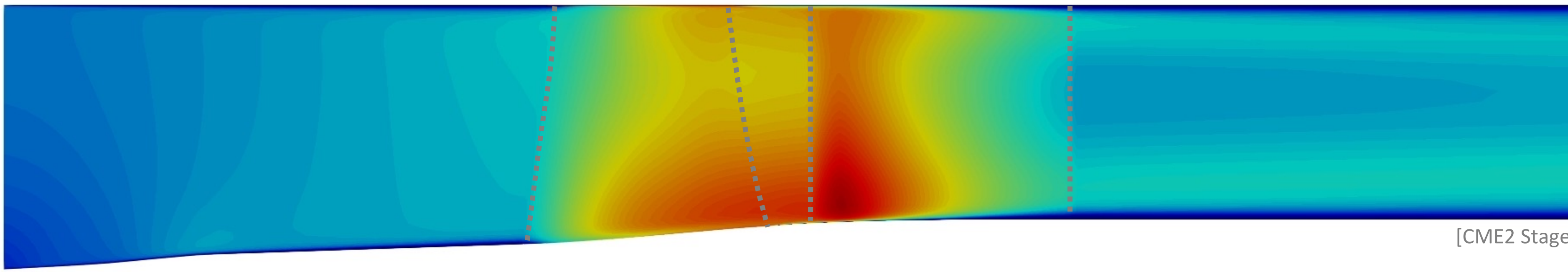
Quantification of geometric variability effects through a viscous through-flow model: sensitivity analysis of the manufacturing tolerance effects on performance of modern axial-flow compressor blades



[CME2 Stage]

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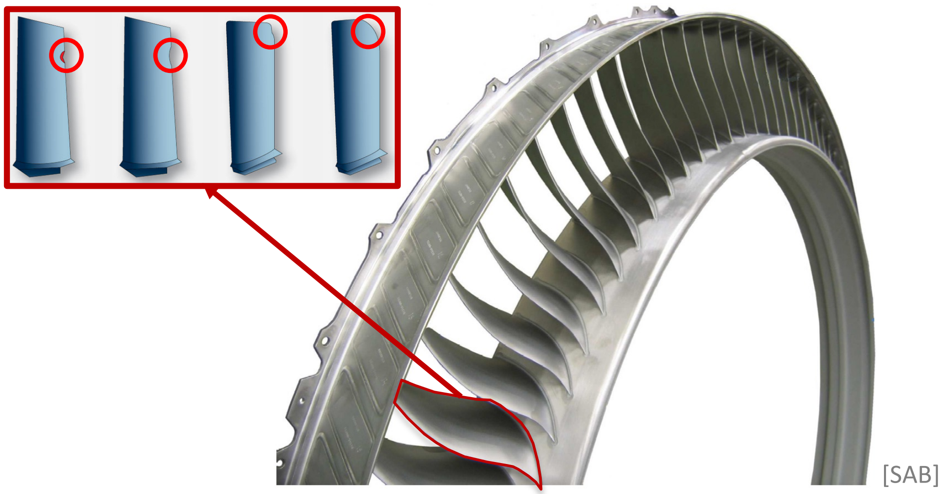
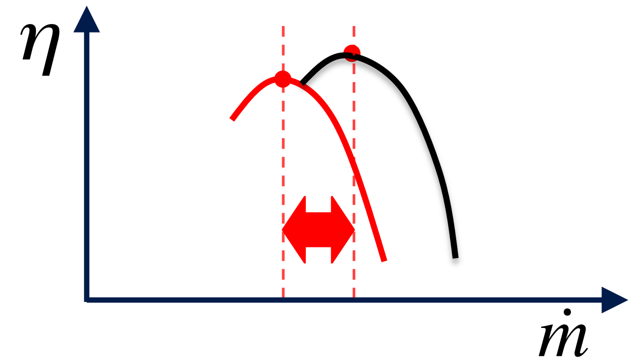
ASME Turbo Expo 2023

Context

Geometric variability of low-pressure compressor blades



Performance variation



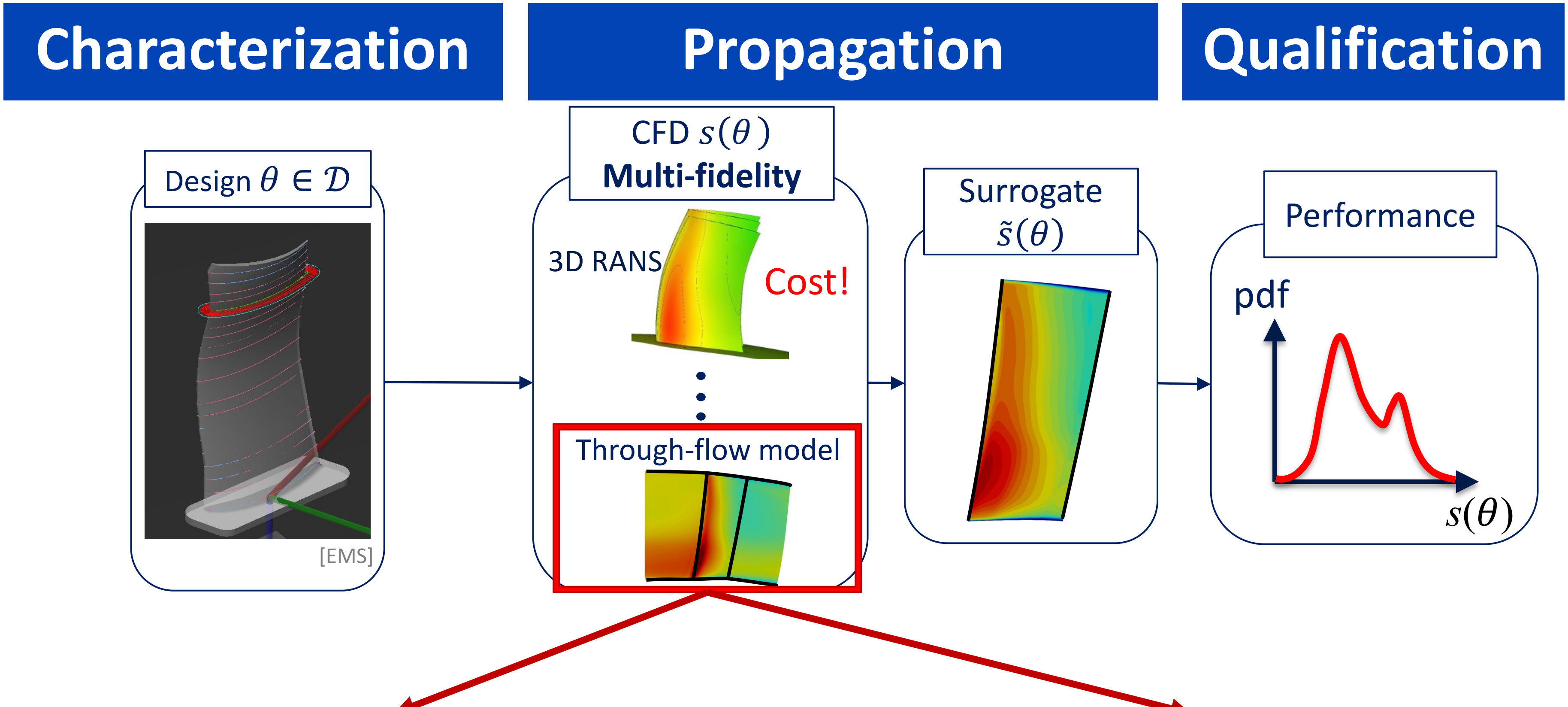
Manufacturing tolerances?

- Need of rigorous/robust definition
- Linked to manufacturing process
- Simplify the treatment of poorly made parts

Trade-off

Cost ⇔ performance

Methodology & objectives



Able to predict performance?

Through-flow model validation

- Consistency
- Choice of model correlations

Able to capture variability effects?

Geometrical variability

- Sensitivity analysis
- (Uncertainty quantification)

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

Model Assessment

Application to an axial LP compressor

3

Geometric variability

[SAB]

Outline

1

Viscous through-flow model

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

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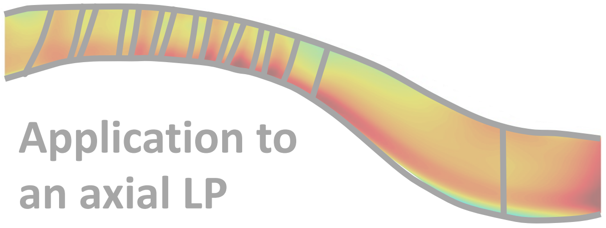
Model Assessment



Application to an axial LP compressor

3

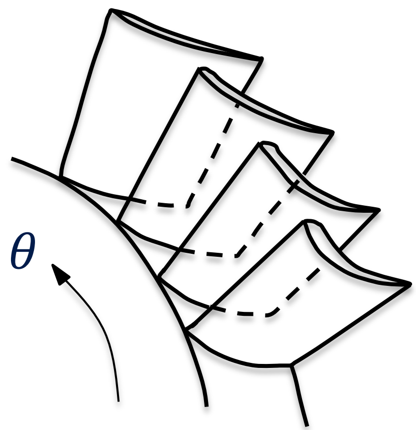
Geometric variability

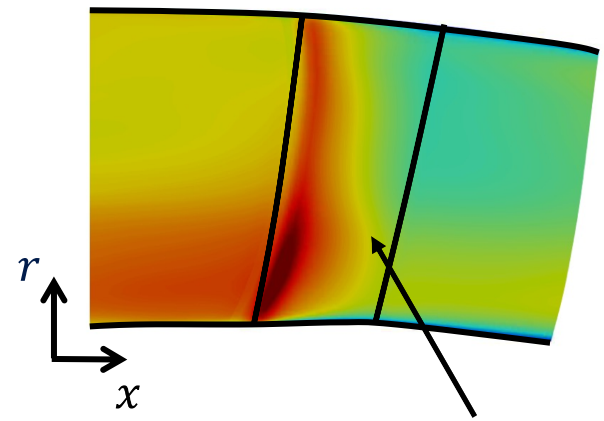
[SAB]

Through-flow model

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

Unclosed!





Implicit presence of the blades

- Azimuthal/pitchwise averaging approach
- Axisymmetric steady flow (meridional plane)
- Empirical correlations
- Low computational cost $\mathcal{O}$(min)

Through-flow formulation

$$\mathrm{D}_t \bar{\boldsymbol{U}}(r,x) = \bar{\boldsymbol{G}}(U,r,x)$$

Governing equations

- Underlying assumptions (NSE, Euler, SLC, …)?
- Consistency?

Closure models

- Exhaustive?
- Assumptions?
- Correlations?

Choices influence **level of empiricism** and determine **error sources**

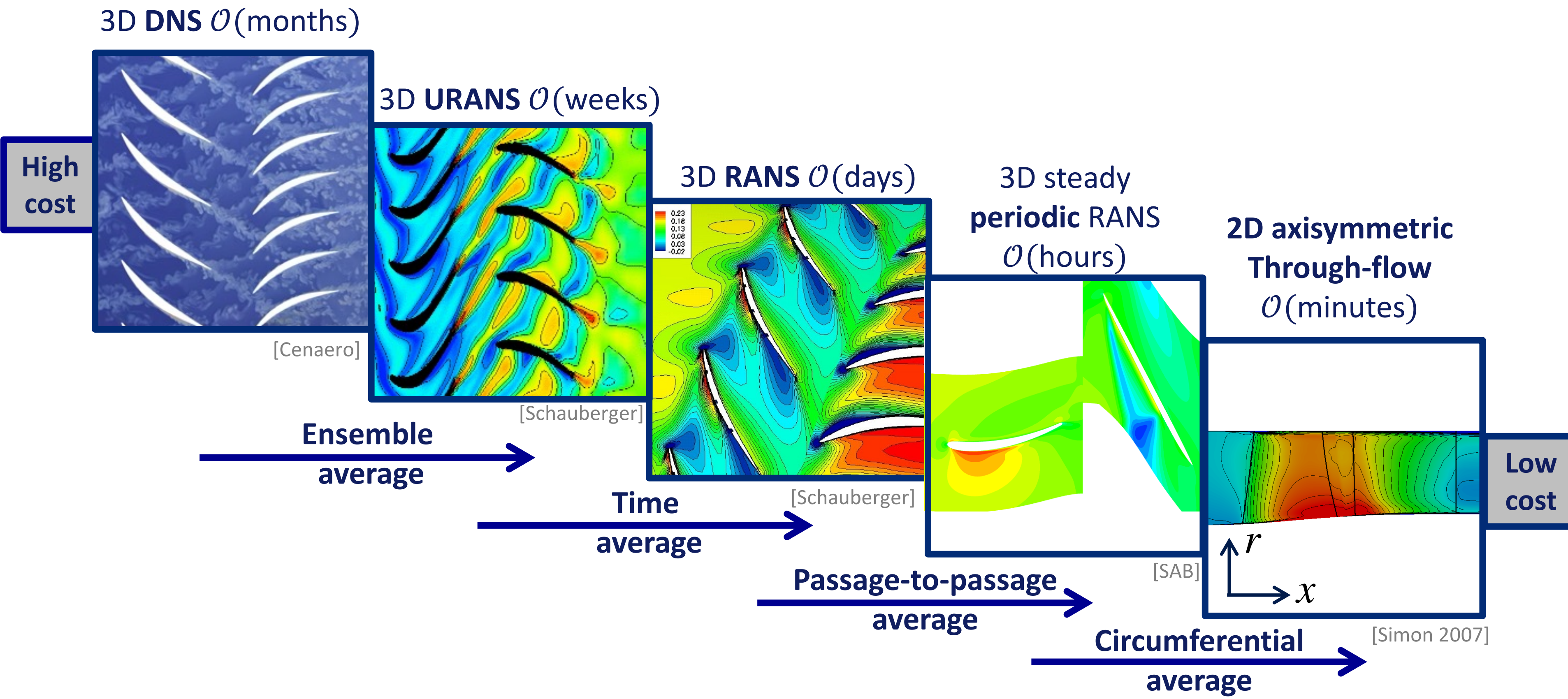
→ **characterize error** in a **rigourous and exhaustive** way

Adamczyck’s cascade

$$\mathrm{D}_t\bar{\boldsymbol{U}}(r, x) = \bar{\boldsymbol{G}}(U, r, x)$$

Unclosed!

- **Exact mathematical** formulation of source terms
- **NSE-based equations**



Adamczyk's cascade: unclosed terms

$$\mathrm{D}_t\bar{\boldsymbol{U}}(r,x) = \boxed{\bar{\boldsymbol{G}}(U,r,x)}$$

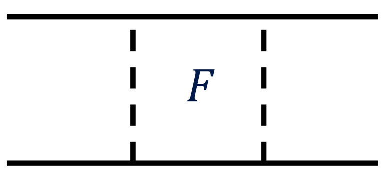
Unclosed terms:

$\overline{\rho V_i' V_i'}$

Non-linear equations

- τ_{reys} ➢ Reynolds
- τ_{uns} ➢ Unsteady
- τ_{ape} ➢ Aperiodic
- τ_{circ} ➢ Circumferential

} **Stresses**



- B_{i} ➢ inviscid
- B_{v} ➢ Viscous

} **Forces**

Empiricism/approximation through model

Relative importance of source terms

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

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

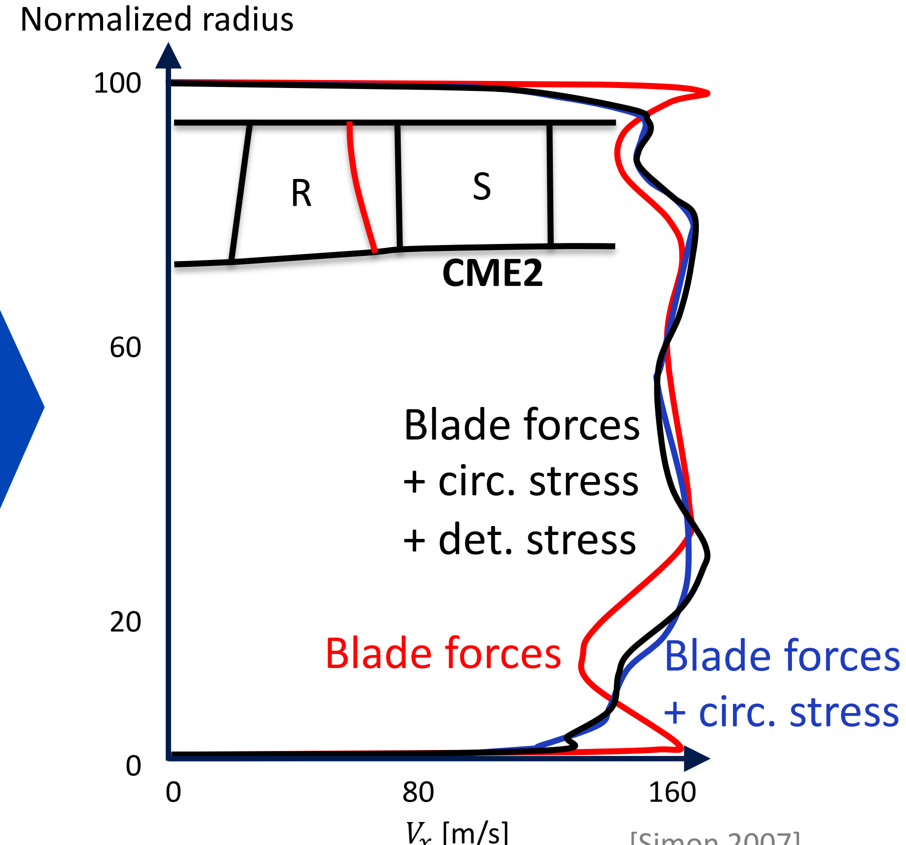
- Reynolds stress
- Inviscid blade force
- Viscous blade force

Major terms

- Circumferential stress
- Unsteady stress

Lower importance

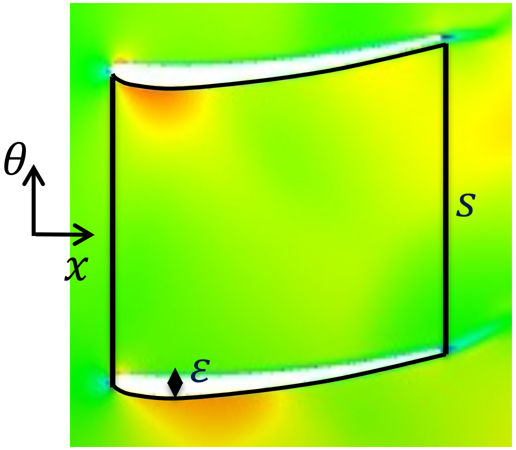
- Aperiodic stress
  → **Generally neglected**



[Simon 2007]

ASTEC: a viscous through-flow model

Circumferential averaged Navier-Stokes equations:



Conservative variables

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

Blockage factor

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

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

Non-intrusive formulation for CFD solver:

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

Blockage factor terms (known)

Viscous TF model: closure models

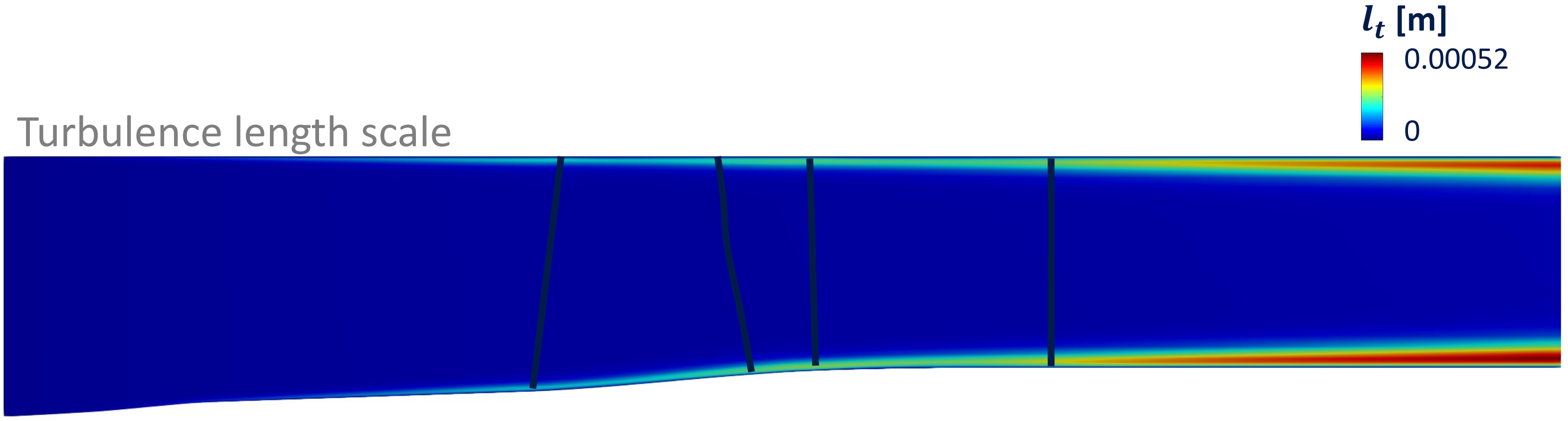
Circumferential averaged Navier-Stokes equations:

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

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

Reynolds stress τ_{reys}: standard **turbulence model** ($k - l$ Smith)

Turbulence length scale



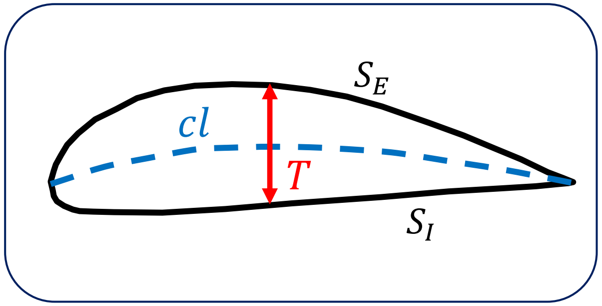
Viscous TF model: closure models

Circumferential averaged Navier-Stokes equations:

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

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

Inviscid blade force decomposition B_i :



B_i

Blade blockage contribution: $B_{\mathrm{i}1} = f\left(\frac{P_{S_E} + P_{S_I}}{2}\right)$

Unknown!

Deflection force: $B_{\mathrm{i}2} = f\left(P_{S_E}, P_{S_I}\right)$

Closure models: blade forces

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

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

Blade blockage B_{i1}

$$B_{\mathrm{i1}} = B_{\mathrm{i1}}\left(\frac{P_{S_E} + P_{S_I}}{2}\right)$$

Averaged pressure

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

Blockage factor: b

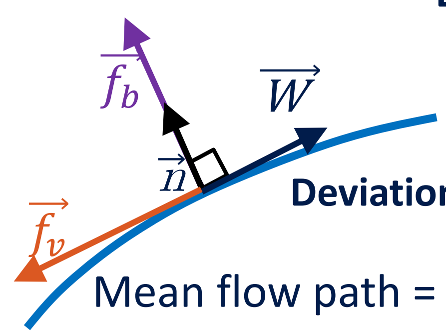
Deflection B_{i2} and viscous force B_{v}

$$B_{\mathrm{i2}} = B_{\mathrm{i2}}\left(P_{S_E}, P_{S_I}\right) \qquad B_{\mathrm{v}} = B_{\mathrm{v}}\left(\tau_{S_E}, \tau_{S_I}\right)$$

Distributed forces:

$$\frac{\partial f_b}{\partial \tau} = -C\left(\vec{W} \cdot \vec{n}\right) \qquad f_v = \rho T \frac{W_m \partial_m s}{W} = f(\boldsymbol{\omega})$$

Loss coefficient



Correlations!

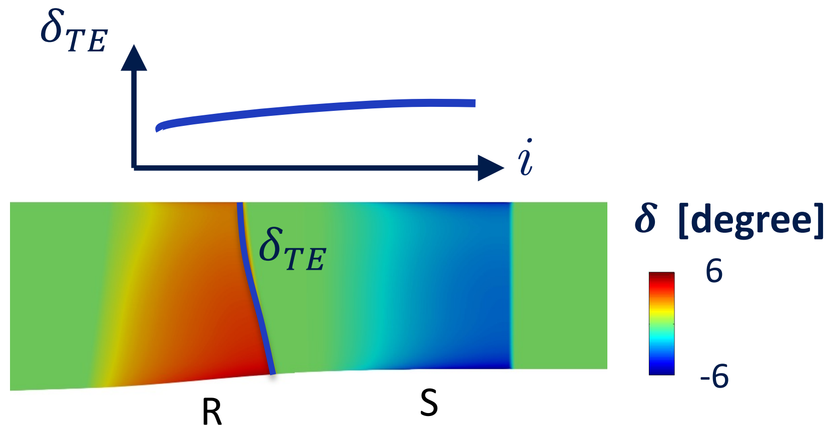
Deviation angle

Mean flow path = $f(cl, \boldsymbol{\delta})$

Correlations for δ and ω

Deviation angle δ → inviscid blade force

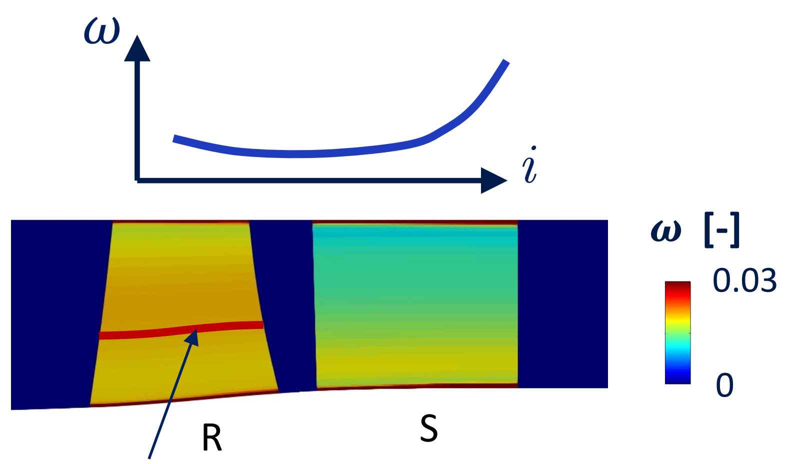
- δ_{TE} from cascade experiments (Lieblein)
- Linear variation with incidence around design conditions
- $\delta = \delta_{TE} \frac{\kappa_{LE} - \kappa}{\kappa_{LE} - \kappa_{TE}}$ ← Blade angle



Loss coefficient ω → viscous blade force

- From cascade experiments (Lieblein)

⚠ Profile loss only



Outline

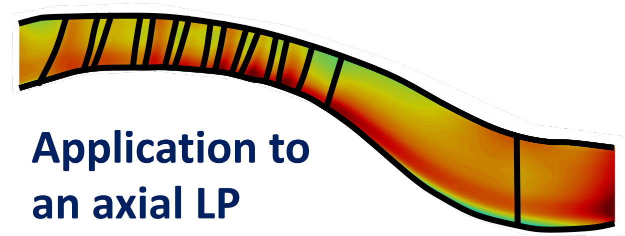
1

Viscous through-flow model

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

2

Model Assessment



Application to an axial LP compressor

3

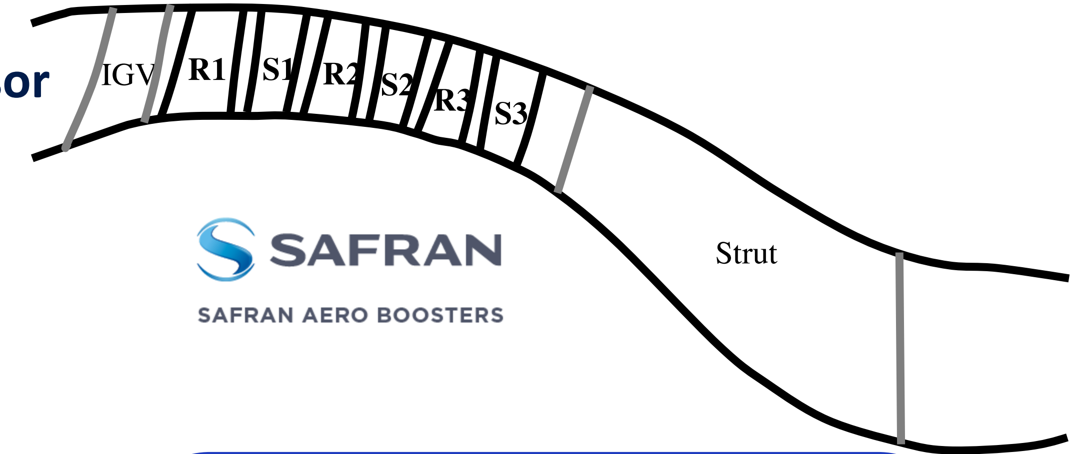
Geometric variability

[SAB]

Closure model assessment

- Quantify closure **model errors**
- Simulations fed with **exact** averaged distribution of $\boldsymbol{\delta_{TE}}, \boldsymbol{\omega}$

Test-case : low-pressure compressor



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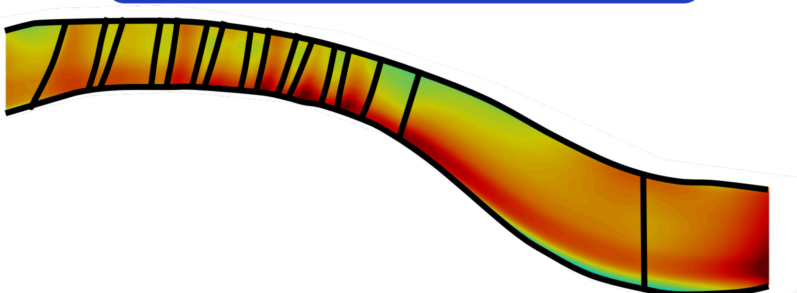
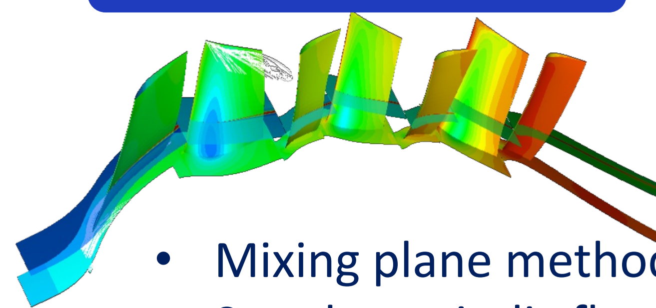
- Highly loaded
- High subsonic Mach number
- 3D modern blades

Through-flow (TF) simulations



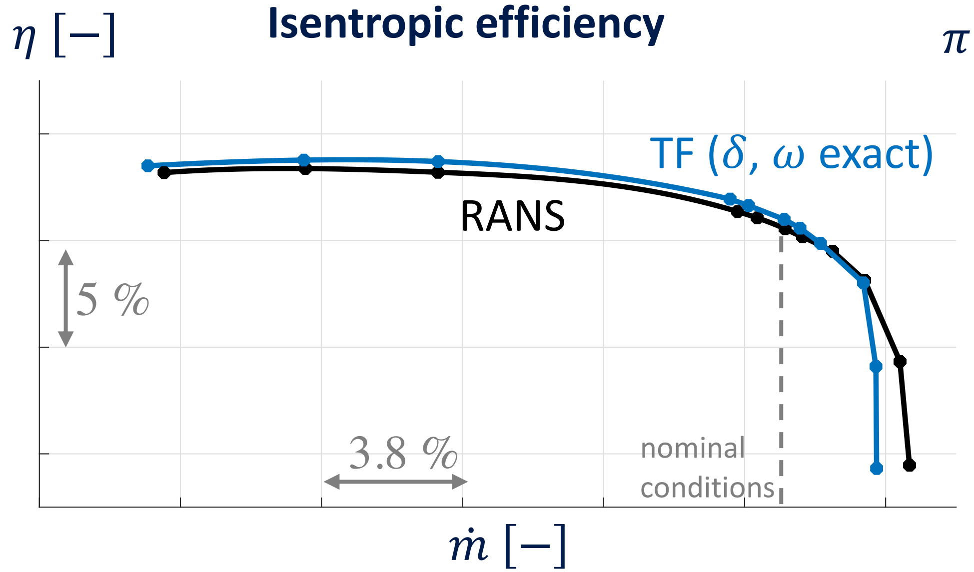
3D RANS simulations

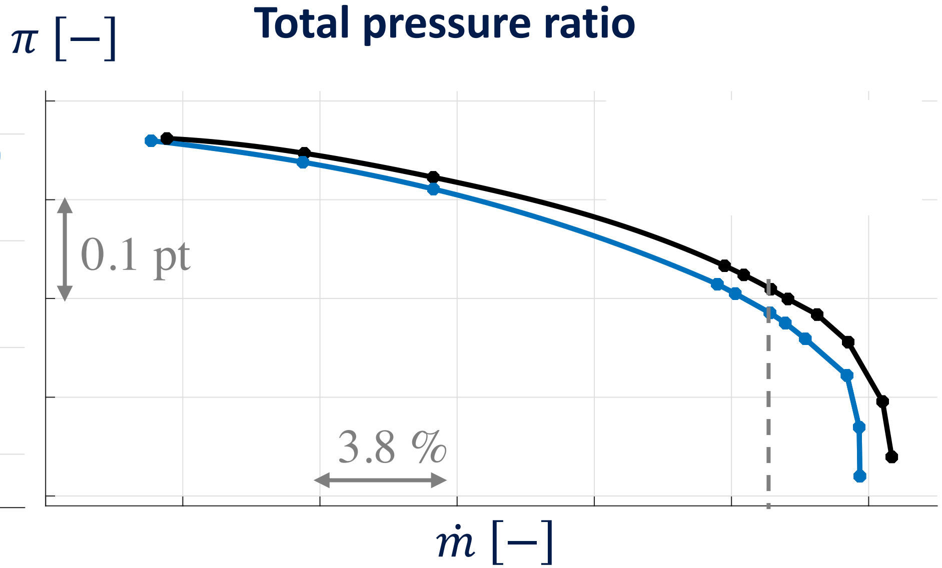


- Mixing plane method
- Steady, periodic flow

δ_{TE}, ω distributions

Closure model assessment





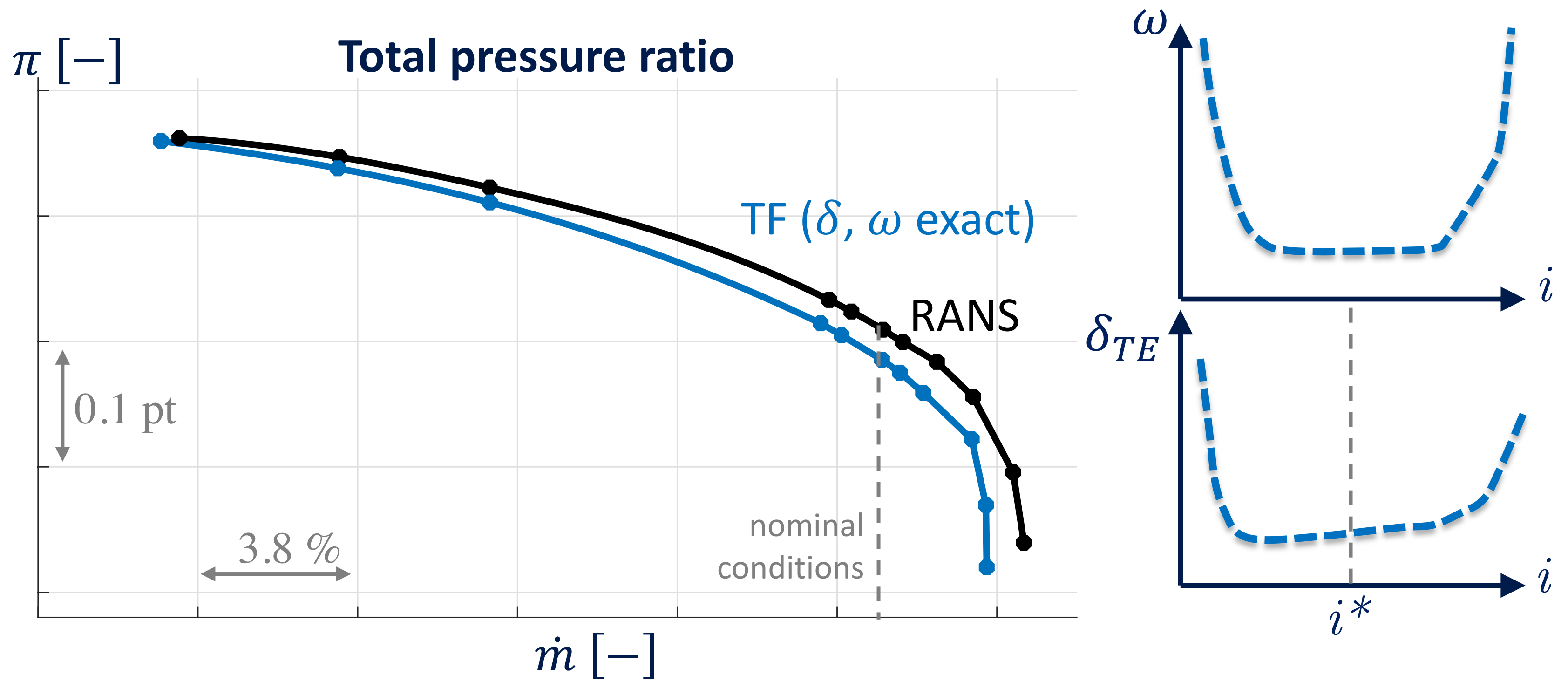
- Good prediction (low margin)
- 600 times faster
- Sources of errors: τ_{circ}, closure model form, δ_{TE} distribution, blockage assumption, turbulence model…

Model able to predict performance

But exact δ, ω unknown in practice…

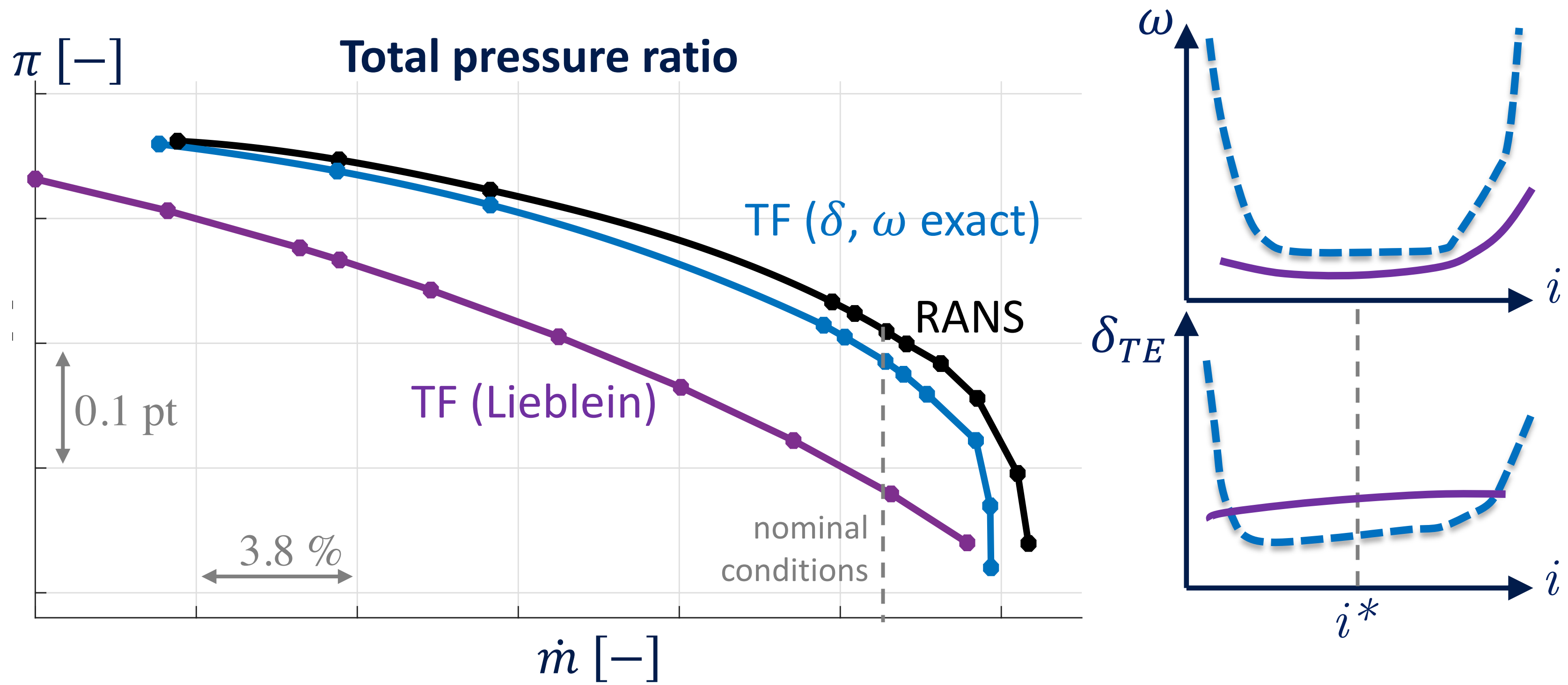
Correlations assessment

- Error quantification of **correlations** for $\boldsymbol{\delta}$, $\boldsymbol{\omega}$



Correlations assessment

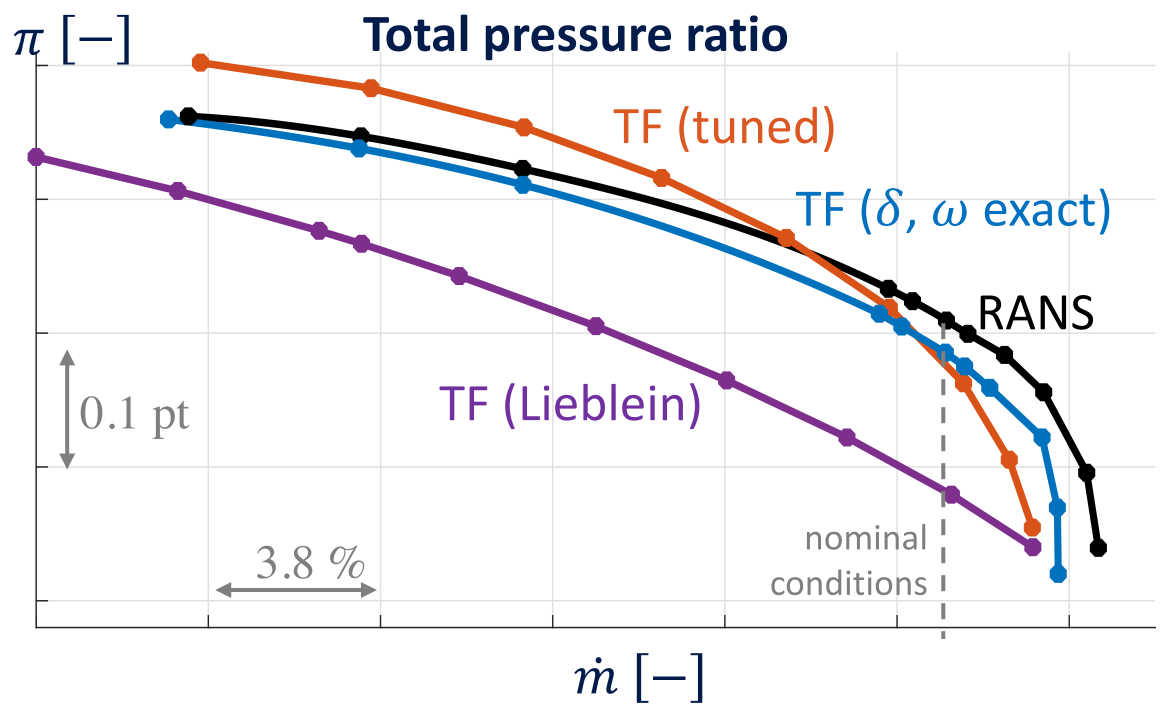
➢ Error quantification of **correlations** for $\boldsymbol{\delta}$, $\boldsymbol{\omega}$

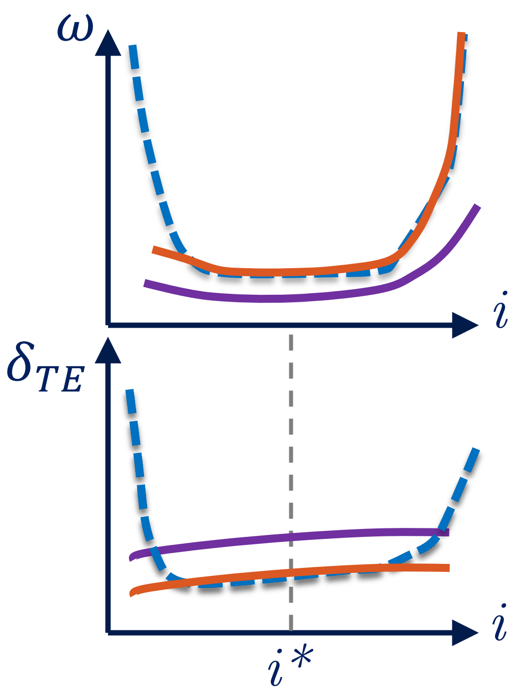


- Inaccurate when applied to the modern compressor

Correlations assessment

➢ Error quantification of **correlations** for $\boldsymbol{\delta}$**,** $\boldsymbol{\omega}$





- **Rotor** deviation angle **correction** → total pressure ratio improvement
- **Mach number effect** added to loss coefficient

Strong dependence of model prediction with respect to correlation accuracy

Outline

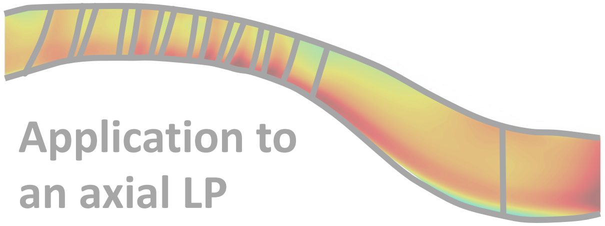
1

Viscous through-flow model

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

2

Model Assessment



Application to an axial LP compressor

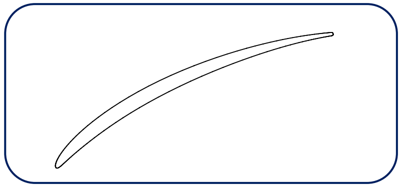
3

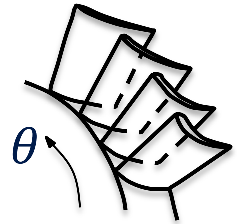
Geometric variability

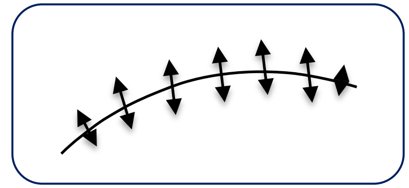
[SAB]

Geometry in through-flow model

$$D_t U(r, \theta, x, t) = G(U, r, \theta, x, t) \quad \xrightarrow{\theta\ -\text{averaging}} \quad D_t \bar{U}(r, \theta, x) = \bar{G}(U, r, \theta, x)$$



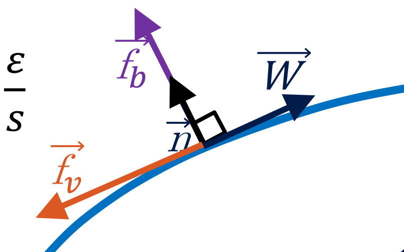




Camber line coordinates
&
Thickness distribution

Blade forces

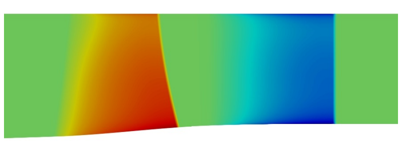
$$b = 1 - \frac{\varepsilon}{s}$$



Direct impact

Correlations

$$\delta_{TE}, \omega, i* = f\left(\begin{matrix}\text{geometry,}\\ \text{flow quantities}\end{matrix}\right)$$



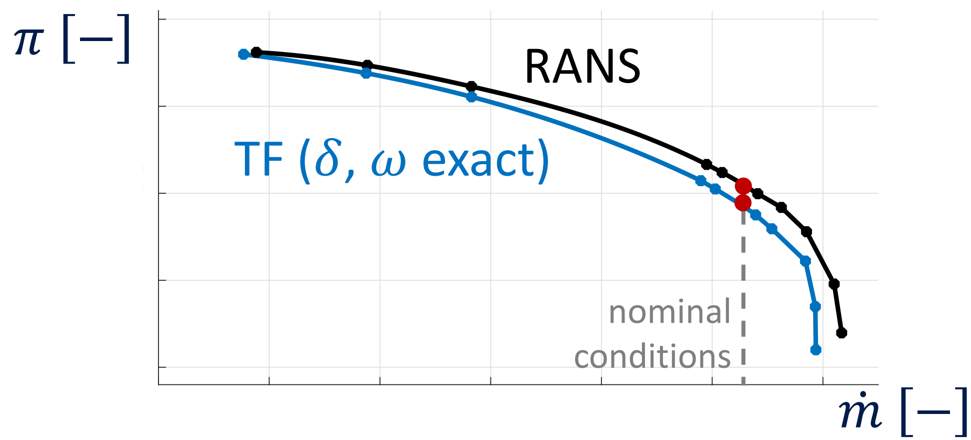
Indirect impact

Geometric variabilities

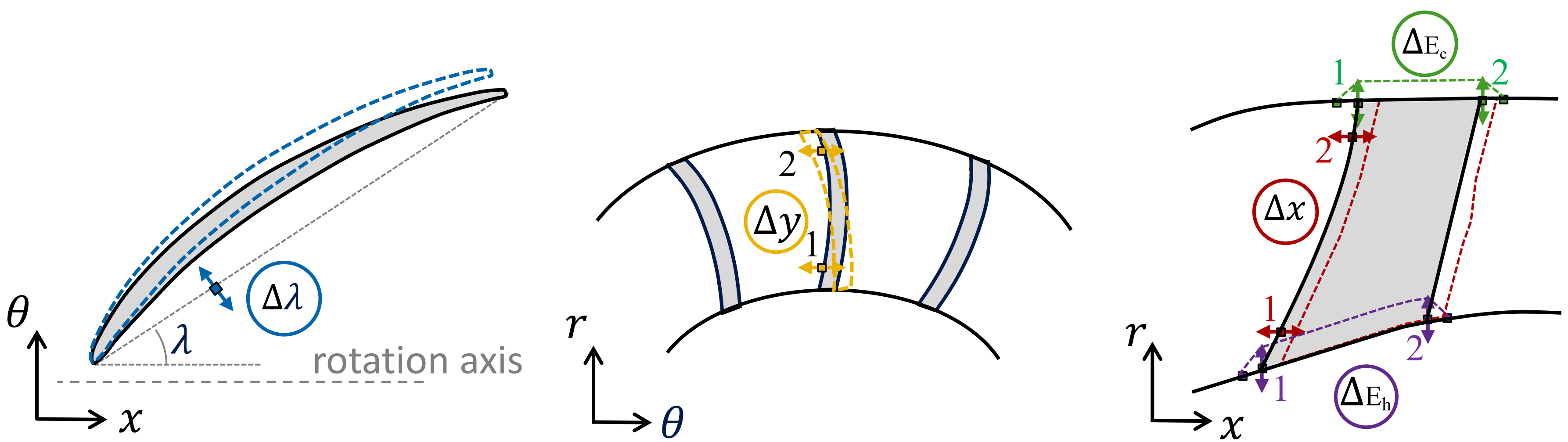
➢ Assess adequacy to predict **performance** variation due to **geometric variabilities**

Preliminary analysis

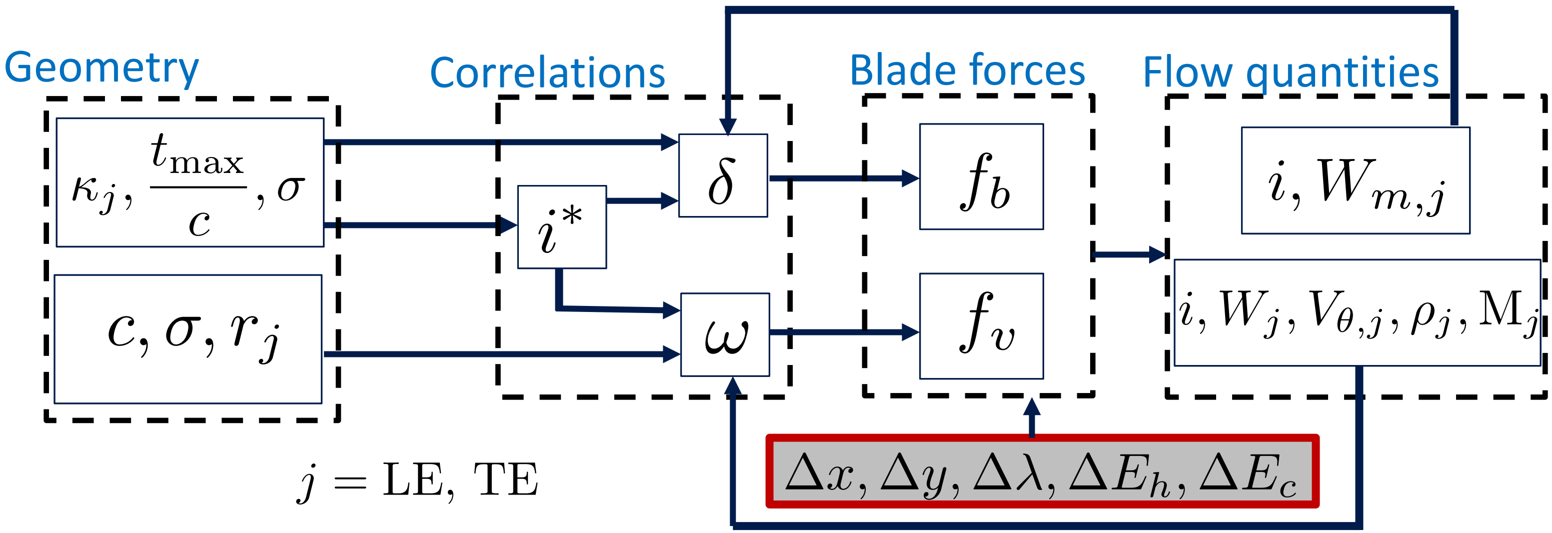
- @ nominal conditions
- Relative variations
- Stator blades



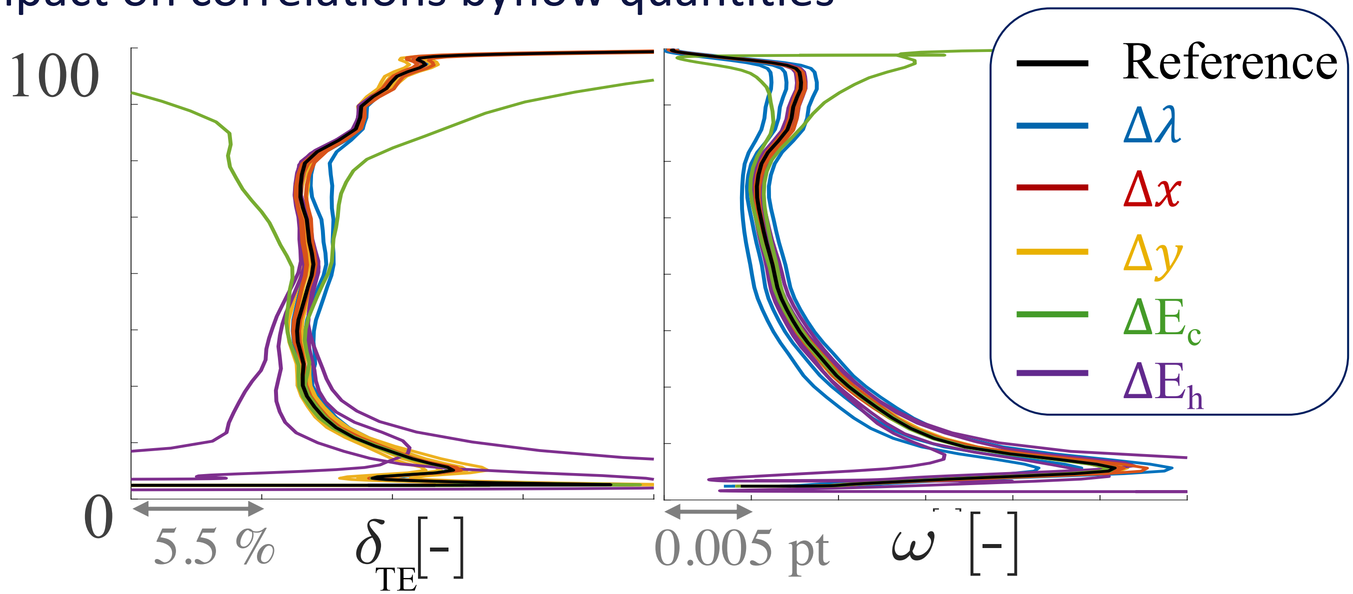
- 3D position of undeformed & endwalls deformation



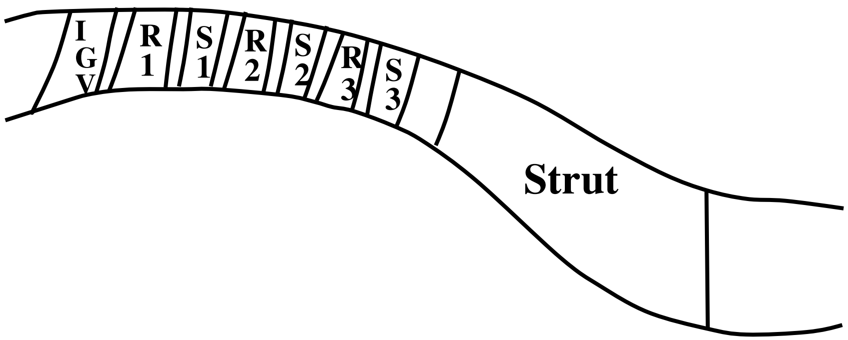
Geometry in through-flow model

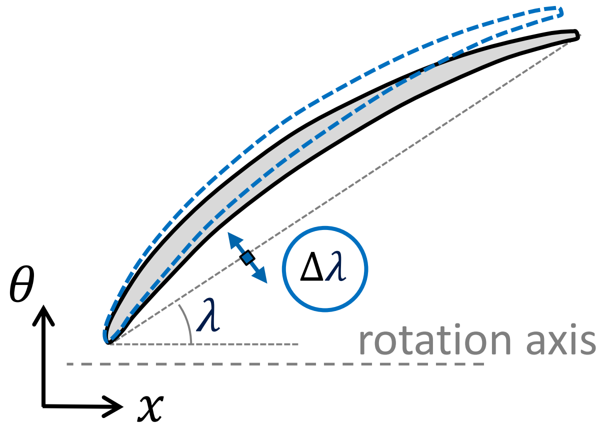


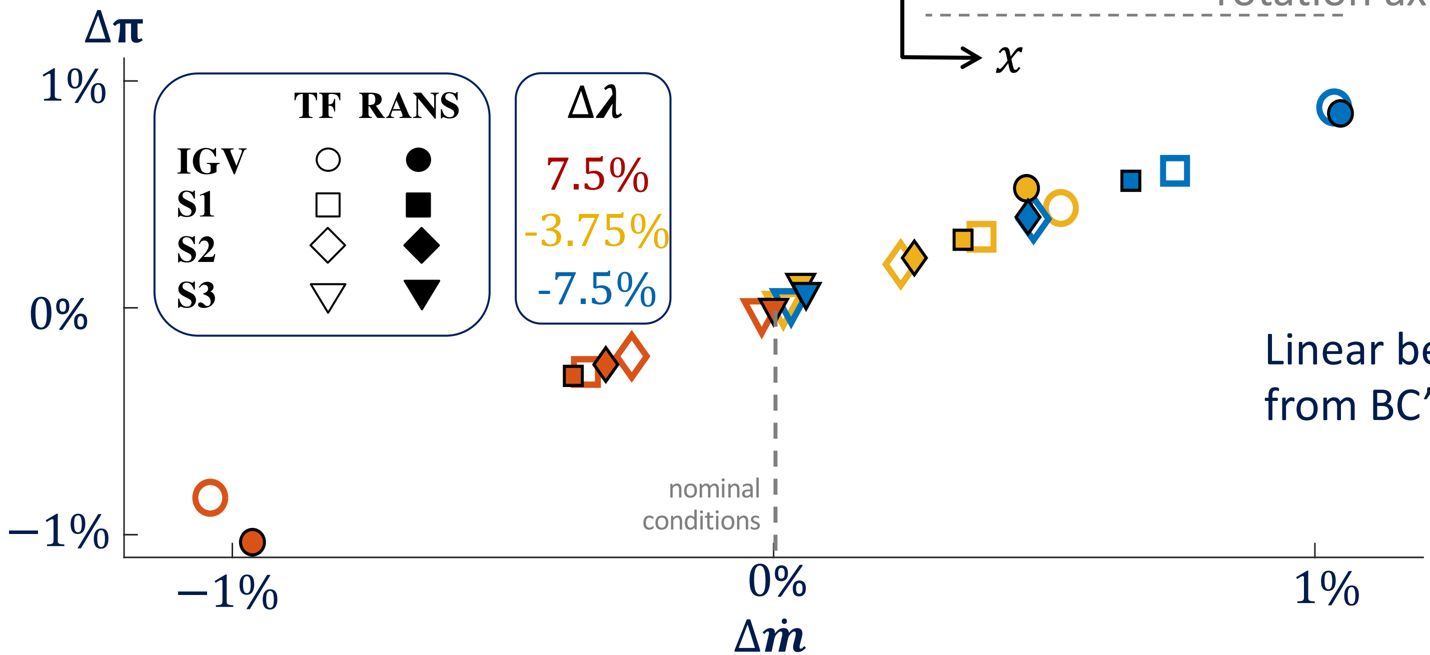
- Indirect impact on correlations byflow quantities



Geometric variabilities: stagger angle



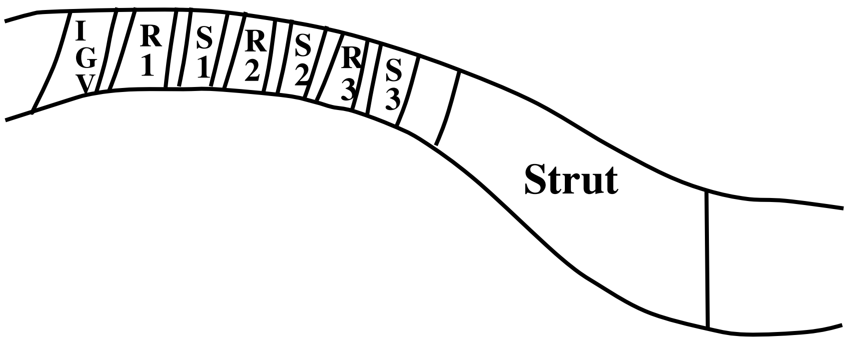


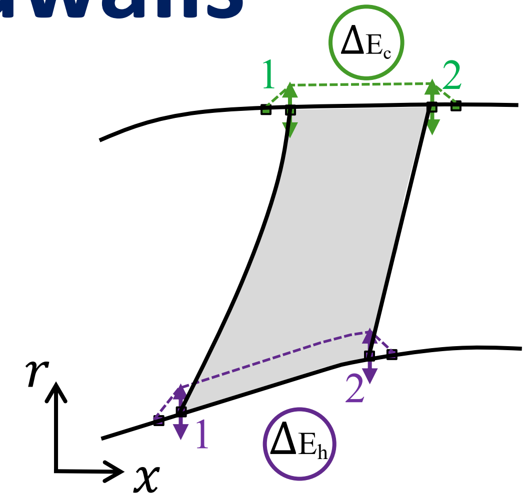


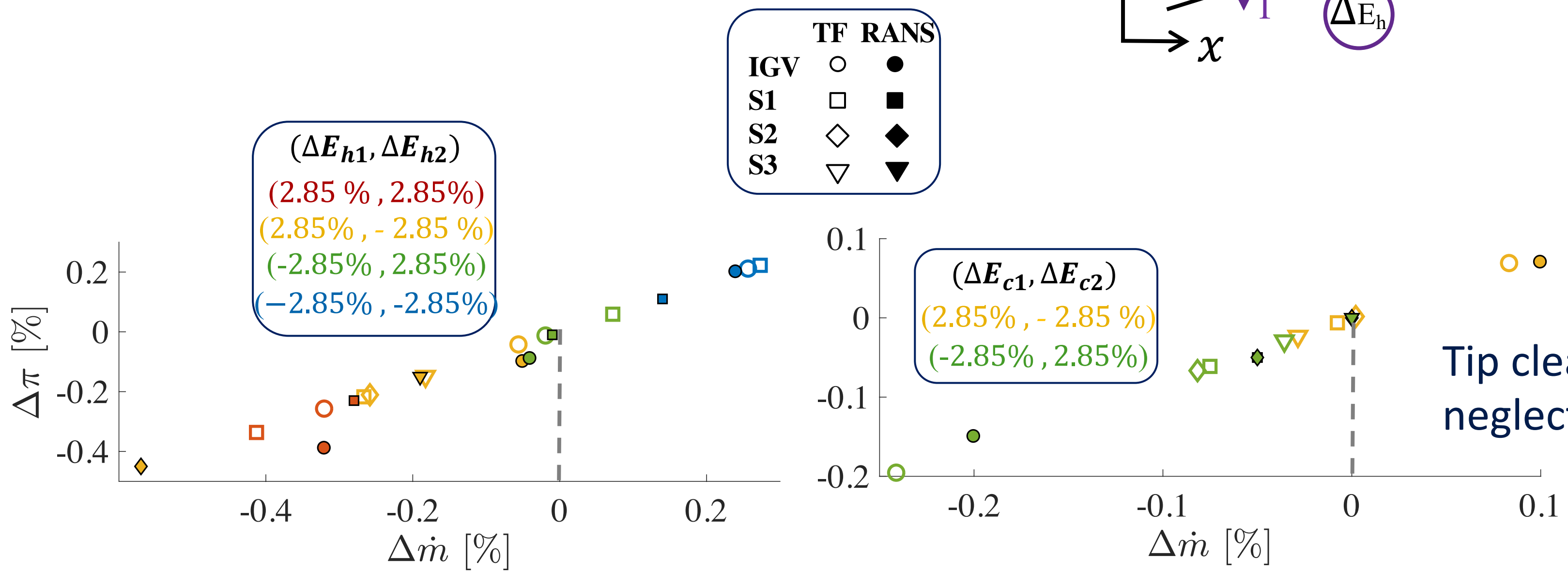
Linear behaviour from BC's

Model able to predict performance variation

Geometric variabilities: endwalls



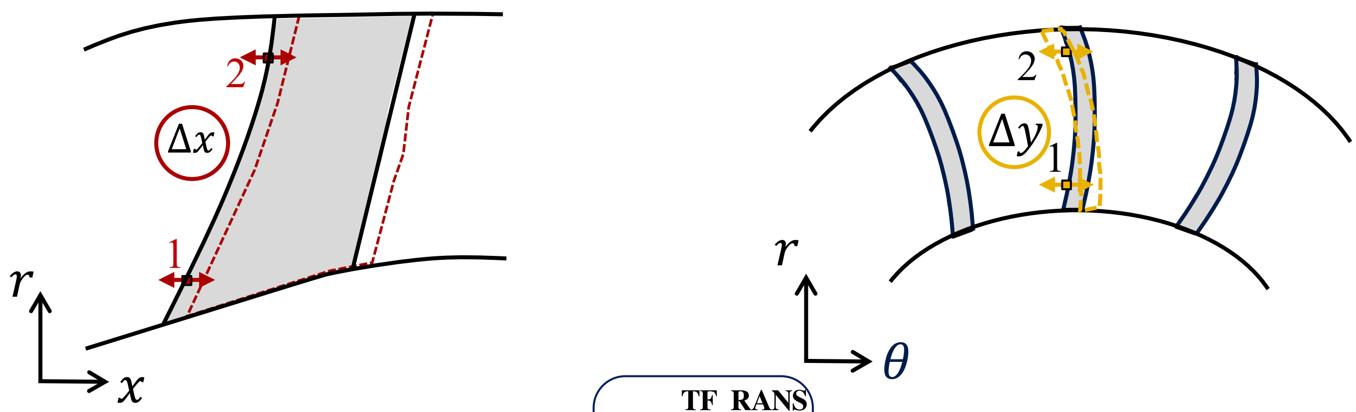


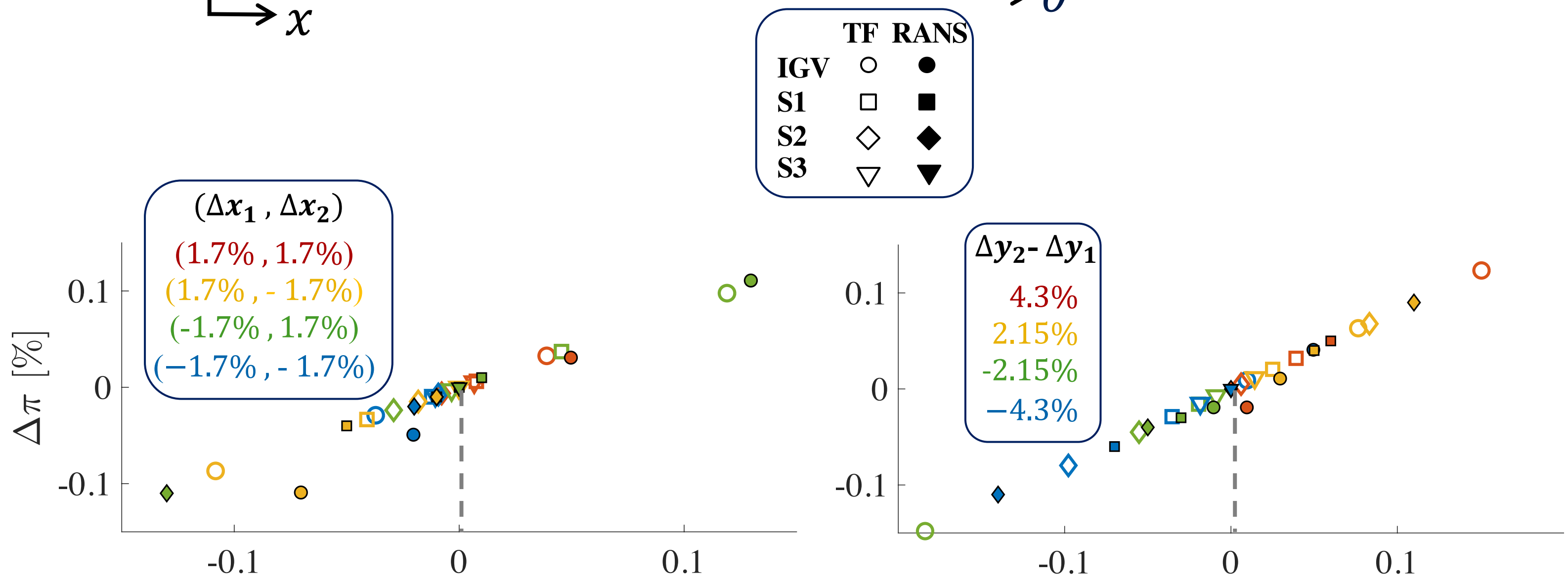


Tip clearance neglected

Model able to predict performance variation

Geometric variabilities: blade position





Model able to predict performance variation

Conclusion

Through- flow model

- **Reliable low-fidelity** method
- **Good prediction** of performance
- Strong **dependence** between performance prediction and **correlation accuracy**
- Promising approach to drastically **reduce CPU cost** compared to 3D RANS for multi-fidelity approach and UQ

Geometrical variability

- Global good agreement for **performance variation**
- **Promising first step** towards the use of TF modeling for geometric uncertainty quantification

Future work

- Correlation **improvement** @ high incidence
- Thorough analysis of **geometric variability propagation**
- **Strength and weakness** of the model

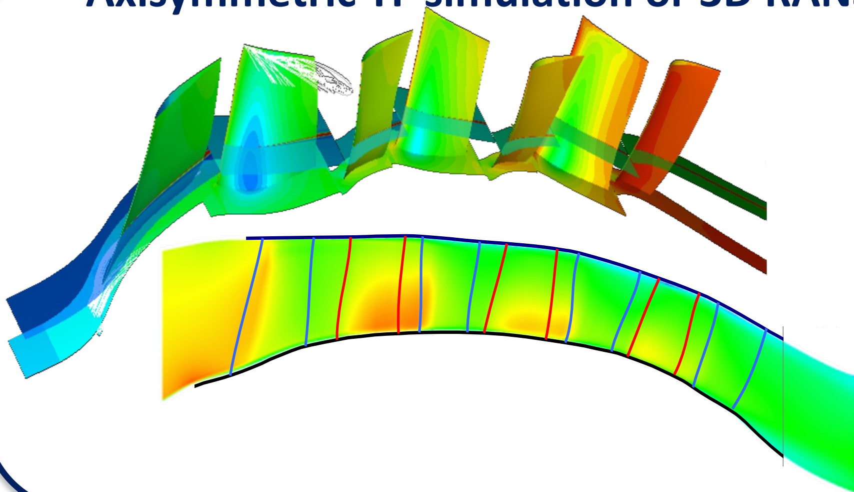
Acknowledgement

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

BACK-UP

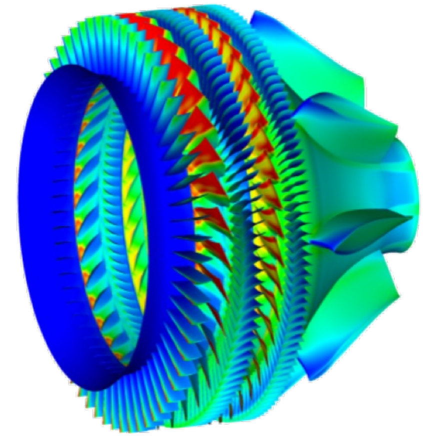
Relevance

Axisymmetric TF simulation or 3D RANS

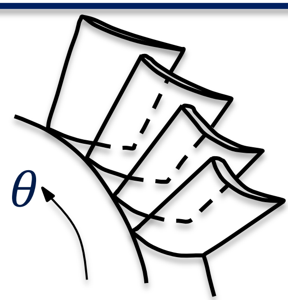


≠

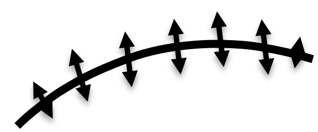
Mistuning



But

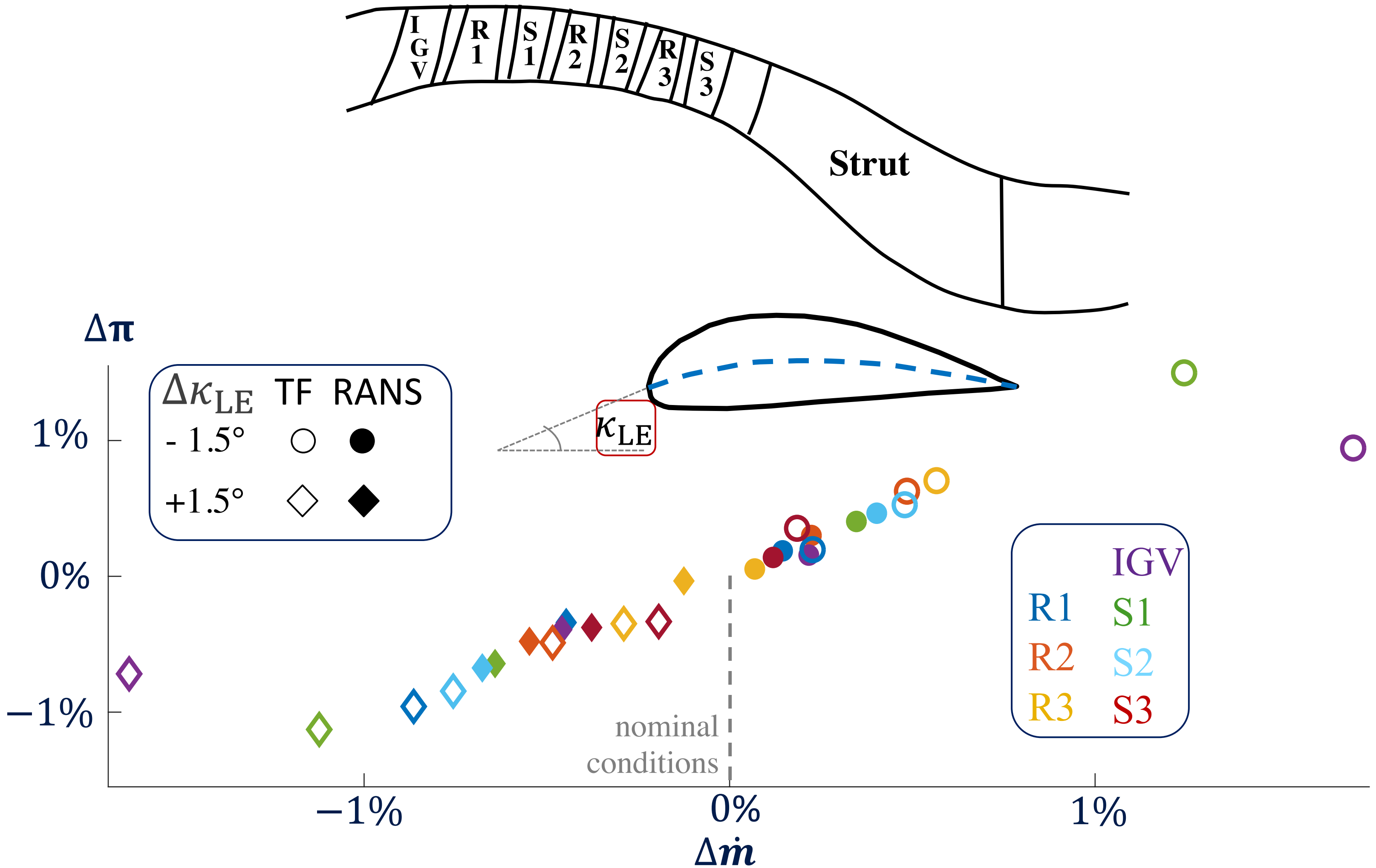


Averaged blade row



- Recurring patterns (tolerances, blade production, …)
- Low deformation distribution

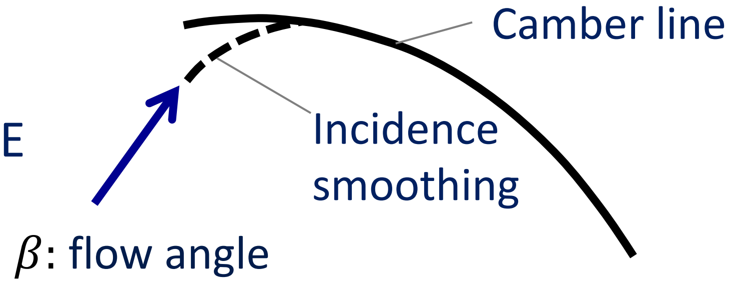
Applications: blade angle variability

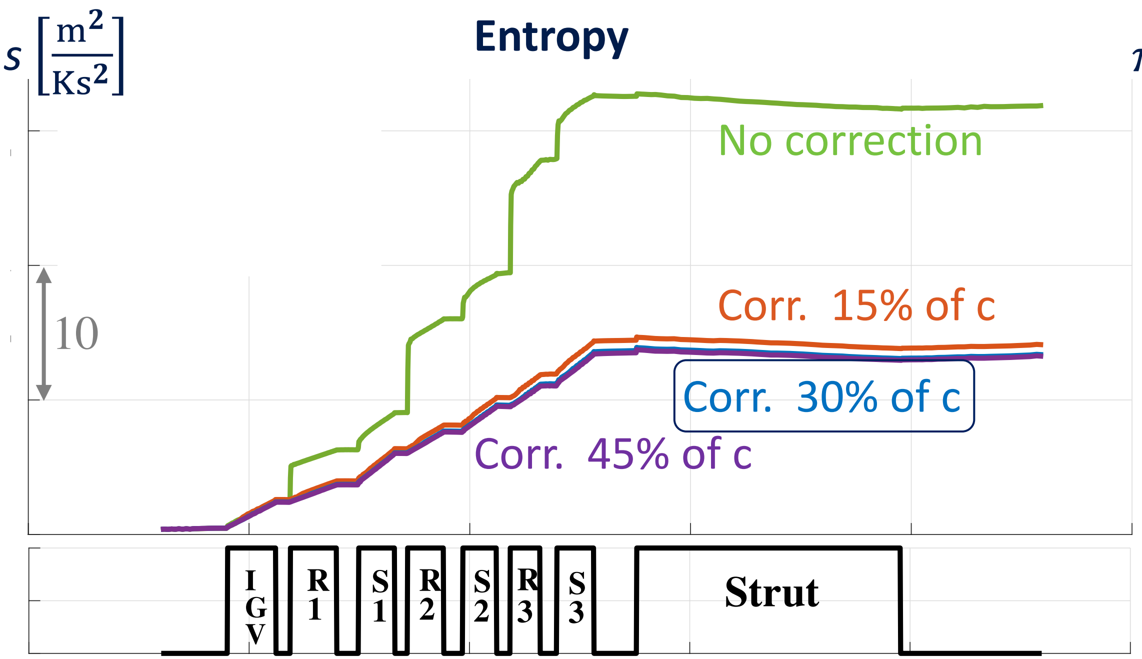


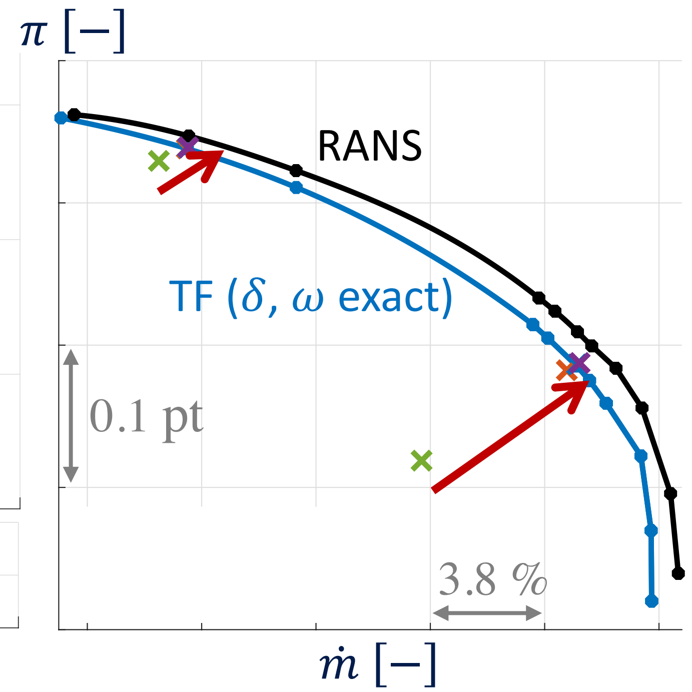
Overestimation of performance variability

Incidence correction

- Avoid flow angle discontinuity
- Modification of blade skeleton @ LE
- Unchanged correlation input

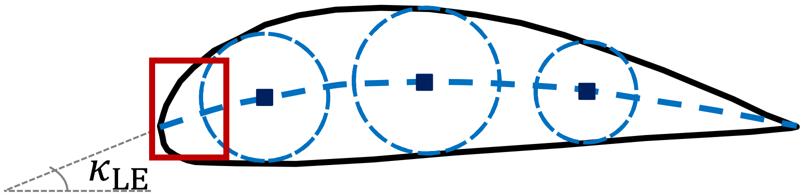


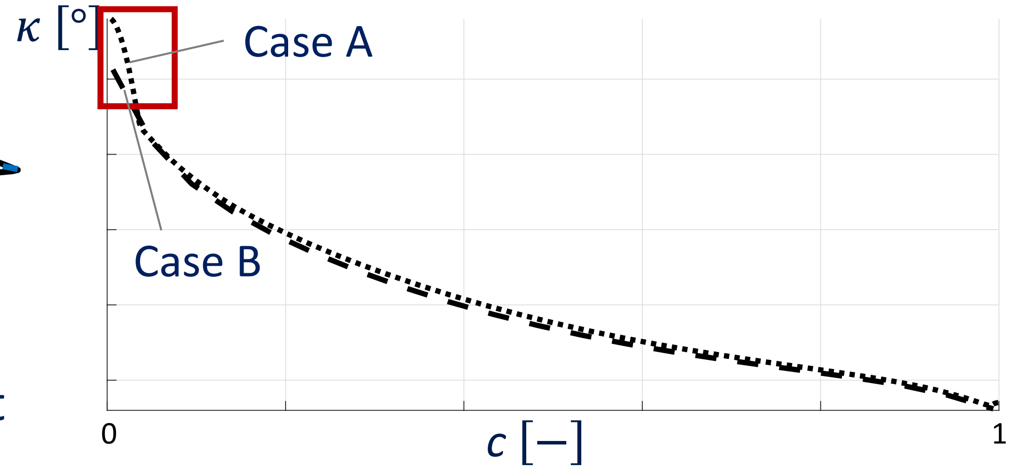




Incidence correction can smooth variability @ LE

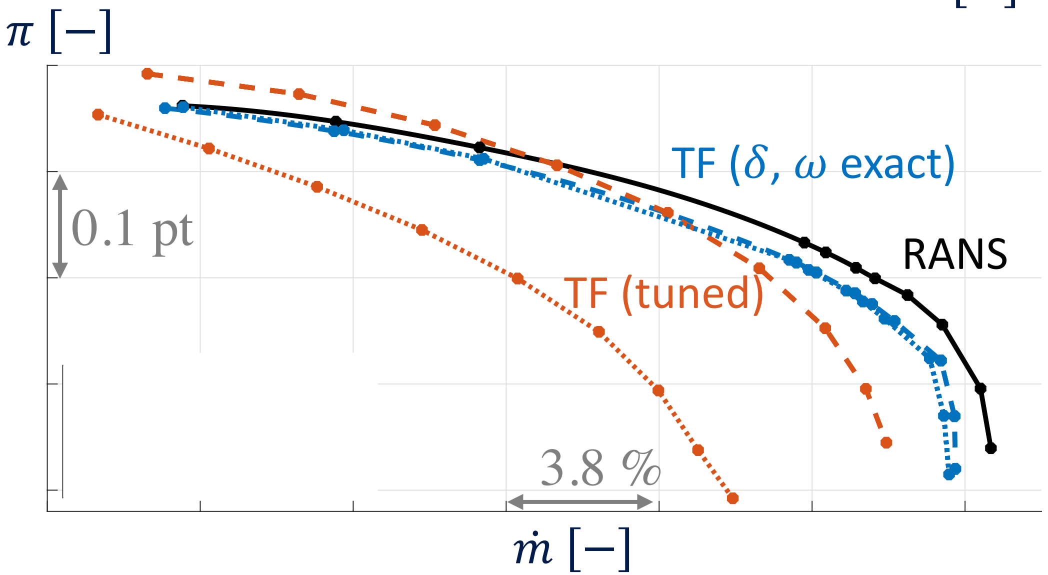
Camber line definition





Definition not unique close to LE

→ Large impact on correlation input

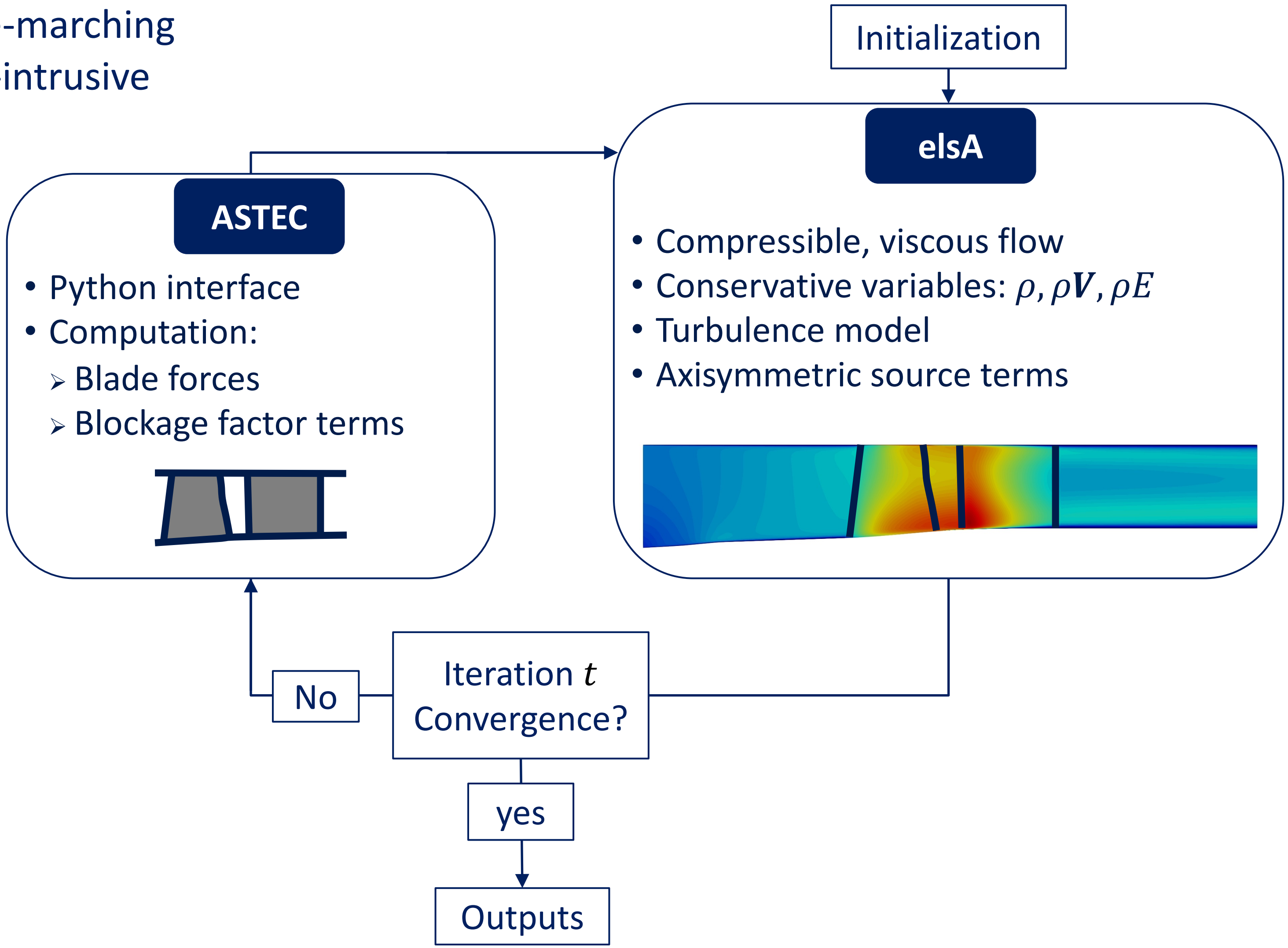


Strong dependence of model prediction with respect to LE blade angle

Viscous through-flow model: ASTEC

Methodology:

- Time-marching
- Non-intrusive



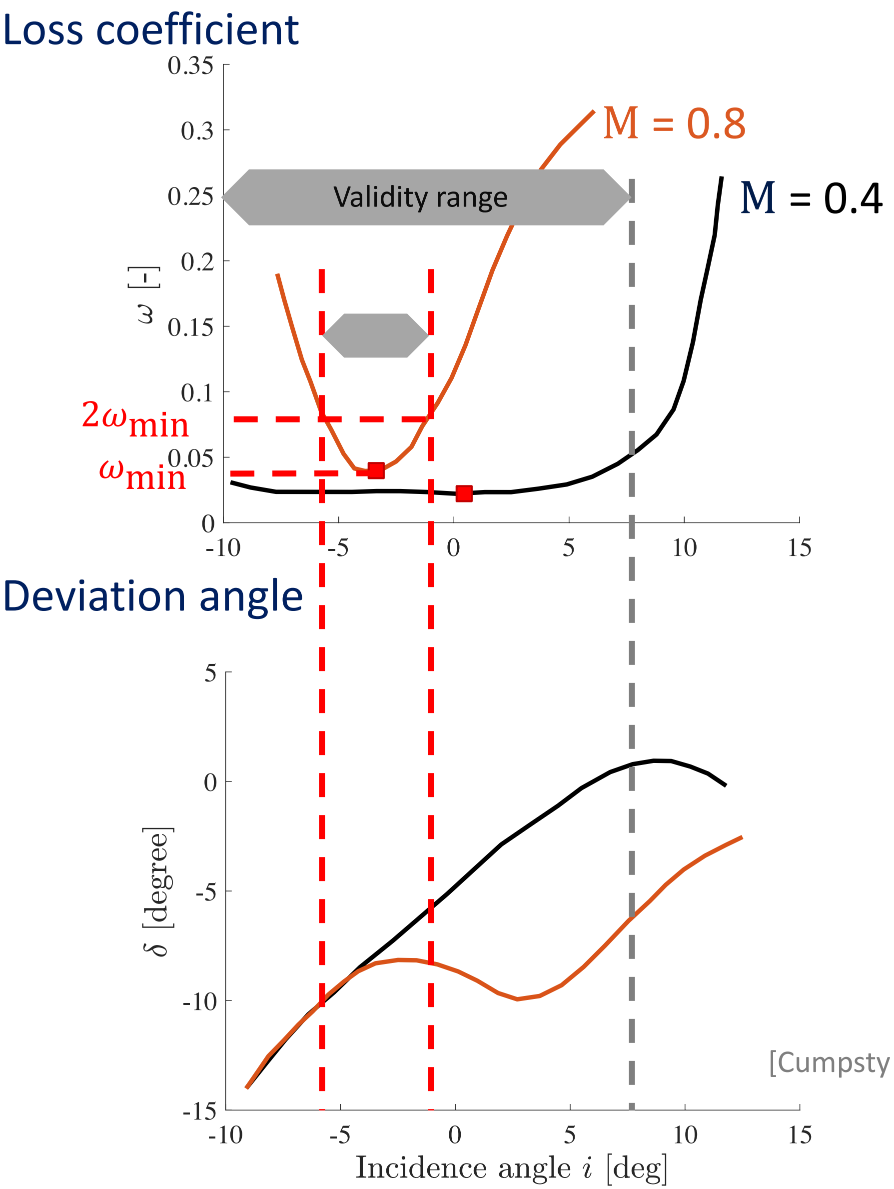
Modern compressor: comparison to RANS

Impact of Mach number

- Minimum-loss incidence angle shifted
- Increase of $\omega_{\min}$
- 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



[Cumpsty 1989]