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Optimesh: Anisotropic Mesh Adaptation with CAD Integrity for Verifiably Accurate CFD Solutions over Complete Aircraft

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Introduction

The accuracy of the numerical solution of a Partial Differential Equation (PDE) is a function of the order of the leading terms of the truncation error of the numerical algorithm. These terms in turn depend both on the higher order derivatives of the solution variables and on the local mesh size. In practical applications it is important to guarantee a sufficient level of accuracy, if not mesh independence, of the solution. This condition is normally reached by comparing solutions obtained on successively refined grids, a procedure that is empirical and time-consuming, and further complicated by the fact that mesh generation is conducted heuristically, since the solution is not known in advance.

Given the nature of the truncation error of the numerical algorithms for the solution of PDEs, two basic methods for improving the accuracy of a solution can be readily identified: a) construction of higher-order schemes or, given a fixed numerical scheme, b) to control the numerical error via grid optimization.

In industry, while run-time efficiency is important, access to a code's source may not be guaranteed and it can be impractical to modify existing codes. In addition, commercial code vendors may not be over-enthusiastic about introducing a generic and revolutionary mesh adaptation process, because it may show the shortcomings of the current version of their code. Therefore, a more effective approach consists in adapting the grid to the solution, without access to the source. The process ideally begins with an arbitrary mesh, hopefully coarse and generated by a non-expert, and leads to a highly adapted customized grid, tailor-made to each application. Thus, no expensive algorithm modifications are required and any CFD code can satisfy a predefined level of accuracy, as desired or as required by the problem specifications, without user intervention. This strategy is ideal for parameter sensitivity studies, for example, where all the different solutions could be obtained on automatically adapted grids generated from a single original grid. In such case one becomes sure that the change in performance I sure to the change in parameter and not due to any sensitivity to the grid.

The code discussed here represents an advanced novel anisotropic mesh adaptation approach for unstructured grids that allows the customization of grids based on a specified error level. Equally important, it maintains the CAD integrity of the given geometry. Perhaps the best showcase of the abilities of this software is the adaptation of unstructured tetrahedral meshes over a complete Airbus 320 and a Boeing 747 with flow-through engine nacelles.

Paper presented at the RTO AVT Symposium on "Reduction of Military Vehicle Acquisition Time and Cost through Advanced Modelling and Virtual Simulation", held in Paris, France, 22-25 April 2002, and published in RTO-MP-089.

Methodology

Any (anisotropic) mesh adaptation algorithm requires two fundamental components: an a-posteriori error estimator and a mechanism to coarsen, refine, swap and stretch the mesh. In general it is impossible to evaluate the exact truncation error of the numerical approximation of a PDE or system of PDEs, since the numerical approximation is only piecewise continuous and in any case the exact solution is unknown. Most of the error estimators in use are based on the first derivative or the residual of a user-specified solution variable. The error estimator proposed here is based on the Hessian (matrix of second derivatives), which is a better representation of the truncation error between the PDEs and the discrete equations actually solved. The Hessian matrix provides not only information on the error density, but also on its directionality, thus making anisotropic mesh adaptation possible.

The edge-based error density γ can be written as:

$$\gamma = \int_0^1 \sqrt{\Delta\mathbf{s}^{\mathrm{T}}\, \mathbf{M}\, \Delta\mathbf{s}}\; dt$$

where Δs is the edge length, M is the Hessian matrix and t is the non-dimensional parametrization variable along the edge. Once the error density is determined for every edge in the grid, the user must select the desired error level for the adaptation. Unless dictated by the specific problem, an appropriate error density can be selected visually with any graphic interface.

The Mesh adaptation procedure consists of four main steps: a) edge coarsening, b) edge refinement, c) edge swapping and d) node movement. Steps a) and b) can be deemed binary operations, since two connected edges are combined into one, or one edge is split in two, respectively. These two operations may produce grids that are not optimal, therefore the edge swapping mechanism will correct the orientation of any edge that might not be properly positioned and lead to distorted meshes. Node movement stretches and realigns the edges along the proper direction, and ensures that the error is equi-distributed and the maximum and minimum edge lengths and the minimum aspect ratio are respected. Coarsening, refinement and swapping can be regarded as accelerators for mesh movement.

Node movement is based on a spring analogy, where each element edge in the grid is represented by a spring with a coefficient of elasticity proportional to the error density. The goal in this case is to equi-distribute the error across the computational domain. The original CAD surface definitions are used at each step to ensure that surface nodes are reprojected on the proper surfaces and the original geometry is fully respected. Since the mesh adaptation procedure is a nonlinear process, steps a) to d) are repeated in cycles at every adaptation.

Several control parameters are available to control the quality of the final mesh, among them aspect ratio and a maximum deviation on curvature. High maximum aspect ratio values can lead to extremely stretched grids, and while FENSAP has no difficulties handling highly stretched grids, other flow solvers might. Maximum deviation on curvature allows one to determine the acceptable level of coarseness on curved surfaces that prevents poor surface rendition. This may be noticeable on the lips of the nacelles or on wing tips, where surface curvature is high. In general the meshes adapted show much more faithful renditions of the original CAD than even the finest original meshes.

There is no question that mesh adaptation provides a useful and necessary tool. The expense incurred in adapting the mesh and recomputing the flow solution again and again is not negligible, therefore the focus of our research is to provide some guidelines to facilitate the choice of parameters by illustrating their effect on the mesh quality and overall solution time. The subject of

grid convergence, important from the point of view of computational efficiency, will also be addressed.

Results: Mesh Adaptation on a Boeing 747 and an Airbus 320

Both the Boeing 747 and Airbus 320 feature fuselage-wing-pylon-nacelle geometries, but the Airbus 320 has simple flow-through engine nacelles, while the Boeing 747 has both engine nacelles and fan shrouds and in addition some detail of the cockpit windows. For both geometries, the outer boundary is a hemisphere with a diameter of approximately 40 fuselage lengths. Flight conditions for the Boeing 747 are: Mach number=0.88, altitude of 35,000ft and AoA of 4º. Flight conditions for the Airbus are: Mach number=0.8, altitude of 30,000ft and AoA of 3º. The CFD solutions were obtained with FENSAP (Finite Element Navier-Stokes Analysis Package), also a proprietary technology of Numerical Technologies International.

For the Boeing 747, the initial tetrahedral grid contains 431,181 nodes and 2.3 million linear tetrahedral elements. The error density target value was set *y*=0.15 and remained constant for all the subsequent adaptations. The minimum and maximum element edge sizes were set at 0.025 in and 25,000 inches. respectively, compared to a fuselage length of approximately 2,700 inches. Eight complete cycles of solution and adaptation were performed. After six adaptations, the final grid size had decreased to 242,310 nodes and 1.3 million tetrahedral elements, an decrease of 43%, for an immense improvement in accuracy.

It should be noted that some intermediate grids, say from iteration 1-3, may become somewhat larger than the original as mesh adaptation begins to cluster the mesh near the salient features (discontinuities and vortices in this case). This phenomenon is related to the density of the original mesh, and how well it captures the initial solution. Initially the discontinuities are smeared and require much refinement, but as they become sharper stretching and coarsening remove some of the grid points and the mesh size begins to decrease. Note that in 3D discontinuities are surfaces and hence it is difficult to estimate the extent of the refinement just by looking at the surface mesh.

The adapted grid shows substantial coarsening on the lower wing surface and refinement on the upper surface. The outboard wing shock is very well captured, and the inboard shock is also beginning to appear. A comparison of the initial and final upper wing grids and corresponding solutions of the Airbus 320 are shown in Figure 1. Figures 2, 3 and 4 show some surface grid details and solutions of the Boeing 747. Note in Figure 5 how adaptation has improved the discretization of the fan cowl lip. Figure 6 shows the Cp distribution at three spanwise locations before and after adaptation. Finally, Figure 7 shows the sequence of error distributions in the computational domain as the adaptation-solution cycles evolve. Note that there is little change from cycle 5 to cycle 6 and the adaptation procedure is converged.

Conclusions

Mesh adaptation is a powerful and cost-effective tool that can be used to increase (or decrease if so desired), to a specified and uniform level, the computational accuracy of any given CFD code without extensive algorithm redesign or initial investment in grid generation. Furthermore the cost of ensuring mesh independence is substantially reduced, and the error level of the results can always be guaranteed.

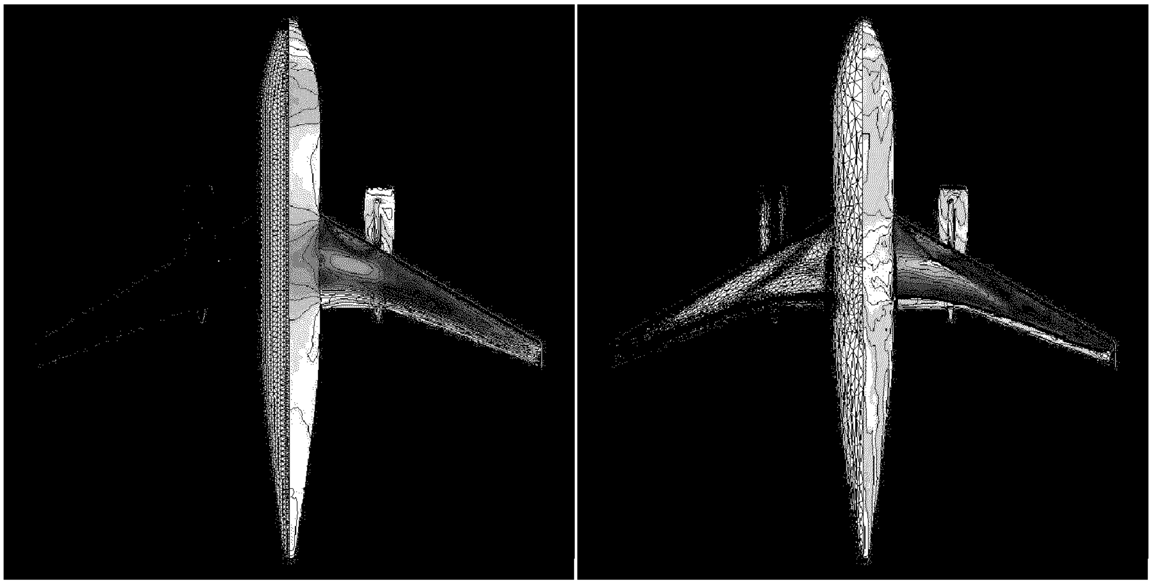

Figure 1. Airbus 320: initial and final grids and solutions after 6 adaptation cycles

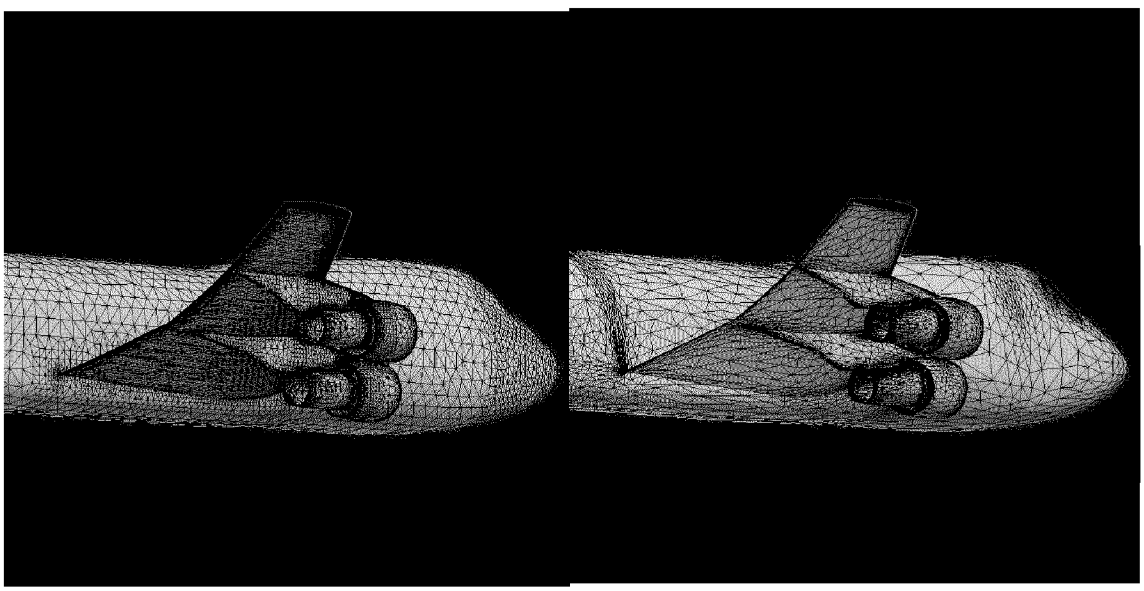

Figure 2. Boeing 747: initial and final grids after 6 adaptation cycles

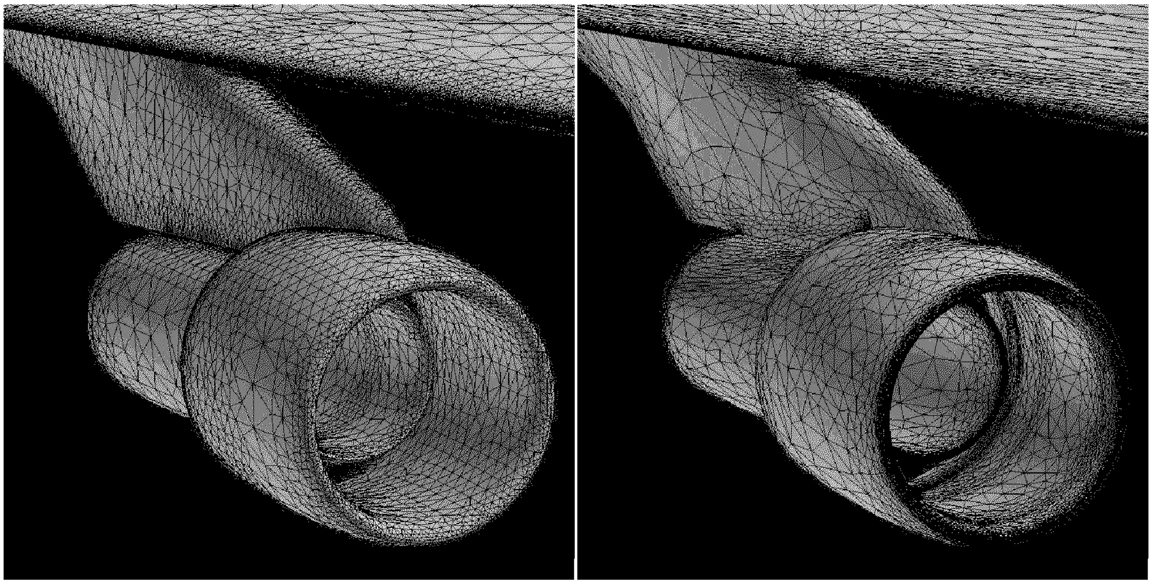

Figure 3. Boeing 747: initial and final grid, pylon-nacelle detail

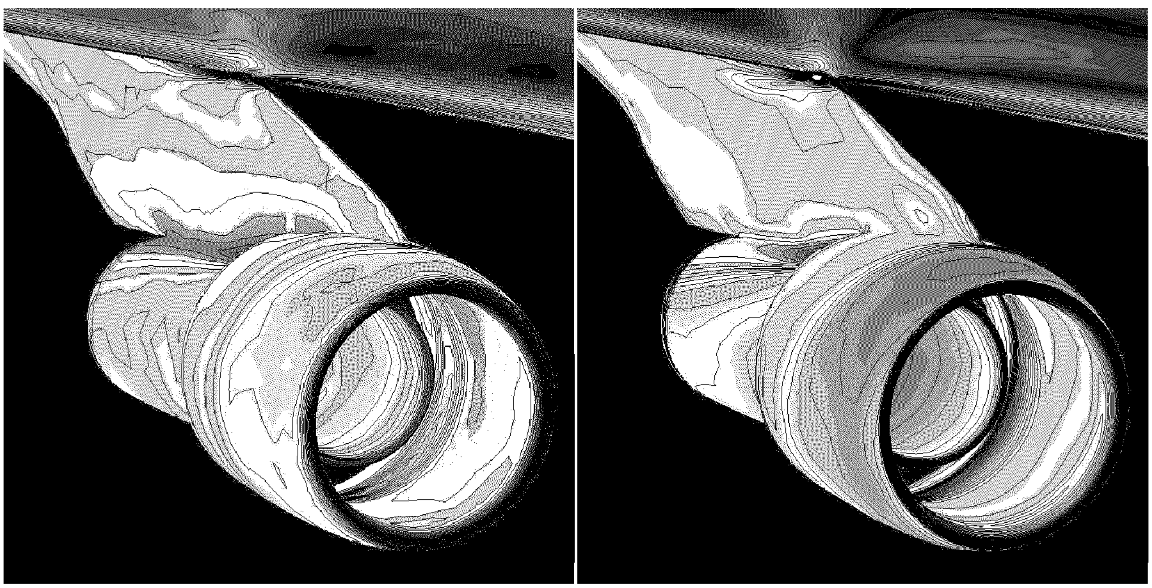

Figure 4. Boeing 747: initial and final grid, pylon-nacelle detail

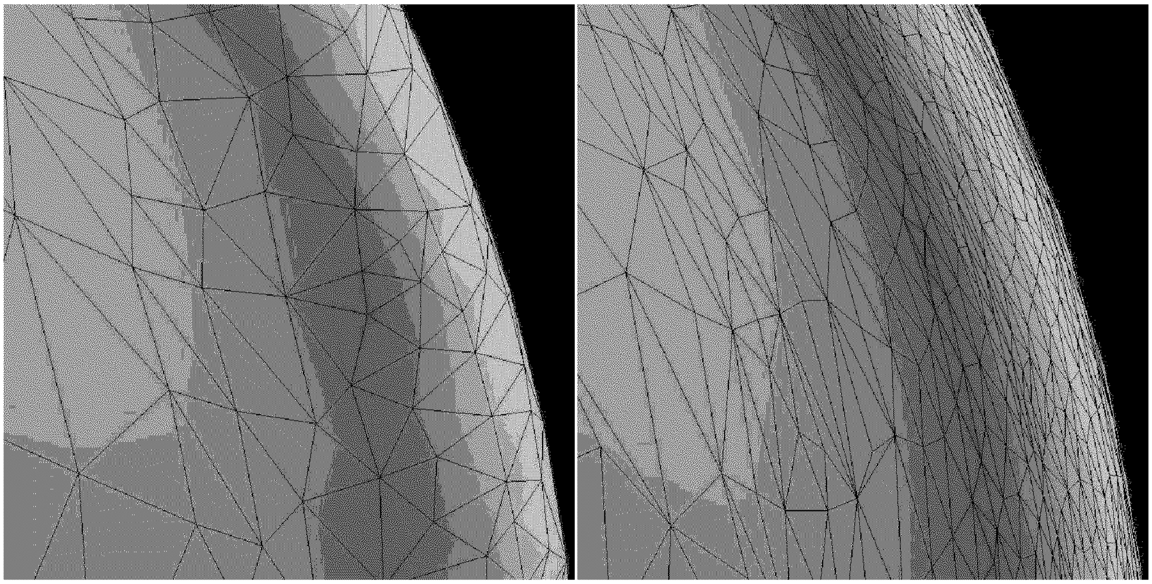

Figure 5. Boeing 747: initial and final grid, fan cowl lip detail

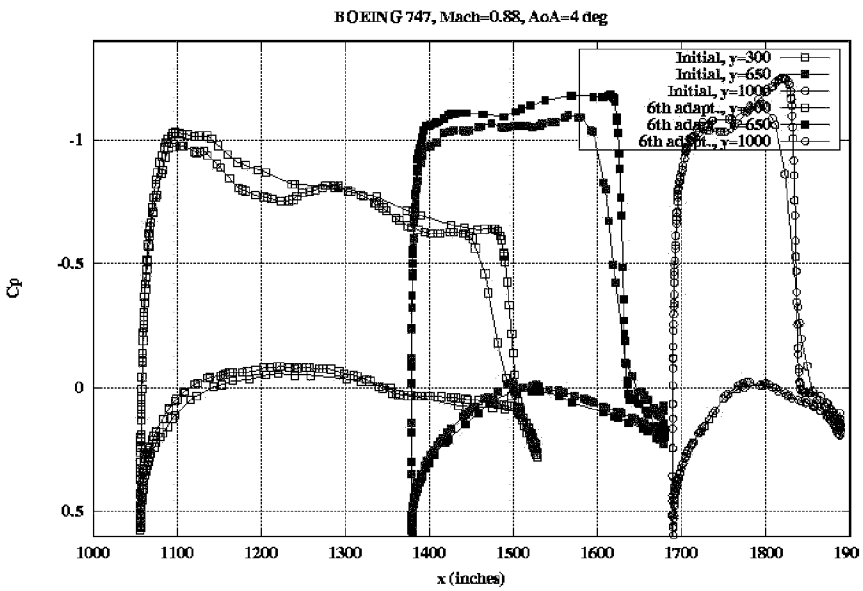

Figure 6. Boeing 747: initial and final Cp distribution at three wingspan stations

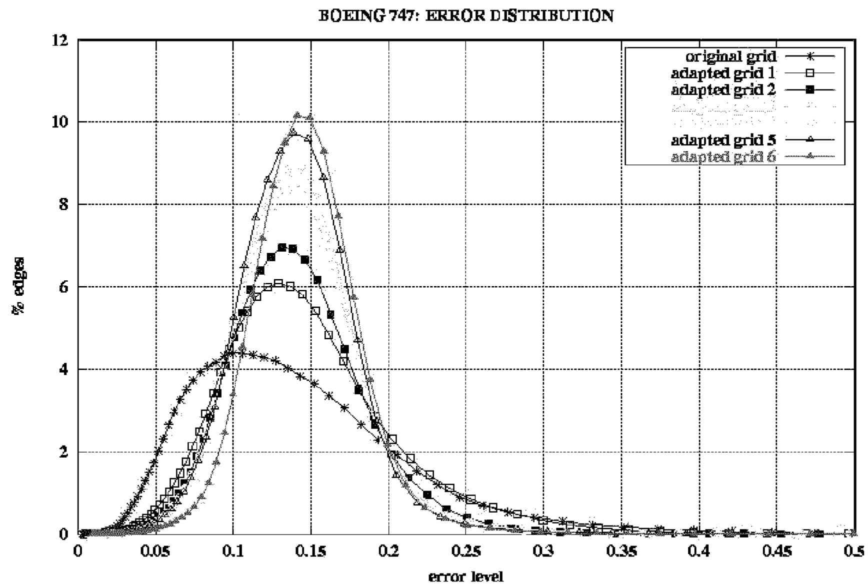

Figure 7. Boeing 747: Error distribution at each adaptation cycle