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Starting off the right foot with foil sock approach and AGR criterion

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1 Introduction

Recent years have seen the importance of foils increase in competitive sailing, from the little bombs of the Mini 6.50 class to the majestic boats of the America's Cup. Computational fluid dynamics (CFD) simulations are now widely used, especially in the early stages of the design of a sailing ship. For foil design, CFD is essential as it allows naval architects and CFD engineers to compare many foil designs through reliable and fast insight into the foil behaviour (drag, lift, sideforce, cavitation etc.). This paper covers a new approach combining two already existing techniques for hydrofoil calculations: a curved domain that follows the shape of the foil with a structured mesh (called a sock mesh below) and a combined refinement criterion based on the free-surface position and on the Hessians of the solution.

2 The FINE/Marine suite

Numerical simulations shown in this paper were performed using FINE/Marine, a marine-oriented computing suite, distributed by NUMECA Int. (now Cadence Design Systems) and used by many naval architects for various hydrodynamic applications. The suite features an unstructured hexahedral mesher called Hexpress, as well as the flow solver ISIS-CFD. The latter is an incompressible unsteady Reynolds-averaged Navier-Stokes solver for multifluid flows which is developed by the METHRIC team of the LHEEA Laboratory.

This solver features a mixture-fluid formulation to model the water-air interface. The flow equations are discretised in a finite-volume framework, using pressure-velocity coupling obtained through implicit time integration with a Rhie & Chow SIMPLE-type method. The discretisation is face-based. While all unknown state variables are cell-centered, the systems of equations used in the implicit time stepping procedure are constructed face by face. This technique poses no specific requirements on the topology of the cells. Therefore, the grids can be completely unstructured, and cells with an arbitrary number of arbitrarily-shaped faces are accepted.

3 Adaptive grid refinement

One of the most important features of FINE/Marine is the Adaptive Grid Refinement (AGR) algorithm, that allows the mesh to be automatically refined locally, during the computation. This powerful tool enhances the capturing of flow details, either for waves, wake flows, or in boundary layers around bodies, especially in our case around hydrofoils edges. The AGR algorithm consists of three steps, the first one being the computation of the refinement criterion using the current flow fields. This criterion is used in the second step to set a flag in each cell, that states if the cell needs to be refined or not. In the third and final step, cells are refined and in a parallel computation, load balancing procedures are called to keep the same number of cells between partitions.

4 New approach: foil sock and combined criterion AGR

4.1 Initial mesh

In FINE/Marine, the standard approach for hydrofoil calculations is to use a box-shaped overset domain around the foil, to allow large body movements thanks to an overlapping mesh around the body, as well as a free-surface AGR criterion to efficiently capture the free surface of the flow (Wackers (2021)). This approach requires a fine Hexpress mesh, especially in areas of the hydrofoils where a precise flow capture is mandatory, like the leading and trailing edges as well as the foil tip.

The first feature of the foil sock approach is the use of a curved overset domain, a technique already used by French naval architects VPLP in partnership with NUMECA International (Mallol et al. (2019)). In a 3D modeler, a foil-shaped domain is created (Fig. 1a), then imported in the IGG meshing software of

the FINE/Marine suite to create a curved mesh that fits this domain (Fig. 1b). This mesh is then imported in Hexpress, where local refinements are performed as usual to correctly capture the foil's geometry.

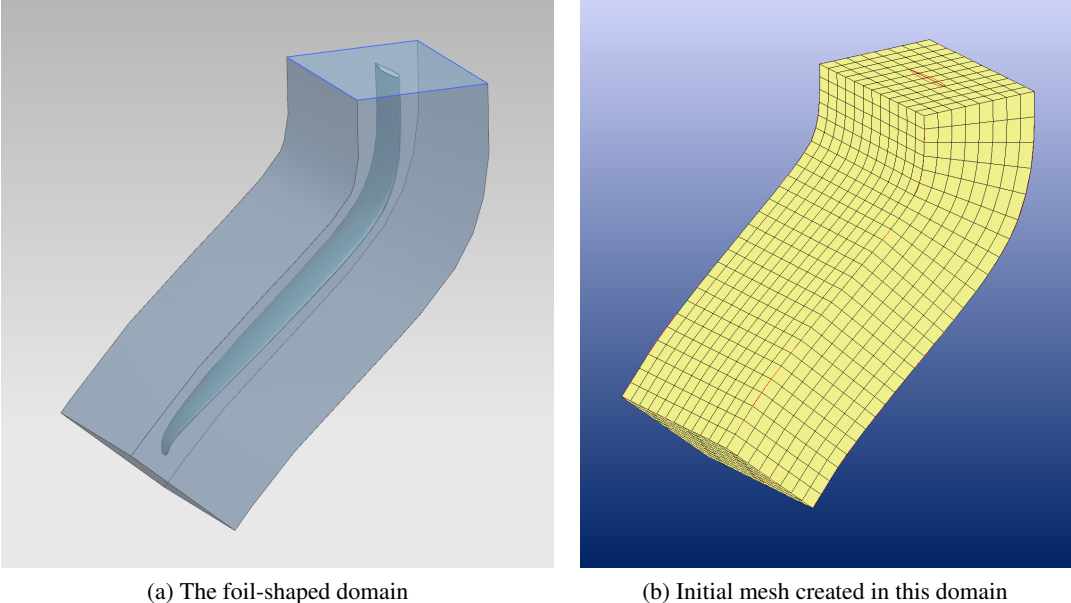


Fig. 1: Example of a sock domain for a NACRA 17 foil

The main benefit of this method is that, since the mesh of the foil overset domain is created from a mesh that follows the shape of a foil, it leads to a reduced number of cells because the complex geometry of the foil is better captured. In addition to this, the resulting mesh is of better quality, as it is better aligned with the geometry and contains less diamond cells. Especially for complex geometries, this is an advantage since the traditional approach results in many of them, and needs a lot of mesh refinement to capture the leading and trailing edge (Fig. 2). With the sock approach, one can obtain a lighter mesh of good quality for CFD computations.

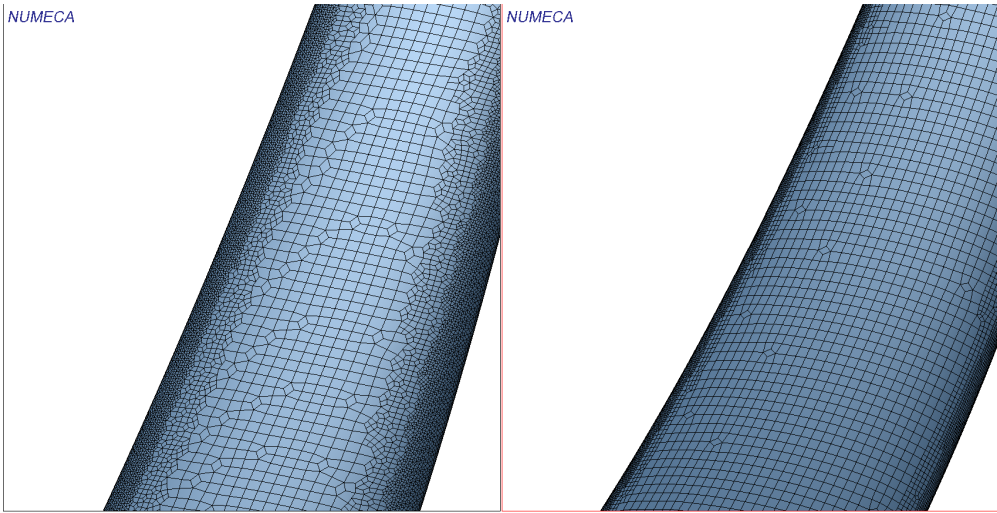


Fig. 2: Detail of the mesh of an IMOCA foil obtained without (left) and with sock domain (right).

4.2 Adaptive grid refinement

The benefits of the sock mesh approach are actually reinforced by the second feature, which is the use of the Multi-Surface and Flux-Component Hessian (MS-FCH) refinement criterion. When using this AGR algorithm, the refinement criterion is based not only on the free-surface position but also on the

Hessian of both pressure and velocity. This computation method makes the MS-FCH criterion the go-to criterion in flows where the user needs a good accuracy for the forces applied on bodies as well as a good understanding of the flow in the boundary layer (Wackers et al. (2017), Wackers et al. (2022)), which is typically the case in hydrofoil calculations. Above all, calculations using MS-FCH criterion allow a user to generate a lighter mesh on bodies, and to leave local mesh refinements to the AGR algorithm. This is actually a big step forward for naval architects and CFD engineers who are used to generate fine meshes for their marine CFD projects.

However, efficient computations with AGR require a careful setup of the initial mesh and the simulation parameters, in order to obtain the correct refined mesh in the end. Simulations shown in this paper all follow the protocol of Richeux (2022), which covers in-depth how to generate Hexpress meshes suitable for MS-FCH AGR, as well as computation parameters to perform and optimize hydrofoil calculations with ease. A consideration for Hexpress is that cells flagged by AGR will have their dimensions divided by two, which means that only a few discrete cell sizes are attainable once the Hexpress mesh is created. Thus, for this mesh, the protocol prescribes target cell sizes for each part of the foil, defined from a characteristic length (typically the foil chord length). These target cell sizes are a compromise between coarse cells which give most freedom to the adaptation, being refined only if the flow requires it, and cell sizes small enough to capture the body geometry accurately. Furthermore, the threshold values which the MS-FCH algorithm requires as inputs are also chosen proportional to the foil characteristic length.

The simulations on which the protocol of Richeux (2022) is based did not include a foil-shaped domain. And yet, sock-domain simulations made so far with its recommendations are promising, provided that the dimensions of the sock that are also proportional to the characteristic length of the foil.

However, even with this new approach, when the initial mesh is of poor quality, AGR might create badly-oriented faces that threaten the speed of the calculation or even its stability. For those critical areas, the initial mesh needs to be refined. On foils, it typically implies to generate a finer mesh on foils tips or trailing edges, especially when the latter are truncated (Fig. 3).

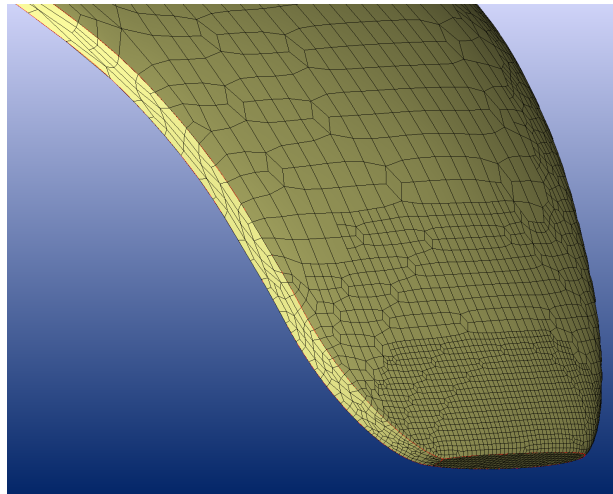


Fig. 3: Certain areas, here the junction between the NACRA 17 foil tip and trailing edge, require user attention.

5 Results

Once calculations are complete, one can observe the mesh that AGR has created during the computation. Compared with the Hexpress plus free-surface refinement approach, the mesh created using the sock approach and the MS-FCH criterion AGR is of much better quality: Fig. 4. shows that cells refined by the MS-FCH AGR algorithm benefit directly of the good quality of the initial mesh, as the refined mesh looks much more regular and there isn't any very small cells around the body.(Fig. 4)

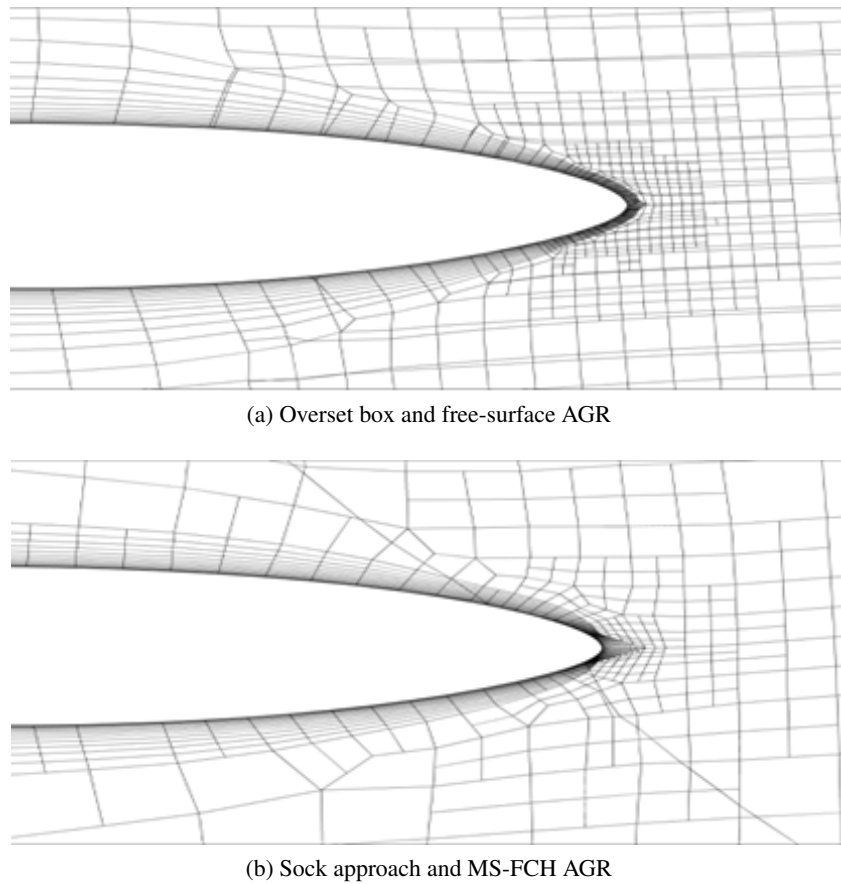


Fig. 4: Cross-section of the mesh obtained after calculation on a typical IMOCA foil calculation (4.5M elements mesh each).

The main difference between meshes created by the two different AGR approaches can be seen around the trailing edge of the foil. Indeed, the free-surface criterion does not refine the mesh around bodies, thus making the capture of the boundary layer inefficient if the Hexpress mesh is not refined enough around the trailing edge of the foil (Fig. 5). However, when using the MS-FCH criterion, one does not need to perform such local refinement in the initial mesh, since it will be automatically refined by the AGR algorithm during the calculation. This ensures that the wake is captured correctly.

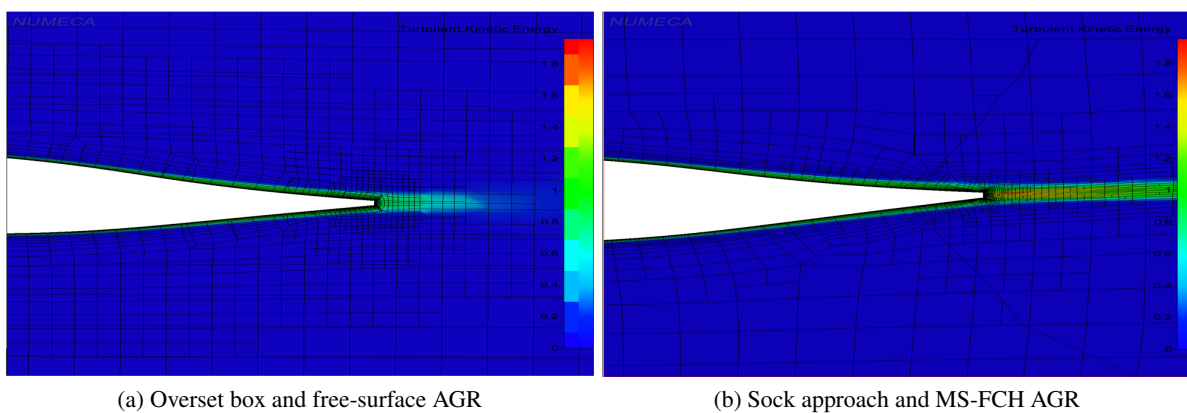


Fig. 5: Mesh around the trailing edge of an IMOCA foil and simulated turbulent kinetic energy.

This method has a direct impact on the number of cells needed to reach numerical convergence: since cells are created only when the calculation requires it, and are created from a better-quality mesh,

the numerical convergence is reached with fewer cells. Figure 6 shows the convergence and estimated uncertainty for series of meshes created with the two approaches, for an IMOCA foil. For the sock approach uncertainty calculation, TrH (the Hessian threshold used in the AGR parameters) is used as the typical cell size, whereas for the overset box approach $(nb.cells)^{-\frac{1}{3}}$ is used.

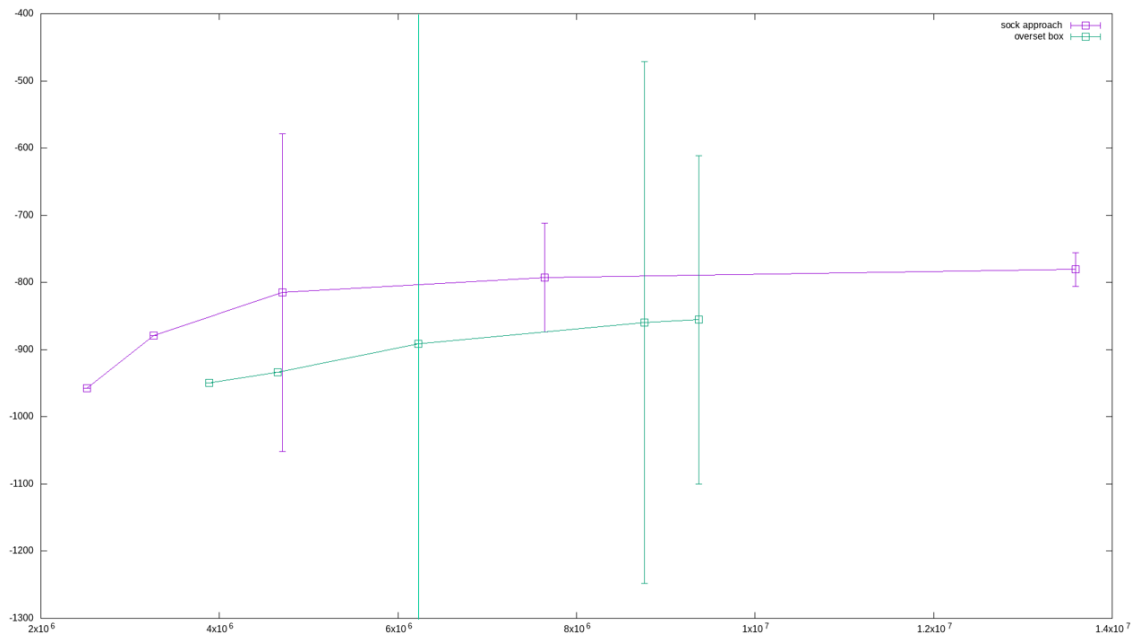


Fig. 6: Mesh convergence for an IMOCA foil using sock mesh approach with estimated uncertainty using the method of Eça and Hoekstra (2014).

It appears that for the two most refined meshes, the sock approach leads to very precise results: 3.17% uncertainty for a 13.5M elements mesh, whereas the finest mesh used with overset box method – 9.37M elements – leads to a 28.53% uncertainty. Furthermore, the sock approach looks very promising for an industrial application by naval architects. Indeed, for the same precision a mesh containing 3 times less cells is needed, which means faster computations and thus the possibility to compare more foil designs.

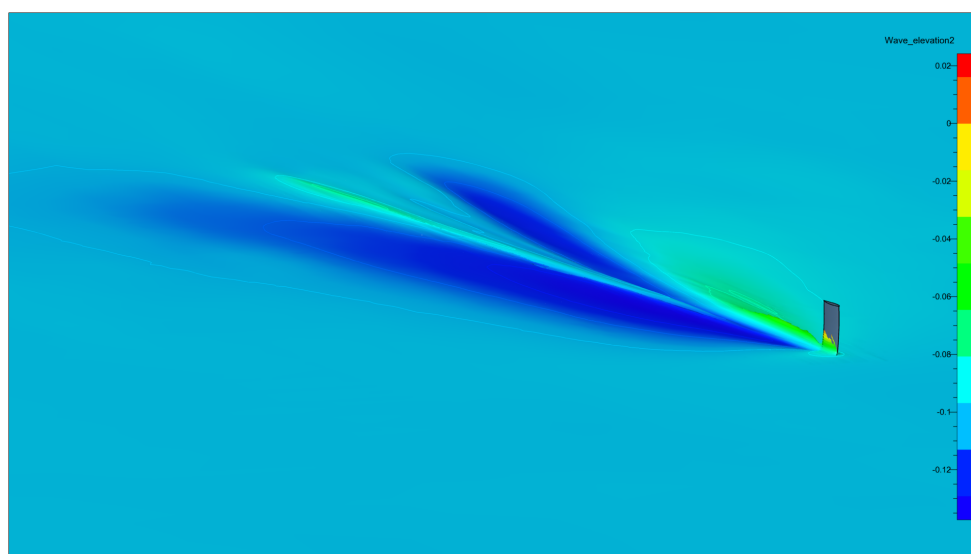


Fig. 7: Flow around the NACRA 17 foil

6 Conclusion

Throughout this study, the relevance of using a curved domain around a hydrofoil combined with the MS-FCH refinement criterion has been shown, as it results in a higher-quality mesh, a better convergence and a better capture of physical phenomena involved in hydrofoils simulations. Moreover, when using the MS-FCH AGR criterion, the user can generate a coarser initial mesh, which leads to gains in mesh generation time as well.

The forces applied on the body are different between the two methods exposed in this paper, even though they may eventually converge to the same value. This makes validation mandatory; it is currently carried out on the NACRA 17 foil previously shown in this paper, to compare results to those obtained by Marimon Giovannetti et al. (2022).

These calculations will need to include fluid-structure interaction, as it can produce up to a 25% difference in lift (Lothode et al. (2013)). On this specific aspect, FSI calculations are made easier to perform with the sock mesh approach as only the foil-shaped domain will follow the body deformation, therefore keeping a very good mesh even for large deformations (Leroyer (2021)).

It could also be interesting to work on the automation of this method to automatically create the foil-shaped domain, set up mesh parameters and AGR numerical parameters, since automation is easy to implement in FINE/Marine.

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