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# The Numerical Propulsion System Simulation: A Multidisciplinary Design System for Aerospace Vehicles

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# THE NUMERICAL PROPULSION SYSTEM SIMULATION: A MULTIDISCIPLINARY DESIGN SYSTEM FOR AEROSPACE VEHICLES

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## Abstract

Advances in computational technology and in physics—based modeling are making large scale, detailed simulations of complex systems possible within the design environment. For example, the integration of computing, communications, and aerodynamics has reduced the time required to analyze major propulsion system components from days and weeks to minutes and hours. This breakthrough has enabled the detailed simulation of major propulsion system components to become a routine part of the design process and to provide the designer with critical information about the components early in the design process. This paper describes the development of the Numerical Propulsion System Simulation (NPSS), a multi-disciplinary system of analysis tools that is focussed on extending the simulation capability from components to the full system. This will provide the product developer with a “virtual wind tunnel” that will reduce the number of hardware builds and tests required during the development of advanced aerospace propulsion systems.

## Introduction

The strategic goals of the Aero-Space Technology Office at the U.S. National Aeronautics and Space Administration (NASA) are defined in terms of advancing transportation capability across the speed spectrum from subsonic for commercial applications to hypersonic for access-to-space applications. These goals are organized under the Three Pillars of Global Civil Aviation, Revolutionary Technology Leaps and Access-to-Space.<sup>1</sup> Within the Three Pillar goals are technical objectives that contain specific goals for revitalizing general aviation, reducing travel time, reducing the aircraft accident rate, reducing noise and emissions, increasing airport throughput, and reducing aerospace product development time and ownership cost. The accomplishment of these

goals will require advanced technologies that will be prohibitively expensive to develop and insert into aerospace products without the availability of advanced design tools that reduce the amount of hardware builds and tests traditionally required in engine development.

The NASA Glenn Research Center is developing the capability to increase design confidence through the use of advanced computational simulation capability known as the Numerical Propulsion System Simulation (NPSS). This “virtual wind tunnel” will enable accurate information about propulsion system parameters such as performance, operability and life to be determined early in the design process before any hardware is built and tested.

NPSS is a cooperative effort of NASA, industry, other government agencies, and universities to integrate propulsion discipline technologies with high performance computing and communications technologies into a complete system to perform detailed full engine simulations. The computing and communications technologies are essential to enabling the complex simulations to be executed in a timely manner and to produce information of value to the designer and analyst. A major engine manufacturer estimates that such simulations could reduce design and development time and cost by about 30 to 40 percent through fewer redesigns, re-tests and rebuilds of costly hardware. This translates into savings of \$100 million and over a year of development time. For example, more accurate prediction of engine efficiency and operability would be possible if the “hot running” geometry of the compressor rotor, blades and casing could be predicted as a result of the integrated aerodynamic, structural and thermal loadings. In advanced high-speed engines, large-scale simulation may be the only viable approach for evaluating the integration of components like the inlet with the engine due to prohibitively expensive testing.

The NPSS system consists of three main elements: (1) The engineering models, (2) The simulation environment and the (3) High-performance computing environment. This integrated, interdisciplinary system

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requires advancements in the following technologies: (1) modeling techniques and data standards to couple the relevant disciplines such as aerodynamics, structures, heat transfer, combustion, acoustics, controls and materials; (2) modeling techniques to couple subsystems, and components at appropriate levels of fidelity; (3) object-oriented software design for a modular architecture; and (4) portable, scalable, reliable system software for integrating large numbers of distributed, heterogeneous computing platforms for parallel processing.

The technology products from NPSS as well as a summary of the technology challenges and possible solutions are described in this paper. A roadmap for the development of capabilities that shows a transition from single discipline components and subsystems to full system simulation into multidisciplinary and dynamic simulations is shown in Fig. 1. Additional details on the NPSS technologies are described in Ref. 2. They are summarized below for completeness.

### The Engineering Models

The modeling capabilities are divided into three sub-elements: (1) component integration to achieve large subsystem and system simulations, (2) multidisciplinary coupling to capture critical interactions amongst the disciplines, and (3) variable complexity analysis to tailor the complexity of the analysis to the design problem under study. These three aspects of the modeling are depicted by the "Rubik's Cube" shown in Fig. 2.

#### Component Integration

The ability to resolve interactions between components in a gas turbine engine is currently limited to two-dimensional models. Most of the full engine simulations are conducted at zero-dimension or parametric levels. These models are unable to resolve the complex multi-dimensional and multidisciplinary flows that exist within the engine. Interactions that are driven by these complex flows are usually unresolved until hardware is built and tested. This is often late in the development process after a significant investment has been made in the design of the engine. At this point, changes in design are very costly and time consuming.

Component integration is the required to understand important interactions between the components. Traditional component design methods assume steady, uniform boundary conditions which are generally not accurate and have resulted in operational problems that were not discovered until late in the development process or until deployment in the field. Two approaches are currently being developed to account for component interaction: (1) establish interface standards

for code-to-code communication that is being addressed under the development of the Simulation Environment and (2) the use of single analysis codes to perform larger scale simulations. The latter require that the appropriate physical processes are represented in one code, such as tip clearance flows, turbulence, heat transfer, etc., and that the code can be run in parallel to reduce the overall analysis time. The current state of development involves a focus on the development of turbomachinery and combustion models to enable the development of a high fidelity, full engine simulation.

In the case of turbomachinery analysis, the problem is very scalable in that the analysis of each blade row can be performed in parallel (fine-grained parallelism) and multiple blade rows can be analyzed in parallel. A recent accomplishment in advancing code coupling is the coupling of an inlet CFD code (NPARC) with a turbomachinery code (ADPAC) to simulate the unsteady interaction between the inlet and the fan in a modern turbofan engine. These interactions are caused by disturbances that enter the inlet from atmospheric turbulence, wind gusts or propulsion/airframe installation effects. The coupling was validated with data from an experiment at the University of Cincinnati using a "collapsing bump" to launch a disturbance into a multistage compressor. The inlet was a straight pipe connected to a compressor. The result is shown in Fig. 3 and documented in detail in Ref. 3. Only the first blade row was modeled in this application which may account for some small discrepancy between the prediction and data. In general, the agreement was very good. The computation was performed on a cluster of SGI Origin 2000 workstations in less than 24 hr. The codes were coupled using the Multi-Disciplinary Computing Environment (MDICE) from CFD Research Corporation.<sup>4</sup> The validation of the approach is important in that it provides a numerical test cell for validating compressor face boundary condition models used in the design process.

In addition to the turbomachinery simulation, high-fidelity analysis of the combustor is also required. Rapid analysis of a combustor design requires not only short processing turnaround but also tools to assist in pre-processing and post-processing the data. Pre-processing is aided by unstructured grid generation to enable complete model buildup from compressor exit to turbine inlet. This includes the complex geometry associated with swirlers and injectors. Post-processing tools are required to reduce the vast amount of data produced by 3-D reacting flow computations into a few design parameters that the designer can use to assess performance and make design decisions. Progress in each of these areas over the past three years has resulted in significant reduction in analysis turnaround time as shown in Fig. 4 for the National Combustor Code.<sup>5</sup>

Clear data exchange standards are necessary to develop the integrated simulation system approach proposed for NPSS. The approach taken by NPSS is to work closely with national and international standards organizations to implement existing standards within NPSS, expand standards as required and develop new standards when necessary. The standards currently being worked on span a broad spectrum from 0-D to 3-D engineering standards to software standards.

### Multidisciplinary Coupling

The physical processes within an airbreathing gas turbine engine are inherently multidisciplinary. Consequently, the accurate simulation of these processes must properly account for the interactions amongst the disciplines. An example is in the high-pressure compressor where aerodynamic, structural, and thermal loadings all contribute to changes in geometry (i.e. casing, blade shape, tip clearances, etc.) that affect the efficiency and stability of the compressor. An accurate prediction of stall margin requires simulation of all of these loadings.

Aerospace propulsion systems are complex assemblies of dynamically interacting disciplines. The traditional analysis approach is to handle the interactions by single disciplines in a sequential manner where one discipline uses information from the preceding calculation of another discipline which is passed through unique, application specific, translators to make it usable by that discipline. This is a lengthy, tedious, and often times, inaccurate process due to the multiple translations taking place. Three different types of coupling are being investigated for inclusion into NPSS. These types are referred to as loosely coupled, process coupled and tightly coupled. A detailed description of the processes is contained in Ref. 6.

The first type is a rationalized version of the traditional sequential coupling process described above. The coupling occurs at the data access level. Separate analysis programs are executed to compute a component's aero, thermal, and structural response. This approach allows users to manually perform coupled analyses and then pass the data on to the next user in the iteration loop. Data access level coupling can be characterized as a very loose form of coupling. The rationalization of this process within NPSS is accomplished by establishing clear geometry and data exchange standards. NPSS is working closely with Product Data Exchange Standards, Inc. to ensure that any standard established are compliant with IGES and STEP. The standards used allow for the elimination of most of the unique, application specific translators. These are replaced with a set of generic translators and a subroutine library communicating through a Standard Data Interface with a database. Greater efficiency is provided through shared

access to all analysis data through a project database. This reduces the time required to perform the analysis and improves accuracy. A prototype of this system is being developed under the Coupled Aero-Thermal-Structural (CATS) project.

The initial focus of the CATS project has been on streamlining the aerodynamic-structural analysis of compressor blading. During each analysis cycle pressures are computed using an existing aerodynamic CFD solver. An Aerodynamic Surface Data Mapper then is used to map the aerodynamic pressures onto the blade geometry. A structural blade preprocessor, SABER, is used next to create a finite element mean camber model with pressure loadings from the loaded blade geometry. A structural finite element analysis is performed and the resulting blade deformations are post-processed, using SABER again, but this time to generate a deformed blade geometry. Finally, the deformed blade geometry is used as input to an aerodynamic grid generator to create an aerodynamic grid from the deformed geometry. The entire process is repeated until a converged set of fluid and structural results are obtained.

The initial phase of the CATS project has been demonstrated by performing Aerodynamic-Structural iterations on the Glenn Rotor 37 test rig using aerodynamic, structural, and the CATS tools. During each analysis cycle, aerodynamic pressure and temperature data along with structural blade deformations were computed. Previously, one cycle required one person-week to map data between aerodynamic and structure analysis codes and the design geometry. With the CATS tools the time was reduced to only several minutes. The current project plans are to continue development of the CATS tools and to integrate these tools into a common user interface. As progress is made on the project, additional efforts will be placed on applying these tools to a broader range of aerospace propulsion applications.<sup>7</sup>

The second type of coupling being proposed for inclusion in NPSS is process coupling. This can be viewed as an implementation of a visual computing environment in the multidisciplinary area. The ultimate goal is to be able to link individual and/or subsystems of tightly or loosely coupled codes together and run in an automated fashion. The current implementation in NPSS has focused on the automation of the loosely coupled systems. In this application, coupling at the process level is similar to the loose coupling at the data access level in that separate analysis programs are executed to compute a component's aero, thermal, and structural response in an iterative manner. However, there is a higher level system that controls the execution of the individual analysis programs and the exchange of data between them. Several different systems

have been investigated for implementing the process level coupling within NPSS. Commercial products such as Advanced Visualization System (AVS) and Access Manager were evaluated. While both had many good features, neither fully meet the NPSS customer requirements. Currently, this capability is being designed into the NPSS architecture through the development of a common interface to commercial computer aided design software.

The third type of coupling being proposed for inclusion in NPSS is tight coupling. In some propulsion system problems the interdependence of the disciplines are so "tightly-coupled" that the loose coupling at the data access and process coupling levels cannot capture the physics of the problem. These cases require an analysis that couples the disciplines at a fundamental equation level. For these problems the entire system matrix must be simultaneously solved using implicit methods. Tightly coupled solutions also have the advantage that the communication overhead is reduced substantially as depicted in Fig. 5. While this approach is able to solve general multidisciplinary problems, the extensive computational demands will likely limit this technique to a small number of tightly coupled disciplines and only individual components. A commercial code, Spectrum from Centric Inc., is currently being evaluated to determine if it meets the NPSS customer requirements in the area.<sup>8</sup>

#### Variable Complexity Analysis

The detailed simulation of a complex system like a gas turbine engine will require computing resources and/or wall clock times which are beyond practical limits for use in industrial design environments. Consequently, it will be necessary to provide modeling techniques that provide the analyst or designer the ability to vary the level of detail of analysis throughout the engine based upon the particular physical processes being studied as a result of a design change. For instance, determining the effect of a change in the shape of a fan blade on engine performance may only require a three-dimensional simulation of the fan stage. The rest of the engine could be modeled at lower levels of detail (two-, one- or zero- dimensional) to minimize simulation setup and execution time.

An example of variable complexity analysis, referred to as zooming, is shown in Fig. 6 through the hybrid turbofan engine model. The high-pressure core of the engine (i.e. compressor, combustor and turbine) is modeled as a zero-dimensional, aerothermodynamic cycle analysis through the use of component performance maps. In this example, however, the low pressure subsystem (i.e. inlet, fan, core inlet, bypass duct, nozzle) is modeled in 3-dimensions using a CFD turbomachinery code,

ADAPC.<sup>9</sup> Aerothermodynamic boundary condition data is exchanged directly between the low and high-pressure subsystems. In addition, shaft power balances are achieved using both the CFD and engine cycle analysis. Since the cycle analysis executes much faster than the three-dimensional simulation, the three-dimensional simulation is executed in parallel over a large cluster of up to 64 workstations to minimize the turnaround time. The hybrid model greatly simplifies the high fidelity simulation of the engine by using 3-D modeling only where required. In this example, the propulsion/airframe integration or the impact of atmospheric disturbances on the engine would be modeled in detail without requiring a 3-D solution of the core engine. The latter would be extremely time consuming to setup, execute and analyze.

Several different types of zooming have been identified for the NPSS system requiring a more robust software architecture. Currently, these capabilities are being integrated into the overall NPSS architecture. The system simulations will be based on the view that only phenomenon that affects system attributes, such as life, reliability, performance and stability of a propulsion system, are of interest to the designer or analyst. While the physics affecting these attributes could be captured by modeling the entire propulsion system at the highest level of fidelity, 3-D, transient and multidisciplinary, two problems prevent this from being a viable option in most cases. First, the level of detailed information needed as boundary and initial conditions to get a converged, validated solution will be extremely difficult to collect. Second, the computational time and cost will be prohibitively high for effective use in a design environment. Therefore, the designer or analyst must tailor the fidelity of the simulation to capture the appropriate physics for each component and discipline. This results in an analysis of variable complexity being performed across components and disciplines which make their integration into an overall subsystem or system simulation extremely difficult. Consequently, the NPSS framework is being developed to allow the physical processes resolved from a detailed analysis of a component or subcomponent to be communicated to a system analysis performed at a lower level of detail for purposes of evaluating system attributes. Conversely, the system analysis will provide the ability to evaluate which physical processes, occurring on the component and subcomponent level, are important to system performance. This will allow the engineer or scientist to focus in on the relevant processes within components or subcomponents.

Zooming requires a hierarchy of codes and models to be in place to provide a wide range of simulation capabilities from detailed three-dimensional, transient analyses down to zero-dimensional, steady-state analyses. Modeling

approaches will be developed for communicating information from a detailed analysis to a filtered, lower level analysis. This will require additional research to understand the mechanisms by which phenomenon on different length and time scales communicate. Research is already underway in computational fluid dynamics and structural mechanics to develop this modeling approach and will be extended to consider processes and scales appropriate for the entire propulsion system.

### The Simulation Environment

The simulation environment for NPSS will provide a common interface for a variety of users to access all of the capabilities within NPSS. This means the interface will have to accommodate users of various skill levels, enable users to modify code, enable users to easily replace analysis tools and enable users to accept data from a variety of sources such as simulations, existing databases, and experiments. In addition, the environment must enable the seamless integration of all of the planned capabilities in NPSS such as multidisciplinary analysis, zooming, and distributed computing on a variety of computing platforms.

The NPSS project is building a simulation environment that provides a generic zero-dimensional component view of an aeropropulsion engine and provides tools and standards for data exchange for the coupling of multidisciplinary codes. The environment allows the engineer to zoom to finer levels of fidelity on a component specific basis while operating at the zero-dimensional view of the engine. NPSS will execute on a variety of computers and allow distribution of engine components in any user-specified fashion. The approach taken for developing NPSS incorporates the following key elements as part of the simulation environment:

1. Clear data interfaces through the development and/or use of data exchange standards;
2. Modular and flexible software construction through the use of object-oriented methodologies;
3. Integrated multilevel of fidelity analysis techniques that capture the appropriate physics at the appropriate fidelity for engine system simulations;
4. High-performance, parallel and distributed computing.

Due to the multidisciplinary nature of propulsion systems and the idea of "Numerical Zooming" between disparate time scale codes, suggests that the engine computations will likely take place in a distributed heterogeneous computing environment. Given this, coupled with the fact that current programming techniques do not facilitate the development of large software systems,

requires a shift in programming approaches. Fortunately, new technologies in software development such as object-oriented languages are becoming available. Object-oriented languages were created to aid software development and management with the following attributes: (1) maximum code reuseability, (2) clear data connectivity and (3) code modularity.

The NPSS architecture is intended to be open and extensible. To this end, the architecture exploits the capabilities of object-oriented programming (inheritance, polymorphism, and encapsulation) as well as modern object-oriented concepts including frameworks, component objects, and distributed object standards, such as the Common Object Request Broker Architecture (CORBA). The objects in the architecture will know how to expand and contract data for zooming from three-dimensional codes to zero-dimensional codes or vice versa. They will know what components are connected up and downstream of themselves for the purposes of generating execution sequences. Objects will know how to connect aeropropulsion disciplines together. In fact, it is because of these object-oriented features that the concept of providing an engine simulation environment like NPSS is conceivable.

Within the environment, an engineer can assemble aeropropulsion simulations without restrictions as to fidelity, choice or location of code. The engineer can accept modules that are resident in the NPSS architecture. The engineer can accept portions of the resident codes and supplement these code with those available at their respective site. The "plug'n play" capability illustrated here is essential for keeping the architecture current and facilitating new analytical approaches. The cornerstone of the NPSS architecture is its development from the object-oriented paradigm and noted for providing a computing and engineering white board from which engine simulations can be created.<sup>10</sup>

An example of how zooming is incorporated into the cycle simulation is illustrated in Fig. 7. The entire engine is modeled at the zero-dimensional level with data exchange from a one-dimensional meanline compressor code. The codes are CORBA compliant and communication is established through the Object Request Broker (ORB). This implementation is a general approach that allows other analyses to be linked in, other mathematical operations to be performed as the data is being expanded or contracted, and allows for distribution of the simulation across a wide area network to facilitate remote team member involvement in the simulation. This capability is being developed under contract with Pratt & Whitney and the United Technologies Corporation.

## High Performance Computing

The detailed simulation of a complex system like the gas turbine engine requires significant computing capacity that is not practically available today. A three-dimensional simulation of the primary flowpath in a full engine requires in excess of  $10^{12}$  Floating-point Operations Per Second (TeraFLOPS). Today this speed is only available in a few very expensive machines and has not been achieved on propulsion system applications. To accomplish all of the capabilities planned for NPSS would require  $10^{15}$  Floating-point Operations Per Second (PetaFLOPS). It is not expected that a serial machine or even moderately parallel machine will be able to accomplish this with current trends in hardware technology. Therefore, the approach in the NPSS Project under the NASA High Performance Computing and Communications Program (HPCCP) is to develop the application software and system software that will enable the use of large numbers of parallel processors. As this approach is followed, technologies that provide good scalability to even larger numbers of parallel computers will be of particular interest. Adding the ability to do distributed computing, allows the user of the system to take advantage of the large number of commodity workstations and personal computers (PCs) that normally exist within an organization and to leverage off of the continuing reduction in the cost/performance ratio of these machines. The NPSS Project with the support of the HPCCP is developing the software required to accomplish this objective under the Affordable High Performance Computing Cooperative Agreement.<sup>11</sup>

The original objective of the effort was to achieve similar performance and reliability of a 1994 vector super-computer at 25 percent of the cost. In so doing, much larger computing resources will be available to the designer, analyst and researcher than ever before. Consequently, the project also demonstrated over an order of magnitude reduction in the time to perform an aerodynamic simulation of a complete high pressure compressor by taking advantage of much larger computing resources than available on a single vector machine. It is estimated that this reduction in analysis turnaround time will result in a 33 percent reduction in the time to design a compressor and a savings of several millions of dollars. The actual performance of the workstation cluster far exceeded the original goal. The cluster actually achieved the same performance and reliability as a vector supercomputer at 8 percent of the cost.

This accomplishment has led to further research in this area of cluster computing to reduce the cost/performance ratio of supercomputing. At the NASA Glenn

Research Center, a cluster of 64 Pentium II processors is being used to achieve another factor of 10 reduction in cost/performance below that of workstation clusters. The Pentium II machines are configured in two banks of 16 machines, each machine with two, 400 MHz processors. The machines are interconnected with Fast Ethernet network and the two banks are connected through a Gigabit Ethernet. The turbomachinery and combustion simulations in use under NPSS are currently being ported to the Pentium processors. At this point, approximately 50 percent of the project's goal has been achieved.

## Conclusion

Detailed, multidisciplinary, full engine simulations are possible with the integration of advanced propulsion modeling with high performance computing and communications technologies. Modeling techniques must include component integration to capture interactions, multidisciplinary coupling to capture key physical processes, and variable complexity analysis to minimize the time-to-solution. Computing and communications technologies must provide system software to manage the execution of simulations over a large number of parallel, distributed, heterogeneous computers and high-speed, low-latency networks to minimize interprocessor communication time. Significant increases in the size and complexity of simulations demonstrate that this goal is now within reach.

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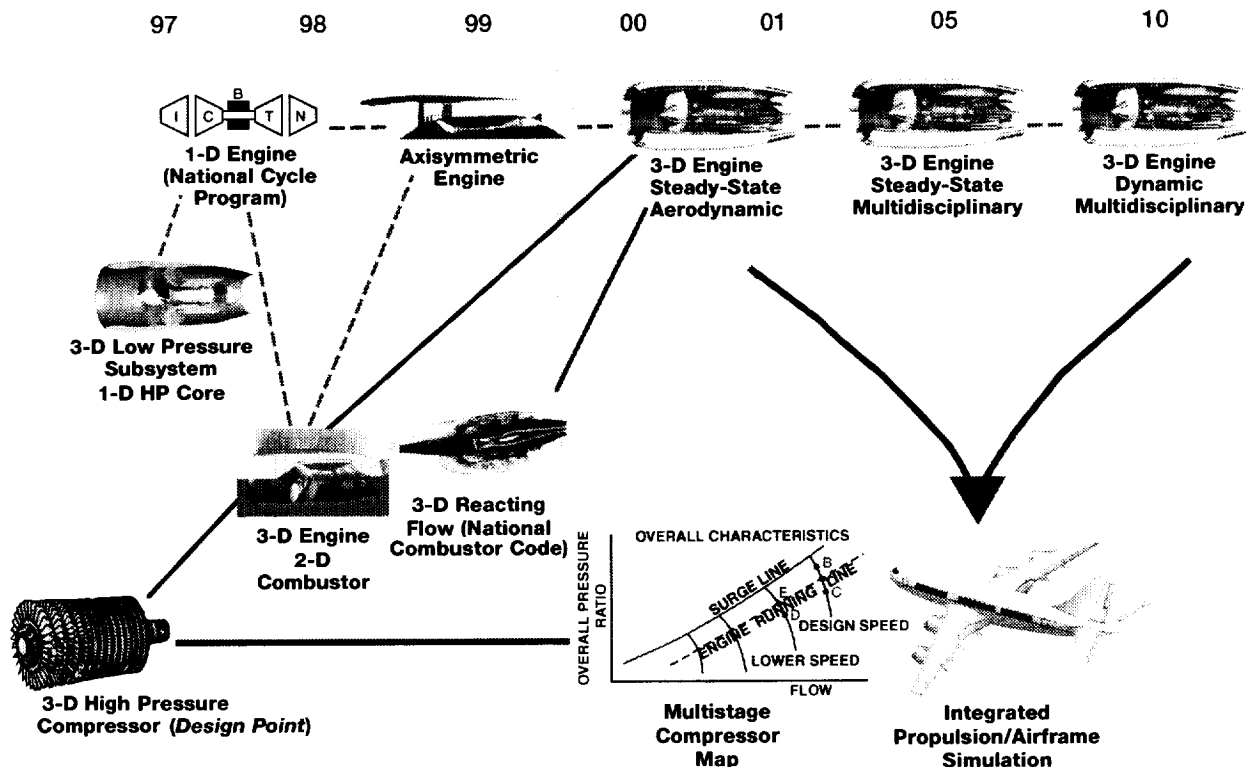


Figure 1.—Roadmap for NPSS overnight simulations.

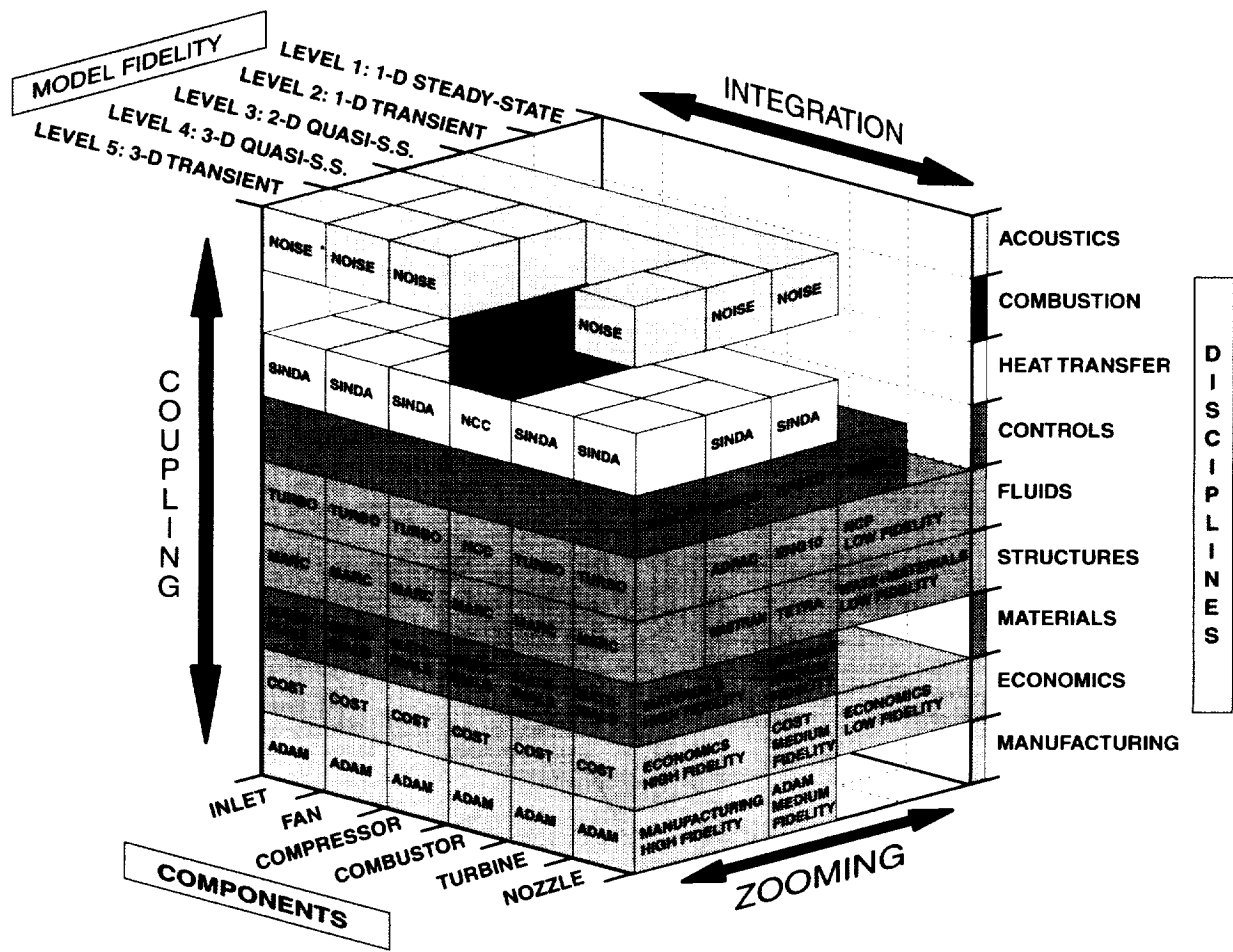


Figure 2.—The three major elements of complex system simulation.

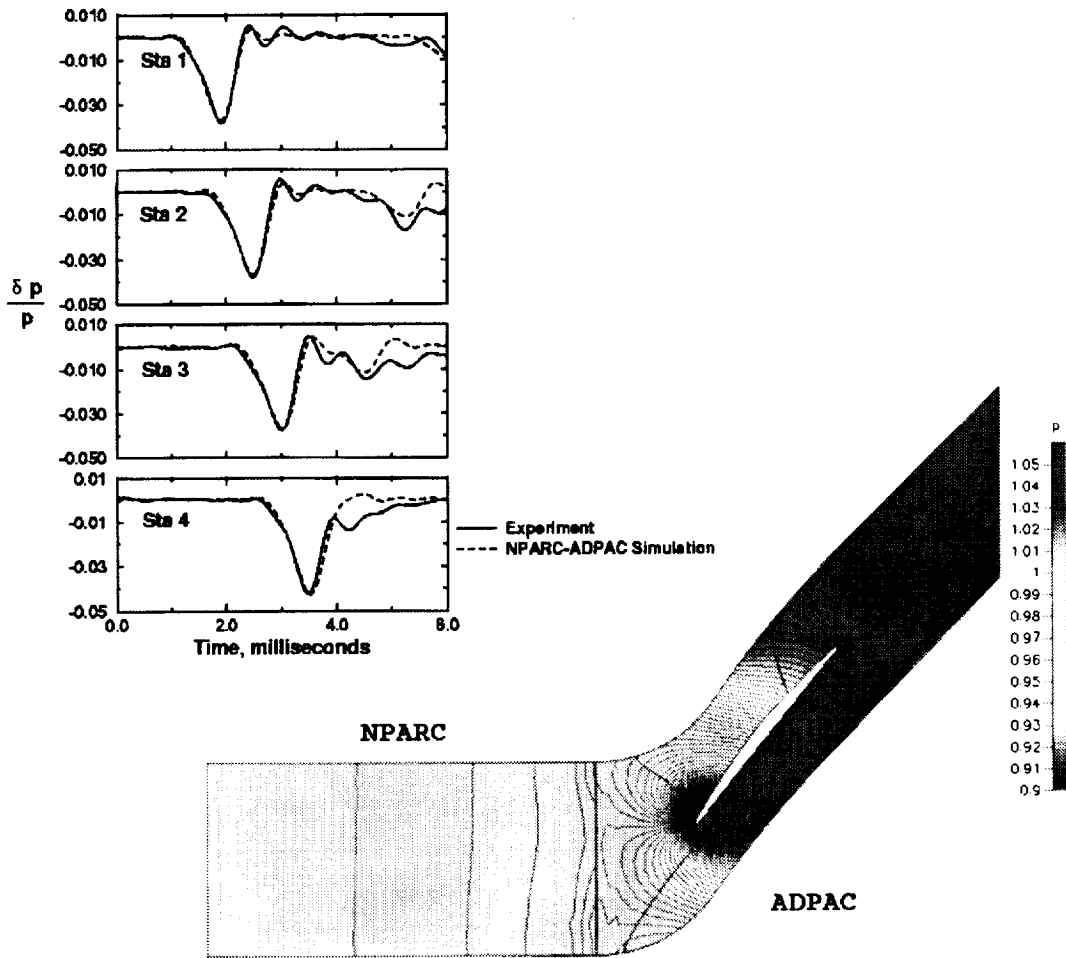


Figure 3.—Validation of code coupling for unsteady inlet-turbomachinery interactions.

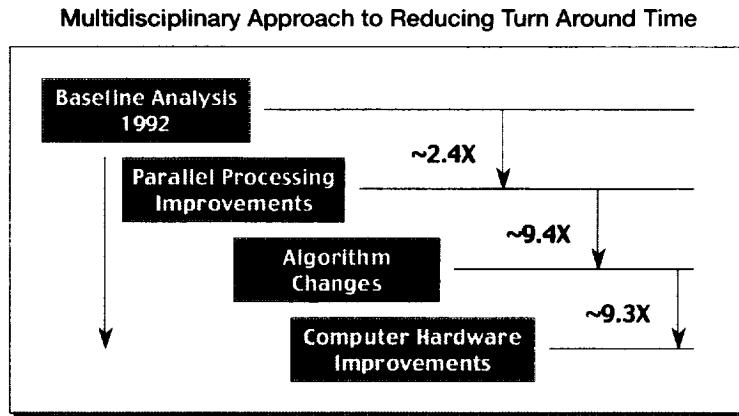
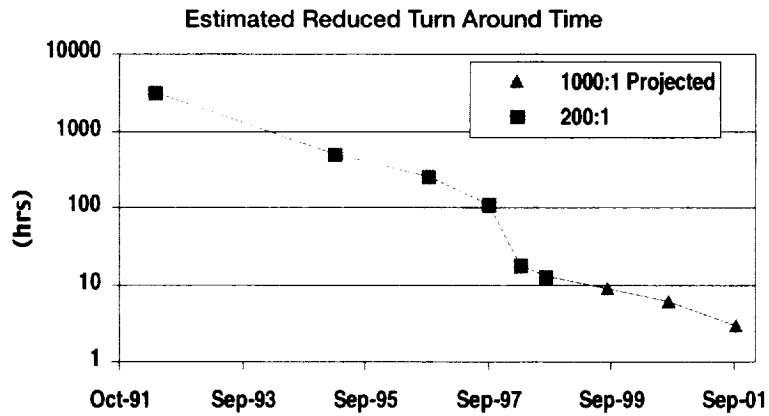
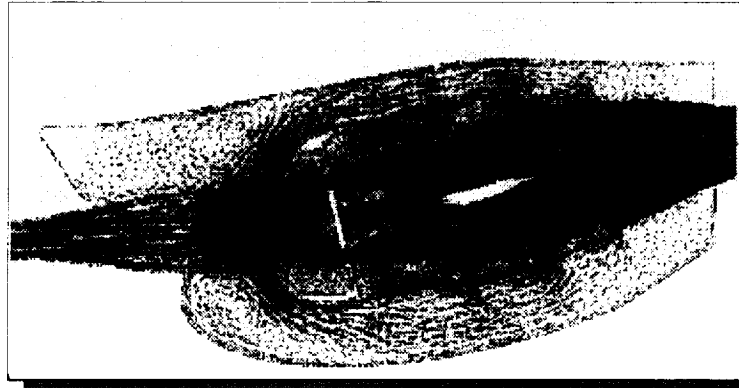


Figure 4.—200:1 Reduction of full combustor simulation time relative to 1992 baseline.

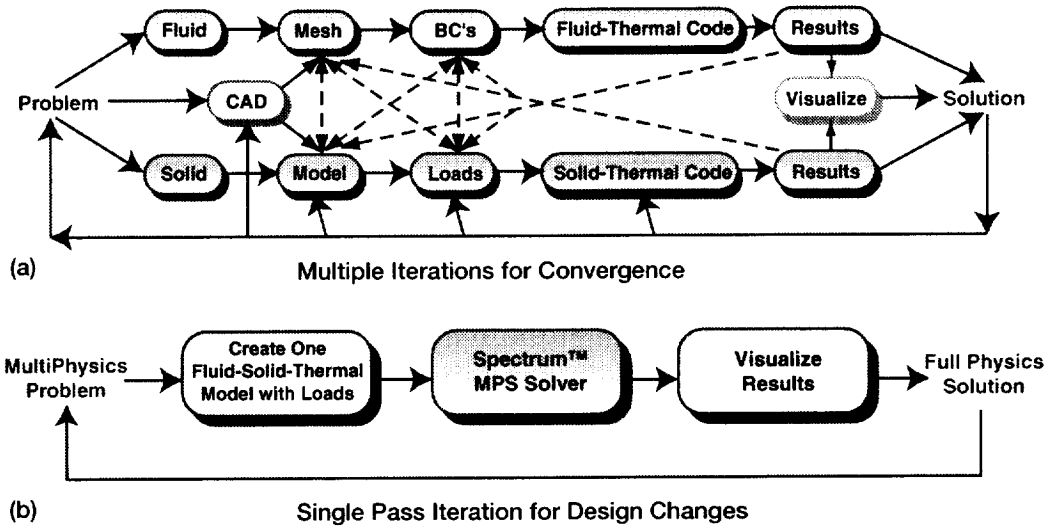


Figure 5.—Tightly coupled multi-disciplinary simulation. (a) Loosely coupled/process coupled approach. (b) Tightly coupled, Spectrum approach.

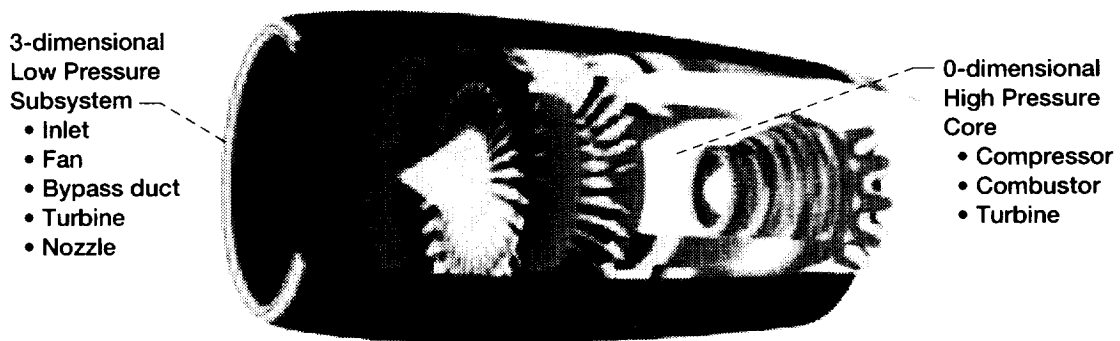


Figure 6.—Hybrid simulation: 3-dimensional low pressure subsystem model coupled to a 0-dimensional high pressure core model.

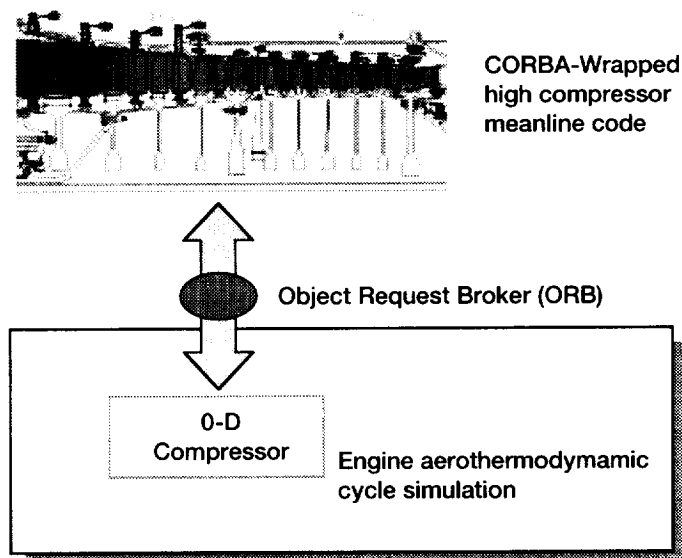


Figure 7.—1-D high compressor meanline analysis integrated with engine aerothermodynamic cycle simulation.

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