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Numerical Zooming Between a NPSS Engine System Simulation and a One-Dimensional High Compressor Analysis Code

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NUMERICAL ZOOMING BETWEEN A NPSS ENGINE SYSTEM SIMULATION AND A ONE-DIMENSIONAL HIGH COMPRESSOR ANALYSIS CODE

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ABSTRACT

Within NASA's High Performance Computing and Communication (HPCC) program, NASA Glenn Research Center is developing an environment for the analysis/design of aircraft engines called the Numerical Propulsion System Simulation (NPSS). NPSS focuses on the integration of multiple disciplines such as aerodynamics, structures, and heat transfer along with the concept of numerical zooming between zero-dimensional to one-, two-, and three-dimensional component engine codes. In addition, the NPSS is refining the computing and communication technologies necessary to capture complex physical processes in a timely and cost-effective manner. The vision for NPSS is to create a "numerical test cell" enabling full engine simulations overnight on cost-effective computing platforms.

Of the different technology areas that contribute to the development of the NPSS Environment, the subject of this paper is a discussion on numerical zooming between a NPSS engine simulation and higher fidelity representations of the engine components (fan, compressor, burner, turbines, etc.). What follows is a description of successfully zooming one-dimensional (row-by-row) high-pressure compressor analysis results back to a zero-dimensional NPSS engine simulation and a discussion of the results illustrated using an advanced data visualization tool. This type of high fidelity system-level analysis, made possible by the zooming capability of the NPSS, will greatly improve the capability of the engine system simulation and increase the level of virtual test conducted prior to committing the design to hardware.

Introduction

The intense global competition in the commercial aviation industry is placing significant pressure on industry to minimize cost while meeting challenging goals for product performance, efficiency, emissions and reliability. An opportunity exists for reducing design and development costs by replacing some of the large scale testing currently required for product development with computational simulations. A greater use of predictive simulations would not only save some of the costs directly associated with

testing, but also enable design tradeoffs to be studied in detail early in the design process before a commitment to a final design is made. A detailed computational simulation of an engine could save 30 to 40 percent in development time and cost.

The goal of the Numerical Propulsion System Simulation (NPSS) Project at the NASA Glenn Research Center is to develop technologies that enable cost-effective computational simulations of a complete air-breathing gas turbine engine in sufficient detail as to resolve the effects of multidisciplinary processes and component interactions currently observable only in large scale engine tests. For instance, more accurate prediction of engine efficiency and operability would be possible if the “hot running” behavior of the compressor rotor, blades and casing could be predicted as a result of the integrated aerodynamic, structural and thermal analysis. Given the market pressures to improve quality, reduce cost and speed time to market, physics-based, system-level simulation is a key enabler to achieving competitive capability.

Specifically, the NPSS Version 1 provides zero-dimensional (component by component) aero-thermodynamic system simulation for the full life cycle of an engine. While NPSS Version 1 focuses on cycle analysis, it by no means represents what cycle simulations had been characterized by in the past. The NPSS Version 1 is designed to have all the features that currently exist in cycle simulations, as well as having the ability to exercise the NPSS concepts of component code zooming, distributed/parallel processing, and introduces, through an application program interface (API), a means to conduct Multi-discipline simulations all from a “Engine System” point of view. The object-oriented paradigm has been used to develop NPSS Version 1.

Zooming

Current “state-of-the-art” engine simulations are zero-dimensional in that there is no axial, radial or circumferential resolution within a given component (e.g., a compressor or turbine has no internal station designations). In these zero-dimensional cycle simulations the individual component performance characteristics typically come from a table look-up (map) with adjustments for off-design effects such as variable geometry, Reynolds effects, and clearances. Zooming means a higher order component analysis code is executed and the results from this analysis are used to adjust the zero-dimensional component performance characteristics within the system simulation. By drawing on the results from a more predictive, physics-based higher order analysis code, “cycle” simulations are refined to more closely model and predict the complex physical processes inherent to engines.

As part of the overall development of NPSS, NASA and industry began the process of defining and implementing an object class structure that enables numerical zooming between NPSS Version 1 (zero-dimensional) and higher order one-, two- and three-dimensional analysis codes. NPSS Version 1 preserves the historical cycle engineering practices, but also extends these classical practices into the area of numerical zooming for use within a companies’ design system.

The zooming capability provides multiple benefits to the engine design and development process:

1. It enables a potential component design to be more fully and rapidly evaluated in the context of an engine system. Zooming automatically provides accurate component boundary conditions (pressures, temperatures, flows, etc.) and an integrated result is provided to the component designer. The fidelity of the result is improved from current practice since the impact of the component on the system is accounted for in the analysis.
2. It enables system-level analysis and optimization to occur more rapidly than possible with today's design process. The effect of potential design changes to a component on the system, and to other components within the system, can be rapidly evaluated without having to take the time to generate an updated zero-dimensional representation of the component for the system simulation.
3. The engine system simulation is more predictive since component performance characteristics can be based on physics-based, 1st principle analysis codes. This increases design confidence prior to commitment to hardware.
4. It permits the resolution and fidelity of the engine model to be tailored to match the analysis requirements. This reduces the computing resource requirements since high fidelity analysis is applied only to the components of interest where the increased fidelity and/or resolution is required to support a particular analysis.

Fundamentally, NPSS is creating an environment that permits the substitution of higher fidelity codes into an overall engine system code as illustrated below.

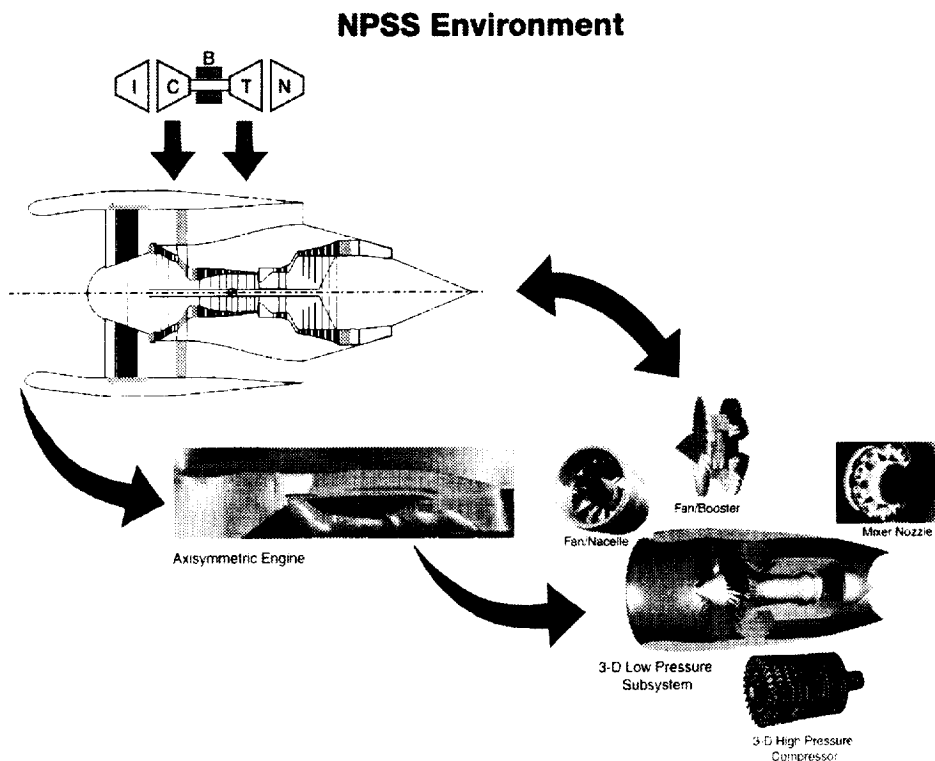


Figure 1: NPSS Fidelity Suite.

While NPSS has developed several prototype two-dimensional and three-dimensional high fidelity engine simulations, Pratt & Whitney's demonstration of a one-dimensional analysis code connected to NPSS Version 1 is the most formal activity focused on the development of the object layer required for zooming. The intent of this zooming demonstration was to determine if the NPSS zero-dimensional object-oriented architecture was conducive to zooming to a higher dimension analysis or if extensive revision to the basic infrastructure would be required.

Pratt & Whitney One-Dimensional Compressor Zooming

A description of zooming one-dimensional (row-by-row) high compressor results back to a NPSS engine simulation are discussed and the results illustrated using an advanced data visualization tool. The ability to zoom from the NPSS engine model to a row-by-row Euler meanline compressor model yields a new level of analysis capability that is beyond the state-of-the-art for the typical engine cycle simulation. Zooming row-by-row high pressure compressor (HPC) analysis results back to the NPSS engine model provides the user with the performance of each row of the compressor and the integrated prediction for the overall system.

NPSS Version 1 Zooming Model Description

A NPSS Version 1 simulation of a generic turbofan engine was created utilizing the zero-dimensional component elements and performance characteristics available within the NPSS system. The simulation setup enabled steady-state operation to fan airflow (total airflow) and fan pressure ratio at sea level static conditions and simulated take-off power. This simulation was then modified from the base NPSS Version 1 configuration to include the software necessary to launch the legacy analysis code, and the calculations required to support the adjustment of the zero-dimensional NPSS compressor with the one-dimensional results. In addition, the simulation incorporated logic checks which caused the NPSS solver to re-balance the system after integration of the one-dimensional results.

Note: In order to establish a baseline for the compressor zooming demonstration, the zero-dimensional compressor characteristics were calibrated such that at the baseline conditions there was no difference between the zero-dimensional high compressor characteristics and the characteristics predicted by the one-dimensional meanline analysis code used in the zooming demonstration.

High Level Zooming Architecture Description

The approach taken was to create a second compressor object which represented the one-dimensional compressor. This object, referred to as the One-Dimensional Compressor Interface Element, would be responsible for communication with the NPSS zero-dimensional HPC counterpart. This element would *not* have the one-dimensional analysis, but would be responsible for calculating the scalar adjustments to the zero-dimensional performance characteristics based on the one-dimensional results. This element also communicated with a C++ routine responsible for launching the

“CORBA-wrapped” one-dimensional HPC meanline analysis. This launch routine had hard coded paths to the meanline analysis software and to a second SUN workstation which served as the client host machine. The new one-dimensional compressor object and the C++ CORBA launch software were compiled and linked with the NPSS engine model to form a new executable. A simplified overview of the resultant NPSS simulation is shown in Figure 2:

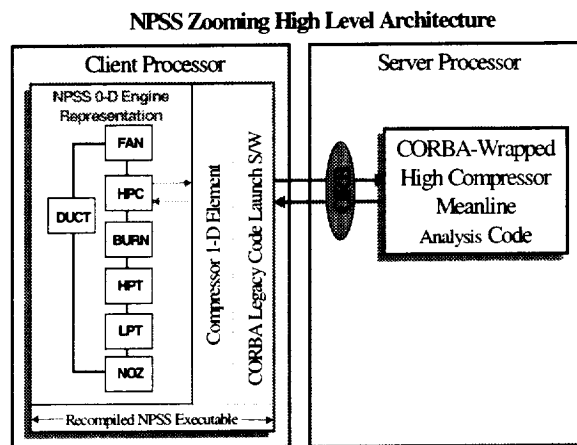


Figure 2

Zooming Process Description

As was stated earlier, the goal in the zooming process is to incorporate the high fidelity results back in the zero-dimensional system simulation so that the system effects can be captured. The high fidelity results will alter the performance of the zoomed component and as a result, the zero-dimensional system model will have to re-converge to a thermodynamic balance. This process is itself iterative. The system convergence process implemented with the NPSS simulation is described below:

1. The base NPSS model (all zero-dimensional components) comes to a thermodynamic balance. This, in the absence of zooming, would be the “answer.”
2. The one-dimensional HPC is then executed at the same boundary conditions (inlet parameters, variable geometry, airflow, exit pressure, etc.) defined by the zero-dimensional simulation. Since the higher fidelity one-dimensional HPC will have a slightly different speed-flow characteristic, speed is allowed to “float” in the one-dimensional model. An efficiency at the same inlet airflow and pressure ratio is then obtained from the one-dimensional analysis.
3. The “new” speed and efficiency is then imposed on the zero-dimensional component by utilizing scalars on these parameters available within the zero-dimensional NPSS compressor element.
4. The entire engine simulation, with the updated HPC performance (speed-flow and efficiency) characteristic, is again brought to thermodynamic balance by the NPSS system solver.
5. A check on tolerances between the converged compressor speed and the previously predicted one-dimensional speed is made. If outside of tolerance, the

one-dimensional code is launched a second time with updated compressor boundary conditions from the thermodynamically balanced system prediction.

Step 5 is repeated until the system is within tolerance—usually 2 to 4 passes. The system simulation now reflects the performance of the higher fidelity compressor analysis. At this point, the result would be the same as if the higher fidelity one-dimensional analysis had been “embedded” within the NPSS as a replacement for the zero-dimensional simulation.

Directly replacing the zero-dimensional code with its one-dimensional counterpart was not attempted as this technique would have destroyed the “plug and play” capability of the NPSS and would have precluded use of a consistent methodology for even higher order analysis (e.g., three-dimensional Computational Fluid Dynamics analysis). In addition, this approach would have severely limited the number of zoomed components that could be executed at one time since the NPSS simulation would quickly become unwieldy as a second or third high fidelity analysis was encapsulated within the system model. The NPSS zooming approach demonstrated offers the potential of exploiting distributed and parallel computing and could be gracefully expanded to include more engine components without such constraints.

NPSS Compressor Zooming Elements and Communication

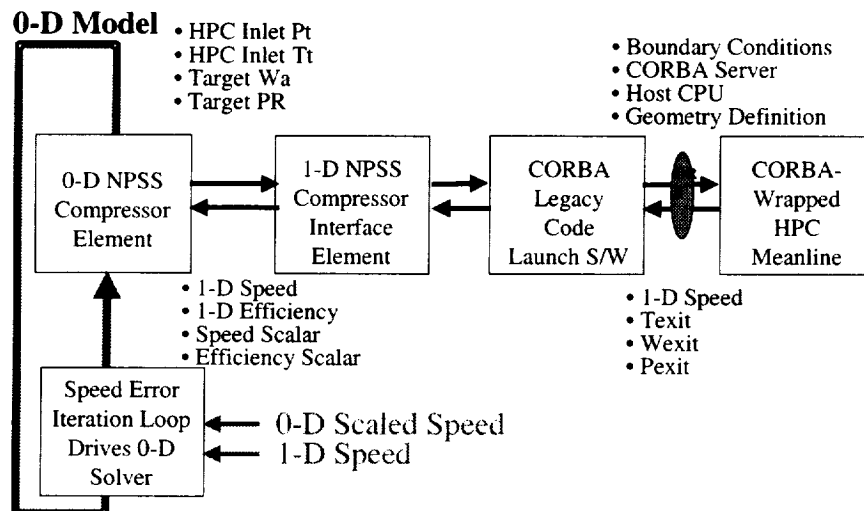


Figure 3

The NPSS high compressor zooming elements, along with a more detailed listing of the communication between the various elements within the NPSS model is illustrated in Figure 3.

As can be seen from Figure 3, the zero-dimensional Compressor HPC element provides boundary conditions (and target flow and pressure ratio) to the One-Dimensional NPSS

Compressor Interface Element. The One-Dimensional NPSS Compressor Interface Element controls activation of the CORBA Legacy Code Launch Software which executes the CORBA-wrapped one-dimensional analysis on the specified host CPU.

Results from the one-dimensional HPC analysis are returned to the One-Dimensional NPSS Compressor Interface Element which then calculates a speed and efficiency scalar for the zero-dimensional NPSS object. If the speed iteration error is outside of tolerances, the NPSS solver will again iterate the system to balance.

Zooming Demonstration Results

In order to illustrate the advantage of zooming to a higher fidelity component analysis within a system simulation, Pratt & Whitney selected two cases for the high pressure compressor zooming demonstration:

1. A 2 percent increase in HPC customer or stability bleed relative to a baseline. The bleed is assumed to be taken at the fifth stage of the six stage HPC.
2. A linear change in HPC rotor tip clearances. In this case, the forward tip clearances were increased and the aft decreased such that there was no change to the "average" HPC clearance.

These two contrived cases were chosen to highlight the benefits the increased fidelity and resolution the zoomed one-dimensional row-by-row HPC analysis brings to the zero-dimensional system simulation. These cases were of interest because there is an attempt to account for the effect of inter-stage bleeds in the performance and efficiency of the high compressor in the baseline zero-dimensional engine simulation. In addition, the zero-dimensional HPC representation attempts to capture the effects of changes in rotor tip clearances with an adjustment to the compressor efficiency as a function of a change in the average compressor clearance from a default value assumed in the base zero-dimensional performance characteristic.

Zooming Demonstration Results

As stated earlier, the zero-dimensional HPC performance characteristics were calibrated to the one-dimensional analysis at the baseline bleed and clearance conditions. In other words, at the baseline conditions there was no difference between the overall performance predicted by the pure zero-dimensional model and model with the one-dimensional HPC zooming "active."

After this calibration, a set of pure zero-dimensional engine simulation predictions were generated with the bleed and clearances changes noted above. This established the baseline zero-dimensional engine performance prediction. These two cases were then re-executed with zooming to the one-dimensional HPC analysis active. The percent change in system, and selected HPC parameters, relative to the baseline zero-dimensional simulation (no zooming) for each of the two cases were then calculated.

The results are shown in Table 1 below:

	+2% Bleed Change	Tip Clearance Change
Fuel Flow	-4.45%	+0.48%
Nozzle Area	-2.18%	+0.23%
Net Thrust	-1.06%	+0.11%
Engine Pressure Ratio	+0.70%	-0.08%
Bypass Ratio	-10.52%	+1.06%
HPC Flow	+4.22%	-0.48%
HPC Pressure Ratio	+2.35%	-0.22%
HPC Efficiency	0.06 (Delta)	-0.006 (Delta)
High Spool Speed	+5.27%	-0.09%

Table 1: Change due to Zooming

As can be seen from the results documented in Table 1, the integration of the higher fidelity one-dimensional HPC model results produced significant differences in the overall system predictions. The magnitude of the change in cycle parameters with a 2 percent increase in inter-stage bleed was somewhat more than expected, since there is an attempt in to account for the effect of the inter-stage bleed in the zero-dimensional model through bookkeeping of work fraction and mass conservation. The zooming results clearly show the zero-dimensional compressor representation was not able to provide a predictive response to the change in compressor bleed at these conditions. Obviously, the benefit of zooming in this case is that the first-order physics represented in the row-by-row compressor meanline analysis provided a much better prediction of the system response (of course, this implies a validated compressor meanline analysis).

A significant difference between the zero-dimensional prediction and the one-dimensional prediction where the individual HPC rotor tip clearances were changed was expected. As with the bleed zooming demonstration, the benefits of the increased fidelity of the one-dimensional HPC representation are obvious. If the user has a validated one-dimensional analysis, the subtle effects of intra-component changes caused by inter-stage bleeds and row-to-row tip clearances changes can be captured, and the effect on the HPC reflected in the engine simulation.

Although the system effects are interesting, this is not the only information available from the NPSS zooming demonstrations. With Zooming, row-by-row HPC information is available for each prediction point and analysis to determine impact to the operability of the HPC (and ultimately the engine) can be conducted.

Zooming Case 1: +2% Customer Bleed HPC Results

Figure 4 shows a generic 6-stage HPC cross section in which the change (delta) in the work loading of each stage relative to the baseline bleed case is displayed. An advanced data visualization tool is utilized to display the data in order to provide a user-friendly means of quickly summarizing the model results and quickly identify anomalies that may indicate the model was not implemented properly.

Change in Stage Loading from Baseline

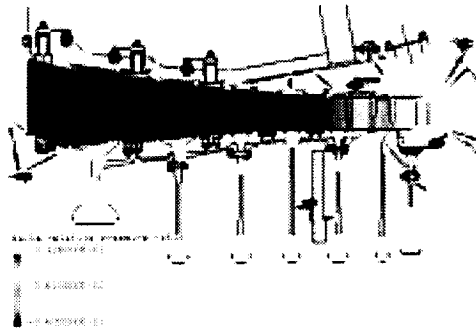


Figure 4: Compressor Bleed Zoomed Results

As can be seen from the visualization, the stage loading of the front four stages are decreased (blue) as expected, and the loading of the rear stages are increased (red, yellow and green) relative to the nominal bleed baseline prediction. Visualizing the HPC component simulation results in this manner quickly tells the user that the bleed was extracted at the proper station (5th stage) and also enables rapid assessment of the impact of the bleed change on the compressor component. Stage loading can be correlated with stability margin and therefore an analysis can be conducted to determine the operability impact of the 2 percent increase in the rear stage bleed on the overall stability of the compressor. Obviously, analysis such as this is not possible with a zero-dimensional simulation.

In today's design process, operability analysis of high compressor stage loadings are typically conducted by stand-alone execution of one-dimensional meanline and/or two-dimensional streamline analysis codes at the HPC operating conditions predicted by a zero-dimensional engine model. That is, the HPC rotor speed, variable geometry, inlet conditions (total pressure and total temperature), inlet flow, and exit pressure are typically based on results from a zero-dimensional simulation executed at various power settings and flight conditions. But, as can be concluded from Table 1, Zooming Demonstration Results, the component boundary conditions from such simulations may not be completely accurate for the integrated system. As a result, the stand-alone analysis is not as accurate as the integrated analysis enabled by the NPSS zooming function.

NPSS zooming enables the entire engine system to re-balance to reflect the impact of the increased HPC bleed based on compressor characteristics predicted by the higher fidelity analysis. The result is more accurate prediction of system and component behavior which could lead to a more optimum design, or perhaps optimized control implementations to accommodate the limits in HPC stall margin. Also, since the NPSS launches the higher fidelity analysis automatically, the analysis can be conducted more rapidly and at more operating conditions than would be practical with manual, stand-alone execution of the one-dimensional analysis. The result is a higher quality, more thorough analysis in a reduced time period.

Zooming Case 2: Clearance Change HPC Results

As stated earlier, the second zooming demonstration involved a change to the high compressor rotor tip clearances such that the *average* clearance was unchanged from the baseline case. Front clearances were opened and rear clearances closed an offsetting amount in order to maintain a constant average clearance. This contrived situation was specifically chosen to illustrate the benefit of NPSS zooming to an increased fidelity (relative to zero-dimensional) compressor analysis code. Since the zero-dimensional simulation has effects for changes in average clearance only, it could not account for the change in row-by-row clearance implemented in the second zooming demonstration.

Change in Rotor Tip Clearance from Baseline

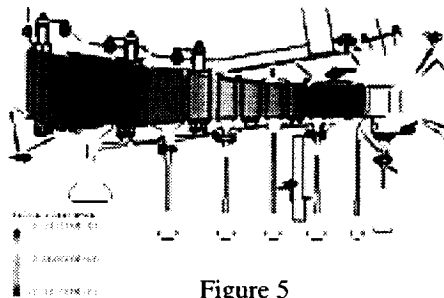


Figure 5

Figure 5 is captured output from the visualization system displaying the change in front-to-back rotor tip clearances from the baseline case. As can be seen in the figure, the front rotors have more open clearances (red) and the rear more closed (blue).

As stated previously, the zero-dimensional NPSS model was incapable of predicting the effect of these row-by-row changes in tip clearances since the average clearance was unchanged. The zoomed results at the system level for this demonstration, shown in Table 1, Zooming Demonstration Results, indicate a minor re-match of the system (approximately 1 percent change in BPR and 0.5 percent change in core flow). In addition to this information, as with the bleed zooming demonstration, row-by-row component information from the one-dimensional HPC analysis is also available.

Data visualization of the change in compressor stage loading from the baseline clearance case is presented in Figure 6. As expected with tighter clearances, the rear stages have higher stage loading (red) and therefore less stability margin than the baseline case. This information could be used to determine if sufficient stability margin existed to accommodate a clearance change of this magnitude. None of this information is available in the traditional zero-dimensional engine simulation. The NPSS zooming result is more accurate prediction of system and component behavior that could lead to a better design.

Change in Stage Loading from Baseline

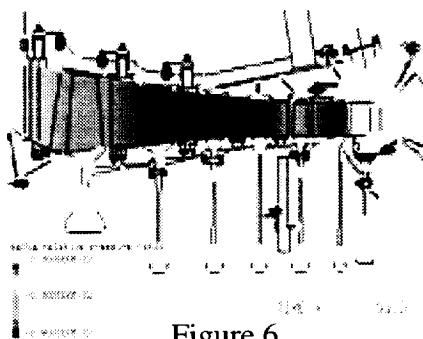


Figure 6

Next Steps

Due to the fact that the current work used Pratt & Whitney a proprietary code, a general deployment of this demonstration was not possible. However, NPSS team has begun to apply the lessons learned and the zooming objects defined on the Pratt & Whitney effort to a publicly available code called HTO300. HTO300 is a streamlined curvature code used to calculate flow-field conditions. Currently, a Boeing version of this code is being used (NAS2-13605). The work on zooming to HTO300 consists of enhancing the NPSS parsing tool to scan the HTO300 FORTRAN for COMMON block information and generate structure definitions to map the COMMON variables onto the NPSS/C++ side. It also generates C++ code to create user accessible NPSS variables that map to the COMMON variables.

Conclusions and Recommendations

The Numerical Propulsion System Simulation is beginning to fulfill its vision of enabling simulations of complete air-breathing propulsion systems overnight on cost-effective computing platforms. NPSS' concept of Numerical Zooming from Zero-Dimensional One-, Two- and Three-Dimensional engine component analysis codes is key in realizing this vision. Significant progress has been made toward this ultimate goal, including the development of an industry-standard engine cycle analysis program called the NPSS Version 1 and, in particular to the subject of this paper, recent implementations of numerical one-dimensional zooming. The Pratt & Whitney NPSS zooming demonstrations illustrate the potential value to industry of such capability. The automated integration of high fidelity component analysis in the context of an overall engine simulation resulted in improved component and system level prediction. Zooming demonstrations within the NPSS framework are proving the functionality of the NPSS architecture as well as while demonstrating the engineering impact of increased fidelity, high resolution analysis.

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