CAPABILITIES AND ISSUES OF UNSTRUCTURED-GRID CFD FOR HIGH-SPEED FLIGHT VEHICLES

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ABSTRACT

A brief review of the current capabilities and outstanding issues for the efficient analysis and design of high-speed flight vehicles using unstructured grids is given. It is concluded that all major areas required in the analysis cycle - grid generation, flow solvers and visualization - have seen major advances in recent years. This trend is expected to continue, leading us to believe that turnaround in a matter of hours or minutes for complex geometries and/or physics will become a reality sometime in the next decade.

1. INTRODUCTION

The ongoing development of new high-speed vehicles, such as High-Speed Civil Transport (HSCT), the X-33 and X-34 demonstrators, several new missiles and planetary re-entry probes, has rekindled an interest in the development of advanced numerical methods for the prediction of these flowfields. Any simulation of flow problems goes through the following stages:

- Geometry acquisition and definition of boundary conditions;
- Grid generation;
- Solution of the Partial Differential Equations describing the physics on the generated mesh;
- Visualization and data reduction.

In the sequel, we describe recent improvements in the capabilities for each one of these categories. At the same time, we point out some of the current difficulties, and ways to overcome them.

2. GRIDDING SUITABLE FOR RANS CALCULATIONS

The generation of isotropic unstructured grids has reached a fairly mature state, as evidenced by the many publications that appeared over the last decade on this subject, and the widespread use of unstructured grids in industry. The two most widely used techniques are the advancing front technique [Per88, Löh88, Löh93b, Sho95, Löh96], and the Delaunay triangulation [Geo91, Geo92, Wea92, Wea93, Wea94]. Hybrid schemes, that combine an advancing front point placement with the Delaunay reconnection have also been used successfully. These isotropic mesh generation techniques tend to fail when attempting to generate highly stretched elements, a key requirement for Reynolds-Averaged Navier Stokes (RANS) calculations with turbulence models that reach into the sublayer. To mitigate this shortcoming, a number of specialized schemes have been proposed [Nak87, Kall92, Löh93b, Pir94, Pir96, Mar95]. Typically, the domain to be gridded is divided into isotropic and stretched element regions, and a blending procedure is provided to transition smoothly between these zones. The stretched mesh region is usually generated first, imposing some form of semi-structured grid limitation. Although we have used such a scheme [Löh93b] for a number of years, we have found several situations in which the requirement of a semi-structured element or point placement close to wetted surfaces is impossible, prompting us to search for a more general technique. Other authors, notably Peraire [Per96], have also sought alternatives to this 'semi-structured followed by unstructured' approach. The path taken here may be summarized as follows:

a) Generate first an isotropic mesh.

b) Using a constrained Delaunay technique, introduce points in order to generate highly stretched elements.

c) Introduce the points in ascending level of stretching, i.e. from the domain interior to the boundary (or interior boundaries).

This procedure has the following advantages:

- No surface recovery is required for the Delaunay reconnection, eliminating the most problematic part of this technique;
- The meshing of concave ridges/corners requires no extra work;
- Meshing problems due to surface curvature are minimized;
- In principle, no CAD representation of the surface is required; and
- A final mesh is guaranteed, an essential requirement for industry.

The disadvantages are the following:

- As with any Delaunay technique, the mesh quality is extremely sensitive to point placement.

Figures 1,2 show a RANS mesh for a generic hypersonic flyer generated using this procedure. The mesh consisted of approximately 6Mtets, 1Mpts and 78Kbpts. We have used the grids produced by this procedure for a number of production runs, and are actively working on improvements, particularly point placement and post-generation smoothing.

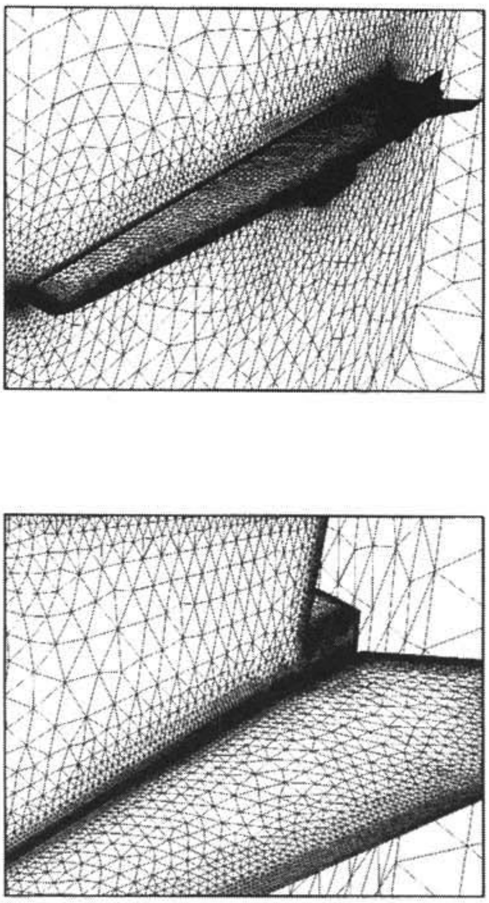


Figure 1 Surface Mesh for Generic Hypersonic Flyer

3. OPTIMAL SOLVERS

The development of solvers continues at a surprising pace. The last years have seen improved flux-splitting schemes, such as HLLEW, AUSM+ [Lio95] and CUSP [Jam93], as well as limiters, that yield crisp shock resolution while retaining favourable cost and convergence properties. Contenders in the race for fastest possible convergence include:

- Space-marching/blocking,
- GMRES-LU-SGS and
- multigrid procedures.

The set of equations resulting from spatial discretization using an edge-based data structure may be written as:

$$\mathbf{M}_l^i \mathbf{u}_{,t}^i = \mathbf{r}^i = \sum \mathbf{C}^{ij} \cdot \mathbf{F}_{ij} \quad , \tag{1}$$

where $\mathbf{M}, \mathbf{C}, \mathbf{u}$ and $\mathbf{F}$ denote, respectively, the lumped mass-matrix (volume), geometry (shape-function derivative) factor, unknowns and fluxes. Space-marching or blocking replaces the sum over all edges by a partial sum over an active set of edges. This region of active edges is converged before it is updated, sweeping the mesh in the main direction of the flow. Spacemarching for fully unstructured grids is rather recent [Nak96], but has shown respectable gains over the already fast explicit solvers currently in use for inviscid (i.e. Euler) steady and unsteady calculations [Nak96, Löh98]. The GMRES-LU-SGS scheme is based on the vectorized LU-SGS scheme [Sha97]. The implicit time integration of Eqn.(1) using a backward Euler scheme with linearization yields:

$$\left[\frac{1}{\Delta t}\mathbf{M}_l^i - \sum \mathbf{C}^{ij} \cdot \mathbf{A}_{ij}\right] \Delta\mathbf{u}^i = \mathbf{r}^i \quad . \tag{2}$$

Denoting by ρ_A the spectral radius of the Jacobian $\mathbf{A}$ and defining:

$$\mathbf{D} = \left[\frac{1}{\Delta t}\mathbf{M}_l^i - 0.5\sum \mathbf{C}^{ij}\rho_A\right]\mathbf{I} \quad , \quad \Delta\mathbf{F} = \mathbf{F}(\mathbf{u}+\Delta\mathbf{u}) - \mathbf{F}(\mathbf{u}) \quad , \tag{3}$$

this system of equations is solved by the following relaxation procedure:

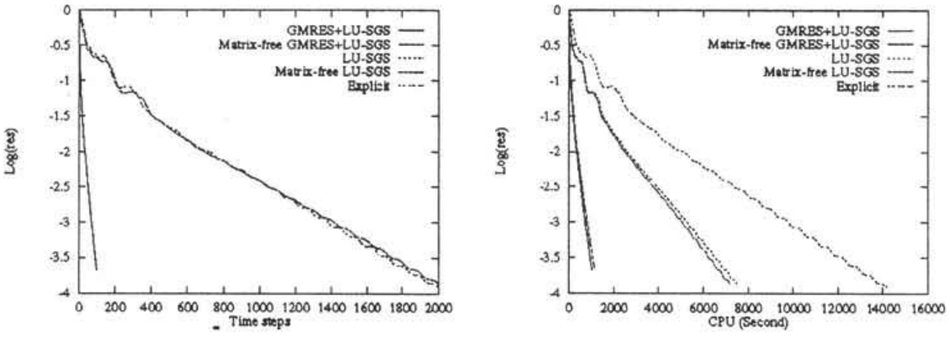
a) Forward Sweep:

$$\Delta\hat{\mathbf{u}}^i = \mathbf{D}^{-1}\left[\mathbf{r}^i - 0.5\sum \mathbf{C}^{ij} \cdot (\Delta\hat{\mathbf{F}}_{ij} - \rho_A \Delta\hat{\mathbf{u}}_j)\right] \tag{4a}$$

b) Backward Sweep:

$$\Delta\mathbf{u}^i = \Delta\hat{\mathbf{u}}^i - 0.5\mathbf{D}^{-1}\sum \mathbf{C}^{ij} \cdot (\Delta\mathbf{F}_{ij} - \rho_A \Delta\mathbf{u}_j) \tag{4b}$$

Luo [Luo98a,b] has shown that this scheme is an excellent preconditioner for the Generealized Minimal RESiduals (GMRES) iterative solver that is by now firmly established in CFD [Saa86, Wig85, Ven95]. Figure 2 shows the impressive speedups that may be obtained by using this technique for the classic ONERA M6 transonic testcase. The mesh had approximately 740Ktets, 136Kpts and 20Kbpts. The times shown are for the CRAY-C90, using one processor. Note that a run of this kind nowadays takes less than 2 minutes.



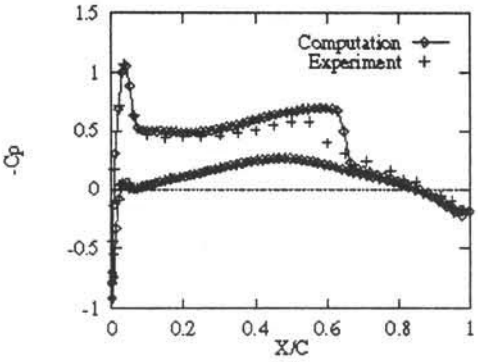


Fig. 2c: Comparison between computed and experimental surface pressure coefficient for wing section at 20% semispan.

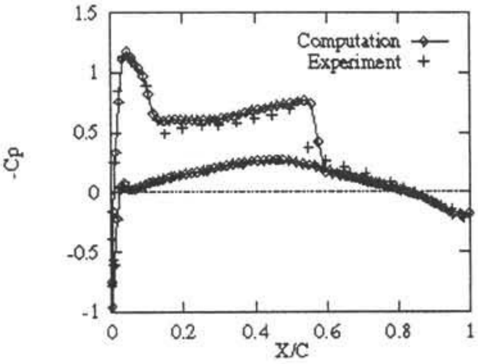


Fig. 2d: Comparison between computed and experimental surface pressure coefficient for wing section at 44% semispan.

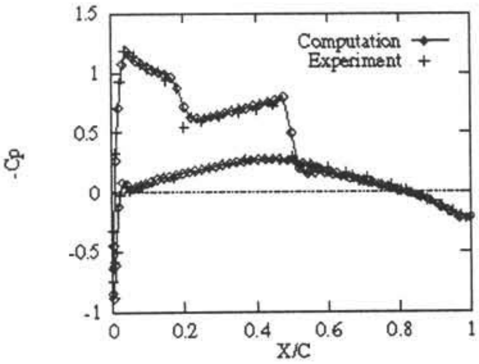


Fig. 2e: Comparison between computed and experimental surface pressure coefficient for wing section at 65% semispan.

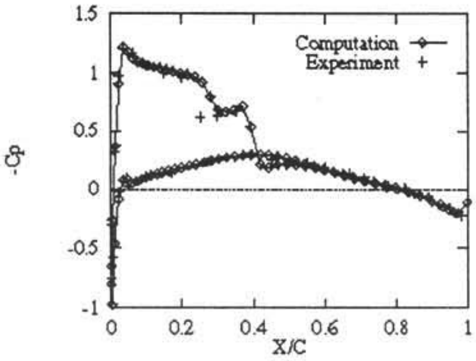


Fig. 2f: Comparison between computed and experimental surface pressure coefficient for wing section at 80% semispan.

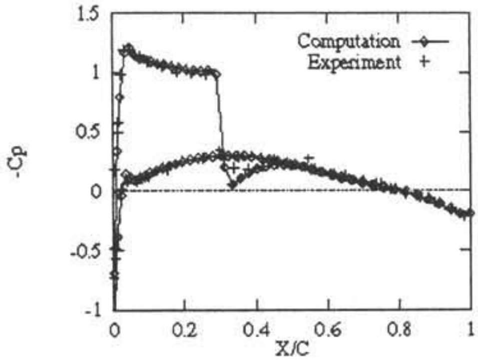


Fig. 2g: Comparison between computed and experimental surface pressure coefficient for wing section at 90% semispan.

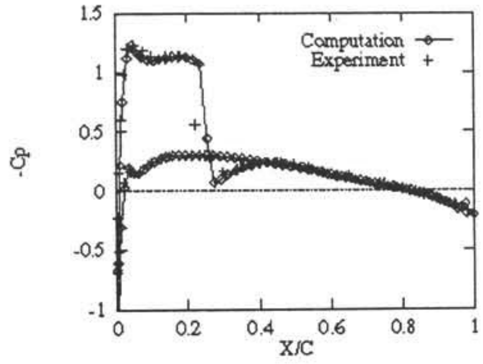


Fig. 2h: Comparison between computed and experimental surface pressure coefficient for wing section at 95% semispan.

Figure 2 ONERA M6

Issues that require further investigation include optimal renumbering for highly stretched meshes, and the parallel efficiency achievable with the LU-SGS scheme.

For sub- or transonic flow, few if any algorithms can compete with multigrid [Alo95, Mav95, Mav96]. Although perceived as delicate and difficult to code, recent progress in spatial discretization, preconditioners and smoothers has led to increased robustness and efficiency for this class of schemes.

4. FLUID-STRUCTURE-THERMAL COUPLING

Due to the strong heating effects encountered in high-speed flows, the accurate prediction of vehicles operating in this flight regime requires a coupled fluid-structure-thermal methodology [Tho88]. This is at present an active area of research. We have pursued a loose coupling technique [Löh95b], whereby the individual 'core discipline' codes for fluids, structures and thermodynamics are linked together with minimal rewriting. The information transfer (see Figure 3) for displacements, velocities, temperatures, stresses and thermal fluxes is carried out using fast interpolation [Löh95a] and conservative projection techniques [Ceb97a,b].

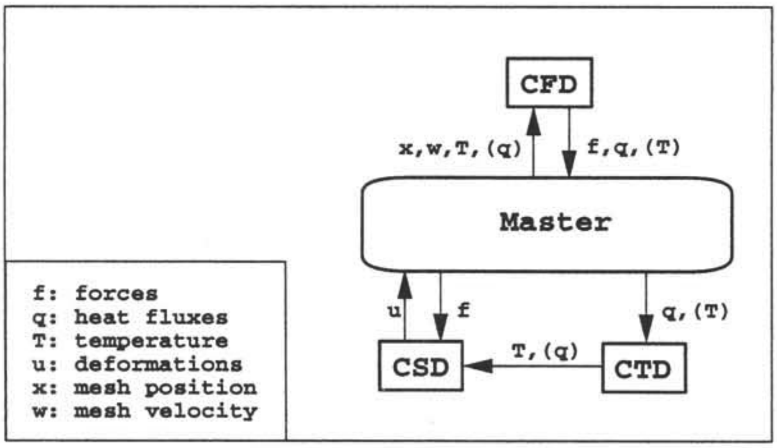


Figure 3 Fluid/Structure/Thermal Coupling

Figures 4,5 show a recent result for a proposed nose-cone experiment. The CFD part of the problem was computed using FEFLO98, and the CSD and CTD with NASTRAN. The incoming flow was set to $M_\infty = 3.0$ at an angle of attack of $\alpha = 10^o$. The Reynolds-nr. was approximately $Re = 2 \cdot 10^6$, based on the length of the code. The solution was initiated by converging the fluid-thermal problem, without any structural deformation. Thereafter, the fluid-structure-thermal problem was solved.

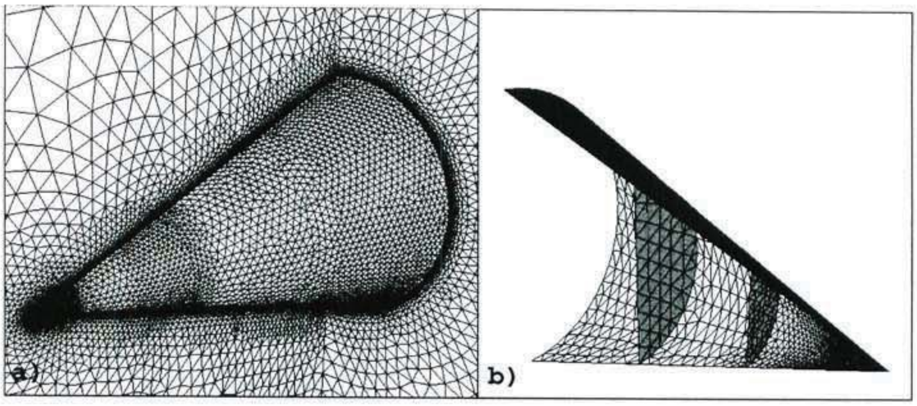


Figure 4 Nose-Cone: Surface Grids for CFD and CSD/CTD

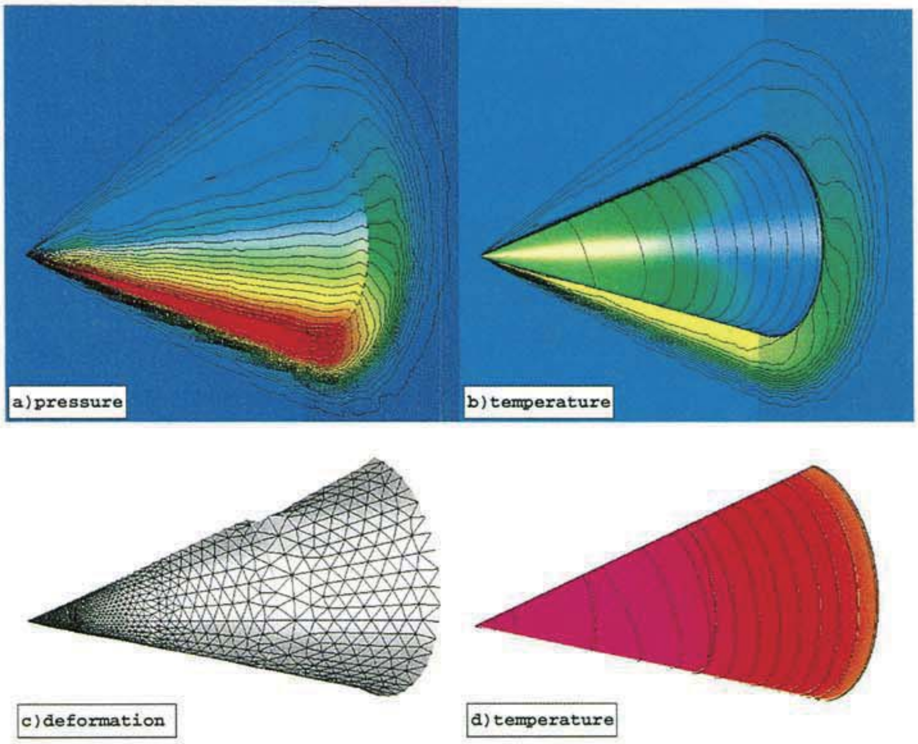


Figure 5 CFD/CSD/CTD Results Obtained

Although this approach has proven successful (see [Löh95b, Bau96, Bau98] for some examples), improvements are required to deal in a more comprehensive way with the different timescales of the fluid, the structure and the temperature field, to enhance the generality of the approach, and to improve user friendliness.

5. PARALLEL, DISTRIBUTED VISUALIZATION

The enormous amounts of output data generated by multidisciplinary, transient runs performed on parallel computing platforms require a user-friendly, rational way of display and assimilation. In addition, large-scale projects are frequently carried out by several teams that are geographically distributed. The rapid increase in throughput of the internet or dedicated networks, together with the emergence of message passing and graphics standards, has made it possible to perform collaborative, on-line visualization of large-scale data stored in a distributed manner (e.g. on different processors/disks of a parallel machine). Several visualizations packages that incorporate this type of capability have recently appeared [Ceb98]. Current research is attempting to incorporate data base concepts into these tools, in order to store, retrieve, trace and analyze in a methodical way the complete design cycle of a new product/physical phenomenon.

6. CONCLUSIONS AND OUTLOOK

A brief review of the current capabilities and outstanding issues for the efficient analysis and design of high-speed flight vehicles using unstructured grids has been given. As one can see, all major areas required in the analysis cycle - grid generation, flow solver and visualization - have seen major advances in recent years. This trend is expected to continue, leading us to believe that turnaround in a matter of hours or minutes for complex geometries and/or physics will become a reality sometime in the next decade.

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