Detailed Simulation of Aircraft Turbofan Engine

Objective
Develop a detailed flow model of a full turbofan engine that runs on parallel workstation clusters overnight. The model will initially simulate the 3-D flow in the primary flow path including the flow and chemistry in the combustor, and ultimately result in a multidisciplinary model of the engine.

Approach
- The 3-D flow analysis models the GE90 turbofan engine using APNASA (NASA's average-passage flow code).
- Leverage form efforts between NASA and GE in developing the APNASA flow code and workstation clustering technology.
- Contract with GEAE NAS3-98004 Task Order #9
- The National Combustion Code (NCC) will be used to simulate the flow and chemistry in the combustor.
- The APNASA and NCC codes shall be coupled together at NASA Glenn Research Center.

Significance/Metrics
The overnight 3-D simulation capability of the primary flow path in a complete engine will enable significant reduction in the design and development time of gas turbine engines.

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Detailed Simulation of Aircraft Turbofan Engine

Contributors:

GE Aircraft Engines:
- Lyle D. Dailey: Technical Manager, compressor and booster simulations
- George Liu: Provided information on GE90 compression system
- Bryan Doloresco: Provided 2-D Euler (CAFMIXII) solution for PIP+ compressor
- Kevin Kirtley: (GE Corporate Research) Fan simulation with APNASA Version 5

Rolls Royce / Allison
- Edward J. Hall: Manager and principal investigator

ASE Technologies:
- Paul Vitt: Project Manager
- Jason Smith: Performed booster, HPC, and turbine simulations

AP Solutions:
- Tim Beach: Provided radial multiblock gridding support (APG)
- Mark G. Turner: Consultant on compression and turbine simulations

AYT:
- Rob Ryder: Consultant on combustion simulations

NASA Glenn Research Center:
- John Adamczyk: APNASA turbomachinery flow code
- Nan-Suey Liu: National Combustion Code (NCC)
- Jeff Moder: NCC and APNASA code coupling
- Le Tran: NCC and APNASA code coupling
- John Gallagher: Combustor CAD geometry to grid generator interface
- Don VanDrei: Task Manager
- Joseph P. Veres: Manager Aircraft Engine Systems

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<td>NASA/MSU</td>
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<td>NASA/APSolutions</td>
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<td>10. Combustor simulation with finite rate chemistry and liquid fuel (NCC Version 1.0)</td>
<td>NASA/AYT</td>
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<td>NASA/MSU</td>
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### Detailed Flow Simulation of Aircraft Turbofan Engine

The high-bypass turbofan engine in this simulation effort consists of 49 blade rows
- Fan
- OGV
- 3-stage booster (7 blade rows)
- Fan frame strut
- 10-stage high-pressure compressor (21 blade rows)
- 2-stage high-pressure turbine (4 blade rows)
- Turbine mid-frame strut
- 6-stage low-pressure turbine (12 blade rows)
- Turbine rear frame strut

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Detailed Flow Simulation of Aircraft Turbofan Engine

FY00 Accomplishments: Turbomachinery Flow Simulations

* NASA and GEAE Developed APNASA Version 5 Featuring:
  * 4-stage Runge-Kutta explicit Navier-Stokes solver
  * Local time steps
  * Implicit residual smoothing
  * Implicit k-ε turbulence model
  * Models multi-stage effects by calculating deterministic stresses with generalized closure
  * Domain decomposition in axial direction
  * Uses MPI message passing
  * Radial and tangential multiblock with l-Grid
  * Cooling and leakages handled by sources terms and endwall model
  * Real gas (linear gamma) model in 3-D

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Detailed Flow Simulation of Aircraft Turbofan Engine

FY00 Accomplishments: Turbomachinery Flow Simulations with APNASA

* Simulation of Fan, Bypass Outlet Guide Vane and Booster Stator 1

* High-Pressure Compressor (HPC)
  * Simulation: Rig and Engine Conditions

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Detailed Simulation of Aircraft Turbofan Engine

FY00 Accomplishments: Turbomachinery Flow Simulations

Critical Computing Capability for High-Pressure Compressor Simulations

- All high-pressure compressor (HPC) simulations used NASA NAS Origin 2000.
- In two-hour wall clock period, total of 320, 480, and 880 iterations can be achieved with 84, 104, and 208 processors.
- Typical 15000 iteration case requires about 93, 63, or 34 hours of wall clock time for 84, 104, and 208 processors, respectively.
- Parallel analyses set up with almost equal distribution of processors (i.e., 4, 5 or 10 per blade row).
- Excellent scaling for APNASA flow simulation between 104 and 208 processors.

HPCCP resources allowed many trials to be completed in a reasonable amount of time even for a large 21 blade row case -- CRITICAL IN DEBUGGING AND DEVELOPMENT

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Detailed Simulation of Aircraft Turbofan Engine

FY00 Accomplishments: Turbomachinery Flow Simulations

Parallel Performance of APNASA on HPCC NAS Origin 2000 Machines

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Detailed Simulation of Aircraft Turbofan Engine

FY00 Accomplishments: HP-LP Turbine Flow Simulation

Aspects of Turbine Simulations

• Transonic aerodynamics
  High work HP turbines have strong shock systems.

• Embedded blade row operating conditions
  Both upstream and downstream blade rows mutually interact during engine operation.
  The average-passage equations actively include the effects of the surrounding blade rows.

• Turbine flight hardware is actively cooled
  Airfoils, platforms and casing are cooled by compressor bleed air.

• Hot gas leaks around the tips of rotors through labyrinth seals

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Detailed Simulation of Aircraft Turbofan Engine

FY00 Accomplishments: Turbomachinery Flow Simulations

Coupled Flow Simulation of High-Pressure / Low-Pressure Turbines Results in Efficiency Predictions Within 0.8 and 0.5 Percent, and Shock Interaction Loss Predicted Within 0.5 Percent

A computer simulation of the air flow in the GE90 turbofan engine’s high- and low-pressure turbines has been created at General Electric Aircraft Engines (GEAE). The 3-D computer simulation was performed using NASA Glenn’s average-passage approach named APNASA. This is the first ever flow simulation of an HP and LP turbine, transition duct and exit guide vanes. The simulation was done using 121 processors of a Silicon Graphics Origin cluster with a parallel efficiency of 87% in 15 hours.

Analysis of the simulation has identified excessive turbine aerodynamic interaction losses that can be reduced by 50%. This 50% reduction in turbine interaction losses will result in a $3 million/year savings in fuel costs for a new fleet of aircraft. The parallel efficiency and accurate simulation with APNASA now make it practical for use in the design environment.

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FY00 Accomplishments: Turbomachinery

3-D Navier-Stokes APNASA Flow Simulation of Closely Coupled HP-LP Turbines

Exit Guide Vanes

High Work Rotor

LP Turbine

Transition Duct

HP Turbine

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Parallel Processing Requirement for HP-LP Turbine Simulation

- Typical average-passage analysis mesh size for a given blade row
  - 280x45x55 ~ 700,000 grid points
- 10-18 blade rows for a combined HP and LP turbine system
  - 7 to 12.6 million grid points
- Design cycle requirements are 24 to 48 hour turnaround time
- Requires 6,000 to 10,000 iterations for convergence, at 8.x10E-05 seconds/iteration/gridpoint (NAS O2K)
  - Total CPU time will be 930 to 2800 CPU-hours (assuming 100% efficient multiple processor usage).
  - Parallel processing using 40 or more processors is required to meet the design cycle time constraints.

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FY00 Accomplishments: Turbomachinery Flow Simulations

Parallel Performance of APNASA on HPCC NAS Origin 2000 Machines

GE90 HPT+LPT (18BR), Cooled Average Passage Results
Blade Row 2490000 Grid points, 966 Total Grid Points
250 MHz Origin 2000 (Hoppe/Steiger) August 1996 Data

Number of Processors

Parallel Speedup Factor

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Detailed Simulation of Aircraft Turbofan Engine

GEAE Conclusions: Turbomachinery Simulation

- Full engine simulation program has led to very useful component simulation capability and understanding of component interaction.
- Booster simulations with APNASA notably successful.
- High-pressure-ratio compressor (HPC) still a challenge for Version 5 of APNASA.
- HPCCP resources extremely useful for debugging and validating code for high-interest problems at GE.
- Quick demonstrated turn-around time allows APNASA code to be used for analysis in a design environment.

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Detailed Simulation of Aircraft Turbofan Engine

GEAE Recommendations for Future Direction

• Pursue coupled simulation of combustor (NCC or other combustion code) and high-pressure turbine (HPT) with the APNASA turbomachinery flow code.
• Demonstrate successful component simulations (e.g., full compression system) before attempting to simulate full engine.
• Pursue component simulations at off-design conditions.
• Investigate better ways to start simulations and achieve faster multistage convergence.
• Pursue large-scale, multistage unsteady simulations to support NPSS activities.

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Detailed Simulation of Aircraft Turbofan Engine

National Combustion Code (NCC)

Objective
Develop an integrated system of codes for combustor design and analysis to enable significant reduction in design time and cost.

Approach
• Develop a comprehensive modeling and simulation capability in NCC.
• NCC features a Navier-Stokes flow solver based on an explicit four-stage Runge-Kutta scheme.
• Unstructured meshes.
• Run in parallel on networked workstation clusters.
• The solver can be linked to any CAD system via Patran file system.
• Simulate the turbulent combustion in a modern turboshaft engine's combustor - GE90.

Significance/Metrics
• Enable the multidisciplinary analysis of combustors from compressor exit to turbine inlet.
• NCC is a key component of the NPSS.
• Significant reduction in turnaround time enables using NCC in a design environment.

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**FY00 Accomplishments:**
National Combustion Code

Hot-Flow 3-D Full Combustor Simulations Were Successfully Performed from Compressor Exit to the HPT Nozzle Exit Using the National Combustion Code

- Combustor model configuration: 24 degree sector; 1 compressor strut; 4 fuel nozzles; 3 turbine nozzle vanes
- Computational domain size: 700,000 tetrahedral elements
- 3-D aerodynamics, k-ε turbulence with wall functions, 4 chemical species fuel oxygen nitrogen and products of combustion
- 1-step eddy breakup combustion model (fuel + oxygen = products of combustion)
- 20,000 iterations to convergence consumes 1/2 gigabyte of RAM
  - Single processor Pentium PC 550 MHz: execution time, 22 days
  - 28 processor NAS Origin workstation cluster: execution time, 1 day

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**Detailed Simulation of Aircraft Turbofan Engine**

**FY00 Accomplishments: National Combustion Code**

*NCC Exploring Mesh Adaptation for Improved Resolution*

Four Levels of Adaptation

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Detailed Simulation of Aircraft Turbofan Engine

FY00 Accomplishments: National Combustion Code

Exploring 3-D Mesh Adaptation on Pressure Gradient for Efficient and Better Flow Resolution with Minimal Impact on Execution Time

3 adaptations on pressure gradient, 20,000 iterations on single processor Pentium PC 550 MHz

<table>
<thead>
<tr>
<th>Mesh Adaptations</th>
<th>Tetrahedral Mesh Size</th>
<th>Execution Time</th>
<th>Accumulative Execution Time</th>
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<tr>
<td>Baseline mesh</td>
<td>700,000</td>
<td>22 days</td>
<td>22 days</td>
</tr>
<tr>
<td>First adaptation</td>
<td>1,500,000</td>
<td>1 day</td>
<td>23 days</td>
</tr>
<tr>
<td>Second adaptation</td>
<td>2,500,000</td>
<td>1 day</td>
<td>24 days</td>
</tr>
<tr>
<td>Third adaptation</td>
<td>3,200,000</td>
<td>1 day</td>
<td>25 days</td>
</tr>
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</table>

Total CPU time for 3,200,000 tetrahedral mesh adapted case = 25 days execution time

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FY00 Accomplishments: National Combustion Code

1 Level Mesh Adaptation on Pressure, Temperature and Speed Gradients

Base mesh: 720,000 tetrahedral elements
Adapted mesh: 1,760,000 tetrahedral elements

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FY00 Accomplishments: National Combustion Code

NCC Exploring Mesh Adaptation to Improve Resolution and Reduce Overall Turnaround Time

- Single CPU (550 MHz)
- Single CPU (550 MHz) with Adaptation

Number of Elements

CPU (Days)

4 CPU Equivalency

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FY00 Accomplishments: Coupling of APNASA and NCC

Develop and Demonstrate Sequential Coupling Methodology Using Standard Data Exchange Between APNASA and NCC in an Annular Duct

APNASA Structured Mesh
51 radial grid elements

NCC Unstructured Mesh
25 radial grid elements

Duct 1, Hexahedral Mesh, APNASA Solutions

Duct 2, Tetrahedral Mesh, NCC Solutions

BC's Transferred (Radial Profile)
- Density
- Pressure
- Velocity components (Vr, Vt, Vx)
- Turbulence quantities (k, ε)

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FY00 Accomplishments: Coupling of APNASA and NCC

Developed and Demonstrated Sequential Coupling Methodology Using Standard Data Exchange Between APNASA and NCC in an Annular Duct

APNASA and NCC interface

APNASA inlet

NCC exit

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File Names:
ap_inlet.profile (standard exchange file at inlet, from APNASA)
ap_exit.profile (standard exchange file at exit, from APNASA)
ncc_inlet.profile (standard exchange file at inlet, from NCC)
ncc_exit.profile (standard exchange file at exit, from NCC)

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FY00 Accomplishments: Coupling of APNASA and NCC

Standard Data Exchange Coupling Methodology (continued)

The velocity components are the cylindrical coordinates components

\[ \begin{align*}
V_r &= \text{radial} \\
V_\theta &= \text{azimuthal} \\
V_z &= \text{axial}
\end{align*} \]

where \((r, \theta, z)\) is a left-handed cylindrical coordinate system; that is, (where \(e_r, e_\theta \text{ and } e_z\) designates the unit vector in the radial, tangential and axial directions):

\[ e_\theta \times e_r = e_z \] (instead of the usual right-handed system of \(e_r \times e_\theta = e_z\))

(Said another way, \(\theta\) (azimuthal coordinate) increases in the counterclockwise direction looking in the positive axial direction.)

The variables \(X_{hub}, R_{hub}, X_{tip}, R_{tip}, \text{span}\) and all flow variables are non-dimensional.

\[ \begin{align*}
\text{Pref}_{-AP} &= \text{reference pressure in units of } \text{psi (lbf/(in}^2) \\
\text{Tref}_{-AP} &= \text{reference temperature in units of } \text{R (Rankine)} \\
\text{Lref}_{-AP} &= \text{reference length in units of } \text{in (inches)} \\
\text{Gasc}_{-AP} &= \text{gas constant, } R_{gas, \text{ in units of } ft^2/s^2/R} \\
\text{Pfac} &= 6894.72 \text{ Pa/psi} \\
\text{Lfac} &= 1716.48 \text{ ft}/12\text{in} \times 0.3048 \text{m/ft} \\
\text{Tfac} &= 1.7857 \\
\text{Gfac} &= 1.0506 \\
\text{Rhub}_{-dim} &= \text{dimensional Hub radius} \]

\[ X_{hub\_dim} = X_{hub} \times L_{ref} \]

\(R_{hub} > R_{tip}\) should always be true

\(X_{tip} = X_{hub}\) must currently be true since coding assumes plane normal = x-dir

\[ \text{Xtip}_{-dim} = \text{dimensional tip axial location} \]

\[ \text{Rtip}_{-dim} = \text{dimensional tip radius} \]

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For SI calculations (NCC), use

\[ \begin{align*}
\text{Pref}_{-AP} &= 6894.72 \text{ Pa/psi} \\
\text{Lfac} &= 1.0ft/12\text{in} * 0.3048 \text{ m/ft} \\
\text{Tfac} &= 1.7857 \\
\text{Gfac} &= 1.0506 \\
\text{Rhub}_{-dim} &= \text{dimensional Hub radius} \\
\text{Xhub\_dim} &= \text{dimensional Hub axial location} \]

\[ \text{Rhub}_{-dim} = \text{Rhub} \times \text{Lref} \]

\[ \text{Xhub\_dim} = \text{Xhub} \times \text{Lref} \]

\[ \text{Xtip\_dim} = \text{Xtip} \times \text{Lref} \]

\[ \text{Rtip\_dim} = \text{Rtip} \times \text{Lref} \]

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FY00 Accomplishments: Coupling of APNASA and NCC

Standard Data Exchange Coupling Methodology (continued)

\( \text{span} = \text{percent of radial span between hub and tip, where 0=hub and 1=tip} \)

\( r = \text{radial location of each data point (dimensional)} \)

\( r = (\text{span} \times (R_{\text{tip}} - R_{\text{hub}}) + R_{\text{hub}}) \times L_{\text{ref}} \)

\( X_{o,\text{dim}}, Y_{o,\text{dim}}, Z_{o,\text{dim}} = \text{Cartesian coordinates of } r=0 \)

assuming the axial direction (in APNASA) corresponds to the +x direction (in NCC)

\( X_{o,\text{dim}} = X_{\text{hub, dim}} = X_{\text{tip, dim}} \quad \text{always} \)

\( Y_{o,\text{dim}} = 0 \quad \text{always} \)

\( Z_{o,\text{dim}} = 0 \quad \text{always} \)

\( \rho_{\text{ref}} = \text{reference density} \)

\( = \frac{P_{\text{ref}}}{(G_{\text{asc}} - T_{\text{ref}})} \)

\( V_{\text{ref}} = \text{reference speed} \)

\( = \sqrt{G_{\text{asc}} - T_{\text{ref}}} \)

\( K_{\text{ref}} = \text{reference turbulent kinetic energy} \)

\( = V_{\text{ref}} \cdot V_{\text{ref}} \)

\( E_{\text{pref}} = \text{reference turbulent specific dissipation} \)

\( = V_{\text{ref}}^2 / 2 \cdot L_{\text{ref}} \)

\( p_{\text{dim}} = \text{dimensional static pressure} \)

\( = p \times P_{\text{ref}} \)

\( \rho_{\text{dim}} = \text{dimensional mass density} \)

\( = \rho \times \rho_{\text{ref}} \)

\( V_{x,\text{dim}} = \text{dimensional axial velocity component} \)

\( = \frac{\rho_{\text{Vx, dim}}}{\rho} \times V_{\text{ref}} \)

\( V_{r,\text{dim}} = \text{dimensional radial velocity component} \)

\( = \frac{\rho_{\text{Vr, dim}}}{\rho} \times V_{\text{ref}} \)

\( V_{t,\text{dim}} = \text{dimensional azimuthal velocity component (left-handed)} \)

\( = \frac{\rho_{\text{Vt, dim}}}{\rho} \times V_{\text{ref}} \)

\( k_{\text{dim}} = \text{dimensional turbulent kinetic energy} \)

\( = k \times K_{\text{ref}} \)

\( e_{p,\text{dim}} = \text{dimensional turbulent specific dissipation} \)

\( = e_{p} \times E_{\text{pref}} \)

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FY01 Plans: Coupling of APNASA and NCC

Develop and Demonstrate Feedback Coupling Methodology Using Standard Data Exchange Between APNASA and NCC in Annular Duct

Bi-directional BC
data exchange between
APNASA and NCC solutions

NCC Unstructured Mesh
25 radial grid elements

APNASA Structured Mesh
51 radial grid elements

Duct 1, Hexahedral Mesh, APNASA Solutions

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FY01 Plans: Coupling of APNASA and NCC

1. Demonstrate sequential and feedback coupling between APNASA turbomachinery code and NCC.
2. NCC combustor simulation with finite rate chemistry.
3. Core engine simulation with APNASA and NCC with finite-rate chemistry and torque.
4. Full engine model; coupled APNASA turbomachinery simulation to NCC model of combustor.

3-D flow simulation of complete compression system with APNASA

3-D flow and chemistry simulation of full combustor with National Combustion Code (NCC)

3-D flow simulation of coupled HP and LP turbines with APNASA

Coupled APNASA and NCC simulations

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Initial Task Discussions

- Prototype integration of MD (3-D aero ST2) analysis into NPSS architecture.
- Implement on 1) Linux, 2) NT in IPG environment.
- Define limitation of CGNS standard.
- Define limitations of CAD API when integrating geometry and analysis.
- Explore/define inclusion of probabilistic analysis.

EEE - Energy Efficient Engine
MD - Multidisciplinary
Multidisciplinary Integration and Analysis

• Objective
  - The objective of this task order is to enhance the NPSS core capabilities by expanding its reach into the high-fidelity multidisciplinary analysis area. The intent is to investigate techniques to integrate structural and aerodynamic flow analyses, and provide benchmark by which performance enhancements to NPSS can be baselined.

• Approach
  - Couple high-fidelity aerodynamic and structural/thermal analysis codes to enable multidisciplinary evaluation of NPSS components.

• Strategy for Success
  - Data processing elements employ standard interface definitions to ensure commonality and modularity.
    • CGNS - CFD General Notation System (CFD standard)
    • CAPRI - CAD data access API (Geometry interface standard)

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Participants in Prototype

• Ed Hall/Joe Rasche - Rolls Royce Corporation (ADPAC, ANSYS)
• Al Magnuson - The ICEM CFD Company (CAPRI, CGNS) interfaces
• Shantaram Pai - NASA Structures Branch (NESSUS/NESTEM)
• Scott Townsend (Executive, CORBA Wrapping)

ADPAC - Advanced Ducted Propfan Analysis Code
NESSUS - Numerical Evaluation Stochastic Structure Under Stress

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Program Technical Elements

- Develop a high-fidelity analysis to calculate the effects on performance of
  - Variations in tip clearance
  - Uncertainty in manufacturing tolerances
  - Guide vane scheduling
  - Effects of rotational speed on the hot running geometry
- Enable calculation of blade deformations between the ADPAC aero analysis and an ANSYS structural analysis.
- Convert ADPAC to use CAPRI library for geometry analysis.
- Determine whether the CGNS standard can represent ADPAC I/O data.
- Incorporate probabilistic analysis (NESTEM/NESSUS) into ADPAC predictions of performance (link the necessary input/output data required to couple aerodynamic, structural, and probabilistic analysis programs).
- Report performance measurements (speedup and scalability) on the HPCC testbeds. Maintain 80% parallel efficiency.
- Estimate the impact of the new methods on the reduction in engine design or development time relative to a 1997 baseline.

Development Milestones

- Hot to Cold Coordinate Conversion
  - Extract cold manufacturing coordinate database based on desired hot running design shape.
- Cold to Warm Coordinate Conversion
  - Develop automated off-design airfoil shape based on off-design speed and aero loads.
- Incorporate Probabilistic Method
  - Produce statistical variations in airfoil coordinates.
  - Automate CFD performance variation estimates based on statistical airfoil variations.

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Developmental Notes

- Starting with a 3-D fan blade to gain an understanding of the interface issues (data requirements, dependencies, etc.).
- Start ADPAC with a cold geometry and get it up to normal operating conditions, transfer info to Scott so he can examine the I/O.
- ANSYS 5.4 start with a 3-D brick element, ANSYS pressures and temperatures will be passed to NESSUS/NESTEM.
- APNASA is currently integrated with NESSUS/NESTEM.
- Phase 1: Hardwire model together.
- Phase 2: CORBA wrapped components.
- Completed by 10/1/01.

Aero/Structural Coupling

ADPAC CFD Analysis

**Input**
Geometry, operating conditions

**Output**
Pressure, temperature

ANSYS Structural Analysis

**Input**
Geometry, operating conditions, pressure, temperature

**Output**
Deformations, stress
Hot to Cold Conversion

NPSS Executive or Design System

Provides desired hot running geometry

Develop parameterized geometry database in CAD system

ANSYS Controller

Upgrade database with cold geometry

Cad Geometry

Cold Geometry

Back out deflections associated with centrifugal load, aero forces, and thermal expansion

ICEM CFD Grid Generation

ADPAC Flow Analysis

ANSYS Structural Analysis

Interface via CAPRI library Independent of CAD system software

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Cold to Lukewarm Conversion

NPSS Executive or Design System

Provides desired operating conditions

Access database of cold coordinate geometry

ANSYS Controller

Upgrade database with cold geometry

Cad Geometry

Cold Geometry

Back out deflections associated with centrifugal load, aero forces, and thermal expansion

ICEM CFD Grid Generation

ADPAC Flow Analysis

ANSYS Structural Analysis

Interface via CAPRI library Independent of CAD system software

Map CFD pressure and temperature to FEM structural model

2000 NPSS Review
## Schedule

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