A TOOL FOR PARAMETRIC GEOMETRY AND GRID GENERATION FOR AIRCRAFT CONFIGURATIONS

Guilherme L. Oliveira*, Luis C. C. Santos*, André L. Martins*, Gilberto G. Becker*
Marcus V. F. Reis, Nicolas Spogis**, Rodrigo F. A. F. Silva****
*** Embraer – Empresa Brasileira de Aeronáutica, Brazil**
****ESSS - Engineering Simulation and Scientific Software, Brazil**

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Abstract

During the early stages of the aircraft design process there is a need to verify the influence of a large number of geometric parameters on the overall configuration. The engineering analyses at this stage might be extremely time-consuming due to the high level of interdependence between the disciplines. Moreover, the processes involved are hardly automated mainly due to difficulties on the interface between the CAD and CAE tools. In order to achieve an efficient design cycle, designers need an environment where geometrical changes can be easily introduced and computational meshes automatically generated, providing full support for the engineering analysis. The scope of this work is to describe a tool that accomplishes these goals. It is based on the integration of CATIA V5 and the family of grid generators Quad/Hexa/Tetra/Prism from Ansys ICEM CFD.

1 Introduction

Over the past decades, single discipline shape optimization has been successfully applied to the design of two-dimensional and simple three-dimensional aerospace product configurations. In recent years, there has been a growing interest in the application of multidisciplinary shape optimization to complex three-dimensional products. That is a challenging task for a complete aircraft configuration, especially given the interest to increase the fidelity of the analysis results relative to actual physics. Such rational introduction of high-fidelity analyses early in the design process is seen as a way to break ties with the sole application of past experience, allowing introduction of true innovation from product conception.

Although tremendous progresses have been reached in geometry and grid modeling in recent years, those tasks are still considered to be the most labor-intensive and time-consuming for complex, high-fidelity computational fluid dynamics (CFD) and computational structure mechanics (CSM) analyzes, forming narrow "bottlenecks" in the overall process. Such conditions are especially adverse for early design work, which usually requires the analyses of large numbers of design variations.

Beyond the inherent, conceptual complexity of such tasks, there are also several obstacles of practical nature that appear in industrial environments. An example is related to modern CAD systems, well established in industry, which apply either or both boundary representations or constructive solid geometry methods to represent physical, solid objects [3]. Such systems are routinely used to represent complex, complete product configurations, CAD models generated by the most common process of direct human interactive work. However, such "human generated" models very often present small scale numerical/geometric imperfections, such as gaps, wiggles, free edges, slivers and transition cracks. Such imperfections are most likely to cause problems for the subsequent grid generation process required for engineering (CAE) analysis. Also, it is not unusual nowadays to find CAD models that employ tens of thousands of geometrical elements (e.g. curves and surfaces) to represent an aircraft configuration, for example [4]. Such level of complexity underscores the interest in having *parameterized* geometry representations to allow *repeatable*, *automated* generation of geometric variations aimed at design optimization studies.

To parameterize a CAD model in a way compatible with automatic grid generation and, at the same time, representative for the design problem at hand, is not a trivial task. The process must be robust, consistent and accurate, yielding a compact and effective set of design variables so that solution times remain feasible within acceptable design cycles. Recent literature reports a number of attempts to apply such concepts to computational engineering design, for instance, by the coupling of an appropriate model parameterization with CFD grid generators and solvers, within optimization environments with explicitly defined design variables and cost functions [2]. He et al. [4] presented a procedure for integrating CAD and CAE systems to support geometry optimization compatible with high-fidelity analysis.

The present contribution to this domain lies in a method for automatic generation of parametric geometries and corresponding grid models, specialized for aircraft design analyses. The methodology exploits the inherent features of the CATIA V5 CAD system together with the ICEM-CFD grid generation software to construct airplane surfaces and meshes complying with typical CFD requirements for preliminary design studies. The aircraft parametric model comprises several families of surfaces controlled through an as small as possible set of parameters, yet respecting geometrical constraints based on previous knowledge, derived from the experience of actual aircraft design programs. This approach ensures that the models generated will respect the constraints at the model level, without having to treat them explicitly in the optimizer, reducing the number of free parameters in the model and the number of design variables for the optimization phase.

2 Geometry and Grid Modeling Background

The present approach assumes the premise that, in order to resolve the conceptual and practical difficulties mentioned previously, geometry and grid generation *should not be seen as independent tasks* for complex computational analyses such as CFD or CSM.

However, when automating geometry and grid generation, the inter-dependence (coupling) between these two activities is naturally augmented; therefore, special care must be taken to allow the generation of accurate and robust models.

2.1 Geometry Parameterization

With the continuous evolution of CAD tools, geometry parameterization has migrated from old scripting techniques to modern systems such as CATIA V5, ProE and UGS NX, where designers can quickly regenerate a model after the modification of parameterized construction dimensions. Based on this technology, parameterization of simple geometry structures has become a straightforward process.

However, to actually represent a complex three dimensional configuration in parameterized form, other aspects must be addressed beyond the CAD parameterization methodology itself. Those aspects can be organized into the following topics: *generality*, *modularity*, *accuracy* and *robustness*.

Generality: associated with the range of configurations that the tool/system would be able to generate in parametric form. This scope will determine to which designs tasks and phases the tool would actually be applied to. The level of generality required for application to aircraft preliminary design has been defined as a finite but comprehensive set or *library* of *topologies* that should be represented by the tool for the aircraft configuration and its sub-elements. The set of topologies foreseen to be covered by the method proposed here is presented in Pictures 2 and 3.

Modularity: the reach of the method's generality depends on the strategy used to represent the different components of the aircraft. A convenient approach is to work with independent *modules* or objects (as in object oriented programming). Such approach is viable in current CAD systems, where the object orientation paradigm is usually applied to the organization of assemblies and components. That approach is appropriate not only for the maintenance and further development of the parametric model, but also because it is compatible with multi-disciplinary team environments. Since the construction of each component involves different techniques and expertise, each module can be generated separately, by dedicated personnel that detain a knowledge base on the part to be parameterized, as well as on the relations with other components. As a result, the model will take into account the most significant parameters for each component, while the consistency among the different modules is preserved.

Accuracy: to make sure a tool for automatic geometry and grid generation can be inserted in the design cycle in industry, it is important that the model generated is *accurate* enough to be representative of the geometry to be used in later phases of the design process. To accomplish this, each component should employ the same techniques (lofting, curves, tangencies, etc) used by CAD specialists during the final geometry specification. In addition, if modularity is well planned, it should also be possible to replace the parametric model used in preliminary design by any intermediary geometry up to the final one, allowing continued automatic grid generation capability for the aircraft configuration as it evolves to later design phases.

Robustness: each geometric entity has to be constructed and parameterized considering all possible variations of the input variables, as well as possible transformations of external references used in the model construction.

2.2 Grid Generation

Grid generation techniques for body fitted meshes can be divided in two main categories: *unstructured* and *structured*.

Unstructured techniques usually do not require too many human knowledge interventions during mesh generation, as the process is almost fully automated. User inputs in this case are usually related to local mesh sizes and a few parameters related to the meshing algorithm. The success of the algorithm depends, however, on the quality of the geometry provided by the user, and on the relation between mesh sizes and geometry details. As a general rule, unnecessary details in the geometry are normally removed before mesh generation, so eventual problems are avoided in these regions.

Structured mesh generation, on the other hand, usually require interaction with the user, resorting to his/her previous experience and knowledge. The analysis domain needs to be subdivided into regular hexahedral blocks or solids which, by their turn, will be further subdivided in regular hexahedral elements once discretization parameters have been specified. Such physical domain discretization steps can be very time consuming for complex geometries if tackled on a case by case basis, which makes the automated reuse of knowledge for common or pre-expected topologies very attractive. However, such automation requires not only the absence of unnecessary geometric model details, but also the construction of support entities (mostly points and curves), which will be associated with the mesh topology, and therefore need to be strategically positioned in the space and regularly associated to the object’s topology. Those entities must be associated with the geometry parameterization, so when the geometry changes, the support entities would change accordingly. In summary, an appreciable amount of knowledge capturing is required to establish a regular, robust, automated process to generate structured meshes for a family of object / products of fixed topology and variable geometry.

It is easy to notice that mesh quality is closely related to geometry quality in both unstructured and structured meshes. Therefore, to guarantee robustness and mesh quality during automatic grid generation, the geometry construction must take all mesh requisites into consideration.

3 The GMA System

GMA – Geometry and Mesh Automation – is a system developed by Embraer and ESSS to regularize and automate the process of geometry and CFD grid generation for a (finite but comprehensive) set of aircraft configuration topologies (as well as for specific sub-assemblies) of interest for preliminary design analyses.

The GMA system has been based on following conceptual premises / requirements:

(a) To reduce the cycle (time) required to execute parametric analyses on complex aircraft configurations.

(b) To allow design engineers to focus on the design problem, separating it from the CAD and grid generation setting problem, the latter to be pre-solved to a large extent.

Therefore, although the system employs advanced CAD and grid generation techniques, the design engineer is left with a relatively small set of parameters relevant to the design problem, while CAD and grid generation parameters are pre-optimized based on previous knowledge.

3.1 Computational Implementation

The Graphical User Interface (GUI) of the GMA system was implemented in Visual Basic, using MS Excel as the platform, which provides a large number of functionalities to the system.

The GUI establishes the communication with parametric model pre-built in CATIA V5 and the mesh generator, Ansys ICEM CFD, as illustrated in the Figure 1.

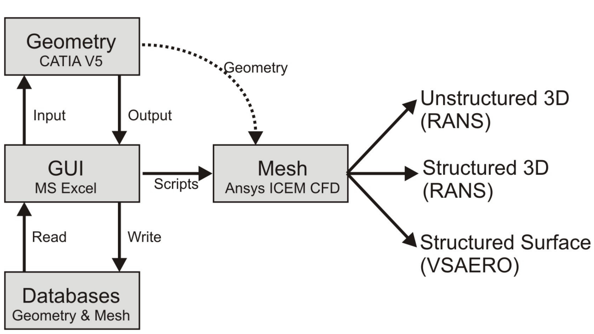

Figure 1 – GMA computational implementation.

3.2 Configuration Topology

Prior to geometry and mesh generation, the definition of the basic problem is based on the selection of the configuration topology, that is, which components will be included in the analyses and how they do relate with each other. The different components available in the GMA system are illustrated in Figures 2 and 3, which partially depicts the main components available and their "parent-child" (object-like) relationship trees.

While some "parent" components can be included and excluded independently (those preceded by a "check box" in Figures 2 and 3, e.g. a wing), others only make sense in the presence of components which require them (those preceded by a "black box", e.g. a wing end patch). Yet, other components are mutually excluding options (those selectable by "radio buttons", e.g. long-duct x short-duct engine nacelle). The dashed lines on the right in Figures 2 and 3 indicate additional dependences between the components that go beyond the parent-child hierarchy; the arrows in these lines indicate the direction of dependency (dependent $\rightarrow$ independent). As an example of such dependency: the user can perform an analysis on the engine alone, by selecting just the engine under the analyses tree. In this case the nacelle is automatically included in the analyses, but pylon must be left out. The under-wing or rear-mounted pylon could only be included in the model if, respectively, the wing or fuselage were selected, so the dependencies for the selected configuration would be respected.

For convenience, the wing structure component tree was omitted in Figure 1. Figure 2 gives an idea of the number of components that can also be considered in the analyses once the wing is inserted in model. Many of the components illustrated in Figure 3 are actually associated with a number of instances, which need to be informed during model specification. So when selecting flap tracking fairings, for example, the user can specify how many instances he wants to insert in the model. It is important to mention that, although all instances utilize the same parameterization strategy, each occurrence can present a different set of parameter values. The same behavior is associated with flaps, slats, spoilers, wing main elements and ailerons.

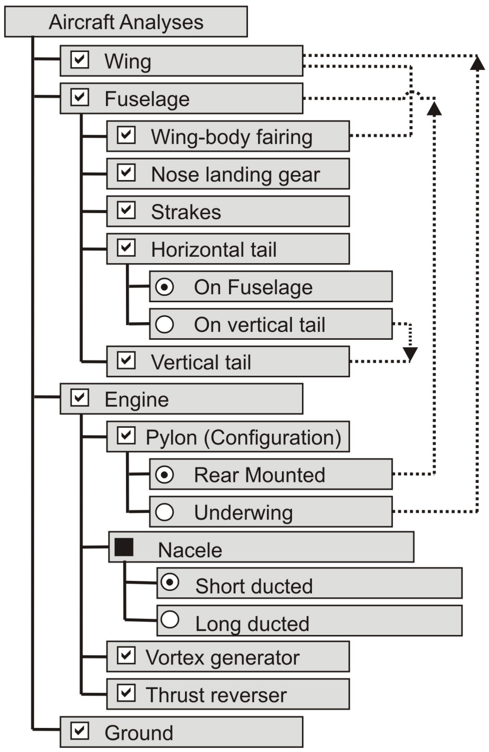

Figure 2 - Configuration topology hierarchy tree.

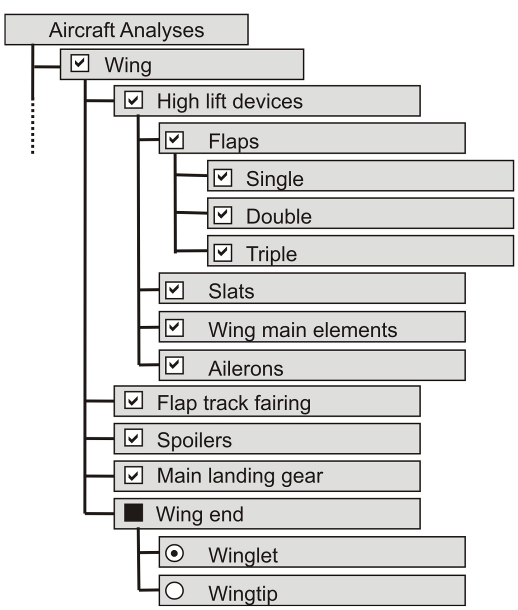

Figure 3 – Components related to wing.

3.3 Geometry Creation

Once the major topological structure of the model has been defined, geometric parameter values need to be defined for each component included in the configuration. Each component has its own set of parameters, listed in a dedicated worksheet. Figure 4 depicts and example, the worksheet for wing parameters definition.

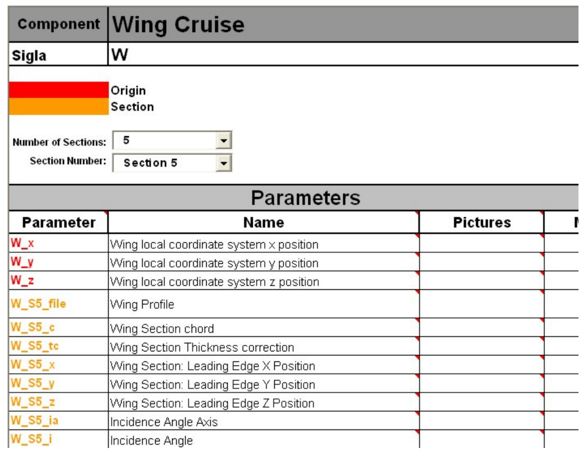

Figure 4 – Wing geometric parameters sheet.

The configuration topology and associated geometry parameters can be saved in a database, which can also be read into the GUI for future usage.

Once the geometry is updated, the system also provides outputs for derived geometric information of interest via an output "geometry audit" module. A comprehensive set of derived relevant figures can be extracted from the geometry, such as cross sectional area distribution (for "area ruling" of the aircraft and/or individual components), reference wing parameters, surface areas, internal volumes, etc.

3.4 Mesh generation

The mesh generation process may be started after the geometry construction. GMA provides means to generate unstructured volumetric meshes (tetrahedric and hybrid tetra-hexahedric), structured volumetric meshes (hexahedric) and structured surface meshes (specially tailored for panel methods analyses). Selection of the mesh type is followed by the definition of mesh parameters, such as boundary layer information (first element height, number of nodes and total height), number of nodes across a given component dimension, etc. The mesh parameters can also be saved in a database, which could be reused in posterior applications.

4 Examples

Aircraft configuration elements may be modeled not only within the full aircraft context, but also in isolated form, as convenient for specific analyses. GMA also incorporates modeling and meshing capabilities for localized elements of special interest, such as auxiliary air inlets, thrust reversers and icing formations. Aircraft wings may be represented either in high speed, cruise configuration (single airfoils) or in low speed, high lift configuration (multiple cascading airfoils). Two-dimensional airfoil geometries and meshes, extensively used during preliminary design, may be generated as well.
Figures 5 to 7 show same examples geometries created with GMA.

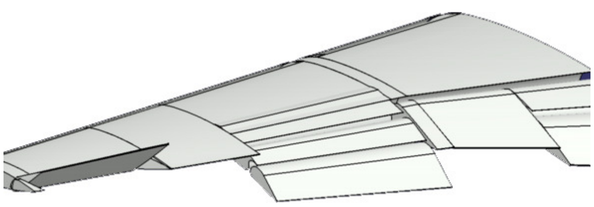

Figure 5 –Wing with high lift devices deployed

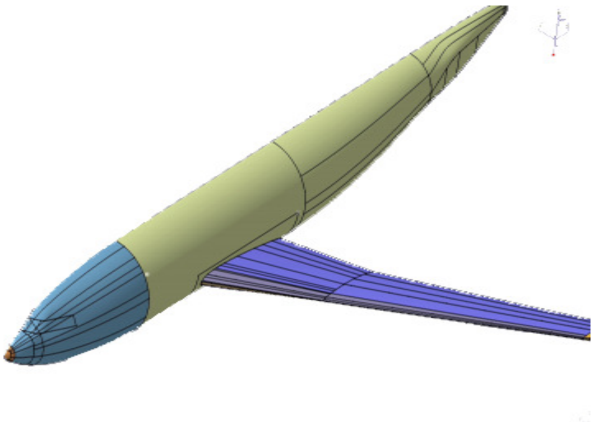

Figure 6 – Wing-fuselage configuration

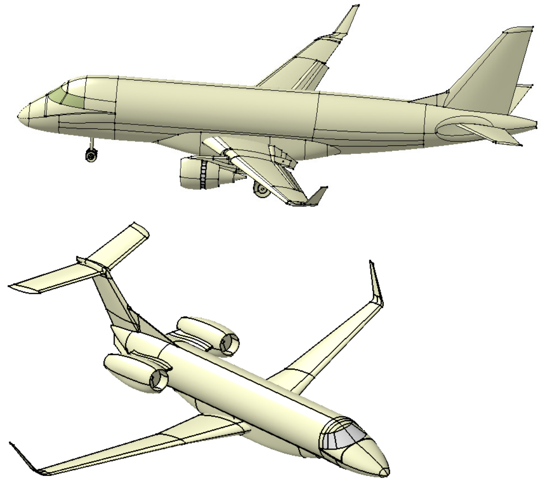

Figure 7 – Full aircraft geometries created with GMA

Both structured (hexahedral) and unstructured (hybrid tetra/prism) mesh configurations have been implemented, with total control over number of nodes, mesh spacing and growing ratios. These methods can reproduce meshes with different refinement levels, ensuring high productivity when mesh convergence studies are performed. Examples of geometries and meshes are depicted in Figure 8, unstructured mesh, Figures 9 to 11, structured meshes.

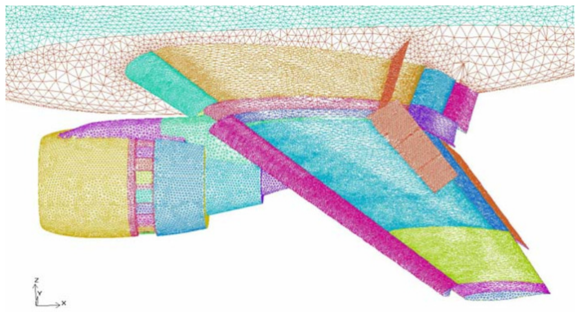

Figure 8 – Landing configuration with spoiler deflected

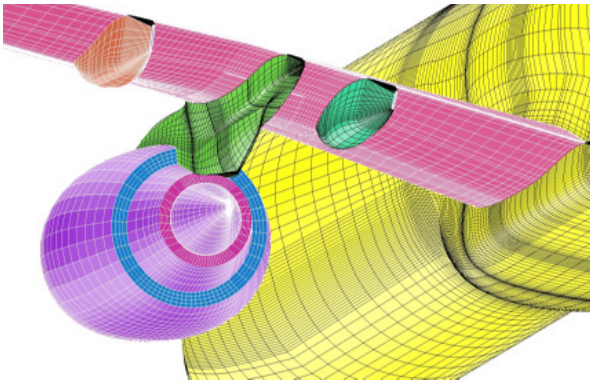

Figure 9 – Under-wing configuration with FTF

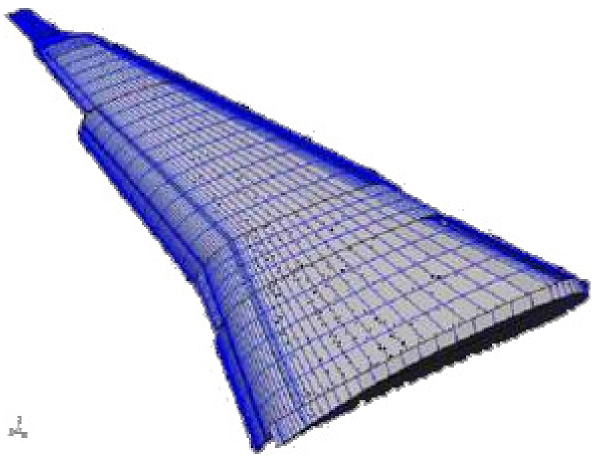

Figure 10 – Wing in takeoff configuration - superficial mesh

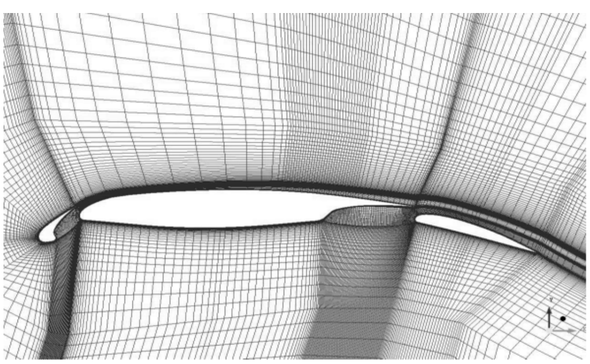

Figure 11 – High lift devices – 2D

The GMA concept is not limited to external aerodynamics applications. Following the same philosophy a set of isolated tools have been developed to attend specific needs of the systems groups.

An application of the GMA structured was developed in an specific environment named *Cool Electronics*. Starting from positioning of electronic equipment represented as boxes, as shown in Figure 12, the user set the parameters of the general unstructured mesh, which can be seen on Figures 13.

The environment has been extended to also set the parameters for FLUENT runs such that the user can conduct the analysis automatically based on an Excel spreadsheet input.

A similar application has been costumized for the analysis anti-ice systems. The D-bay of an aircraft wing/tail leading edge has been parametrized including the piccolo tube. The use can set up the geometric and mesh parameters and also set up a FLUENT case in order to obtain the surface temperatures and heat transfer coefficients for different sets of piccolo parameters (number and position of holes, diameters, etc). An example can seen in Figure 14.

Both tools have been included in optimization cycles allowing the user to perform several cases for a fraction of the time when compared to a more manual approach.

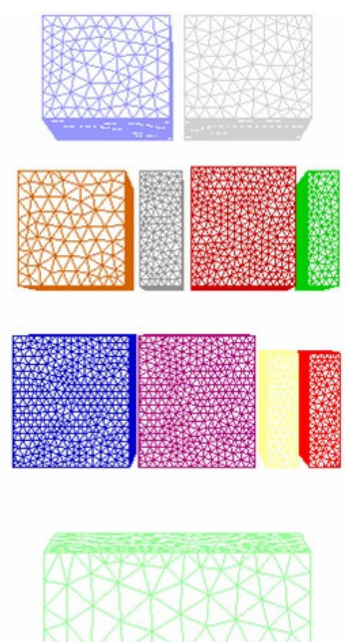

Figure 12 – Electronic Equipment represented as boxes in the *Cool Electronics* environment.

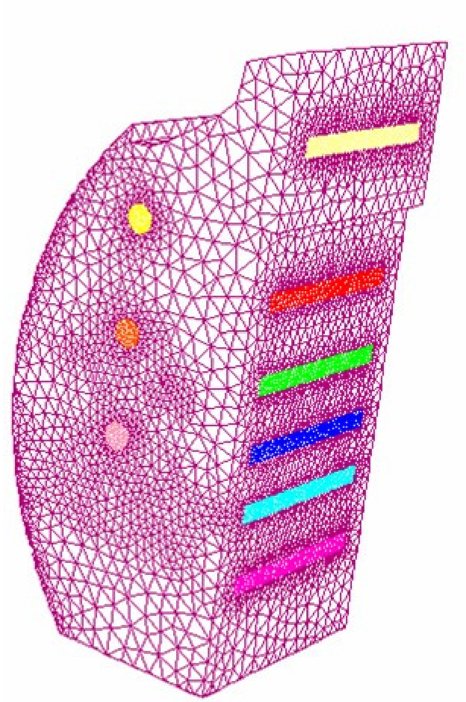

Figure 13 – Electronic rack mesh external view

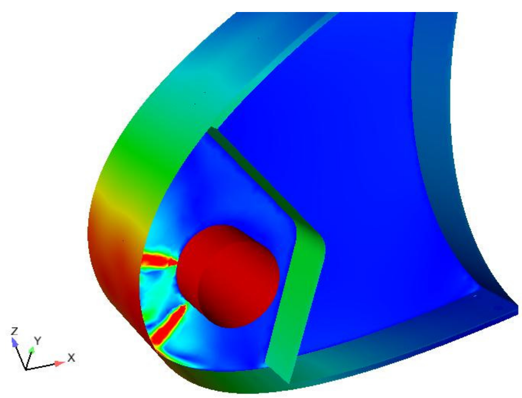

Figure 14 – D-bay temperature field obtained after the application of the GMA plus FLUENT set up analysis tool.

5 Conclusions

After application in a number of actual aerospace product development programs, the GMA methodology has shown the ability to drastically reduce the geometry and grid generation cycle, unifying and disseminating geometry and mesh knowledge through an organized database than can be made available to the entire organization. The result has been an actual reduction of the gaps between the several engineering design phases, as well as between the disciplinary areas involved in the product development process.

References

[1] Bentamy, A., Trépanier, J-Y, Guibault F., Wing Shape Optimization Using a Constrained NURBS Surface Geometrical Representation, *ICAS*, 2002.

[2] Samareh, J. A., Geometry Modeling and Grid Generation for Design and Optimization, ICASE/LaRC/NSF/ARO *Workshop on Computational Aerosciences* in the 21st Century, 1998.

[3] Samareh, J. A., Status and Future of Geometry Modeling and Grid Generation for Design and Optimization, Journal of Aircraft, Vol. 36, No. 1, 1999, pp. 97-104.

[4] He, B., Rohl, P. J., Irani, R. K., Thamboo, S. V., and Srivatsa, S. K., CAD and CAE Integration With Application to the Forging Shape Optimization of Turbine Disks, Paper 98-2032, AIAA, Apr. 1998.

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