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Intermediate Fidelity Closed Brayton Cycle Power Conversion Model

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Abstract

This paper describes the implementation of an intermediate fidelity model of a closed Brayton Cycle power conversion system (Closed Cycle System Simulation). The simulation is developed within the Numerical Propulsion Simulation System architecture using component elements from earlier models. Of particular interest, and power, is the ability of this new simulation system to initiate a more detailed analysis of compressor and turbine components automatically and to incorporate the overall results into the general system simulation.

Introduction

This paper describes an intermediate fidelity model of a closed Brayton cycle power conversion system. The phrase "intermediate fidelity" refers to the use of conceptual and preliminary design and analysis simulations in conjunction with an overall system performance simulation.

The simulation system presented in this paper is based on an overall system performance model created using the Numerical Propulsion System Simulation (NPSS) software. This model is linked with one-dimensional meanline turbomachinery analysis tools that model the compressor and turbine. The resulting system simulation will be used to determine the performance of closed Brayton cycle power conversion systems. Creating this type of complex model will enable the system performance engineers and turbomachinery design engineers to easily interact when designing the overall system, thus allowing a clearer and more complete understanding of component interactions during the design phase.

This paper describes how these models are linked together. It describes some of the possible pitfalls that must be avoided when building complex models of this type. Finally, it gives some examples as to how these types of simulations are beneficial to the overall design team.

NPSS Background

NPSS has been developed as a joint project between NASA, DOD, and industry. The initial goal of this development was focused on airbreathing aircraft engines. However, the environment was kept general enough to allow the system to be applied to any thermodynamic system. Given the success with aircraft engine systems the capability of the NPSS environment was demonstrated by modeling both rocket engine and hypersonic applications.

The vision for the NPSS environment is to enable high fidelity solutions to be applied early in the design process. The following figure shows the goal. Note that most of the design decisions involved in creating a new thermodynamic (propulsion or power) system are done early in the design process during the conceptual design phase. Higher fidelity analysis tools are not used until after most of the design decisions have already been made. The desire is to have an environment where the higher fidelity analysis tools can be applied early in the design process, before the major design decisions have been made. Figures 1(a) and (b) visualize the difficulties associated with the current design process and highlight the advantages of the early use of higher fidelity component representations. Of course, cost is not the only concern; performance, reliability, and durability, to mention a few, will be positively impacted by this early insertion of more descriptive simulations. Note, however, that this does not mean the entire system needs to be modeled at the high fidelity level. The goal of the environment is to be flexible enough that the engineers can select the areas of concern and model them at a higher level of fidelity. For example, suppose uncertainty analysis indicates that the error in predicting the performance of the turbine is giving unacceptable results for the overall system. The systems analysis engineer could then work with the turbine performance engineer to create a higher fidelity model of the turbine. The experts could then work together to understand the turbine design and reduce the uncertainty in the turbine performance and take corrective action early in the design process.

Tremendous Physics Modeling Capability Has Been Inserted Into Preliminary, Detailed Design, and Validation

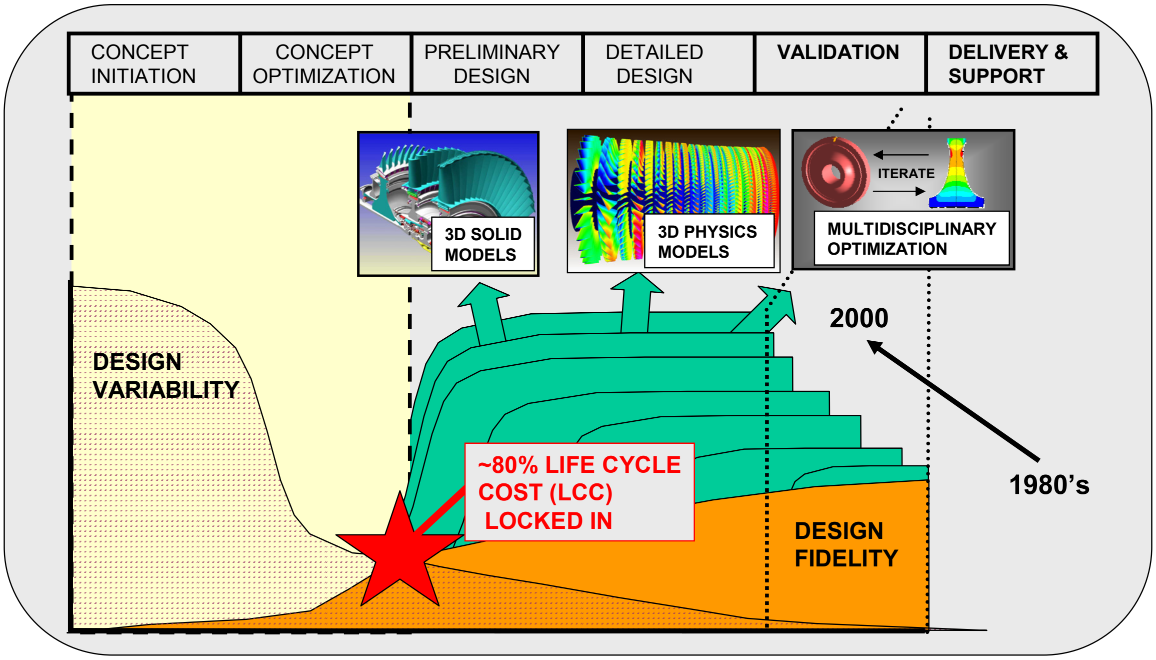
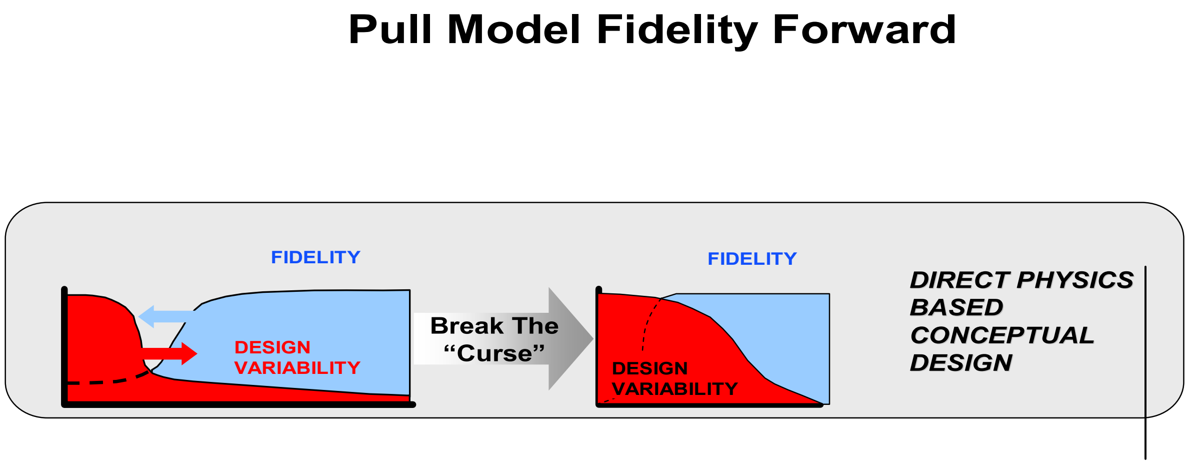


Figure 1(a).—Relationship between design variability and design fidelity in the design cycle.



Pull Model Fidelity Forward

Break The "Curse"

DIRECT PHYSICS BASED CONCEPTUAL DESIGN

Figure 1(b).—Effects of early insertion of advanced modeling on the design process.

The NPSS package is based on object oriented principles. There are five objects that the engineers primarily deal with when creating models: elements, subelements, functions, ports and variables. The engineers will create system models by assembling these objects together to represent complex engineering systems. The input files that end up being created look much like C++ code. The objects that are used can either be part of the standard library or they can be custom elements that are created outside of the main NPSS package. A more general overview of the system can be found in a paper by Lavelle (ref. 1).

The NPSS system is currently being used extensively in industry. Both General Electric and Pratt and Whitney are using the environment to support the simulation requirements of their new engine programs. In addition to the increased fidelity that is possible, both organizations have found advantages in the flexibility of the architecture. It is easy for the companies to implement their own algorithms at their specific locations. In addition, having a common tool between the companies has made it much easier for them to team on new engine projects, such as the GP7200 Turbine (a joint GE/PW effort to power the new Airbus A380 airplane).

RTD/Quik3 Background

Quik3 and the Radial Turbine Design (RTD) codes are one dimensional design programs created to perform preliminary design and analysis of radial flow turbomachinery. Quik3 is used to design centrifugal compressors while RTD is used to design radial turbines. Both are FORTRAN programs developed at the Glenn Research Center (formerly the Lewis Research Center) and subsequently enhanced over the course of 30 years by their authors. Quik3 was developed by Jerry Wood and RTD was developed by Art Glassman.

Quik3 is based on correlations of specific losses, lumped into one-dimensional models, which include inlet guide vane, impeller inlet shock, impeller incidence, impeller clearance, blade loading, channel skin friction, rear disk friction, recirculation, vaneless diffuser friction and diffuser losses. Data to develop these correlations were acquired from seven centrifugal compressor stages ranging in size between 2 and 66 lbm/sec and pressure ratios between 1.15 and 8. Both inputs and outputs are in the form of formatted text files. In the design mode, Quik3 requires pressure ratio, upstream conditions, mass flow rate, and necessary geometry conditions. Output provided can include compressor efficiency and exit state conditions, detailed component losses, and one-dimensional geometry information. Quik3 does not calculate ducting or scroll losses; however, the user can estimate these losses and input appropriate parameters to correct for these losses.

Likewise, RTD is based on loss models for stator and rotor passages, trailing edges, vaneless space, disk friction, and rotor exit clearance. The simulation assumes optimum incidence entering the rotor and requires power, flow rate and rotative speed as inputs. RTD output provides rotor-tip diameter, flowpath dimensions, diagram velocities and angles, and total and static efficiencies. As with Quik3, RTD provides output in formatted text files but the software requires the input files to be written as namelist variables.

The Brayton System Model

The first step in the simulation development process was to create a 0-D closed loop Brayton Cycle Capability in the NPSS environment. The tool that is being used for closed Brayton cycle analysis was the NASA Glenn Closed Cycle Engine Program (CCEP) (Barrett (STAIF 2004) ref. 2 and Johnson (STAIF 2005) ref. 3), a derivative of the NASA Engine Performance Program (NEPP) (ref. 4). CCEP provides both power balanced thermodynamic solutions and preliminary component design results (size and weight). In order for NPSS to be an acceptable simulation for studying these types of systems, it, as a minimum, needed to duplicate the capabilities of CCEP. Of course, the NPSS architecture would need to eventually provide additional capabilities to justify its use in preference to CCEP.

There were two basic steps that were required to make the transition from CCEP to NPSS. First, NPSS had to support the thermodynamic properties for the working fluids to be used in this system. Second, the engineering calculations required to support these types of systems had to be incorporated into NPSS elements.

A system schematic of a possible closed Brayton cycle configuration is shown in figure 2. There are two main loops shown in the system. In the first loop a gas mixture is heated in a heat source in heat exchanger and moves through a turbine, recuperator, cooler, compressor and back through the other side of the recuperator before completing the loop in the same heat exchanger. Attached to the common compressor/turbine shaft is an alternator that transforms the energy from the turbine into electrical power. The second loop contains a heat sink heat exchanger that is used to collect excess heat and pass it through a radiator to remove it from the system.

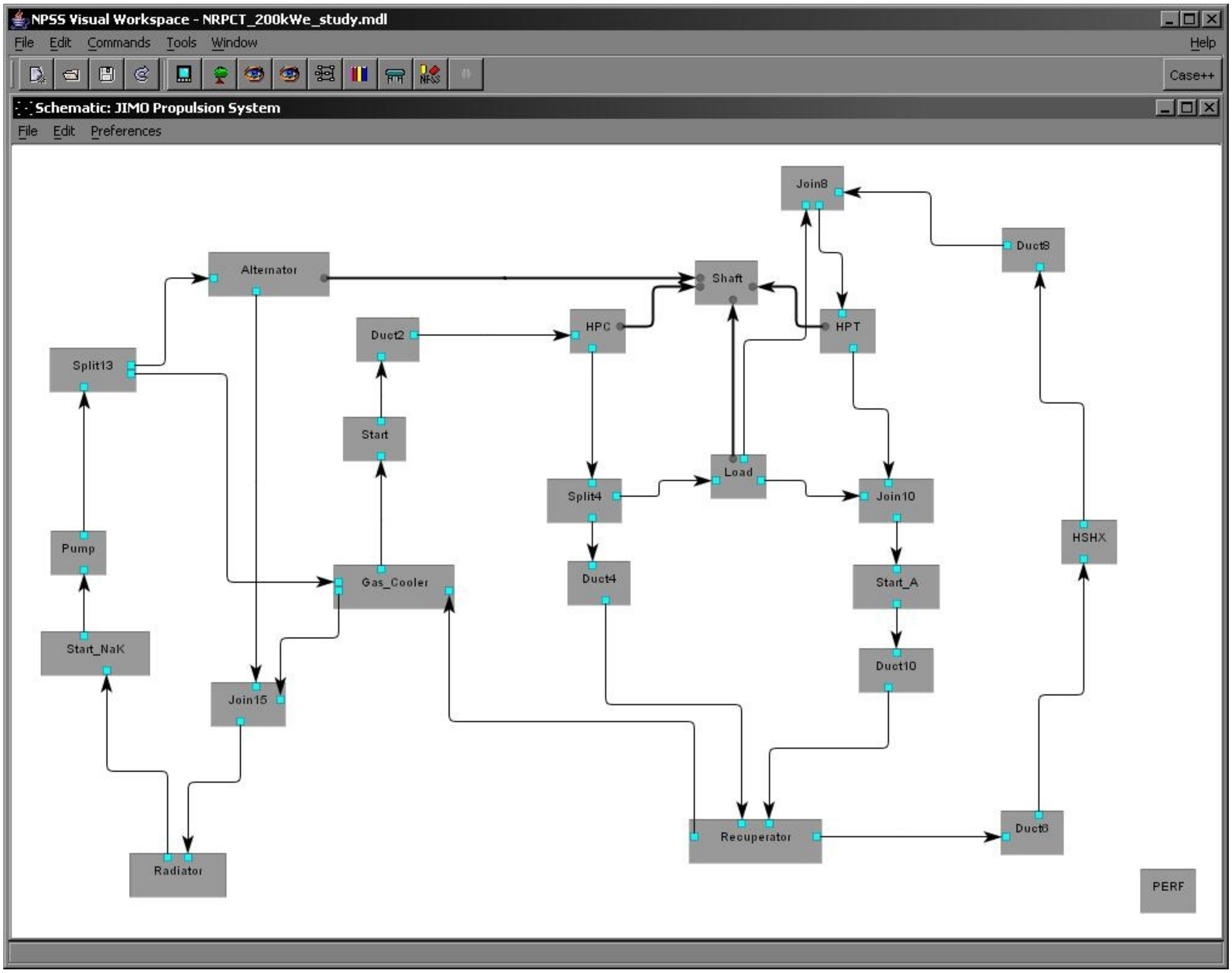


Figure 2.—NPSS GUI showing Brayton Cycle simulation.

Elements

The next step in the process was to create the elements that are required to model this type of system. The main elements are as follows: alternator, load, compressor, duct, heat source, pump, radiator, recuperator, shaft, turbine, and waste heat exchanger. The flow elements, such as ducts, compressors, turbines, etc., were based on the aircraft elements that already exist. The heat transfer elements, the recuperator, waste heat exchanger, and radiator, had to be completely written using CCEP algorithms as a guide.

The new elements were created using the interpreted element option of NPSS. This option allows the user to create new engineering elements and include them at run time without recompiling. There are three basic requirements for the creation of a new element. First, the user must list the inputs and outputs of the element. Second, the user must list the connections the element has with other components in the system. Third, the user must describe the engineering calculations that element performs to determine its exit conditions. The elements can do much more than this, but this is the minimum required for functionality. A converter program is also available to turn interpreted elements into compiled code when the user is satisfied with them. The compilation of new elements is done for performance reasons. The initial version of the Brayton cycle took over two minutes to converge when the elements were interpreted. This was reduced to five seconds when the elements were compiled.

An example of a simple pressure loss interpreted file is shown in figure 3. (Note that the elements are capable of containing more information than what is shown.)

```
class Duct extends Element{
 real dPnorm{
 value = 0.; description = "Normalized pressure drop"; units = "NONE";
 }
 FluidInputPort Fl_I{
 description = "Inlet fluid port";
 }
 FluidOutputPort Fl_O{
 description = "Outlet fluid port";
 }
 void calculate(){
 // pass flow information along
 Fl_O.copyFlow( "Fl_I" );
 //determine exit conditions
 real hout = Fl_I.ht;
 real Pout = Fl_I.Pt *( 1 - dPnorm );
 // set exit conditions in outlet station
 Fl_O.setTotal_hP( hout, Pout );
 }
}
```

Figure 3.—Interpreted duct pressure loss.

The elements can also contain other objects. For example, the Brayton Cycle elements have been made to contain the solver independents and dependents that are associated with these elements and instructions defining when they should be used. This enables them to be included automatically when new elements are added to the system.

Thermodynamic Properties

The thermodynamic properties were supported using the fluid property table capability in NPSS. This capability allows engineers to use new fluids by creating a file that describes the thermodynamic properties of the fluid. Once this file exists, that fluid can be used in the system simulation model. The format of a fluid property file is shown in figure 4.

```
// Fluid Property Table
description = "Fluid property Table";
// Specific Heat at constant pressure, BTU/lbm-R
 indeps = {"Tt"};
Table Cp( real Tt ) {
 Tt = { list of temperature array values separated by “,”
 }
 Cp = { list of corresponding Cp values
 }
}
// Thermal Conductivity, BTU/ft-hr-R
indeps = {"Tt"};
Table k( real Tt ) {
 Tt = { list of temperature array values separated by “,”
 }
 k = { list of corresponding k values
 }
}
// Density, lbm/ft^3
 indeps = {"Tt"};
Table rho( real Tt ) {
 Tt = { list of temperature array values separated by “,”
 }
 rho ={ list of corresponding rho values }
 }
// Absolute Viscosity, lbm/ft-hr
 indeps = {"Tt"};
Table mu( real Tt ) {
 Tt = { list of temperature array values separated by “,”
 }
 mu = { list of corresponding mu values
 }
}
real s(real Tt) { return NaN; }
// h as a function of T
hTindeps = {"Tt"};
Table h_T( real Tt ) {
 Tt = { list of temperature array values separated by “,”
 }
 }
 ht = { list of corresponding ht
 }
}
// T as a function of h
 Table T_h( real ht ) {
 ht = { list of temperature array values separated by “,”
 }
 Tt = { list of corresponding ht values
 }
}
```

Figure 4.—Format of a fluid property table (fpt) file.

One should note that if additional fluids or materials are to be considered, the user would simply create another property table file (".fpt").

Zooming

At this point in the process there exist both overall system models and more detailed turbomachinery models. The next step in the process is to assemble them into a more complex "system of systems" model. This capability is referred to as zooming.

Keep in mind that the system will be multi-fidelity to enable the engineer to examine in more detail areas of concern to explore design options and understand system difficulties that must be addressed. The system level simulation serves as a backbone with the higher fidelity simulations added as needed. Thus the system level simulation (0-D) provides boundary conditions and other input parameters for the more detailed component simulations. In addition, the system level simulation is used to order the solution sequence and insure an overall consistency between the various component level simulation results and the system simulation results. This concept is represented schematically in figure 5 below.

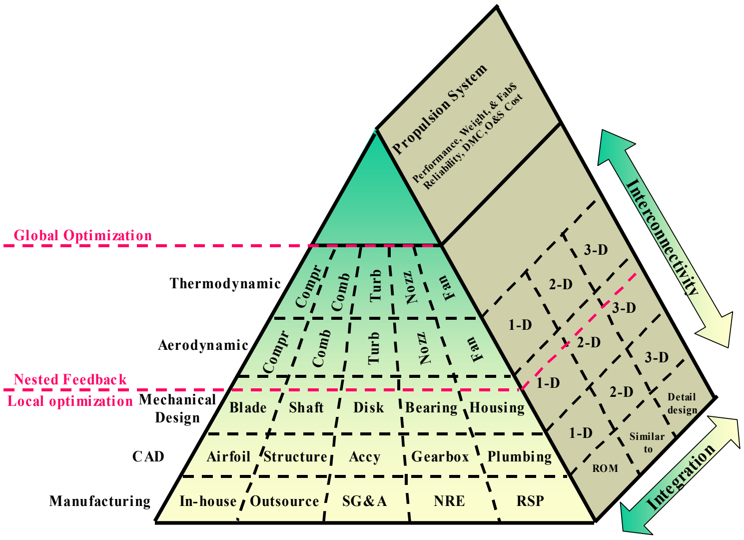
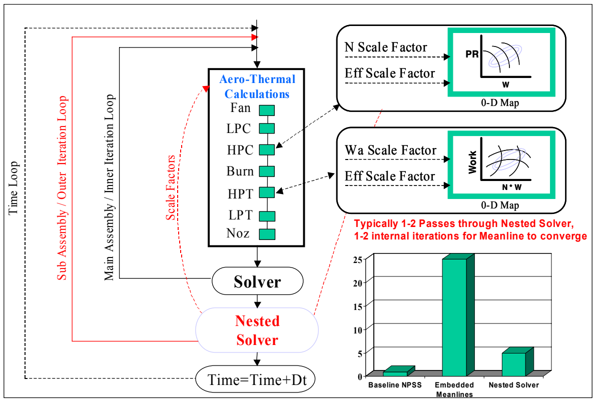


Figure 5.—Information hierarchy in propulsion system design (Sirica, ref. 5).

Also note that these models are not sequential in nature, but are highly iterative. As such, it is not practical, nor sometimes possible, to include a higher order code directly in the overall power balance of a thermodynamic system. Further, higher order codes can be very time consuming and, typically, they have not been designed to be part of an overall solution. Also, they may introduce too much numeric "noise", preventing the overall system from reaching conversion. The solution schemes that drive these complex "systems of systems" must take this factor into account.

One way to deal with this issue is to use multiple Newton-Raphson solvers to drive the overall system to convergence. In this case the 0-D solution is used as the governing structure for managing the calculation procedure. This concept is shown schematically in figure 6. The converged results are then used to launch the higher fidelity codes. Should the higher fidelity codes give results that are different than the 0-D solution, those results are taken into account by updating a scalar or adder in the 0-D model. The 0-D model is then run again and the entire process repeated until the overall system reaches convergence.



Generic Approach to "Zooming"

Use 0-D Modeling System as Focal Point

Scale Components to Match High Fidelity
Ensure Boundary Conditions are Met

Nested Solver Approach

Minimize Internal Iterations
Keep High Fidelity Tools in Design Space

Figure 6.—Generic approaches to nested solution.

The process described above works well when combining low fidelity results with intermediate fidelity tools such as 1-D meanline and 2-D stream line codes. However, additional thought is required when coupling with a full 3-D CFD solution. In this case, further steps must be taken to minimize the number of iterations at the system level. There have been several attempts to address this issue that will be briefly described here.

The first method involves using the higher dimensionality tools to create "mini-maps" around the operating point of interest. In this method, the system simulation is run to convergence. Then, the component simulation is run at a number of operating points that surround the operating point of interest thus creating a mini-map. This mini-map is then used in the place of the meanline codes (component simulations) in the method listed above. Once the mini-map has reached convergence with the rest of the system, the component simulation can be run one last time to get "as is" conditions. The mini-map capability is amenable to parallel processing. For example, if four points are chosen to create a map, each can be executed in parallel by farming the processes off to a different processor. This can be extended to include multiple components if more than one in the system is being studied. Thus, any number of components can be added without increasing the overall runtime. This parallel capability has been built into the NPSS system and was demonstrated by an undocumented NASA Glenn task on a rocket engine.

The second method involves using the high fidelity tools to "tune" the appropriate 1-D codes. Then those 1-D codes are used to generate a performance maps. In this case the entire engine is run for one pass using higher dimensionality tools. The results are then used to tune the loss parameters previously used to generate 1-D meanline results. The 1-D mean-lines are then used in conjunction with the 0-D maps to determine the overall solution. The advantage to this method is that since the entire engine is run at high fidelity, the 3-D effects between the components are captured. They are not lost by integrating the results to 0-D results and then transferring them to the next component. This work is explained in detail by Turner et al. (ref. 6)

Intermediate Fidelity Brayton Cycle

The techniques described above were used to create an intermediate fidelity model of a closed Brayton cycle power conversion unit. The 0-D model was an NPSS model of the Brayton unit describe above. The meanline models were the Quik3 and RTD turbomachinery codes.

The first step in the process was to create models of the turbomachinery codes to be integrated into the low fidelity model. Note that the overall process here was to integrate the models, not the tools. A tool is code that can produce results. A model is a specific use of a tool that can produce results over a limited design space as defined by an expert user. The model created by the expert user is what is integrated into the system model.

The model is built by creating a bit of code that takes a predefined input file for the higher order component model and overwrites some of the inputs with values from the system model (low fidelity) results. The component model is then executed and the results are parsed out of the output file and made available to the overall system model. A Quik3 compressor model will take the values of temperature, pressure, weight flow and speed and return compressor efficiency. The RTD turbine model will take the values of pressure, temperature, power, speed, and weight flow and return turban efficiency. The process is controlled by the overall system solver until the efficiency used in the cycle to determine turbomachinery boundary conditions matches the efficiency produced by the turbomachinery models. Figure 7 shows the execution process.

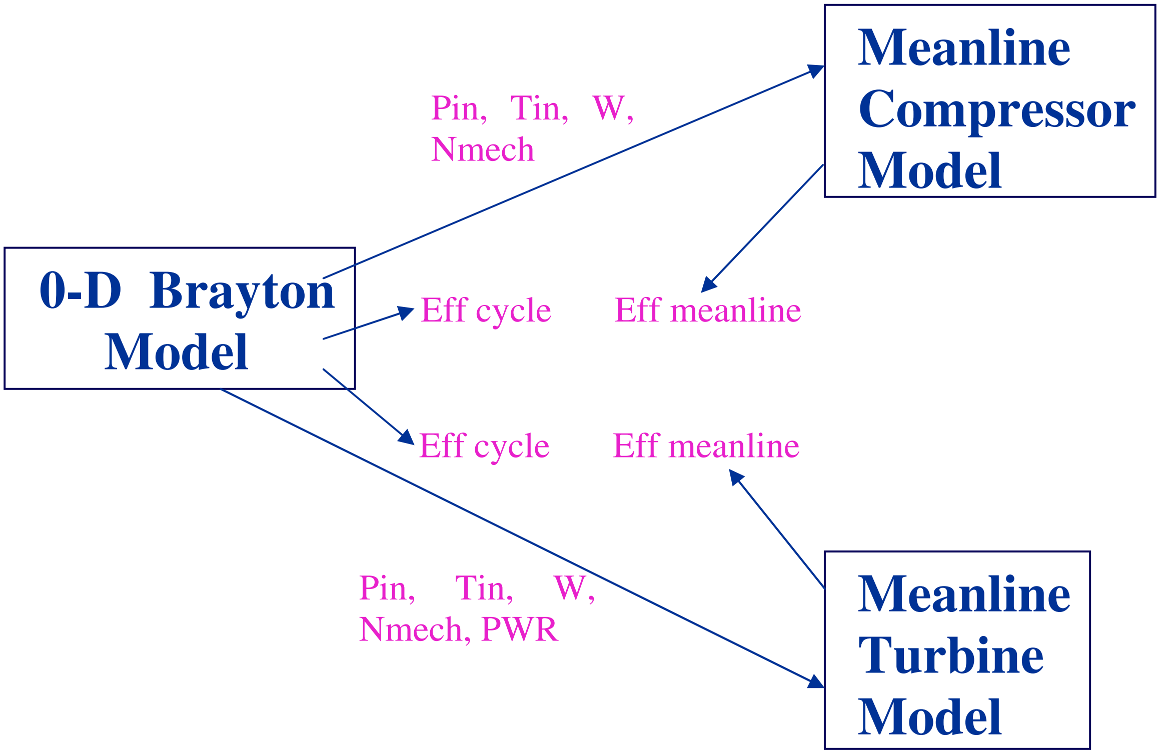


Figure 7.—Solution scheme for multi-fidelity Brayton model.

There are several advantages to this approach. First, since the detailed models are being used directly, there is less of a chance for a data mismatch to occur due to human interactions. Second, it enables more design variables to be exposed at the higher level. This enables more complete optimization and parametric studies to be performed. Third, more detailed information from the high fidelity codes is available to the system for operation at the different conditions. This additional information is, of course, lost when a map is created and “unnecessary” information is deleted. Remember, the goal is not to replace designers but to create an environment that enables them to work together to improve the design and the efficiency of the design process.

Summary and Conclusions

NASA Glenn has created a multi-fidelity model of a Brayton Cycle that integrates meanline turbomachinery analysis with a system level model. It can also be extended to include higher fidelity representations of other components as well. These combined models enable teams of engineers to get a better understanding of component and overall system performance.

References

1. Lavelle, Thomas, Hah, Chunill, Puterbaugh, S.L., and Copenhaver, William W., “Unsteady Aerodynamic Phenomena in A Transonic Compressor Stage,” AIAA paper 93–1868, 1993.
2. Barret, Michael and Reid, Bryan M., “System Mass Variation and Entropy Generation in 100-kWe Closed-Brayton-Cycle Space Power,” AIP Conference Proceedings V. 699, pp. 445–452, 2004.
3. Johnson, Paul K. and Mason, Lee S., “Design and Off-Design Performance of 100 kWe-Class Brayton Power Conversion Systems,” AIP Conference Proceedings V. 746, pp. 711–718, 2005.
4. Fishbach, L.H. and Caddy, M.J., “NNEP: The Navy/NASA Engine Program,” NASA/TMX 1975–71857.
5. Sirica, Steven, “NPSS: More Than a Cycle Simulation”, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Session 42–ABP–7 Room Palm B, July 13, 2004.
6. Turner, Mark G., Reed, John A., Ryder, Robert, and Veres, Joseph P. “Multi-Fidelity Simulation of a Turbofan Engine With Results Zoomed Into Mini-Maps for a Zero-D Cycle Simulation,” NASA/TM—2004-213076, GT2004–53956; Turbo Expo 2004, Vienna, Austria, 14–17 June 2004, 20041101; November 2004.

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