



Towards an Automated Full-Turbofan Engine Numerical Simulation

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TOWARDS AN AUTOMATED FULL-TURBOFAN ENGINE NUMERICAL SIMULATION

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Abstract

The objective of this study was to demonstrate the high-fidelity numerical simulation of a modern high-bypass turbofan engine. The simulation utilizes the Numerical Propulsion System Simulation (NPSS) thermodynamic cycle modeling system coupled to a high-fidelity full-engine model represented by a set of coupled three-dimensional computational fluid dynamic (CFD) component models. Boundary conditions from the balanced, steady-state cycle model are used to define component boundary conditions in the full-engine model. Operating characteristics of the three-dimensional component models are integrated into the cycle model via partial performance maps generated automatically from the CFD flow solutions using one-dimensional meanline turbomachinery programs. This paper reports on the progress made towards the full-engine simulation of the GE90-94B engine, highlighting the generation of the high-pressure compressor partial performance map. The ongoing work will provide a system to evaluate the steady and unsteady aerodynamic and mechanical interactions between engine components at design and off-design operating conditions.

Introduction

The NASA Glenn Research Center is developing the capability to decrease aerospace

product development time through the use of computational simulation technology known as the Numerical Propulsion System Simulation (NPSS). NPSS will be capable of analyzing the operation of a propulsion system in sufficient detail to resolve the effects of multidisciplinary processes and component interactions currently only observable in large-scale tests¹. The ultimate goal of NPSS is to create a "numerical test cell" that enables engineers to examine various design options without having to conduct costly and time-consuming real-life tests. As a result, NPSS will dramatically reduce the effort and expense necessary to design and test aircraft engines.

Historically, the design of an aircraft engine begins with a study of the complete engine using a relatively simple aerothermodynamic "cycle" analysis. The operating characteristics of the engine's components (fan, compressor, turbine, etc.) are represented in the study by performance maps, which are based on experimental test data. As the process moves forward, the design of the individual engine components is further refined, simulated and experimentally tested in isolation by component design teams. These results are then used to calibrate the component performance maps and improve the cycle analysis of the complete engine. The process continues, with component designs being refined, until both component and engine performance goals are met.

Component design teams rely on advanced numerical techniques to understand component operation and achieve the best performance. Streamline curvature methods², which calculate flow properties at multiple streamlines across the component's span, continue to be widely used in turbomachinery design and analysis. More recently, improvements in the speed and availability of computer processors have enabled advanced two- and three-dimensional numerical techniques to be applied to the design of isolated components. Methods for simulating multistage turbomachinery have also been developed, and are now being applied in the design process³⁻⁵.

While advanced numerical simulations of isolated components may yield detailed performance data at unique component operating points, they do not systematically account for interactions between engine components. Overall engine performance is dependent on the components working together very efficiently over a range of demanding operating conditions, and several components are sensitive to interactions with adjoining components. For example, compressor performance is very sensitive to steady inlet and outlet flow conditions, and abrupt flow changes in the compressor can unstart a supersonic inlet.

Consequently, it is important to consider the engine as a system of components which influence each other, and not simply isolated components. Although performance maps attempt to capture component interactions, a high-fidelity full-engine simulation can provide more details about component interactions. Towards that end, the present work was undertaken to extend engine simulation capability from isolated components to the full engine, by integrating advanced component simulations to form a full, three-dimensional turbofan engine simulation.

The detailed simulation of a complete aircraft engine requires considerable computing capacity. A three-dimensional (3-D), viscous, unsteady aerodynamic simulation of a gas turbine engine requires approximately 10^{12} floating-point operations per second (FLOPS) with multidisciplinary analysis two to three times that value⁶. Today, this computing power is available in a few, expensive supercomputers with large numbers of processors. This capacity is also beginning to appear in the form of grid computing⁷⁻⁹, in which large numbers of commodity workstations and personal computers are linked via fast networks to form distributed computing systems. In order to be an effective design tool, the wall-clock execution times for a full engine simulation must be reduced to the point where it can impact the design process. This translates into

approximately 15 hours so that the simulation may be run overnight.

In addition to providing high-performance computing capabilities, other approaches, such as improved modeling techniques, are necessary to reduce the computing requirements for detailed simulation of the entire engine. One technique being explored in NPSS research is variable complexity analysis. Variable complexity analysis, which is referred to as "zooming" in NPSS publications¹⁰⁻¹², allows a designer to vary the level of detail of analysis throughout the engine based upon the physical processes being studied. For example, the effects of changing the shape of a fan blade on engine performance may require a three-dimensional simulation of the fan. The remainder of the engine may be modeled at lower levels of detail to minimize simulation setup and execution time¹⁰.

In this paper, we describe the progress we have made towards demonstrating an automated three-dimensional aerodynamic simulation of a complete turbofan engine. The simulation is comprised of coupled 3-D, computational fluid dynamics (CFD) component simulations for both the core and bypass flow paths. We also utilize a form of variable complexity analysis to reduce setup and simulation times for the 3-D analysis by coupling a cycle model to the 3-D model. The cycle model uses partial performance maps ("mini-maps") to obtain a balanced steady-state engine condition. The balanced cycle model then provides boundary conditions to each 3-D engine component to enable them to operate correctly in the full engine simulation. The mini-maps are generated from 1-D meanline programs whose input data is obtained automatically from the isolated 3-D component's flow solutions.

In addition to demonstrating a high-fidelity simulation system capable of identifying component interactions through aerodynamic coupling, this approach has the potential capability to demonstrate mechanical coupling by obtaining a power balance in the CFD model — a requirement generally neglected in reported full engine simulations.

Methodology

The GE90-94B turbofan engine, which is a production engine offered on the Boeing 777-200ER aircraft, was used in this demonstration (see Fig. 1). A sea-level, Mach 0.25, take-off condition was selected for the simulation. The main reason for this selection was that cooling flows for the turbine represent a significant amount of boundary condition information for the simulation, and these are well known at take-off. It also represents a condition where there are the highest temperatures and most

stress in the engine, and is therefore an important point to simulate.

The automated full-turbofan engine simulation utilizes the NPSS¹³ thermodynamic cycle system modeling software along with toolkits developed for NPSS, to couple the high-fidelity 3-D CFD software. NPSS is a component-based, object-oriented, engine cycle simulator designed to perform cycle design, steady state and transient off-design performance prediction.

An NPSS engine model is assembled from a collection of interconnected *elements* and *sub-elements*, and controlled by an appropriate numerical solver. The model is defined using the NPSS programming language, and executed in interpreted or compiled form by the NPSS software. For the GE90-94B, the NPSS model consists of forty-three elements representing the primary and secondary bleed flow, shaft and control system components. The input data for the model was obtained from a General Electric cycle model of the GE90-94B at the take-off conditions described above. This data was also used to verify and validate the NPSS model.

The high-fidelity full-engine model consists of three-dimensional CFD models of the fan, booster, high-pressure compressor (HPC), combustor, high-pressure turbine (HPT) and low-pressure turbine (LPT). The combustor model is simulated using the National Combustor Code¹⁴⁻¹⁷ (NCC) combustor model, while the turbomachinery component models are simulated using APNASA¹⁸ software. All turbomachinery component simulations have been analyzed and compared with GE90 component test data to validate and calibrate the simulation. These efforts have been presented by Turner¹⁹, Turner et al.²⁰, and Adamczyk³.

NCC is a parallel-unstructured solver that uses a preconditioner to efficiently handle low Mach number flows. The Navier-Stokes equations are solved using an explicit four-stage Runge-Kutta scheme. Turbulence closure is obtained via the standard $k-\epsilon$ model with a high Reynolds number wall function, or a non-linear $k-\epsilon$ model for swirling flows.

NCC can be run with a gaseous fuel or by modeling the spray combustion process. Several combustion models have been implemented in the software, including finite-rate reduced kinetics for Jet-A and methane fuels, thermal emissions for nitrogen oxides, and a turbulence-chemistry model which solves the joint probability density function for species and enthalpy.

The average passage approach of Adamczyk¹⁸, is incorporated into the APNASA program. The foundation of the APNASA Navier-Stokes solver is an explicit four-stage Runge-Kutta scheme with local time-stepping and implicit residual smoothing to

accelerate convergence. Second and fourth difference smoothing as applied by Jameson²¹ is employed for stability and shock capturing. A $k-\epsilon$ turbulence model is solved using an implicit upwind approach similar to that presented by Turner and Jennions²² and Shabbir et. al.²³. Wall functions are employed to model the turbulent shear stress adjacent to the wall without the need to resolve the entire boundary layer.

Mini-map Generation

As described in the introduction, performance characteristics of the 3-D CFD components are represented in the cycle simulation by partial performance maps. These “mini-maps” define component operating characteristics over a small operating range around some desired point. They provide a physics-based estimate of component performance and replace the default maps within the NPSS cycle model.

Two approaches were developed for the mini-map generation. In the first, the APNASA and NCC programs are run at a small number of operating conditions by varying their inlet and/or exit boundary conditions. The flow solutions are then area-averaged to generate the individual map points. This option has now 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, data from the 3-D multistage simulations is extracted and used as input to one-dimensional (1-D) meanline programs. This has been demonstrated for the HPC. The APNASA model and its flow solution are post-processed to obtain input data for a 1-D meanline stage-stacking program (STGSTK)²⁴ which generates a compressor mini-map. The pressure ratio and efficiency are input for each stage along with the absolute flow angle at the mean line into each rotor. The hub and casing radii are needed at the inlet and exit of each rotor. The rotor and stator leading edge angles at the meanline are also input to define the incidence angles which are used along with solidity in an efficiency loss correlation. The code has been modified slightly to allow additional output and to input a design bleed amount so that the solution from an APNASA simulation can be used to define the “design” point in order to create individual stage characteristics and to stack the stages together to create an overall compressor map. Two other modifications to the code were also made to allow it to work with the 10-stage GE90-94B HPC compressor, and to be consistent in the definition of efficiency.

In order to be as consistent as possible between the high fidelity APNASA simulation and the STGSTK code, the post processing has been done in the following way:

1. Stations between the blade rows are used to define the hub and case radii. This same station is post-processed in the 3-D simulation.
2. The following are defined at each station by integrating the flowfield: The mass-averaged values of total pressure ($\overline{P_T}$), total enthalpy ($\overline{H_T}$), and angular momentum ($\overline{rV_\theta}$). The mass flow rate (\dot{m}) and the annular area (A_z) are also needed. The annular area comes from the hub and tip radii (r_t and r_h). Quantities with an under-bar are derived.

$$A_z = \pi(r_t^2 - r_h^2) \quad (1)$$

$$r_m = \sqrt{r_t^2 - \frac{A_z}{2\pi}} \quad (2)$$

$$V_\theta = \frac{\overline{rV_\theta}}{r_m} \quad (3)$$

$$\overline{\rho V_z} = \frac{\dot{m}}{A_z} \quad (4)$$

$$V = \sqrt{V_z^2 + V_\theta^2} \quad (5)$$

where the radial component of velocity is ignored in STGSTK and this analysis.

$$h = \overline{H_T} - \frac{V^2}{2} \quad (6)$$

T and T_T come from h and $\overline{H_T}$ and the enthalpy-temperature relation used in APNASA.

$$P = \overline{P_T} \frac{T}{T_T}^{(\gamma/(\gamma-1))} \quad (7)$$

$$\rho = \frac{P}{RT} \quad (8)$$

$$V_z = \frac{\overline{\rho V_z}}{\rho} \quad (9)$$

Equations (5)-(9) are iterated to convergence.

$$W_\theta = V_\theta - r_m \omega \quad (10)$$

$$\alpha = \tan^{-1} \frac{V_\theta}{V_z} \quad (11)$$

$$\beta = \tan^{-1} \frac{W_\theta}{V_z} \quad (13)$$

This equation system is evaluated at each station, and the meanline flow angles are input into STGSTK.

Currently, the fan, booster, HPT and LPT performance maps used in the cycle simulation are based on experimental data of similar components. These will be replaced with mini-maps generated in the same manner as the HPC.

Full Engine Simulation Process

The full-engine simulation is executed by first running the NPSS cycle model to a steady-state power-balance near the GE90-94B take-off point using the mini-maps. Engine inlet, component exit boundary conditions, and shaft speeds from the converged NPSS model are used to define the boundary conditions (BCs) for the full-engine 3-D model. The BCs are applied to each 3-D model 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 new input text files. The 3-D full-engine model is then simulated by executing the 3-D component models in an upstream to downstream sequence. The loosely-coupled CFD engine component simulations exchange radial profile boundary conditions at the inlet and exit plane of each adjacent component. This process is illustrated in Figure 6.

Execution of the 3-D CFD programs (and other auxiliary programs) is currently handled by a set of NPSS classes²⁵. These classes set-up and submit the APNASA and NCC programs as Portable Batch System²⁶ (PBS) jobs to a host computer, execute the programs, and manipulate files (such as "flip"ing the APNASA output files). Figure 2 shows a simplified flowchart illustrating how the APNASA Fan model is simulated using these classes (other components are handled similarly). The APNASA program, using mesh files and other input files, generates a set of flow solution files. The APNASA circumferential averaging tool, APNASACAT, uses these files to generate the 2-D averaged flow solution. This data is then used by a profile generator program to create a radial profile of the flow, which is concatenated with a user-defined input file to form the common input file for the next sequential component (in this case the booster). This process is repeated for each 3-D component in the engine model except for the following: 1) no averaging is performed, nor radial profile generated for the LPT, and 2) no radial profile is generated by the HPC for the combustor. Special processing is required between the HPC and combustor due to differences in modeling methodologies between APNASA and NCC.

APNASA and NCC Component Coupling

Coupling between the APNASA and NCC codes takes place at an interface plane. Several key quantities are conserved from one code to the next, including mass flow, mass-averaged total enthalpy, total 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 unstructured meshes of the APNASA and NCC codes, respectively. This approach also increases the accuracy of the circumferential mass-averaging. A similar approach is used at the combustor-turbine interface. Special modeling techniques have been developed to deal with the strong variation in the blade-to-blade plane in the turbine simulation due to the potential effects of the thick turbine nozzle, and to account for combustor reactions at the turbine inlet.

Results

Currently we have completed both the cycle and high-fidelity engine simulations of the GE90-94B at seal-level take-off condition. The NPSS model of the GE90-94B has been developed, tested and verified against GE cycle data. In a comparison of 131 key cycle parameters, the NPSS 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. The model has also been run successfully at several off-design conditions using the HPC mini-map. However, no GE off-design data was available, so off-design operation has not yet been validated.

NPSS utility classes have been written to take the converged cycle model component's boundary conditions and generate input files for the APNASA and NCC components, and the NPSS code needed to execute the 3-D components in an automated manner on a single machine using the PBS queuing system is complete.

A mini-map has been created for the GE90-94B HPC by supplying input from the 3-D APNASA HPC simulation to the modified 1-D meanline stage-stacking code, STGSTK. The resulting mini-map is shown in Figures 3 and 4. The APNASA simulation is near choke at what is shown as the 100% line; all corrected speeds quoted are relative to this value. Five speed lines have been run, each of which are 1% different. The current take-off cycle point is also shown. The cycle point is about 2.5% higher in flow, and with a slightly higher pressure ratio at 100% corrected speed. Figure 4 shows the efficiency. The highest level of efficiency is at the APNASA level since the input corresponds with a "design" point. For qualitative comparison, the GE Energy Efficient

Engine (EEE) high-pressure compressor map is shown in Figure 5. Off-design points, roughly corresponding to cruise (0.84 Mach, 35,000 ft., same thrust level), are also shown in Figures 3 and 4. The EEE@35K point was generated using a scaled EEE HPC performance map (99.1% corrected speed); the GE90@35K point was generated using the GE90-94B HPC mini-map. The final point, GE90@0K, was created by running the cycle model at take-off conditions using the HPC mini-map. The HPC mini-map represents a slightly different compressor than would otherwise be used in the cycle. Consequently, the cycle balances the engine differently. These differences are small and represent how this system can be used in a predictive way. The difference in total temperature at the LPT inlet for the EEE@35K and GE90@35K cases was 11.33°R, and 14.53°R between the Cycle and GE90@0K cases. These temperatures are often used in production engine tests and differences like these can be seen from engine to engine. The use of the HPC mini-map in the cycle simulation makes the cycle more consistent with the 3-D engine model. With the addition of the remaining mini-maps, the cycle and 3-D engine model will be fully consistent.

The high-fidelity 3-D full-engine simulation consists of 49 blade rows of turbomachinery and a 24-degree sector of the combustor. The fan is 120 inches in diameter and consists of 22 composite wide-chord blades. The fan outlet guide vane (OGV) has several types with differing camber; only the nominal type is modeled in the simulation.

The booster consists of 3 stages (7 blade rows). A frame strut separates the booster and HPC, which consists of 10 stages (21 blade rows). The HPC simulation in this full-engine simulation is built on the HPC component simulation presented by Adamczyk³.

The combustor is a dual dome annular design consisting of 30 pairs of fuel nozzles around the annulus. Due to periodicity of the geometry, only 2 pairs of the fuel nozzles (a 24-degree sector) need be modeled. The combustor simulation is explained by Liu¹⁵, Ryder and McDivitt¹⁶, and Ebrahimi et al.¹⁷

The 2-stage (4 blade rows) high pressure turbine (HPT), the mid-frame strut, and the 6-stage (12 blade rows) low pressure turbine (LPT) are modeled as a single component. The turbine simulation is identical to that reported by Turner et al.²⁰, except that the combustor profiles have been used as a boundary condition and the shaft speeds were set to match values defined by the NPSS cycle simulation.

Figure 6 (top) shows a contour plot of the axisymmetric-averaged normalized pressure overlaid on the GE90-94B engine geometry. This data is representative of the detailed output generated by the full-engine simulation.

Conclusions and Future Work

This paper has presented the progress made towards the automated 3-D simulation of the full GE90-94B turbofan engine. Three-dimensional CFD simulations of the fan, booster, HPC, HPT and LPT have been performed using APNASA turbomachinery code. The combustor flow and chemistry were simulated using the National Combustor Code, NCC. A cycle model of the engine was developed and verified, and used to provide boundary conditions to the 3-D CFD component simulations for the 0.25 Mach, sea-level take-off condition.

A new method was presented for generating partial performance maps (mini-maps) by extracting data from the 3-D CFD flow solutions for use in a 1-D meanline program. This was demonstrated on the APNASA HPC component using a modified version of the stage-stacking program, STGSTK. The HPC mini-map was used successfully in the cycle model at both on- and off-design operating points. This modeling approach will significantly improve our ability to include physics-based data in the cycle model. For example, Reynolds-number effects can be extracted from the 3-D model and included, via mini-maps, in the cycle model. This in turn will improve the both the cycle and 3-D models by highlighting interactions in both models.

The next step in this research is to complete the mini-map generation for the remaining turbomachinery components. Fan and booster maps will be generated in the same fashion as the HPC using the modified STGSTK program. We are currently evaluating turbine meanline programs to use in generating the HPT and LPT mini-maps.

Using the mini-maps, we will then run the full simulation to reach a power-balance in the 3-D CFD engine model. One aspect of the simulation we expect to address at that point will be consistency between the CFD and cycle models. Beyond simply assuring that boundary and input parameters are identical, issues such as thermodynamic inconsistencies between APNASA, NCC and NPSS will need to be resolved. Other issues such as techniques for modeling bleeds must be addressed.

Currently, the turbomachinery simulations assume constant geometry so that CFD mesh files do not need to be regenerated. This limits the operation of the CFD models to a small operating region where geometry effects are not significant. For example, the variable stator vanes (VSVs) are designed to move according to a schedule based on operating conditions. To better simulate the interactions of components over the full range of engine operation, it would be desirable to allow grid regeneration.

The automated full-turbofan engine simulation is designed to be carried out in a distributed computing environment. In future simulations, the NPSS software, acting as the simulation master-controller, will be executed at the Glenn Research Center, while the APNASA and NCC software execute on NAS computers at Ames Research Center. A CORBA-based toolkit²⁷ being developed for NPSS, will be used to exchange the boundary condition data via the Internet, and to remotely control the execution of the APNASA and NCC software. In addition to the current PBS queuing capability, NPSS programs will be able to distribute the high-fidelity simulations onto NASA's Information Power Grid²⁸ (IPG), using Globus^{29,30}. This will allow the simulation to take advantage of grid-computing to improve simulation times.

Nomenclature

A	= annular area
h	= enthalpy
P	= pressure
r	= radius
R	= gas constant
T	= temperature
V	= velocity
\dot{m}	= mass flow rate
	= density
	= shaft rotational speed
	= specific heat ratio

Subscripts:

h	= hub
t	= tip
T	= total or stagnation conditions
$-$	= tangential
z	= axial

Superscripts:

$\overline{\quad}$	= mass-averaged
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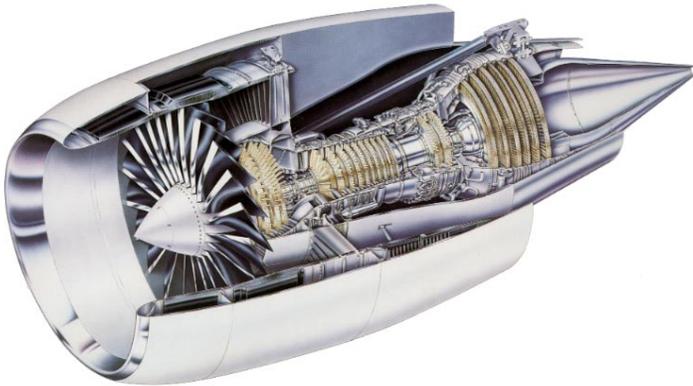


Figure 1.—Cutaway view of GE90 engine.

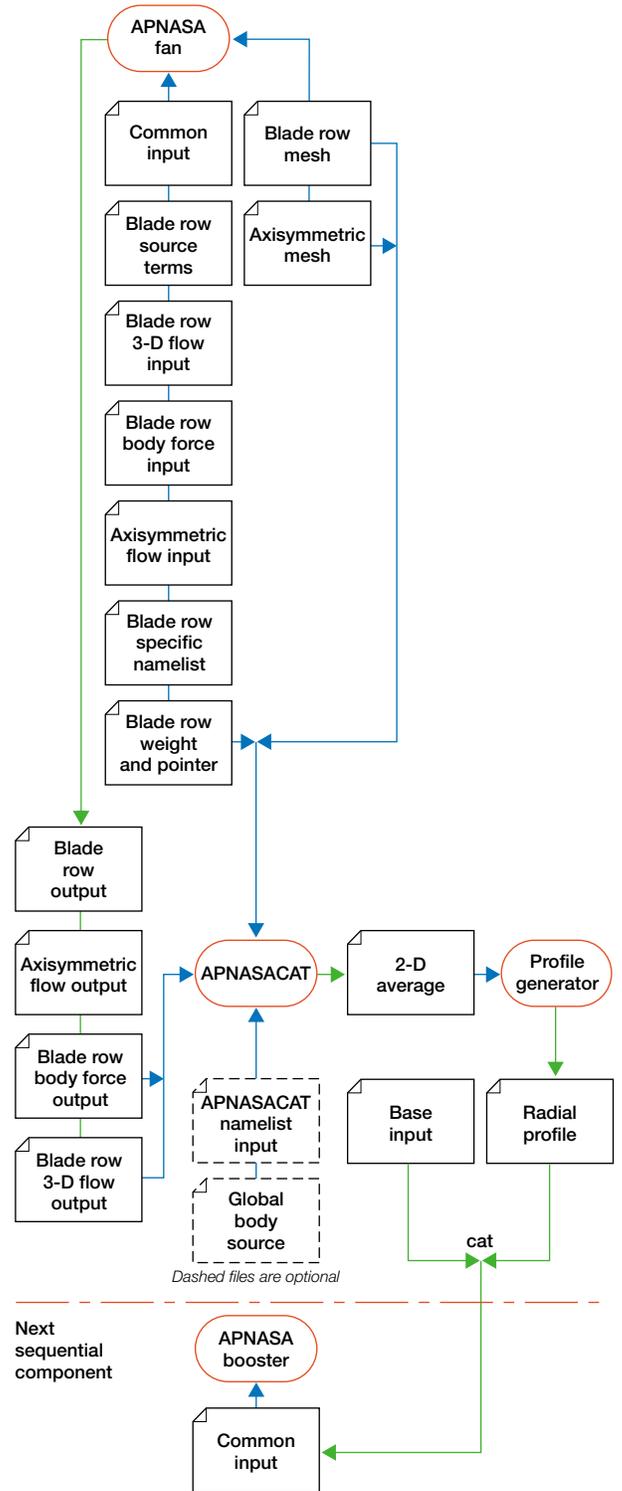


Figure 2.—Simplified flowchart illustrating how APNASA program is executed for the fan component. Darker lined boxes indicate user-supplied input files.

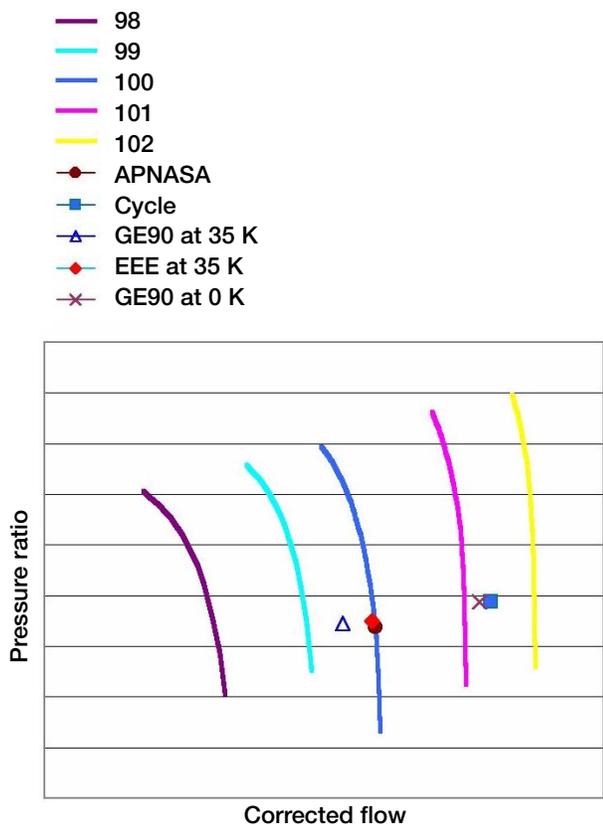


Figure 3.—Pressure ratio mini-map for HPC created from STGSTK code with inputs supplied by APNASA simulation.

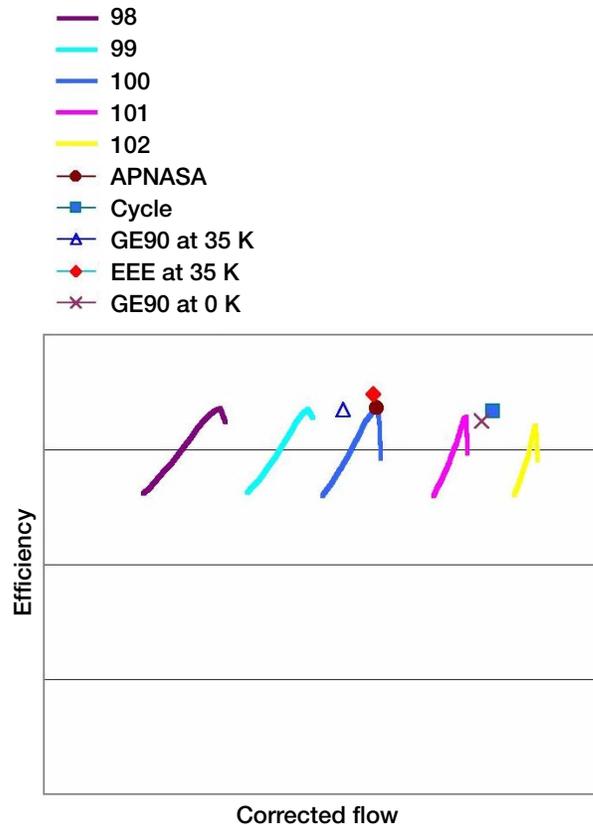


Figure 4.—Efficiency ratio mini-map for HPC created from STGSTK code with inputs supplied by APNASA simulation.

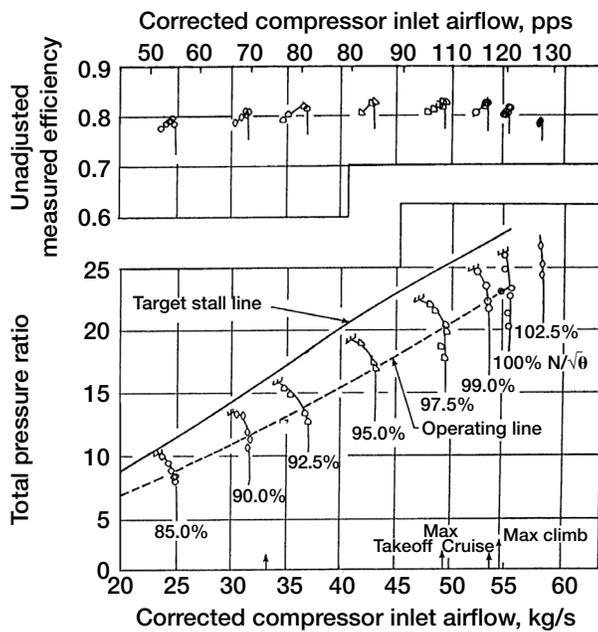


Figure 5.—Energy Efficient Engine (EEE) high-pressure compressor map (see ref. 31 for similar map).

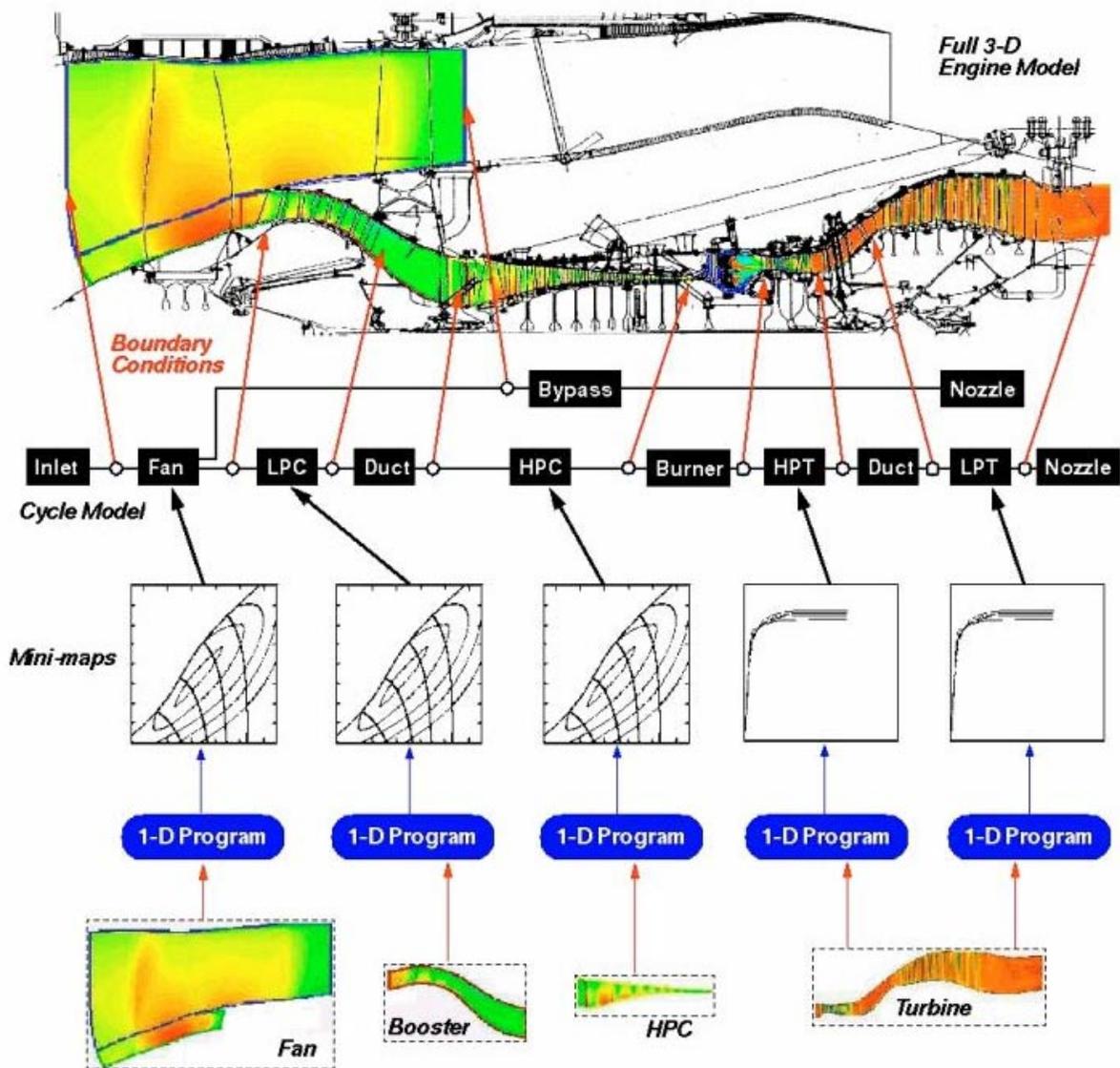


Figure 6.—Coupling of 3-D full engine model with 0-D cycle model. From bottom to top: 3-D CFD component model flow solutions are automatically used by 1-D meanline programs to generate mini-maps. Maps are included in appropriate components in GE90 cycle model. Converged cycle boundary conditions are used to set boundary conditions in CFD components for coupled full-engine simulation. Top of figure shows axisymmetric plot of absolute Mach number overlaid on GE90 engine geometry.

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