A REVIEW OF HIGH FIDELITY, GAS TURBINE ENGINE SIMULATIONS

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Abstract

The concept of a fully integrated, multi-disciplinary simulation of a complete gas turbine engine remains an overarching goal with substantial progress made by several research groups [1-4]. This paper reviews previous efforts to gain perspective on the current capability to perform these complex system simulations. We draw on our most recent modeling results for the GE90 and the Energy Efficient Engine (EEE) gas turbine engines to explore key physical concepts underpinning these simulations and address fundamental questions such as: What level of accuracy is available from the component simulations? Do inaccuracies accumulate and hinder overall system simulation fidelity? What are the controlling variables that must be matched to correctly simulate these complex systems?

1 Introduction

Complex engineered products are increasingly being created using Product Lifecycle Management software. Frequently, these products are produced without expensive mock-up or prototypes, using only the “virtual” representation of the product to design and build complex machines. Modern gas turbine engines benefit from these technologies, but the complexity of each individual component has limited the “testing” or prototyping of these engines. They still rely on extensive component and full engine testing. Computational tools that reduce this expensive rig testing are being developed, but they are focused only on individual component behavior. Ever-increasing computing power and developing multi-disciplinary software is leading toward a systems-based process for engine development that relies on “virtual” testing.

Several groups are working to make “virtual engine testing” a reality. The most computationally intensive group, Stanford under the ASC program[1], has simulated a complete gas turbine engine (designed and built by United Technologies) using a combination of Large Eddy Simulation (LES) and Reynolds Averaged Navier Stokes (RANS). One of these simulations requires approximately two weeks of continuous computing using a 700 node computer. More practical engineering approaches have been developed by Hall [2], Turner [3] and finally our efforts Claus [4]. These engineering approaches eschew the time-accurate LES simulations for more computationally inexpensive component simulations that can typically be achieved in a one-day computing cycle with a modest computing cluster (less than 100 nodes).

All of these efforts employ different models and different methods that may affect the validity of the simulation. Stanford made radial comparison at a few locations in the engine, Hall and Turner made similar comparisons, but at more locations due to the relative wealth of test data. Our comparisons attempt to match system level data for all the engine components.

With the wide variety of models and approaches toward full-engine simulation, it seems an excellent time to reflect on the current status of these calculations. This paper critically examines the efforts documented in open publication and suggests where these efforts will go in the near-term future.

2 Simulation Models and Techniques

A number of models and techniques have been used for high-fidelity engine simulation. The ASC Stanford group [1] has employed the most computationally intensive methods. For each blade row of turbomachinery a RANS simulation was used. These outputs and inputs were coupled to a LES analysis of the combustor. One crucial factor to this approach is the development of appropriate interfaces that maintain the unsteadiness of the LES at both the inflow and outflows of each calculation while passing appropriate mean profiles. The turbulence kinetic energy transferred in the RANS to LES interface, employs turbulence statistics from a similar channel flow simulation. At the LES to RANS interface, a time-average of mean flow parameters is used. For the turbulence parameters, the process is somewhat more complex. The LES mean values are transferred to a duct simulation that is run until the RANS turbulence parameters in a two-equation model reach equilibrium with the mean flow. These equilibrium values are then transferred into the RANS downstream calculation. At both intersections, a duct simulation is used to transfer appropriate turbulence parameters between the two models. Both interfaces assume that the turbulence is dominated by local production, and convective transport is small.

The Stanford approach is fairly computationally intensive. On their coarse mesh, a 20 degree annular sector requires on the order of 2 weeks of full-time computation with a 700 node parallel computer. This estimate is based on a single flow-through time period and one might speculate that several flow-through periods are needed if the engine simulation employed a coupled high and low speed shaft. The current approach appears to use a proscribed high and low speed shaft speed that is not driven by calculated component torques. If the shaft speed were determined by the calculated torque, it is reasonable to assume that the fully-coupled system would require several flow-through time periods to reach steady-state operation.

The other major efforts to simulate a complete engine system used a 0D cycle simulation to provide the coupling between the various engine components. Hall [2] used an EEE engine cycle modeled using NNEP [5]. All sequent efforts used NPSS [6] which can be configured with a series of custom scripts to control and execute the entire simulation form 0D cycle to post-processing of 3D CFD results. The NPSS scripting system [7] is quite flexible with control job execution on a single computer or a large supercomputer.

Hall used ADPAC [8] to simulate the EEE engine. This code employs a mixing plane model to approximate the rotor / stator interactions in turbomachinery. This model averages the wakes and while it ensures conservation of mass and momentum, the averaging process ignores significant physics associated with downstream wake transport.

A higher-order model is used by Turner in the APNASA code [9]. APNASA is a steady-state, three dimensional CFD code for turbomachinery employing the average-passage formulation to transfer body forces between the various stages of the rotating machinery. It represents the unsteadiness created by wake passages by invoking a closure similar to the models developed for two equation turbulence models. In this manner, additional equations for transport, and dissipation of the wake passage influence are solved and added as body forces over an extended computational zone (typically including one blade before and after the blade row of interest). This technique has shown good results for a variety of High Pressure Compressors [9, 10].

These high fidelity models for turbomachinery display a wide range of approaches to capture the unsteadiness of the rotor / stator interactions in modern gas turbines. Equally important is the technique to integrate the three (potentially four) dimensional results with the 0D cycle model. The Stanford efforts did not couple shaft speeds based on computed torque and therefore did not integrate results at a system level. Their coupling was direct three dimensional data transfer. Hall used the computed torque from the CFD analysis to over-write the values computed in the cycle model. Turner used a mini-map process, but admitted that this was an area needed additional research [10]. Our research has taken the various component maps typically used in the cycle simulation and either scaled or replaced these maps to correctly integrate the system level values for both simulations.

Multi-Fidelity 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 it difficult to match system variables. APNASA, the various mean-line codes and NPSS all use slightly different thermodynamic properties. For most practical purposes, these differences are small and do not significantly alter the analysis. However, it was found in some cases that the mass flow inconsistencies in CFD results can hinder reaching an exact zero level of convergence across all analyses. This was especially troubling for the turbine and the High Pressure Compressor (HPC).

Convergence of the multi-fidelity analysis was judged to be complete when updated boundary condition values (RPM, Inlet Pt, etc.) changed less than 0.25%. Numerous tests indicated that this was a fairly strict requirement and that lesser levels might have been used.

3 Full Engine Simulations

3.1 Hall's Research

The earliest effort to conduct a full-engine simulation was conducted by Hall, et al [3]. This full-engine analysis used geometry representations that were included in the design reports for the EEE engine [11]. For the turbomachinery, the hot, design point geometry was transferred into an IGES representation that could be read into a CAD system or directly read into a grid generation system. The geometry lacked important details such as tip clearance, leakage cavities and the axis for stator rotation. Best estimates were made based on Allison engine experience and used in the detailed CFD calculations.

At the time of this effort, techniques to match CFD results with a cycle simulation of the full engine were still under development. Hall chose to integrate CFD with the cycle through the use of computed torque. The power consumed or produced for each component of the EEE engine at cruise is displayed in figure 1. As seen in this figure, the HPC and High Pressure Turbine (HPT) consume or produce the highest levels of power. The engine power balance is strongly influenced by the fidelity of the HPC and HPT simulations. A cycle simulation of the full engine typically employs maps for mass flow, efficiency and total Pressure Ratio across the component. A torque is then established for the component (work in or work out) and this is used to balance shaft speeds to reach an equilibrium with the other components in the simulation. Hall's coupling used only the CFD computed torque with the component maps being "disconnected" from this calculation. Figure 2 displays the results seen in this study.

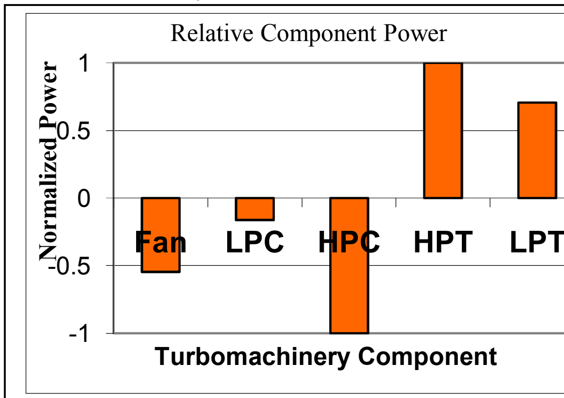

Figure 1. Relative normalized engine component power levels for the EEE at cruise.

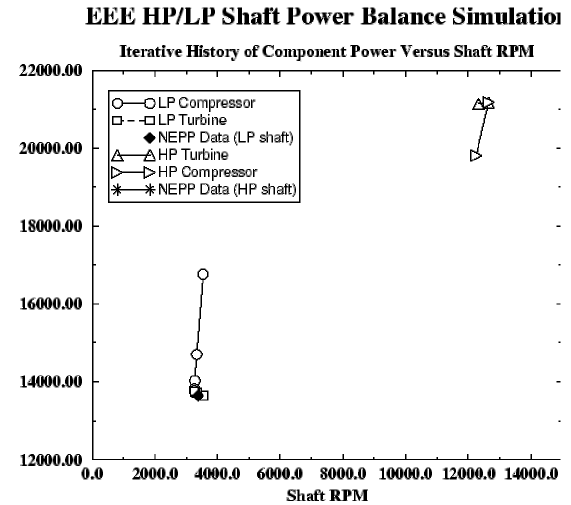

Figure 2. Fully coupled EEE engine simulation using shaft torque for the power balance.

Fig 2 is quite busy, but it illustrates certain basic trends. The simultaneous solution of the High Pressure (HP) and Low Pressure (LP) shaft required five iterations to reach an equilibrium state. An equilibrium state is where the cycle is fully balanced and the CFD computed torques are being used for each component. Each iteration involves a full computational cycle as seen in figure 3. First, the cycle sets the boundary conditions for the CFD then the CFD results are post-processed and the cycle is re-run to develop the boundary conditions for the next iteration. The iterative process is stopped when the calculated change in boundary conditions is less than a preset criteria (1% for Hall's work, 0.25% for our efforts).

Many of the component CFD representations are fairly close to the original starting values (which provide a close correlation to engine data) as seen in Table 1. As these component representations are fully coupled, the fidelity of the torque calculation is indicated in figure 2. For example in figure 2, the HP shaft starts at a RPM of about 12400 and exits at approximately the same RPM, which matches the starting data or engine data. The LP shaft sees a greater variation, starting at 3370 RPM and exiting at about 3250, a 3.7% variation. Table 1 illustrates how the components associated with the high speed shaft (HPC, HPT) are better simulated than the low speed shaft components (LPT, LPC, Fan).

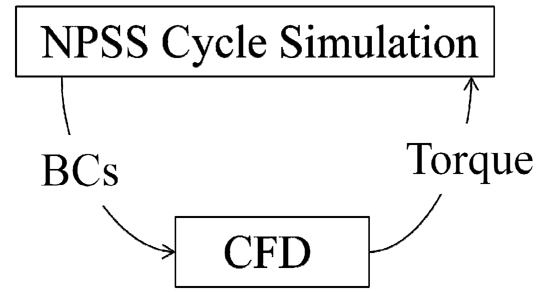

Figure 3. The full computational cycle of one iteration involving the transfer of boundary conditions from the cycle to the CFD and the transfer of computed torque to the cycle.

	Wc	PR	Eff
FAN	3.23%	-1.80%	1.16%
LPC	0.59%	-1.67%	1.99%
HPC	-0.29%	-0.22%	-0.30%
HPT	-6.17%	-6.11%	-2.88%
LPT	10.11%	11.49%	-1.32%

Table 1. Variation from baseline data and the starting CFD values for the EEE

The combined EEE HP/LP engine simulation provided an indication of what may be achieved in this type of analysis. Current approaches, however, use a more comprehensive coupling of the CFD and 0D cycle maps. Our approach employs the computed Total Pressure Ratio (PR), Corrected Exit Mass flow (Wc) and Adiabatic Efficiency (Eff) to provide scalars adjusting the usual NPSS component maps. When fully converged, these parameters should be the same in both the CFD calculation and the NPSS 0D cycle analysis to within a small tolerance.

Figure 4 displays the results of a Zooming calculation of the High Pressure Compressor (HPC). In this figure, we display the change in the baseline system parameters (Wc, PR, Tr and Eff) when the CFD results are used to generate new scalars for the 0D cycle. The very low levels of variation indicate that the CFD and baseline cycle parameters are very closely matched. From the first iteration to the last, the deviation from the baseline is generally less than 0.3%. The ability of the CFD to match design values for the HPC is remarkable. Other components, however, do not match as closely. The mass flow variations in the turbine are especially troublesome as seen in table 1.

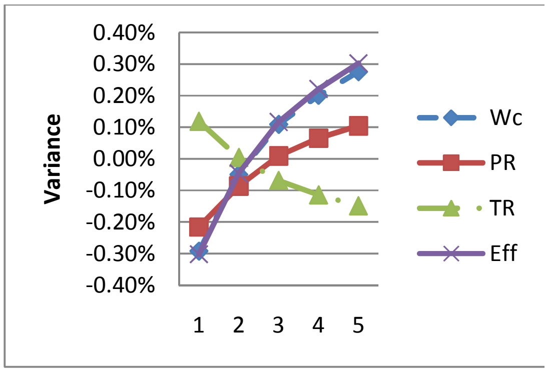

Figure 4. Results of a Zooming calculation of the EEE HPC.

3.2 Turner's Research

Following the EEE simulations by Hall, Turner et al developed a full engine simulation of the GE90 engine [2, 12]. The timing was advantageous due to the extensive amount of component rig testing that was being conducted during engine development. This included profile surveys and system level parameters for all the components so that the numerical simulations could be firmly grounded by experimental data. This effort employed a version of APNASA [13] to simulate all turbomachinery components and NCC [14] to simulate the combustor. The APNASA code attempts to simulate the rotor-stator interactions in multistage turbomachinery using body force terms to transport the wake-related unsteadiness analogous to a turbulence closure. Many references have reported good results with this model [9, 10].

Table 1 displays the system level metrics achieved in this research [12]. For all of the variables, the simulation matches the baseline parameters to within 4% and most parameters are within + or – 1% of the baseline (a close match to engine data).

	Wc	PR	TR	Eff	Nc
Fan	0.71%	0.45%	-0.2%	2.32%	1.09 %
Booster	0.08%	-0.60%	0.08%	-1.37%	1.09 %
HPC	0.75%	-0.49%	0.05%	-0.29%	0.97 %
HPT	1.21%	-3.52%	0.06%	1.79%	0.99 %
LPT	-2.3%	2.35%	-0.2%	-1.54%	1.00 %

Table 2. Relative difference of various component system variables from the baseline data on the GE90 engine.

An important limitation of Turner's research was the application of a "single pass" process, where the CFD boundary conditions were not continuously updated. The boundary conditions were set only once to match the cycle values, and then "mini-maps" were generated to be feed into the cycle.

3.3 Current Research

Our research benefited from the efforts of Turner et al [2]. For the GE90, we started using their established CFD results and crafted a series of NPSS scripts to automate the computing process and eliminate manual data transfers. The major difference between Turner and our research involves the integration of the three-dimensional results with the 0D cycle simulation. As noted in the previous section, our calculations fully integrates the high fidelity results with the cycle by fully updating the boundary conditions and iterating until the changes were less than a small tolerance. In addition, we scaled the turbomachinery maps to equate the system variables: Wc, PR and Eff, such that fully converged solutions match the CFD and cycle values for these quantities.

Figure 6 displays the iterative results of a fully-coupled, full engine simulation of the GE90 gas turbine engine. The simulation is started from a 0-D model of the GE90 that was closely calibrated to match engine data. Three-dimensional simulations of the turbomachinery (Fan, compressors and turbines) were used to create new component maps and reintegrated with the 0-D model. Figure 6 shows how the overall simulation slowly reaches a fully converged state – where updates to the three-dimensional simulations reach a small convergence criteria and no longer alter the simulation results. The high and low speed shafts display differing magnitudes, but follow generally similar trends to reach a converged state that approaches 0-0.5% variation from a baseline that is in close agreement with experimental engine data.

The variation in spool speed is indicative of many of the changes in the engine simulation. Table 3 displays the system-level agreement for the turbomachinery components of this same simulation at the final, converged state. In this table, system level parameters such as Total Pressure Rise, Total Temperature Rise, corrected exit mass flow and component efficiency are used to assess the fidelity of the simulation. The differences seen in Table 3 show only a small variation, typically less than 1%. Some parameters and components are less well predicted. For example, the LPC displays a high variation from data (or the baseline) with the efficiency under-predicted by about 15 percent, but overall, the results are encouraging.

Table 4 displays the system-level component values (as measured from the baseline) for the GE90 engine before coupling with the NPSS model. The HPC is less well predicted than the EEE results (Table 1). The other components display similar levels of accuracy.

	Wc	PR	TR	Eff	Nc	PWR
Fan	1.13%	0.77%	-0.22%	3.67%	0.59%	-0.55%
Core	-1.30%	0.21%	-0.50%	5.77%	0.59%	-6.06%
LPC	-1.77%	-2.01%	0.57%	-14.7%	0.84%	5.39%
HPC	0.56%	0.87%	0.56%	-0.57%	0.10%	-0.26%
HPT	0.10%	-0.04%	-0.01%	0.18%	-0.22%	-0.26%
LPT	0.05%	-0.36%	-0.16%	-0.01%	0.20%	-0.61%

Table 3. Variations in the overall engine system component performance when all simulations are fully coupled for the GE90.

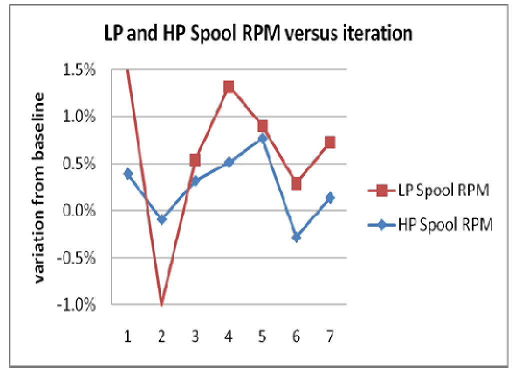

Figure 6. Convergence history for a complete simulation of the turbomachinery in a GE90 gas turbine engine.

	Wc	PR	Eff
FAN	1.34%	1.03%	3.49%
LPC	-1.80%	-4.02%	-13.49%
HPC	-1.89%	-1.47%	-1.56%
HPT	-1.59%	-4.09%	0.40%
LPT	-2.14%	0.09%	-1.39%

Table 4. Relative difference of various component system variables from the baseline data on the GE90 engine before coupling with the 0D NPSS model.

3.3 ASC Research

The ASC effort at Stanford was an attempt to simulate a "Grand Challenge" scale problem, essentially, one that is nearly beyond today's simulation capability [15]. Certainly, a full-annulus, time accurate, LES of a gas turbine is beyond current capabilities. However, approximating the blade counts for each blade row and computing a 20 degree annular sector with RANS, the problem becomes tractable. This is the approach taken. RANS simulations of the turbomachinery were integrated with LES simulations of the combustor as noted in section 2. A coarse mesh calculation employed 8 million grid points and was noted to require approximately 2 weeks of continuous computing on a 700 node supercomputer. The fine mesh calculations require approximately 4000 nodes with similar computing time. These calculations employed a flexible software coupling program, labeled CHIMPS [16], to integrate the various components.

To validate the simulation a series of radial profiles for total temperature and pressure were compared at 3 locations in the P&W gas turbine. The circumferentially averaged profiles compared reasonably well, however some profile discrepancies near the hub or the casing can be seen. The difficulty is that some critical engine data (the secondary flows) was not available and the amount of engine data was sparse. To the author's knowledge, no systems level data was available for comparison. Another limitation was the lack of full, system-level coupling between the turbomachinery components. The flow boundary conditions allowed for a downstream coupling, but the shaft speeds were kept constant without the feedback that could result from a torque balance.

The ASC effort was clearly a proof-of-concept, where the details of secondary flows and system level parameters may not have been important for this goal. However, it does represent a high mark in computational modeling for a gas turbine and the lack of system-level validation is disappointing.

4 Summary

Let's re-examine those questions posed at the start of this paper:

What level of accuracy is available from the component simulations?

As can be seen in tables 1 and 4, the component system-level variables can usually be simulated in a range that is within a few percent of actual engine data, but some components are less well predicted. For coupled engine simulations, the turbine component calculations were commonly too poorly predicted to yield good full-engine simulations.

Do inaccuracies accumulate and hinder overall system simulation fidelity?

Admittedly, this range of simulations is a small sample, but for this small sample, the results are encouraging. Generally, the over-prediction of a system variable compensates for an under-prediction elsewhere. For example, in the GE90 simulations, the fan over-prediction (in efficiency) appears to compensate for the under-prediction in the HPC and elsewhere.

What are the controlling variables that must be matched to correctly simulate these complex systems?

To couple the complete engine system, one of the most important system variables is mass flow. A poor mass flow calculation in one component might readily "choke" the remaining components as the system is fully coupled. Less critical is the system performance of a "small" contributor, like the Low Pressure Compressor (LPC). The performance of this component is overwhelmed by the more important (higher power producing / consuming) components such as the Fan, HPC and HPT.

5 Concluding Remarks

There have been numerous research efforts to perform a high-fidelity full engine simulation of commercial gas turbines. A decade ago these simulations were mere "stunts" or demonstrations, but the advances in computing power and modeling techniques have greatly improved the practically of these simulations. The most comprehensive of the full-engine simulations was the work of Turner and our follow-on efforts, due largely to the availability of extensive engine testing data and proprietary geometry and core flow data. The ASC effort employed much more comprehensive computing tools, but the validation was weakened by a lack of proprietary information on the complete system and the computing times may have been prohibitive if the calculation were fully coupled through system parameters (torque, mass flows, etc.).

Remaining unclear is what modeling technique will enable the development of virtual engine testing. Even the ASC project could not model the turbomachinery with time-accurate, LES, but instead had to rely on RANS modeling. The EEE and GE90 simulations suggest that RANS modeling techniques provide accurate simulations (to within a few percent) of the compression system, but the turbine needs additional detail / modeling. Improved modeling and better integration of tools that can resolve hot / cold shape geometries would provide significant benefits [12].

One of the greatest barriers to the common implementation of these techniques for design is the substantial manual effort required to create grids and flow details that are needed in these simulations. However, this burden has several one-time manual construction costs that would be minimal for the next engine design. In other words, the creation of these complex simulations will benefit from a steep learning curve, such that future simulations will be much more easily implemented. With the continued increase in computing power and advances in multidisciplinary tools [17], high-fidelity simulations of complete gas turbines may become routine over the next decade.

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