Multi-fidelity Simulations of Propulsion Systems

Dr. John K. Lytle
The NASA Glenn Research Center at Lewis Field
Cleveland, Ohio 44135 USA

Abstract

The advances in computing and communications technologies over the past decade have revolutionized the simulation of large, complex systems. This paper presents the progress in developing the Numerical Propulsion System Simulation, a multi-fidelity simulation of a complete propulsion system. 0-dimensional, 1-dimensional, and 3-dimensional simulations have been integrated into a system simulation at a single operating point and executed in a time frame practical for use in the design environment. Plans are in place for extending the simulations to enable automatic transition through multiple operating points in the near future.

Introduction

The vision for propulsion simulations at the NASA Glenn Research Center is to develop technologies that enable high-fidelity, multi-disciplinary full propulsion system simulations to reduce the cost and risk associated with the development of future aerospace vehicles. The combination of propulsion engineering and computer engineering disciplines will enable accurate, three-dimensional simulations of full aircraft and space transportation engines in less than 15 hours. Rapid simulations of complex propulsion systems will make available to the designers and analysts un-precedented levels of details about system performance and cost early in the design process before any hardware is built and tested. This vision is being implemented through the Numerical Propulsion System Simulation (NPSS).

NPSS is comprised of three main elements that are required to enable large-scale complex simulations to become a routine part of the design environment. Those elements are: 1. engineering models for multi-disciplinary, multi-fidelity full system simulations, 2. a simulation environment for rapid construction of complex simulations that integrates people, data, computing resources and analysis tools, and 3. computing platforms for low-cost, parallel, distributed processing. Multi-disciplinary analysis is necessary to capture the key physical interactions early in the design process in a more tightly coupled manner than is common practice today. Multi-fidelity analysis is necessary to minimize the size of the full system simulations while providing the designer and analyst with the detailed information required to resolve design issues. The simulation environment is one of the most critical parts of the NPSS since it directly increases the productivity of the designer and analyst by automating many of the routine tasks associated with assembling and manipulating data required to initiate complex analyses. These tasks can occupy up to 50% of a designer or analyst’s time. The computing platform must be low-cost and high-performance to be practical in an industrial design environment. In addition, results must be produced quickly, at least within 15 hours (i.e. overnight), to be useful in a design environment. Today this can only be accomplished through the use of low-cost computing platforms that execute code in parallel using 100s to 1000s of processors. The principle source of low-cost computing today is large numbers of interconnected commodity machines such as personal computers. To take advantage of these machines, the propulsion computational tools must be optimized for efficient parallel execution with at least 80% efficiency in the range of 100s to 1000s of processors.

The NPSS capability currently consists of a US industry standard engine aerothermodynamic cycle (0-dimensional) simulation with the ability to rapidly integrate one-dimensional component analyses that can be distributed across remotely located team members and computing resources (NPSS V1.6). Applications can be built and executed using web-based interfaces. A major US aircraft engine manufacturer has estimated that the new object-oriented architecture in NPSS will result in a 55% reduction in the time to build new, complex engine simulations and implement those simulations throughout the product life cycle. NPSS V1.6 is available to US entities directly from NASA or from its commercial partner, Wolverine Ventures, Inc. of Jupiter Florida. The paper will describe the progress in each of the main elements of the simulation: 1) the engineering model, 2) the simulation environment, and 3) the high-performance computing platform.

Engineering Model

Multi-fidelity simulation capability requires new modeling techniques to be developed to ensure that conservation of mass, momentum, and energy are maintained across the component interfaces of the system. This capability, also referred to as “zooming”, allows the designer or analyst to vary the level of detail of analysis throughout the engine based upon information required and the physical processes being studied. For example, the effects of changing the shape of a fan blade on engine performance may require a 3-dimensional simulation of the fan and adjacent components (i.e. inlet and compressor). The remainder of the engine could be modeled at lower levels of detail (e.g. 0-dimensional) to minimize simulation setup and execution time. The ability to integrate analysis codes at various levels of fidelity into a full system simulation is illustrated in Figure 1.

The tools to enable the integration of the 3-dimensional analysis codes with NPSS V1.6 are being developed through a prototype simulation of a GE90-94B turbofan engine, which is the production engine on the Boeing 777-200ER aircraft (see Figure 2). The initial operating condition is sea-level take-off condition at Mach 0.25. Cooling flows are well known at this condition and are important boundary condition data for the simulation. The simulation is comprised of coupled 3-dimensional computational fluid dynamics (CFD) component simulations. The National Combustion Code (NCC) is used for the combustor and the Average Passage NASA (APNASA) code is used for all of the turbomachinery. A cycle model of the GE90 in NPSS V1.6 operates as the overall executive to ensure convergence. The 3-dimensional analyses communicate with the NPSS cycle analysis through partial performance maps (“mini-maps”) to obtain a balanced, steady-state engine condition. The balanced cycle model then provides boundary conditions to each 3-dimensional engine component simulation to enable them to operate correctly in the full engine simulation. The mini-maps are generated from 1-dimensional meanline programs whose input data is obtained automatically from the isolated 3-dimensional component’s flow solutions.

Two approaches were developed for the mini-map generation. In the first, APNASA and NCC are run at a small number of operating conditions by varying their inlet and/or exit boundary conditions. Their output is then area averaged to generate the individual map points. This option has been replaced by the next approach due to noise in convergence and the computational time required for the mini-map creation. In the second approach, the data from the 3-dimensional component simulations is extracted and used as input to the 1-dimensional meanline programs. For example, in the high pressure compressor the pressure ratio and efficiency are input for each stage along with the absolute flow angle at the meanline into each rotor. The hub and casing radii are also input at the inlet and exit of each rotor. The rotor and stator leading edge angles at the meanline are input to define the incidence angles which are used along with the solidity in an efficiency loss correlation. The meanline program then generates the high pressure compressor pressure ratio and efficiency at corrected flows and speeds that vary by plus and minus a few percent around the selected operating point. A schematic diagram of the data flow is shown in Figure 3.

Simulation Environment

The multi-fidelity, full engine simulations require that massive amounts of data be pre-processed to set-up and execute the simulations and to be post-processed to analyze and interpret the results so meaningful assessments and corrective actions can be made regarding the system. This can occupy a significant amount of the designer and analyst’s time, leaving little time available to understand the results of the simulation and to develop innovative and creative solutions to problems that may exist with the design. Even today with traditional simulations performed at lower levels of fidelity, as much as 50 to 60% of a designer or analyst’s time is spent pre- and post-processing data associated with the simulation. To address this problem, NPSS has incorporated software engineering methodologies to remove the burden of the data handling from the designer and analyst through improved software design and implementation of data interface standards.

The NPSS Team has adopted a formal software development process that involves formal requirements definition, design reviews, verification and validation throughout the software development process, and acceptance reviews of the final product by the end-user. The Team is composed of members from the end-user organizations representing both propulsion and software engineering disciplines. The end-users of NPSS are NASA, DOD and the US aerospace industry. Involvement of the end-user throughout the software development process is essential to ensure that the technologies are effectively transferred and implemented.

The requirements for the simulation environment are recorded in a systems requirements specification document that is eventually approved by representatives of all of the end-user organizations. The requirements describe in detail what is expected of the software in the areas of multi-fidelity, multi-disciplinary, full system simulations. These cover aspects of system components to be included in the simulations, user interfaces, computing platforms, distribution of simulations, geometry definition, and standard libraries and interfaces.

The analysis of the requirements drove the software design to be based upon the object-oriented paradigm written in the C++ programming language. This approach greatly simplifies the definition of the data interfaces and enables new methods and components (i.e. objects) to be easily added to the system. In addition, the organization of the software is much more intuitive since the components of the physical system being modeled can be mapped directly onto the object class hierarchy used in the design of the software. Other benefits of the object-oriented programming include rapid object creation, duplication, and customization, by an interpretive engineering environment provided in the architecture, an ability to build much larger simulations resulting from the ease of “plugging in” large, complex models, and ease of distributing components and subsystems of the simulation across remote locations. The latter is an important characteristic of NPSS that greatly facilitates partnering and collaboration in the development of airbreathing engines. Standard representations of engine systems, subsystems and components are available through NPSS to streamline the data exchange process[3].

The simulation environment is being developed through a series of software releases. The first release, NPSS V1, was in March 2000. V1 represents the basic software infrastructure to facilitate the implementation of all of the planned NPSS capabilities. In addition, V1 possesses the functionality of 0-dimensional aerothermodynamic engine analysis commonly referred to as a (Brayton) cycle analysis. As a result, the end-users are implementing V1 into their design systems to meet current engine cycle analysis requirements and to enable incorporation of high-fidelity computational tools into full engine simulations in the near future.

Full Engine Simulation

The full engine simulation was performed on the GE 90-94B engine at sea-level take-off condition. The simulation includes 49 blade rows of turbomachinery and 24 degree sector of the combustor. The sector represents the smallest combustor segment to achieve periodicity. The fan is 120 inches in diameter. The fan outlet guide vanes vary in camber around the engine annulus. A nominal vane shape was selected to simplify the computation. The booster consists of 3 stages (7 blade rows). A frame strut separates the booster and high pressure compressor (HPC), which consists of 10 stages (21 blade rows). The HPC is built upon the simulation performed by Adamczyk[4]. The combustor is dual dome annular design consisting of 30 pairs of fuel nozzles around the annulus. Due to periodicity, only 2 pairs of the fuel nozzles (a 24 degree sector) was modeled. The combustor simulation is described by Liu[5], by Ryder[6], and by Ebrahimi[7]. The level of complexity of the simulation is illustrated by the combustor graphic shown in Figure 4. The 2-stage (4 blade row) high pressure turbine (HPT), the mid-frame strut, and the 6-stage (12 blade row) low pressure turbine (LPT) are modeled as a single component. The turbine simulation is described is in detail by Turner et al.[8], with the exception that the actual combustor exit profiles were used as the turbine inlet boundary condition and the shaft speeds were set to match values computed by the NPSS cycle simulation.

The full engine simulation is executed by initially running the NPSS 0-dimensional (parametric) cycle model to a steady-state power balance near the GE 90-94B take-off point using the mini-maps. Engine inlet, component exit boundary conditions, and shaft speeds from the NPSS model are used to define the boundary conditions for the full engine 3-dimensionsal model. The boundary conditions are applied to the 3-dimensional CFD models through the APNASA and NCC input files. An auxiliary NPSS program is used to automatically extract the desired parameters from the cycle model and generate the input test files. The 3-dimensional full engine model is then simulated by executing the 3-dimensional component models in an upstream to downstream sequence. The loosely coupled CFD component models exchange radial profile boundary conditions at the inlet and the exit plane of each adjacent component.

The coupling between the APNASA and the NCC codes takes place at the interface plane between component boundaries. Several key quantities are conserved from one code to the next, including mass averaged total enthalpy, mass flow, toatal enthalpy, and total pressure. For turbomachinery, angular momentum is also conserved. At the compressor-combustor interface, the compressor exit is gridded with a structured polar mesh to eliminate interpolation errors between the structured and the unstructured meshes of the APNASA and the NCC codes, respectively. This approach also, it should be noted, increases the accuracy of the circumferential mass averaging. A similar approach is used at the combustor-turbine interface[9].

Computing Platform

The ability to effectively execute the large-scale simulations in a design environment is dependent upon the availability of high-performance and low-cost computing[10]. Since the approach adopted by NPSS is based upon parallel processing, the computing platforms currently under investigation to achieve high levels of parallel processing are the shared memory architectures of the Silicon Graphics Origin family of computers and the distributed memory architectures of clusters of personal computer (PC) processors. The benchmark case for the simulation described in this paper was executed in less than 11 hours on the 512 processor SGI Origin 3000 (CHAPMAN) located at the NASA Ames Research Center[8]. The PC cluster for comparison is the AEROSHARK cluster at the NASA Glenn Research Center. AEROSHARK contains 128 processors (1.7 GigaHertz processor speed, 64 GigaByte total memory, 2000 Megabits per second network speed). The advantage of the PC cluster over the shared memory machines is low cost. The performance to cost ratio of AEROSHARK relative to the Origin 3000 is in excess of a factor of 10 (Ref. 3). All of the analysis codes required for the simulation also run effectively on the AEROSHARK PC cluster at the NASA Glenn Research Center. However, the full engine simulation was not executed on AEROSHARK.

Results

The multi-fidelity simulation described in this paper consists of coupled 0-dimensional, 1-dimensional and 3-dimensional analyses of the GE 90-94B engine components at sea-level take-off condition. In a comparison of 131 key cycle parameters, the NPSS cycle model deviated no more than 0.5% from the GE baseline data, with a majority of the parameters deviating less than 0.01 % from the baseline[9]. The comparison of the full 3-dimensional CFD simulation with the engine cycle data at the component interfaces is shown in Figure 5. Note that the maximum deviation is less than 5% which occurs in combustor temperature rise and pressure drop. Both of these variances are related to the component simulation and possibly linked to assumptions made in modeling of the cooling holes. This deviation is considered within the acceptable range to provide valuable information to the engineering design and development process.

Conclusions

The advancement in computing and communications technologies has enabled significant progress to be made in performing high-fidelity simulations of complex systems in the design environment. The application of these technologies to airbreathing propulsion systems has been demonstrated through the Numerical Propulsion System Simulation. The implementation of parallel processing on low-cost PC clusters is enabling significant reductions in the 3-dimensional analysis of compressors. This advancement coupled to the application of software engineering to the development of new analysis tools is enabling large subsystems, like a high-pressure core engine, to simulated in less than 15 hours. The application of computing and communications technologies to airbreathing engine simulations will continue produce major advancements leading to routine use of 3-dimensional simulations of complete engines in the near future.

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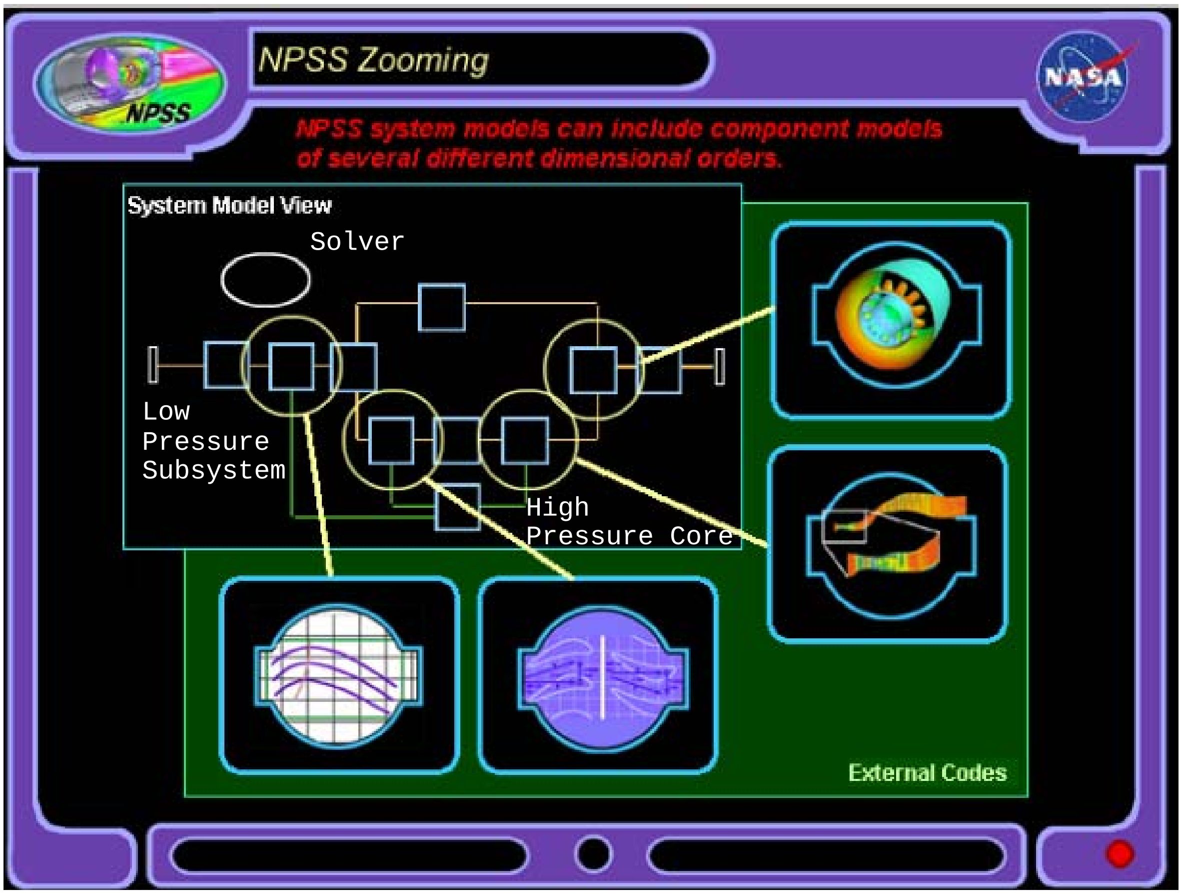


NPSS Zooming

NPSS system models can include component models of several different dimensional orders.

Figure 1. The illustration represents the NPSS simulation environment as a modular, “plug ‘n play” environment for linking codes of various fidelity into a full system simulation.

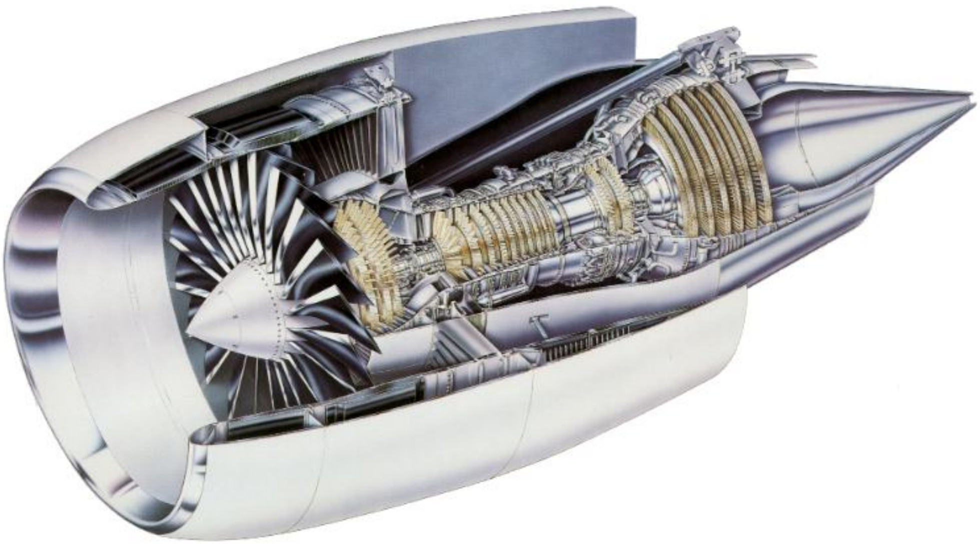


Figure 2. The illustration shows the GE 90 – 94B high bypass ratio turbofan engine being modeled with the NPSS.

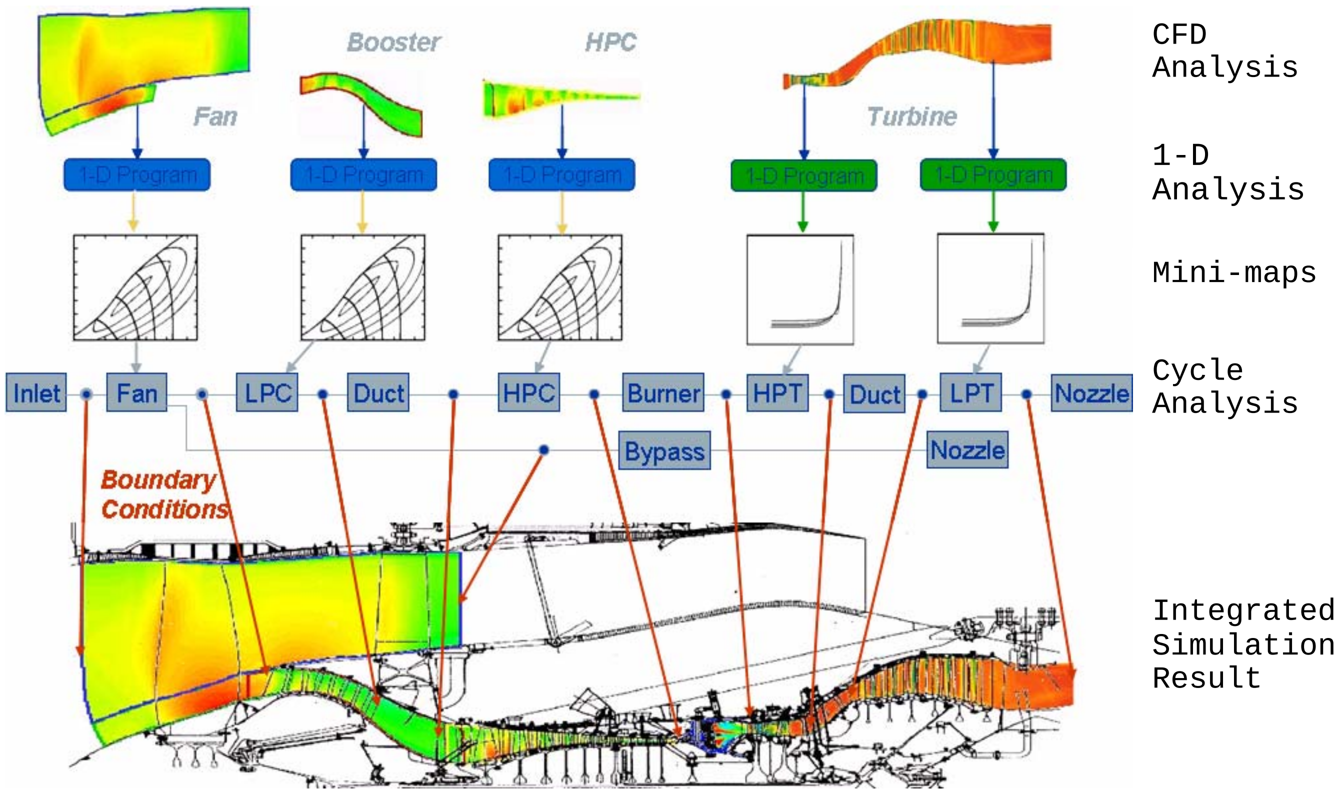


Figure 3. The illustration shows the data flow amongst the NPSS V1.6 engine cycle code, the 1-dimensional analysis codes, the 3-dimensional CFD codes, and the “mini-maps”.

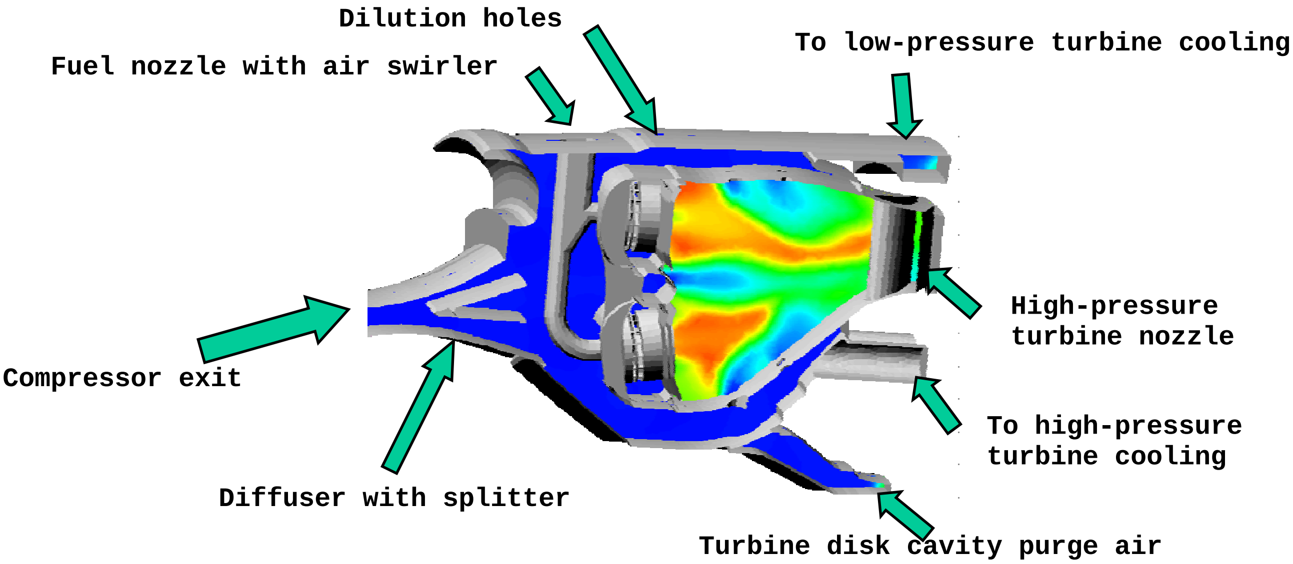
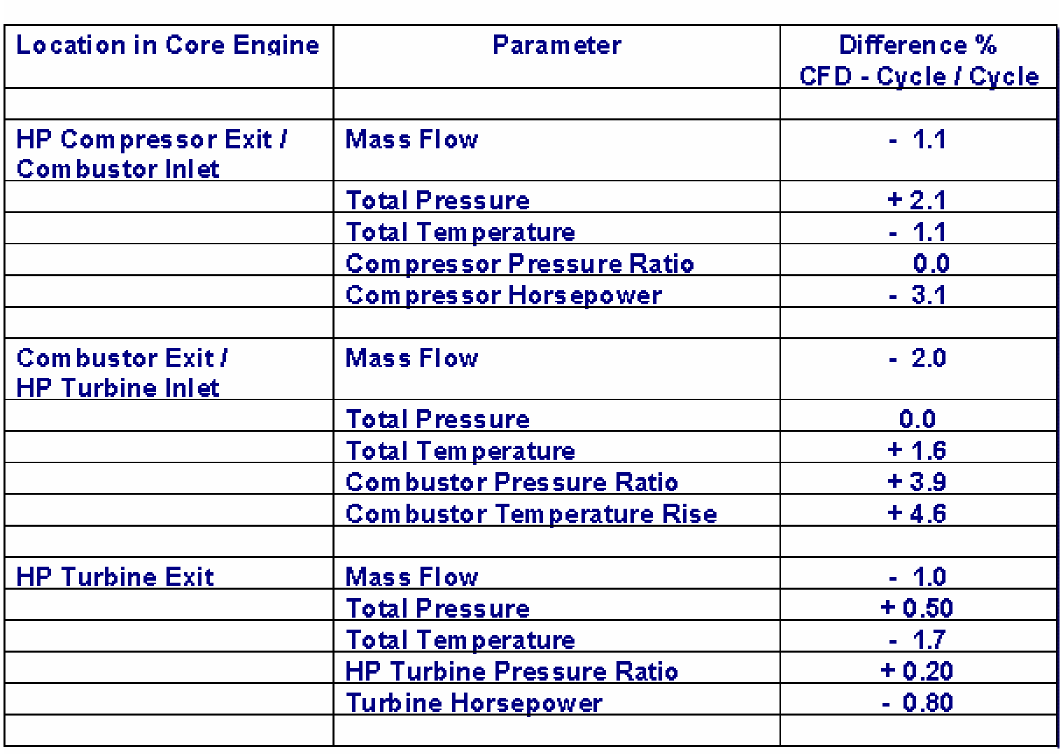


Figure 4. The illustration shows the combustor elements being modeled in the NPSS core engine simulation.



Location in Core Engine	Parameter	Difference % CFD - Cycle / Cycle
HP Compressor Exit / Combustor Inlet	Mass Flow	- 1.1
	Total Pressure	+ 2.1
	Total Temperature	- 1.1
	Compressor Pressure Ratio	0.0
	Compressor Horsepower	- 3.1
Combustor Exit / HP Turbine Inlet	Mass Flow	- 2.0
	Total Pressure	0.0
	Total Temperature	+ 1.6
	Combustor Pressure Ratio	+ 3.9
	Combustor Temperature Rise	+ 4.6
HP Turbine Exit	Mass Flow	- 1.0
	Total Pressure	+ 0.50
	Total Temperature	- 1.7
	HP Turbine Pressure Ratio	+ 0.20
	Turbine Horsepower	- 0.80

Figure 5. The comparison of engine properties computed by the integrated 3-dimensional CFD analysis to the engine cycle analysis.