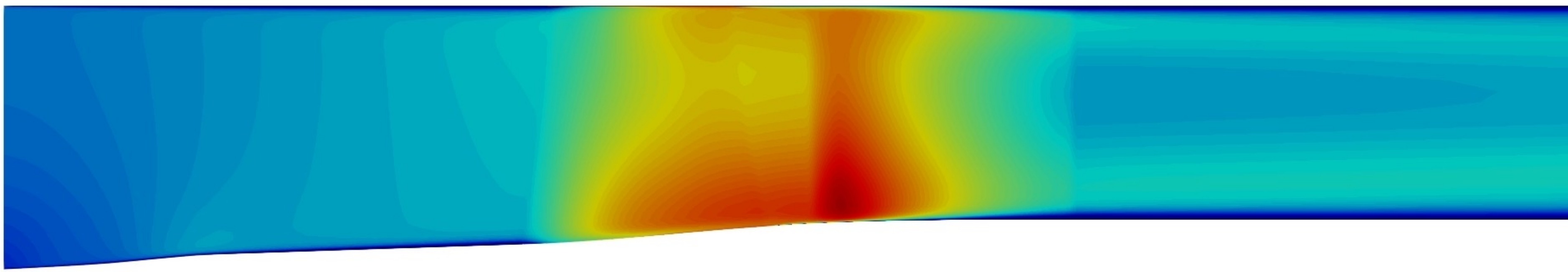
Application of a viscous through-flow model to modern axial compressors



Arnaud Budo[1]

Vincent E. Terrapon[1], Maarten Arnst[1], Koen Hillewaert[1]

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ASME Turbo Expo 2021

LIÈGE université (1)

(2) SAFRAN

Context

Geometrical variability of aerodynamic parts of low-pressure compressors

[SAB]

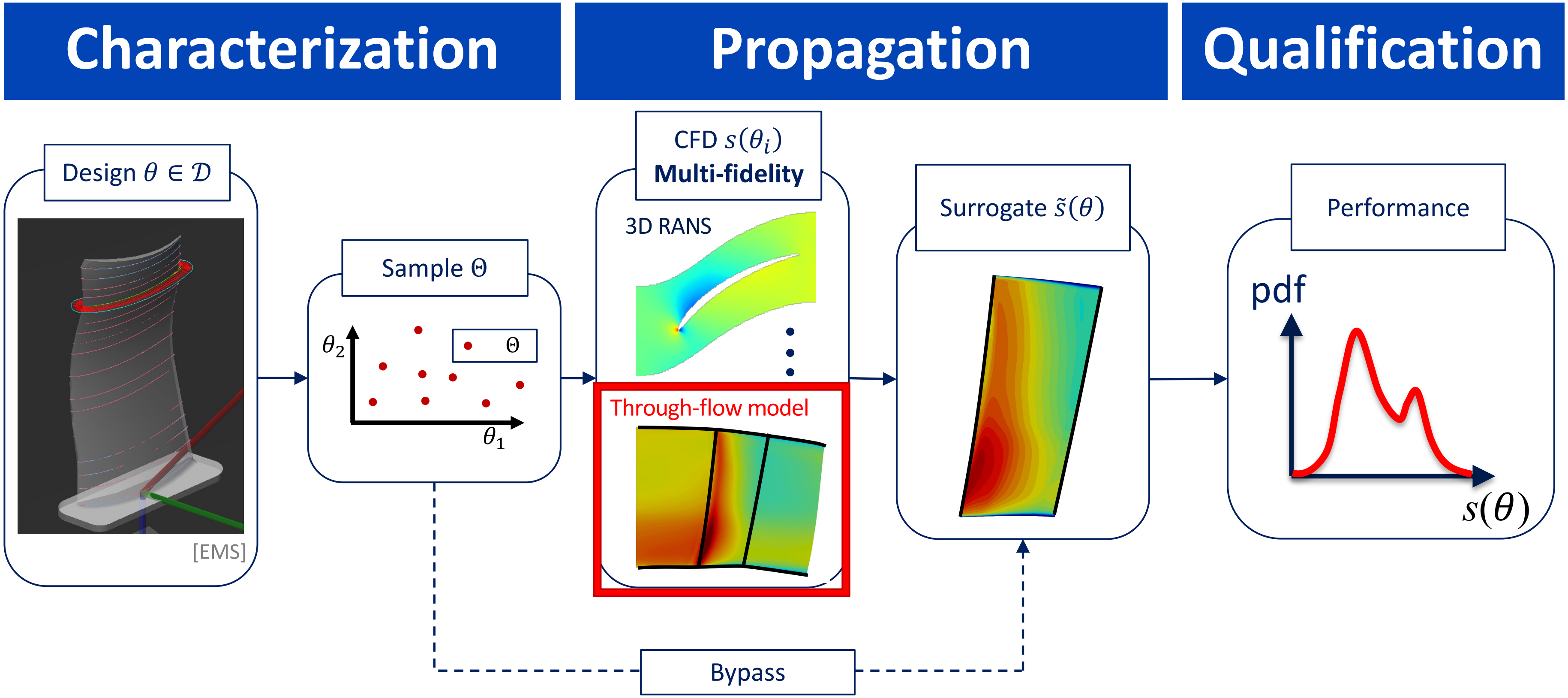
Technical and economic performances

Manufacturing tolerances?

- Rigorous/robust methodology
- Choice of manufacturing process
- Simplify the treatment of poorly made parts

Decrease the overall cost

Methodology

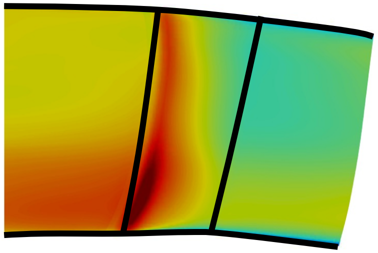


Skywin Wallonie
LIÈGE université
SAFRAN
SAFRAN AERO BOOSTERS
Cenaero
ems

Outline

1

Through-flow model



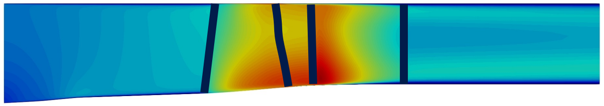
2

ASTEC: a viscous through-flow model

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial (\boldsymbol{F} - \boldsymbol{F}_v)}{\partial x} + \frac{\partial (\boldsymbol{G} - \boldsymbol{G}_v)}{\partial r} = \boldsymbol{S}$$

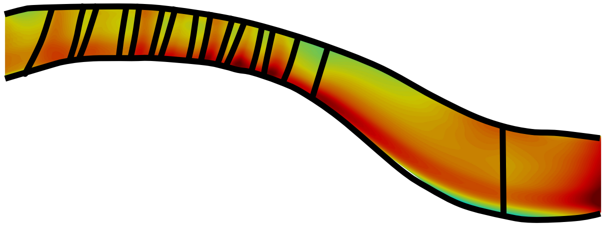
3

Application to the CME2 compressor stage



4

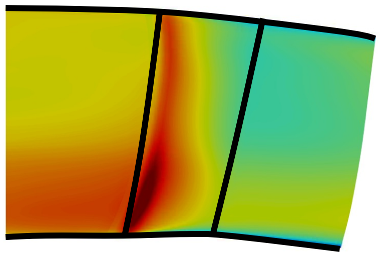
Application to an axial LP compressor



Outline

1

Through-flow model



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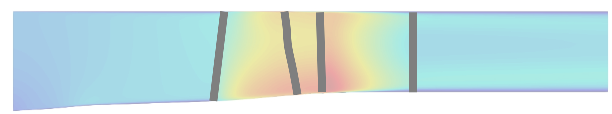

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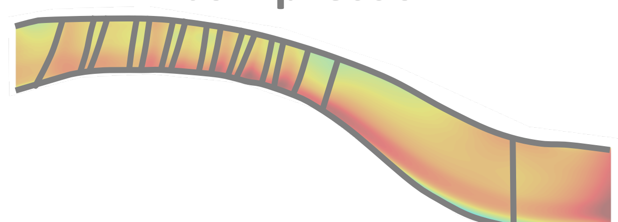
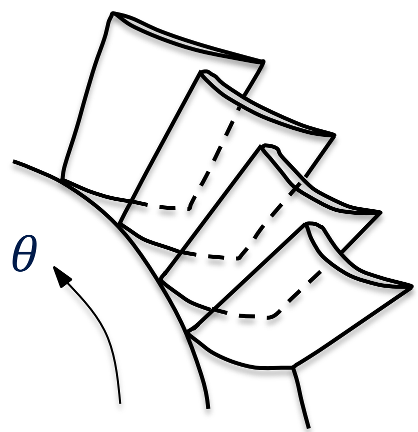
Application to an axial LP compressor

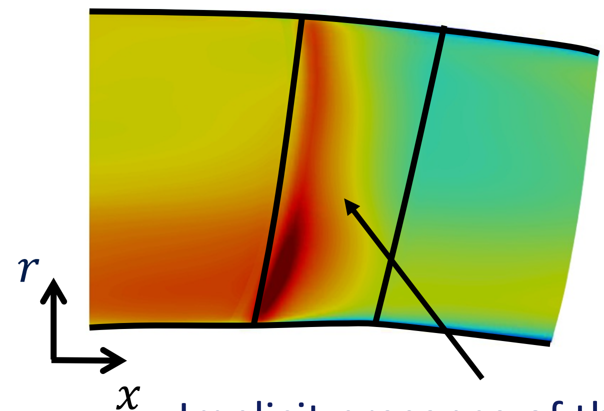


Through-flow model

$$\mathrm{D}_t \boldsymbol{U}(r, \theta, x, t) = \boldsymbol{G}(U, r, \theta, x, t) \xrightarrow{\text{averaging}} \mathrm{D}_t \bar{\boldsymbol{U}}(r, x) = \bar{\boldsymbol{G}}(U, r, x)$$

Unclosed!
Blade forces + stresses





Implicit presence of the blades

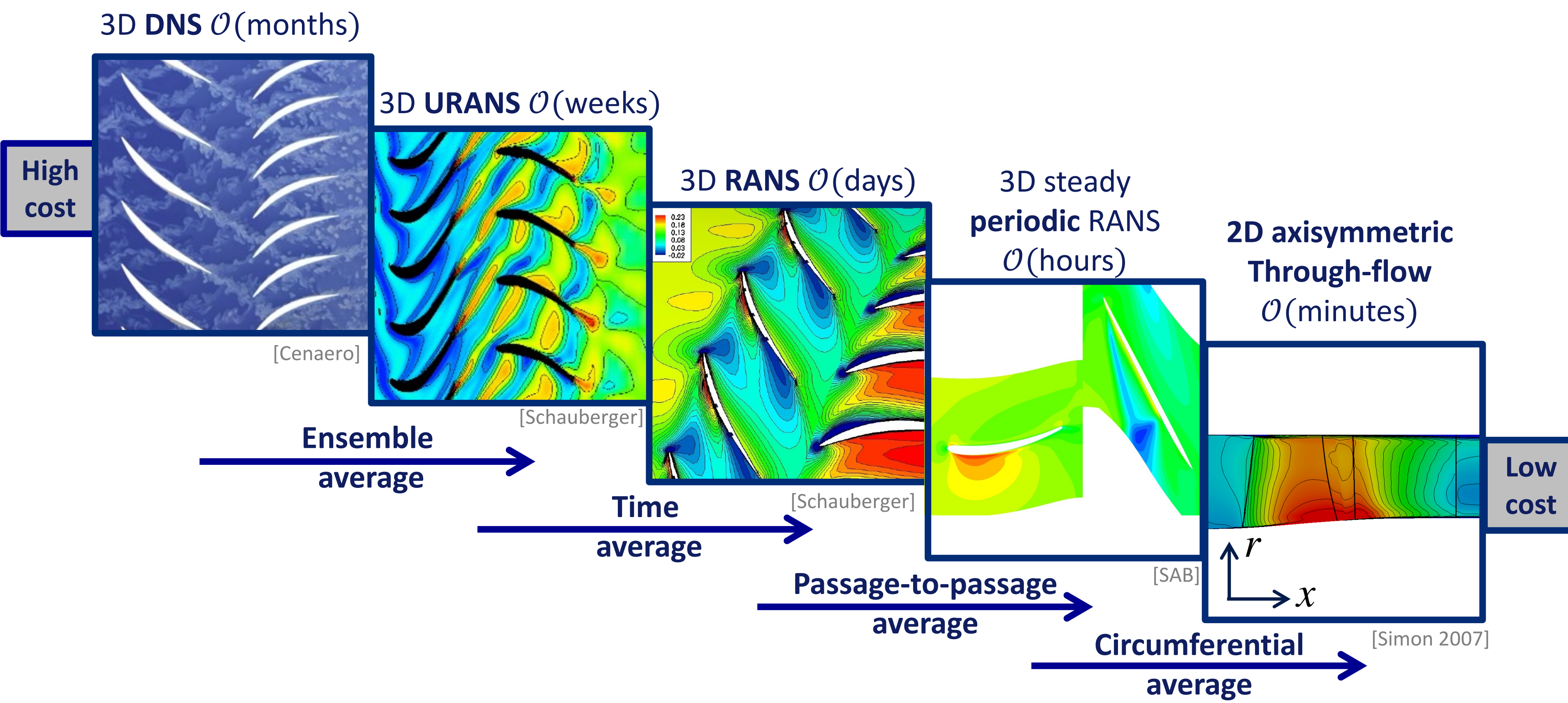
- Navier-stokes based
- Closure implementation
- Validation

Adamczyck's cascade

$$D_t\bar{\boldsymbol{U}}(r, x) = \bar{\boldsymbol{G}}(U, r, x)$$

Unclosed!
Blade forces + stresses

- **Mathematical** formulation of source terms
- **Robust** and **exhaustive** definition of closures



Closure definition

$$D_t \bar{\boldsymbol{U}}(r, x) = \bar{\boldsymbol{G}}(U, r, x)$$

Unclosed!
Blade forces + stresses

Relative importance of source terms:

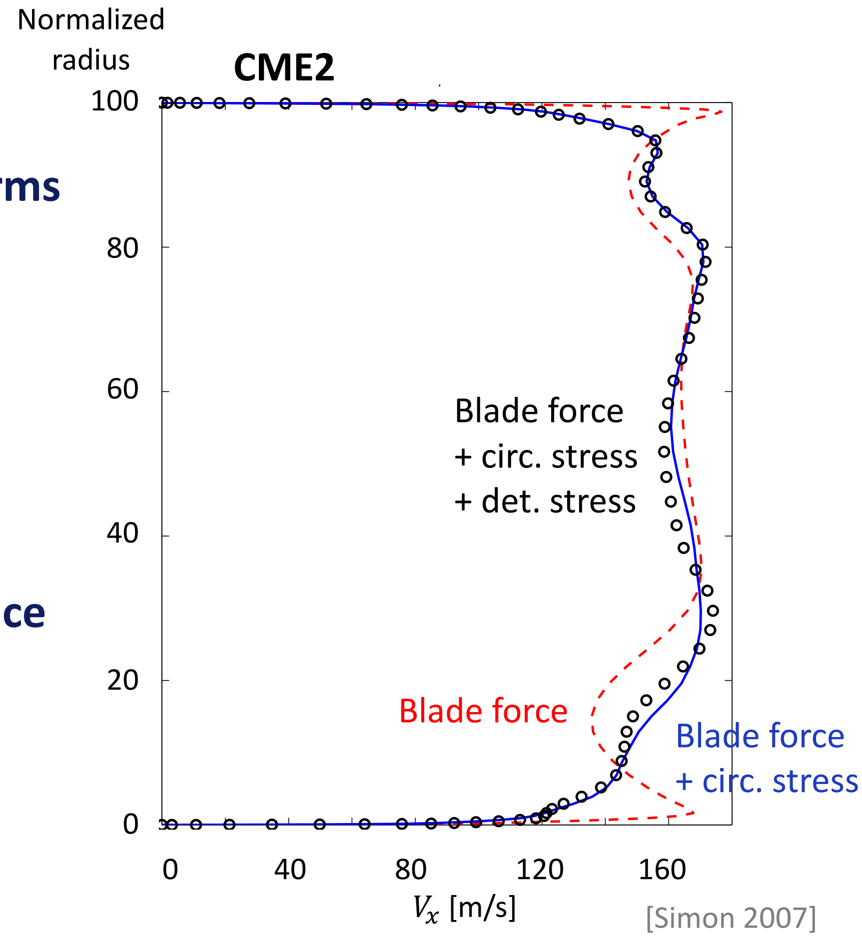
- Reynolds stresses $\boldsymbol{S}_{s1}$
- Inviscid blade forces $\boldsymbol{S}_{bi}$
- Viscous blade forces $\boldsymbol{S}_{bv}$

Major terms

- Circumferential stresses $\boldsymbol{S}_{s4}$
- Deterministic stresses $\boldsymbol{S}_{s2}$

Lower importance

- Aperiodic stresses $\boldsymbol{S}_{s3}$
  → generally neglected

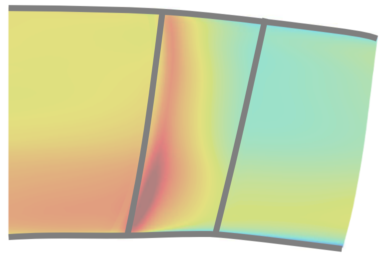


[Simon 2007]

Outline

1

Through-flow model



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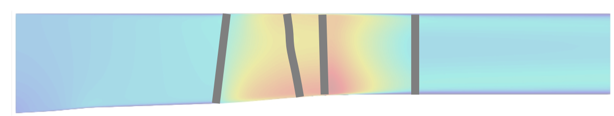
Application to the CME2 compressor stage



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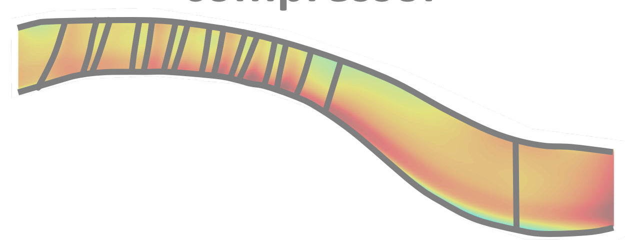
Application to an axial LP compressor



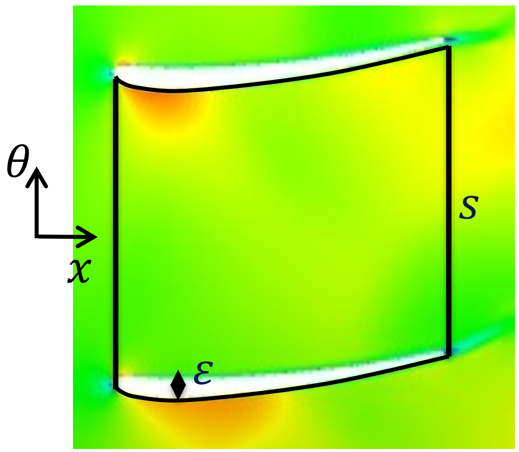
Viscous through-flow model: ASTEC

Circumferential averaged Navier-Stokes equations:

Conservative variables

x-fluxes, r-fluxes

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{1}{b}\frac{\partial b(\boldsymbol{F}-\boldsymbol{F}_v)}{\partial x} + \frac{1}{b}\frac{\partial b(\boldsymbol{G}-\boldsymbol{G}_v)}{\partial r} = \boldsymbol{S}$$



Blockage factor

$$b = 1 - \frac{\varepsilon(x)}{s}$$

- Inviscid blade force
- Viscous blade force
- Reynolds stress
- Axisymmetric source terms

Consistent formulation for elsA:

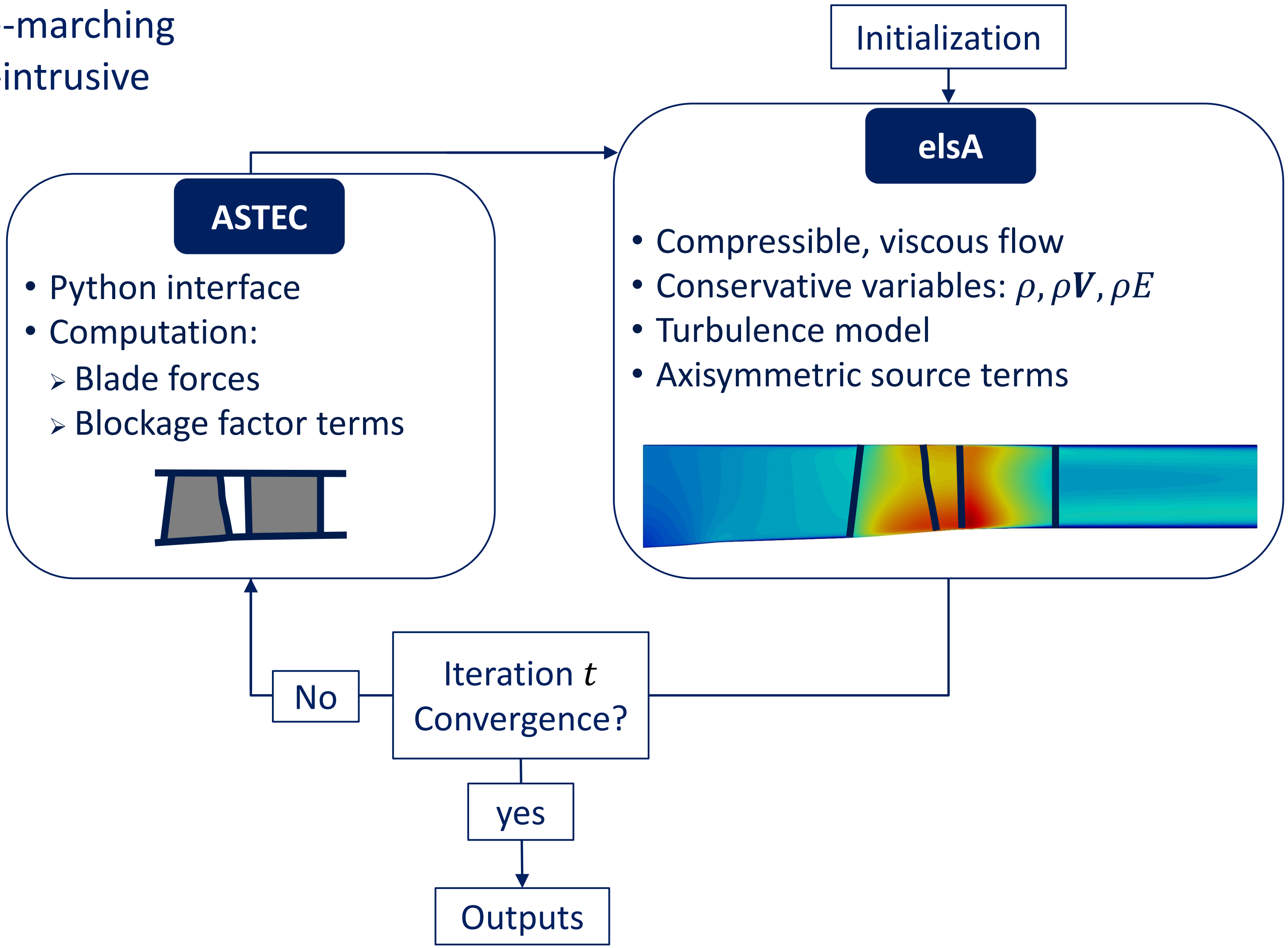
$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial(\boldsymbol{F}-\boldsymbol{F}_v)}{\partial x} + \frac{\partial(\boldsymbol{G}-\boldsymbol{G}_v)}{\partial r} = \boldsymbol{S} + \frac{(\boldsymbol{F}_v-\boldsymbol{F})}{b}\frac{\partial b}{\partial x} + \frac{(\boldsymbol{G}_v-\boldsymbol{G})}{b}\frac{\partial b}{\partial r}$$

Blockage factor terms

Viscous through-flow model: ASTEC

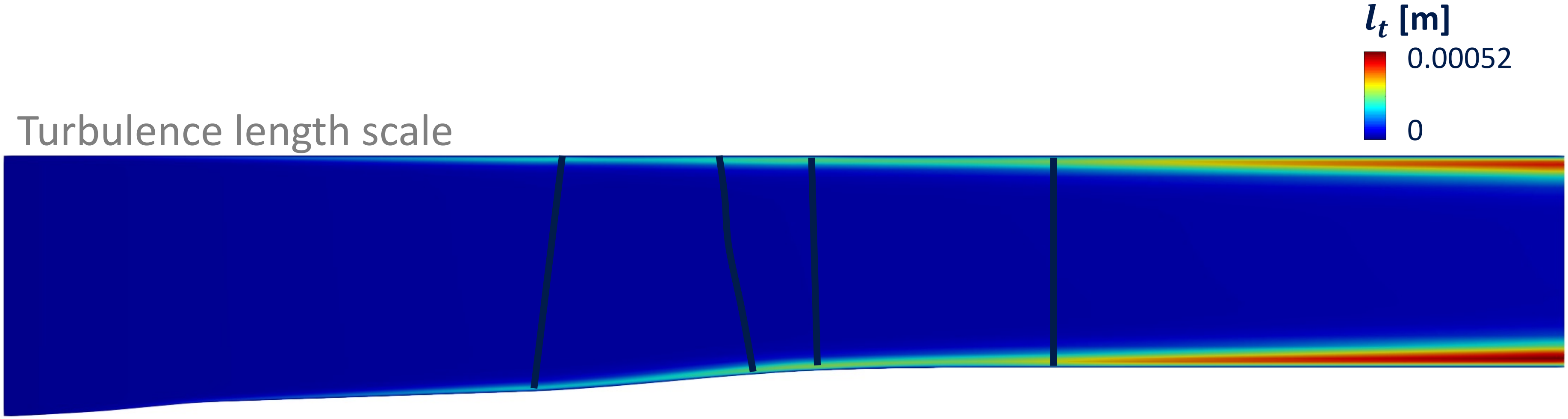
Methodology:

- Time-marching
- Non-intrusive



ASTEC: Reynolds stress

- Turbulence model: $k - l$ Smith
- Endwall boundary layers
- Handled by elsA

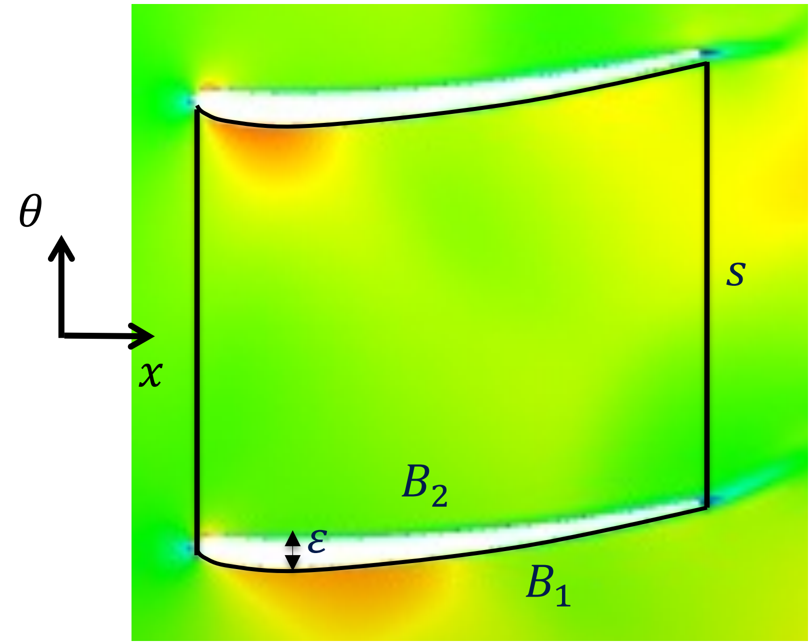


ASTEC: Inviscid blade force

Contributions: { **Blade blockage** / Deflection force $\overrightarrow{f_b}$

- Streamtube contraction
- Known (averaged pressure p + geometry)
- Added to blockage factor terms

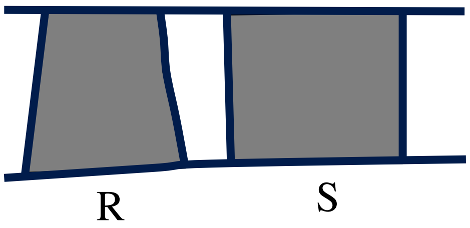
$$\boldsymbol{S}_{bi1} = \begin{bmatrix} 0 \\ \frac{p}{b}\frac{\partial b}{\partial x} \\ \frac{p}{b}\frac{\partial b}{\partial r} \\ 0 \\ 0 \end{bmatrix} - \frac{F}{b}\frac{\partial b}{\partial x} - \frac{G}{b}\frac{\partial b}{\partial r}$$

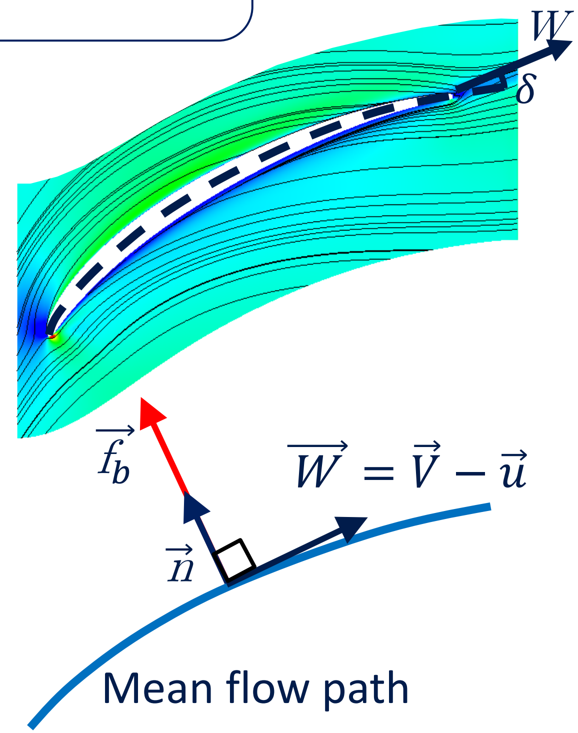


$$b = 1 - \frac{\varepsilon(x)}{s}$$

ASTEC: inviscid blade force

Contributions: $\begin{cases} \text{Blade blockage} \\ \textbf{Deflection force } \vec{f_b} \end{cases}$





- Flow slips on the mean flow path (camber line + deviation angle δ)
- No entropy generation
- Iterative procedure:

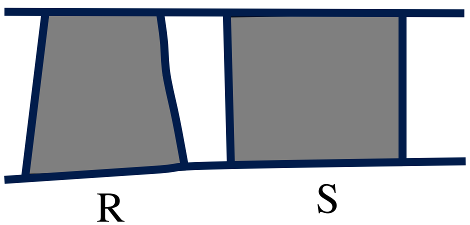
$$\frac{\partial f_b}{\partial \tau} = -C\left(W_x n_x + W_r n_r + (W_\theta - \overbrace{\Omega r}^{u}) n_\theta\right)$$

[Simon 2007]

u : shaft rotation velocity
V: velocity
W: velocity in the relative frame
Ω : shaft angular velocity

ASTEC: viscous blade force

- Distributed force $\overrightarrow{f_v}$



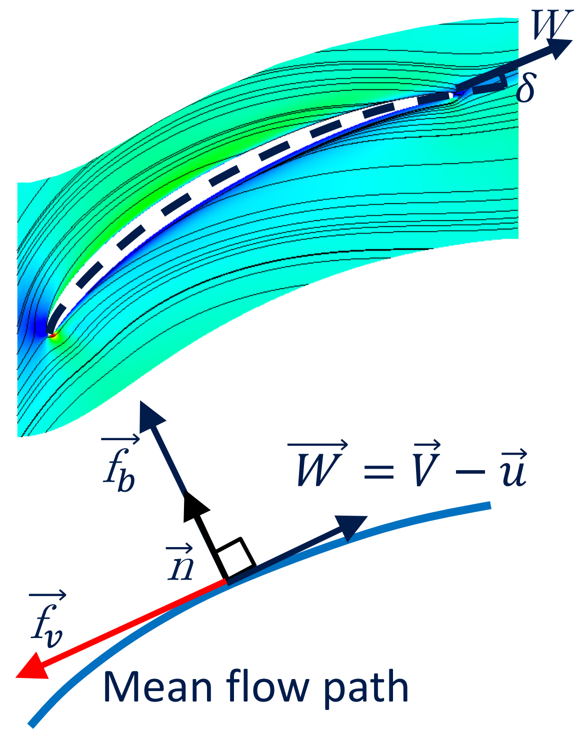
- Entropy s generated:

$$f_v = \rho T \frac{W_m \partial_m s}{W}$$

$\partial_m s = f(\omega)$ — Loss coefficient (ω)

ρ: density, T: temperature

[Hirsch 1988]



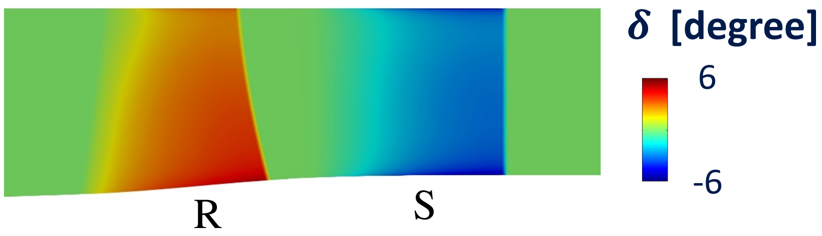
✓ Euler equations

~ N-S equations

ASTEC: correlations for δ and ω

Deviation angle δ

- From cascade experiments (Lieblein)
- Linear variation with incidence around design conditions
- $\delta = \delta_{TE} \frac{\kappa_{LE} - \kappa}{\kappa_{LE} - \kappa_{TE}}$ ⟵ Blade angle

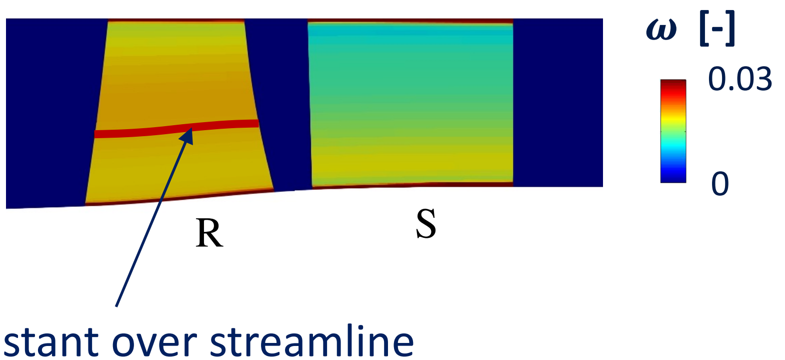


- NACA65
- C4
- Double circular arc

Loss coefficient ω

- From cascade experiments (Lieblein)
- Design + off-design parts

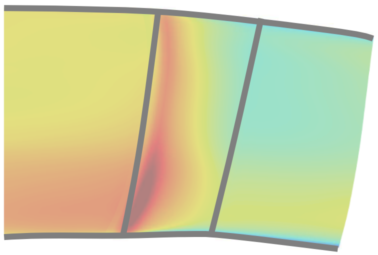
⚠ Profile loss only



Outline

1

Through-flow model



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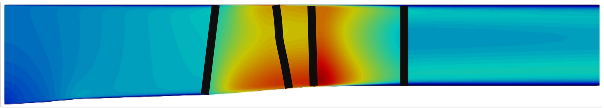
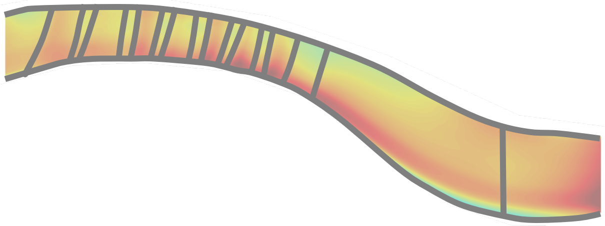
Application to the CME2 compressor stage

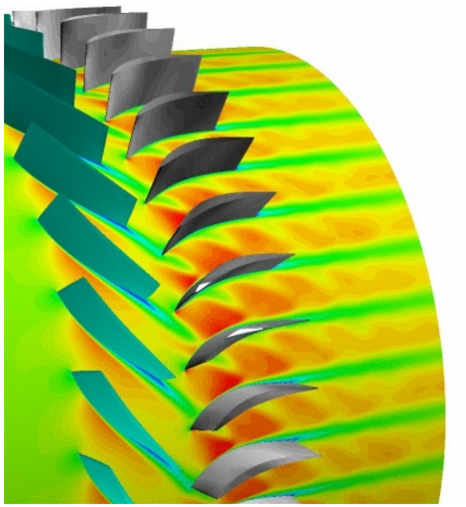


4

Application to an axial LP compressor

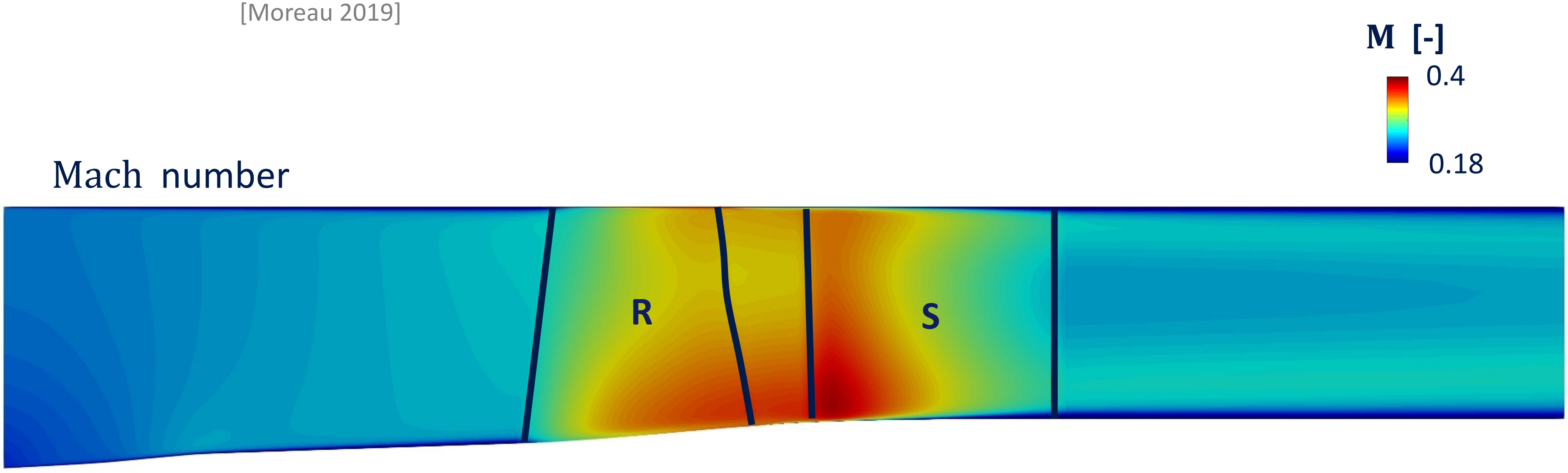


CME2: Overview



[Moreau 2019]

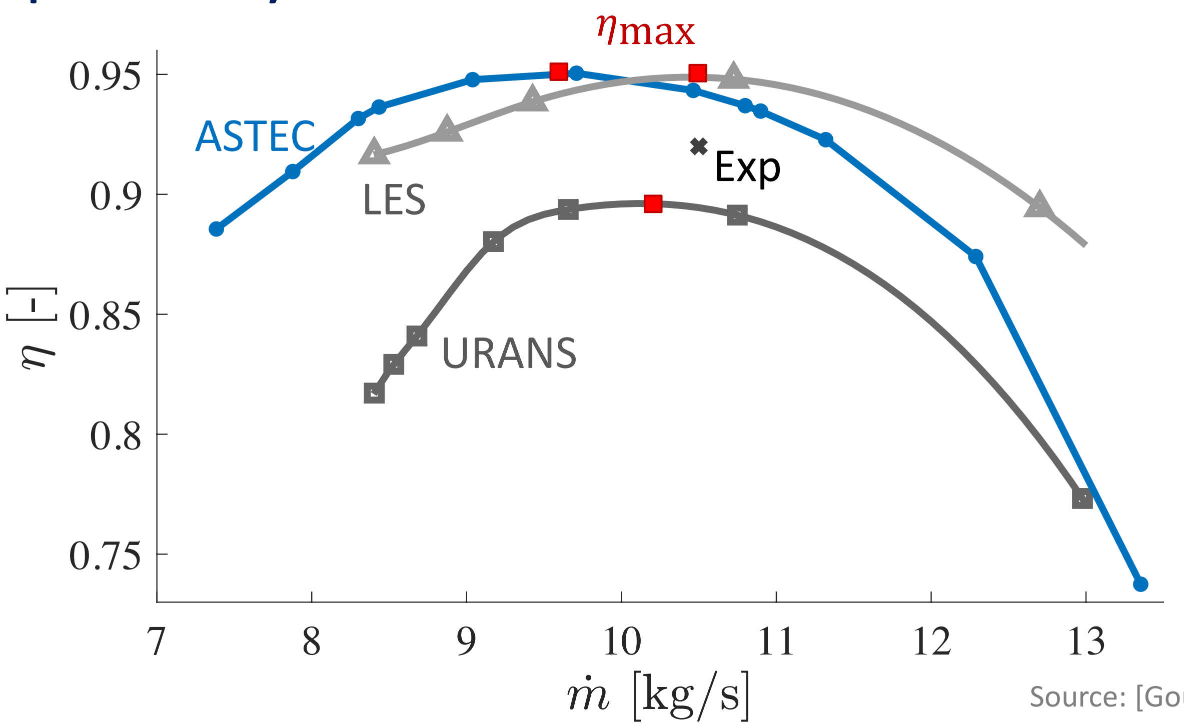
- Research compressor designed by Safran Aircraft Engines
- Low speed flow
- NACA65A012 blades
- Correlations calibrated at these conditions



CME2: results

- **Globally good agreement**
- ASTEC maximum peak efficiency close to LES prediction
- Relative difference lower than LES-URANS discrepancy
- Slight shift of mass-flow rate

Isentropic efficiency

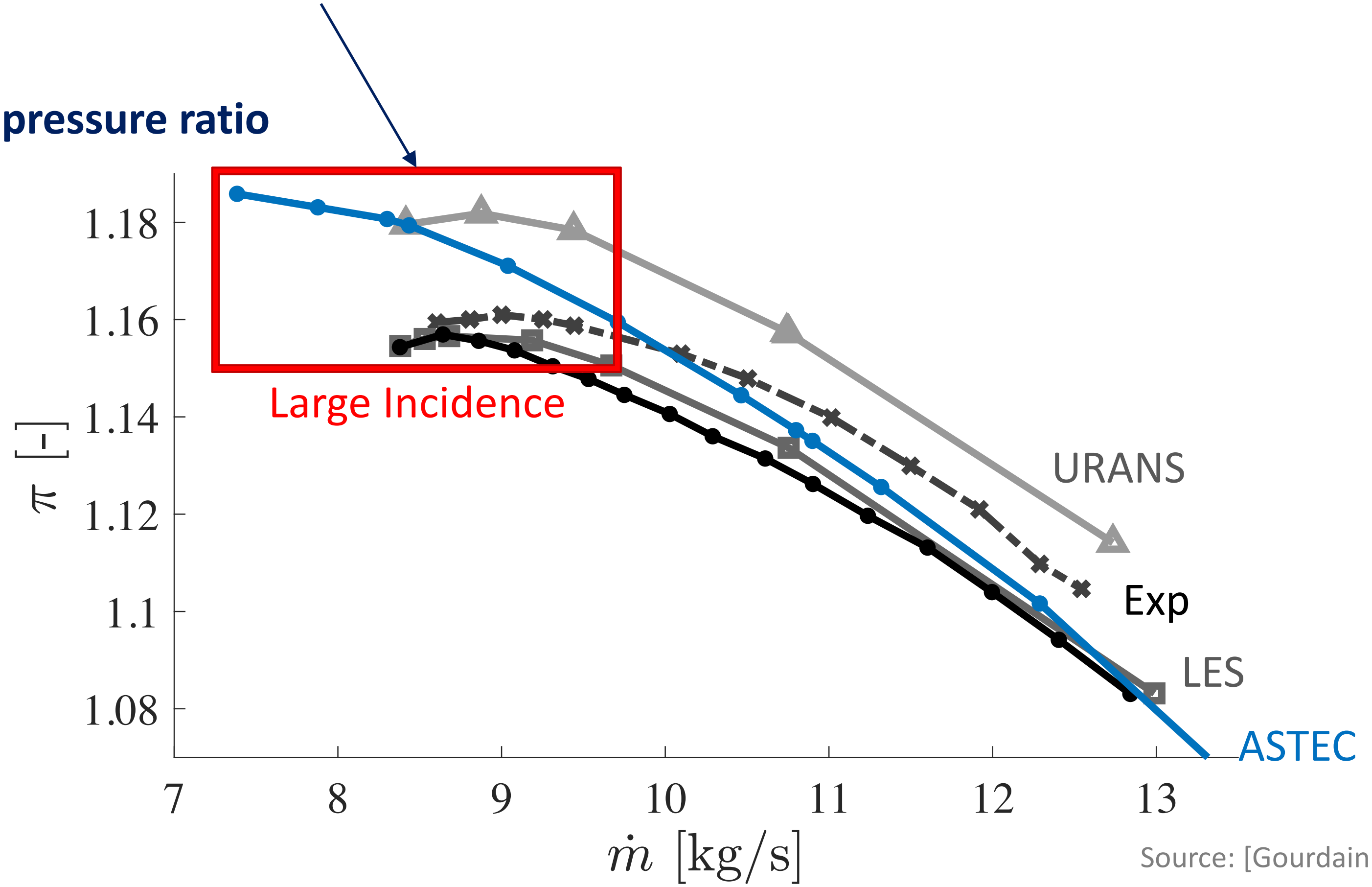


Source: [Gourdain 2015]

CME2: results

- **Global good agreement**
- Relative difference lower than LES-URANS discrepancy
- Discrepancies near stall

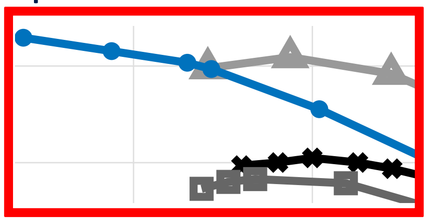
Total pressure ratio



Source: [Gourdain 2015]

Viscous through-flow model: ASTEC

Total pressure ratio

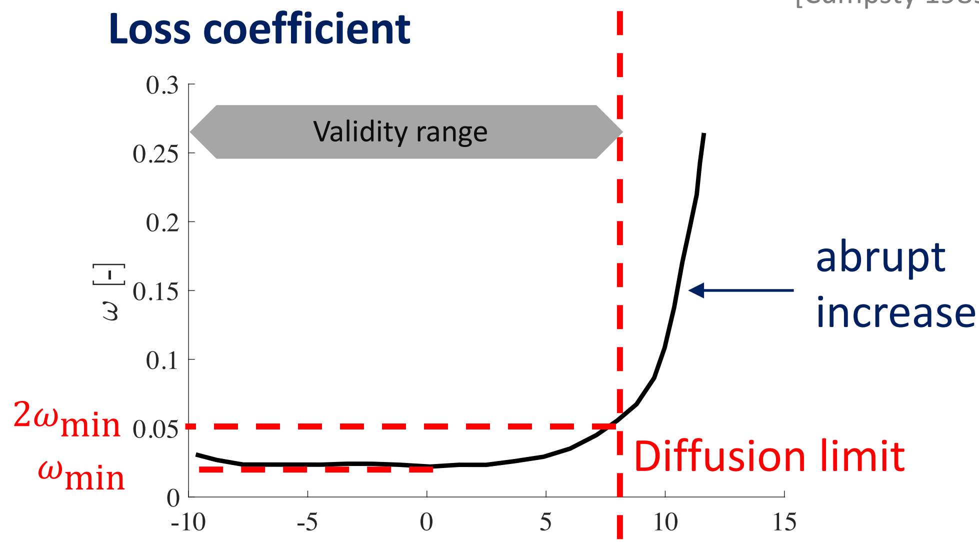


Assumptions of loss correlations not valid beyond diffusion limit at large incidence i

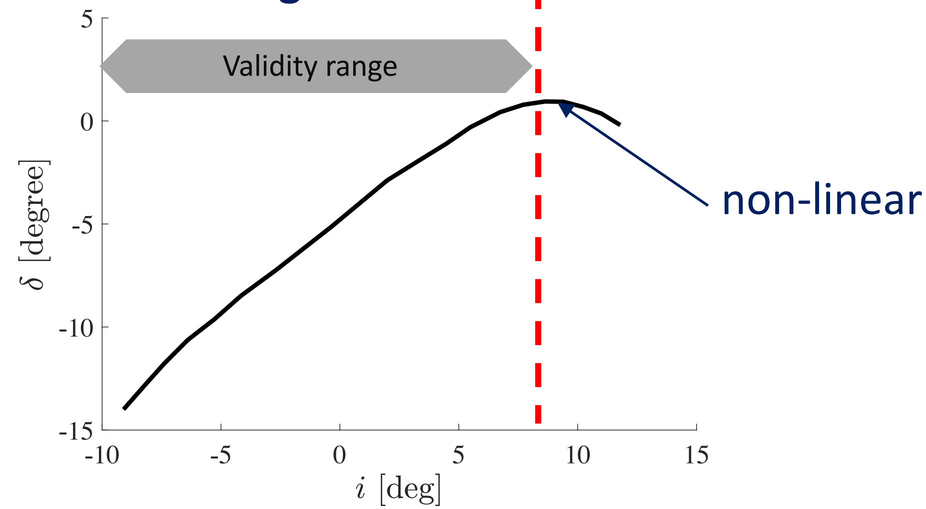
Measurements of C4-series cascade (M = 0.4)

[Cumpsty 1989]

Loss coefficient

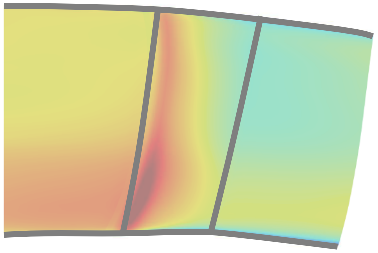


Deviation angle



Outline

1 Through-flow model



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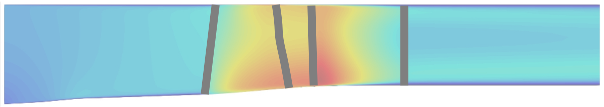
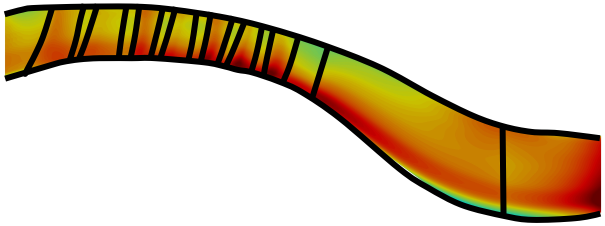
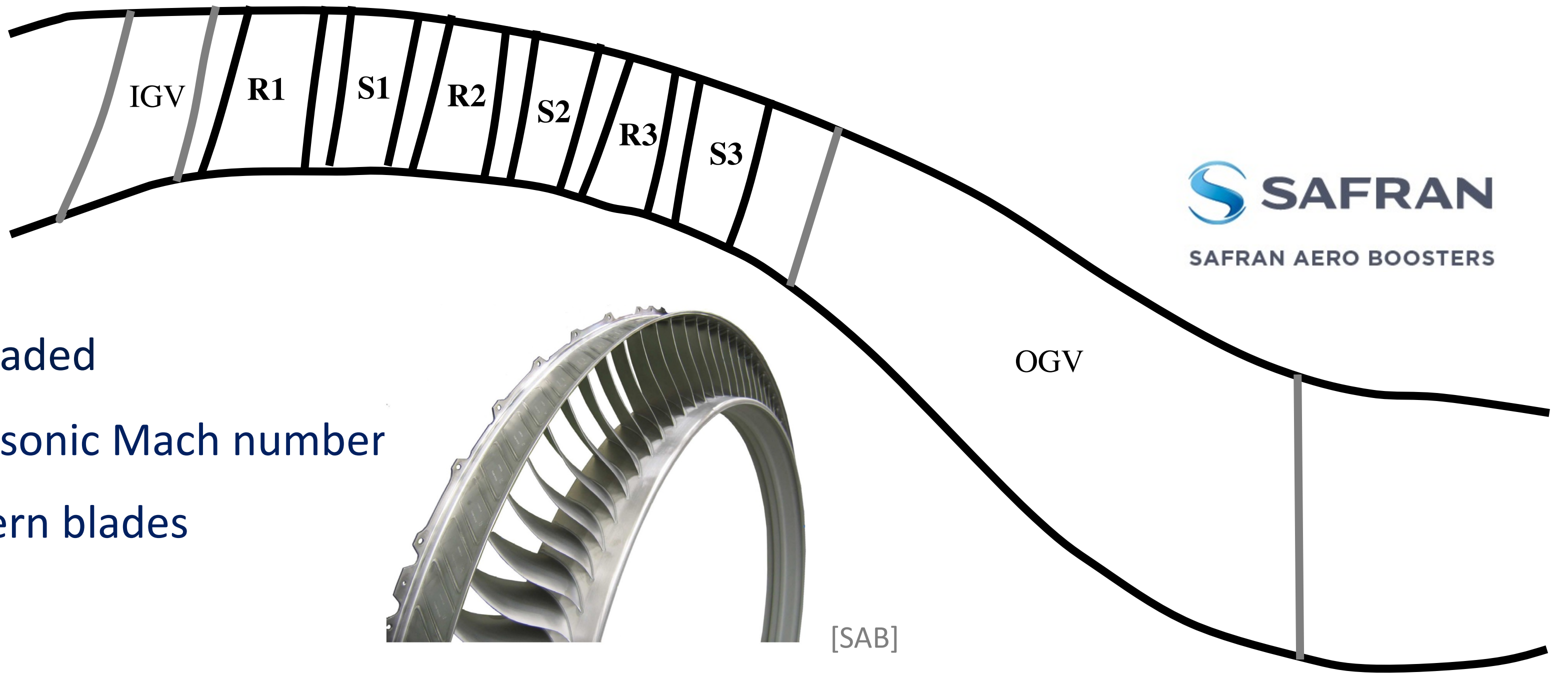
3 Application to the CME2 compressor stage



4 **Application to an axial LP compressor**



Modern high-loaded axial LP compressor



SAFRAN
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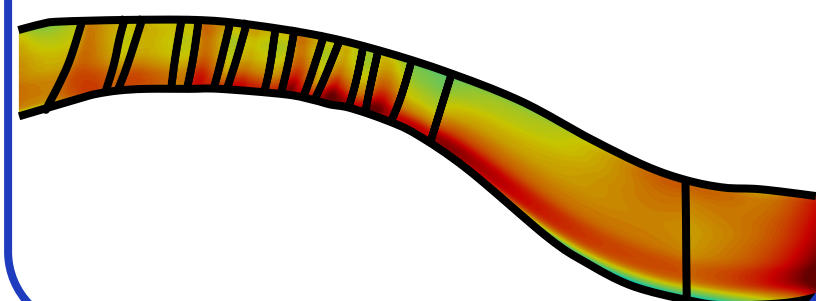
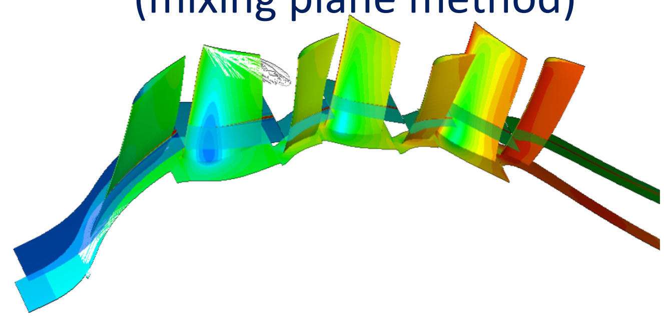
- Highly loaded
- High subsonic Mach number
- 3D modern blades

ASTEC

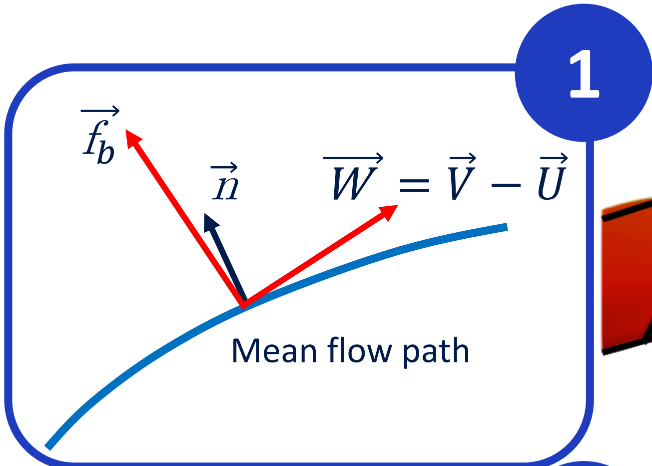


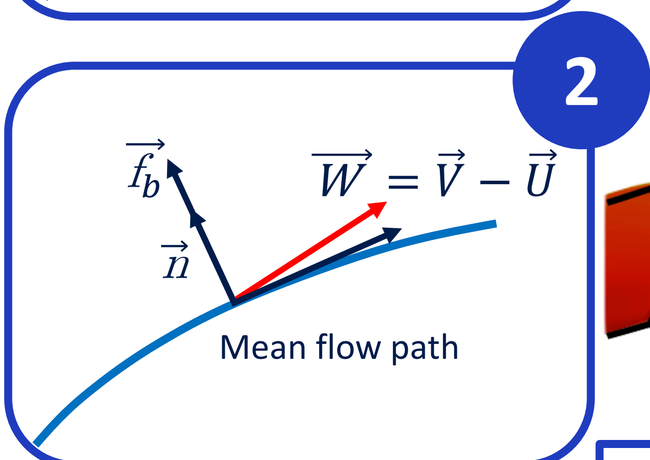
3D RANS

(mixing plane method)



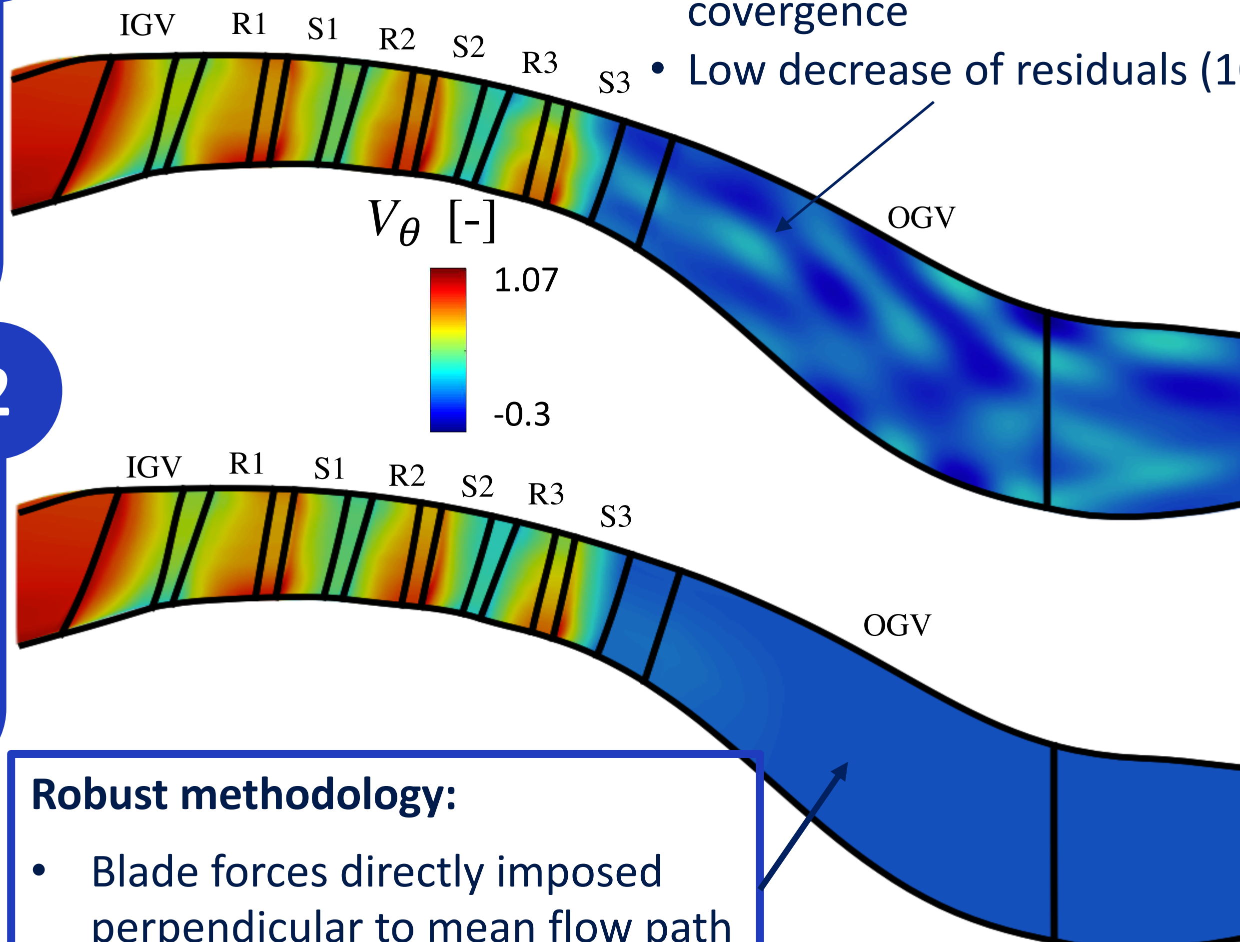
Modern Compressor: deflection force





Unphysical behaviour

- Symmetric blade
- Flow direction oscillates during covergence
- Low decrease of residuals (10^{-2})



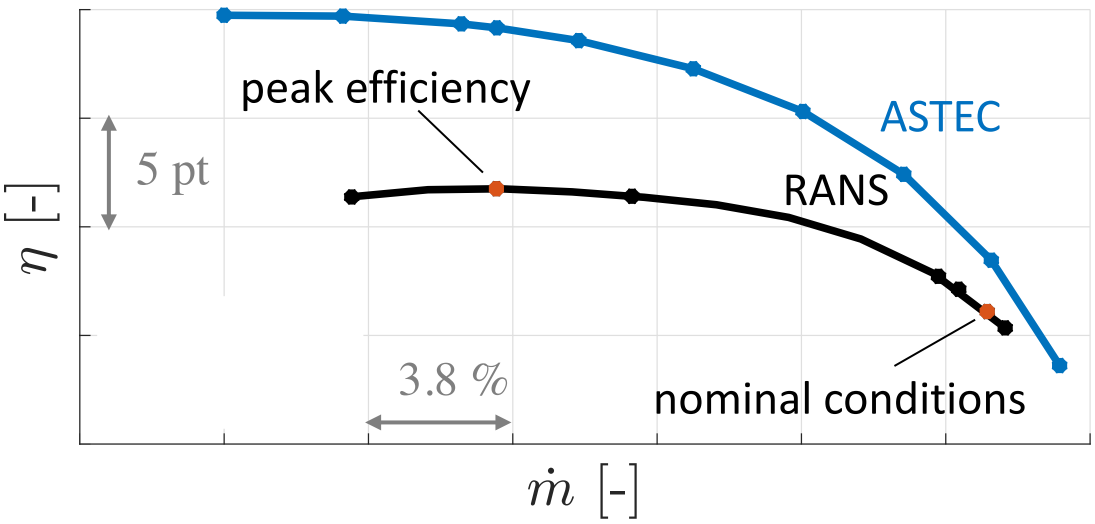
Robust methodology:

- Blade forces directly imposed perpendicular to mean flow path
- High decrease of residuals (10^{-8})

Modern compressor: comparison to RANS

- Low margin at nominal conditions
- More than 400 times faster (not yet optimized for speed)
- Increasing discrepancies near peak efficiency

Isentropic efficiency



Correlations not calibrated for

- **Optimized 3D blade geometries**
- **High subsonic Mach number**

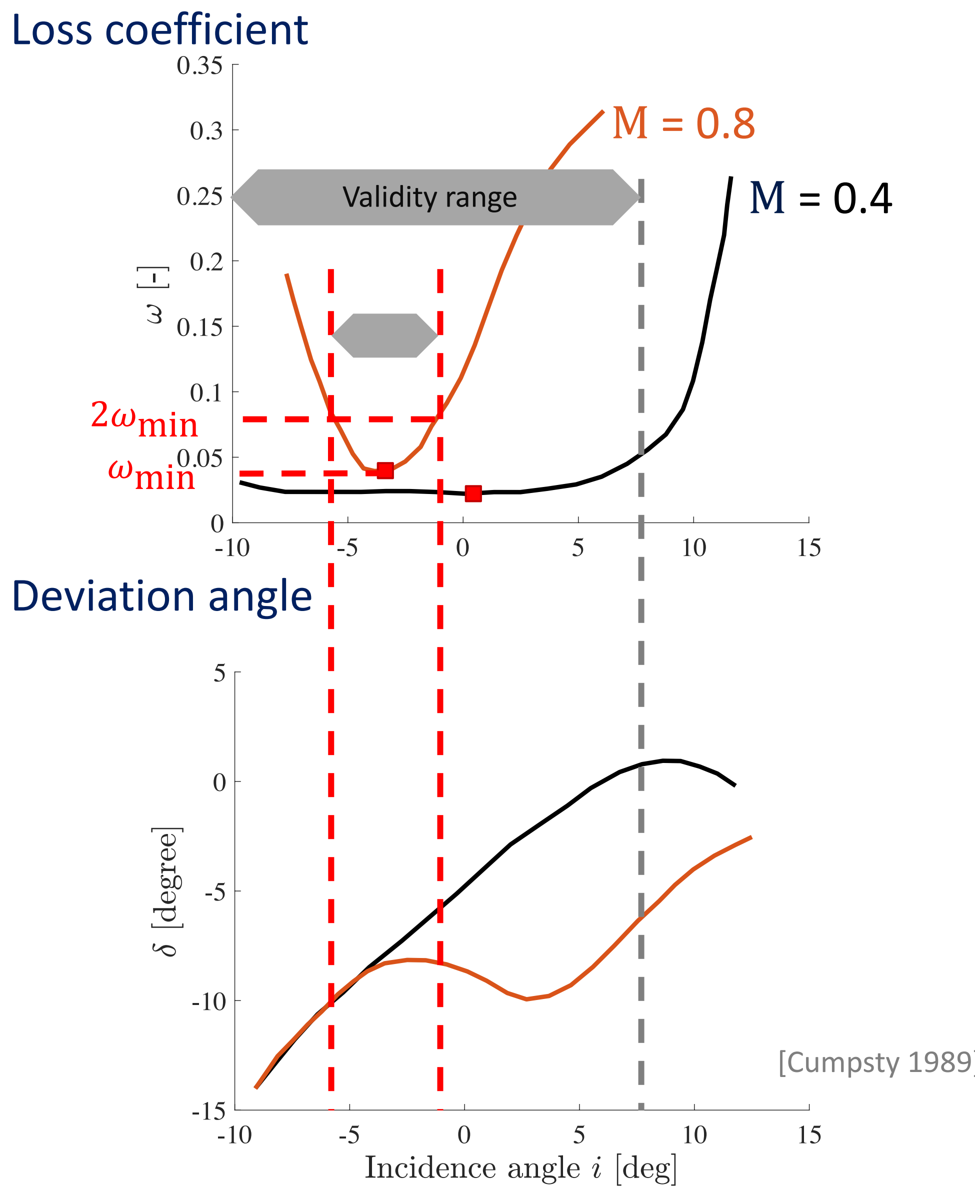
Modern compressor: comparison to RANS

Impact of Mach number

- Minimum-loss incidence angle shifted
- Narrow range of validity
- Increase of $\omega_{\min}$
- Inconsistency between loss validity range and deviation linear range

Correlations **not calibrated** for these **flow conditions**

Measurements of C4-series cascade

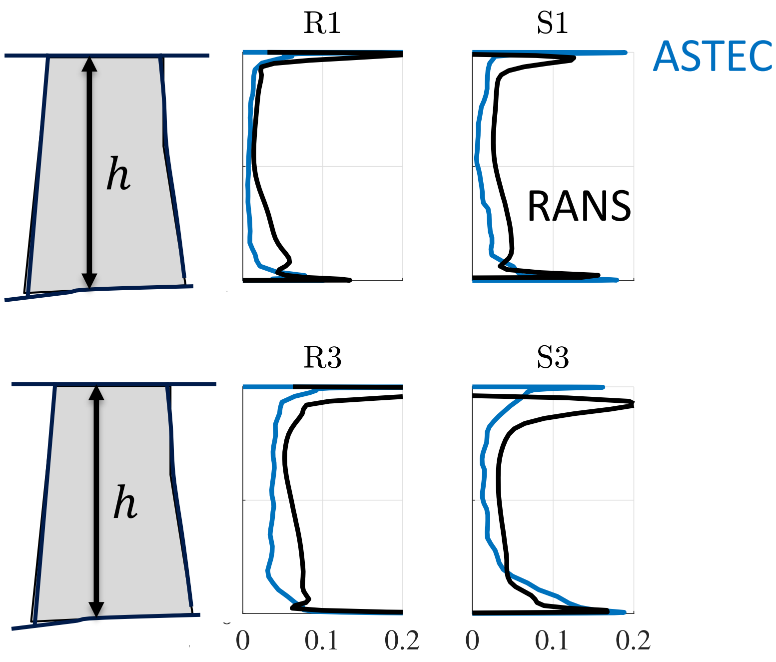


Modern compressor: comparison to RANS

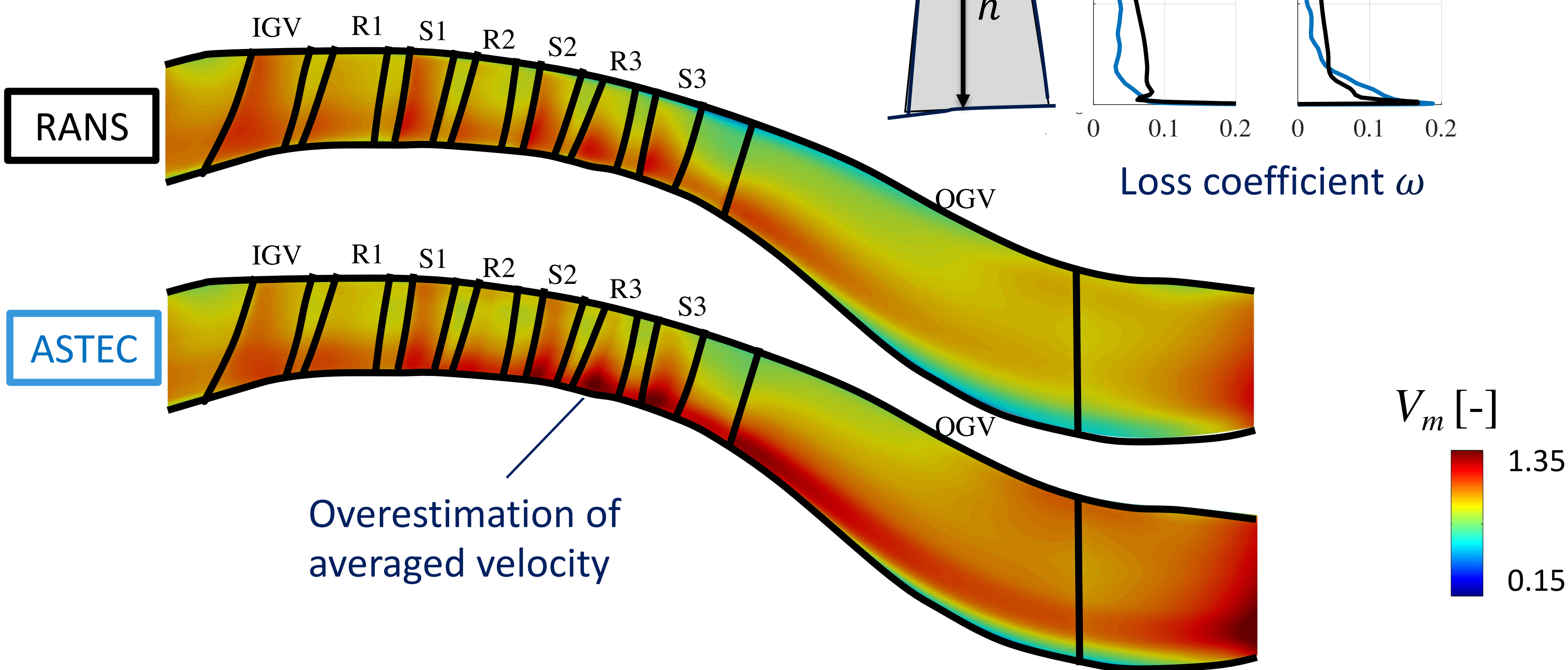
@ nominal conditions

- Correlations not calibrated for such **optimized 3D blade geometries**
- Loss coefficient under-estimated

→ profile loss underestimated

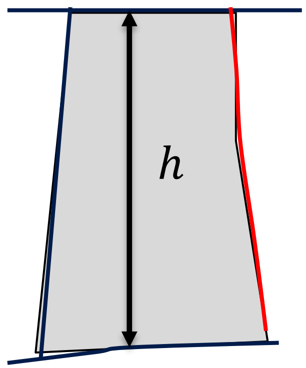


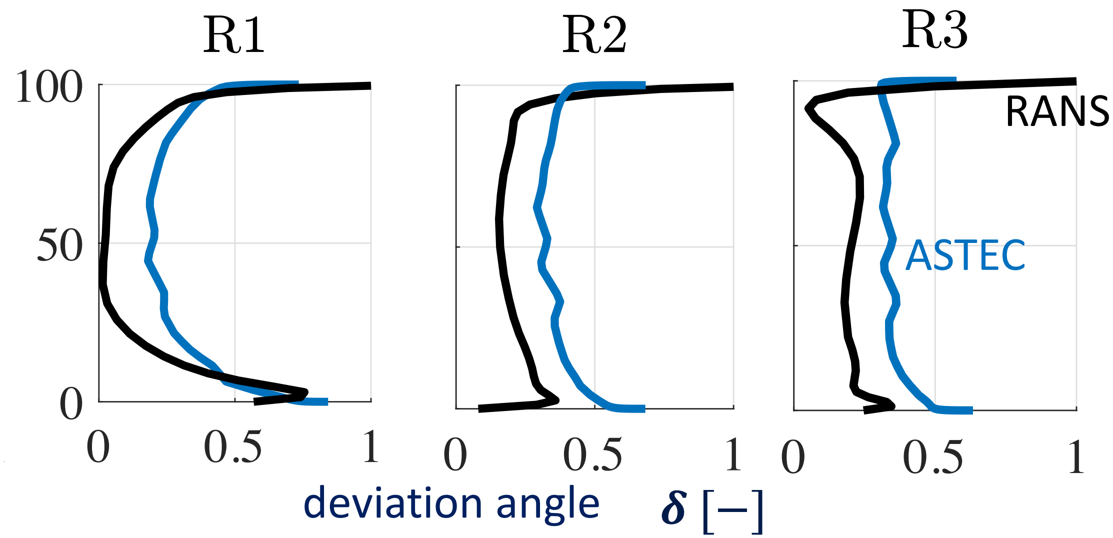
Loss coefficient ω



Modern compressor: comparison to RANS

@ nominal conditions



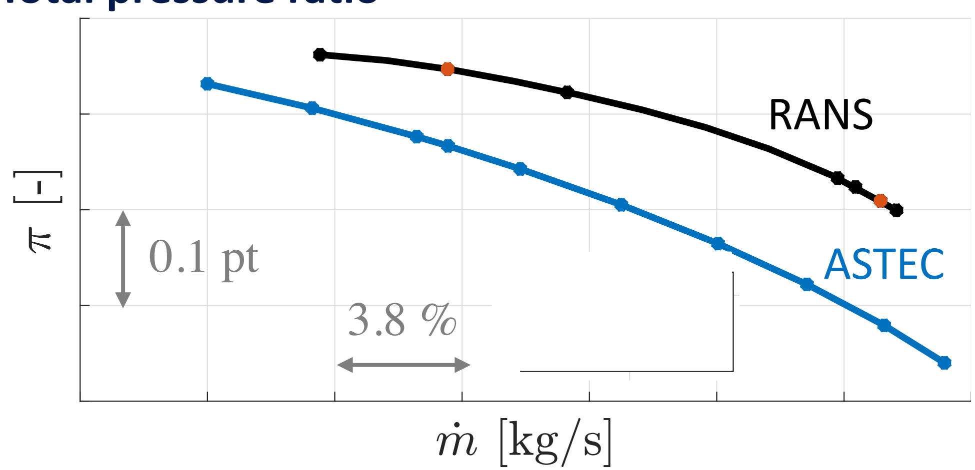


Large overestimation of the deviation angle for rotors

→ Underpumping

→ Under-estimated compression ratio

Total pressure ratio



Conclusion

ASTEC

- **Navier-stokes** based through-flow model
- Closures: blade forces + turbulence model
- Correlations:
  - deviation angle
  - loss coefficient (profile loss)

Application to compressors

- Global good agreement for **CME2** compressor stage
- Improvement required for **modern axial-flow** compressor at high subsonic Mach
- Promising approach to drastically **reduce CPU cost** compared to 3D RANS

Future work

- Extend validity range of **loss correlations** (beyond diffusion limit)
- Include **Mach number correction**
- **Tune correlations** for optimized blade geometries through cascade simulations
- Include **other sources of loss** (tip gap model, leakage flow, …)

Acknowledgement

Funding for this research is provided by the Walloon region, under grant no. 7900, and Safran Aero Boosters in the frame of the project MARIETTA