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INDUSTRIAL APPLICATION OF ADAPTIVE GRID REFINEMENT – THE CASE OF FINE™/MARINE

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Abstract. This paper analyses the introduction of an adaptive mesh refinement capability in the commercial flow simulation suite FINE™/Marine. By correlating the technical evolution of the method with its acceptance by users, the paper studies the factors which are of importance for successful mesh adaptation in industry.

1 INTRODUCTION

Industrial application of automatic mesh adaptation is gaining momentum. While adaptive refinement originates from academic research, the CFD Vision 2030 [8] identified it as a future key technology for industry. Today, for example, the Unstructured Grid Adaptation Working Group [10], the growing community around the open-source (re)mesher MMG [6], or the recent release of mesh refinement in StarCCM+ [9], show the growing industry awareness of mesh adaptation and its increasing maturity for industrial use. Still, the step to successful industry application puts requirements on mesh adaptation which are different from those in academia. This is a new challenge for research.

This paper analyses the introduction of adaptive grid refinement in the commercial flow solver FINE™/Marine [2]. This simulation suite, dedicated to hydrodynamic flow simulation for marine applications, is developed by NUMECA International in collaboration with EC Nantes / CNRS who provide the unstructured flow solver ISIS-CFD[1].

Mesh refinement has been available in this flow solver since 2009, but it found little industrial use in the beginning; systematic use by a significant number of industry clients started suddenly around 2017. Figure 1, which represents the part of the marine-related talks at NUMECA user meetings that mentioned adaptive refinement, reflects this sudden

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[1] This work is based on my personal opinion and does not necessarily reflect the views of NUMECA Int., the owners of ISIS-CFD (CNRS / EC Nantes), or the collective authors of this flow solver. The purpose of this work is scientific, any implication of either praise or criticism of FINE™/Marine is unintentional – although I may have difficulty hiding that I am proud of what we achieved.

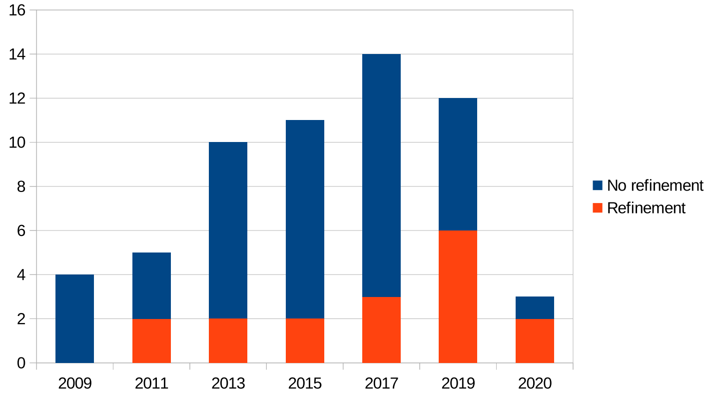


Figure 1: Marine-related talks at NUMECA User Meetings, indicating those that mentioned adaptive refinement. The 2020 meeting was a short online event.

growth. The increase in popularity of adaptive refinement, several years after its introduction, allows us to study which factors changed over that period, since these may be aspects of the mesh adaptation method which dissuade or attract industry users.

In this paper, I will provide my personal analysis of this question. As principal developer of the mesh adaptation in ISIS-CFD, I will focus on the technical aspects. Communication by NUMECA contributed significantly to the increased use of grid refinement and the generally increasing awareness of adaptation in industry probably helped as well. However, these aspects are insufficient without good technical performance. Thus, an analysis of technical aspects as a driver for user acceptance appears valid.

The paper, based partially on [11], starts with an overview of FINE™/Marine and its flow solver (section 2), plus a profile of its clients (section 3). The final three sections discuss different aspects of mesh refinement and their influence on users. It is my hope that this discussion can contribute to the awareness of the challenges in industrial mesh adaptation and help with the industrialisation of other grid adaptation methods.

2 THE FINE™/MARINE SUITE

2.1 Overview

The simulation suite FINE™/Marine, introduced in 2007, combines the flow solver ISIS-CFD with NUMECA's unstructured hexahedral mesh generator HEXPRESS™, the visualisation tool CFView, and a dedicated graphical user interface (GUI). HEXPRESS™ is a volume-to-surface full-hexahedral unstructured mesher that uses hanging-node topologies; body-fitted viscous layers are inserted as a final meshing step.

The C-Wizard makes it possible for a user to setup computations in a matter of minutes, without expert knowledge. This tool automatically selects the meshing and computational parameters for most standard types of simulations based on a few user-specified parameters (ship length and velocity etc.) User scripting via Python is also available.

2.2 The flow solver ISIS-CFD

ISIS-CFD, developed by EC Nantes / CNRS, is an incompressible unsteady multifluid Navier-Stokes solver [1, 7]. The solver is based on the finite volume method to build the spatial discretisation of the transport equations. The discretisation is face-based, so cells with an arbitrary number of arbitrarily-shaped faces are accepted. The code is fully parallel using the MPI protocol. Turbulence is mainly modelled with the Reynolds-averaged Navier-Stokes equations; free surfaces are captured with a mixture-model approach [7]. Finally, techniques such as overset (multi-domain) meshes allow the 6 DOF resolution of body motion and coupling with other fluid or structure solvers is possible.

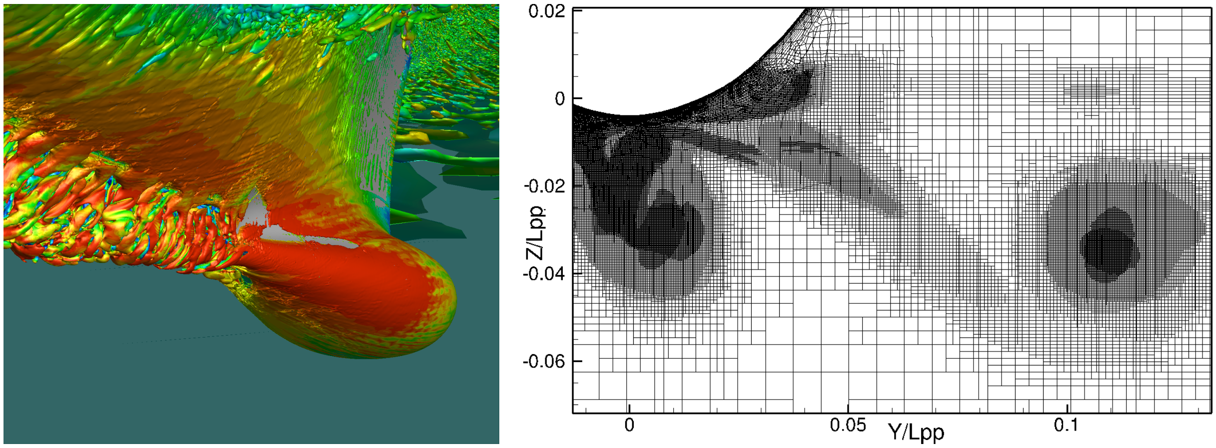


Figure 2: An example of mesh adaptation in ISIS-CFD: Detached-Eddy Simulation of a ship in sideslip and a cut through the adapted mesh for this simulation.

2.3 Mesh adaptation

The adaptive grid refinement in ISIS-CFD [11], which was started in 2007 as a follow-up of the Ph.D. thesis by A. Hay [4], performs anisotropic refinement of unstructured hexahedral meshes through cell division. Earlier refinement can be undone and the mesh adaptation, performed in parallel, includes an automatic dynamic load balancing. The refinement criteria are based on metric tensors following P.L. George [3], where the objective of the cell division is to make the hexahedral cell sizes in the metric space, in all directions, equal to a constant T_r. Refinement criteria are based on Hessians of the pressure and velocity, on the position of the water surface, or on a combination of both. An example is shown in figure 2. Finally, for overset meshing, adaptive refinement can be used to make the cell sizes in the overlapping and background meshes equal.

3 FINE™/MARINE USERS

In naval architecture, design and consultancy offices are often small enterprises, employing between two and six people. Even in the larger shipyards, the design departments are often small. This implies that, although most naval architects today are trained in the use of CFD, there are rarely any dedicated CFD specialists in these companies. Furthermore, ships are mostly one-off designs, which means that design budgets are limited. Therefore, earlier ship designs are often reused with minimal changes. For simulations, this means that consistency with the company's backlog of simulations for earlier designs is crucial. Also, especially for sailing yachts, large numbers of computations in different conditions are often required for the same geometry.

These aspects lead to a tendency to standardise and automate the computational process, so that computations can run in a repeatable manner with little or no user supervision. Many companies use the C-Wizard almost exclusively and others have created their own Python scripts to setup and run computations. Users often choose FINE™/Marine because the software, with its dedicated marine workflow and far-going automation, makes it easy to consistently produce accurate and reliable simulation results with little user intervention. This point is crucial for mesh adaptation, since industry users will not adopt the technique until it satisfies the same criteria.

4 USER GUIDELINES AND USABILITY

In the early years, many clients told me that they tried out the mesh adaptation, but abandoned it because they were unable to set the right parameter values. Especially T_r, the reference length for the cell sizes, proved to be difficult to choose since it does not correspond to anything tangible. My advise at the time was to try out different settings and to inspect the adapted meshes to see if the choices were right, but for the reasons outlined in the previous section, this was not an acceptable practice for users.

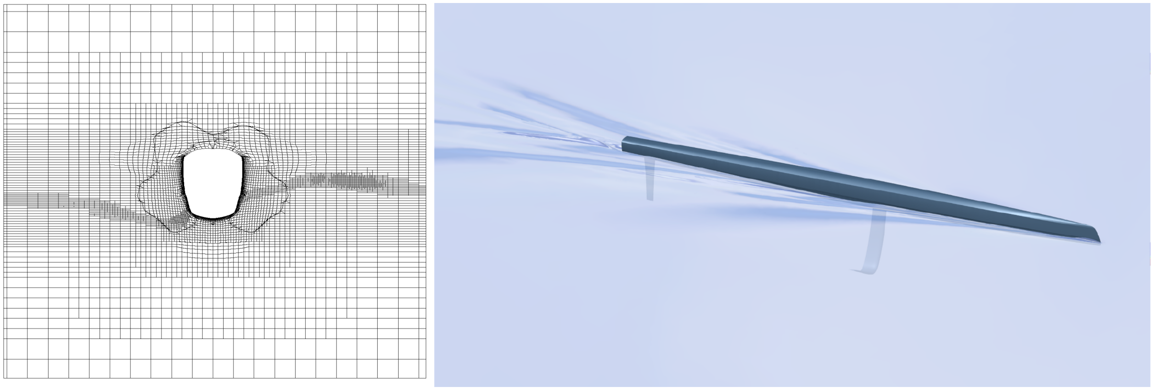
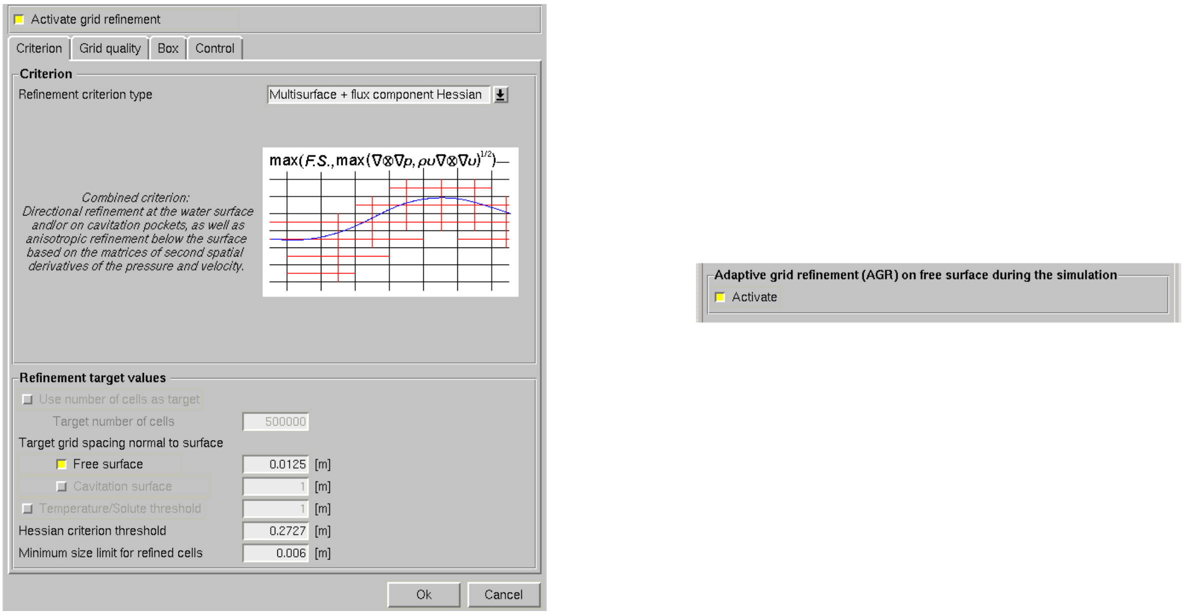


Figure 3: Catamaran hull simulated with free-surface refinement, using automated Python-based setup.

A step forward was to perform the refinement in a non-dimensional setting, where the metric fields do not depend on the size and velocity of the simulated object, but only on the non-dimensional flow parameters (Reynolds, Froude) and the geometry of the object. These dependencies proved to be small, so that the same T_r could be used for classes of simulations [11]. Thus, by reducing the number of parameters that influence the magnitude of the metric field, the non-dimensionalisation simplifies the guidelines for choosing the threshold. The scaling of the metric field by its integral over the domain, which makes the number of elements directly proportional to a complexity parameter [5] is another way to achieve the same effect.

The problem of user guidelines was finally solved when our own experience at EC Nantes grew. Most early use of mesh adaptation was refinement around the free surface, to capture the wave pattern of ships. After about six years of use, we had discovered best-practice guidelines for T_r, for damping at the outflow side, for the frequency of the adaptation steps, etc. which were precise enough to be implemented in a Python script similar to the C-Wizard. This script performed simulations with adaptive grid refinement, without any user intervention (figure 3). Interestingly, the script used only capabilities that were present in the 2009 release; the difference was our increased user experience.



☑ Activate grid refinement

Criterion

Refinement criterion type: Multisurface + flux component Hessian

Combined criterion: Directional refinement at the water surface and/or on cavitation pockets, as well as anisotropic refinement below the surface based on the matrices of second spatial derivatives of the pressure and velocity.

Refinement target values

☐ Use number of cells as target

Target number of cells: 500000

Target grid spacing normal to surface

☑ Free surface: 0.0125 [m]

☐ Cavitation surface: 1 [m]

☐ Temperature/Solute threshold: 1 [m]

Hessian criterion threshold: 0.2727 [m]

Minimum size limit for refined cells: 0.006 [m]

Adaptive grid refinement (AGR) on free surface during the simulation

☑ Activate

Figure 4: Mesh adaptation menus in the FINE™/Marine user interfaces. Left: the standard user interface (tab 1 of 4). Right: the adaptation part of the C-Wizard.

Today, most mesh adaptation users perform free-surface refinement through the C-Wizard. Figure 4 shows the full adaptation menu from the standard interface, compared with the mesh adaptation part of the C-Wizard interface. Such a one-button interface appears important for successful industrial use and, by a combination of parameter dimension reduction and gathering user experience, it can actually be achieved.

5 BUGS AND LIMITATIONS

A second blocking point in the years up to about 2016 was the presence of bugs and code limitations, i.e. mesh topologies that the adaptation could not handle. Users who are faced with tight production schedules do not have the time to look for ways around such reliability issues and will abandon the adaptation if they occur too often.

A particular consulting project is of interest here. In 2016, NUMECA obtained a contract which required them to provide series of 256 simulations, within a week of receiving a geometry from the client. Their initial intention was to capture the free surface for these simulations using adaptive refinement. However, they were faced with about 10 simulation failures in each batch due to a problem in the adaptive load balancing. This 96% success rate led them to abandon the mesh adaptation for the project. Later on, when this issue had been solved, the batches ran generally without errors, which indicates less than 1 failure in 1000 computations or 99.9% success. This was considered acceptable.

For development, this leads to conflicts with the requirements of academia. The goal of academic research is to prove concepts, which can be done with reasonably but not perfectly bug-free code. And fixing bugs and removing code limitations takes time: I probably spent the better part of 2015 and 2016 fixing every single bug that we had ever discovered, which meant that little time was available for publishing. But for industry, this was a necessity.

It is useful to accept beforehand that time will be needed to make the code robust. But robustness can also be anticipated in the software design, for example by choosing simple algorithms and modular routines which interact as little as possible, and by rigorously using tools such as version control, automated testing and bug tracking software. These are all part of a successful industry introduction project.

6 BREAKTHROUGH APPLICATIONS

By the end of 2016 the software was reasonably bug-free and easy to use. But still, it was not widely adopted. A probable reason for this is the reluctance of industry users to change their simulation procedures, since many rely on a back catalogue of standardised simulations as a reference for new designs. This implies that an absence of dissuading factors is not enough; users will only switch to mesh refinement if there is a significant positive reason to do so.

In our case, widespread use started with the emergence of two new types of simulations (both shown in figure 5) that were practically impossible without mesh refinement. The first breakthrough application was something that I personally considered as unimportant compared to flow-based adaptation: overset refinement. The overset or chimera technique is a way to achieve large object movements by moving an overset mesh through the main background mesh and dynamically coupling these meshes through interpolation. For the quality of this interpolation, it is important that the cells in the two domains have locally the same size. We achieve this through adaptive refinement, by 'reverse-engineering' a metric from the existing meshes and exchanging this between the domains.

The reason that overset refinement took off is that without this adaptation, the entire background domain should be meshed with fine cells, which increases the cell count to unrealistic values. Also, overset refinement was available from the introduction of overset meshing in FINE™/Marine, so users did not have existing procedures without this feature. And finally, it is easy to use, requiring only an on/off button.

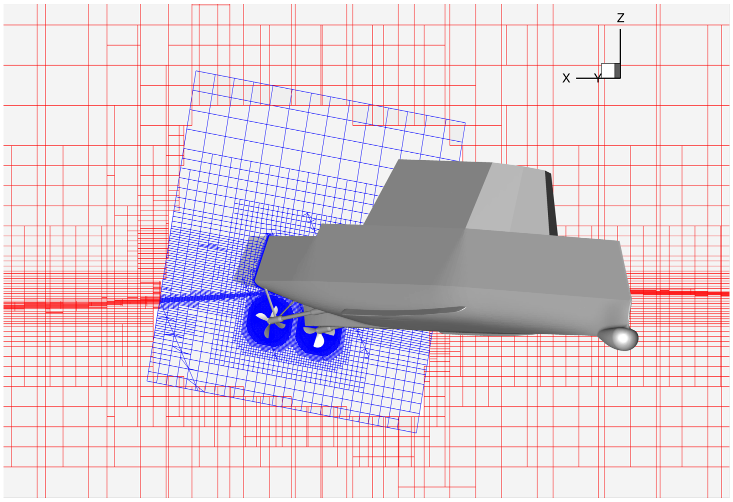


Figure 5: Self-propelled ship in oblique waves, simulated with overset and free-surface refinement.

The second breakthrough application was free-surface capturing refinement for fast planing ships and lifting hydrofoils. Contrary to classical ships, fast hulls and hydrofoil-borne ships may significantly change their attitude between the position at rest and the (unknown) stable position at speed. For traditional meshing, this is a challenge: either large zones of very fine cells are needed to cover all the possible positions of the water surface, or the simulations must be performed in multiple iterations, where the first simulations only serve to predict the stable position for meshing purposes.

Creating the free-surface mesh with adaptive refinement solves this problem completely: a fine mesh is now inserted only at the actual free-surface position, in one simulation. And NUMECA had studied this procedure well enough to configure it automatically via the C-Wizard. These advantages were significant enough to convince users to adopt the procedure and it is now the standard for fast-ship simulation.

These two applications created confidence in the mesh adaptation and paved the way for more widespread use. For example, free-surface refinement is used more and more for other applications than fast ships and has already become standard practice for simulating ships in waves (figure 5). We intend to keep this dynamic going by introducing even more types of computations, such as average-based refinement for highly unsteady flows (see figure 2), Hessian-based refinement for drag computation and waves, and uncertainty estimation using adaptation. With this evolution, adaptive refinement can eventually become part of the majority of FINE™/Marine simulations.

7 CONCLUSION

The case study of FINE™/Marine gives reason for optimism, since it shows that the successful transfer of mesh adaptation from an academic setting into routine industrial application is possible today. However, this is a long and slow process, which requires a higher level of attention to coding details and a more rigorous organisation than what is often required in academia; it is not something that is undertaken lightly.

Is hands-on involvement in the industry application of mesh adaptation a useful goal for academic research? This point is debatable, but my point of view is that the transfer of knowledge to industry works best when the researchers are directly involved. Also, the industry environment provides the most stringent test of mesh adaptation methods that is possible, so it can help academia in selecting and improving these methods. This has happened for FINE™/Marine: its mesh refinement method would never have had the capability that it has today without feedback from industry. And finally, it is a source of satisfaction to know that one's work is actually helping others. In my opinion, these points make industry application a worthwhile pursuit for a researcher.

ACKNOWLEDGEMENTS

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