COUPLED HIGH-FIDELITY ENGINE SYSTEM SIMULATION

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Abstract

Modern aerospace products are driving the need for increasingly complex system simulations. However, foundational research on the best approaches to develop these complex simulations is sparse. This report will review various techniques that enable complex system simulation for, at least, one type of gas turbine engine. These simulations employ high and low fidelity simulations combined with integration software that couples component calculations into one unified representation of a complex system. We detail the physical and numerical challenges of simulating a modern aerospace gas turbine engine and compare our results with actual engine test data. To perform component improvement studies, the simulation must closely track the "real-world" performance of both the component and the system. Computational results demonstrate that this goal is dependent on the accuracy of each individual component calculation, but surprisingly resilient to some mis-matching of the simulation results across the various levels of analysis.

1 General Introduction

The traditional design and analysis procedure for complex, aerospace systems decomposes the system into a series of isolated components and focuses development on each single discipline or component. Consequently, the interactions that naturally occur between components and disciplines can be masked by the limited communication between teams or individuals doing the design and analysis. This can pose serious problems for today's highly integrated propulsion systems, where multidisciplinary issues can adversely impact the overall system performance. Typically, these problems are found late in the design process when early prototypes are tested under realistic operating conditions. If several design-test cycles occur, the new product is usually behind schedule and over-budget.

The Numerical Propulsion System Simulator (NPSS) [1] was created to address this problem. NPSS is a virtual test cell for propulsion system analysis and design. By harnessing the computing power of both inexpensive computing clusters [2] and high-performance computing [3] within an object-oriented software framework [4], NPSS can analyze a complete engine system at a variety of resolution levels. NPSS research has focused in three critical areas: 1) variable fidelity analysis (or "Zooming") allows the detailed examination of a critical performance element within the engine, 2) object-oriented framework permits the creation of complex software systems, and 3) multidisciplinary tools that enhance detailed analysis of critical components or sub-systems. This paper uses the NPSS framework and its multidisciplinary tools to assess the accuracy of variable fidelity analysis.

Recent high-fidelity simulations have demonstrated that complex aerospace systems, such as a gas turbine engine, can be analyzed within an over-night time frame [5]. This goal was achieved by employing a variable-fidelity analysis capability (i.e. "zooming") wherein high-fidelity, three-dimensional, CFD calculations are averaged and used to establish one-dimensional flow parameters where the system performance is balanced. This first detailed simulation was a tremendous achievement but important limitations in this demonstration limited the value of such a calculation in a "benchmarking" assessment. First, the calculations did not fully converge across all levels of analysis – only a single pass of data was exchanged between the various levels of analysis. Second, the process of transferring data across multi-levels of analysis involved significant manual analysis and translation. This type of process is potentially error-prone and generally difficult to replicate in other simulations. Third, the simulation was conducted at only one operating point, Sea Level Take-Off (SLTO). Many of the empirical correlations used in mean-line analysis are validated at only the design point. A fair assessment of analysis tools requires simulation at multiple engine operating points.

System analysis is challenging to validate. It requires accurate analysis of multiple components where a miscalculation in one component can adversely impact the overall system performance. Traditional component validation data is needed, such as three-dimensional velocity and temperature profiles, but also overall system performance parameters throughout the complete system. This combination of detailed and high-level system data is rarely available in the open literature. These systems are highly proprietary with highly-protected, key technologies that make the engine successful. Some engine component data is available from the government funded Energy Efficient Engine (EEE) efforts [6], however this effort terminated before a complete engine was developed. Even if a complete engine had been developed, the storage and synthesis of large volumes of systems data provides a significant barrier to a comprehensive assessment.

The following assessment uses engine data from the GE 90. Although the geometry and several component data remain proprietary, a recent Space Act [7] permits NASA to assess and improve systems analysis tools using the GE 90 engine data. In most of the data tables, computed values were normalized by the proprietary engine data. While the use of proprietary data limits some reportable information, it does not compromise the quality of the overall assessment.

The objective of this assessment was to determine the accuracy of current, state-of-the-art computer codes to predict engine system performance for a modern gas turbine engine. The goal is to have sufficient accuracy to numerically simulate the impact of small changes in component improvement (approximately one or two percent) on the overall system performance. For example, a one-percent improvement in adiabatic efficiency for a single component like a Low Pressure Turbine may result in a different operating speed that degrades the performance of another component (e.g. High Pressure Compressor), resulting in a potential total system degradation. To track these inter-component changes should require highly accurate simulations of the baseline geometry. This assessment examines the current capability to make such simulations.

2 NPSS

The multidisciplinary framework of NPSS is illustrated in Figure 1. It highlights the three primary characteristics of the simulation environment: coupling, integration and zooming. Coupling refers to the need to perform analysis among all relevant disciplines such as aerodynamics, structures, heat transfer, combustion, controls and materials. Integration involves uniting multiple component simulations into one total system. Finally, zooming enables the individual component simulations to be done at different levels of fidelity within the system simulation.

The NPSS framework makes extensive use of object-oriented programming principals. The primary cycle model uses component maps to capture component behavior (so called "zero" or "one dimensional" properties). The system model is written in an NPSS interpreted language that is modeled on an object-oriented language such as C++ or Java. Much of the typical component object properties and behaviors have been created and precompiled for gas turbine engines or similar power systems. The usage of precompiled objects greatly improves computational efficiency and users can create their own precompiled objects with custom data and behavior. An engine system model defines all the objects within the system to be simulated and how they are interconnected. For calculations requiring distributed / parallel processing, either Common Object Request Broker Architecture (CORBA), Message Passing Interface (MPI) or custom NPSS scripts are used. CORBA [8] is an object-oriented framework that uses Interface Definition Language (IDL) to define clear interface(s) between remote or local objects. It can be used to unite a complete system simulation (low computational demand) with a more detailed simulation of a single component or sub-system that uses extensive computing resources. More typically, a series of NPSS scripts are created that distribute simulations throughout a parallel computing architecture. The script can submit a job request that describes procedures to invoke a detailed analysis, such as a three-dimensional Computational Fluid Dynamics (CFD) analysis that uses MPI [9] to distribute work in a parallel computer.

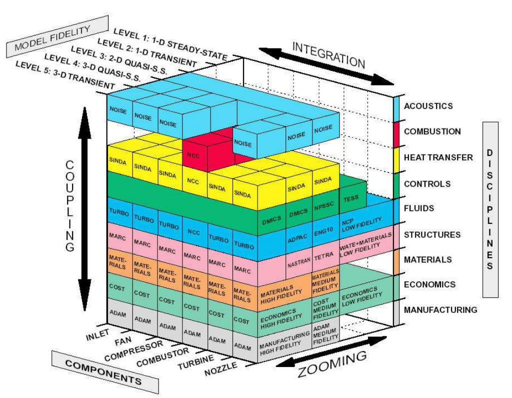

Figure 1. Illustration of the NPSS multidisciplinary framework.

3 Zooming

Zooming is the process of integrating high-fidelity numerical analysis with the overall (0 or 1D) engine system model. It is illustrated in Figure 2. Here a detailed CFD analysis called APNASA is used to generate a map that provides compressor subsystem performance data for a complete engine simulation. Component properties such as pressures, temperatures, and mass-flows are averaged in the three-dimensional analysis and used to generate the engine system compressor map. Transforming one-dimensional flow field data into three-dimensional flow conditions and vice versa is required and special care must be taken to ensure consistency of primary flow variables, such as mass-flow and enthalpy. Schemes that conserve mass and energy have been studied with success [4].

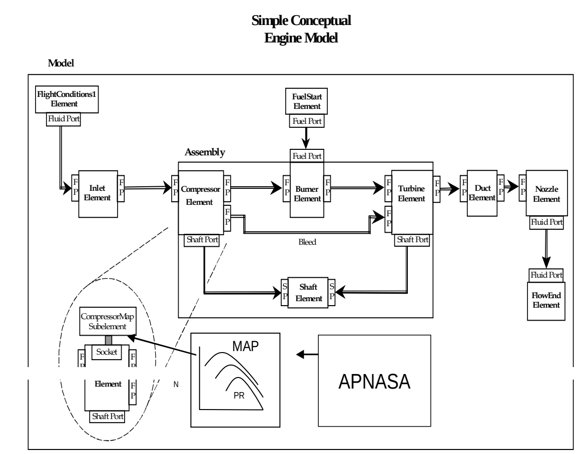

Figure 2. An illustration of the zooming process.

Previous efforts to simulate complete engine systems have either focused on a smaller sub-set of the entire system [2] or they have employed a single pass technique to transfer data from the high fidelity analysis into the 0D system models [5]. The term “single pass” refers to an approach were high fidelity 3D values are averaged and input into lower-level mean-line analyses only one time. When this technique is employed, the resulting performance maps created by the mean-line analysis have the potential to alter the operating point of the complete system. Indeed, this commonly happens for all the analyses studied in this report. The major drawback of this technique is that not all levels of analysis are fully converged and it is not clear how much the “first pass” results vary from fully converged final results.

For turbomachinery zooming examined in this assessment, three different approaches to create the “zoomed” maps, that transfer information from the high fidelity calculations to the 0D cycle analysis, are examined. One technique involved the use of so-called “mini-maps” that provide a component map that is matched to the CFD data, but provides operating performance data for only a small range around the CFD operating point (typically + or – 5 percent). This model was studied for the turbine component and is referred to as the Entropy Loss Model [5]. A second approach is to use a so-called generic performance map to represent component performance. These maps are frequently used in 0D cycle simulation to perform trade studies using component maps from historically archived data. A limitation of this technique is that the additional mean-line analysis data (such as inter-stage flow properties) is not available, although appropriate averaging of the 3D simulation can provide similar results. The main drawback to this technique is that extrapolation using historical data is likely to be inaccurate for new technology systems. A new compressor utilizing higher blade loadings is unlikely to be well represented using extrapolation from historical data.

The primary approach chosen to create “zoomed” maps involves averaging the 3D CFD information and using this data to develop new component maps using mean-line analyses. Mean-line analyses, STGSTK [10] and BRSTK [11] are used for compression systems and AXOD [12] is used for turbines. Each mean-line analysis code was initially set-up for the GE 90 geometry and flow conditions, then automated scripts were constructed using the NPSS scripting language [13] to transfer appropriate flow values between the detailed CFD analysis and the mean-line analyses.

AXOD is a mean-line turbine analysis code that has been extensively used since 1967 [12], yielding a series of validation test cases that span 3-4 decades. The most recently published test cases displayed excellent agreement between the Energy Efficient Engine (EEE) turbine and analytical predictions. General industry practice has concluded that AXOD can predict turbine performance to within one percent [14]. The difficulty with this code is that it was created for obsolete computer architecture in an old form of FORTRAN. While the backward compatibility of FORTRAN enables this code to execute and run on today’s computers, the coding was constructed to minimize memory usage and is extremely difficult to trace or follow.

AXOD is compared to the Entropy Loss Model of reference 5. This model was constructed in the NPSS scripting language and provides an excellent integration between the high fidelity, three-dimensional calculations and the 0D cycle simulation.

STGSTK [10] is a simple and robust code to analyze multi-stage compressors. Its strength is the ease of setup and the generally robust behavior of the solution algorithm. A weakness is the assumption that the compression system is running at its peak performance. Application of STGSTK to off-design operating points may compromise accuracy.

When STGSTK or AXOD are used to connect the three-dimensional CFD results to a cycle simulation, an averaging post-processor, APNASACAT, is used to extract one-dimensional values of the flow angles at each stage of the turbomachinery and mean values of flow properties, such as total and static pressure, temperature and enthalphy. These flow angles are input into the mean-line analysis and the appropriate mass flow and other state variables are supplied as input tables to the mean line analysis. For AXOD, the stator and rotor efficiencies / flow coefficients are initialized at the cycle values, and then iteratively adjusted to match the CFD values. These values of efficiency and flow coefficient are then fixed, and flow angles and input state values are adjusted during each cycle of the CFD to mean line to cycle and back loop. For STGSTK, APNASACAT generates an initial input file, with approximate metal blade angles. Then the “true” blade metal angles are determined from the flow angles (output by STGSTK) by adjusting the blade values until the incidence angle is zero. A final run is then performed to generate maps for the cycle analysis.

The detailed analysis code used for turbomachinery zooming was APNASA [16 and 17]. APNASA is a steady-state, three dimensional CFD code for turbomachinery employing the average-passage formulation to transfer averaged, body forces between the various stages of rotating machinery [16]. Key features include a multi-block calculation capability that provides geometric flexibility.

4 Full Engine Simulation Results

A complete-coupled, systems analysis that employs multiple levels of analysis and multiple components is a highly non-linear system. A good comparison might be made to the use of multi-grid algorithms used in fluid flow analysis to accelerate convergence of the non-linear flow equations. A zero-dimensional cycle analysis serves as a type of "course mesh" to improve communication between the "fine mesh" detailed component calculations. In principle, the complete system should converge to an accurate representation of the simulated engine as long as all the subcomponent models / maps are accurate and correctly interconnected. In practice, however, these simulations suffer from several different types of problems. First, it can be challenging to exactly match the operating characteristics of the detailed analysis with a composite map. These maps are a function of the shaft speed, component pressure and temperature ratio, and adiabatic efficiency. Depending on the zooming integration approach taken, substantially different results can be obtained between the detailed and the 0D maps. This will be discussed in subsection 4.1 of this report. Subsection 4.2 discusses the results of several engine simulations using the "zooming" techniques discussed previously (Section 3).

4.1 Multi-Level Matching

Ideally, matching system parameters between three-dimensional and zero-dimensional analyses should be straightforward. In practice, however, a number of sometimes small discrepancies can make the matching challenging. Figure 3 displays the normalized error (a summation of differences in component power, pressure ratio, temperature ratio and RPM) produced in a matching of the three-dimensional and zero-dimensional parameters. This error was driven to a minimum value using non-gradient based optimization scheme. As can be seen in the chart, the error does not monotonically diminish, but displays a discontinuous error profile that diminishes unevenly. In this case, a mean-line analysis (AXOD) is used to generate the zero-dimensional component map which is used as a surrogate for the high-fidelity calculations. The discontinuous objective function indicates that the AXOD output is non-linear and discontinuous. The empirical models and the differing thermodynamic properties in AXOD make it impossible to exactly match the three-dimensional and zero-dimensional properties, but a close approximation is obtained.

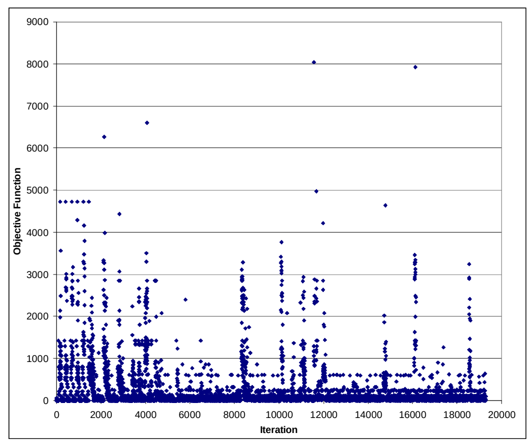

Figure 3. Optimization output of the AXOD matching process. Minimizing the objective function provides the best match between high-fidelity and cycle maps.

The component zooming technique employed can also result in significant mismatches between different calculated system variables. Figure 4 displays the component maps created using both map generation and map scaling for the Low Pressure Compressor (LPC) (details of the technique are provided in Section 3). Each map iteration is displayed in the figures with the 7th iteration (NcMap=7) reaching a converged state across all levels of analysis. These maps present the pressure ratio produced by the component as a function of mapped rotor speed. A comparison of two maps clearly indicates that the two zooming techniques result in significantly different operating characteristics. The map generation approach (using STGSTK) yields lower pressure ratios for the same rotor speed leading to a lower mass flow as illustrated in table 1.

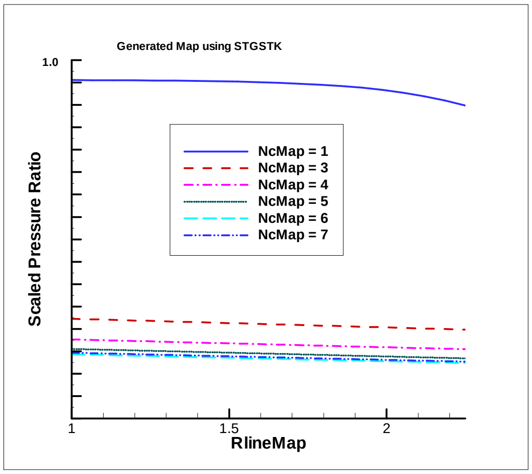

Figure 4a. LPC component map using a generated map from STGSTK.

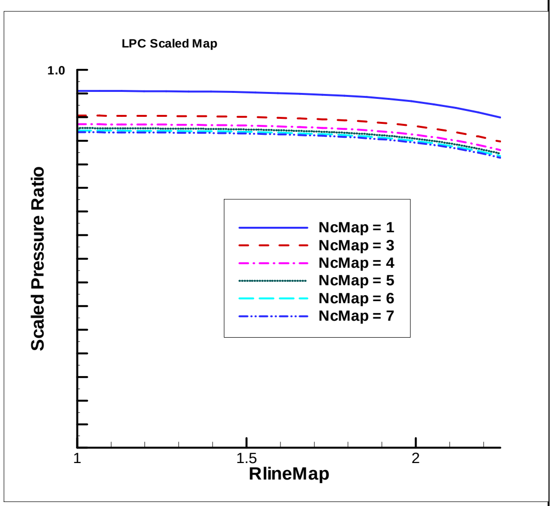

Figure 4b. LPC component map using a scaled map. Displayed is the scaled pressure ratio across the component versus the rotor operating speed. The index indicates the convergence history of the maps with the 7th iteration resulting in a full multi-level convergence.

Table 1 displays the system variables for two different zooming techniques applied to the LPC. Also seen are the "isolated" CFD results which were used to initiate the zooming calculation. The LPC cycle variables displayed in table 1 have been normalized by engine data. (A value of 0.0% indicates no deviation from the engine data.) Neither zooming technique appears to be superior in capturing the influence of the high fidelity calculation into the 0D cycle calculations. The map generation technique provides a better match with the inlet corrected mass flow (in terms of matching the CFD data), but results in a substantially poorer representation for the exit mass flow. Both approaches result in a small change in the rotational speed of the Low Pressure shaft. The starting CFD shaft speed exactly matches the engine data shaft speed as it is a specified boundary condition.

	Isolated CFD	Map Scaling	Map Generation
Inlet Corrected Mass Flow	-4.39%	-1.18%	-4.53%
Exit Corrected Mass Flow	1.49%	1.13%	5.65%
Exit Total Temperature	-0.57%	0.25%	-1.14%
Exit Total Pressure	-5.52%	-2.10%	-9.99%
LP Shaft Speed	0.00%	-0.28%	-0.48%

Table 1. Normalized LPC system variables for two alternate zooming techniques. Only the LPC is zoomed and the starting (isolated) CFD results are shown.

The same phenomenon occurs in the turbine. Figure 5 displays High Pressure Turbine (HPT) component maps produced using either the Entropy Loss Model [5] or the mean-line analysis AXOD [12]. The two maps are qualitatively and quantitatively different. The Entropy Loss Model displays a much higher level of mass flow and a substantially different operating curve than the AXOD map. The AXOD map displays a fairly flat mass flow profile which agrees with the expected behavior of a choked turbine nozzle. Most modern turbine systems have a choked nozzle at these flow conditions which results in the turbine operating at near constant flow characteristics. The Entropy Loss Model lacked a choked flow treatment that would likely result in an improved representation of the component map.

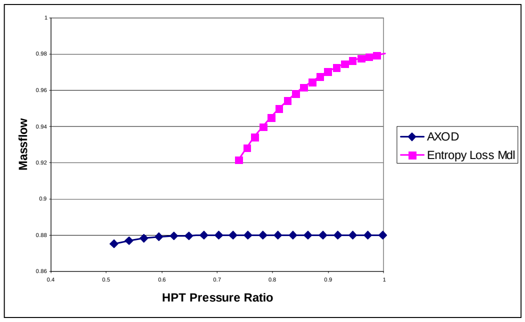

Figure 5. HPT component maps using either AXOD or the Entropy Loss Model.

4.2 Zooming Simulation Results

Table 2 illustrates the results of single component "zooming" of the GE90 turbomachinery components. Each component is individually zoomed and the results are presented in the labeled row. Although a single component zooming calculation alters the state variables throughout the engine, this table displays only the component variables for each component zooming simulation. These variables usually capture the largest change from the experimental data. The state variables displayed in this chart were selected to best represent the performance of the component. The three columns shown in the table illustrate the "zooming" approaches, either through map generation or scaling. The first column displays how much the baseline, isolated CFD calculations vary from the engine data. These calculations are started using the cycle inflow and outflow conditions as boundary conditions and serve as the initial conditions for the zooming simulations. As can be seen, the isolated CFD calculations typically match the engine data to within five percent. In general, when the CFD is fully coupled to the cycle analysis, the agreement with data can be either improved or degraded. Map Scaling shows differences frequently below 2%, whereas, the isolated CFD results are frequently greater. The map generation for the LPC appears to provide an inferior representation of the component map. Map Generation using STGSTK was not applied to the Fan. Since the fan flow is split between to inner and the Bypass flow fields, it was felt the STGSTK would provide a less accurate representation of this flow field.

Component	Isolate CFD	Scale Map	MAP Gen
Fan			
Bypass Ratio	-2.66%	-2.28%	
Bypass PR	-2.06%	0.36%	
Bypass TR	-0.66%	0.012%	
Bypass Exit Massflow	0.67%	0.09%	
LPC			
Exit Mflow	1.49%	1.13%	5.65%
PR	-5.64%	-2.19%	-10.32%
TR	-0.60%	0.19%	-1.52%
HPC			
Exit Mflow	1.77%	0.08%	
Component Efficiency	-0.94%	0.88%	
PR	-4.77%	1.02%	
TR	0.02%	0.56%	
HPT			
Exit MFlow	-3.27%		2.82%
Component Efficiency			0.41%
PR	-4.59%		0.70%
LPT			
Exit MFlow	-3.07%		0.05%
Component Efficiency	-1.39%		-0.57%

Table 2. Key variables in several "zooming" calculations. The isolated CFD column indicates starting variations between the validated engine cycle data and CFD values. The Map Scaling column employs a generic map. The Map Generation column uses either STGSTK or AXOD

While the LPC displays fairly large variations from the experimental data, it is important to note that this component has a relatively small impact on the overall cycle. Essentially, the Low Pressure Turbine (LPT) drives the Fan and to a much smaller extent the LPC. Also the LPC imparts only a relatively small pressure or temperature rise on the working fluid (air), such that even large discrepancies do not greatly alter the operating behavior of the engine. For all the power produced by the LPT, the fan consumes about twenty times more energy than the LPC.

4.3 Coupled Component Simulations

Despite the mis-matching that occurs while transferring 3D information to the 0D cycle analysis, reasonably good agreement with experimental data can be achieved through coupled component simulations for a variety of engine parameters. Figure 6 displays the convergence behavior of a coupled Low Pressure Spool (LPS) calculation that coupled the Fan, LPC and LPT component simulations. (As before, these values have been normalized by a baseline analysis that matched experimental data.) Corrected mass flow for the LPC and High Pressure Compressor (HPC) are shown with both the high speed and low speed shaft speeds. As the various components update their boundary conditions due to the multi-level data matching, the first few iterations display a large deviations (~3%) for the first few iterations. But the for the shaft speeds (LP and HP RPM) values settle down to a low (under 1 percent) variance after 5 iterations through all levels of analysis. The overall thrust of the coupled simulation varied approximately 1.01% from the baseline values.

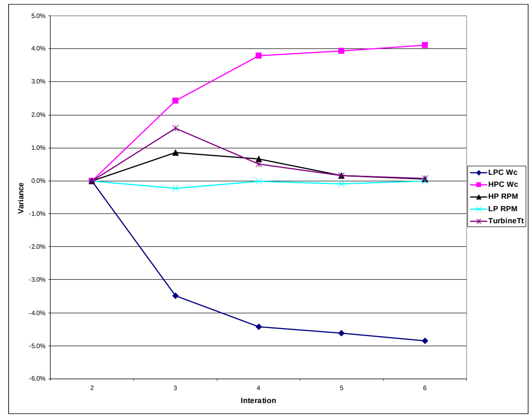

Figure 6. Convergence history for coupled Low Pressure Spool simulation (Fan, LPC and LPT).

The corrected mass flow for the LPC steadily decreases as the coupled simulation converges. Counter-acting this decrease, the HPC experiences a corresponding mass flow increase. The two changes appear to largely cancel each other out, yielding overall results for other system variables that are within 1% of the baseline.

A coupled simulation across both the high-speed and low-speed shafts displays a similar resiliency. Figure 7 displays the convergence behavior of a coupled HPT and LPT component simulation. This simulation requires additional iterations to reach an acceptable level of convergence but as can be seen in the figure an overall level of approximately 1% variance can be achieved.

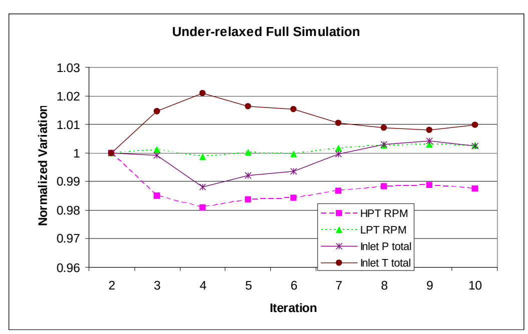

Figure 7. Convergence history for coupled HPT / LPT simulation.

5 Conclusions

Multidisciplinary systems analysis is rapidly becoming a practical tool for the most complex aerospace systems. However, the approach undertaken must be strongly grounded in practical application with a close validation through full system experiments. The results seen in this report indicate that for many components, good results can be achieved using mean line analyses to unite the high-fidelity and low fidelity (cycle) simulations. However, many issues remain:

a. Thermodynamic inconsistencies and empirical models make the integration of zero-dimensional and three-dimensional properties inexact.

b. Multi-component coupling simulations have required approximately 5-10 iterations across the multiple levels of analysis to reach a fully converged state. This imposes an additional computational burden, but each additional iteration does not require a full restart.

On the positive side:

a. A poor representation of one component may not compromise the accuracy of the complete-coupled simulation. For example, the coupled LPS simulation started with a CFD simulation of the LPC that was off by -5.6% in total pressure rise, but the resulting coupled system matched overall thrust values to around 1%.

b. For the coupled simulations achieved to date, the simulations are surprisingly resilient and most overall system values can be matched with data to around 1%. This still leaves much room for improvement and follow-on studies will determine if this remains true for fully coupled complete engine simulations.

References

[1] Claus, R.W., Evans, A.L., Lytle, J.K., Nichols, L.D., "Numerical Propulsion System Simulation," Computing Systems in Engineering, Vol. 2, No. 4, pp. 357-364, 1991.

[2] Evans, A., Follen, G., Naiman, C., and Lopez, I. "Numerical Propulsion System Simulation's National Cycle Program," AIAA-1998-3113, 1998

[3] Holst, T., Claus, R, Sala, M., "The NASA Computational Aerosciences Program – Toward TeraFLOP Computing, " AIAA -1992-558, 1992.

[4] Irani, K, Graichen, C., Finnigan, P., "Object-Based Representation for Multidisciplinary Analysis," AIAA-94-3093, 1994.

[5] Turner, M., Reed, J.A., Ryder, R., Veres, J.P., "Multi-fidelity Simulation of a Turbofan Engine with Results Zoomed into Mini-Maps for a Zero-D Cycle Simulation," ASME GT2004-53956.

[6] Holloway, P.R., Knight, G.L., Koch, C.C., and Shaffer, S.J., "Energy Efficient Engine High Pressure Compressor Detail Design Report", NASA CR-165558, May 1982.

[7] NASA Space Act No: SAA3-791, "Technical Management and Software Development Support of the Virtual Engine."

[8] Slama, D., Garbis J., Russell P., 1990, "Enterprise CORBA", Prentice Hall PTR, Upper Saddle River, NJ.

[9] Gropp, Lusk and Skjellum, "Using MPI", MIT Press, 1994.

[10] Stienk, R.J., "STGSTK: A Computer Code for Predicting Multistage Compressor Performance by a Mean-line Stage-Stacking Method," NASA TP 2020, 1982.

[11] Schmidt, James F., "BRSTK Guide: A Meanline Blade-Row, Characteristic, Off-Design, Computer Code for Calculating the Aerodynamic Performance of Axial Flow Fans and Compressors", NASA NPSS Document # BRSTK, May 2005.

[12] Glassman, Arthur J., "Modeling Improvements and User Manual For Axial-Flow Turbine Off-Design Computer Code AXOD," NASA CR – 195370, 1994.

[13] NPSS User Guide November 5, 2006.

[14] Flagg, E.E., "Analytical Procedure and Computer Program for Determining the Off-Design Performance of Axial Flow Turbines," NASA CR-710, 1967.

[15] Private communication with Scott Carson and of General Electric.

[16] Adamczyk, J.J., "Aerodynamic Analysis of Multistage Turbomachinery Flows in Support of Aerodynamic Design," J. Turbomachinery, 122(2), 2000, pp.189-217.

[17] Turner, M.G., "Full 3D Analysis of the GE90 Turbofan Primary Flowpath," NASA CR-2000-209951, March 2000.

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