Progress in the Simulation of Steady and Time-Dependent Flows with 3D Parallel Unstructured Cartesian Methods

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The proposed paper will present recent extensions in the development of an efficient Euler solver for adaptivel- refined Cartesian meshes with embedded boundaries. The paper will focus on extensions of the basic method to include solution adaptation, time-dependent flow simulation and arbitrary rigid domain motion. The parallel multilevel method makes use of on-the-fly parallel domain decomposition to achieve extremely good scalability on large numbers of processors, and is coupled with an automatic coarse mesh generation algorithm for efficient processing by a multigrid smoother. Numerical results are presented demonstrating parallel speed-ups of up to 435 on 512 processors. Solution-based adaptation may be keyed off truncation error estimates using τ-extrapolation or a variety of feature detection based refinement parameters. The multigrid method is extended to for time-dependent flows through the use of a dual-time approach. The extension to rigid domain motion uses an Arbitrary Lagrangian-Eulerlarian (ALE) formulation, and results will be presented for a variety of two- and three-dimensional example problems with both simple and complex geometry.

1. Introduction

The proposed paper documents substantial improvements in a new adaptive inviscid flow solver designed for multilevel Cartesian meshes with embedded boundaries[1]. Such methods have become increasingly popular in the last decade chiefly as a result of their ability to automatically handle extremely complicated geometries[2]. With the addition of adaptation, domain motion and robust automatic multigrid acceleration such solvers provide a very powerful platform for the rapid computation of aerodynamic loads on complex configurations with many components.

Figure [1] shows an example typical of those studied with this package. In this particular case, the analysis focuses on the aerodynamic effects of multiple positions of the body-flap component of a space shuttle configuration. From the component geometry shown in (a) the mesh systems (b) are automatically generated as are the underlying hierarchy of coarse meshes for the multigrid accelleration[1]. Since mesh generation is extremely fast (under 5 minutes on 1 CPU[2]), meshes for the different component positions shown in (c), (d) and (e) are generated in parallel on-the-fly. The baseline solver[1] then computes the flow and aerodynamic loads on the configurations and the component geometry using as many processors as are available to the user at the current run time.

The parallel flow solver takes the unpartitioned mesh and decomposes it upon startup using the parallel space-filling curve based domain decomposition algorithm outlined in Ref. [1]. Figure [2] examines the parallel performance of the
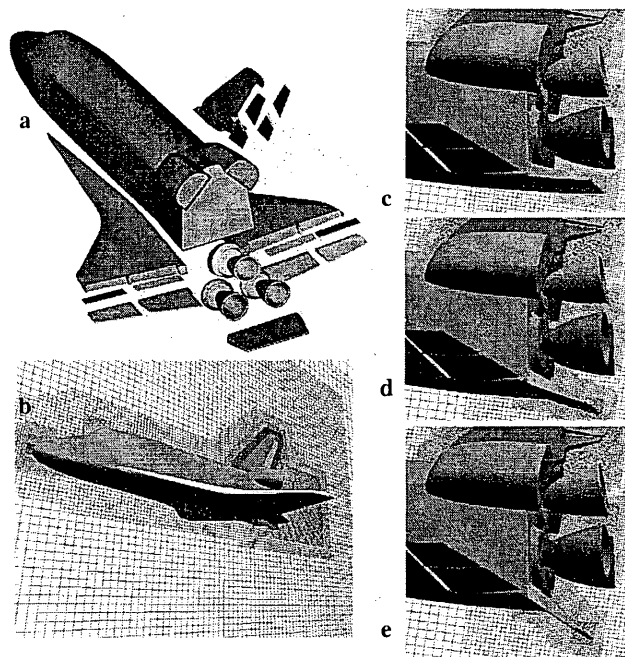

Figure 1. Typical example studied with the unstructured Cartesian mesh approach in Refs.[2] and [1] Geometry motion, mesh generation and flow solution are fully automated and tightly coupled for prescribed component motion. Meshes in these examples contain ~2.5 M cells.

multigrid solver on a typical example. This plot shows parallel speed-ups of over 435 on 512 processors of an SGI Origin 3000 with a net computing speed of over 45 gigaflops.
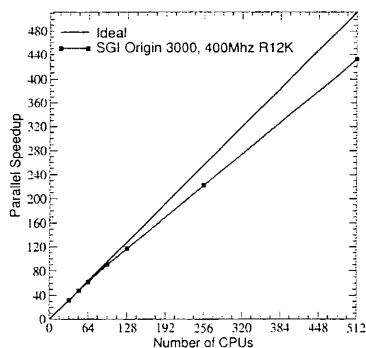
Figure 2. Parallel scalability of the baseline multigrid solver.

2. Solution Adaptation

The basic method outlined in the previous section has been extended to incorporate robust solution adaptation. Adaptation can be driven either by error estimates based upon multilevel error estimates obtained through τ-extrapolation or by refinement parameters based on normalized solution differences and gradients[3][4]. The τ-extrapolation approach exploits both the multigrid framework and the nested nature of Cartesian grids. The fine grid solution is restricted to the first coarse grid in the multigrid sequence where the spatial operator is then re-applied. Residuals on this grid may be shown to be directly proportional to the local truncation error and therefore can be used as a basis for adaptation[4]. The final paper will include details of these methods. In this abstract we include preliminary results from this develop-
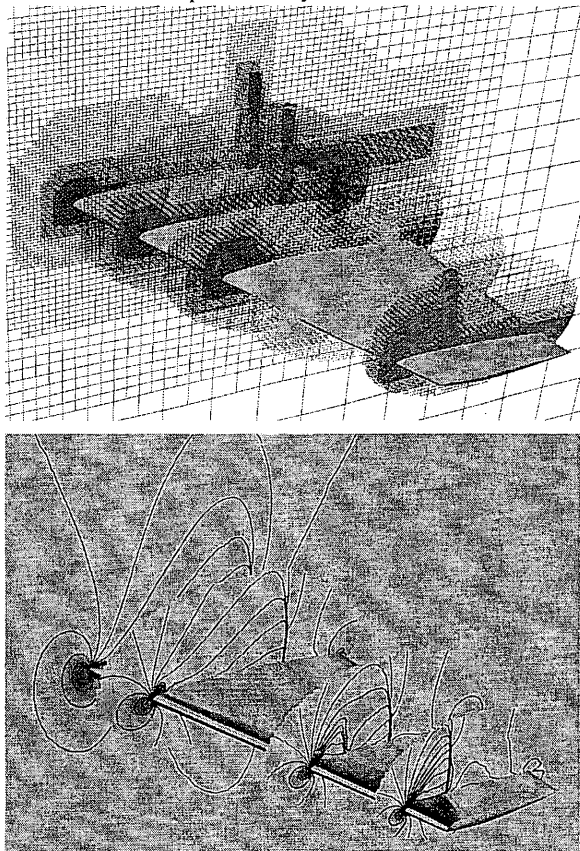

Figure 3. ONERA M6 wing simulation showing adapted multilevel Cartesian mesh and density contours in the final discrete solution. The final adapted mesh contains ~1.5M cells and was converged 6 orders of magnitude in 65 multigrid cycles on the final mesh.

ment for the benchmark case of inviscid flow over the ONERA M6 wing at 3.06° angle-of-attack and a Mach number of 0.84. Figure[3] outlines results from this case.

3. Time Dependent Flows and Domain Motion

The baseline multigrid solver has also been extended to time dependent flows using an implicit dual-time approach similar to that in Ref.[5]. The current work extends this earlier work to include a variety of A-stable schemes which are unconditionally stable for all physical time steps. Details of this extension will be covered in the final paper.

Further extensions to this method include the ability to permit generalized domain motion through the use of an Arbitrary Lagrangian-Eulerlarian (ALE) framework. Figure presents results for the time dependent flow around an oscillating NACA 0012 airfoil at the $M = 0.77$ pitching with $\alpha = 0.016 + 2.51\sin(2\pi\ 62.5t)$[6]. As the airfoil oscillates, hysteresis in the fluid makes the loads on the airfoil path-dependent. This hysteresis is evident in the plot of C_n vs. α, where the normal force coefficient for a given angle-of-attack is multi-valued depending on the direction of pitch. The performance of this algorithm is comparable to those for other inviscid solvers found in the literature. The final paper will include comprehensive documentation and three dimensional results.
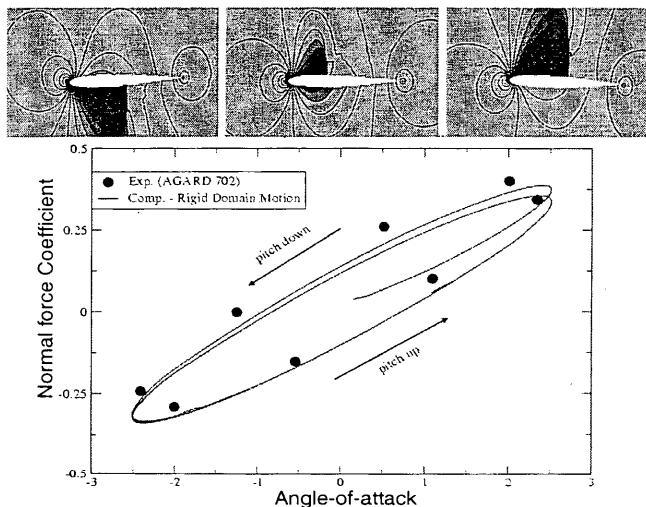

Figure 4. Time history of normal force coefficient for pitching NACA 0012 airfoil from AGARD-R-702. M = 0.77, $\alpha = .016 + 2.51\sin(2\pi\ 62.5t)$

4. References

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