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A Perspective on Future Directions in Aerospace Propulsion System Simulation

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A PERSPECTIVE ON FUTURE DIRECTIONS IN AEROSPACE PROPULSION SYSTEM SIMULATION

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SUMMARY

The design and development of aircraft engines is a lengthy and costly process using today's methodology. This is due, in large measure, to the fact that present methods rely heavily on experimental testing to verify the operability, performance, and structural integrity of components and systems. The potential exists for achieving significant speedups in the propulsion development process through increased use of computational techniques for simulation, analysis, and optimization. This paper outlines the concept and technology requirements for a numerical propulsion simulation system (NPSS) that would provide capabilities to do interactive, multidisciplinary simulations of complete propulsion systems. By combining high performance computing hardware and software with state-of-the-art propulsion system models, the NPSS will permit the rapid calculation, assessment, and optimization of subcomponent, component, and system performance, durability, reliability and weight - before committing to building hardware.

INTRODUCTION

The design and development of aircraft engines is a lengthy and costly process using today's methodology. The process, as illustrated in figure 1, can take up to 10 years and cost billions of dollars. This is due, in large measure, to the fact that present methods rely heavily on the experimental testing of components and complete systems to verify the operability, performance, and structural integrity of designs and that this generally requires a large number of design-build-test cycles.

The potential exists for achieving significant speedups in the propulsion design process through increased understanding of the governing physics of propulsion systems and the application of rapidly advancing, high performance computing technologies to propulsion system simulation. In addition to speeding up the development process, these powerful simulation tools will allow designers to be more aggressive and innovative, providing a means to assess designs that extend far beyond the bounds of experience and empirical data bases. Improvements in propulsion simulations will result from advances in computational fluid dynamics (CFD), computational structural mechanics (CSM), and computational material science. In each discipline, simulation developers are striving to build more and more of the relevant physics into mathematic models and numerical solvers. The availability of powerful supercomputers, such as the NASA Numerical Aerodynamic Simulator (NAS), is now making it practical to use numerical simulations to investigate highly complex (real) propulsion system configurations over wide ranges of operating conditions.

While significant benefits are to be derived by continuing these computational advances in the individual disciplines, an even grander vision of what is possible in propulsion simulation can be had by considering the use of future high performance computers to implement numerical simulations that combine all of the major propulsion phenomena (fluid flow, heat transfer, combustion, structures, materials, controls, . . .). Figure 2 illustrates the concept of a numerical propulsion simulation system (NPSS) that would provide the capability to do interactive, multidisciplinary simulations of complete propulsion systems. As such, the NPSS would permit the rapid calculation, assessment, and optimization of subcomponent, component, and system performance, durability, reliability and weight - before committing to building hardware. Thus, the propulsion designer would be able to explore the full range of design space and to combine simulations of candidate propulsion systems with vehicle simulations to evaluate mission suitability and performance.

In this paper, the evolution of a plan to develop and demonstrate technology for an NPSS is discussed along with the potential benefits of such a system.

BACKGROUND

In order to set the tone of this paper, let us start by using our imagination. What if we had the capability to "compute" an engine. This means that any parameter of interest could be computed with satisfactory engineering accuracy, in a reasonable time, for a reasonable cost. What would be the benefit of having such a capability? Ultimately, this would mean the elimination of the design-build-test-redesign loop in the engine development process. Engines could go directly from design to production, as illustrated in figure 3. Most of the "testing" would be done in the "numerical test cell" with savings in engine development time and cost estimated to be in the range of 25 to 40 percent.

Why can't we do this today? To answer this question is to identify critical, enabling technologies that need to be worked for the NPSS. In broad terms, the technical barriers extend across all areas. We are limited by our inability to understand and model important physical phenomena, such as turbulence. We are constrained by the limited power of today's computer hardware and software. Extensive simplifications to propulsion simulation models are required for running on even the most powerful supercomputers. And we are limited by the capabilities of existing numerical methods (i.e., algorithms, grid generation methods, etc.). Achieving the goals of a numerical propulsion simulation system is truly a grand challenge, requiring a coordinated, multidisciplinary research effort.

While NPSS may never completely eliminate the need for experimental hardware testing, one expects continued advances in NPSS technology to have a growing effect on the relative importance and use of numerical simulations in aerospace propulsion research and development. The expected shift in balance between testing and computing is depicted in figure 4.

The potential impact of NPSS can, perhaps, be best illustrated by considering an example of a multidisciplinary project being conducted at the NASA Lewis Research Center and the complexity of the design process caused by limitations in today's computational tools.

The example involves the conceptualization, design, building, and testing of a supersonic throughflow fan stage. Figure 5 shows the steps involved in the fan design process. In this case, the selection of the fan design point was dictated, not by aircraft mission requirements, but rather by aeropropulsion research objectives. The design point had to be suited to the data bases and computational capabilities at hand and had to result in a fan design that could be produced at reasonable cost for the initial hardware testing.

The initial blade shape selection was made via the NASA Lewis Compressor Design Program (CDP). That program requires the designer to provide baseline loss data and deviations that will be appropriate for the computed blade shape. In practice, this step is heavily dependent upon the designer's skill and the available experimental data base. In the case of the supersonic throughflow fan, the experimental data base was practically nonexistent. The initial loss data were provided using a "best-guess."

Once the loss data were specified, the three-dimensional blade shapes for both the rotor and stator were computed by the CDP. Approximately five two-dimensional sections were then extracted from the three-dimensional blade shape and analyzed with a two-dimensional Navier-Stokes flow code. Using results from the two-dimensional analysis, the designer was able to modify the two-dimensional sections, as needed, to produce an aerodynamically acceptable blade shape. At this point, the resulting losses and deviations could be fed back from the Navier-Stokes code to the CDP to obtain new three-dimensional blade shapes. However, lack of confidence in the loss predictions from the two-dimensional Navier-Stokes code caused the designer to only feed back the recomputed deviations. Once the designer was satisfied with the results of the two-dimensional analysis, the three-dimensional blade shapes were analyzed with a three-dimensional Euler code and an interactive boundary layer calculation to determine whether any strong three-dimensional inviscid effects were present.

Once the blade shape was acceptable from an aerodynamic standpoint, the design was passed to a structural engineer who analyzed the blade rows for steady-state stresses. One of the early designs suffered from high steady-state stress levels, forcing the designer to repeat the entire aerodynamic design process in order to accomodate the required increased blade thickness.

After steady-state stresses were deemed acceptable, the fan was analyzed for unsteady stresses. At that point, the design was judged to have a potential flutter problem and the blade chord was lengthened to increase the flutter margin. This, of course, resulted in yet another iteration through the design process. The test fan is currently being fabricated and will undergo testing to determine if the design goals were met.

The supersonic throughflow fan design is but one example of where the availability of a proven, multidisciplinary (i.e., aerostructural) analysis and optimization capability would have greatly simplified and accelerated the design and development of advanced propulsion system components.

APPROACH

While the ultimate goal of NPSS is to allow detailed, front-to-back, computation and analysis of engine behavior (e.g., aerothermodynamic-structural-material interactions, performance and durability predictions, controlled response to disturbances), achieving this capability will require a step-wise, building block approach, involving the development/incorporation of a hierarchy of engine system models.

As used here, the term "model" refers to an operation that translates a set of specified inputs to a set of delivered outputs. In this sense, any computer code can be considered to be a model, with the fidelity of the model measured by the level of detail required in the inputs and outputs and the required accuracy of the outputs relative to the actual, physical processes being represented. In many cases, a model of a component or physical process will actually consist of a series of models. An example of this model hierarchy is the turbulence model contained in a computational fluid dynamics (CFD) code.

As conceived, the NPSS will contain a spectrum of models that will be available to the user for propulsion system analysis. These will range from simple, interpolating functions to codes that solve the full Navier-Stokes equations. The user will be able to tailor an analysis to the task at hand. In some cases, attention may be directed to a specific component or phenomena with detailed models of that component phenomena combined with less sophisticated models for the rest of the engine. This "coupling" of models will also carry over to the integration of disciplines, as illustrated in figure 6. NPSS will allow multidisciplinary analysis to be accomplished in a variety of ways. For loosely coupled processes, the user will be able to transfer information between single discipline models. To simulate tightly coupled processes (e.g., aeroelasticity), multidisciplinary models and algorithms will be available.

As viewed by a user, the NPSS might appear as a pyramidal structure, as shown in figure 7. The user would enter at the top and reach down to lower levels, as needed, to obtain the appropriate level of detail for the specific analysis. During the course of the analysis, the user would be able to pass back and forth between levels of the system, a process that was described earlier for the supersonic fan design. A "smart shell," perhaps in the form of an expert system, would serve to guide and assist the user in selection of the appropriate models and analysis tools. The development of this "smart shell" will be one of the keys to the success of NPSS. It will provide a framework for development and integration of the various models and codes that will make up the NPSS.

CONCLUDING REMARKS

Advances in the physical and computational sciences are enabling researchers to better understand, model, and simulate the complex physical processes that determine propulsion system performance, durability, and life. While progress has been made in the application of numerical simulations to propulsion (e.g., computational fluid dynamics, computational structural mechanics, computational materials science, controls), the overall impact of numerical simulation on propulsion system design and development can and needs to be greatly expanded. Successfully doing so will yield significant reductions in the time and cost of developing propulsion systems while also resulting in higher quality products. However, major technological advances are needed to bring numerical simulations to the point where many of the critical design issues can be settled on the computer.

The NPSS concept has been proposed as a way of focusing and integrating research and technology efforts in propulsion system modeling, algorithm and code development, and high performance computing to develop and demonstrate the required simulation, analysis, and optimization capabilities. NPSS will be an evolving capability. By continuously incorporating the best available hardware and software tools that are emerging from disciplinary and multidisciplinary research programs, NASA Lewis, in partnership with industry and academia, will be establishing a unique, powerful, and versatile simulation test-bed representing the state-of-the-art in multidisciplinary simulation, analysis, and optimization capabilities.

While the challenges are great, the potential rewards warrant a concerted, long-term effort by government, university, and industry researchers. Savings in time and cost of engine development, that would result from NPSS technology, have been estimated at between 25 and 40 percent.

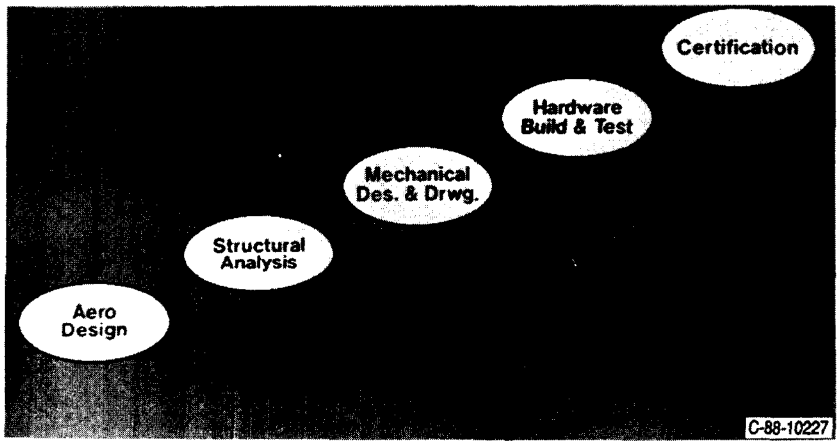

Figure 1. - Aircraft engine development cycle; today's methodology.

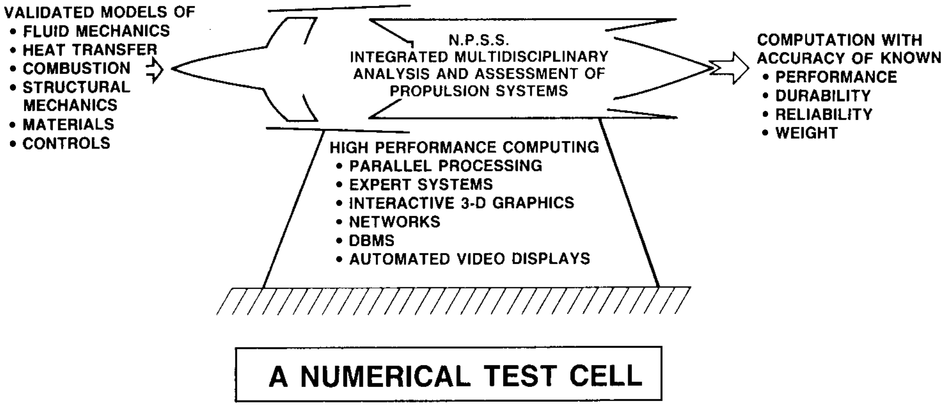

Figure 2. - Numerical propulsion simulation system (N.P.S.S.)

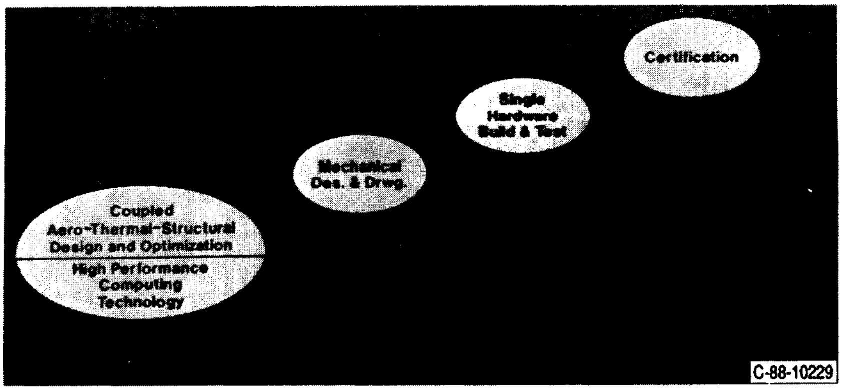

Figure 3. - Aircraft engine development cycle; future methodology via NPSS.

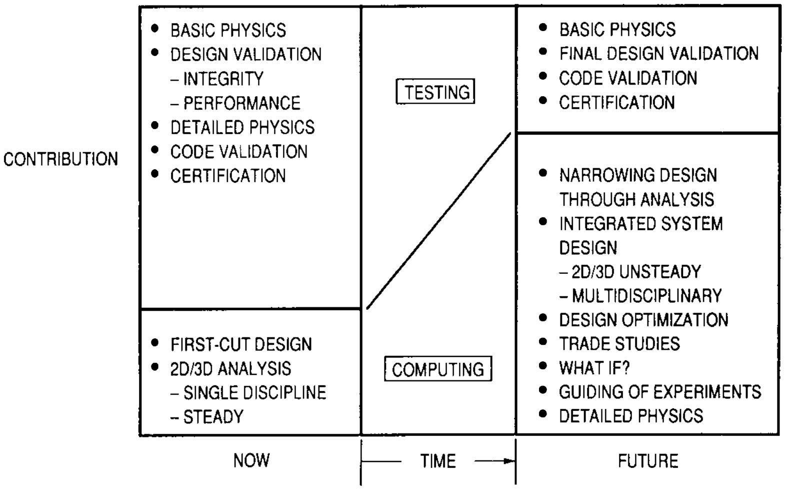

Figure 4. - Expanding the role of numerical simulation in Aerospace Propulsion R & D.

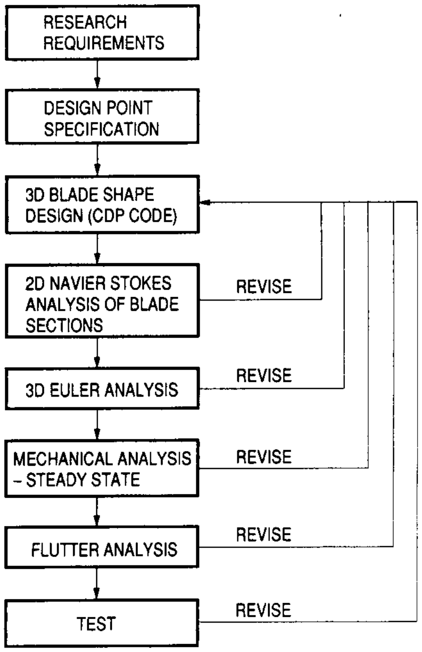

Figure 5. - Supersonic fan design process.

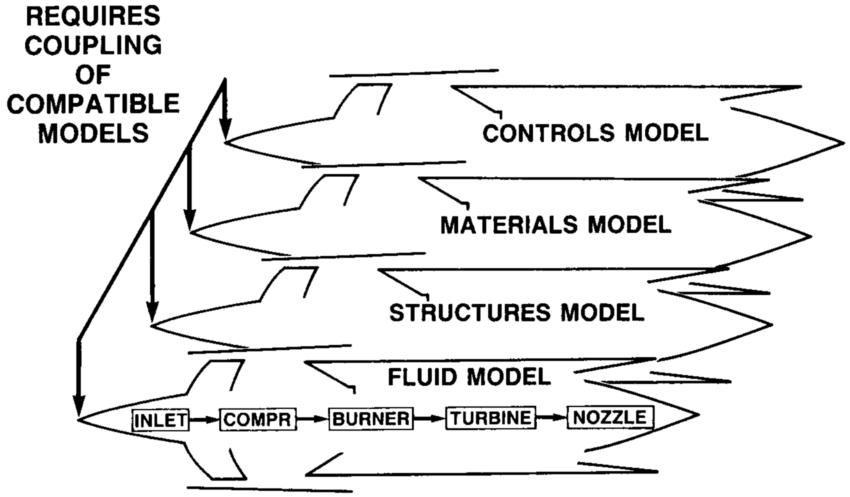

Figure 6. - NPSS integration of disciplines.

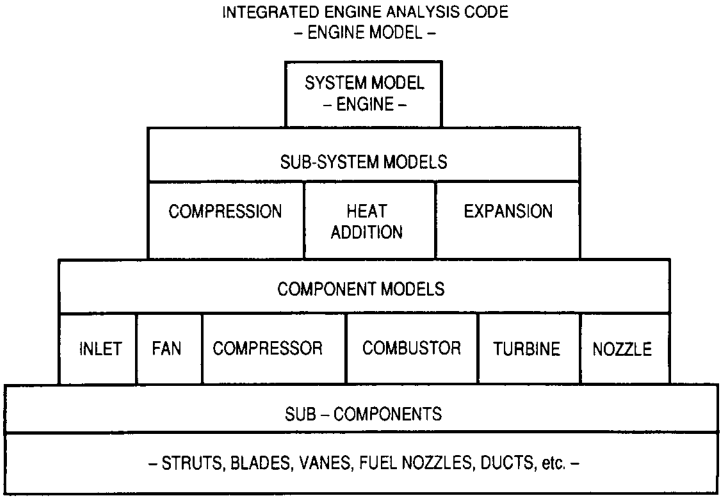

Figure 7. - Numerical propulsion system simulation.

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