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Executive Summary of the Thesis

Preliminary development of a modelling framework for the prediction of hydro-abrasive wear in Pelton turbines.

Laurea Magistrale in Mathematical Engineering - Ingegneria Matematica

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1. Introduction and scope

Hydropower is a major renewable energy source. Especially in view of the increased demand and emissions caused by nonrenewable energy sources, it is important to improve several aspects of the design of hydropower plants [1]. A relevant problem in this context is the structural damage of turbine components working in a sediment-laden environment. This phenomenon is called hydro-abrasive wear. In this work, the focus is on Pelton turbines, as these machines are often located in geologically recent regions, which are therefore characterized by sediment-laden water. Hydro-abrasive wear could eventually lead to the breakdown of the machinery which turns out to be very expensive to repair. Consequently, it is extremely important to estimate the useful lifetime of Pelton turbines subjected to hydro-abrasive wear, in order to improve the machine design and develop the strategies of the scheduled maintenance of the plants.

There are several approaches for the estimation of hydro-abrasive wear.

A number of erosion correlations has been developed for the practical estimation of the material removal from hydro-turbines starting from a set of input parameters. These formulas are very simple from a mathematical point of view, thereby easy-to-use, but none of them is applicable to a wide set of conditions because they are very case-specific. The main problem with these formulas is the poor accuracy and, additionally, the lack of information on the applicability conditions.

Another method is to conduct laboratory experiments. In the case of Pelton turbines it is not possible to test the actual devices in the laboratory because of their large dimensions. The only feasible way is to conduct laboratory experiments on a reduced scale model of the machine. However, the full-scale and the reduced scale model must ensure geometric, kinematic, and dynamic similarity, but this is hard if not impossible to achieve. For instance, reducing the dimensions of the sediments might result in different patterns of the particle-laden flow. Moreover, reducing the scale, there is a reduction in the velocity involved resulting in a very long erosion process. As a result, experiments on reduced scale models are unlikely to provide useful information for full scale machines, whereas experimental data could be used to validate numerical simulations.

A third way to predict erosion is to carry out numerical simulations. This method is very useful for all systems in which experiments are unfeasible, such as Pelton turbines. In fact, the computer simulation allows virtual testing of a full scale Pelton turbine without the need of referring to a reduced scale model. However, there are also several issues associated with this approach. A significant challenge is that those equations are approximate in nature because considering a fully physically based model would result in unfeasible simulations. Thus, in order to be practically solvable, the equations are manipulated by introducing coefficients, closures, sub-models and parameters. Experimental data are needed to calibrate and validate an approximated model. This requires to set up an experimental validation, so that all the problems related to experimental testing would arise again. Based on the above considerations, the numerical simulation is an appropriate approach for the engineering handling of hydro-abrasive wear of Pelton turbines, but this method is not exempt from criticism. This thesis provides a throughout discussion of the aspects which make the numerical prediction of hydro-abrasive wear of Pelton turbines particularly challenging. This allows to understand how to address these issues and study their relevance in an application-oriented context, with the long-term goal of proposing a CFD framework which will become a tool for the optimized design and management of hydro-power systems. Referring to benchmark cases of increasing complexity, the first steps towards the development of the predictive framework have been successfully made.

2. Challenges in the numerical simulation of turbine erosion

The goal of this section is to identify the most critical aspects of the numerical simulation of hydro-abrasive wear of turbines. In particular, the idea is to span over all the aspects that make the numerical predictions highly uncertain and complex. These challenges are related with the multi-physics and multi-scale nature of the problem, in addition to the multi-phase nature of the flow and the jet-blade interaction, as summarized graphically in Figure 1.

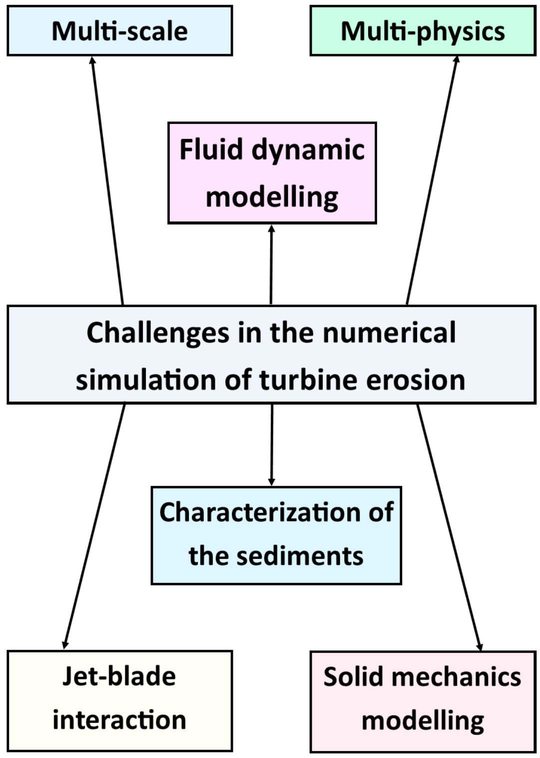

Figure 1: Challenges in the numerical simulations.

First of all the problem is multi-physics, as it involves both fluid mechanics and solid mechanics.
Then, it is also multi-scale, as it spans from the macroscopic scale of the turbine blade to the microscopic scale of the particles that collides against the surface of blade. All scales are relevant to the process in analysis. In particular, micro-scale cannot be neglected, as the small pits caused by the continuous collision of particles against the surface of the blade cause the visible structural damage.
Specific challenges are found regarding the modelling of the fluid dynamic processes governing hydro-abrasive wear of turbines. These are primarily due to the fact that the flow is turbulent and multi-phase. In fact, the operation of the turbine consists water jet released in an air environment and hitting the turbine blades. When the water jet contains solid particles, the turbine is subjected to erosion. Hence, the flow is turbulent and three-phase, consisting of water, air, and sediment. Modelling such a type of flow is extremely difficult, and demands for the most appropriate method within the multiphase CFD framework. Due to the low value of solids concentration which characterizes hydro-

abrasive wear of turbine (of the order of 0.1% [1]) the coupling in this case is "one-way". This issue, in turn, is approached in a decoupled manner, that is, by selecting first a two-phase model to simulate the free water jet without particle and then a method to determine the motion of the sediments. In order to simulate the water jet without particles, either homogeneous or inhomogeneous models can be used. In the first case the mass and momentum conservation equations are solved once for all the phases while in the second case mass and momentum equations are solved individually for each phase. The inhomogeneous methods are more general in nature, but the higher number of solved equations leads to an increase in the number of uncertain coefficients and parameters compared to homogeneous methods, thus making their solution less "controllable". Conversely, homogeneous methods, although less accurate, are in the end a more robust and "controllable" method. Thus, a homogeneous model is chosen in this thesis, also considering the preliminary nature of the study. In particular, based on a literature review on previous numerical studies on Pelton turbines, it has been considered the Volume of Fluid (VOF) method [2, 3].
Once the water jet without particles is simulated, the sediments' trajectories are calculated using a Lagrangian Particle Tracking approach. Making the tracking a posteriori (one-way coupling regime assumption) greatly reduces the computational burden, and it is possible because, as already mentioned, the sediment concentration is low in the application considered.
A final element of complexity is given by the modeling of the jet blade interaction. Specifically, the blade moves as a consequence of the impact of the jet on it; thus, the speed at which the blade rotates is not defined a priori, but it is a consequence of this interaction. However, simulating the fluid-structure interaction would lead to very high computational costs, so alternative approaches would be useful to keep the computational burden within acceptable limits. This issue was shelved for future research; in this thesis, the blade has been modeled as fixed.

3. Case studies

Following a step-by-step approach, two test cases with increasing complexity were investigated. The first is the particle-laden flow in a 2D model of a fixed Pelton blade, the second is the hydro-abrasive wear of a Pelton blade. In turn, the first case is divided in three sub-cases, adding one phase at a time.

3.1. Particle-laden flow in a 2D model of a fixed Pelton blade

In the first test case, only a transversal section of a Pelton blade was simulated as fixed in time through a steady-state, 2D model. This choice was essentially made to reduce the computational costs, thereby opening the possibility to perform a higher number of simulations, keeping, at the same time, fundamental elements of the problem, particularly its three-phase nature.

3.1.1 Submerged water jet

Firstly the water jet is modeled submerged in still water it has been considered as fluid dynamic model RANS coupled with standard $k-\varepsilon$ turbulence model, and the standard wall function. Then it has been created the geometry of the domain in Design Modeler, taking as reference the value of the parameters of the thesis of Leguizamon [1]. The followed workflow is shown in figure 2.

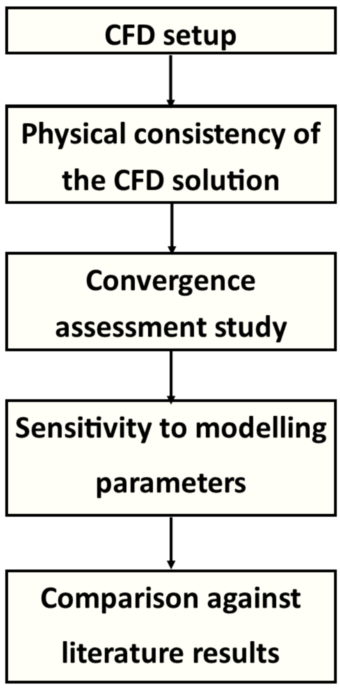

Figure 2: Workflow of the submerged jet case.

Firstly, the physical consistency of the solution was checked by inspecting the color plots of relevant fluid dynamic quantities, such as the Reynolds-averaged velocity magnitude, v, and the turbulent kinetic energy, k.

Then a convergence analysis was performed by considering both the convergence of the solution algorithm and the grid independence. In this regard, 7 different computational grids were defined, considering as target parameters the mean and the maximum of k in the entire computational domain and the profiles of V and k along a vertical chord. Some mesh dependency could be detected only with regards to the local peaks of k. Nonetheless, the variability of k was unlikely to affect the particle-wall impact statistics in the particle-laden flow case, as it was partially proved in the second case study. Thus, the grid independence study was regarded as satisfactory.

So, a sensitivity analysis could be performed with respect to the various turbulence models to see if there was a strong dependence of the result on the choice of this modelling feature. As for the grid independence study, the turbulence model had some effect on k. In the lack of criteria to decide the best option, the standard $k-\varepsilon$ was used, which provides estimates roughly in the middle.

To conclude the analysis, it would have been necessary to validate the model using experimental or possibly numerical data. However, no reference data were found in the literature for the single-phase case. Additionally, it shall be noted that it is virtually impossible to reproduce a literature case for a complex geometry such as a Pelton blade, since all the information needed to reconstruct the domain are not available.

Thus, only a qualitative comparison would be made with respect to the numerical results reported in the PhD thesis of Leguizamon [1], which, however, refer to a fully-coupled, free particle-laden water jet in air. With all these limitations in mind, the values were found comparable in terms of velocity and turbulent kinetic energy, giving some confidence in the suitability of the single-phase model used for the simulations.

3.1.2 Free water jet

Then, the water jet was simulated as free, that is, in a open air environment. The RANS formulation of the VOF was used to simulate the two-phase, air-water flow, coupled with the standard $k-\varepsilon$ turbulence model and the standard wall function.

The same workflow shown in figure 2 was followed for the two-phase case. The color plots of velocity magnitude, v, turbulent kinetic energy, k and volume fraction of water, α_w were consistent with the underlying physical phenomenon. The grid independence study showed that, also in this case, k is the only parameter influence by the grid used, whereas v and α_w are substantially grid-independent. However, this was not a big issue since the particle-wall impact statistics, and thus the erosion estimates, were found only minorly affected by k. The sensitivity analysis was performed referring to difficult-to-decide features of the VOF, such as the modelling of surface tension effects and of the interface between water and air. The results suggested that the best configuration is the one with no surface tension included in the momentum equation (the high velocity of the jet makes the surface tension negligible) and sharp interface modelling (assuming the jet not to split into droplets).

As for the submerged jet case, only a qualitative validation of the results could be made referring to the color plots of velocity and turbulent kinetic energy reported in the literature for similar (yet not equal) cases. Again, the values were consistent with those of previous studies.

3.1.3 Sediment-laden free water jet

As a third step, the particles are injected into the system and their trajectories are calculated over the VOF solution (Figure 3). In particular, steady particle tracking was performed. In the specific case, in the equation of motion are considered the drag force and the pressure gradient force. The particle wall impact statistics were obtained dividing the wall boundary into small segments, and calculating the mean impact velocity, the mean impact angle, and the number of impacts per unit length for every segment. The influence of the number of particles and of the number of the subdivision of the target wall was investigated, obtaining substantial independence. In Figure 4 is reported an example considering the impact velocity considering $\Delta s = 0.0121$ m and 50000 particles injected.

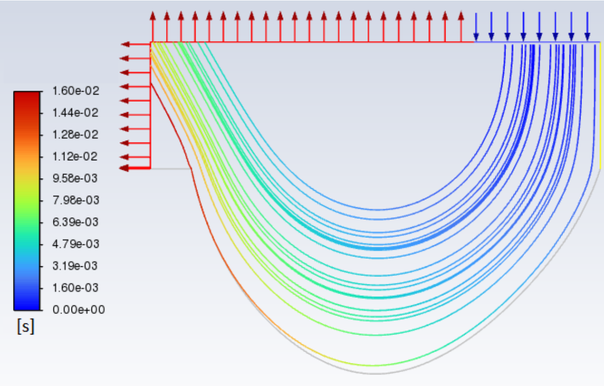

Figure 3: Particles trajectories in the 2D case.

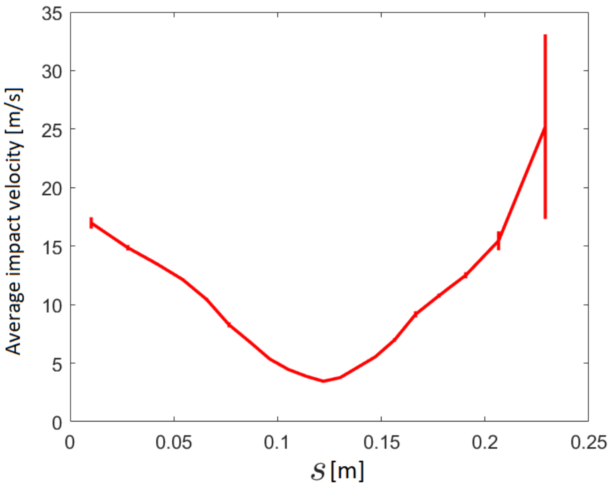

Figure 4: Impact velocity.

3.2. Hydro-abrasive wear of a fixed Pelton blade

In the second test case, the hydro-abrasive wear of a Pelton blade was evaluated. Once again, the blade has been modeled as fixed. All the findings of the previous 2D case were considered as a starting point to define the numerical set up of the 3D case.

The geometry was obtained from the Website mimicking the blade simulated in the PhD thesis by Leguizamon [1], for which the geometry files were not avaialable. Particular effort was put into the manipulation of the geometry and the creation of the fluid domain, shown in Figure 5.

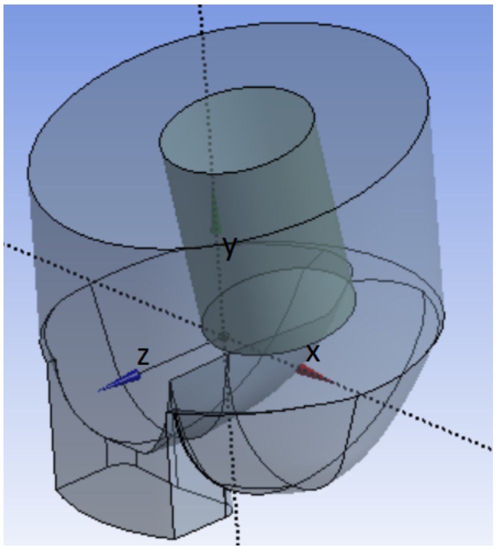

Figure 5: Fluid domain of the 3D case.

The free water jet was simulated for using the RANS version of the VOF coupled with standard $k-\varepsilon$ turbulence model an standard wall function. After verifying the consistency of the water-air flow field, the trajectories of the sediments were calculated. Figure 6 shows an of particles trajectories.

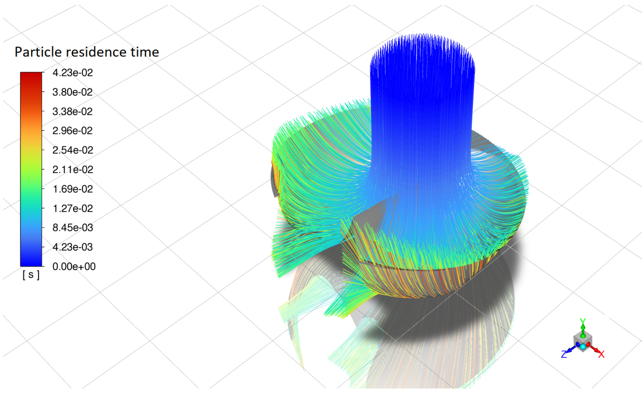

Figure 6: Trajectory of particles.

Finally, the particle-wall impact statistics are calculated over the surface of the blade and erosion of the blade was estimated by using the DNV erosion model [4]. The resulting map of local erosion rate, that is mass removal by each wall element per unit time, is shown in Fig. 7.

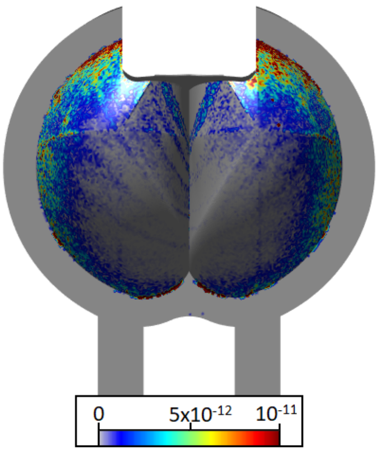

Figure 7: Erosion rate.

The particle-impact statistics and the erosion estimates were considered as target parameters for a convergence study with respect to the mesh resolution and the number of tracked particles, revealing substantial independence. Note that, however, the study was made by visual inspection of color plot, and no quantitative comparison was made.
Finally, the results were obtained with the findings obtained by Leguizamon [1]. Similarities and differences were detected. Particularly, the elements of similarity consist of inlet velocity, bucket width, inlet slope, and inlet distance from the blade, while the differences mainly in blade shape and the fluid dynamics model considered. Note that, however, a direct comparison with the data of Leguizamon could not be made, owing to the differences in the geometry and in the simulation model, particularly the erosion model which is known to have a great impact on the erosion rate estimates.

4. Conclusions

The goal of this thesis is to take the first steps towards the development of a CFD framework for the prediction of hydro-abrasive wear of Pelton turbines. The objective is therefore to build a methodology to understand how to predict erosion, in order to combine the choice of models to solve the problem as correctly as possible, while keeping the computational cost within acceptable limits.
After identifying the most critical modelling challenges, a step-by-step analysis was conducted, adding one element of complexity at a time. Two test cases were considered in this thesis, namely, the particle-laden flow over a 2D slide of a Pelton blade and the hydro-abrasive wear of an actual (3D) Pelton blade. In both cases, the movement of the blade was ignored. For each of the two cases, the physical consistency of the solution was verified, as well as its numerical convergence and the sensitivity with respect to modelling parameters. Finally, a qualitative comparison to literature results referring to similar cases was made as, unfortunately, no quantitative validation was possible owing to the lack of information to reproduce the actual geometries. The thesis provides a good starting point to introduce further elements of complexity, such as the rotation of the blade.

References

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