Turbomachines: Unsteadiness and Manufacturing Tolerances

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Unsteadiness

- Increase Aircraft Performance
  ↓
- Reduce component weight
  ↓
- Axial space reduced, higher blade loading
  ↓
  - higher unsteady interactions
  - unsteady design

 Courtesy of Rolls-Royce
Manufacturing Tolerances

- Increase GT performance – Higher reliability
- Smaller core, higher TET
  - more complex systems (coolant, geometry etc)
  - manufacturing deviations: critical

Courtesy of Mitsubishi Heavy Industry
High Pressure Turbines: higher temperature


Courtesy of Rolls-Royce: The Jet Engine
Combustion Chamber: Exit Temperature Distribution

Courtesy of Rolls-Royce: The Jet Engine
Nozzle Location
Hot Streaks Migration

rotor is critical, unsteady simulation must be used!
Uncertainty on temperature distribution

Better for the rotor tip
Low Pressure Turbines: less blades


Courtesy of Rolls-Royce
Low Pressure Turbines: No Unsteady Wakes

$\text{Mach}_s$

$i=0 \ g=21 \ Re=30.000$

$S/S_0$
Low Pressure Turbines: No Unsteady Wakes

\[ \text{Mach}_{\text{s}} \]

\[ \text{S}/\text{S}_{\text{o}} \]

separation

\[ i=0 \ g=21 \ \text{Re}=30.000 \]

\[ i=0 \ g=24 \ \text{Re}=30.000 \]
Wake Induced Transition

High loading blade can be used.
Wake passing reduces the separation.
Low Pressure Turbines: hot gas ingestion

Unsteadiness and Real Geometry: GE LM2500+G4

Monte Carlo analysis
Simplified network
Prediction Hot Gas Ingestion: life + 40%

25% pitch
PS

50% pitch
@LE

75% pitch
SS

\[ f(\text{teta}) \ [\text{deg}] \]

\[ f(p) \ [-] \]

\[ \phi = 0.2 \]

\[ \phi = 0.4 \]

\[ \phi = 0.6 \]
Axial Compressors: stall margin


Low Speed Compressor - BRR1

Two simulations:
steady (mixing plane)
unsteady (sliding plane)

Reduced count ratio 3-4
(75 rotor- 96 stator blades)

20 times more doing the right problem!
Computational cost

100 times more expensive
Characteristic Steady vs Unsteady

- Steady Stall Point
- Unsteady Stall Limit
- RANS
- URANS
- Efficiency, $\eta$
- Pressure Rise Coefficient, $\psi$
- $\frac{Va}{U_{mid}}$

Arrows indicating experimental (Exp) and numerical (RANS) data points.
Radial distribution stator losses

\[ \frac{(P_0 - P_{\text{in}})}{(0.5 \rho U^2)} \text{ [-]} \]

Span %

Exp

URANS

RANS

r1 s1 r2 s2 r3 s3 r4 s4
Unsteady effects at midspan-casing
Wakes at Midspan: URANS
Wake convection at midspan

\[ \frac{\Delta U'}{\Delta U} = \frac{ab}{a'b'} < 1 \]

\[ \Gamma = \int_{a}^{b} U_w \cdot ds + \int_{c}^{d} U \cdot ds = ab \cdot \Delta U \]
Decay of Velocity Defect

\[ \frac{\Delta U}{\Delta U} = \frac{ab}{a'b'} < 1 \]

\[ R = 1 - \left( \frac{L_{\text{inlet}}}{L_{\text{exit}}} \right)^2 \]

Smith’s recovery 1966
Smith’s recovery effect

\[ \frac{\Delta U}{\Delta U} = \frac{ab}{a'b'} < 1 \]

Adamczyk (1996) mixing loss proportional to square of the wake deficit

- Losses URANS < Losses RANS
Casing – tip leakage vortex
Casing - tip leakage vortex recovery

\[ \frac{\Delta U}{\Delta U} = \frac{ab}{a'b'} < 1 \]

Recovery

Vax/Umid

0.43 0.45 0.47 0.49 0.51 0.53
Casing at design point

RANS

URANS

r1 s1 r2 s2 r3 s3 r4 s4

Mach
0.08
0.07
0.06
0.05
0.04
Casing near stall

RANS

URANS
Explanation on stability margin

The cause is the flow near the casing
Lesson learnt

- Midspan unsteadiness reduces the losses
- Casing modifies stall margin

Cost: 100 times!

Is there any cheaper solution?
Coupled steady-unsteady?

Is it possible? Not directly

Unsteady

Steady

[Graph showing mass flow over iterations]
Hybrid RANS-URANS

Unsteady → Unsteady time averaged

Steady
Computational cost

Reduced computational cost

URANS
URANS-RANS

elements, M  iterations, K  CPU cost (CPUs It)
Conclusions

• Unsteadiness plays a role in axial compressor

• Computational cost of URANS calculation very high

• RANS-URANS hybrid method developed

• Reduced computational cost
Montomoli F., Massini M., Salvadori S., Martelli F.: "Geometrical Uncertainty and Film Cooling: Fillet Radii", *J. of Turbomachinery*
Film cooling: how accurate is our geometry?

- General Electric: hole accuracy 10% of diameter
- variation +20°C metal temperature about -33% component life
  (Bunker R.: GT2008-50124)

- i.e. Laser Percussion Drilling

manufacturing uncertainty without in service variations
Film cooling test case

(Saumweber and Shultz 2008)
Computational domain

- 2M elements for geometry
- 64 simulations

Inlet coolant $0.15 < \text{Ma}_c < 0.6$

Outlet coolant

Outlet hot gas

Inlet hot gas

Viscid wall

Inviscid wall

Periodic

$0.15 < \text{Ma}_c < 0.6$
Discharge coefficient, sharp edge r/D=0%

\[ C_D = p_{tc} \left( \frac{p_m}{p_{tc}} \right)^{2k} \left( \frac{2k}{(k-1)RT_{tc}} \left( \frac{p_{tc}}{p_m} \right)^{k-1} - 1 \right) \frac{\pi}{4} D^2 \]
Discharge coefficient, sharp edge $r/D=0\%$

\[ C_D = \frac{m}{p_{tc} \left( \frac{p_{m}}{p_{tc}} \right)^{\frac{k+1}{2k}} \sqrt{\frac{2k}{(k-1)RT_{tc}} \left( \left( \frac{p_{tc}}{p_{m}} \right)^{\frac{k-1}{k}} - 1 \right)}} \pi D^2 \]
Flow structures, 0.15<\text{Mach}<0.45

- What is the difference with a “standard” plenum condition?
Effect of fillet on discharge coefficient, Mach=0.30
Effect of fillet on discharge coefficient

- code prediction: lower Cd for Mach=0.60, higher for Mach=0.30
Cd for $0\% < r/D < 5\%$
Probability distribution of fillet radius
Cd – probability distribution

- For r/D=0.0%, Cd=0.68
- For r/D=0.5%, Cd=0.71, diff. 4%

![Graph showing the probability distribution of Cd with r/D as the percentage range from 0 to 5% and probability values from 0.68 to 0.82.](image)
Cd – probability distribution

- Cd – probab. distr., Cd=0.73, diff. 7%
- In order to obtain Cd=0.73, equivalent r/D=1%
Cd error as function of $\sigma$ and $r/D$

- $r/D=2\%$ is “robust”
- $r/D=0\%$, error up to $11\%$
Conclusions

- Sharp edge modifies up to 11% Cd respect to r/D=5%

- Including the manufacturing distribution a mean value for Cd can be obtained

- An equivalent r/D is defined to take into account the manufacturing variations

- It is possible to identify robust configurations, less dependent from modifications
Conclusions

• Unsteady Effects in Compressors are Important for Stall Margin

• Robust Design: reduce-take into account unknowns