Numerical simulation of unsteady interaction of hot streams with HPT rotor blades using harmonic balance method

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Frequency-length scales of unsteady phenomena in turbomachinery

The main generating factors of unsteady flows

Unsteady rotor-stator interaction

Hot streaks

A.A. Inozemtsev and others. “Gas turbine engines. Volume 1” and Machine Building 2008 (in Russian)
NUMERICAL METHODS OF ROTOR-STATOR INTERACTION

Steady

FROZEN ROTOR  HARMONIC BALANCE (HB)

Unsteady (TRS)

SECTOR  FULL-DOMAIN
Transient Rotor/Stator (TRS) Method
(Moving Rotor - STAR CCM+)

THE IMPLICIT UNSTEADY SOLVER WITH COUPLED FLOW
AND COUPLED ENERGY MODELS
(5-20 inner iterations in each time step).

SOLVE FULL 360 DEGREES OR EQUAL SECTOR FOR BLADE ROWS.

TYPE OF CONNECTION ON THE INTERFACES - IN-PLACE OR REPEATING TOPOLOGY.

CONVERGENCE OF TIME DOMAIN SOLVER → PERIODIC BEHAVIOR OF SOLUTION IS ACHIEVED

COMPUTATIONAL MESH FOR THE TIME DOMAIN SIMULATION OF THE 36-42-36
(equal sector 60 degrees 6-7-6)
Harmonic Balance Method

Solution function $W$ is periodic in time and represents by the Fourier series:

$$W(\hat{r}, t) = \sum_{m=-M}^{M} W_m(\hat{r}) \exp(i\omega_m t)$$

$M$ is the number of modes or harmonics

$$W_m(\hat{r}) = \frac{1}{N} \sum_{k=0}^{N-1} W^*_k(\hat{r}, t_k) \exp(i\omega_m t_k)$$

- Non-reflecting, far field boundary conditions

Single passage in each row and complex periodicity conditions

$$N = 2M + 1$$ - number of time levels

$k$-th discrete time level

$$t_k = \frac{kT}{N}$$

Frequencies for blade row $j$

$$\omega^j = \sum_{i=1}^{Z} m_i B_i (\Omega_j - \Omega_i)$$
<table>
<thead>
<tr>
<th>Merits and demerits of HB and TRS methods</th>
<th>HB</th>
<th>TRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence model</td>
<td>Spalart-Allmares, k-ε</td>
<td>Any</td>
</tr>
<tr>
<td>Thermophysical properties</td>
<td>Constant</td>
<td>Variable</td>
</tr>
<tr>
<td>Conjugate problem</td>
<td>Non available</td>
<td>Available</td>
</tr>
<tr>
<td>Frequency spectrum</td>
<td>Discrete</td>
<td>Continuous</td>
</tr>
<tr>
<td>Number of solvable equations</td>
<td>Depends on the number of modes</td>
<td>Constant</td>
</tr>
<tr>
<td>Time step</td>
<td>Time step is not used as the problem is a steady one</td>
<td>Depends on the type of the problem and the dimension of the grid</td>
</tr>
<tr>
<td>Computational grid volume</td>
<td>One blade passage is used</td>
<td>Depends on the number of blades in rows</td>
</tr>
<tr>
<td>Volume of stored and processes data</td>
<td>Only average values of variables and Fourier coefficients are stored</td>
<td>Depends on the number of recorded time steps and the number of analyzed variables. It is difficult to obtain average values</td>
</tr>
</tbody>
</table>
Experimental setup (gas turbine)

$$Re_2 = 3.7 \cdot 10^5$$

$$M_2 = 0.464$$
Basic parameters for physical modeling

FLOW SCHEME AND MEASUREMENT LOCATIONS IN THE TURBINE STAGE

\[ Z_s = 24 \]

\[ Z_R = 48 \]

\[ \Omega = 5000 \text{ rpm} \]

\[ \text{Re}_2 = 3.7 \times 10^5 \]

\[ M_{w2} = 0.464 \]

<table>
<thead>
<tr>
<th>SECTION</th>
<th>D</th>
<th>( g_1 )</th>
<th>( g_2 )</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( \alpha_1 ) DEGREES</th>
<th>( \beta_1 ) DEGREES</th>
<th>( \beta_2 ) DEGREES</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOTTOM</td>
<td>0.36</td>
<td>0.0471</td>
<td>0.0269</td>
<td>0.078</td>
<td>0.035</td>
<td>25°10'</td>
<td>34°16'</td>
<td>36°30'</td>
</tr>
<tr>
<td>MID - SPAN</td>
<td>0.43</td>
<td>0.0562</td>
<td>0.0322</td>
<td>0.078</td>
<td>0.037</td>
<td>26°20'</td>
<td>58°25'</td>
<td>34°32'</td>
</tr>
<tr>
<td>TOP</td>
<td>0.50</td>
<td>0.0654</td>
<td>0.0374</td>
<td>0.078</td>
<td>0.043</td>
<td>28°20'</td>
<td>94°50'</td>
<td>30°16'</td>
</tr>
</tbody>
</table>
Measurement results of instant velocity behind NGV
Measurement results of instant velocity behind wheel in three sections
Mesh = 1.3 million Hex cells
$
Y^+ = 1.0 \div 16.
$
CFL number = 5.0
Time step for TRS = $5 \times 10^{-5}$s
Convergence history

Periodic behavior of velocity - TRS solver model

Harmonic balance solution residuals for a five modes trial
COMPUTATIONAL RESULTS
0-fourier mode

Fourier mode 0 on the stator

Stator

Surface pressure (Pa)

Axial position (m)

Simulation data
Experimental data
Comparing of experimental and numerical results

position No.28
Role of turbulence level in prediction of instant velocity

![Graphs showing turbulence level influence on velocity over time](Image)
Pressure and temperature amplitude-frequency characteristics

- Maximum Power Spectral Density
  - Press. Point 1: 3180
  - Temper. Point 1: 0.0011
  - Temper. Point 2: 0.0011
  - Velocity Point 3: 0.0278
  - Velocity Point 4: 0.0111

- Frequency (Hz): 2000, 4000, 6000, 8000, 10000, 12000, 14000, 16000, 18000, 20000

- Stator: 4000 Hz, 8000 Hz, 12000 Hz, 16000 Hz, 20000 Hz
  - Rotor: 2000 Hz, 4000 Hz, 6000 Hz, 8000 Hz, 10000 Hz
Dimensionless value of operative memory referred to the appropriate size for variant HB-5 Mode
Dimensionless CPU time (per 1 iteration) referred to the appropriate CPU time for variant HB-5 Mode

- TRS - Full 360deg
- TRS - Sector 15deg
- HB - 1 mode
- HB - 3 mode
- HB - 5 mode

Dimensionless CPU time

TRS - Sector 15deg
HB - 1 mode
HB - 3 mode
HB - 5 mode
Boundary conditions for non-uniformity total temperature at NGV inlet

$T^{\text{max}}/T^{\text{aver.}} = 2.16$
TRS calculation results: Blade temperature in monitoring points
TRS calculation results: Temperature AFC

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Stator</th>
<th>Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>4000 Hz</td>
<td>2000 Hz</td>
</tr>
<tr>
<td>4000</td>
<td>8000 Hz</td>
<td>4000 Hz</td>
</tr>
<tr>
<td>8000</td>
<td>12000 Hz</td>
<td>6000 Hz</td>
</tr>
<tr>
<td>12000</td>
<td>18000 Hz</td>
<td></td>
</tr>
</tbody>
</table>

Maximum Power Spectral Density

<table>
<thead>
<tr>
<th>Temper. Point</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temper. Point 1</td>
<td>6.28</td>
</tr>
<tr>
<td>Temper. Point 2</td>
<td>20.3</td>
</tr>
</tbody>
</table>
HB and TRS calculation results

Time=0.0371s
HB and TRS calculation results

Time=0.0372s
HB and TRS calculation results

Time=0.0373s
HB and TRS calculation Results

Time = 0.0374s
HB and TRS calculation results

Time=0.0375s
HB and Mixing Plane calculation results

Mixing Plane

HB

Total Temperature

270.00  296.00  322.00  348.00  374.00  400.00
HB and Mixing Plane calculation results

\[ DT^* = T_{HB}^* - T_{mixing\ plane}^* \]
Calculation results: $T^*$ behind NGV

<table>
<thead>
<tr>
<th>Mixing Plane</th>
<th>$\frac{T^<em>_{\text{max}}}{T^</em>_{\text{aver}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRS</td>
<td>-1.7</td>
</tr>
<tr>
<td>HB 3</td>
<td>-1.63</td>
</tr>
</tbody>
</table>

$T^*$ vs TETA (deg)
Calculation results

- TRS - PS
- HB - PS
- Mixing Plane

ΔT = 30°
Conclusions

- During calculation of unsteady time and space periodic gas flows in turbomachines the HB method is considerably more effective in terms of the calculation costs in comparison with TRS method;
- Comparison of the calculation results with the experimental data has shown a good match for both methods excluding the interaction of the NGV wake with the rotor wheel at the turbine outlet;
- Calculations of effect of the circular temperature non-uniformity on the temperature of the rotor blades have proved a possibility of use of the HB method for the engineering analyses with a possible inaccuracy of up to 8-9%;
- Similar match of the calculation results using HB and TRS methods permits to use effectively the HB method for optimization calculations.
Thank you very much for your attention

HB method

TRS method

Time: 0 (s)
Povorot: 0 (deg)
TRS calculations results

Velocity

Flow lines