Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45546

INTEGRATED PRELIMINARY DESIGN APPROACH FOR TURBOMACHINERY DESIGN

Vinod Chaudhari*
GE Aviation
Bangalore, Karanataka, INDIA

Thomas Moniz
GE Aviation
Cincinnati, Ohio, USA

Chandrakant NaikTari
GE Aviation
Bangalore, Karanataka, INDIA

Daniel Waslo
GE Aviation
Lynn, MA, USA

Mohan Kanase
GE Aviation
Bangalore, Karanataka, INDIA

ABSTRACT

Turbo machinery preliminary design is an iterative process that begins with an initial Cycle design and culminates with a cross-section of an engine that meets performance, weight and cost criteria. There is a need to have an integrated system that can allow designers to work seamlessly with the conceptual design process involving Cycle, aero and mechanical preliminary design methods. This becomes a huge challenge considering the minimal inputs available at the initial design stage, complexities of design requirements and the multi-disciplinary skills required to come up with accurate design concepts that can satisfy aero and mechanical design requirements. Also, it becomes a highly challenging task to assess the impact of design changes on the downstream design phase for realistic trade-offs.

This paper focuses on providing an Integrated Design approach called IPD system (Integrated Preliminary Design) to reduce design cycle time (by 50% per design iteration) and improve fidelity of engine cross-sections at the preliminary design stage (weight & cost prediction improvement by 5%). The IPD system smoothly connects different multi-design disciplines including Cycle design, Flowpath design, nacelle aeroline design and system level mechanical and architectural design across all conceptual and preliminary design stages. Apart from system level design, the IPD system helps the designer to create components iteratively and update the system level model accordingly arriving at a solution that meets aero and mechanical design requirements. This design approach also provides a high fidelity system plan to optimize the system level design that can meet performance, weight and cost requirements.

* Address all correspondence to this author.

1. INTRODUCTION

Gas Turbine engine development is a highly coupled multidisciplinary process. In a market with ever-increasing demands in terms of cost, performance and environmental aspects like noise, emissions, and fuel consumption, the availability of high-fidelity analytical tools early in the design phase is a necessity to build an optimized product. This paper focuses on improving preliminary design deliverable and smooth handover of design data to downstream design group for detailed design. There were several successful efforts across industry to integrate Cycle design and Flowpath design at the conceptual design stage. This paper focuses on integrating conceptual design and preliminary design to downstream design disciplines.

Mere automation of individual design disciplines is not sufficient to achieve a greater design cycle time reduction; one needs lesser design iterations and increase in design fidelity. Different design disciplines should seamlessly exchange data amongst themselves and quickly assess the impact of the change in design for each of them.

Seamless data exchange mechanisms with an integrated design environment is a must for the successful collaboration and effective utilization of time difference across different geographical locations to foster product design, where all the participants in the design process need real-time access to all the relevant up-to-date design data.

GE Aviation team used a lean six sigma approach to develop the Integrated Preliminary Design system and developed value stream mapping that helped the team to identify non-value activities across the process, design data needed for other disciplines and the flow of design data across these disciplines. As a result, this system (i.e. IPD) can respond faster to given changes in the design. Higher fidelity design in early design stage and faster turnaround time enables engine architects to explore a wide spectrum of design space which has helped GE Aviation to develop world-class engine architectures. This system is applicable to a wide spectrum of engines ranging from 800 shp turbo prop to 120,000 lb thrust turbo-fans and can handle different engine configurations.

2. TRADITIONAL PRACTICES FOR PRELIMINARY DESIGN

Traditionally, preliminary design is assumed to be an iterative process with manual intervention for moving designs across different design disciplines. The preliminary designer starts with new Cycle design and tries to scale and map existing engine cross-sections to the new cross-section obtained through aero & Flowpath design. There are too many iterations between aero designers and mechanical designers working on design of cross-section to come up with initial mechanical design that validates the aero and Cycle assumptions and provides the necessary feedback.

Once the initial cross-section is created, there is a need to improve the individual components' designs to meet required design requirements. Main inputs at this stage are Flowpath pitch line temperatures and rotor RPM. At the end of this step, all the individual component design validations are completed along with detailed sizing of cross-section. Further, this cross-section is resized to get cold cross-sections that can be supplied to product teams for detailed design.

One of the major drawbacks with the traditional approach is disconnected design iterations, where designs are not in sync with the entire system level multi-discipline environment. Another constraint is the lack of availability of the latest data to design iterations carried out in downstream stages. Also, it is important to have ready availability of legacy data for benchmarking at the designer's fingertips. So, it is felt that there is a need to create an integrated design system, which can address all these issues resulting in a high fidelity design with faster turnaround cycle.

3. LOW FIDELITY SYSTEM LEVEL DESIGN

Conceptual design demands faster turnaround in exploring a large design space and identifying relatively few viable designs. Conceptual design starts with an engine Cycle design for a given thrust/power range where the entire design space is explored for feasible design points. Cycle design coupled with Flowpath design (i.e. gas path) is used to down select between different engine architectures meeting customer requirements. Low fidelity system models are represented as parametric models with a high-level engine schematic at the Flowpath design stage. It represents system level modeling and does not have detailed component level geometry. Fig. 1 illustrates low fidelity system level design.

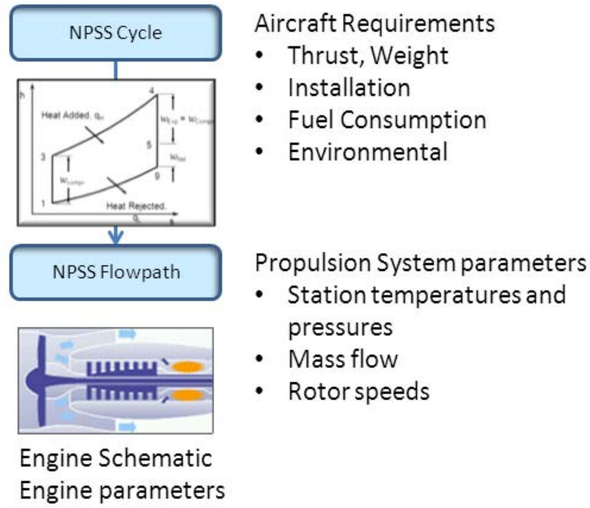

Figure 1 Low fidelity system level design

Low fidelity design provides fast designs based on customer requirements with a handful of design parameters. Selected outputs of low fidelity design after several design trade-offs become input to develop high fidelity cross-section. Low fidelity design filters several designs based on constraints and optimizes the output. This output is in the form of a high level engine schematic along with stage-by-stage variation in engine parameters. Typically, to start with, the Cycle model is low fidelity and as the design progresses it turns into high fidelity. When it comes to Flowpath design, it can accurately represent the gas path after iterations with aero design, but does not have detailed component level geometry representation.

The amount of data and design iterations at this stage of design is huge. One of the biggest challenges in the traditional design approach is exchanging data between low fidelity designs to high-fidelity engine cross-sections that can be delivered for detailed design.

4. HIGH FIDELITY SYSTEM LEVEL DESIGN

Connecting low fidelity system models to medium/high fidelity models is vital for the success of reducing design iterations, design cycle time and increasing accuracy. Fig. 2 illustrates a high level view of the IPD system and the flow of process from low fidelity design to high fidelity design.

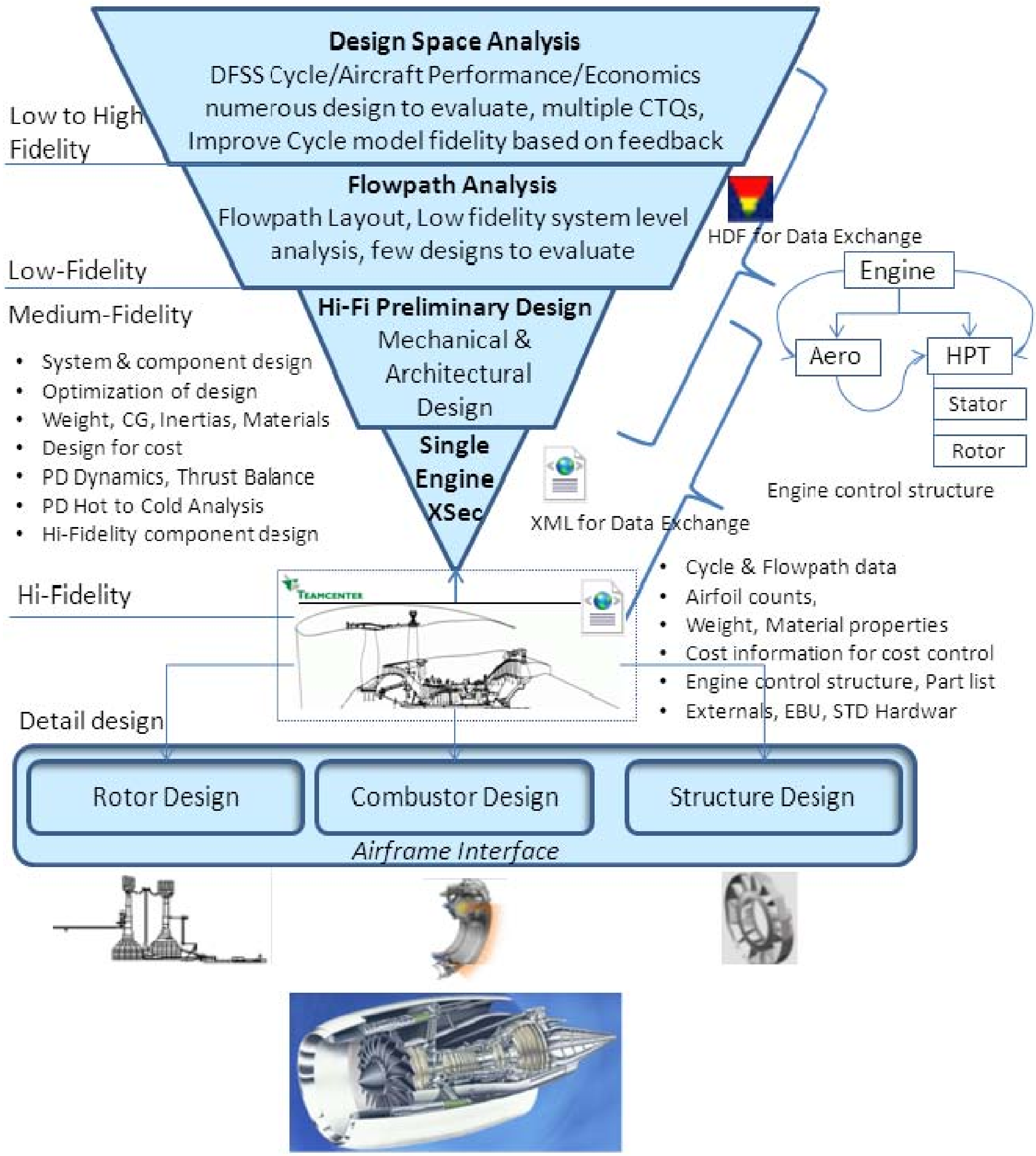

Figure 2 Design flow from Cycle design to high fidelity engine cross-section

4.1. Developing high fidelity model for analysis

High fidelity models are represented as Unigraphics (UG) models and traditionally do not carry all engineering information needed for design analysis and trade-off studies. So, establishing linkage between low and high fidelity models is a highly challenging task. IPD connects low fidelity to high fidelity model by generating or scaling cross-sections based on low fidelity parametric models. IPD also provides mechanisms to change these parameters, so, depending on changes in geometry in high fidelity UG cross-sections; the designer can quickly check impacts on compressor, turbine and nacelle performance.

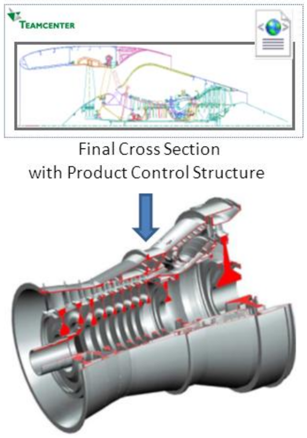

Figure 3 Product Control Structure useful for generating 3D model

IPD generates context sensitive UG cross-sections with a Product Control Structure so that the downstream design teams can use the entire engine structure along with a part list as shown in Fig. 3. For example, if the Cycle designer changes bypass exit areas then the IPD system can update the UG geometry of nacelle with a new value of bypass exit areas.

IPD system was conceptualized after a lean six sigma event across different disciplines where all the major stakeholders highlighted their design process and their top design challenges. IPD system uses the six-sigma design tool kit to explore the impact of design changes and ensure the outcome falls within an acceptable margin of robustness. This approach ensures designed products are robust with respect to variation in design, execution & environment.

4.2. System level trade-off

Fig. 2 illustrates how initial medium fidelity engine cross-sections is analyzed for multiple disciplines and finally turned into high fidelity designs. The IPD system provides a mechanism to update Cycle and Flowpath models so that the designer can assess the impact of change in design at every stage. This way the IPD system helps the designer to optimize different design CTQs (Critical to Quality). System level trade-off studies using detailed engine cross-sections provides quick feedback to upstream design like Flowpath and Cycle so that the Cycle designer can improve the fidelity of Cycle models that in turn help the downstream designer to predict accurate performance. The IPD system can help designers to evaluate engine performance at design as well as off-design points.

4.3. Component level design and optimization

Fig. 4 illustrates a component design and optimization example. Using the IPD system for each component design iteration, the designer can see design margins/performance, cost and weight and can update the system level model on the fly and even assess the impact of a change in component design on compressor and turbine performance. Updating system level models on the fly is achieved through building a context sensitive cross-section with Product Control Structure (i.e. engine part tree). The IPD system provides an engine level report on component design and comparison across different design iterations.

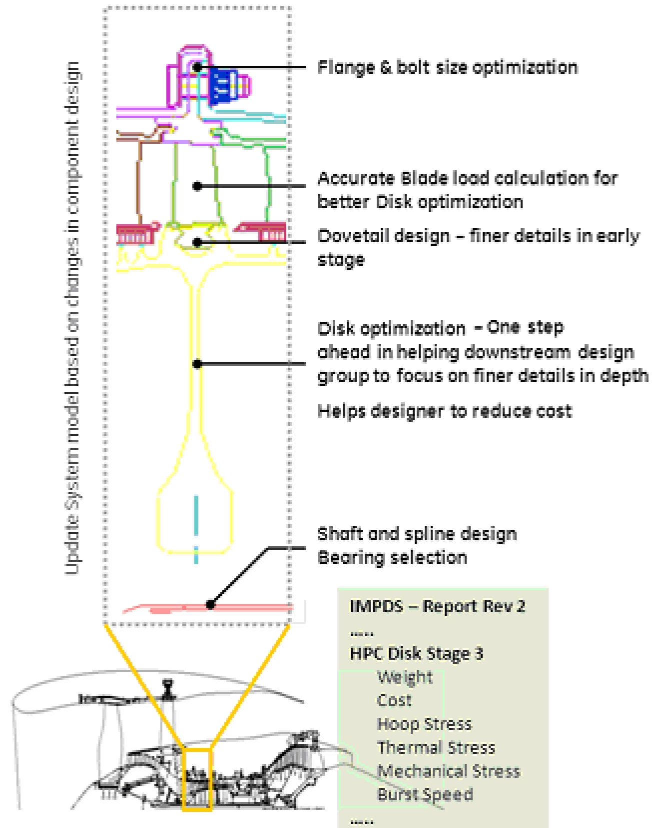

Figure 4 IPD Component design

5. THE TOOL ARCHITECTURE FOR INTEGRATED PRELIMINARY DESIGN APPROACH

IPD architecture is designed in such a way that different design tools can interact with the system level model and exchange design data seamlessly. The designer can get visual feedback like stress distributions, deflections and component geometry. These component-based design calculations are pluggable tools to the IPD system where all pluggable tools have a predefined contract for response from the system model so that information can be accessed at run time. Fig. 5 shows the high level IPD tool architecture where UG cross-section update is based on call back mechanism.

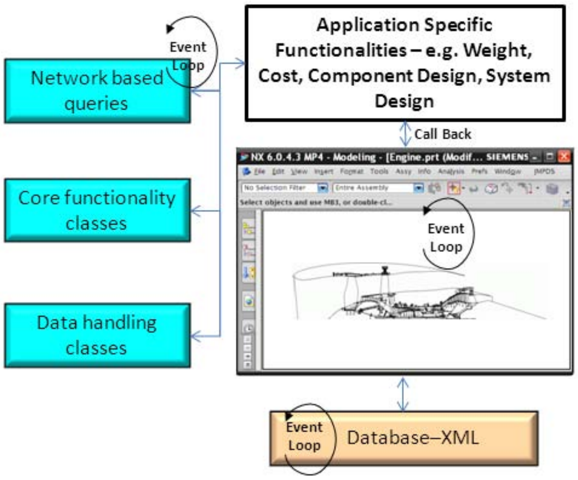

Figure 5 IPD framework

Fig. 6 shows the front end of the IPD system, and how it is connected to Cycle and Flowpath. Output of the IPD system is a high fidelity UG cross-section along with design data attached to it. Designers can see a detailed report showing key design parameters and major design iterations.

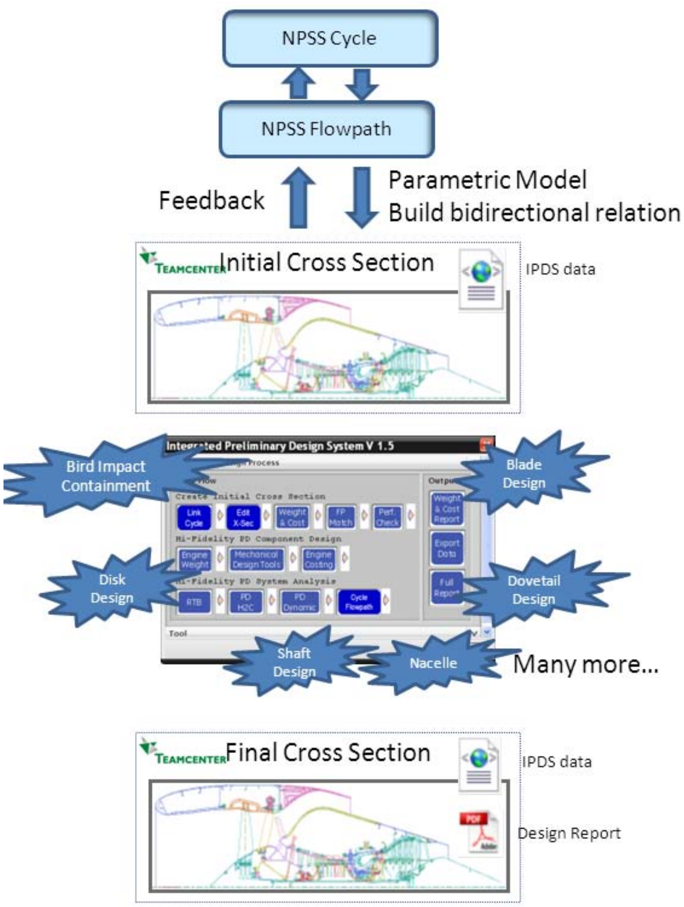

Figure 6 Integrated Preliminary Design System in use

5.1. Design iterations

Fig. 7 illustrates how change in blade profile impacts dovetail shape and disk shape. The IPD system helps the designer to track all major design iterations so that the designer can visualize the impact of change in design of one component to other component. For every change in design of a component, the designer can quickly rerun the other components and check cost, weight and design margins/performance. In the same way, the IPD updates the system level model and one designer can see how changes of another designer impact the system level model.

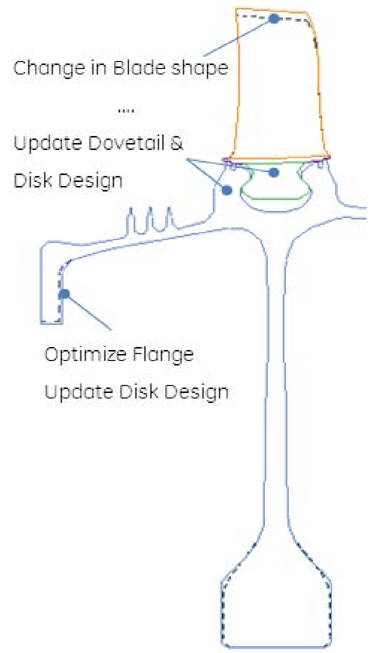

Figure 7 IPD System – Component design iteration

5.2. Data exchange mechanism

The IPD system uses a hierarchical database to store data as objects like engine, modules (i.e. HPC, LPC etc.) and components. Any component design tool can access this database with a predefined contract in place. After the design is completed, the data is saved back as a result and parameters with respective design iteration so that designer can see system level view of design at any time. Fig. 8 shows typical data that is stored along with a high fidelity cross-section. The downstream design groups can access this data.

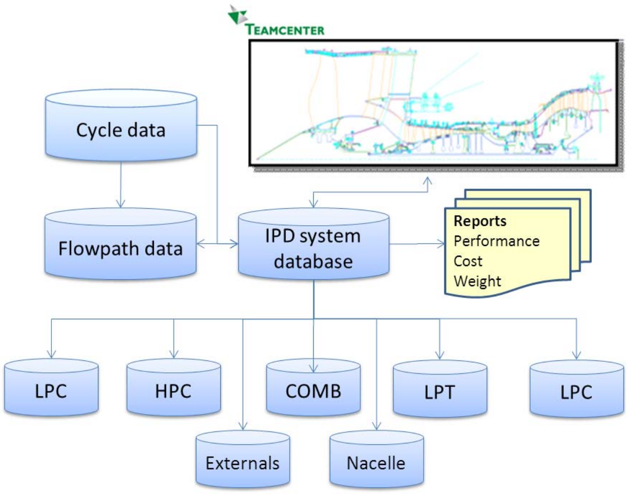

Figure 8 IPD database structure

6. CONCLUSION

Integrated Design approach at the preliminary design presented in this paper connects low fidelity system models to medium fidelity models which is vital for reducing detailed design iterations and cycle time and increasing fidelity of design upstream during product development. Further, the lean six-sigma approach helped the GE Aviation team to identify non-value added activities, the waiting time and design data requirement of multiple disciplines.

The IPD system integrates Cycle design, Flowpath design, Nacelle aeroline design, system level mechanical design and component design disciplines. With the IPD system, the engine architect can update a design based on Cycle and Flowpath changes and can respond quickly to the customer's requirements with competitive design margins. The integrated system also assists designers in eliminating time-consuming manual data exchange and associated risks.

The IPD system provides framework and methods to achieve higher fidelity designs during the preliminary design stage. These methods are developed for system and component designs by capturing the actual physics for a given design discipline. The results for system design were comparable with the detailed 2D analysis model and the results for component design were comparable with 3D analysis using finite element methods.

Initial results from the IPD system has shown large cycle time reduction (by 50% per design iteration) and demonstrated improved fidelity of engine cross-sections at the preliminary design stage (weight & cost prediction improvement by 5%). Improvement in weight prediction is mainly achieved through improved component design calculations and large cycle time reductions that led designers to explore a wider spectrum of design configurations. Going forward, more detailed design disciplines can be brought under the IPD framework that will lead to a complete paradigm shift in the preliminary design of turbo-machinery.

NOMENCLATURE

NPSS: Numerical Propulsion System Simulation is developed by NASA. The NPSS team consists of propulsion experts and software engineers from GE Aviation, Pratt & Whitney, the Boeing Company, Honeywell, Rolls-Royce Corporation, Williams International, Teledyne Ryan Aeronautical, Arnold Engineering Development Center, Wright-Patterson Air Force Base, and the NASA Glenn Research Center.
Cycle model: Term Cycle model is referred for Brayton cycle modeled in NPSS.
Flowpath: Term Flowpath is referred as path of gas.
UG: Unigraphics
XSec: Cross-section
HDF: Hierarchical Data Format
XML: eXtensible Markup Language

ACKNOWLEDGMENTS

Authors would like to thank Pankaj Sharma and Surender Reddy (GE Aviation, Bangalore India) for doing experiment studies and validating the fidelity of the system.

The authors would like to acknowledge support of Randy Cepress, Benjamin Huizenga, Ron Plybon, Kemper Paul, Steve Schrantz, Sean McGowan (GE Aviation, Cincinnati, USA) and Venkataramanan Ramachandran, Dinakar Deshmukh, Abhishek Banerjee, Anshu Vijayvargiya, Bhaskar Mondal, Kishanjit Pal (GE Aviation, Bangalore India)

Author also like to thank Vinay Ramanath (GE Aviation, Bangalore India) session co-chair ASME IGTI for reviewing the contents of this paper and providing his expert feedback.

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