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Future Requirements in Surface Modeling and Grid Generation

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SUMMARY

The past ten years have seen steady progress in surface modeling procedures, and wholesale changes in grid generation technology. Today, it seems fair to state that a satisfactory grid can be developed to model nearly any configuration of interest. The issues at present focus on operational concerns such as cost and quality. Continuing evolution of the engineering process is placing new demands on the technologies of surface modeling and grid generation. In the evolution toward a multidisciplinary analysis-based design environment, methods developed for Computational Fluid Dynamics are finding acceptance in many additional applications. These two trends, the normal evolution of the process and a watershed shift toward concurrent and multidisciplinary analysis, will be considered in assessing current capabilities and needed technological improvements.

INTRODUCTION

Surface modeling and grid generation technology has long been recognized as a critical issue in practical applications of Computational Fluid Dynamics (CFD) analyses. Tools have been developed to implement these geometry modeling technologies in a reasonably versatile and efficient manner. These tools, developed for CFD applications, are rapidly gaining acceptance in additional elements of the aerospace design process: surface grid generation for processing data from pressure sensitive paint tests, surface and volume grid generation for electromagnetics and other field simulations. Technology from these thrusts also is, in a sense, returning to its roots by providing enhanced capabilities in generating surface panel networks for linear aerodynamic analyses.

In addition to the technical capabilities of the product, the development community also must consider issues of quality (i.e., fitness to intended purpose) and risk. Surface models and computational grids, of course, are not the desired end product - they are a necessary step toward producing CFD predictions or other types of data. Therefore, surface models and grids are of value only so far as they allow high-quality flow predictions to be made at an acceptable cost. Quality of the product, therefore, is determined by the CFD flow solver, and by the accuracy of the resulting flow predictions. Several types of risk must be considered in our ability to attain these products. We can identify technical risk (product may not be fit for the purpose), schedule risk (job can't be done in the planned amount of time) and budget risk (job can't be done in the allocated budget). Schedule and budget risk often derive from the use of complex tools which are inadequately tested for representative problems, or inadequately integrated into the overall design process. CFD analysis, considering the whole process, often is seen as being somewhat unpredictable in budget and schedule risk. Therefore, many program managers appreciate the benefits of CFD analysis but are unwilling to use CFD if it becomes the pacing item in the design cycle.

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Surface modeling tools have gained great sophistication in the last ten years. However, the interface to the subsequent CFD analysis codes often is cumbersome and restrictive. Functionally, this process is unchanged since the 1980's, though it now may be carried out in a somewhat automated fashion.

Ten years ago, surface grid generation tools were highly tailored toward specific classes of geometry. High versatility was unattainable, except at a tremendous cost in calendar time and manhours. Non-interactive ("batch") computer tools were the dominant technology, and they had attained impressive power and wide acceptance. This line of technology reached its culmination in the EAGLE code, developed at Mississippi State University under USAF funding.

Batch codes such as EAGLE are capable, in the hands of an expert, of providing a suitable grid about a wide range of geometries. However, a substantial trial-and-error process often was required to integrate the surface geometry input and the batch command streams to produce a satisfactory grid. As a result, the technical capability was available, but often it could not be used on a range of high-end problems with reasonable costs, by non-specialists, producing acceptable grid quality the first time. The outcome, too often, was the frustrating situation where the expert could generate tantalizing results which could not be produced, in a practical sense, by the engineer in the design environment. Furthermore, these methods often had topological or block connectivity restrictions (e.g., point-match between blocks) which greatly reduced their usefulness in many design applications.

Part of the solution to this bottleneck was the development of interactive procedures implemented through the engineering workstation. Many efforts were initiated, through different organizations. However, the effort which exemplified this watershed technology shift was the development of GRIDGEN by General Dynamics, under USAF and NASA funding (Ref. 1). Today, in CFD technology the term "grid generation" is almost synonymous with interactive, graphics-oriented technology.

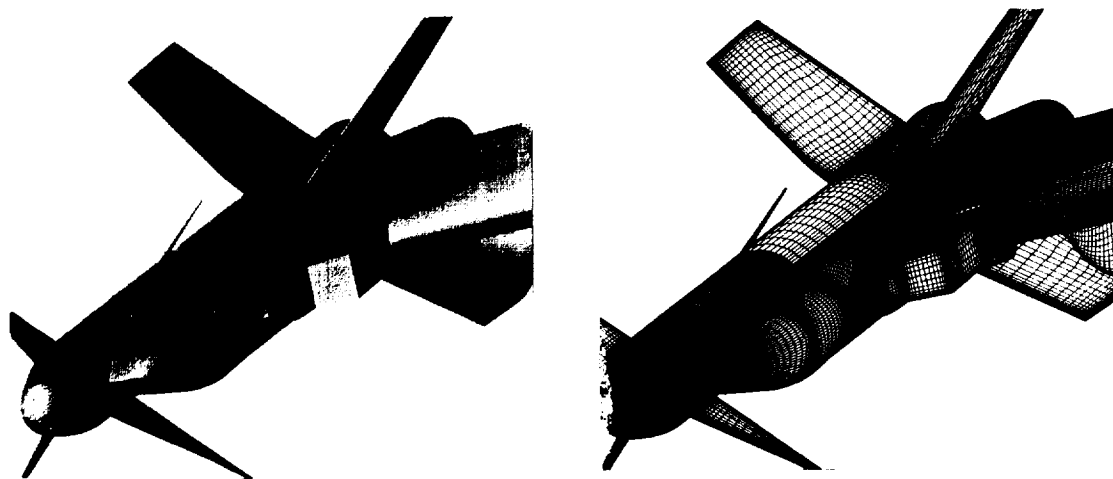


Figure 1 - Pylon/Launcher/Missile Assembly

These technologies have enabled the routine generation of usable grids about almost-arbitrary complex shapes of practical interest (as seen in Figure 1 and Figure 2). They have enabled the penetration of CFD analysis into many elements of the aerospace aero-propulsion design process.

However, the quality of the grids we can produce remains a problem (remember, quality is defined in terms of producing cost-effective flow predictions which are fit for the purpose of the study). We generally lack tools to conduct a comprehensive assessment of surface model and grid quality. The only comprehensive assessment is provided by the flow solver, which means that any defects requiring correction will inevitably have a major impact on the cost and schedule of the CFD study. Furthermore, even if we set aside quality issues, the process of surface modeling and grid generation remains a bottleneck in the total design process, consuming large resources (manhours, skilled specialists, calendar time).

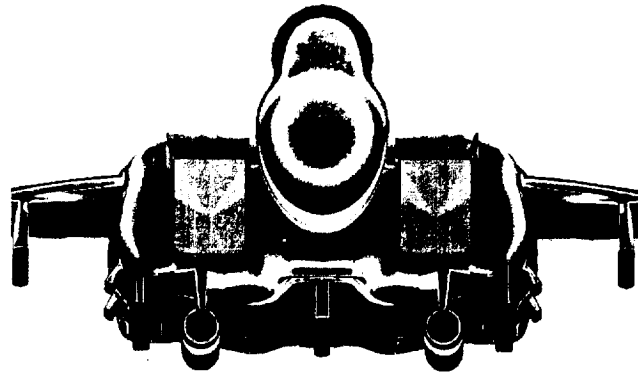


Figure 2 - F-15E Geometry Modeled for CFD Analysis (Outboard Wing not Displayed)

The observations and opinions presented here are based on the author's experience. I believe that the issues which are discussed below, in large degree, are common industry concerns. However, the material in this paper ultimately represents personal observations and opinions.

REQUIREMENTS

Design Process Issues - Surface modeling and grid generation technologies, of course, do not produce a vehicle design. They are components of a complex design process. Thus, to consider future requirements for surface modeling and grid generation technology, the current limitations and future directions of the aerospace design process must be considered.

The aerospace design process is under tremendous pressure to reduce cost. Certain forms of cost, such as the value of the direct engineering labor and the capital assets used in the process, can be identified easily. Other additional costs perhaps cannot be easily evaluated, but these costs often are more critical than the direct costs to the success total design effort (see Figure 2).

A large-scale engineering project usually is very sensitive to calendar time. Economic competitiveness depends very strongly on bringing the most advanced product to the market, quickly and affordably. Further, the

<p>Direct Costs</p> <ul style="list-style-type: none"> • <i>Engineering Manhours</i> <ul style="list-style-type: none"> - <i>Grid Generation Engineer</i> - <i>Specialist Support (CAD?)</i> • <i>Value of Computer Assets</i> <p>Additional Costs</p> <ul style="list-style-type: none"> • <i>Calendar Time</i> • <i>Highly Skilled and Specialized Labor</i> • <i>Risks (Process Variability)</i> <ul style="list-style-type: none"> <i>Technical Quality</i> <i>Budget</i> <i>Schedule</i> <i>Identified risks - cost of mitigation plan</i> <i>Surprises - cost of correction</i>

Figure 3 - Forms of Cost

ability to compress the schedule will (a) bring the product to market ahead of the competition, and (b) produce a smaller development cost. Thus, schedule compression leads to economic success in several ways.

Depending on the type of study, either the manhours or the calendar time may be the more important measure of cost. The importance of geometry acquisition and grid generation in these cost measures is illustrated in Figure 4. These data are taken from a high-end study performed in 1992-93 using Navier-Stokes structured grid methods.

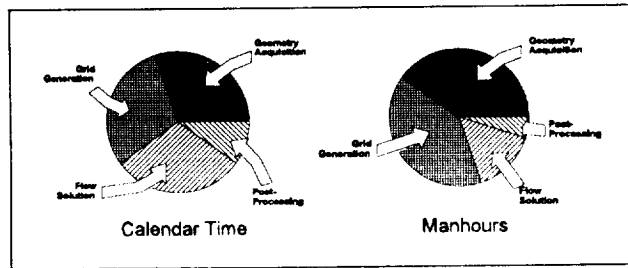


Figure 4 - Distribution of Costs in a High-End CFD Study

Generally, smaller advanced design programs are more sensitive to manhour costs, while large development programs are more sensitive to calendar time. The tasks related to geometry acquisition and grid generation consumed a substantial portion of the resources for the total task in this example. This work prior to running the flow solver code consumed about 80% of the total manhours! Clearly, in reducing the manhours and thus the direct cost of CFD analysis we should focus on the tasks of handling the geometry and building the grid. These also are important issues in reducing the calendar time of the total CFD analysis process.

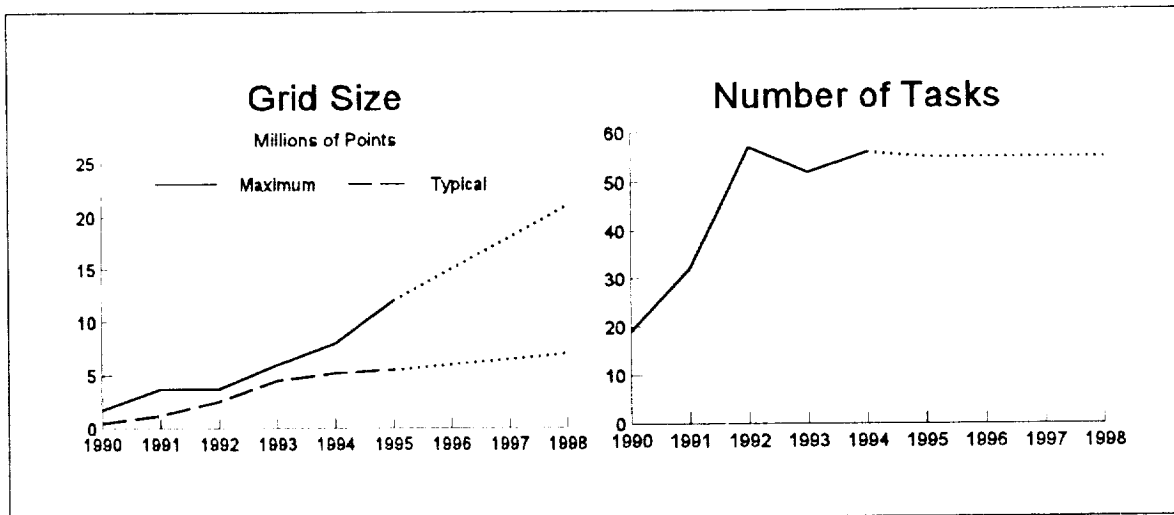


Figure 5 - Recent History and Projection of Grid Generation Requirements

Without improvements in the process, we can expect the surface modeling and grid generation phase of the process to become a far worse bottleneck in the next few years. As we succeed in establishing confidence in CFD predictions, the demands for data have increased. With these data demands have come demands for higher accuracy. One element of providing increased accuracy is to use grids with higher fidelity. This means the future grids will represent more complete modeling of the vehicle, and they will be at higher grid density to provide higher accuracy. These trends, based on our experience, are illustrated in Figure 5. Without an upturn in the overall level of engineering activity, we probably should not anticipate an increase in the number of CFD application tasks performed each year (a task is one study, consisting of a set of related grid generation and flow solution activities). However,

continuing acceptance of CFD allows the overall number of tasks to remain constant despite a generally downward trend in overall engineering activity. The demands for higher accuracy, coupled with the evolution of flow solver technology toward parallel processing platforms (allowing the solution of larger problems), provides continuing pressure toward rapid generation on ever larger and more complete computational grids.

Another “additional” cost is the need for highly skilled and specialized labor in elements of the surface modeling and grid generation process. By definition, if a certain skill is described in those terms, it is also a scarce skill. Thus, the need for specialized skills is a potential choke point in the process.

Concurrent Processes - Another strong goal is to increase the concurrency in the aerospace design process. In the jargon of computer technology, the process is shifting away from serial sequences of tasks, and shifting toward synchronized tasks spanning multiple technical disciplines. This thrust is often identified under the label of multi-discipline design or optimization. However, concurrent analysis might be a better descriptor in terms of current trends.

This thrust has several implications (additional impacts are being discovered, nearly every day). One clear implication is to identify common tools and common elements of the design process which can support multiple disciplines. Clearly, surface modeling and grid generation is a high-leverage technology in this process - it can support traditional aerodynamic analyses, wind tunnel model development, and new areas of application such as signature estimation. Surface/grid technology developed for CFD has been critical in surface mapping procedures for quantitative reduction of data from pressure sensitive paint tests.

Another, more subtle, impact of concurrent analysis is the need for high-fidelity analyses in all stages of the process. Aggressive schedules generally are not consistent with a multi-stage, hierarchical buildup in the fidelity of the supporting analyses. The new goal is to do the task once, completely and accurately, and then move to the next task. This requirement leads to a requirement for very low “latency” in the ability to produce high quality surface geometry and grids supporting the design analyses.

A third impact of concurrent engineering also must be considered. In a concurrent design process, multiple elements of the process are intertwined. A delay or failure in one element of the process will have an immediate, cascading effect throughout the process. An undetected defect in analysis products will have a much more drastic impact in a concurrent design process, compared with the impact in a more traditional sequential process. Therefore, (as always) it is important - critically important - to minimize any possibility of producing defective data. However, we must recognize that true perfection cannot be achieved. Therefore, it is also important to develop procedures to test and verify the quality of all intermediate products in the analysis process, and identify unfit products at the earliest opportunity (Figure 6).

A schedule for elements of the design process, once established, must be maintained. The entire project (perhaps several thousand people) cannot be put in the

When Discovered	Probable Cost
Immediately	1-2 hours, 1 person
During flow solution	1 week, 1 person
During subsequent analysis	1-2 months, 2-4 people
During design verification	3-12 months, 4-20 people
During production	1+ years, many people Product failure ???

Figure 6 - Impact of a Grid Generation Defect

position of waiting for a few CFD people to complete a tardy task. But, building reserves into the schedule so that delays can be accommodated will, just as surely, produce the same non-competitive outcome - if a competitor is more successful at managing their schedule.

Risk Issues - One of the major impediments to wide acceptance of the CFD process is the perception that the process exposes the customer to high risk, i.e., that the final technical quality, schedule or budget will not be what was expected at the beginning of the CFD process. This perceived risk is mitigated by setting conservative goals (thus failing to use the full potential of the technology) and by setting aside reserves (schedule time or budget) to cover CFD variations. Thus, the current emphasis on reducing all forms of cost leads to the following goals:

- **Reduce risks** by eliminating process variability or uncertainty (technical quality, budget, and schedule).
- With variability under control, **improve the process** by reducing budget and schedule requirements, and by improving the technical quality.

CURRENT PROCESS, ISSUES, CAPABILITY SHORTFALLS

Three broad classes of grid technology can be identified: structured grids (both overlapping and non-overlapping), unstructured grids (various types), and hybrid grids (combining structured and unstructured methods). All of these grid methods, however, obtain geometry from common sources in surface modeling.

Grid Strategy - An assessment of current issues in grid generation must consider the differing maturities of structured and unstructured grid generation. For multi-block structured grid generation, both the patched (non-overlapping) and the overset (Chimera, or overlapping) grid technologies can be said to be approaching maturity. That is, tools are available which allow these technologies to be used for (nearly) any problem by a range of engineers (i.e., not solely by experts). The standards for quality are generally understood, though achieving quality for complex problems remains difficult. Thus, the challenges in these areas, for the most part, are to improve the production capabilities of these technologies. The research goals for structured grids are process issues: elimination of bottlenecks in the work flow, improving the efficiency of the process, and ensuring that acceptable (high) quality is always achieved in the products of the process.

Unstructured grid technology is also reaching production status for several types of applications, but certainly not in the comprehensive sense in which structured technology has reached production status. With unstructured technology, process issues (see previous paragraph) are important, but other more fundamental issues of technology also can be identified. At present, Navier-Stokes unstructured grid generation for 3-D geometries remains difficult, and often requires the direct participation of the resident expert to achieve success. Standards of quality are difficult to assess and are not fully understood, except in the most clear-cut cases. At present, we usually rely on the capabilities of the grid generation tools as demonstrated in relatively simple problems. We often cannot evaluate the quality of the grid product except by the behavior and the product of the flow solver. Visual inspection of the volume grids, prior to beginning the flow solution, is virtually worthless. Useful quality standards are not accepted, and quality assurance tools are almost non-existent.

An intermediate level of technology, hybrid structured and unstructured grids, has received relatively little attention. This technology, perhaps, offers an operational compromise. It might permit the engineering community to use proven viscous flow methods on structured grids near walls (maybe restricted to very near the walls), and take advantage of the versatility of unstructured methods in complex, multiply-connected volume regions between vehicle components.

Domain Decomposition - For multi-block structured grid methods, volume grid generation must be preceded by definition of the block boundaries. In overset grid methods, the exact location of block boundaries away from the vehicle surface may not be a critical issue. Hyperbolic grid generation procedures often are used, due to their high efficiency and the grid quality which they now can produce (since the location of the outer edge of the grid block is usually not crucial). However, this overset grid approach leads to difficult issues in generating the boundary condition coupling (interface) data between communicating grid blocks (more on this later).

With structured/patched grid methods (i.e., non-overlapping or marginally overlapping grids), the locations of block boundaries are quite important. These boundaries must be defined across the computational domain at about the same point in the process where the surface grids are generated. This process of defining block boundaries, often called "domain decomposition," consumes much time (both calendar time and manhours). Several research efforts are underway with the goal of developing automated tools for domain decomposition, often with the aid of artificial intelligence technologies. As an intermediate step, perhaps the techniques of 3-D visualization can be used with interactive cutting planes to define block boundaries quickly (in seconds or minutes).

Surface Modeling - For several years, the preferred source of surface geometry has been Computer-Aided Design (CAD) systems, such as the Unigraphics system used at McDonnell Douglas. Often, the CAD geometry must be edited - to correct defects, to trim the surfaces (i.e., to eliminate non-physical edges of surface elements), or to modify the true geometry for the purposes of the analysis. Next, the geometry often is converted to closely-spaced mathematical section cuts or a pointwise definition for use in the CFD grid generation system.

Usually, the geometry is first defined within the CAD environment as a wireframe model. Next, the wireframe is surfaced (i.e., all geometry is defined to produce a complete 3-D definition of the exposed surfaces). This step of CAD surfacing can be time consuming, particularly if higher-order constraints must be enforced for continuity in surface slope or curvature across abutting surface elements.

CAD geometry ideally consists of surface patches or volume elements which abut cleanly, with no gaps, overlaps, doubly defined regions, or non-physical protrusions. In reality, these and other types of defects occur, as are illustrated in Figure 7.

Correcting these geometry definition defects is perhaps the chief bottleneck of the process. This is a non-value-added step. Ideally, surface modeling tools would use safeguards to avoid generating these defects in the geometry.

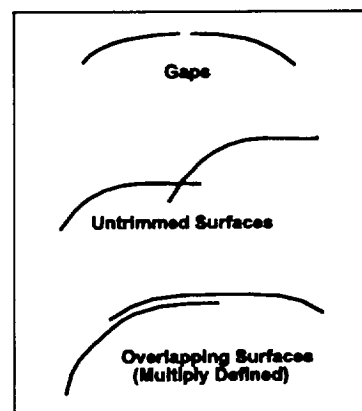


Figure 7 - Examples of Surface Geometry Defects

One needed step is to develop surface modeling tools, outside the CAD environment, which can either correct these defects or generate a suitable surface grid despite the defects. However, a fundamental issue remains: which definition is to be used where the surface is multiply defined? Can an automated algorithm be established which can determine whether a protrusion in the surface geometry is correct or a defect? Can an automated algorithm fully address the issue of gaps in the geometry - what if the gaps are intentional (for example, inlet bleed slots)? It seems that semi-automated tools are needed, to locate potential defects for human inspection, with automated correction depending on the outcome of the inspection. The development of tools which are tolerant of surface defects would greatly improve the cycle time of the CFD analysis process. Some of these issues are summarized in Figure 8.

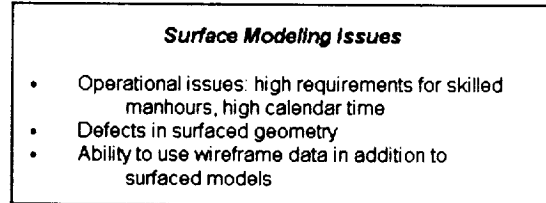


Figure 8 - Surface Modeling Issues

Another needed step is to develop tools which allow grid generation to begin with an arbitrary wireframe model, rather than a fully surfaced model. Perhaps high precision would not be required in slope continuity across surface patch abutments, and for CFD purposes it probably would not be necessary to provide continuity of curvature. These tools would be useful mainly in the advanced design environment; for more accurate data in the later stages of design it would be necessary to use "official" CAD surface geometry for consistency. The ability to use arbitrary wireframe data as input to the grid generator, for advanced design purposes, would greatly improve CFD turnaround.

A third approach, which is gaining popularity, is to base the grid generation process on a 3-D surfaced model external to the CAD system. The NASA IGES format (Ref. 2) is gaining favor in this role.

Surface Grid Generation - The next step in the process is surface grid generation. This step, for the most part, is common for all grid methods. A quality surface grid, or mapping, must be applied to all geometry surfaces which are to be retained in the analysis. For most methods, this step requires careful definition of all intersection lines between components. This is the step which becomes highly subjective if defects remain in the surface modeling. Some issues and requirements for this step are presented in Figure 9.

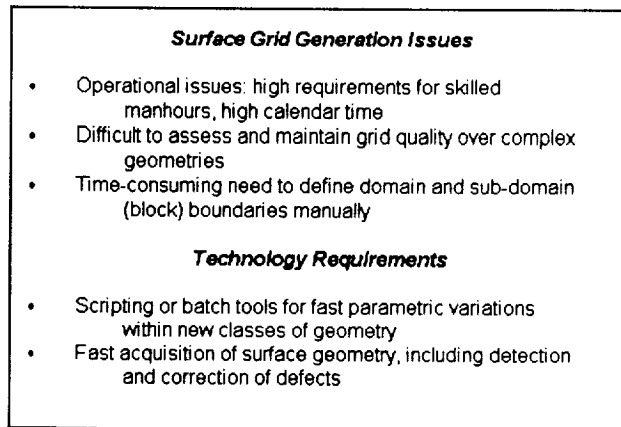


Figure 9 - Surface Grid Generation Issues

Surface grid generation, or a similar step to produce a satisfactory surface mapping, is a time-consuming step in the overall process. The quality of the surface grid has a large impact on the overall quality of the final analysis product. Our experience has shown that many methods do not ensure that the final surface grid points lie exactly on the original defined surface. Indeed, systematic variations have been noted, which can produce large-scale, erroneous, structures in the subsequent flow solutions. However, it is at present very difficult to assess surface grid quality (orthogonality, stretching, curvature, alignment) by any means other than visual inspection. Inspection, of course, is not a systematic process. The expertise and the sensitivities

of each inspector are different. Further, there are very few absolute measures of quality. This approach leaves a high probability that defects will not be detected at this stage, and they will remain in the surface grid to have a magnified impact in later steps of the process.

Volume Grid Generation - Volume grid generation is the process of filling a defined volume with a grid, using either structured or unstructured technology. This step of the process, by either technology route, is fairly mature today. As indicated above, the major issues are process issues (speed, reliability, versatility) rather than basic technical capability (see Figure 10).

- | Volume Grid Generation Issues | |
|--------------------------------------|--|
| • | Set grid density, stretching requirements manually in every block. |
| • | Scripting or batch tools for fast parametric variations within new classes of geometry |
| • | Automated domain decomposition |
| • | Improved control of orthogonality near walls |
| • | Batch/Script tools for fast generation of surface grids in subdomains |
| | - Structured Grids |
| | - Unstructured Grids |
| • | Default generation of volume grids within defined subdomains |

Figure 10 - Issues in Volume Grid Generation

In the area of structured grids, several quality issues must be resolved. Elliptic methods are popular for the generality of their capabilities. However, these methods still have unresolved, systematic problems maintaining acceptable grid quality near both concave and convex corners. Convex corners invariably lose grid packing, while concave corners yield grid line crossovers and negative volumes. For unstructured grids, we lack systematic useful standards of quality - useful in terms of ability to represent the performance of the flow solvers without being excessively restrictive.

Block Boundaries - For multi-block structured grids, either patched or overset, the next step is to generate the block boundary coupling pointers. This is an identification of the grid point matchups between neighbor grids, for the purpose of coupling the flow solutions between adjacent grids. This is a key problem area for both types of structured grid technology. Since this issue falls somewhat ambiguously between grid technology and flow solver technology, often this issue is addressed inadequately. Avoidance of this problem is one of the major attractive features of unstructured grid technology (see Figure 11). Another quality issue is related to the placement of the overlapping boundary (high-gradient regions in the flowfield should be avoided - shocks, wakes, etc.). Further, cell sizes should be comparable in the two grids which are being coupled in the overlapping region.

- | Block Boundary Issues | |
|------------------------------|---|
| • | Difficult to assure quality in setting up coupled block boundary conditions - structured/patched, structured/overset, hybrid. |

Figure 11 - Block Boundary Issues

For patched (non-overlapping) grids, the problem is perhaps slightly easier since the coupling pointers are generated on two-dimensional surfaces (in the mathematical sense). For overset grids, the coupling occurs in a three-dimensional volume which is common to two or more grids. In either approach, the goal is to locate boundary points of one grid in terms of the mapping of the neighbor grid(s). Quality must be achieved, without any errors, in this process or the subsequent flow solution in all probability will be fatally compromised. This step of quality verification is time-consuming, though semi-automated procedures are available to assist the engineer effectively in this step of the process.

A similar problem may occur with unstructured grids, if the subsequent flow analyses are to be performed on a parallel processing computer system. For this application, a type of domain

decomposition must be accomplished on the full unstructured grid to establish subsets which will be passed to each processor. This decomposition can have a significant impact on the convergence rate of the composite solution and the processing time for each iteration. However, optimal characteristics of this decomposition are not fully understood at present.

FUTURE STATE

An attractive future state can be identified, within the context of current structured and unstructured grid generation technology. This future state, I hope, can be achieved as a product of specific research into issues such as those which have already been noted. Strawman estimates of the time required to model a full aircraft configuration are noted for each step.

- The nominal geometry (i.e., before any modifications based on analysis goals) is generated in the CAD system. Either the CAD system or a separate procedure is used to identify defects, omissions, etc., in a timely manner, so that they are corrected before the geometry is used for any subsequent process. In the current process, these defects usually are to be corrected in the CAD process, which can take several days. With a more robust process, as discussed above, the required time should be greatly reduced.
- The geometry is modified, within the CAD environment, as appropriate for the subsequent analyses.
- The analytical tools for surface modeling and grid generation operate directly on the CAD surface models, or on a data format that is immediately derived without compromise from the CAD models. (Time for geometry acquisition: 2 minutes - a file transfer only).
- Semi-automated tools are used for surface grid generation and domain decomposition. These tools "suggest" default surface and block face grids, subject to approval by the engineer. Presumably, this process must take into account the goals of the analysis: parameters to be predicted, required precision, flow analysis code to be used. If the engineer chooses not to accept the suggestions, the same grid generation environment provides full tools, with high automation, to implement the engineer's desires. Quality of the final surface grid or mapping is verified by automated procedure at the end of this step. (Time to generate surface and block face grids: 4 hours).
- Overall parameters of the volume grid blocks - number of points, stretching functions, etc. - are set by a semi-automated process (automatic recommendations, with engineer having opportunity to modify the recommendations). This step, too, must take into account the goals of the analysis. Having set the overall parameters of the grid blocks, the actual grid is generated by a fully automated process. Quality of the grid is verified at the end of the process. (Time to generate volume grids: 1 hour)
- Block interface data is generated by a fully automated process. Quality of the interface data is verified at the end of the step. (Time to generate interface data - 10 minutes).

Each of these steps seems achievable over the next five years, with an appropriate research focus. It should be noted, the strawman process times to generate a complete multiblock grid for a complete aircraft, starting from a complete high-quality CAD definition, add up to less than six hours in this

vision of the future. Achieving this vision will be a major step toward providing the fast cycle time needed to support intensive use of analysis-based design for future aerospace vehicles. Of course, major improvements in calendar time for the flow solution and post-processing also will be needed.

Many technical communities in addition to CFD and the aero-propulsion community will benefit from this research. The surface grids produced by this process will be of value to many other technical communities in the design process that require definition of the exposed vehicle shapes.

SUMMARY AND CONCLUSIONS

The process of surface modeling and grid generation is, at present, based on interactive (manual) operations from start to finish, often requiring some of the most highly skilled specialists in the analysis community. This technology fills the gap between the design community (based on CAD systems) and the analysis community. These specialists must be conversant in both sets of technology.

Some of the key, recurring problems in this area were mentioned previously. Several suggestions for future technology development have been identified. Another key issue has been mentioned, in various contexts, earlier in this paper. To maintain the highest quality in the products of surface modeling and grid generation, we first must be able to measure the quality. Metrics and tools are needed for a meaningful assessment of quality at every step of the process. A summary of these quality measurements needs is presented in Figure 12.

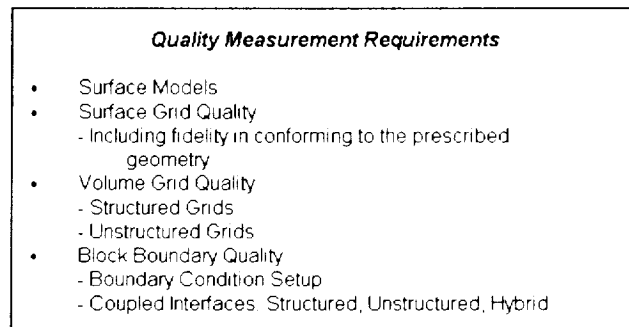


Figure 12 - Quality Measurement Requirements

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