AIAA JOURNAL
Vol. 43, No. 9, September 2005

Multidisciplinary Design Optimization of Aircraft Combustor Structure: An Industry Application

Yuexi Xiong,* Mike Moscinski,† Mark Frontera,‡ and Su Yin†
General Electric Global Research Center, Niskayuna, New York 12309
and
Mehmet Dede§ and Mike Paradis¶
General Electric Aircraft Engines, Evendale, Ohio 45215

A real design case of an aircraft engine combustor is presented. The design requirements are practical constraints involving thermal, mechanical, and lifing areas. Design optimization of the full combustor structure has been carried out in the federated intelligent product environment. Several enabling technologies have been developed and used, including intelligent master modeling, automated mesh generation, and linked model environment for thermal/mechanical analyses. Whereas the main objective of the project was to introduce the advanced multidisciplinary design analysis/multidisciplinary design optimization technologies to business product development programs, the output of the work served as a design improvement for future modifications.

Introduction

THE current economic climate compels aircraft engine manufacturers constantly to reduce the time-to-market, lower the life cycle costs, and improve the quality and reliability to excel in the competitive global marketplace. Design engineers are facing great challenges to develop robust and optimal engineering systems and processes to meet aggressive design requirements with reduced design cycle time and increased analysis accuracy. To address these challenges, a research program has been underway at General Electric (GE) Global Research Center to develop advanced design technologies and tools (ADTT) in collaboration with GE Aircraft Engines (GEAE) and GE Power Systems. The ADTT program deals with important design aspects of aircraft engines and power generation systems from conceptual design, system layout, and preliminary design to detailed component level design and analysis covering geometry modeling, grid/mesh generation, aerocomputational fluid dynamics (aeroCFD), heat transfer, thermal, mechanical, and life prediction.[1–5]

The design of an aircraft engine combustor is a truly multidisciplinary process involving aeroCFD, combustion, heat transfer computational fluid dynamics (CFD), dynamics, thermal, mechanical, and life prediction.[6,7] One of the focuses of the ADTT program is to develop advanced combustor design analysis technologies with an objective to meet aggressive new product introduction (NPI) analysis requirements. In this work, a multidisciplinary design optimization (MDO) has been conducted for an aircraft engine combustor structure. The objectives of the work were twofold. One was to develop standard procedures for design optimization of complex turbomachinery systems in the federated intelligent product environment (FIPER). The other was to obtain an optimum design of a real combustor structure that would meet practical but conflicting design constraints and serve as a design improvement for future modifications.

Several enabling technologies have been developed and applied including intelligent master model (IMM), automated mesh generation, and linked model environment (LME) for thermal/mechanical analyses. These technologies made the design optimization of a full combustor structure possible.

IMM is the fusion of knowledge-based engineering (KBE) with top-down product control structure (PCS), conventional master model, and the LME. The combustor geometry master model was generated based on data from UNIGRAPHICS®[8] (UG) iMAN that captured the requisite information, both geometry and nongeometry. After necessary defeaturing in the master model, a context model was generated through UG WAVE and parameterized for key design variables in which tag names were assigned as the attributes to help apply appropriate boundary conditions and construct meshes. Mesh generation plays a critical role in an integrated design process. In this paper, automated meshing strategies using ICEMCFD HEXA® were developed, and high-quality all hexagonal meshes were generated. Based on the parametric geometry model and automated meshing procedures, an LME has been established that provided automated procedures for CFD data mapping, thermal model generation, and mechanical analyses. An in-house developed code was used to predict the low-cycle fatigue (LCF) life of the combustor. The analysis procedures in each discipline were wrapped up as a FIPER, service and an optimization scheme was developed in FIPER. Detailed information about the procedures and the final optimization results are presented in the following sections.

Statement of Problem

The design of combustor structures of aircraft engines in service is constantly being improved for better efficiency and performance. An annular combustor is usually considered as a cyclic symmetric structure, and therefore, only a sector model needs to be worked on for the purpose of design and analysis, as shown in Fig. 1.

The combustor consists of three main components: inner liner, outer liner, and dome assembly. Each component contains a few subcomponents such as nuggets, dilution hole panels, multihole panels, flanges, and supports for the two liners. One of the important subcomponents is the support of the two liners, as shown in Fig. 2, that must be appropriately designed to meet the mission requirements.

The problem under consideration was to achieve an optimal geometry configuration of the inner-liner and outer-liner supports that would keep the total combustor weight to the minimum while satisfying performance constraints on the vibration frequency and life

Received 16 January 2004; presented as Paper 2004-4422 at the AIAA Multidisciplinary Design Optimization Conference, Albany, NY, 30 August–1 September 2004; revision received 25 January 2005; accepted for publication 4 March 2005.

*Senior Design Engineer, Lifting Technology Laboratory, One Research Circle. Senior Member AIAA.
†Mechanical Engineer, Device Synthesis Laboratory, One Research Circle.
‡Mechanical Engineer, High Energy Physics Laboratory, One Research Circle.
§Manager, Design Analysis Methods Section, One Neumann Way.
¶Six Sigma Black Belt, MBB Reliability, One Neumann Way.

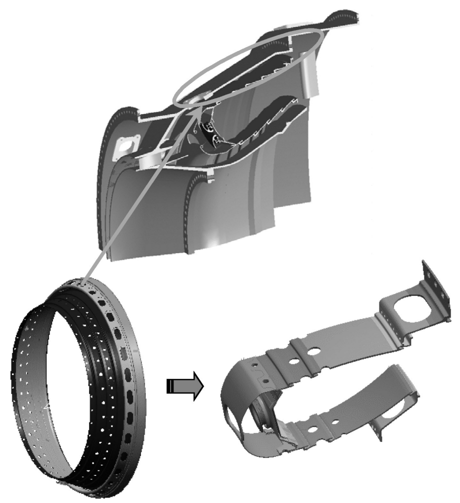

Fig. 1 Annular combustor structure.

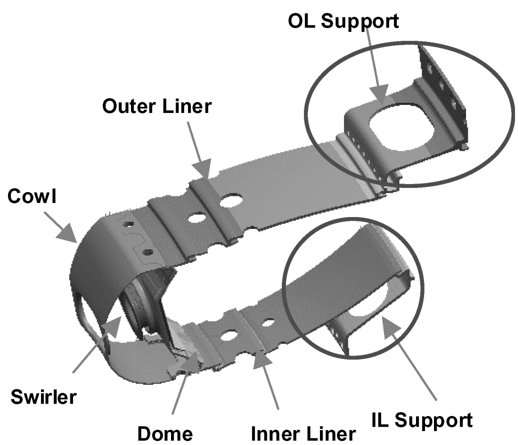

Fig. 2 Combustor sector mode.

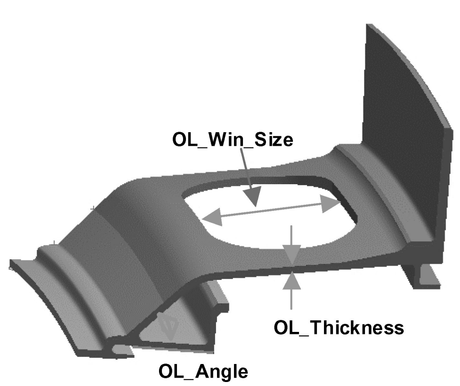

Fig. 3 OL support design parameters.

cycles. A total of five geometry parameters, three for outer liner and two for inner liner, were determined to be the design variables. As shown in Fig. 3 for the outer-liner support, the three design variables were panel thickness, support angle, and window size. Whereas for the inner-liner support, two design variables were chosen, which were panel thickness and window size. The mechanical performance constraints dictated that both frequency and LCF life be above respective specification limits to satisfy operational and safety requirements under typical mission conditions. In addition, all of the design variables had certain geometric constraints based on manufacturing limitations.

The mathematical formulation of the present design problem is to minimize

$$\boldsymbol{W}(\boldsymbol{t}_{\mathrm{ol}}, \boldsymbol{A}_{\mathrm{ol}}, \boldsymbol{H}_{\mathrm{ol}}, \boldsymbol{t}_{\mathrm{il}}, \boldsymbol{H}_{\mathrm{il}})$$

subject to

$$\boldsymbol{\omega}(\boldsymbol{t}_{\mathrm{ol}}, \boldsymbol{A}_{\mathrm{ol}}, \boldsymbol{H}_{\mathrm{ol}}, \boldsymbol{t}_{\mathrm{il}}, \boldsymbol{H}_{\mathrm{il}}) \geq \varpi$$

$$\boldsymbol{L}(\boldsymbol{t}_{\mathrm{ol}}, \boldsymbol{A}_{\mathrm{ol}}, \boldsymbol{H}_{\mathrm{ol}}, \boldsymbol{t}_{\mathrm{il}}, \boldsymbol{H}_{\mathrm{il}}) \geq \boldsymbol{L}$$

$$(\boldsymbol{t}_{\mathrm{ol}})_{\min} \leq \boldsymbol{t}_{\mathrm{ol}} \leq (\boldsymbol{t}_{\mathrm{ol}})_{\max}$$

$$(\boldsymbol{A}_{\mathrm{ol}})_{\min} \leq \boldsymbol{A}_{\mathrm{ol}} \leq (\boldsymbol{A}_{\mathrm{ol}})_{\max}$$

$$(\boldsymbol{H}_{\mathrm{ol}})_{\min} \leq \boldsymbol{H}_{\mathrm{ol}} \leq (\boldsymbol{H}_{\mathrm{ol}})_{\max}$$

$$(\boldsymbol{t}_{\mathrm{il}})_{\min} \leq \boldsymbol{t}_{\mathrm{il}} \leq (\boldsymbol{t}_{\mathrm{il}})_{\max}$$

$$(\boldsymbol{H}_{\mathrm{il}})_{\min} \leq \boldsymbol{H}_{\mathrm{il}} \leq (\boldsymbol{H}_{\mathrm{il}})_{\max}$$

where $\boldsymbol{W}$ is the combustor weight function, $\boldsymbol{\omega}$ is the vibration frequency with a lower specification limit ϖ, $\boldsymbol{L}$ is the LCF life with a lower specification limit $\boldsymbol{L}_s$, and the design variables are $\boldsymbol{t}$ panel thickness, $\boldsymbol{A}$ angle, and $\boldsymbol{H}$ window size.

Master/Context Geometry Models and LME

A master model[2] captures the requisite information, both geometric and nongeometric, to enable context-specific views of necessary design, manufacturing, test, and service data. Development of a production design system that supports early requirement definition and flowdown requires that the underlying representation be flexible to geometry, attribute, feature, and knowledge-based changes. The master model concept enables design collaboration and easy access to the latest design update. The IMM is a major enhancement to the master model approach, elevating the functionality of traditional CAD systems to a new level by adding PCS, product assembly (PA), LME, and KBE.[8]

The combustor assembly represents a master model that serves a variety of functions for different purposes such as manufacturing drawings, weight and cost estimates, and assembly. The PCS and PA provide high-level framework and facilitate the assembly of the combustor using top-down and bottom-up modeling strategies that enable control over the positioning of critical interfaces while retaining necessary detail in the three-dimensional components to represent actual hardware. A critical function of the combustor master model is the basis for a single, consistent definition of the combustor for detailed analysis to mode l aerodynamics, combustion, heat transfer, stress and vibration. Each of the different functions of the master model requires a different view of the master model that is considered a context model. Each context model consists of a linked copy of the master model and all of the additional geometry operations required for a particular context. Because the context model is a linked copy of the master model, which is in turn linked to the PA and PCS, all geometry updates made to the PCS and PA will automatically flow down to the context model.

The LME provides a means to transfer seamlessly associative CAD information to analysis packages such as pThermal[9] and ANSYS[10] for heat transfer and mechanical analyses, respectively. The key to the LME is the attributes that identify geometric entities to which analysis information can be associated. These attributes are implemented as tag names on the CAD edges, surfaces, and solids. The relationship between the attributes and the geometry is published in the mesh generator and analysis codes so that analysis data such as boundary conditions and material properties can be associated with the tagged CAD entities and mesh entities as well. In this way, model development can be automated using scripts by associating analysis data, CAD entities, and mesh entities through the attributes. When the underlying geometry is updated from the PCS and PA, the context model and analysis model can be automatically updated. This LME capability is essential to enabling optimization and probabilistic design of complicated structures.

Shown in Fig. 4 is a combustor master-context model architecture for the purpose of heat transfer and mechanical analyses. The CAD package UG[8] was used for all geometry modeling. Following this architecture, the geometry context model used in the present design was generated, as shown in Fig. 2.

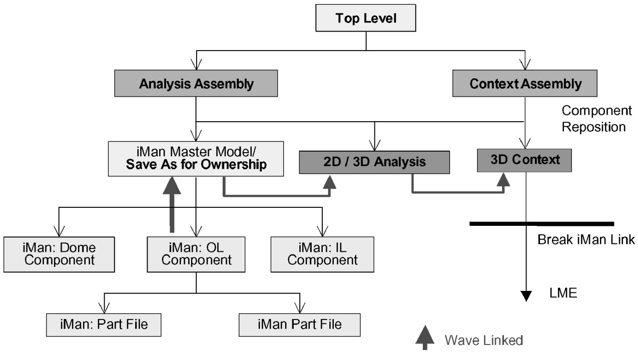

Fig. 4 UG file structure.

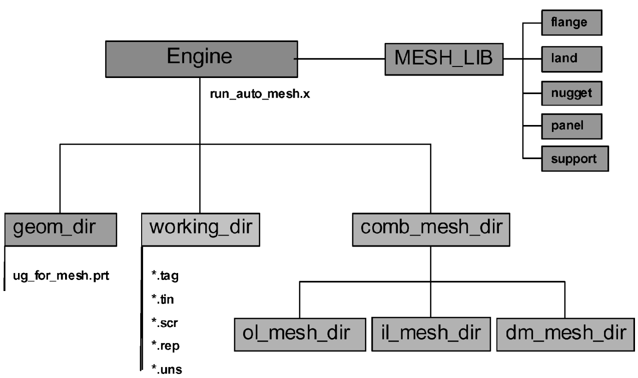

Fig. 5 Meshing file structure.

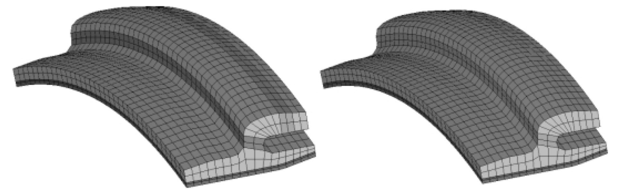

Fig. 6 OL nugget meshes.

Fig. 7 Full combustor mesh.

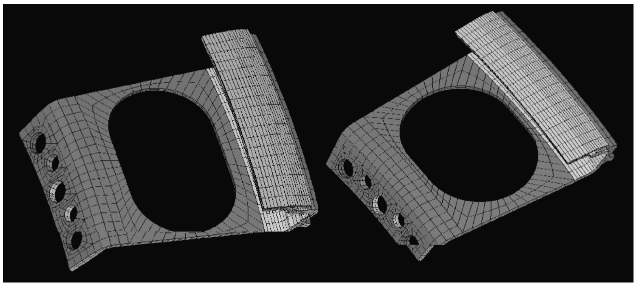

Fig. 8 Mesh update as IL_SUP window changes.

Automated Mesh Generation

Once the parametric geometry model is developed, the next step is to generate the mesh. Mesh generation plays a critical role in the automated design process. Not only does the mesh quality have a significant effect on the analysis accuracy, but the meshing procedures also must be replayable, without human intervention. Meshing strategies that are the procedures in mesh generation need to be developed to generate high-quality meshes in an automatic fashion. In this work, an all-hexahedron mesh was required for the full combustor sector model to ensure the analysis accuracy. To this end, the commercial package ICEMCFD[11] was used as the mesh generator because its program HEXA offers unique features with the required capability and flexibility. Also ICEMCFD has a good interface with UG, and the mesh-generation process can be easily scripted.

For the ease of mesh generation and local modifications, the full combustor sector model was divided into three main components: inner liner, outer liner, and dome assembly. Each component was further divided into a set of subcomponents. A meshing file structure is shown in Fig. 5. It is essential to translate the UG geometry context model into an ICEM tetin files for mesh generation. Because of the meshing approaches in ICEM HEXA, not all geometry entities in the UG context model were needed. Because the combustor structure is typically cyclic symmetric based on the number of fuel nozzles, in most cases, the subcomponents were meshed from a two-dimensional mesh on one of the side cutting surfaces, which was then revolved around the engine axis.

After the UG preparation was done, a tetin file was generated for each subcomponent using a script called prt2tetin along with the corresponding tagname file. To ensure the cyclic symmetry, the tetin file for each subcomponent was then modified by defining periodicity. The next step was to generate a replay file for each subcomponent that was used in the meshing scripts. The replay files were stored in the meshing library that could be reused for subcomponents with similar topologies. Shown in Fig. 6 are two outer-liner nugget meshes generated using a generic replay file. With the replays for all subcomponents generated, the meshes were integrated into a component model by running an ICEM script, and a master meshing script was run with options to generate a mesh for each individual component or the full combustor model. It was noted that each subcomponent mesh must have identical mesh pattern at the interfaces with its neighboring subcomponents so that nodes at the interfaces could be merged during mesh integration. In addition, identical mesh patterns were required on the contact faces between the components to generate accurate gap convection data for pThermal analysis. The same requirement needed to be met on the two corresponding cutting surfaces of the sector model so that thermal coupling and cyclic symmetry boundary conditions could be applied for thermal and modal analyses, respectively.

Following these procedures, an all-hexahedron mesh was generated for the full combustor sector model, as shown in Fig. 7, that contains 168,000 elements and 113,000 nodes. The meshing scripts were run at each iteration step of optimization. An automated mesh update of the inner-liner support with a changing window size is shown in Fig. 8.

CFD Mapping and Heat Transfer LME

Heat transfer analysis of the combustor assembly was performed using theoretical and experimental cold-side convection correlations in conjunction with hot-gas path CFD results, returned from the Concert CFD solver.

The UG context model introduced earlier was the foundation of the three-dimensional heat transfer analysis. All surface faces in the UG solid model were tagged using a standard naming convention allowing for communication between the geometry, mesh, and boundary condition database. Each surface tagname defines geometric surface properties to be returned to the LME database.

These included minimum and maximum axial, radial, and angular positions in space, in addition to face surface area. Adiabatic or convection heat transfer correlations were assigned to all surfaces of the model. For modeling and meshing simplification, small cooling holes were modeled as cooling planes. Cold-side convection coefficients were assigned to these internal surfaces. Additionally, surface tagnames were also used to define axisymmetric heat transfer linkages and gap convection linkage.

Standard heat transfer correlations were used for derivation of cold-side heat transfer balance equations. These correlations, based on theoretical and experimental heat transfer and engine combustion practices, leveraged a collection of geometric and flow inputs. Inputs populated the LME database structure as a function of UG geometry and user input.

Construction and derivation of Concert CFD results will not be discussed in this paper. The CFD finite element mesh was generated separately from the solid mesh. To map the heat transfer inputs onto the solid mesh, the CFD results must be interpolated onto the solid mesh. This was performed through in-house nodal mapping programs. The executables to these CFD mapping codes were generated by LME, as a function of hot-side CFD mapping tagnames. The PATRAN Convection identification number, user input grid, and offset were returned for each correlation and used to structure the CFD mapping inputs. The CFD mapping routines returned a PATRAN thermal results neutral file to be used as energy input to the LME heat transfer model.

The LME database structure consists of node, element, material properties, material knockdown methods, convection, radiation, and structural method storage tables. The database entries are a function of user-input engine parameter definitions, allowing for the application of the database methods across multiple engine lines. Additionally, the flexibility of the table size and speed of inquiry lookup was optimized by a dynamic database structure. Reliance on a static procedural code was removed, allowing for a single update to flow across all influenced parameters. The usage of the standardized database structure automated up to 85% of the required inputs of a thermal model by leveraging geometric properties and standard procedures of the combustor model.

For each entry required for a boundary condition input correlation, the methods table was called to return the standard procedure, which launched into look-ups for returned geometry and flow inputs and assigned the input to associated surface elements, nodes, and a standard correlation. This allowed for a uniform linkage across all PATRAN heat transfer inputs, allowing the user to communicate with standard tagnames, not hard-coded identification parameter numbers required by PATRAN pThermal.

The LME logic enabled the automated generation of thermal coupling and gap convection coefficient input files. A geometric nodal match, based on cylindrical coordinate orientation on matching tagged surfaces, was used to associate coupled surfaces. The gap convection preparation routine calculated an associated element application area to assign to the local node pair, in conjunction with a user-defined gap convection coefficient.

Hot-side radiation parameters were assigned to surfaces exposed to the hot-gas path. Each correlation referenced a user-defined air node input and emissivity, in conjunction with geometric properties of the surface. Additionally, a standard list of cold-side surfaces loosed energy to the engine case through cold-side radiation. Both conditions were accounted for in the present work.

Comprehensive validations have been conducted to verify the accuracy of the LME approach. Shown in Fig. 9 is a comparison of the temperature contours on the hot side of the outer-liner metal structure obtained from LME and manually generated models. The LME steps were followed to predict the temperature distributions in the full combustor model during the optimization process.

Modal Analysis, Stress Analysis and LCF Life Prediction

The software package ANSYS was used to perform the cyclic symmetric modal analysis and stress analysis of the full combustor model. One of the outputs of the LME process was a mesh, based on

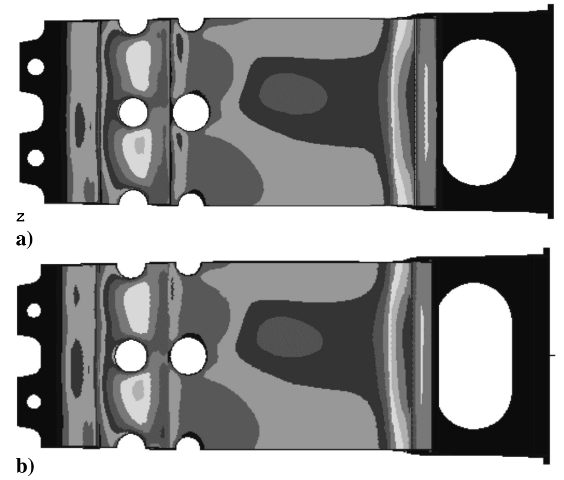

Fig. 9 OL hot-side temperature contour: a) LME and b) manual.

the ICEM-generated mesh, in an ANSYS friendly input file format. This file provided ANSYS with an accurate rendition of the full combustor geometry, without recreating the actual solid geometry, and was the backbone of the ANSYS stress analysis.

This mesh model still required the application of material properties and boundary conditions. The ANSYS component definition file, automatically generated by the LME process, facilitated both their assignments. Each component was assigned their proper material properties, some of which were temperature dependent. Because the boundary conditions were time dependent, proper application entailed additional complexities. Whereas for static stress analysis the nodes on the two cutting surfaces of the sector model were coupled by constraint equations, cyclic symmetric boundary conditions were applied using internal ANSYS commands.

In cyclic symmetry modal analysis, what was of interest was how the lowest frequency changes with the nodal diameters. To reduce the modal analysis time during the optimization process, a course mesh model was generated with only half of the mesh size used for the stress analysis. In the coarse mesh model, the bond coat and thermal barrier coating layers were simulated using surface quad elements, and the swirler and flare were simulated using point masses. To ensure the prediction accuracy, it is important to have matched component weight with the original geometry model. As a verification of the simplified model, the frequency results were compared against those from the fine mesh model, and it was found that the difference of the lowest frequency between the two models was less than 1%.

To capture accurate peak stresses, the short period of time surrounding the aircraft's takeoff required detailed analysis. Rather than perform a fully transient stress analysis, the strategy of a series of steady-state runs was preferred. The time points of the thermal results returned from pThermal dictated the stress execution time points. These pThermal calculated nodal temperatures were applied to the entire ANSYS model as body forces. For each time value, the appropriate displacement, pressure, and nodal force values were determined, from an external table, and applied to their designated portions of the combustor.

The resulting nodal stress values, along with their temperatures, were stored as separate load cases in one ANSYS results file for later extraction. To get a more comprehensive study of the combustor operating cycle, additional time points could be included in the stress analysis. In addition to the standard results, a summary file was generated consisting of maximum stress values for the two defined regions around the inner- and outer-liner support windows. As an illustration, Fig. 10 shows the stress contour around the window of the outer-liner support.

To predict the LCF life, an in-house analysis tool called Xlife was utilized. This tool requires nodal stress and temperature values and returns the crack initiation life of the analyzed component. Xlife is sophisticated enough to read directly in the ANSYS result file to obtain the necessary temperature and stress data as well as the ANSYS database to obtain the necessary node and component definitions. For our application, the life prediction was restricted to the high-stress support window regions.

For each time point, the principle stresses and temperature of each designated node were obtained. Based on the assigned material, a series of stress-life curves were referenced, and nodal life cycle value was predicted. Through the use of Minors rule, these life predictions were combined to calculate a mission cycle life for each node. These nodal results were reviewed, and a total mission cycle life value was obtained programmatically for each defined component. These values were then extracted into a summary file for later reference.

Optimization Scheme in FIPER

The objective of FIPER was to develop an advanced engineering design environment that facilitates multidisciplinary analysis and optimization in a global and business-to-business heterogeneous environment. This was accomplished through an extensively designed Java architecture. To achieve the required ease of process integration, the concept of providers was implemented. In this approach, each analysis tool is wrapped as a generic FIPER provider. These providers can then be quickly strung together to model accurately almost any multidisciplinary process. Ultimately, this process can then be incorporated into any desired optimization routine. To demonstrate the efficiency and accuracy of the optimization process using FIPER, a numerical example of minimum mass for a simple block model, as shown in Fig. 11, was conducted. The objective was to minimize the mass, and the design variables are hole diameter thin edge, and thick edge. The constraints are maximum stress <138 MPa, frequency 1 <1000 Hz, frequency 2 <1500 Hz, and frequency 3 <2000 Hz. Figure 12 shows the changes of the objective function, design variables, and constraints vs the number of iterations.

Fig. 10 Stress contour at OL support window.

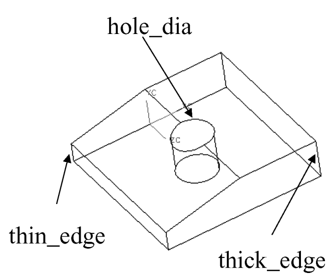

Fig. 11 Simple block model with three design variables.

For this particular project, nine separate providers were required to capture the design and analysis process for the combustor liners. This captured process can be seen in Fig. 13. An extensive mapping network was generated between these providers for passing the appropriate data between analysis programs. Figure 14 shows the integration complexity of this analysis process. Each arrow in Fig. 14 represents a dependency on one or more component parameters.

Five separate geometric inputs were identified as the design variables to be studied, and each was constrained to a particular range. A sensitivity analysis was performed within FIPER to determine the impact and effect each of these parameters had on the design constraints of life and frequency as shown in Fig. 15. As can be seen, among the five design variables, the inner-liner thickness, inner-liner (IL) window size, and the outer-liner (OL) window size have the most significant effects on the design constraints of life (stress) and frequency.

After reviewing the sensitivity analysis, our ability to reach the frequency constraint was suspect. Several additional runs were performed, using the relationships unveiled by the sensitivity analysis, and it was concluded that the desired frequency could not be met within the design space defined. With no additional adjustability available in the currently identified design inputs, it was apparent that new design variables would be required.

With assistance from the seasoned combustor designers at GEAE, the concept of ribs was adopted as shown in Fig. 16. Rather than spend the time and effort into incorporating these ribs into the solid model, the use of additional beam elements was investigated. A study was performed where the addition of beam elements was compared to a similar-sized nodal offset of the original mesh, and

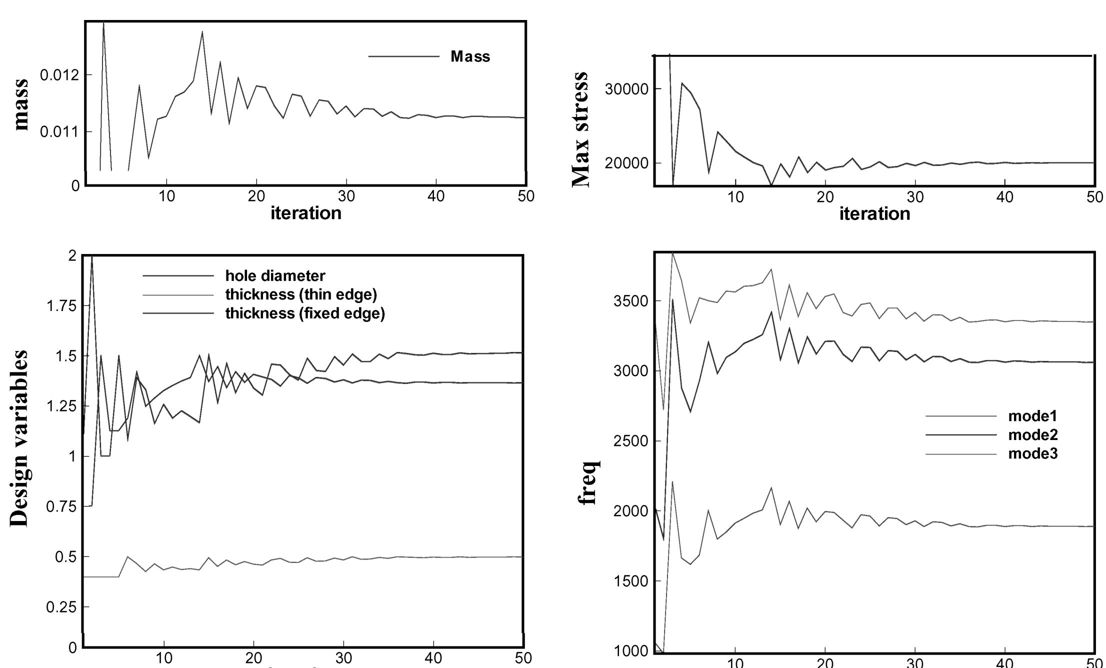

Fig. 12 Optimization of a simple block.

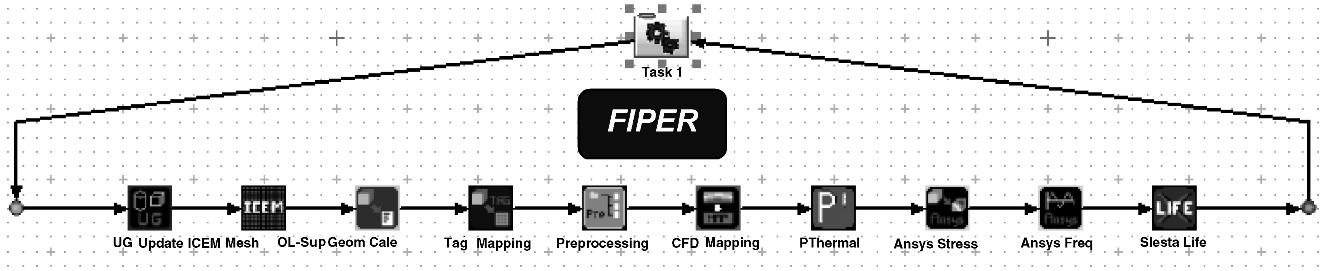

Fig. 13 FIPER workflow for combustor analysis.

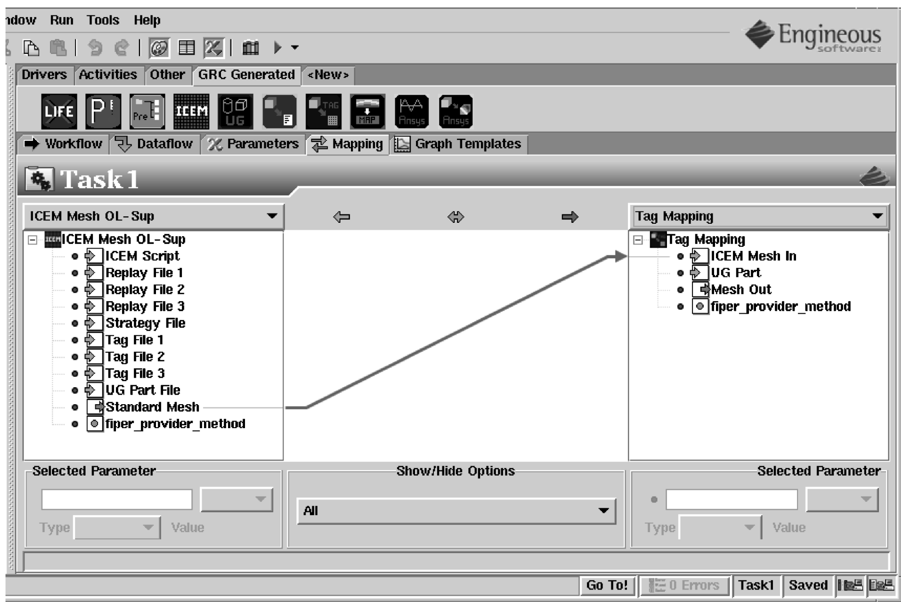

Fig. 14 Data mapping between FIPER providers.

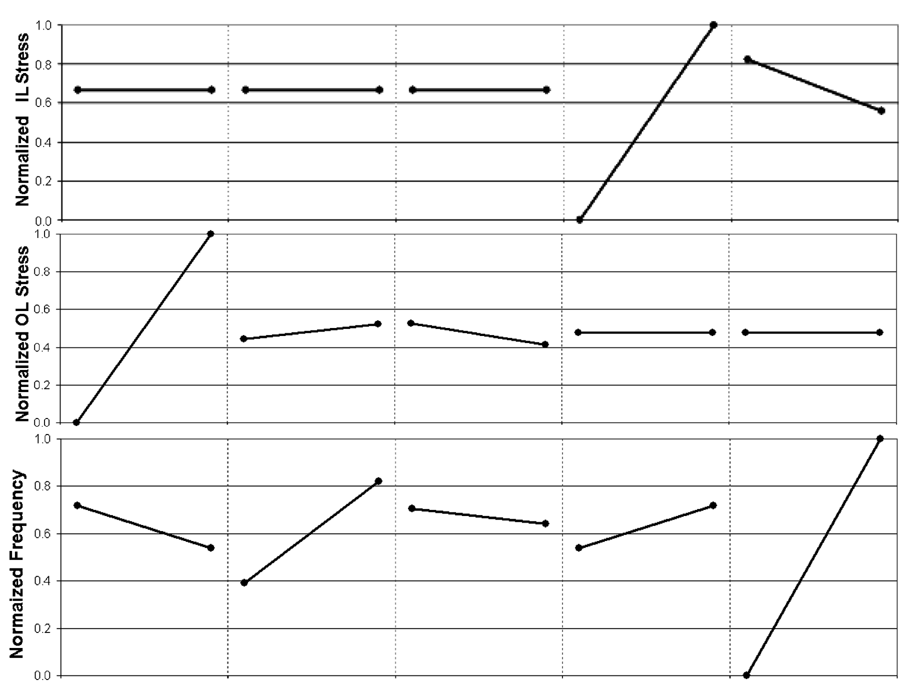

Fig. 15 Sensitivity data for each response variable.

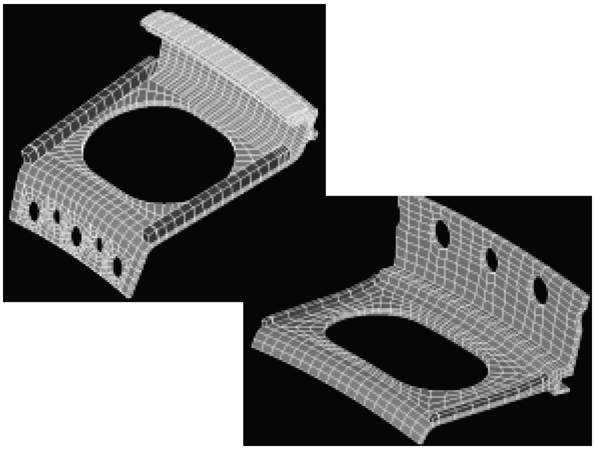

Fig. 16 Liner support with beam enhancement.

the results obtained were nearly identical. The beam elements were added to the baseline design, which is a one-time manual process. That is, the values of the original five design variables were fixed and various beam configurations were considered with four new variables, beam width, and height on ILs and OLs.

Inclusion of these beam elements was very enabling. Because they can be added directly to the mesh, a majority of the analysis preparation process could be skipped. With the overall execution time now significantly reduced, several large central composite design of experiments (DOEs) were performed to determine the effect these newly added ribs had on the combustor's life and frequency.

A regression was performed on these DOE results, and a transfer function obtained for both frequency and life. The calculated R-squared adjusted values for these predictions were very promising. The transfer functions were incorporated into a gradient-based optimization model embedded in FIPER, and all the design constraints were provided. After a few seconds of computation, an optimal rib design, which met all of the design constraints, was determined.

These rib parameters were then incorporated into the full analysis process for validation. The values calculated were nearly identical to those predicted by the optimization routine. Therefore, with all of the design constraints met, and with minimal impact on weight, this optimized support design was accepted.

Conclusions

A MDO has been carried out on an aircraft engine combustor with constraints involving mechanical performance and life cycles, as well as geometry limitations. Using the LME technologies as the backbone, the optimization process was integrated in the FIPER environment. An optimal configuration of the liner support structures has been obtained that would serve as the future design improvement. The following conclusions could be made during the course of the work:

1) The master-context model concept with geometry parameterization based on UG geometry modeling is a key technology for automated design optimization involving multidisciplines.

2) Another important technology for efficient design optimization is automated mesh generation. The meshing strategies using ICEMCFD HEXA provided high-quality meshes for complex combustor structural components.

3) The LME methodologies that standardize the procedures of heat transfer and mechanical analyses can significantly reduce the design cycle time and serve as the foundation for the MDO work.

4) The FIPER environment is a suitable design framework with great potential for complex industrial multidisciplinary design analysis and optimization problems.

Acknowledgment

This work has been carried out under the General Electric (GE) Global Research Advanced Design Technologies and Tools Program, Project 2158414100 Combustion Technologies Integration. The funding received from GE Aircraft Engines is gratefully acknowledged. The authors would like to acknowledge the valuable input received from Charles Seeley of GE Global Research and Jason Hoppa, Charles Zhang, Sundaram Venkitarama, and Shanker Subramanian of GE Aircraft Engine Combustion Center of Excellence. Thanks are also extended to David Mika, who participated in the early phase of the project.

References

[1]Rohl, P. J., He, B., and Finnigon, P., "A Collaborative Optimization Environment for Turbine Engine Development," AIAA Paper 98-4734, Aug. 1998.

[2]Bailey, M. W., Irani, R. H., Finnigan, P. M., Rohl, P. J., and Badhrinath, K., "Integrated Multidisciplinary Design," International Society for Air Breathing Engines, Paper ISOABE IS-181, Florence, Italy, Sept. 1999.

[3]Rohl, P. J., Kolonay, R., Irani, R., Sobolowski, R., Kao, K., and Bailey, M., "A Federated Intelligent Product Environment," *Proceedings of the 41st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Reston, VA, 2000.

[4]Rohl, P. J., Kolonay, R., Paradis, M., and Bailey, M., "Intelligent Compressor Design in a Network-Centric Environment," *Proceedings of ASME Design Engineering Technical Conferences, Computers and Information*, Pittsburgh, PA, Sept. 2001.

[5]Kao, K. J., Seeley, C. E., Yin, Su, Kolonay, R. M., Rus, T., and Paradis, M., "Business-to-Business Virtual Collaboration of Aircraft Engine Combustor Design," *ASME Design Engineering Technical Conferences, Computers and Information*, DETC2003/CIE-48282, Chicago, Sept. 2003.

[6]Lefebvre, A. H., *GasTurbine Combustion*, McGraw–Hill, Washington, DC, 1983.

[7]Seeley, C. E., Tangirala, V. E., Kolonay, R. M., and Bailey, M. W., "A Network-Centric Method for Combustion Sub-System Multidisciplinary Analysis and Optimization," International Society for Air Breathing Engines Conf., Bangalore, India, Sept. 2001.

[8]*UNIGRAPHICS® V18 User Documentation,* Engineering Data Systems Corp., URL: http://www.unigraphics.com [cited 31 March 2003].

[9]*P-Thermal User Documentation*, MSC.Software Corp., URL: http://www.msc.software.com [cited 5 April 2003].

[10]*ANSYS® V 7.0 User Documentation*, Ansys, Inc., URL: http://www.ansys.com [cited 25 June 2003].

[11]*ICEMCFD® V4.2 User Documentation*, ICEM CFD Engineering, URL: http://www.icemcfd.com [cited 28 June 2003].

E. Livne
Associate Editor