete is sometimes modeled through a body-force paddle model [2], or by a full multi-body model of the kayaker [3] using SPH as fluid model. For this latter case, the modeling of turbulence and the computation of the friction drag are not detailed at all, although this is the main part of the drag resistance for such a hull.

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Fig. 1: (a) parametric model provided by the manufacturer.; (b) video capture during data recording.

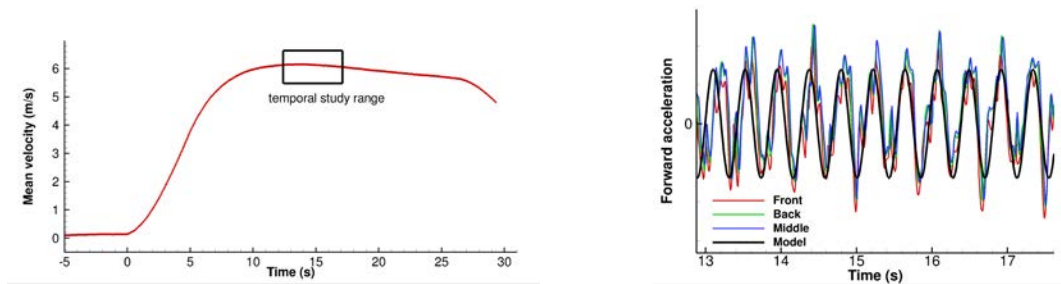


Fig. 2: Measured signals (a) Mean velocity against time — localisation of the temporal study range (b) Raw forward acceleration against time.

Here, we present a prospective work, carried out in collaboration with the French Canoe Federation, whose goal is to study the influence of some parameters on hull velocity. In this perspective, a model of full unsteady loads from the kayaker to his hull was first built from on-site measurements of the hull kinematics using sensors daily used by French team, in conjunction with RANSE-CFD simulations. Then, the CFD solver was used to compute the flow around this K1 kayak, free to move according to the model of loads previously obtained. On this basis, the influence of some parameters, such as the longitudinal position of the athlete, was investigated.

## 2. Modelisation of the K1 hull kinematics

### 2.1. Experimental campaign

The campaign was achieved with the help of an international elite athlete selected by the French Canoe Federation, after checking that a parametric description of the geometry of his boat and its fin is available from the manufacturer (see Fig. 1(a)). Unfortunately, the numerical model of the hull geometry was not clean enough to be operable by the mesh generator software. A tedious CAD cleaning task was therefore required to succeed in meshing the geometry. Note that such a problem often occurs, and represents a major waste of human time. Mass and position of the centre of gravity of the hull were measured using two accurate weight scales, as well as the total weight of the boat including the kayaker. Kinematic data were recorded during a 200m race speed training session, with this elite kayaker. This measurement campaign was done with favorable weather conditions: very light wind and wave, see Fig. 1(b). Kinematics was recorded through three GPS/Accelerometry/Magnetometry Minimax Catapult systems, which are daily used by the French team. Two of them were located at 20 cm from the front and back tips of the hull. The third one was located near the middle of the hull. A video recording was also made from the coach motor boat.

### 2.2. Treatment of the experimental data

The three files corresponding to the three Minimax sensor systems were exploited. After extracting the data of interest and converting into a readable format by the visualization tool Tecplot, a synchronisation procedure was applied. The temporal range of study was chosen around  $t = 15$  s, where all the signals seem to be close to a periodic regime and where the mean velocity is nearly constant equal to 6 m/s (see Fig. 2(a)). A first data analysis was

achieved to know which signals could be exploited, and to list the constraints to fulfill, in order to build an analytical and periodic kinematic model. Assuming the hull as a rigid body, all the recorded signals bring redundancy, which was used to evaluate the consistency and the accuracy of the measured data: orientation should remain the same for the three systems — the pitch angle is related to the vertical motion at the two tips of the hull, so as the yaw angle with the sideways motion.

Except the forward motion, for which only the temporal evolution of velocity is needed, all the other degrees of freedom (DOF) require the reconstruction of position (for translation) and angle (for rotation) as a function of time. Furthermore, all the signals need to be multiple of the same nominal frequency to have a fully periodic kinematic model. This nominal frequency was evaluated to 1.18 Hz. Roll, yaw and sideways need to have the same phase and a zero mean value too. Additional constraints come from the rigid body assumption, which linked some signals to other ones, as discussed previously.

Regarding translation DOF, only the acceleration signals are exploitable. The forward acceleration signals (Fig. 2(b)) were consistent with each other and were used to deduce a periodic acceleration through the first harmonic of a Fourier transform of the averaged signal. This periodic acceleration was then integrated including a zero averaged value constraint, and added to the mean velocity value previously found. A similar procedure was applied to the sideways motion, but for this DOF, two integrations were needed to proceed until position. Furthermore, signal deviation had to be removed. For the vertical motion, the raw acceleration signals from the two devices located at the tip were used to build a heave motion consistent with the pitch angle. However, the mean value of the heave motion (i.e. the mean vertical position of the hull with respect to the free surface) remains unknown and cannot be deduced with the experimental data. This issue will be discussed in section 3.2.

As far as angular reconstructions are concerned, the angles measured by the devices were used. The roll signals were quite consistent with each other, allowing to build directly an analytical model through a Fourier transformation (see Fig. 3(a)). For the pitch and the yaw measured angles, deviations were found. Note that for the middle device, the yaw angle record was broken (see Fig. 3(b)). A specific treatment was applied to remove the mean deviation value, while keeping fluctuations frequencies multiple of the stroke frequency. With the extra constraint of zero mean value for the yaw evolution, the analytic reconstruction was complete, whereas for the pitch, the pitch value remains to be determined. Fig. 4 shows some other comparisons between the raw experimental data and the analytical model, namely the lateral acceleration. Note that these two analytical signals are built with the constraint to be consistent with the model of yaw motion (assumption of rigid body).

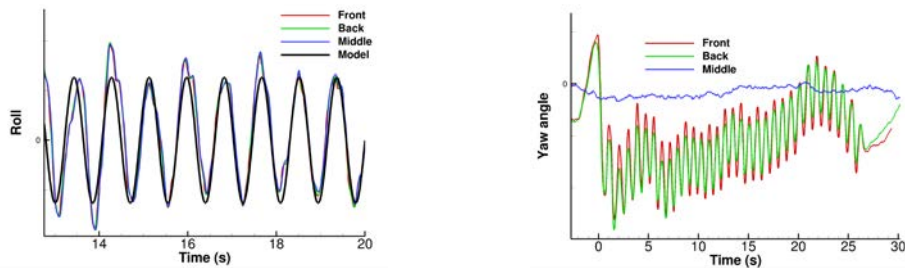


Fig. 3: Measured signals (a) Raw roll angle against time; (b) Raw yaw angle against time.

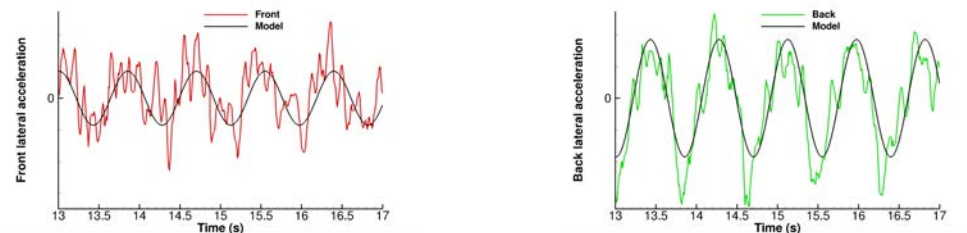


Fig. 4: Comparison between raw signal and analytical model (a) Front lateral acceleration against time ; (b) Back lateral acceleration against time.

Although the simplified kinematics cannot match perfectly the raw signals, due to noise, the limited accuracy of the device system and the fact that the real kinematics is not fully periodic, we succeeded in building a 6-DOF periodic and analytic motion, which catches the main trends of the experimental data. It can thus be considered as a simplified but credible motion (which was confirmed by the French national coaches' eye). However, two parameters remain unknown at this stage: the mean pitch and the mean heave values.

### 3. Numerical simulation

The solver used for the simulations is ISIS-CFD, i.e. the core of the FINE<sup>TM</sup>-Marine computing suite, solver which is developed by the METHRIC group of the *LHEEA Lab. of Ecole Centrale Nantes, UMR-CNRS 6598*. More details about the numerical methods can be found in [4].

#### 3.1. Pre-treatment and settings

After cleaning the CAD model, two meshes were built using the hexahedral mesh generator Hexpress<sup>TM</sup>, for a complete configuration including fin and for a bare hull. Note that the fin is separated from the hull by a small gap (see Fig. 5). Hence, forces on each of body can be computed without the classical problem of non-closed body which appears when the root of the fin starts from the hull. Comparison between the two configurations are then easier. The bare hull mesh contains 1.34 million cells whereas the one with the fin has 1.85 million cells. The length of the hull  $L$  is about 5 meters, yielding a nominal Reynolds number of  $2.6e7$  and a Froude number equal to 0.85. The domain size is  $5L$  long,  $2.5L$  width and  $1.6L$  height. The middle of the hull is located at  $1.6L$  from the front of the domain and at  $1.2L$  from the bottom. Far field flow conditions are used everywhere on the sides of the domain and an hydrostatic pressure field is imposed on the top and on the bottom of the fluid domain. Wall-function conditions are used at the hull wall with  $y^+ \approx 30$  for the first mesh layer. The  $k - \omega - SST$  of Menter ([5]) is used for all the simulations. One kayak stroke requires about 1.25 hour using 24 cores. A dozen of strokes are needed to reach a periodic solution.

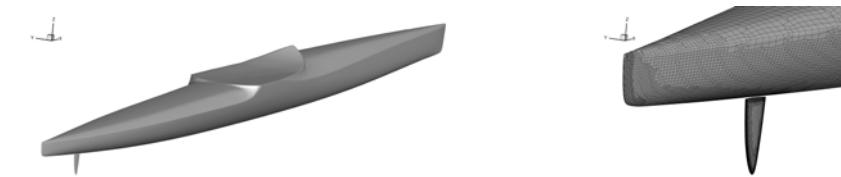


Fig. 5: (a) general view of the configuration with the fin; (b) zoom around the fin with the surface mesh.

#### 3.2. Evaluation of the mean heave position and mean pitch value

Since the generation of the hull kinematics let two unresolved parameters, a preliminary study was carried out to determine their values. For this computation, the 6-DOF motion obtained with the analytical model was imposed to the hull, associated with different mean pitch values (between  $1.5$  and  $2^\circ$ ). Only the mean heave value was allowed to evolve freely during the computation, to reach an equilibrium in average between the vertical fluid force  $F_z$  and the total weight of the boat. Here, we assume that the average vertical force generated by the paddles is negligible compared to the weight of the boat (hull+kayaker). This equilibrium was obtained through a quasi-static approach ([6]), but applied to a moving average value of  $F_z$  (over one period). According to the results obtained with these different configurations, especially the position of the front tip of the hull with respect to the free surface (see Fig. 6), we deduce by comparison with the video that the mean pitch value of  $1.75^\circ$  fits the best with the reality. This result has been validated by the coach.

During this study, we also checked that the results, in terms of forces, were rather insensitive to mesh refinement and that the time step (200 steps per period) is fine enough so that the numerical error to be under control.

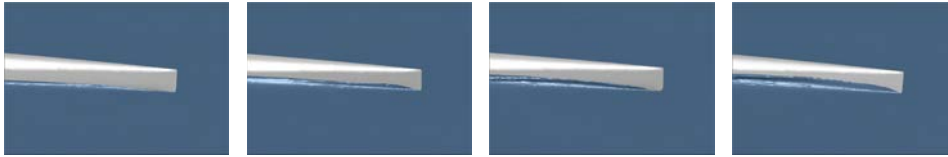


Fig. 6: Visualisation of the front tip at different times for average pitch equal to  $1.75^\circ$ .

### 3.3. Evaluation of the action of the kayaker and verification of the configuration with imposed forces validation

The simulation using imposed motion and resolution of the vertical equilibrium with the average pitch angle at  $1.75^\circ$  yields the fluid forces acting on the hull. Since we also know the whole kinematics and the inertia parameters (mass and evaluation of the inertia matrix assuming a uniform surface density on the hull), we can also compute the inertia terms, i.e. the rate of change of linear and angular momentum. Then, applying the Newton-Euler equations to the hull system, the only unknown variables are the loads by the kayaker acting on the hull. As a consequence, they can be extracted numerically. An analytical model which matches very well with the numerical signals can be deduced through Fourier transformation using some of the first harmonics (see Fig. 7)

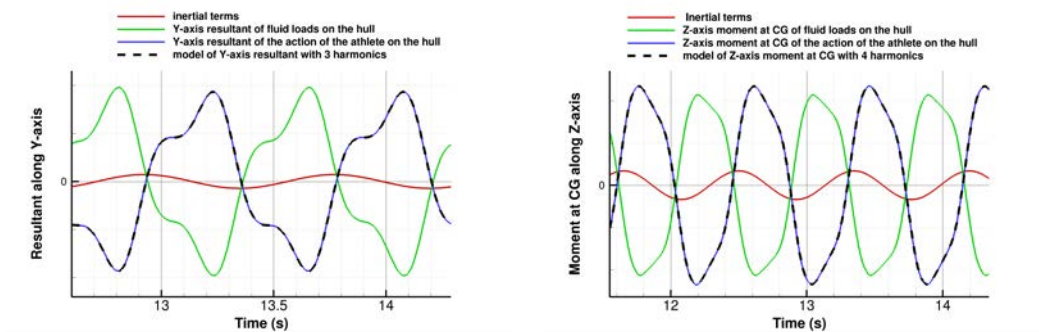


Fig. 7: Visualization of the inertial terms, the fluid loads acting on the hull and loads of the athlete on the hull for the Y-axis resultant and the Z-axis moment at CG.

Finally, new computations can be performed by imposing these external loads, reproducing the action of the kayaker and allowing the hull to move freely. Only the roll was kept imposed since it is an unstable DOF controlled by the athlete. A control of the yaw angle was also added to the Z-torque so that the hull does not deviate from the forward X-axis. We check that this simulation reaches the same periodic motion as the one previously imposed, even if we start from rest (Fig. 8(a)), which validates the whole procedure.

### 3.4. Ready to study parameters and optimize

Due to the lack of accurate experimental database available, we were not able to validate the fluid flow on this kind of unsteady motion in calm water. The accuracy of the turbulence model for this specific flow remains then questionable, even if the numerical model has been extensively validated on different benchmarks available in classical naval hydrodynamics. However, the whole workflow to simulate the action of the athlete through imposed loads to the hull is now verified. This procedure can now be coupled to an optimization algorithm, to determine the best values of some parameters allowing to maximize the time-averaged kayak velocity. Due to the complexity of the system considered, and the associated computational burden, we select as optimizer a statistical learning approach [7], included in the optimization package FAMOSA developed at Inria Sophia-Antipolis Center. This approach only requires performance estimations and can account for the numerical noise that can arise during the simulation process (discretization or iterative error) [8]. Basically, this algorithm relies on a statistical Kriging model, constructed thanks to an a priori design of experiment campaign, and then refined in most interesting areas.

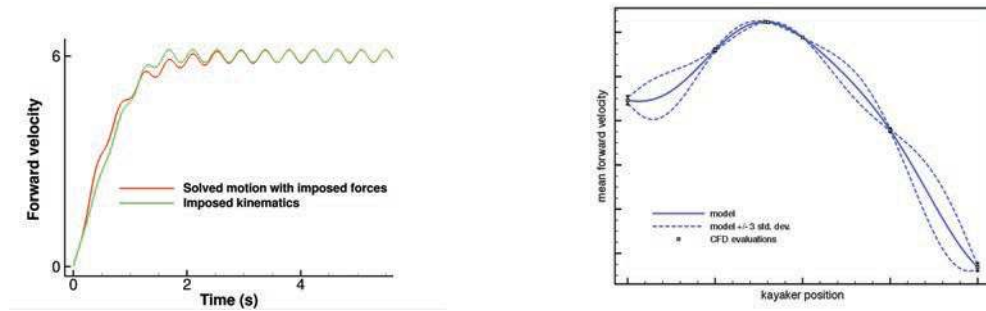


Fig. 8: (a) Comparison between the simulations "imposed kinematics" and "solved motion" for the forward velocity ; (b) results of the optimization of longitudinal position .

As illustration, Fig. 8(b) shows results obtained by optimizing the longitudinal position of the kayaker to maximize the mean forward velocity using the configuration with fin. The uncertainties related to instabilities of the time evolution of the performance are taken into account to construct the statistical model, whose mean and standard deviation are shown and exploited to determine the best position value. On-going work aims at studying the influence of some other parameters, such as hull shape, assuming that the kayaker action remain unchanged (which is the stronger assumption of this work).

#### 4. Conclusion

The described procedure which aims at reproducing the action of the kayaker on his hull is now verified. The numerical approach uses the most popular physical models employed for advanced industrial applications, which allow to be quite confident in the accuracy of the results, despite the fact that the impact of the turbulence model would require more validation on such an specific unsteady motion. Such a computational chain offers great possibilities to investigate the influence of some parameters on the performance, especially by using optimization techniques based on statistical Kriging model. Beyond the confidence level on the flow results obtained, the most questionable assumption regarding the proposed procedure is that the action of the kayaker on his hull remains unchanged despite modification of his environment.

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