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Three-dimensional unsteady flow calculations in an advanced Gas Generator turbine

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Abstract

This paper deals with the application of a three-dimensional, unsteady Navier-Stokes code for predicting the unsteady flow in a single stage of an advanced gas generator turbine. The numerical method solves the three-dimensional thin-layer Navier-Stokes equations, using a system of overlaid grids, which allow for relative motion between the rotor and stator airfoils. Results in the form of time averaged pressures and pressure amplitudes on the airfoil surfaces will be shown. In addition, instantaneous contours of pressure, mach number etc. will be presented in order to provide a greater understanding of the inviscid as well as the viscous aspects of the flowfield. Also, relevant secondary flow features such as cross-plane velocity vectors and total pressure contours will be presented. Prior work in two-dimensions has indicated that for the advanced designs, the unsteady interactions can play a significant role in turbine performance. These interactions affect not only the stage efficiency but can substantially alter the time-averaged features of the flow. This work is a natural extension of the work done in two-dimensions and hopes to address some of the issues raised by the two-dimensional calculations. These calculations are being performed as an integral part of an actual design process and demonstrate the value of unsteady rotor-stator interaction calculations in the design of turbomachines.
THREE-DIMENSIONAL UNSTEADY FLOW CALCULATIONS
FOR AN ADVANCED GAS GENERATOR TURBINE
(PRELIMINARY RESULTS)

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Scope

Perform three-dimensional unsteady computations for the single stage Gas Generator Oxidizer Turbine

Provide results to the Turbine Stage Design Team such as

- Time averaged and unsteady pressure envelopes

- Unsteady secondary flow features
Design requirements of next generation turbines are

- **High specific work per stage**
- **Low weight and small size**
- **High efficiency**
- **Durability**
Background contd...

These design requirements imply

- **High turning angles per stage**
- **Unconventional airfoil shapes**
- **Small axial gaps**
- **Large unsteady interactions**

Effects of unsteady interactions on turbine performance
still in the process of evaluation

Need a more powerful predictive capability

- **Model as much of the flow physics**
- **Issues of accuracy**
Background contd...

Unsteady rotor-stator interaction codes have been developed at NASA Ames

- **Have demonstrated the ability of predicting flow quantities such as**
  - Time averaged pressure distributions on airfoil surfaces.
  - Pressure amplitudes and phase on the surface of the airfoils.
  - Time averaged total pressure defects in wakes.

- **These codes have attained a level of maturity to warrant their use in the design process of a turbomachine**
Computational Details

Time-accurate solutions to the 3D thin-layer Navier-Stokes equations.

High-order, upwind, finite-difference algorithm used

Algorithm set in iterative, factored and implicit framework

Flowfield discretized using a system of overlaid grids

Rotor grids move relative to stator grids

Turbulent eddy viscosity computed using Baldwin-Lomax model
Boundary conditions

- Inlet total pressure input as a function of radius
- Reimann variable as a function of radius
- Flow angles
- Exit static pressure input as a function of radius
Study of accuracy

A study of accuracy was initiated in two-dimensions

Motivations for this study were

- Development of a hybrid structured/unstructured code
  - For unstructured codes, incorporating high order terms may not be straightforward
  - Grid adaptation is simpler for unstructured solvers

- Nonlinear rotor-stator interactions
Figure Hot-streak calculation: original and adapted grids for the stator
Figure: Hot-streak calculation: original and adapted grids for the rotor
PRESSURE CONTOURS IN THE GGG BY A HYBRID STRUCTURED/UNSTRUCTURED SOLVER (FIRST-ORDER ACCURATE)

THE INTERACTION SHOCK IS NOT PREDICTED
PRESSURE CONTOURS IN THE GGG BY A HYBRID STRUCTURED/UNSTRUCTURED SOLVER (SECOND-ORDER ACCURATE)
AN INTERACTION SHOCK IS PREDICTED
MACH CONTOURS OBTAINED FROM A STRUCTURED METHOD (STAGE-2)

THIRD-ORDER ACCURATE
SHOWS INTERACTION SHOCK

FIRST-ORDER ACCURATE
SHOCK FREE FLOW

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
0.30000
0.35000
0.40000
0.45000
0.50000
0.55000
0.60000
0.65000

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
0.30000
0.35000
0.40000
0.45000
0.50000
0.55000
0.60000
0.65000

ORIGINAL PAGE IS OF POOR QUALITY
Preliminary 3D Results for the GGOT

Results are preliminary because

- Solution has not completely converged to a time periodic state
- Grid is coarse (in radial direction)
Geometry Rescaling

Turbine Geometry

Number of stator blades = 20
Number of rotor blades = 42

Rescaled Geometry

Number of stator blades = 21
Number of rotor blades = 42
Turbine operating conditions

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<td>INLET MACH NO.</td>
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<td>INLET TOTAL PRESSURE</td>
<td>542.77 PSIA</td>
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<tr>
<td>EXIT STATIC PRESSURE</td>
<td>200.00 PSIA</td>
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<tr>
<td>INLET TOTAL TEMPERATURE</td>
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</tr>
</tbody>
</table>
Pressure Variation on Stator

Axial Distance (x)

Pressure Coefficient (Pstatic/Protal)

-1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2

Time averaged
Maximum
Minimum

MID PLANE
PRESSURE VARIATION ON ROTOR
Pressure Variation on Rotor

Pressure Coefficient (Pstatic/Total)

Axial Distance (x)

Time averaged
Maximum
Minimum

MID PLANE
Pressure Variation on Stator

![Graph showing pressure coefficient variation with axial distance](Image)

- Pressure Coefficient (Pstatic/Total)
- Axial Distance (x)

Legend:
- Time averaged
- Maximum
- Minimum
Pressure Variation on Stator

![Graph showing pressure coefficient variation with axial distance](image)

- **Pressure Coefficient (Pstatic/Total)**
- **Axial Distance (x)**

Legend:
- **Time averaged**
- **Maximum**
- **Minimum**
Pressure Variation on Rotor

Pressure Coefficient ($P_{\text{static}}/P_{\text{total}}$) vs. Axial Distance ($x$)

- Time averaged
- Maximum
- Minimum
Pressure Variation on Rotor

Pressure Coefficient (P_{static}/P_{Total})

Axial Distance (x)

- Time averaged
- Maximum
- Minimum
Summary and conclusion

A coarse grid calculation for the GGOT is nearing completion

- There are similarities as well as differences with the corresponding two-dimensional solutions
  - Issues of accuracy
  - Two-dimensional modelling (stream-tube contraction)

- Flow field solutions will serve as a good starting solution for a finer grid calculation on the C-90

- Input from the design team as to what aspect of the flow field needs to be investigated further