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AUTOMATIC GRID REFINEMENT FOR THE ACCURATE COMPUTATION OF FREE-SURFACE FLOW AROUND SHIPS

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Abstract. *A metric-based refinement criterion computation technique is presented for the automatic grid refinement procedure implemented in ISIS-CFD, the unstructured finite-volume flow solver developed by CNRS and Ecole Centrale de Nantes. For this general technique, two refinement criteria are presented: one that refines at the location of the water surface, and one that is based on the second spatial derivatives of the pressure. Two test cases show that these criteria produce accurate flow solutions in an effective way.*

1 INTRODUCTION

An automatic grid refinement procedure has been developed for ISIS-CFD, the unstructured finite-volume RANS solver for hydrodynamic flows, created by the Numerical Modelling group at ECN [8]. As this commercialised flow solver is used for solving large-scale realistic flow problems of industrial complexity, strong requirements are posed on the grid refinement procedure in terms of efficiency, robustness, and flexibility. Therefore, the method performs anisotropic refinement of the unstructured hexahedral meshes that ISIS-CFD uses, it allows the easy exchange and implementation of refinement criteria, and it is fully parallelised including automatic dynamic load balancing [10].

For ship flow computation, several physical phenomena of a highly different nature play a role. Typically, the flow around a ship involves the generation of a wave pattern at the free surface, as well as vorticity production and viscous effects on the ship hull. A grid refinement procedure must be able to adapt a grid to each of these features, even to multiple features at once.

Therefore, flexibility in the choice of the refinement criterion, which indicates where the grid must be refined, is essential; this paper presents a metric-based refinement criterion strategy that offers a very flexible basis for the development of criteria, and the possibility to easily combine several criteria. After an introduction of the flow solver and refinement procedure in section 2, the section 3 defines this strategy. Then section 4 introduces two ship flow refinement criteria, which are applied to flow computations in section 5. The paper ends with a conclusion.

2 FLOW SOLVER AND REFINEMENT PROCEDURE

ISIS-CFD, available as a part of the FINE$^{\mathrm{TM}}$/Marine computing suite, is an incompressible unsteady Reynolds-averaged Navier-Stokes (RANS) method [2, 8]. The solver is based on the finite volume method to build the spatial discretisation of the transport equations. The unstructured discretisation is face-based, which means that cells with an arbitrary number of arbitrarily shaped faces are accepted.

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, transport equations for the variables in the turbulence model are added to the discretisation. Free-surface flow is simulated with a multi-phase flow (VoF) approach: the water surface is captured with a conservation equation for the volume fraction of water, discretised with specific compressive discretisation schemes [8].

The method features sophisticated turbulence models, 6 DOF motion for simulated ships [7], and the possibility of modelling more than two phases. For brevity, these options are not further described here.

Recently, an automatic grid refinement capability has been integrated in ISIS-CFD [10]. The goal of the development was to produce a method that can be used in daily practice for all the applications of this code and that can be easily maintained as the code develops over the years. Therefore, the mesh adaptation method has been made general: it allows unstructured grids around complex geometries, directional refinement to keep the size of 3D refined grids low, and derefinement of refined grids to enable unsteady flow simulation. The method is flexible to allow the easy changing of refinement criteria and, like the flow solver, it is fully parallel. The refinement procedure is completely integrated in the flow solver.

To ensure robustness and flexibility of the grid refinement method, it is divided into three distinct parts that exchange only minimal information. First, the refinement criterion is computed, a scalar or tensor field that indicates the local desired cell size. Based on this criterion, the decision is taken which cells to refine or to derefine. Finally, the actual grid adaptation is performed. This step includes automatic load balancing with the ParMETIS library [5]. During a computation, the grid refinement method is called every few time steps, to keep the grid well adapted to the flow solution as it develops.

3 METRIC-BASED REFINEMENT

For the refinement criterion computation, we recently developed a strategy based on metrics. This technique has been used often for the generation, and the adaptive refinement, of unstructured tetrahedral meshes (see e.g. [3]). For the unstructured hexahedral meshes that we use, it is the most flexible way of specifying any type of anisotropic refinement.

In the method, the refinement criterion is computed as a field of 3×3 SPD tensors. The metric tensor $\mathcal{C}_i$ ($\mathbb{R}^3 \rightarrow \mathbb{R}^3$) in each cell is considered as a geometric operator that transforms each cell Ω_i in the physical space into a deformed cell $\tilde{\Omega}_i$ in a modified space. Then, in each cell, directional refinement is applied to produce a grid that is as nearly uniform as possible in the modified space (see figure 1). Using suitable tensors C_i, desired cell sizes in any given direction can be specified.

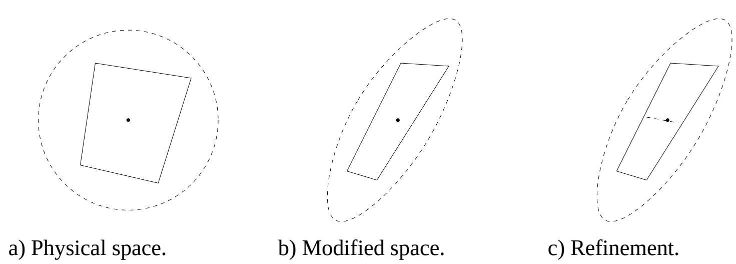


Figure 1: Tensor refinement criterion. Cell Ω_i and unit circle (reference) in normal space (a), deformed cell $\tilde{\Omega}_i$ and deformed circle after application of the transformation C_i (b), and refinement to create a uniform grid in the modified space (c).

As the metric formulation is very general, it can be used to implement refinement criteria based on different quantities. These criteria can also be easily combined, it is enough to take, in each cell, the approximate maximum of two or more criterion tensors using an approximation like the one given by [3].

Interestingly, the combination of metric-based refinement with a fixed original grid gives a highly robust procedure. The major problem in metric-based tetrahedral grid generation is the prevention of singular tensors, that produce infinite-sized cells. Here, the maximum cell size is limited by the original grid, so singularity in the tensors is not a problem. On the contrary, we use singular tensors to our advantage, to specify refinement in one direction only (see the next section for an example). Thus, any symmetric positive-semidefinite tensor can be used as a refinement criterion.

4 REFINEMENT CRITERIA FOR SHIP FLOW

We present two criteria to be used for the computation of the flow field generated by a ship. To accurately simulate water waves numerically, it is necessary to have a fine grid at the location of the water surface; this gives good resolution of the volume-fraction equation used in ISIS-CFD to indicate the surface position. Thus, our first criterion refines at the location of the water surface. However, the orbital velocity fields of the waves must also be resolved correctly, as well as the water flow below and around the ship's hull, that drives the wave making. Therefore, another criterion is chosen based on the Hessian of the pressure, to capture the pressure and velocity fields that produce the waves. It is our intention to finally combine these two criteria into one.

4.1 Free-surface criterion

Our first criterion refines in the neighbourhood of the water surface. Directional refinement is employed to refine the grid in the direction normal to the surface only. Where the free surface is diagonal to the grid directions, isotropic refinement is used, but where the surface is horizontal, directional refinement is chosen; the resulting zone of directional refinement includes the undisturbed water surface, as well as smooth wave crests and troughs. This is essential to keep the number of grid cells low, as the water surface is often nearly undisturbed in most of the domain. Figure 2 gives an illustration of this refinement principle.

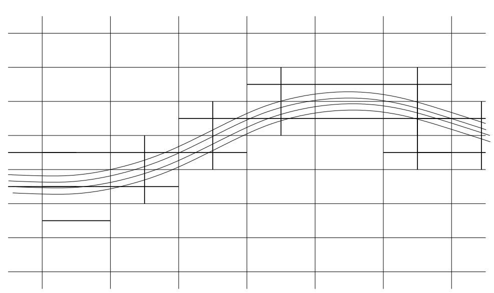


Figure 2: Isotropic and directional refinement at the free surface. The curves represent volume fraction isolines.

Directional refinement normal to the free surface implies, that the refinement criterion imposes a constraint on the cell size in that normal direction only. The cell size in all other directions is kept as large as possible. Thus, cells that are oriented diagonally to the interface must necessarily be refined in all directions, but cells that are aligned with the interface can be refined in one direction only. In the context of tensorial refinement, this is obtained by specifying tensors with only one non-zero eigenvalue, associated with an eigenvector normal to the surface. As explained above, this poses no problems from a numerical point of view.

4.2 Hessian-based refinement

The Hessian matrix of second spatial derivatives of the solution is a common choice as a refinement criterion. We base this criterion on the pressure field, so it reacts both to wave fields and to vorticity at the ship hull.

The major difficulty in using the Hessian tensor as a refinement criterion is the accurate evaluation of the second derivatives, independent of the mesh. If the criterion computation is perturbed by local grid refinement, it may react more to existing grid refinement than to the pressure field. To prevent this undesired effect, numerical errors in the computed second derivatives must be significantly smaller than the derivatives themselves in all cells.

A particular problem associated with unstructured hexahedral meshes, is that the grid remains irregular when it is refined. For structured grids, and even for most unstructured tetrahedral meshes, when the grid is refined the cells get more and more the same shape and size as their neighbours. On unstructured hex meshes however, there will always be cells that are two times smaller than their direct neighbours. This means, that numerical schemes which rely on mesh regularity to get good accuracy are not suited for these meshes; a useful scheme must give sufficient accuracy for arbitrary cell configurations.

For the computation of second derivatives, we use a least-squares method based on third-order polynomials. In each cell, the polynomial is computed that best fits the pressure in the cell, its neighbours and its neighbours' neighbours, in the least-squares sense. The approximated Hessian is constructed from the second derivatives of this polynomial. The least-squares procedure guarantees that the difference between the approximating polynomial and the real pressure is not in the space of third-order polynomials; therefore, it is at least fourth-order. Hence, the approximated second derivatives are second-order accurate, independent of the mesh geometry. For simpler methods like the well-known Gauss integration, this cannot be guaranteed.

5 TEST CASES

5.1 KVLCC2 tanker

To test the Hessian-based criterion, the flow around the KVLCC2 (KRISO Very Large Crude Carrier) tanker is computed. This model scale computation at $Re = 4.6 \cdot 10^6$ was one of the test cases in the Gothenburg 2000 workshop, see [6]. It is a double model test, so the water surface motion is not taken into account. The computations are performed with a single fluid (water) and a symmetry boundary condition is imposed at the position of the undisturbed water surface. The anisotropic EASM turbulence model is used to obtain good resolution of longitudinal vorticity.

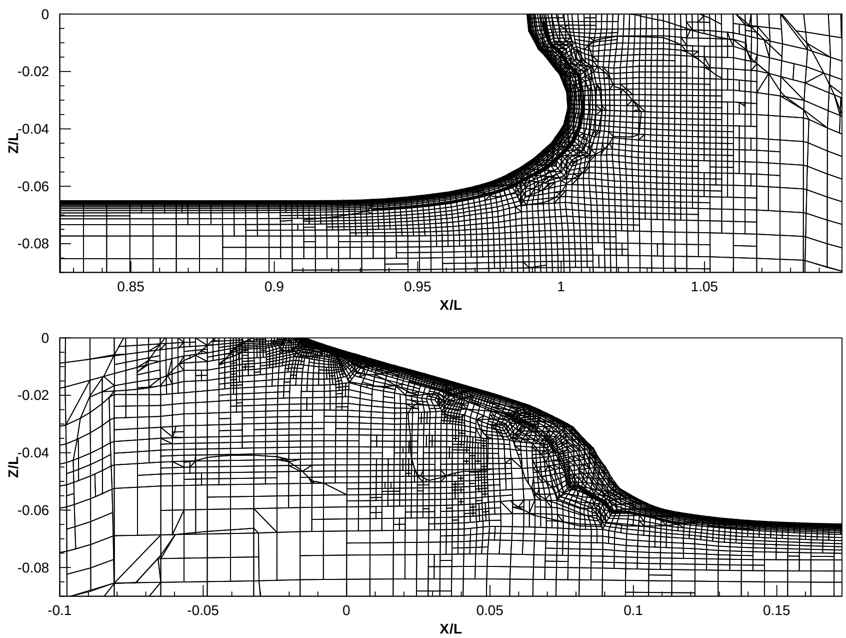


Figure 3: KVLCC2 tanker, cross-sections of the grid at $Y/L = 0.02$ at the front of the ship (top) and at the back (bottom).

Figure 3 shows two Y cross-sections of the refined grid (having 600k cells), created from a coarse original grid that has 58k cells. The pressure-based refinement is clearly concentrated at the front and the back of the ship, the regions where the pressure changes most. At the very front and back, all refinement is isotropic. However, further to the ship's centre and aft of the ship, where the flow is mostly aligned with the X-axis, directional refinement appears. Thus, the tensor-based procedure is effective in detecting the main flow directions.

The axial flow in the propeller plane ($X/L = 0.0175$) is given in figure 4. The principal feature of this flow is a hook-shaped region of low axial velocity. On the original grid, this hook shape is not resolved. But on the refined grid (showing refinement that is concentrated in the zone around the propeller) the hook shape appears, closely resembling the experimental results. This result is excellent for a grid of 600k cells; when computing this flow without grid refinement, usually about 1M cells must be used to obtain similar results. This also proves the efficiency of the grid refinement procedure.

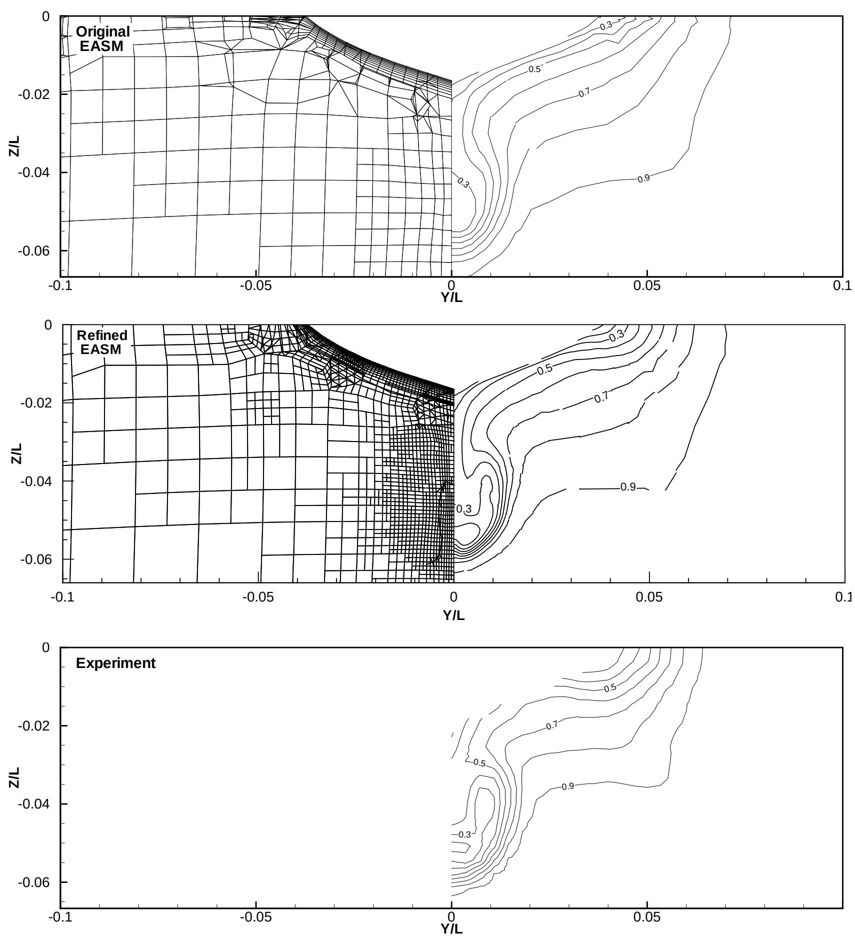


Figure 4: KVLCC2 tanker. Grid cross-sections and axial velocity u/U_∞ isolines are shown on the original coarse grid and the refined grid. The velocity is compared with experiments.

5.2 DTMB 5512 in head waves

As a test of the free surface refinement criterion, we compute the wave diffraction problem for the DTMB 5512 destroyer at $Fr = 0.28$ with fixed attitude in head waves of wave length $\lambda = 1.5L$ and specific amplitude $A_k = \frac{2\pi A}{\lambda} = 0.025$, which corresponds to case 4 of the Tokyo 2005 workshop [4].

For this case, a fine grid is made with a grid spacing of $L/1000$ in z-direction at and around the free surface, as advised for ISIS-CFD to accurately capture an incoming wave field. Next to the ship, a large box of fine cells is placed to capture the diffracting waves from the hull. This fine grid has 2.31M cells. A coarse grid is made as a basis for the grid refinement, with 2 times coarser cells, in all directions, around the free surface and in the fine box. This grid has 0.83M cells. Automatic grid refinement is then used to get a grid spacing of $L/1000$ normal to the water surface. During the computation, the number of cells oscillates between 0.94M and 0.99M.

Figure 5 shows the time evolution of the drag and pitch moment coefficients. The values

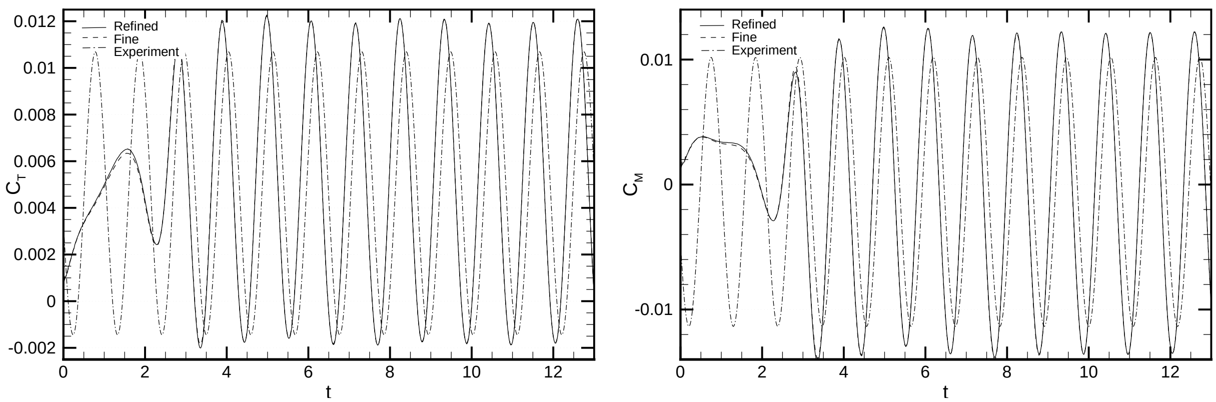


Figure 5: Time evolution of the drag coefficient C_T and the pitching moment coefficient C_M, compared with experiments (mean + first harmonic) from [1]. $t = 0$ corresponds to the beginning of the computation.

compare reasonably well with experiments from IIHR, the phase difference is observed in other computations as well [1]. Most importantly, the refined-grid and fine-grid solutions are nearly indistinguishable.

Wave patterns at four different instants are given in figure 6, compared with the fine-grid results which correspond well with experiments (as shown in [9]). On the refined and fine grid, the wave height near the hull is equivalent; the breaking bow and stern waves are even captured more sharply on the refined grid. The incoming wave fields are nearly identical. Only in the diffracted waves away from the hull, the fine-grid solution is sometimes marginally better. Here, a combination with Hessian-based refinement below the water surface would be useful.

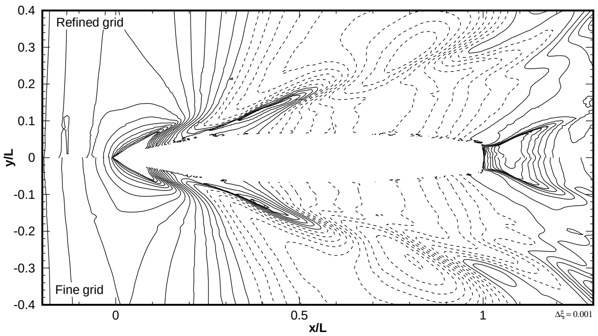
Altogether, the grid refinement produces a solution of similar quality as the fine-grid solution, using 2.5 times less cells.

6 CONCLUSIONS

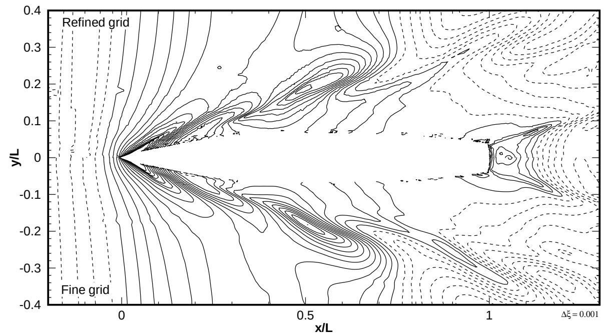
A metric-based refinement criterion computation strategy is presented for the automatic grid refinement procedure of the ISIS-CFD finite-volume flow solver. This procedure gives a flexible and general framework for anisotropic grid refinement, is robust with respect to the singularity of the tensorial refinement criterion, and allows the easy combination of several refinement criteria.

Two refinement criteria for free-surface water flow are described. The first produces directional refinement normal to the water surface; this criterion uses tensors that have only one non-zero eigenvalue. The other criterion is based on the second spatial derivatives of the pressure. A least-squares method with third-order polynomials is used to get a second-order accurate evaluation of the second derivatives, on any mesh.

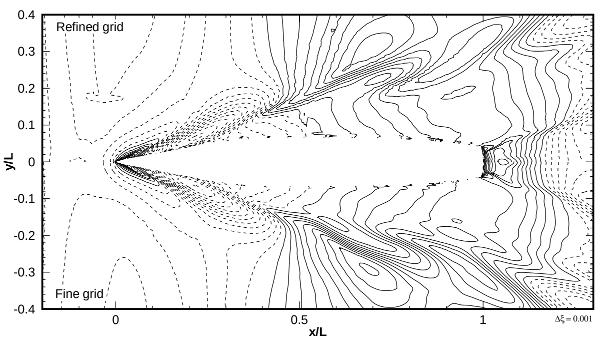
Two test cases, the double-model flow around the KVLCC2 tanker and the DTMB 5512 destroyer in head waves, show that the two refinement criteria produce accurate



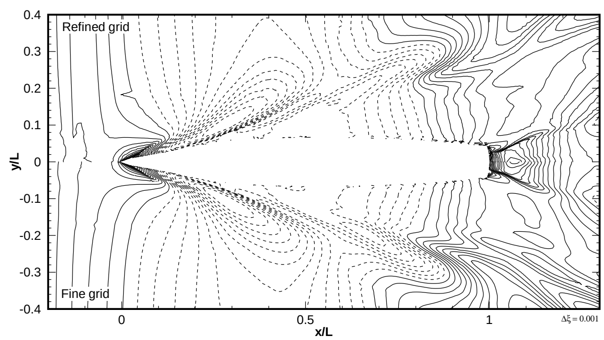
(a) $t/T_e = 0.0$



(b) $t/T_e = 0.25$



(c) $t/T_e = 0.5$



(d) $t/T_e = 0.75$

Figure 6: Comparison of wave patterns on the refined and the fine grid for the DTMB fixed in head waves. The images show four different instants; T_e is the wave encounter period and $t = 0$ corresponds to a wave crest passing $x = 0$.

solutions in an effective way. It is also shown that combining the two criteria may be useful; we plan to implement this combination in the near future.

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