PROPULSION AIRFRAME INTEGRATION DESIGN, ANALYSIS AND CHALLENGES GOING INTO THE 21ST CENTURY

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Abstract

Propulsion airframe integration design and analysis has many challenges as we move into the 21st century. Along with the conventional challenges of integrating a propulsion system on an aircraft, new technologies and new business drivers dictate innovative approaches to the design process be developed and applied.

On the technical side, new innovations in jet noise suppression and new aircraft concepts such as the Blended Wing Body (BWB) will give rise to many challenges in propulsion system performance, operability, and meeting system requirements such as thrust reverse capability. Aircraft engine and aircraft manufacturers must have the appropriate design and analysis tools in place which provide the ability to react quickly to inevitable design changes, driven by constantly changing requirements, during the product development cycle.

On the business side, the rapid globalization of the business dictates that the latest electronic technology be utilized to enable speed in communication with global customers as well as revenue sharing partners. More than ever, cost and schedules dictate the use of analytical methods to minimize the amount of qualification testing. Design and analysis software must be flexible and capable of integrating CAD/CAM and CAE tools while maintaining configuration control of the product.

The following paper describes some of the new technical challenges facing the industry. Innovative methods of addressing those challenges are described.

Introduction

Propulsion airframe integration presents unique challenges to the development of an aircraft system. Many of these challenges arise from the fact that the airframe integration issues involve major interfaces between aircraft and engine manufacturers. Good working relationships [1,2] between these two entities is essential for a successful business venture.

From the engine manufacturers point of view, each working relationship with each aircraft manufacturer is different. In fact, even with the same aircraft manufacturer, relationships for different applications can vary. Items which vary from program to program include which business entity has responsibility for various components, such as inlets, exhaust systems, thrust reverser, engine mount pylons, etc.

This significant variation in responsibility from program to program places a unique challenge to the installation aerodynamics organization of the aircraft engine manufacturer. The success of any manufacturing concern in the present highly competitive global market place dictates that standard processes be institutionalized to ensure speed in the product development cycle, while maintaining quality

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and high customer value. GE Aircraft Engines through its Six Sigma and e-business initiatives has put these standard processes in place, and is continuously improving each process.

Two key enabling technologies are required to meet the challenges ahead for the installation aerodynamics technology discipline; The use of high fidelity analytical tools, primarily CFD, and the use of rapidly developing information technology including tools that enable concurrent product development, Product Data Management (PDM), and product configuration control. CFD is well established today in the design community but productive, CFD based, design systems, which can be developed and maintained at a reasonable cost while producing high quality results, are not as prevalent. When these systems are put in place effectively, the rate at which design iterations can be evaluated, can quickly make the effort required to manage the data generated significant. Advanced information technology is required to maintain and document the design, analysis and evaluation process.

In this paper, we will examine the use and development of advanced analysis methods, using specific installation aerodynamics examples. We will then describe how these tools can be integrated, using advanced information technology, to address future propulsion airframe integration challenges, in a multidisciplinary design environment.

CFD Based Design Systems

CFD based design systems have been used effectively now for several years. Essential to a productive design system is an efficient method of geometry definition. For commercial installations, GE aircraft engines has developed a

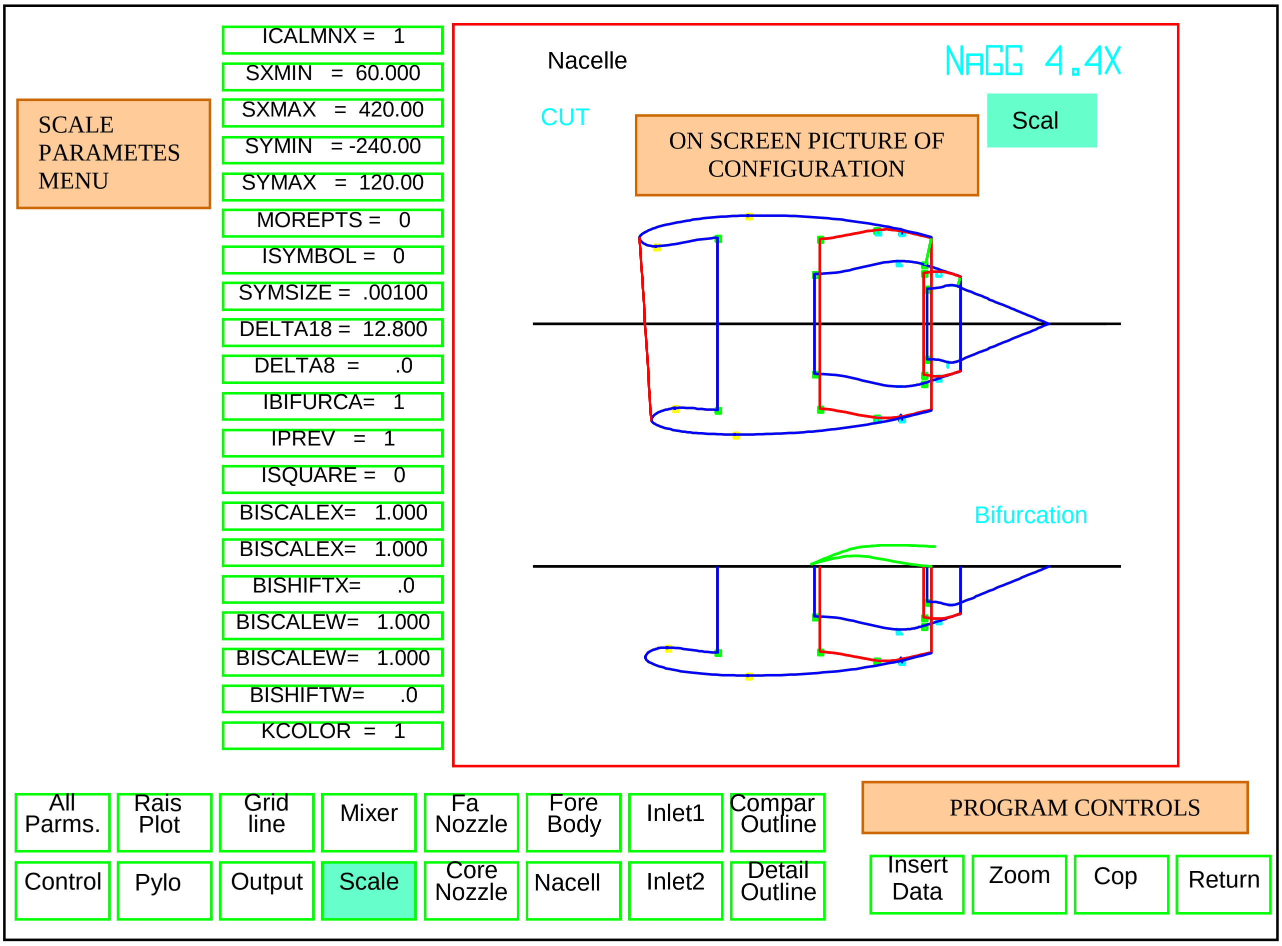

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Figure 1. Nacelle geometry generation tool user's view.

nacelle geometry generation package (Figure 1) that can rapidly generate nacelle flow lines. Virtually every component of the entire three-dimensional geometry can be generated using a set of standardized parameters. This includes the inlet, from the fan face through the highlight and outer flow path, the nacelle external geometry including consideration for the thrust reverser and nacelle internal components and accessories, the fan duct, fan nozzle, core cowl, aft center body and duct bifurcation's.

All of the above flow lines are generated using established geometric curve design practices and take into account lessons learned from previous designs. Also built into this package are design rules which, based on the geometric and historical data, calculate initial weight, loss and inlet capability estimates.

Once the flow lines have been generated, they are transferred as input to individual component CFD analysis tools tailored to that particular component. An example of one these component tailored tools is illustrated in figure 2, which is used for the aerodynamic analysis of isolated nacelles [3]. The plot shows predicted static pressure distributions, (plotted as ideal Mach number), compared with experimental data. Excellent agreement of this type can be obtained on a routine basis using these types of tailored tools.

This tool, in conjunction with the nacelle geometry package, is used extensively to rapidly screen nacelle inlet design concepts and evaluate design changes encountered during the product development cycle. The tool can also be used to rapidly evaluate operating condition changes to existing products such as an increased thrust rating for an existing engine or using a common nacelle on a new derivative engine.

Output from this particular component analysis are used to evaluate, nacelle aerodynamic loads, inlet recovery and drag for engine and aircraft performance, high angle of attack and cross-wind capability, and inlet distortion to aid in the evaluation of engine operability characteristics.

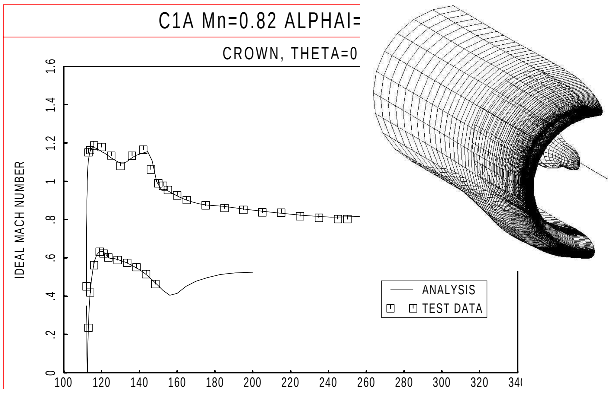

Figure 2. Isolated nacelle analysis CFD based design system results compared with test data.

Exercising these design tools very early on in the preliminary design phase of an aircraft system program, enables a high degree of confidence in predicted quantities over a wide range of operating conditions. By evaluating a range of operating conditions which includes possible requirement changes during the aircraft system development, as well as potential growth applications, flow paths can be set extremely early in product development. This allows for early evaluation by other downstream functions to minimize the throughput cycle.

Of course CFD has not totally replaced the need for component testing. It has significantly reduced the time required to optimize a design in relative terms, often to the extent that only one configuration is required to be tested to determine the absolute value of key performance parameters.

The use of the tailored design system can be very productive but there are drawbacks. Maintenance of the system, to add new features and functionality, can be expensive. Furthermore, analysis of designs not originally created within the system can be difficult if not impossible.

Integrated Design Systems

The tailored design system described works extremely well for conventional configurations. New design innovations however may not lend themselves to the established design rules in an existing system. Advanced methods must be used which can evaluate new design concepts efficiently. The following is a specific example of how these advanced methods can be used on unconventional design challenges.

For many applications currently under development, innovative concepts to reduce jet noise are under investigation. Most prominent among these concepts is the use of chevron exhaust nozzles [4] (Figure 3).

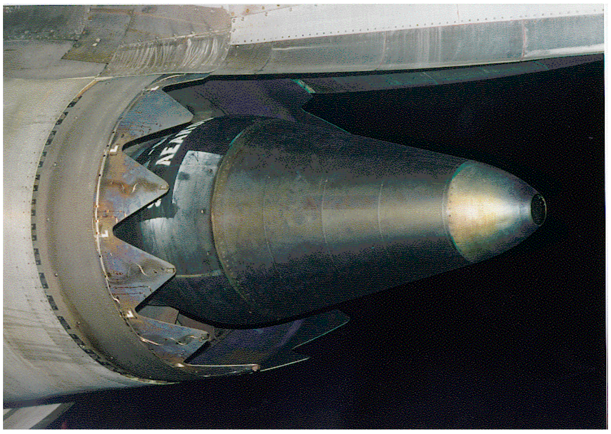

Figure 3. Chevron core exhaust nozzle

These nozzles have been demonstrated to decrease jet noise effective perceived noise levels while having little impact on thrust performance. Reduced noise is essentially achieved by changing jet plume mixing rates to move the noise generated to frequency ranges that are less annoying to the human ear.

There are two major markets for chevron exhaust nozzle technology, retrofit of current engines in the fleet, and as an offering to new applications. From an aircraft integration point of view, the chevron nozzle could impact the mounting aft pylon, jet plume impingement characteristics on flaps, landing gear doors and in extreme cases, the aircraft tail structure, and the extent of exhaust hazard zones for ground operations.

The challenge is to have tools in place to rapidly evaluate these designs not only from the engine acoustic and performance perspective but also in terms of aircraft integration. A large historical database exists for conventional planer exit exhaust systems. From this database, well-established analysis techniques have been developed to quickly predict aircraft integration impacts. These methods are often not applicable to chevron exhaust nozzle designs and more advanced methods including high fidelity CFD must be used.

As with the well-established component design methods, the new productive design methods start with flexible geometry definition. Of course geometry is the basis of most downstream engineering functions once the aerodynamic flow path has been set. High-end CAD systems now have the capability to define 3D geometry using engineering based parameters. These parameters can be driven by engineering design rules. The electronic model can be viewed differently depending on the engineering function, e.g. aerodynamic or mechanical design. Electronic CAD models that utilize these advanced features are referred to as master models.

Figure 4 shows the aerodynamic representation of a parametric master model used to generate chevron nozzle geometry. The three

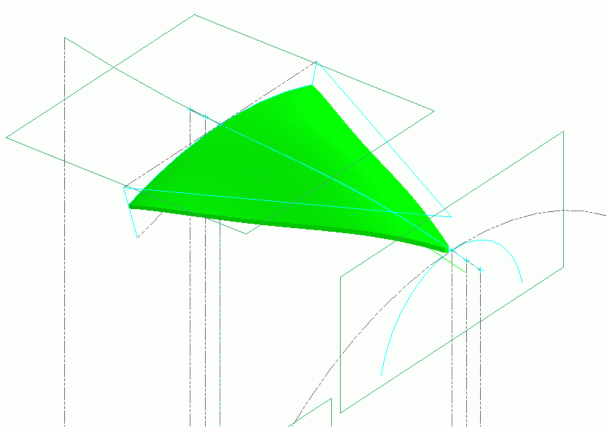

Figure 4. Aerodynamic representation of chevron paramtric master model.

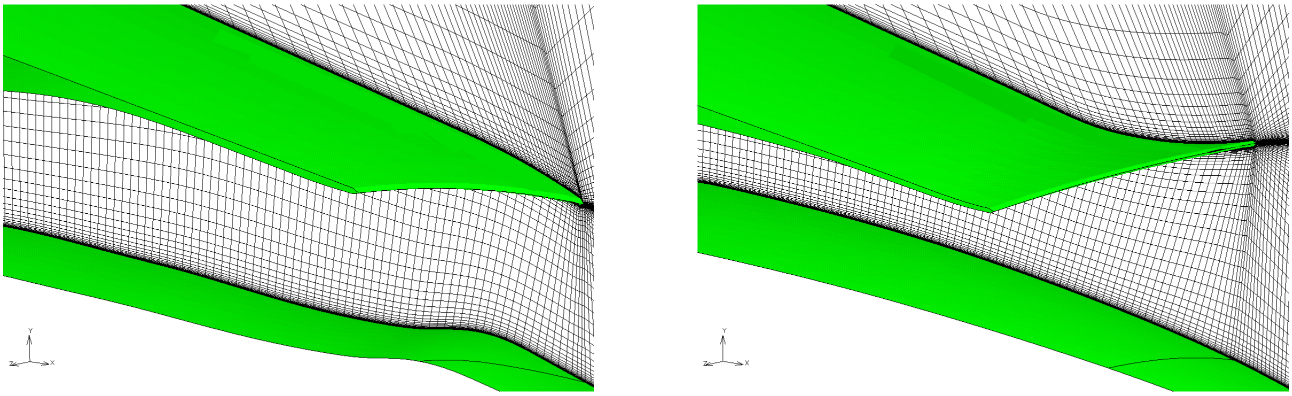

Figure 5. CFD computational grids, of chevron nozzle periodic sectors, generated using automated re-playable method driven by CAD parametric master model.

dimensional representation of the nozzle can quickly be generated using knowledge based [5] parameters. These parameters can describe geometric features and functions that are based on rules which capture the methodology used for aerodynamic design and analysis, mechanical stress, and manufacturing process development.

This master model can then be used by multiple downstream functions ensuring interdisciplinary commonality. From the installation aerodynamics point of view, this function is primarily CFD for aerodynamic performance evaluation, and preliminary screening of acoustic performance. Essential to the CFD analysis process is the generation of a high quality computational grid. Consideration must be given to the type of grid to be used depending on the intent of the prediction. For this particular application a blocked structured grid (Figure 5) is used for a higher degree of confidence in the turbulent mixing prediction capabilities.

Accurate geometric representation is important to ensure quality results. Fortunately, developers of commercially available software, applicable to different parts of the design cycle, are cognizant of the need for common geometric representation. Some suppliers of this type of software have even collaborated to develop essentially direct interfaces between their products through Application Programming Interfaces (APIs). This capability allows direct transfer of CAD generated geometry into the grid generation software, ensuring geometric integrity.

Depending on the level of integration between the products, functional parameter values used in the downstream function can actually be assigned in the CAD system. For a CFD application this includes grid density and spacing parameters, surface boundary specification etc. This offers a tremendous advantage in productivity during the design iteration process. If the design change is such that the grid block structure topology does not change, a new computational grid can be generated in a matter of minutes.

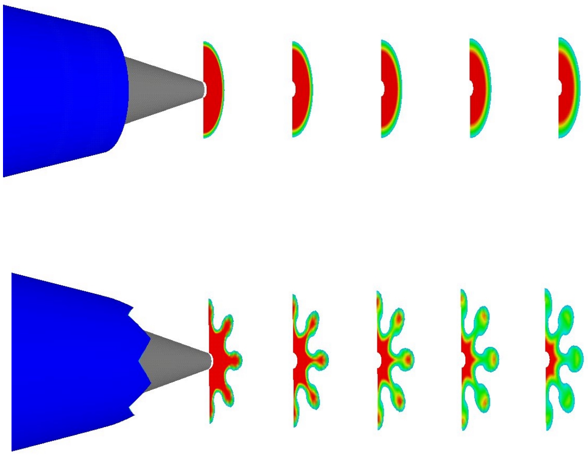

Figure 6. CFD prediction of conventional planer exit and chevron exhaust nozzles

The two grids shown in figure 5 were generated using this technique. This type of model and system can be used effectively to conduct Design of Experiments (DOEs) analytical studies. This allows for a rapid understanding of the design space in terms of performance and acoustic trades for a particular application. Figure 6 shows CFD predicted temperature contours and plume mixing characteristics from such a study.

Installed Analysis

The installed engine flow field analysis for propulsion airframe integration analysis is inherently more challenging than the isolated component analysis. The use of block structured grid techniques to solve this problem can be very time consuming to the point that CFD analysis can not readily impact the design cycle. Chimera grid techniques have been used in this application with only moderate improvement in design iteration time.

Unstructured grid generation tools, using primarily tetrahedral cells instead of hexahedrons, and their accompanying solvers, have been developed to the point that once geometry is provided in the required format, they can be used productively in a design environment. In the past, the specification of this geometry was ad hoc and could not respond quickly to the significant geometric changes. The key to productive use of any of these techniques is the use of standardized underlying geometry, e.g. a parasolid. This geometry representation is used by many of the commercially available CAD, CAE, and CFD software suppliers.

For installed predictions, the isolated components of the fuselage, wing, and nacelle are assembled within the CAD system. The individual components, and their relative positions, can be defined parametrically. The parametric representation allows for rapid changes. Once the configuration is set, a parasolid of the fluid is created. This parasolid is then imported into the grid generation package.

If viscous effects are important to the prediction, some packages now have the ability to inflate a prismatic grid from the solid surface. This technique offers greater accuracy and more economical use of grid than the use of tetrahedral cells in the boundary layer. Figure 7 shows a prismatic layer, inflated from the surface, beneath the tetrahedron cell volume.

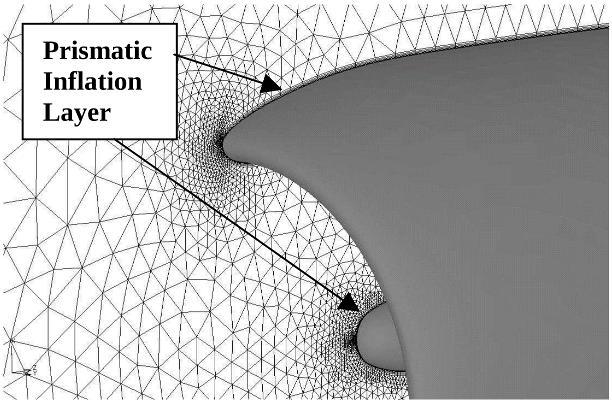

Figure 7. Inflated prismatic grid beneath tetrahedron volume grid for accurate prediction of viscous effects on a nacelle inlet.

In addition to providing grid that can accurately predict viscous effects, the unstructured grid must conform and add grid density to geometric regions with discontinuities and high curvature. Some of these solvers have adaptive capabilities to cluster the grid not only to resolve geometric features, but flow field features as illustrated in figure 8. The ability to adapt the unstructured grid to local flow field

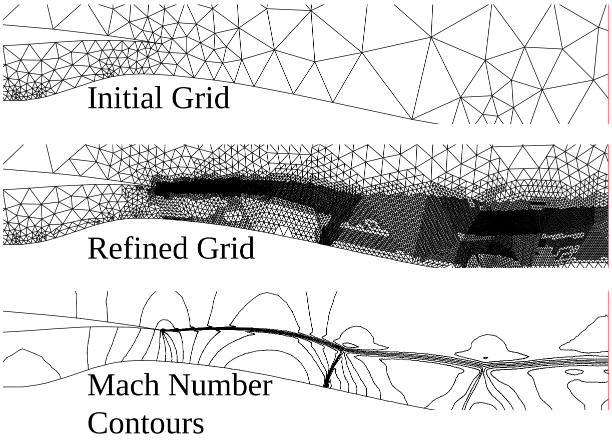

Figure 8. Automatic local grid refinement used to accurately resolve flow field features.

gradients is important in that the unstructured grid solvers inherently use more computer resources for a given number of computational cells. In order to take advantage of the productivity increases, which automatic grid generation of unstructured codes offer, automatic grid flow field adaptation is essential.

For the installed propulsion system problem today, these unstructured grid techniques are used extensively to evaluate qualitative flow field effects. Qualitative insight into the complex installed flow field can have dramatic impact on the installation. Often quantitative deltas between two designs can be determined. Figure 9 shows a typical result for a fuselage engine mounted application. As computer capability and software robustness improves, and appropriate validation of these methods is performed, detailed quantitative predictions will become possible.

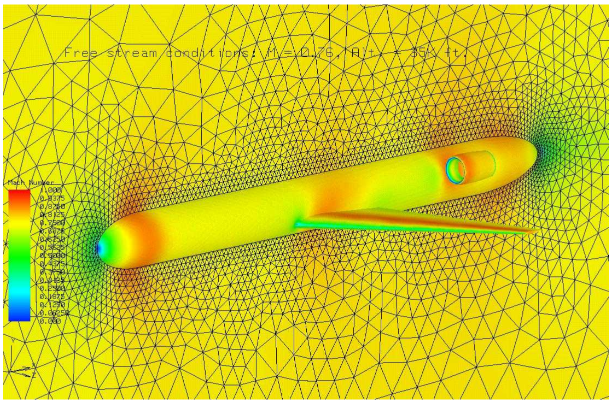

Figure 9. Unstructured flow field analysis of fuselage mounted installation.

Design Challenges

The commercial airline industry is growing rapidly in terms of the current fleet's passenger and freight usage, as well as in new product development. Stricter noise and emissions regulations are requiring engine modifications or replacements. At the same time new aircraft are being developed requiring new engine applications.

The turbofan engine has established a stronghold in the regional market through the Bombardier CRJ. New entries by Fairchild-Dornier and Embraer are also being offered. These applications represent the first time that relatively high bypass turbofans are being used in this thrust class and size of aircraft. In the latter two applications, wing mounted installations are being employed.

On the other end of the spectrum, the development of the Airbus A3XX and the Boeing 777-200/300 will offer unprecedented entries in the long-range market. The diverseness of the marketplace, the establishment of the true global economy, and the complex business relationships of these new business ventures, present significant challenges to develop high quality designs in a competitive, productive environment. High quality design tools and standardized processes to apply these tools are required to meet these challenges.

In the future, the challenge of analyzing advanced designs will dictate the use of advanced techniques for quantitative analysis. Several unconventional concepts are being examined to achieve greater capacity and improved performance [6]. Concepts like the BWB configuration (Figure 10) where engine inlets and airframe are closely coupled, will make it very difficult to analyze components isolated from one another.

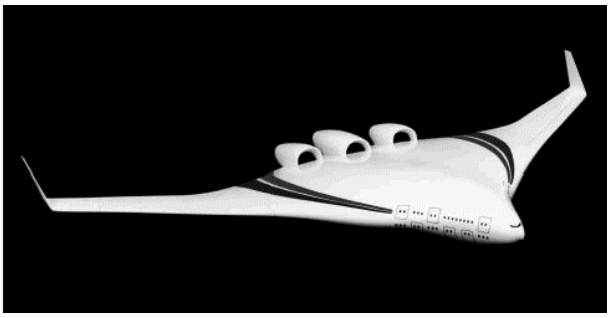

Figure 10. Blended Wing Body concept, with highly integrated, “buried”, engine inlets [6]. Published with Permission

The highly integrated inlet and airframe of such concepts could have significant impact on the propulsion system characteristics including engine operability and thrust reverse operation.

In order to reduce the drag of pylons which classically offset the engine nacelle from the aircraft surface flow path, concepts like the BWB will allow the boundary layer developed forward of the engine face to be ingested by the inlet. This could impact not only engine performance, but the total pressure distortion seen by the engine fan, could be detrimental to its operating characteristics.

Innovative flow control mechanisms like micro-blowing and synthetic jets will undoubtedly need to be developed to minimize or eliminate these potential adverse effects. These devices have been shown in laboratory type environments to control boundary layer thickness and reduce the tendency for separation.

The flow field phenomena produced by these devices are of a scale and complexity such that they are not typically considered in the present mainstream, design and analysis environment. They typically involve geometric features that are of much smaller scale than the characteristic dimensions typical of propulsion airframe integration predictions. They also often utilize unsteady flow phenomena at very high frequencies. Again, characteristics not routinely considered.

Techniques must be developed to simulate these devices in a design environment. It is possible that the flow characteristics they produce could be simulated through the use of innovative surface boundary conditions in CFD or other conventional methods. If not, other more innovative techniques will need to be developed, up to and including direct simulation. As computer capabilities increase, this may be possible but this capability will not be available in the near future at least in a production design environment.

Engine thrust reverse capability, if required on highly integrated concepts, needs to be carefully examined. Over the decades, large commercial aircraft have come to rely on engine reverse thrust for braking on landing. Indeed, in inclement weather, reverse thrust can be essential for safe operation.

Significant practical experience has been developed to design and evaluate thrust reverse capability on conventional aircraft. There are several significant factors which must be considered in thrust reverse operation. From the engine stand point, turbo-machinery operability is of key concern. This involves the ability to create reverse flow splay patterns from the engine fan stream which provide minimal pressure distortion impact on the fan.

Hot gas re-ingestion must also be considered for engine operability. This involves ensuring that while in reverse thrust operation, interactions between the reverse flow stream, aircraft flow field, and ground plane impingement, doesn't cause hot gases to be re-ingested into the engine inlet.

From the aircraft point of view, reverse stream fuselage impingement and aircraft control must be considered. This includes aircraft attitude stability and control as well ensuring that the reverse thrust flow field does not negate aircraft drag also needed for braking purposes.

Of course the engine and aircraft considerations are highly integrated. Designs with high degrees of propulsion airframe integration, will require significant development of both analytical and experimental methods, for accurate predictions.

Multidisciplinary Design Integration

In order to develop advanced designs in the future, in the product development cycle time that the industry demands, multidisciplinary design integration systems must be utilized. These systems must integrate not only the sub-functional disciplines of aerodynamic design and analysis as described in this paper but other major functional disciplines. These include product definition, mechanical stress and life analysis, and manufacturing process development.

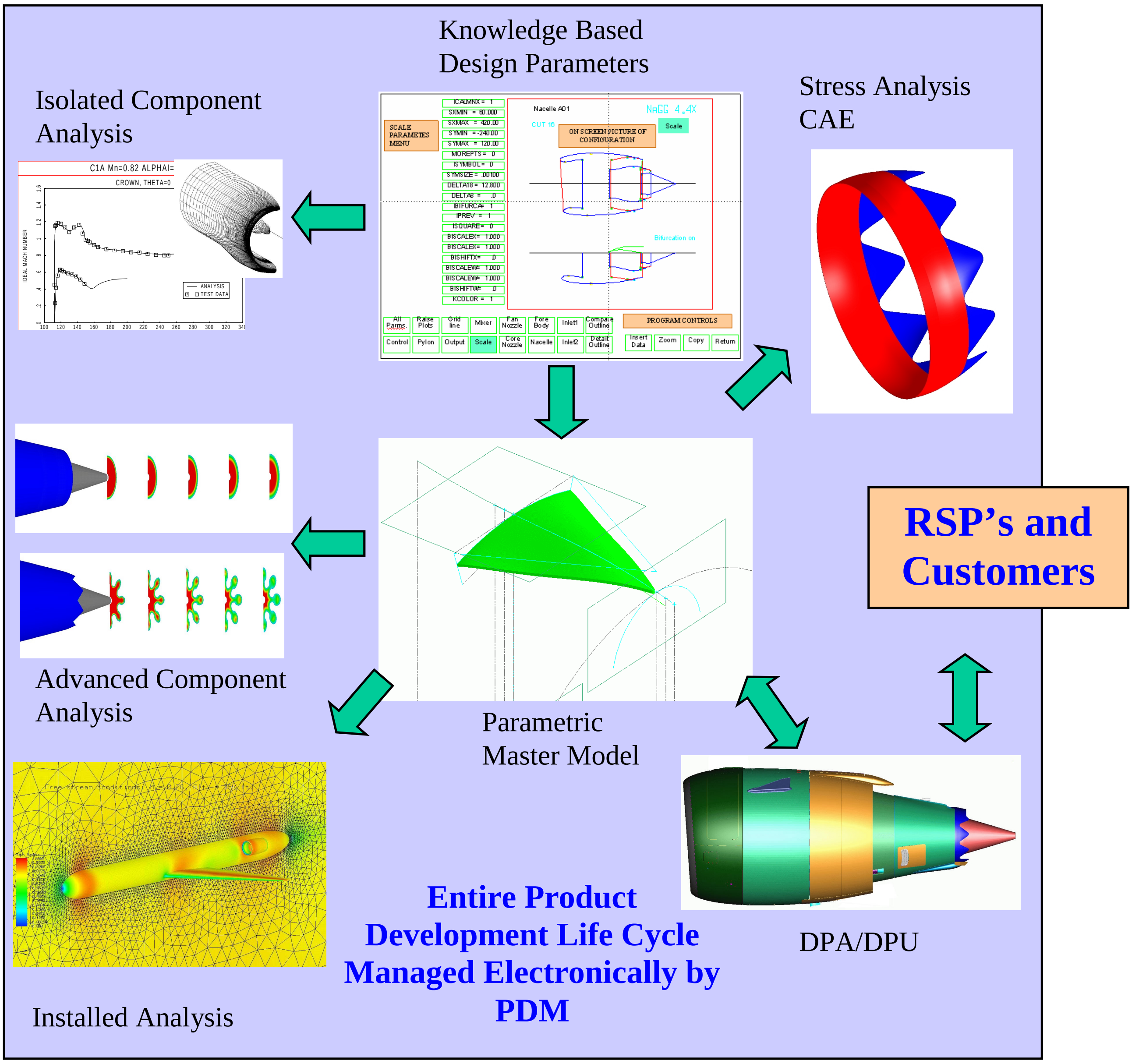

Figure 11. Schematic description of a linked model, multidisciplinary design environment

Each of these functions have developed productive design systems which are essentially stand alone in the sense that geometry is often generated, analyzed, changed, and re-analyzed within the particular disciplines own environment. Once the design has been developed to a point that the specific discipline's requirements are met, the results are passed on to other functions performing design and analysis of their own. Often the results indicate that the designs are in conflict and major, often expensive, design changes must be made.

As stated in the introduction, this interaction process can be more difficult for propulsion airframe integration development since, in addition to multiple disciplines, multiple companies are involved.

Most companies are developing electronically based, concurrent product development systems. Advanced information technology has made it possible to develop product data management systems in which engineering analysis software can be encapsulated within the PDM.

Many of these systems are being developed by CAD software providers and indeed are often fully integrated with the CAD system. This is fortunate since many engineering functions, including propulsion system development, are utilizing CAD based development tools. These systems are based on relational databases. If Revenue Sharing Partners (RSPs) and customers are also using a similar based product, data may be transferred electronically and remain under configuration control.

The PDM provides a means of providing revision control to the multitudes of design iterations, which are made possible by ever increasing computer speed and information technology. This is important not just from a particular discipline's point of view, but to ensure all functions are using the proper revision of other disciplines in which their effort is dependent.

The other major advantage of the PDM is that it enables the use of the exact same data. Storing all data in a central location accomplishes this. All disciplines using that data access it from the central location, not from a copy stored at their local workstation. This in combination with revision control ensures that all disciplines have access to the latest revision of all data immediately upon its release. Analysis models are electronically linked to this geometry and can be updated automatically to reflect the latest revision. A schematic of this linked model environment is shown in figure 11. Most PDMs are being developed using web technology. This allows for rapid notification of effected disciplines when a new design revision has been released.

In the schematic shown, all of the functions described earlier, plus other discipline functions, are driven from a common master model, developed from knowledge based parameters. All of the functions are encapsulated with in the PDM, as symbolized by the large blue rectangle. This ensures all functions are using the same geometry, and revision control is maintained.

One of the functions shown is the Digital Pre Assembly / Digital Mock Up (DPA/DMU). The DPA/DMU is now an integral part of the interfaces between a particular manufacturer and their RSP's and customers. Through the use of translators, common geometry can be maintained with these entities as well. If these entities are also using PDM technology, revision control can be maintained across companies.

Conclusions

This paper has discussed just some of the challenges being faced in the area of propulsion airframe integration today. These challenges will only become greater as highly integrated designs evolve, and global business relationships continue to increase.

Some of the tools required to meet these challenges have been discussed. Advanced computer technology is well established, but advanced CAD and information technology is truly revolutionizing the way design and analysis can be utilized in the present, and on the challenges to be faced in the future. It is essential that all these technologies be integrated in a controlled environment, so that we can remain successful, as we head into the 21st century, and the second century of powered flight.

References

[1] Berry, Dennis L. Engine/Aircraft Integration Aerodynamic Design – Boeing 777 & Beyond. The Boeing Company, Published by AIAA, Inc., with permission, 1997.

[2] Tiegarden, Fred W., GE90 Integration with the B777 – A Success Story, Royal Aeronautical Society Paper, RAes Conference, Nottingham England, October, 1992.

[3] Uenishi, K., Pearson, M.S., Lehnig, T.R., Leon, R.M. CFD-Based 3D Turbofan Nacelle Design System.

AIAA 8th Applied Aerodynamics Conference, Portland, OR, AIAA-90-3081, 1990.

[4] Norris G. Aircraft & The Environment, Silence Please, Flight Internationl, 20-26 October, 1999.

[5] Bailey, Michael W. Integrated Multidisciplinary Design, XIV ISABE Conference, Florence Italy, September, 1999.

[6] Yaros, Steven F., McKinley, Robert E. Jr., et. al. Synergistic Airframe-Propulsion Interactions and Integrations, NASA/TM-1998-207644, March, 1998.