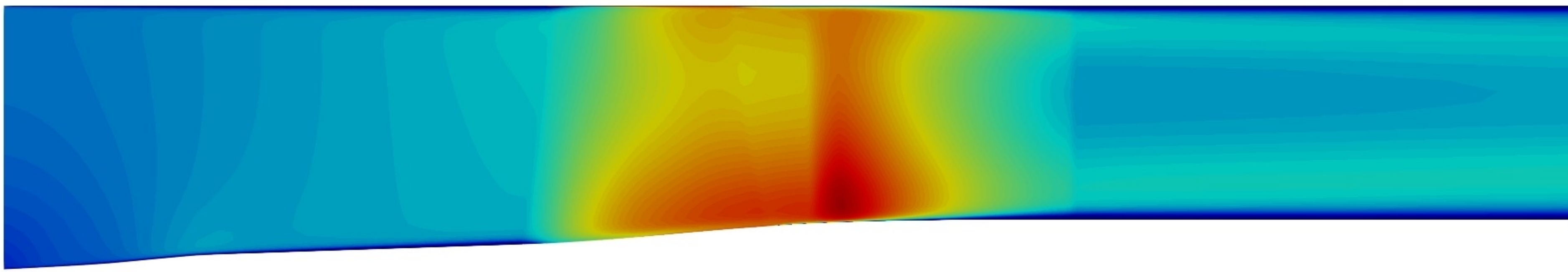
# Geometric uncertainties in through-flow models



**Arnaud Budo[1]**
Octobre 2018 → Octobre 2023

Vincent E. Terrapon[1], Maarten Arnst[1]
Sophie Mouriaux[2], Jules Bartholet[3]

**Journée des doctorants HAIDA 2021**

LIÈGE université (1)
Safran Tech(2) SAFRAN
SAFRAN (3) SAFRAN AERO BOOSTERS

# Context

Geometrical variability of aerodynamic parts of low-pressure compressors


[SAB]

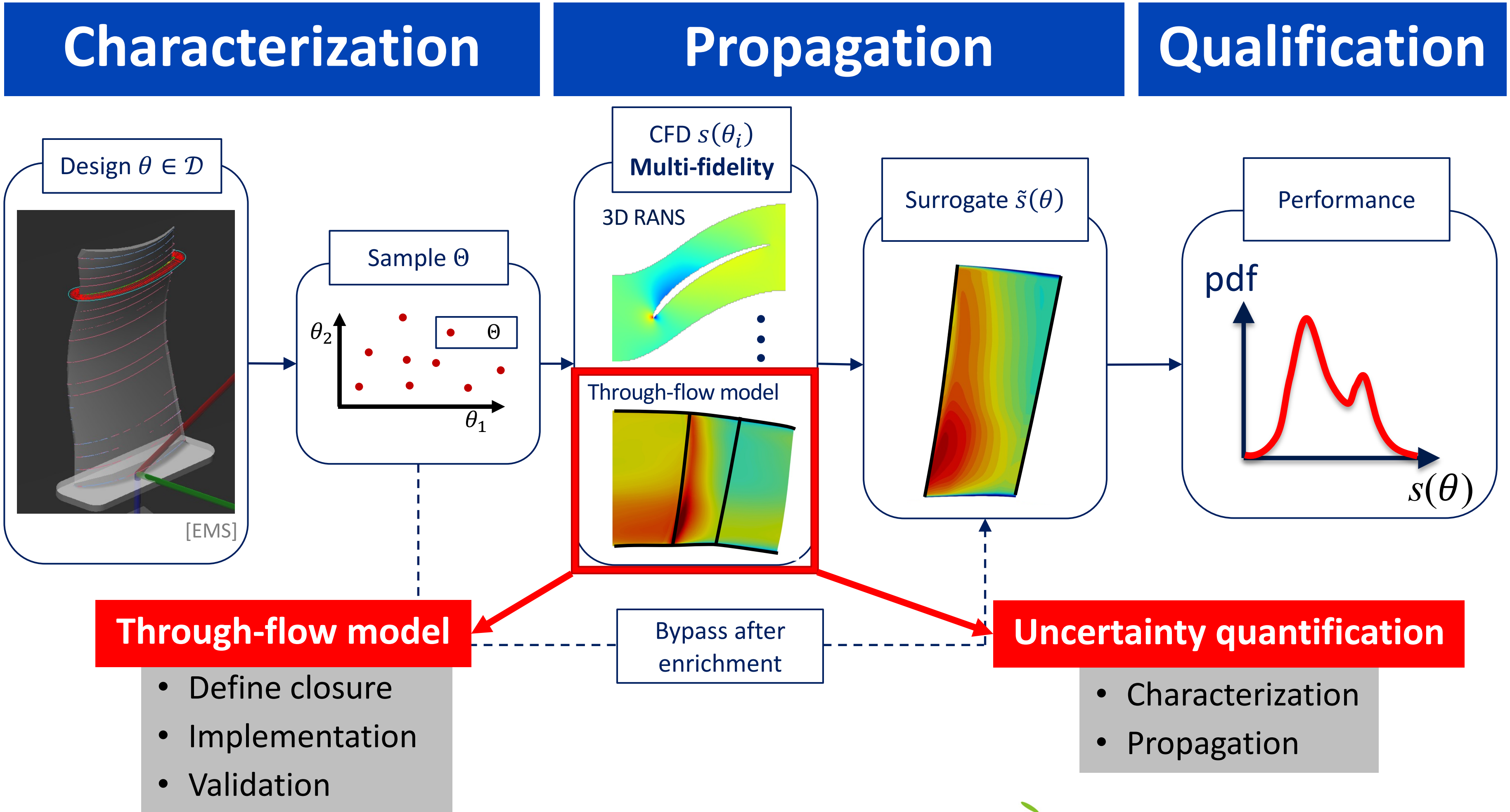
Technical and economic performances

**Manufacturing tolerances?**

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

Decrease the overall cost

# Methodology



# Outline

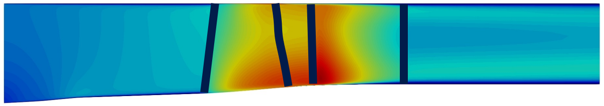
1

**Viscous through-flow model**

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

2

**Application to the CME2 compressor stage**



3

**Application to an axial LP compressor**

4

**Future work**

[SAB]

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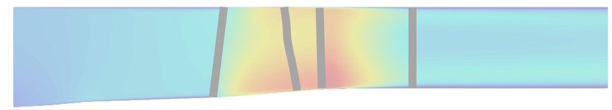

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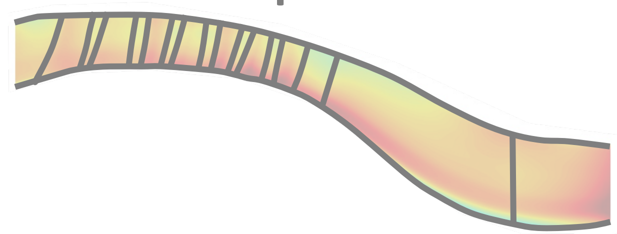

4

**Future work**

[SAB]

# Viscous through-flow model

## Circumferential averaged Navier-Stokes equations:

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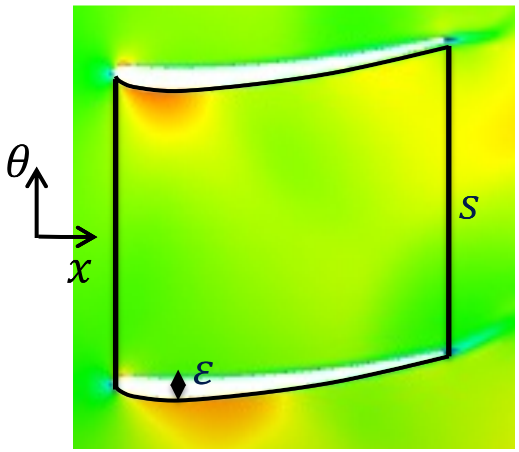



Conservative variables

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

**Blockage factor**

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

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

## Non-intrusive formulation for elsA:

[Onera]

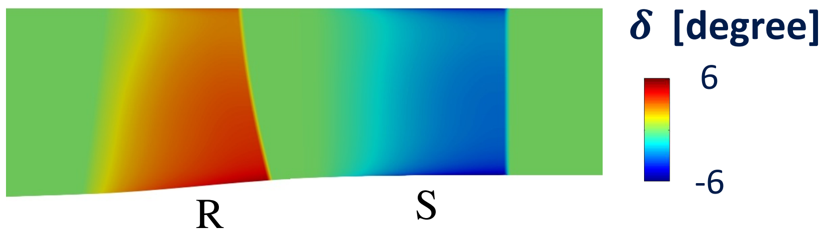
$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial(\boldsymbol{F} - \boldsymbol{F}_v)}{\partial x} + \frac{\partial(\boldsymbol{G} - \boldsymbol{G}_v)}{\partial r} = \boldsymbol{S} + \boxed{\frac{(\cancel{\boldsymbol{F}_v} - \boldsymbol{F})}{b}\frac{\partial b}{\partial x} + \frac{(\cancel{\boldsymbol{G}_v}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

Blockage factor terms

# ASTEC: correlations for $\delta$ and $\omega$

### Deviation angle $\delta$ (inviscid blade force)

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

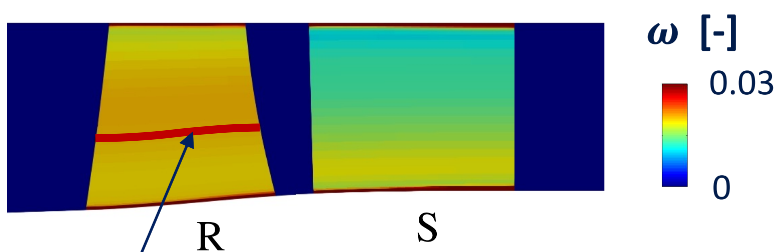



- NACA65
- C4
- Double circular arc

### Loss coefficient $\omega$ (viscous blade force)

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

Profile loss only




Constant over streamline (0D)

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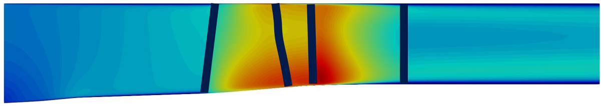

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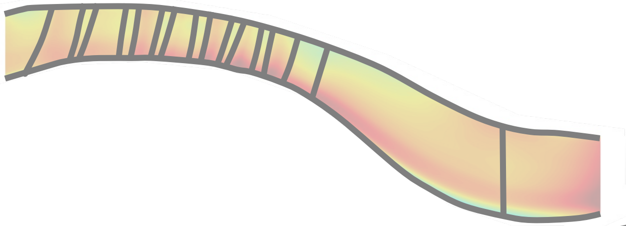
Application to an axial LP compressor

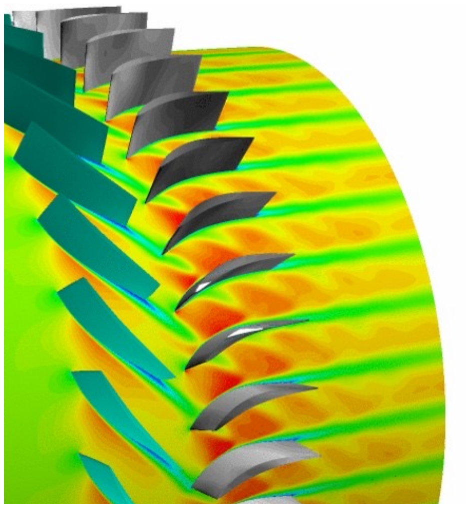


4

Future work

[SAB]

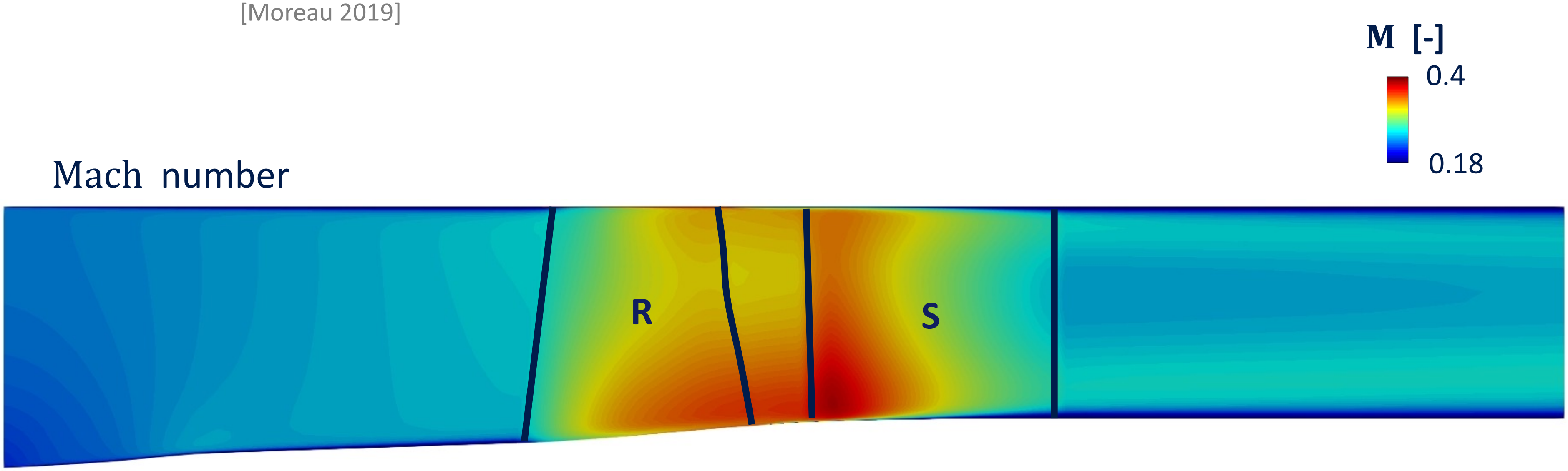
# CME2: Overview



[Moreau 2019]

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

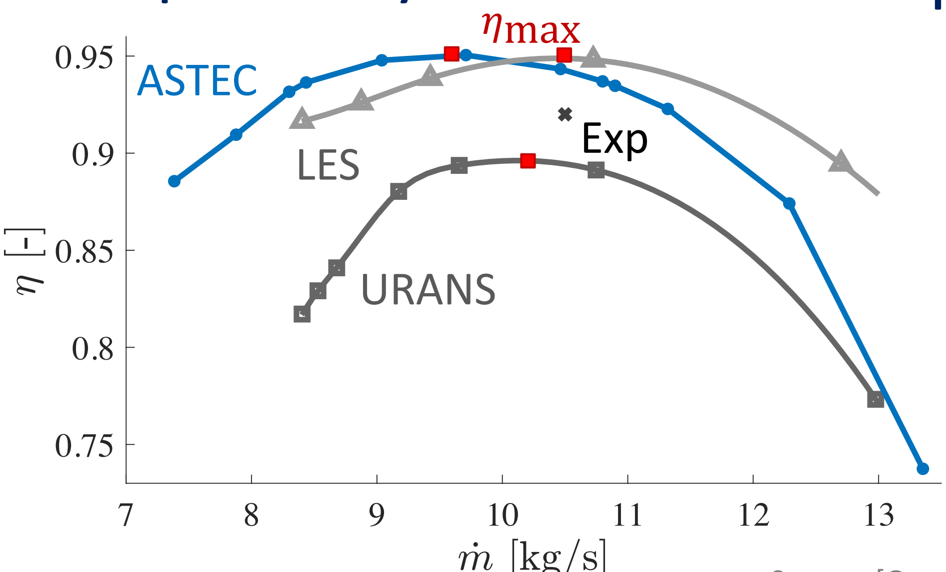
Mach number



# CME2: results

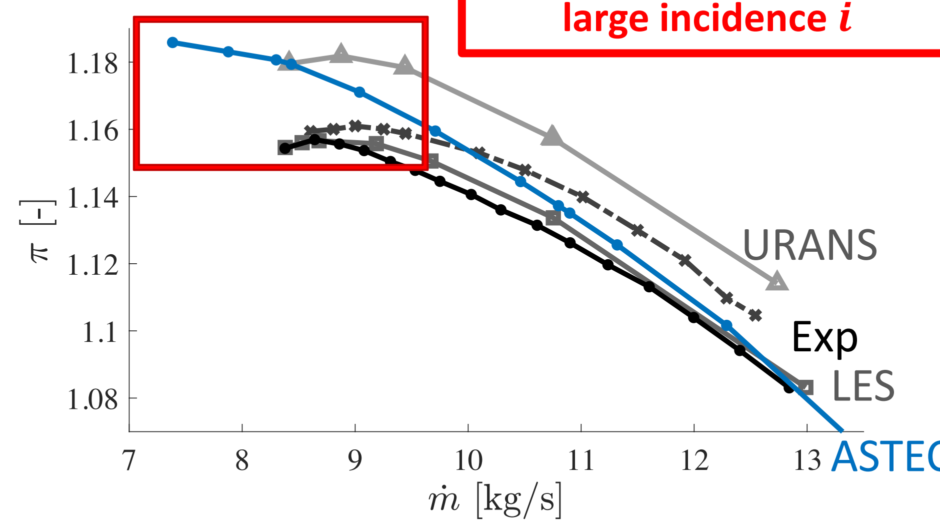
- **Globally good agreement**
- Relative difference lower than LES-URANS discrepancy
- ASTEC maximum peak efficiency close to LES prediction
- Slight shift of mass-flow rate
- Discrepancies near stall

**Isentropic efficiency**




**Total pressure ratio**

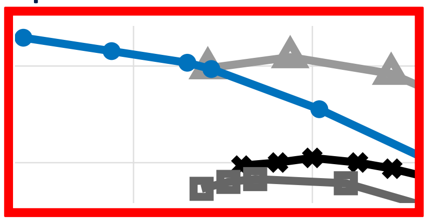
**Assumptions of loss correlations not valid beyond diffusion limit at large incidence $i$**




Source: [Gourdain 2015]

# CME2: Diffusion limit

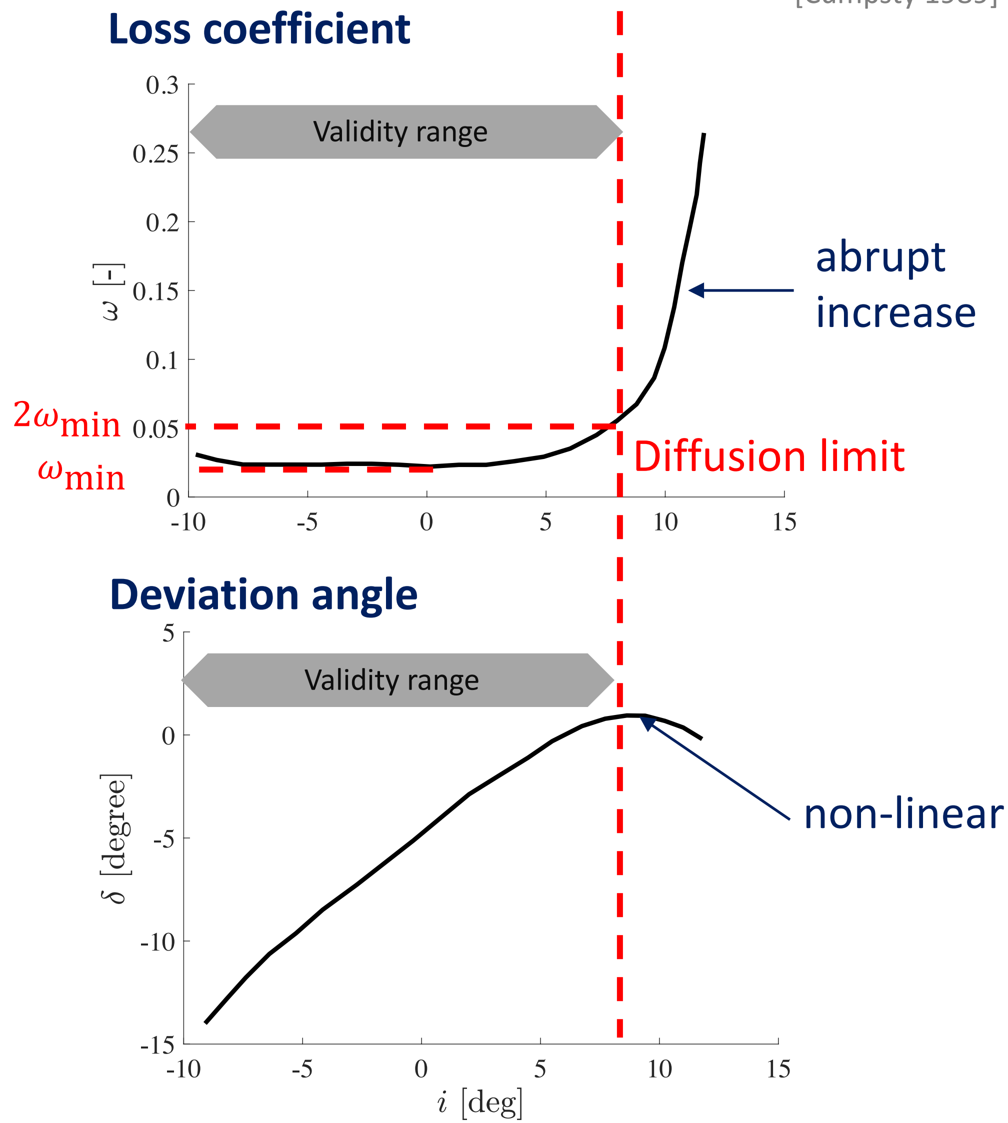
Total pressure ratio



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

**Measurements of C4-series cascade (M = 0.4)**

[Cumpsty 1989]



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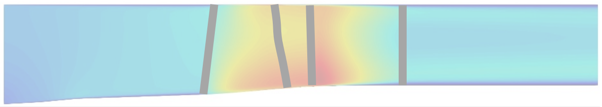

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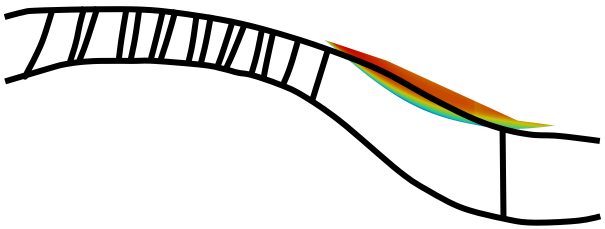
**Application to an axial LP compressor**

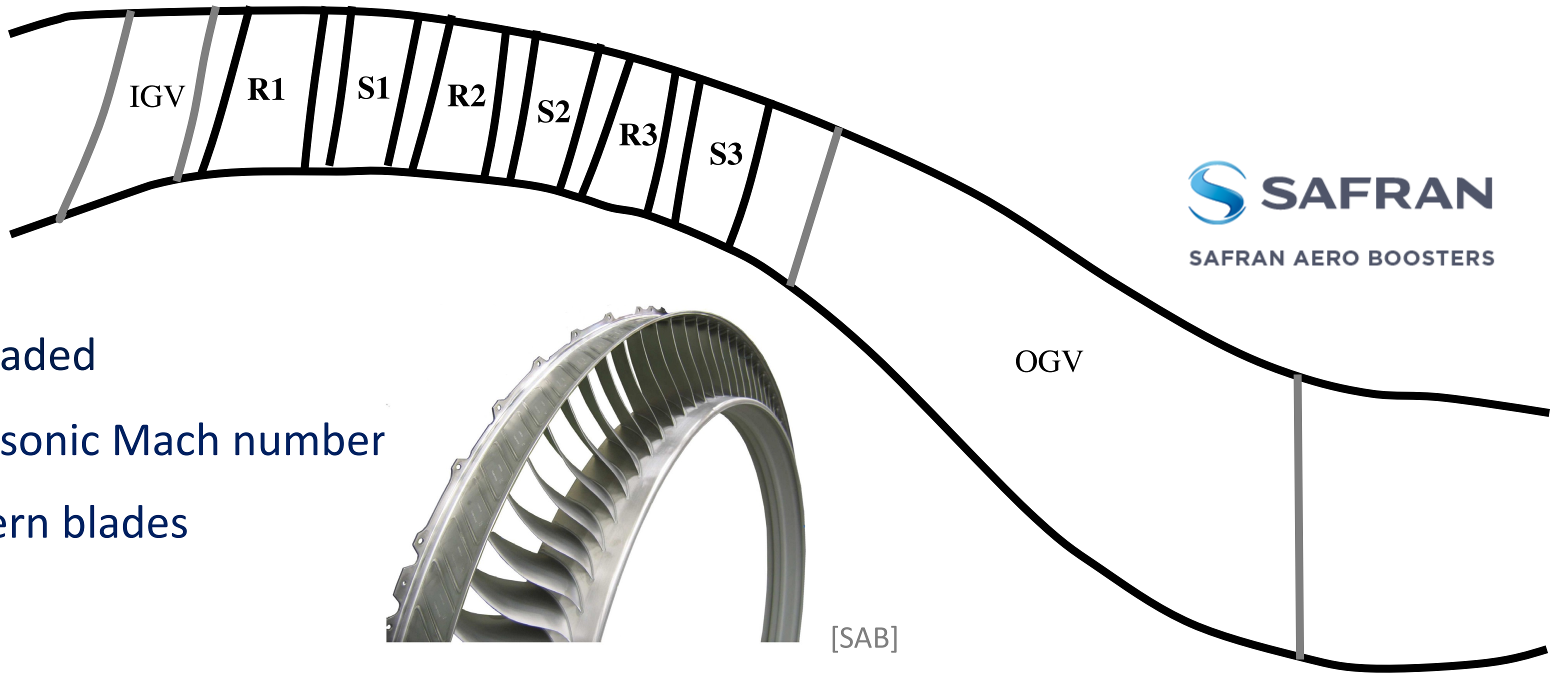


4

Future work

[SAB]

# Modern high-loaded axial LP compressor

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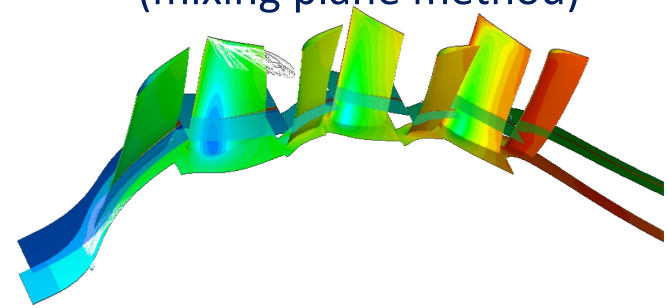
- Highly loaded
- High subsonic Mach number
- 3D modern blades

[SAB]

**ASTEC**

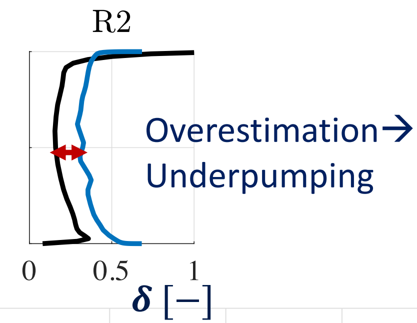
**3D RANS**

(mixing plane method)

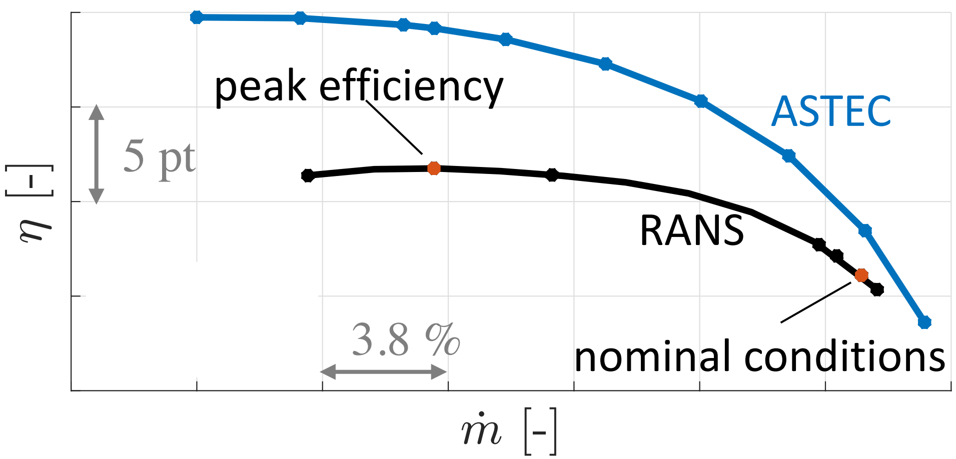


# Modern compressor: comparison to RANS

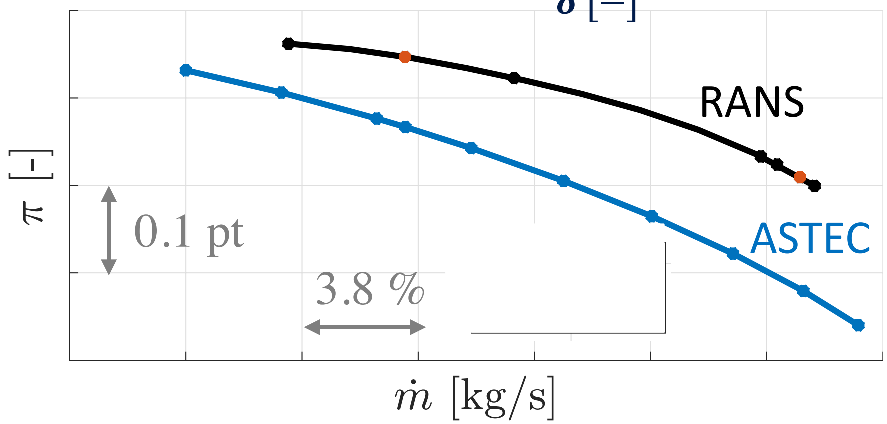
- Low margin at nominal conditions
- More than 400 times faster (not yet optimized for speed)
- Increasing discrepancies near peak efficiency




**Isentropic efficiency**




**Total pressure ratio**




**Correlations not calibrated for**

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

Closure model improvement

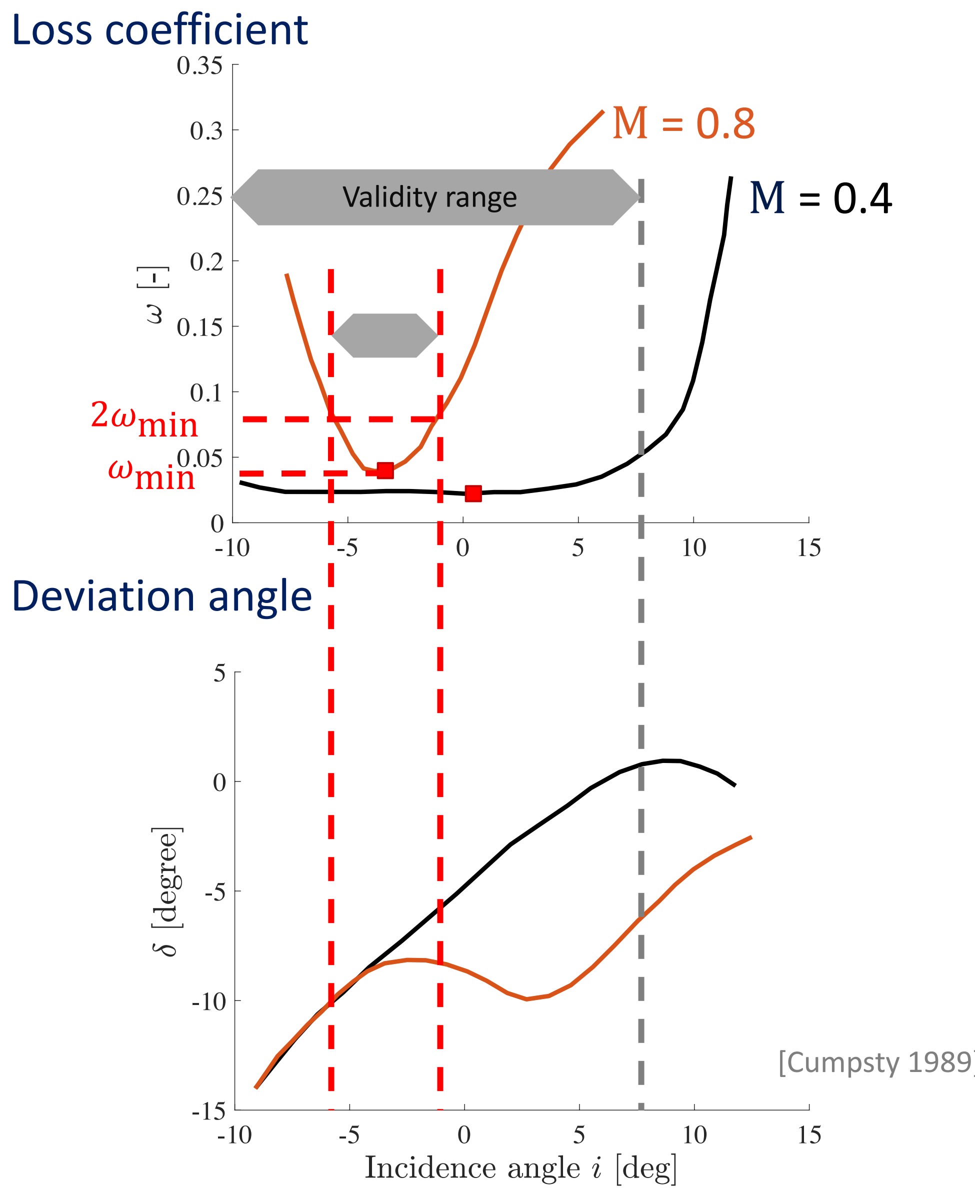
# Modern compressor: comparison to RANS

### Impact of Mach number

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

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

**Measurements of C4-series cascade**

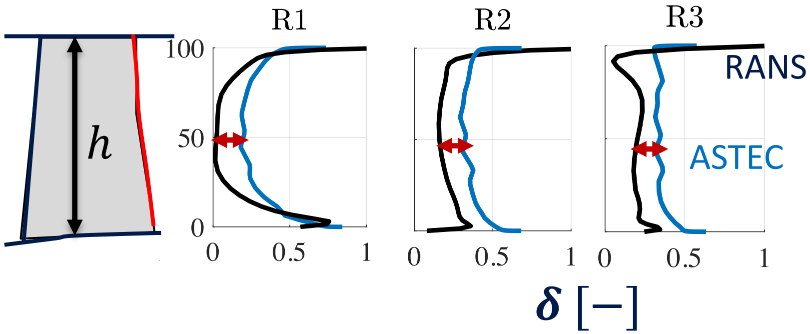


# Modern compressor: comparison to RANS

**König's profile loss model (**Bart Ruis' Master thesis)

- Mach number effect
- Valid beyond diffusion limit
- Compressibility

Correction for **Lieblein's** deviation angle:

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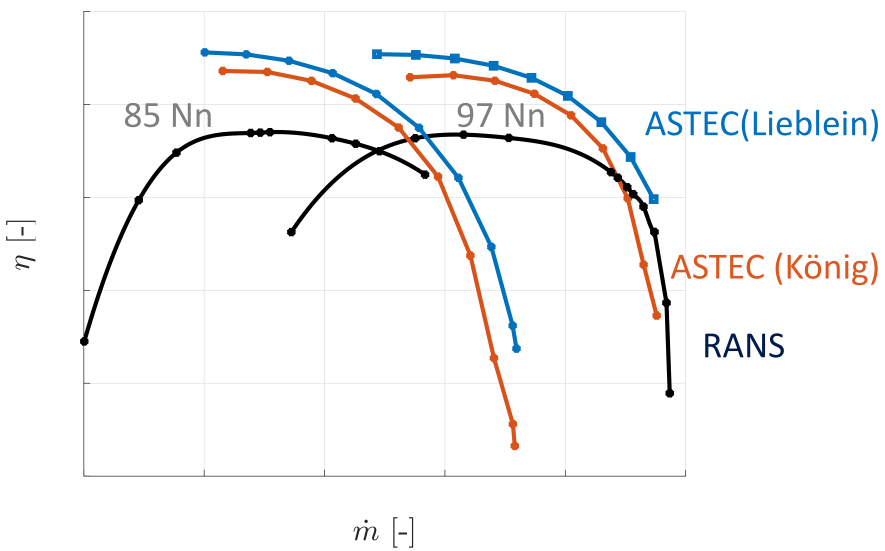
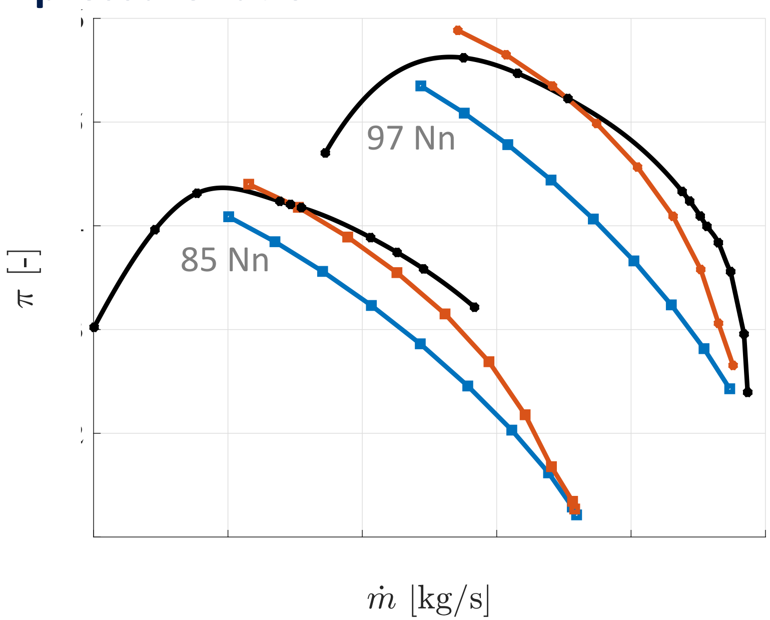



**Total pressure ratio**



# Conclusion

**ASTEC**

- Closures computation: blade forces
- Coupled with **elsA** [Onera]
  →**Navier-stokes** based through-flow 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

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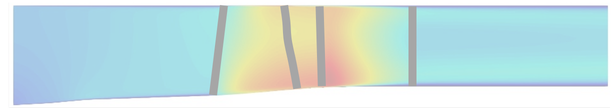

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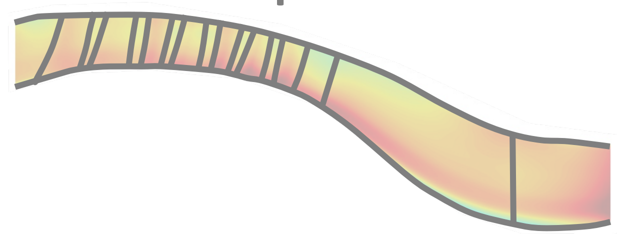

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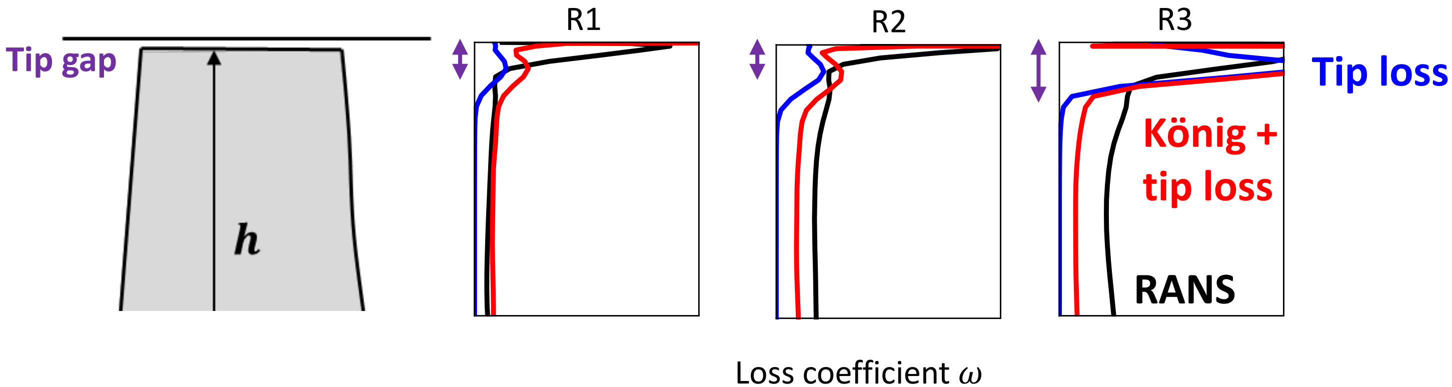
**Future work**

[SAB]

# Future work: other sources of loss

- **Tip gap model: Lakshminarayana models**




  - ➢ **Not efficient** for small tip gap (B.L. dominates loss production)
  - ➢ **Endwall loss** partly taken into account by **NS model** but measurements used for correlations usually not performed close to endwalls (~ 5% of blade height)

- **Secondary flows: in progress**

Corner vortex, horseshoe vortex, passage vortex
[Roberts, Ricci]

# Future work: geometrical uncertainties

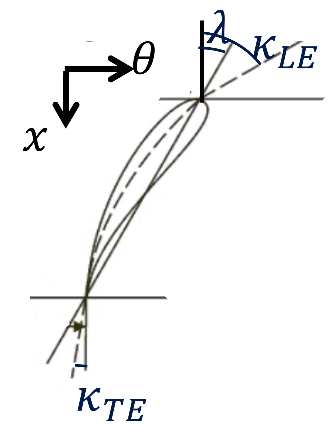
## Parametric model

- Based on ASTEC's input parameters
- **Bounds based on SAB tolerances?**

(Axisymmetric → no mistuning as 3D steady computation)

→ **Sensitivity analysis on performance and source terms**

No data from scanned blades



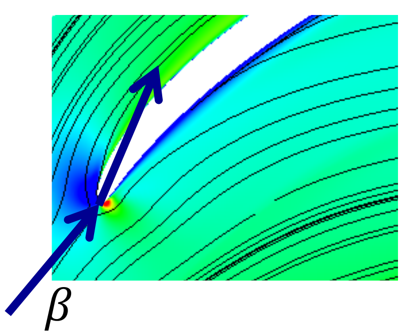

## Uncertainties vs incidence correction

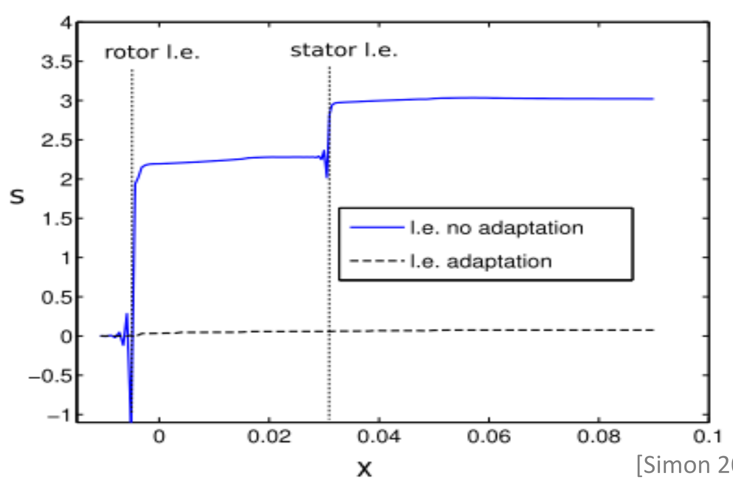
LE variabilities → large impact on performance

**But** Axisymmetric model not able to predict flow prerotation at LE

→Smoothing from upstream flow angle and flow angle imposed by models/blade geometry

→ Geometrical variabilities partially rubbed out




[Simon 2007]

# 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

# BACK-UP

# Viscous through-flow model: ASTEC

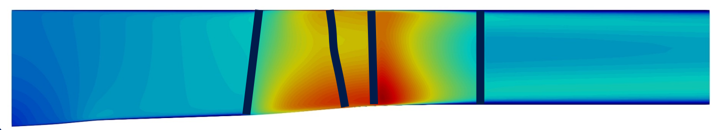
**Methodology:**

- Time-marching
- Non-intrusive

Initialization

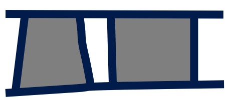
**elsA**

- Compressible, viscous flow
- Conservative variables: $\rho, \rho\boldsymbol{V}, \rho E$
- Turbulence model
- Axisymmetric source terms



**ASTEC**

- Python interface
- Computation:
  - Blade forces
  - Blockage factor terms



Iteration $t$
Convergence?

No

yes

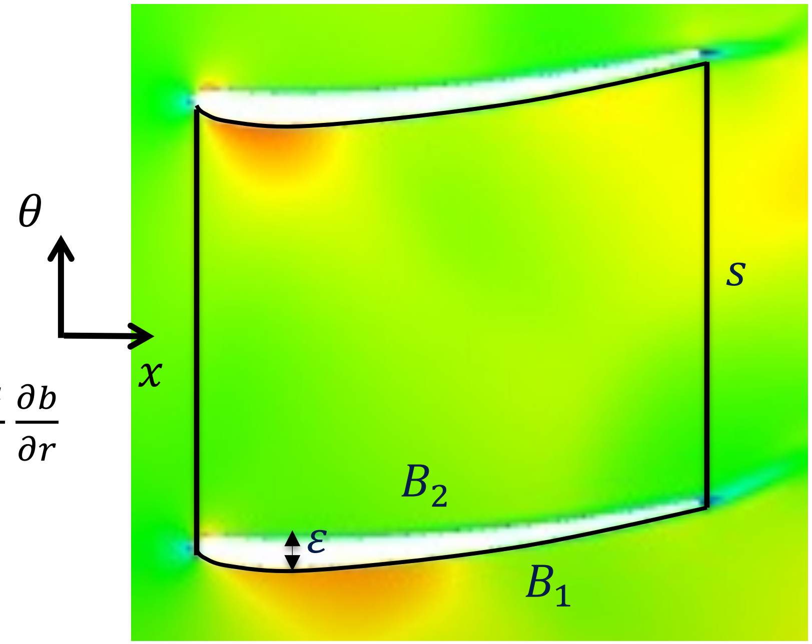
Outputs

# ASTEC: Inviscid blade force

Contributions: $\left\{\begin{array}{l}\textbf{Blade blockage} \\ \text{Deflection force } \overrightarrow{f_b}\end{array}\right.$

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

$$\boldsymbol{S}_{bi1} = \begin{bmatrix} 0 \\ \dfrac{p_{S1}+p_{S2}}{2b}\dfrac{\partial b}{\partial x} \\ \dfrac{p_{S1}+p_{S2}}{2b}\dfrac{\partial b}{\partial r} \\ 0 \\ 0 \end{bmatrix} \Rightarrow \boldsymbol{S}_{bi1} = \begin{bmatrix} 0 \\ \dfrac{p}{b}\dfrac{\partial b}{\partial x} \\ \dfrac{p}{b}\dfrac{\partial b}{\partial r} \\ 0 \\ 0 \end{bmatrix} - \frac{F}{b}\frac{\partial b}{\partial x} - \frac{G}{b}\frac{\partial b}{\partial r}$$

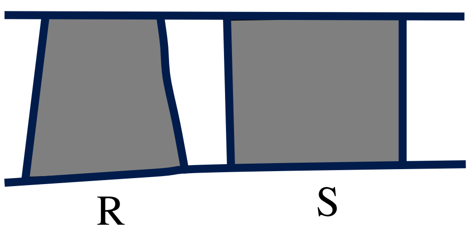


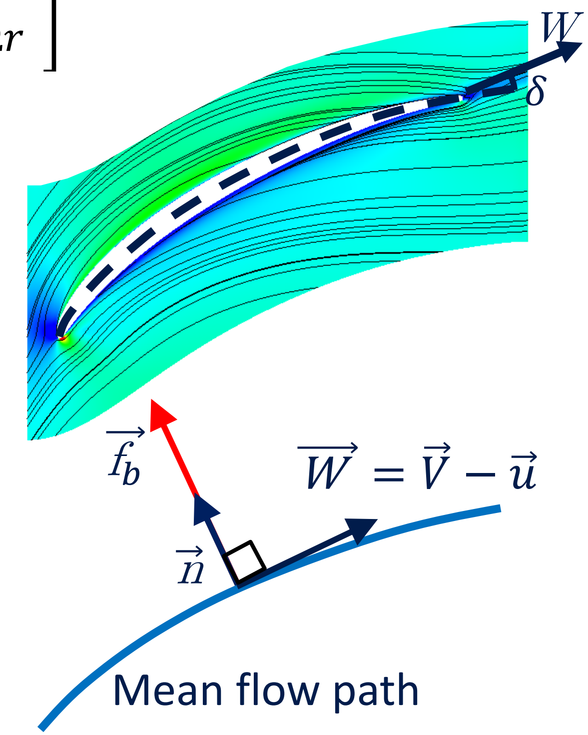

$$b = 1 - \frac{\varepsilon(x)}{s}$$

# ASTEC: inviscid blade force

Contributions: $\left\{ \begin{array}{l} \text{Blade blockage} \\ \textbf{Deflection force } \overrightarrow{f_b} \end{array} \right.$

$$\boldsymbol{S}_{bi2} = \frac{N}{2\pi b} \begin{bmatrix} 0 \\ -[p]_{S1}^{S2} \left.\frac{\partial\theta}{\partial x}\right|_{cl} \\ -[p]_{S1}^{S2} \left.\frac{\partial\theta}{\partial r}\right|_{cl} \\ \left[\frac{p}{r}\right]_{S1}^{S2} \\ -\left[\frac{p}{r}\right]_{S1}^{S2} \Omega r \end{bmatrix} \Rightarrow \boldsymbol{S}_{bi2} = \begin{bmatrix} 0 \\ f_{bx} \\ f_{br} \\ f_{b\theta} \\ f_{b\theta}\Omega r \end{bmatrix}$$




- Flow slips on the mean flow path (camber line + deviation angle $\delta$)

- No entropy generation

- Iterative procedure:

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

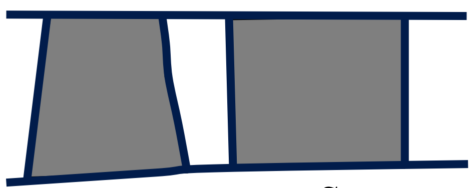
[Simon 2007]

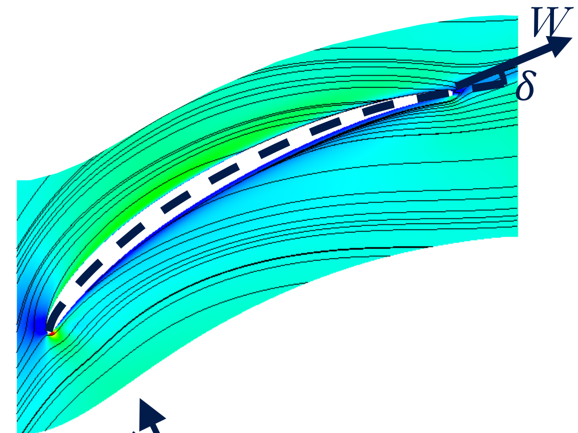
$u$ : shaft rotation velocity
$V$: velocity
$W$: velocity in the relative frame
$\Omega$ : shaft angular velocity

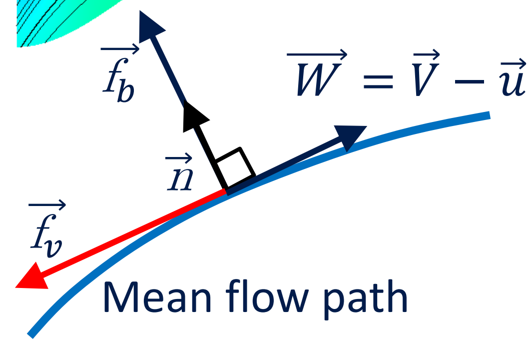
# ASTEC: viscous blade force

- Distributed force $\overrightarrow{f_v}$

$$\boldsymbol{S}_{bv} = \frac{N}{2\pi b}\begin{bmatrix} 0 \\ \left[\tau_{xj}\frac{\partial\theta}{\partial j}\right]_{S1}^{S2} \\ \left[\tau_{rj}\frac{\partial\theta}{\partial j}\right]_{S1}^{S2} \\ \left[\tau_{\theta j}\frac{\partial\theta}{\partial j}\right]_{S1}^{S2} \\ \left[\tau_{\theta j}\frac{\partial\theta}{\partial j}\right]_{S1}^{S2}\Omega r - \left[q_j\frac{\partial\theta}{\partial j}\right]_{S1}^{S2} \end{bmatrix} \Rightarrow \boldsymbol{S}_{bv} = \begin{bmatrix} 0 \\ f_{vx} \\ f_{vr} \\ f_{v\theta} \\ f_{v\theta}\Omega r \end{bmatrix}$$




- Entropy $s$ generated:

Loss coefficient

$= f(\omega)$

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

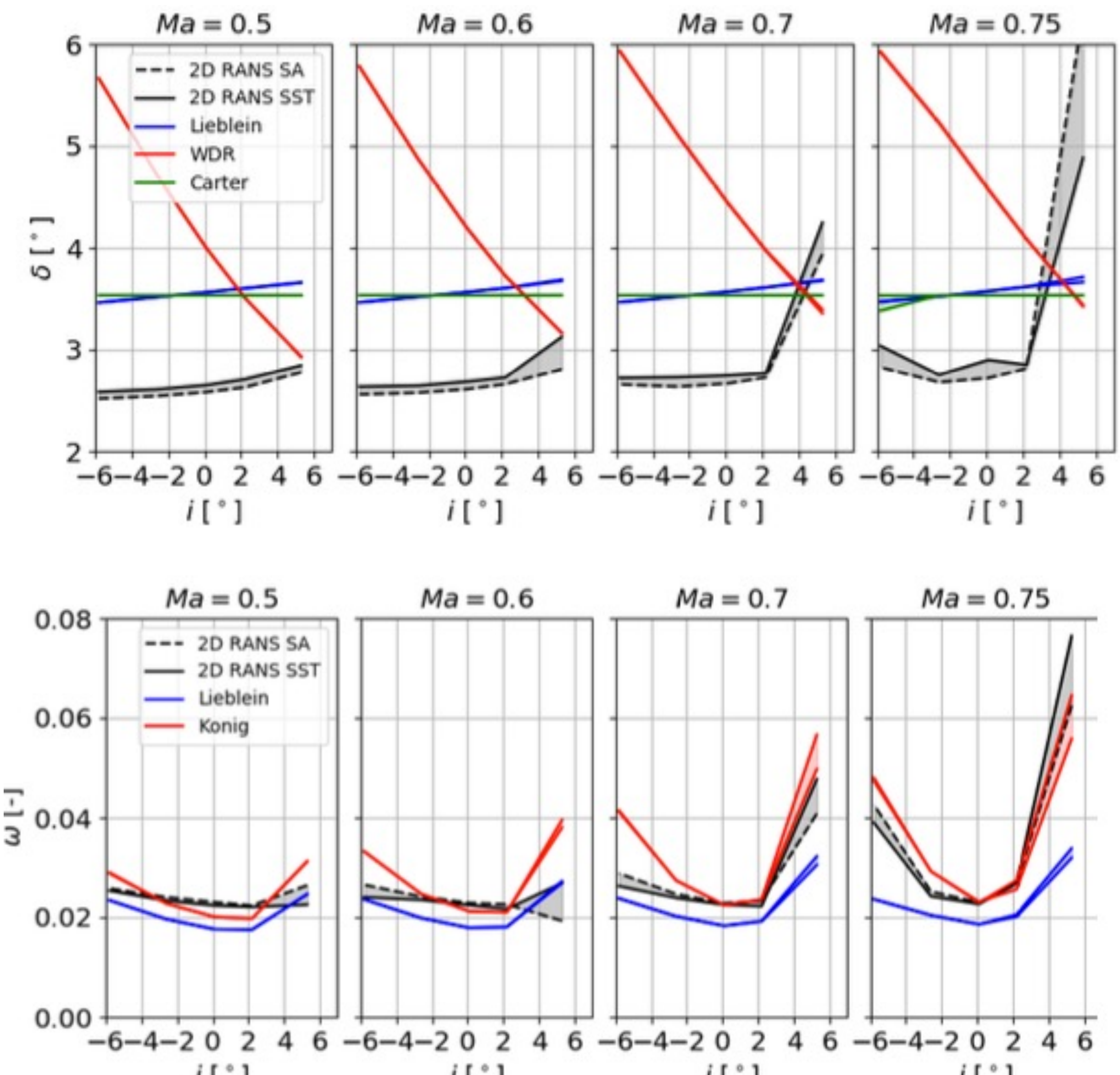
density temperature

[Hirsch 1988]

✓ Euler equations

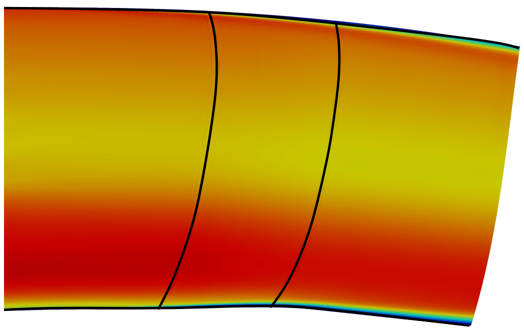
~ N-S equations

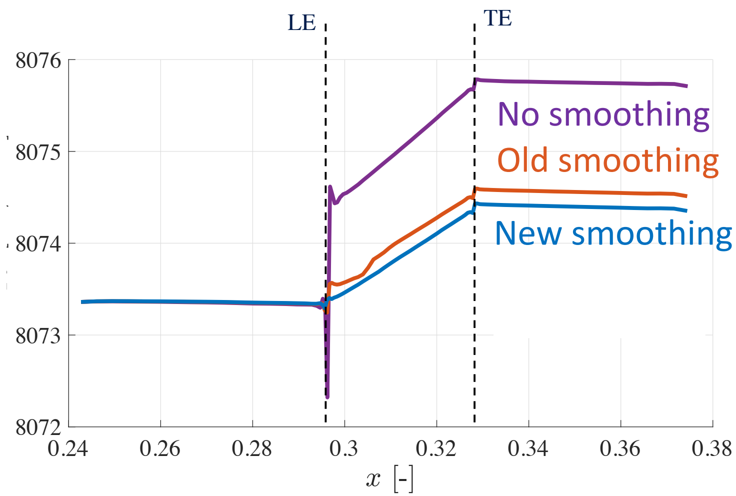
# Cascade computation (Bart Ruis)



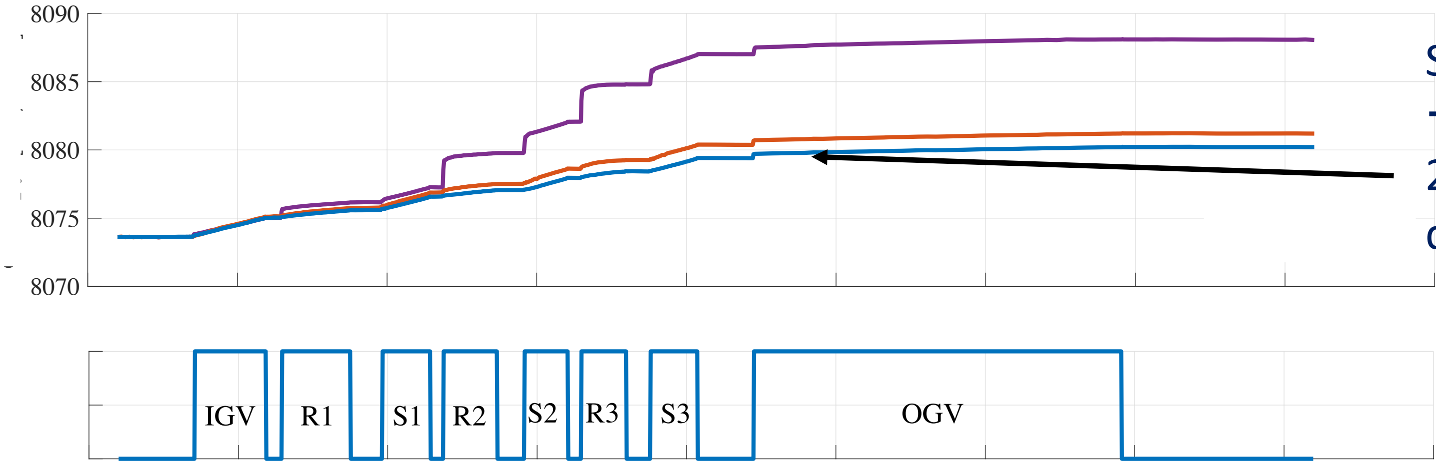
# ASTEC: Mesh & incidence correction

Implementation of **linear** smoothing






New smoothing takes into account the deviation angle from correlations




Small peak
→ improvement:
2nd order/ hyperbolic distribution