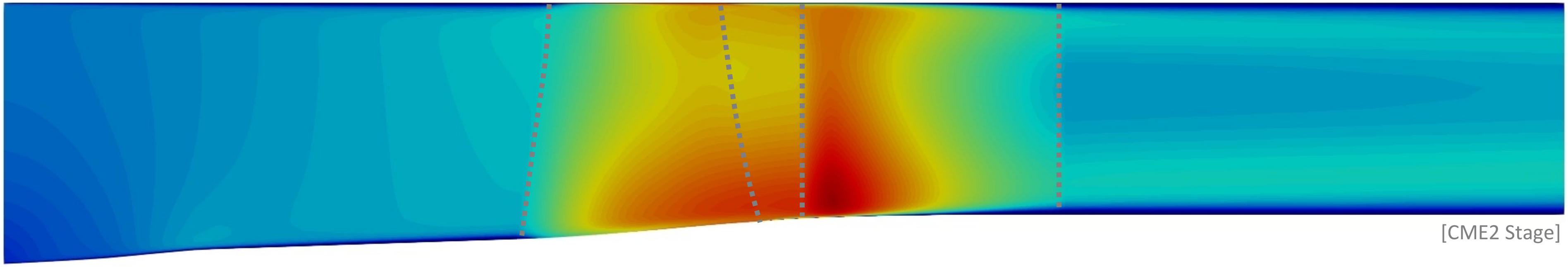
Geometrical variability in a through-flow model: manufacturing tolerance effects on compressor blades



[CME2 Stage]

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ACOMEN 2022

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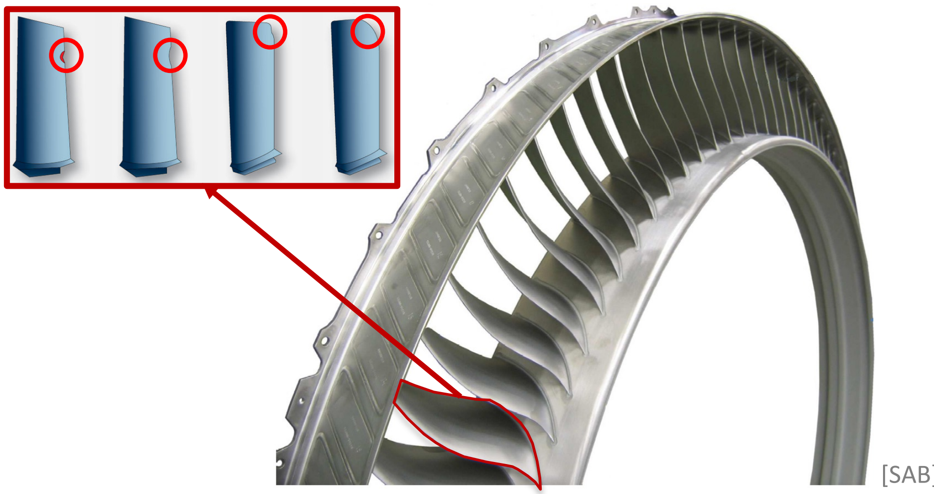
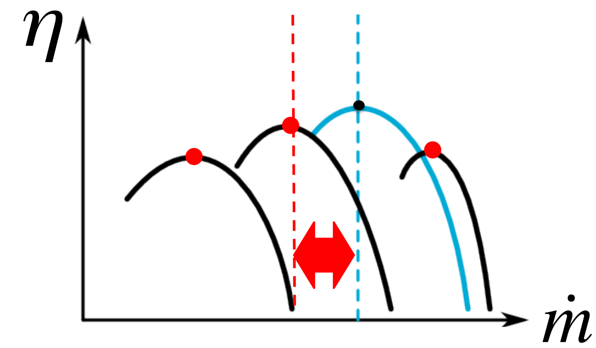
SAFRAN AERO BOOSTERS

Context

Geometrical variability of low-pressure compressors blades



Performance

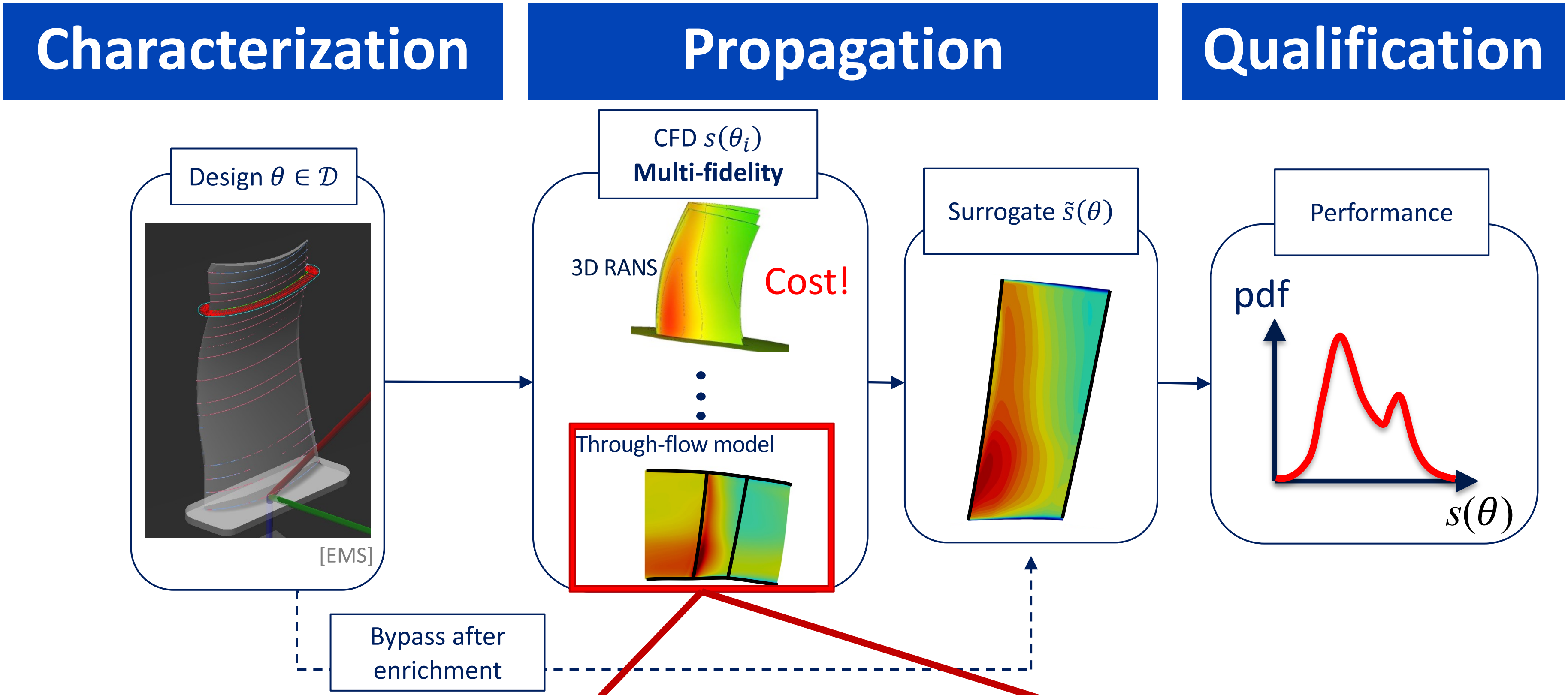


Manufacturing tolerances?

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

Trade-off cost/performance

Methodology



Able to predict performance?

Through-flow model validation

- Low-fidelity approach
- Choice of model correlations

Able to capture variability effects?

Geometrical variability

- Sensitivity analysis
- Uncertainty quantification

Outline

1

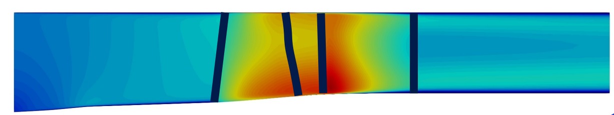
Viscous through-flow model

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

2

Application to an axial LP compressor

Application to the CME2 compressor stage



3

Geometrical variability

[SAB]

Outline

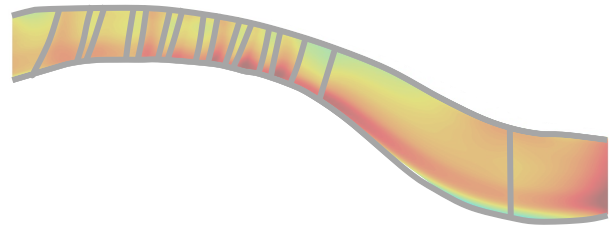
1

Viscous through-flow model

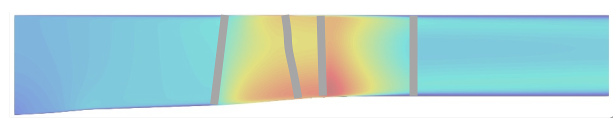
$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial(\boldsymbol{F}-\boldsymbol{F}_v)}{\partial x} + \frac{\partial(\boldsymbol{G}-\boldsymbol{G}_v)}{\partial r} = \boldsymbol{S}$$

2

Application to an axial LP compressor



Application to the CME2 compressor stage



3

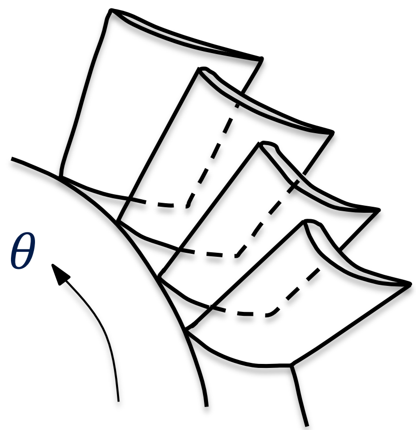
Geometrical variability

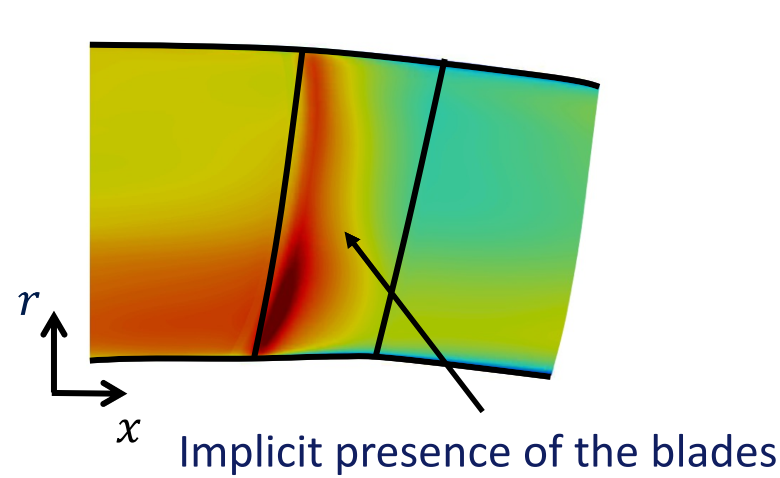
[SAB]

Through-flow model

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

Unclosed!





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

Through-flow formulation

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

Governing equations

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

Closure models

- Exhaustive?
- Assumptions?
- Correlations?

Choices that influences the **level of empiricism** and determines **error sources**

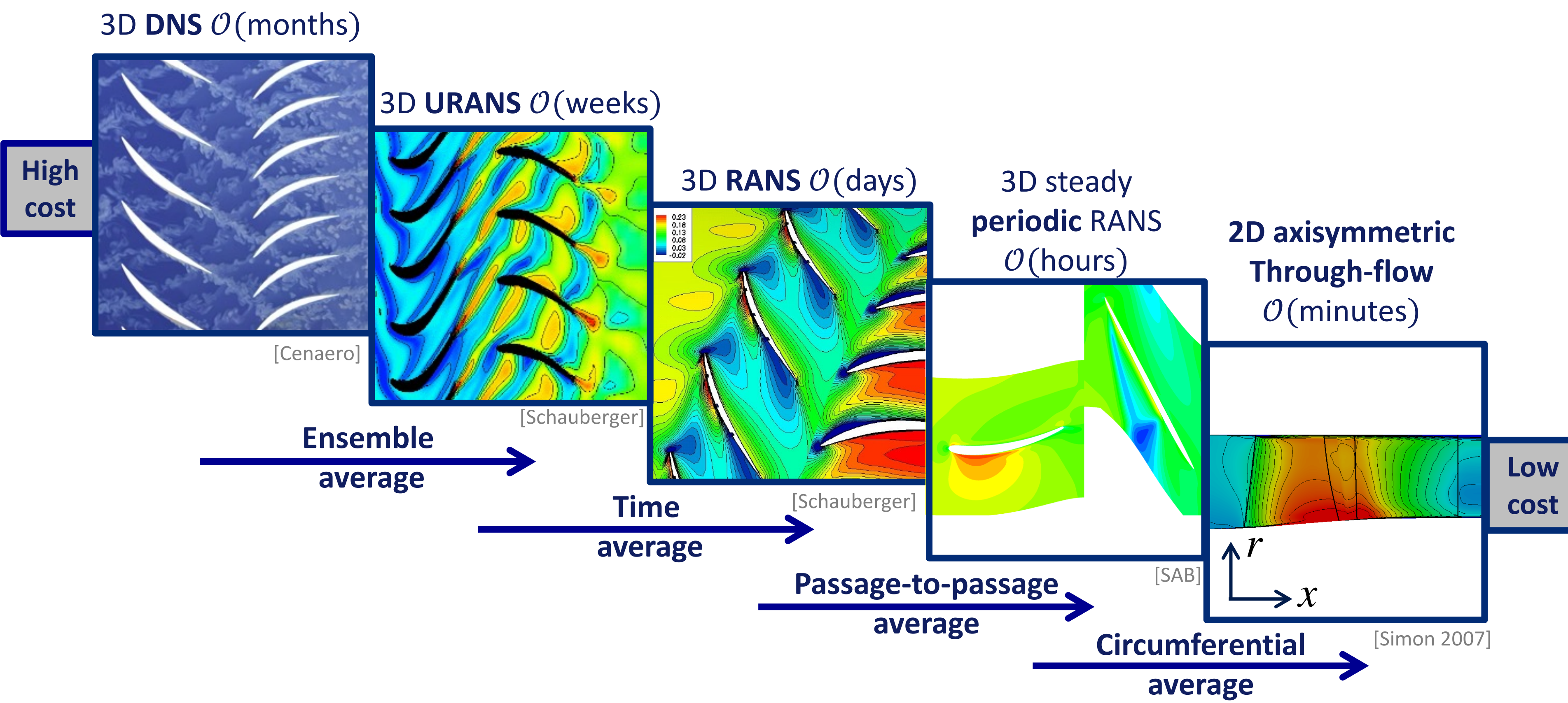
→ **need of characterizing error in a rigourous and exhaustive way**

Adamczyck's cascade

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

Unclosed!
Blade forces + stresses

- **Exact mathematical** formulation of source terms
- **Robust** and **exhaustive** definition of closures
- **NSE-based equations**



Adamczyk's cascade: unclosed terms

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

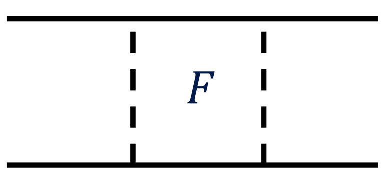
Unclosed terms:

$\overline{\rho V_x' V_x'}$

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

Viscous through-flow model

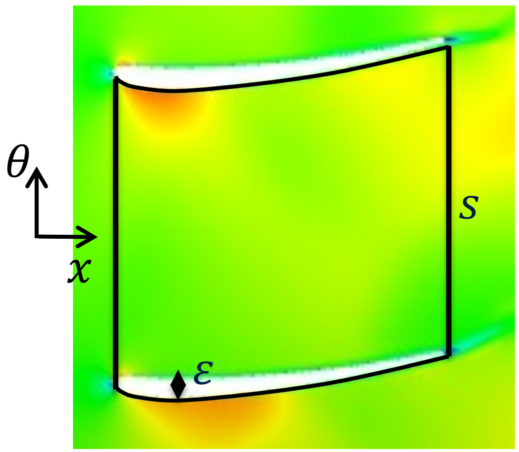
Circumferential averaged Navier-Stokes equations:

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

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

- 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)

Relative importance of source terms

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

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

Not exhaustive!

Relative importance of exact source terms:

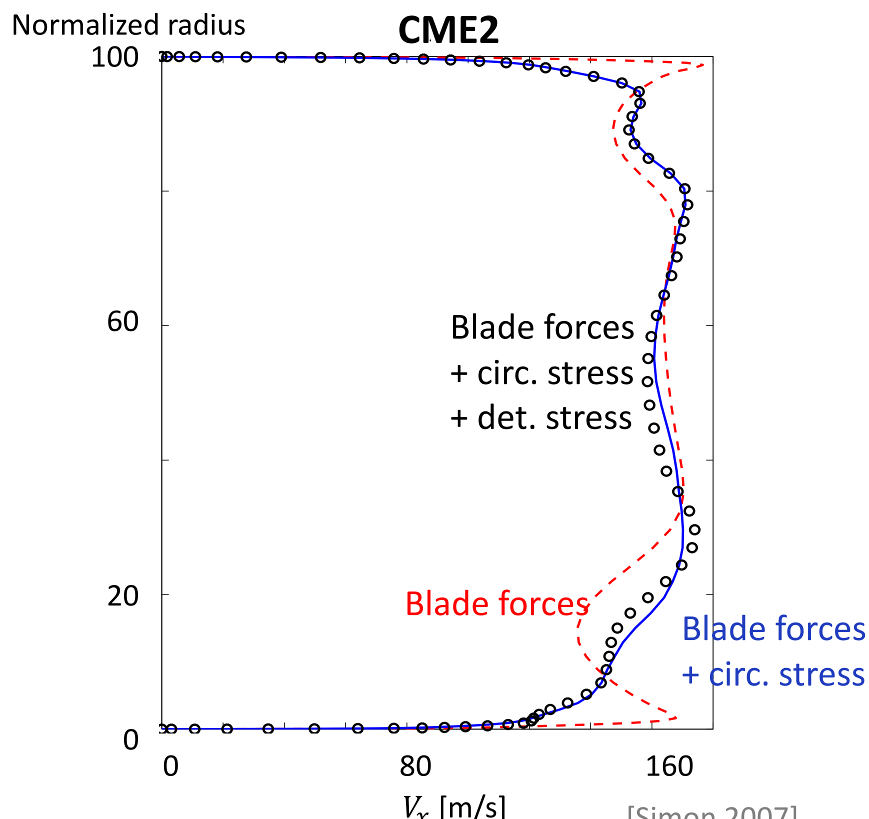
- Reynolds stresses
- Inviscid blade forces
- Viscous blade forces

Major terms

- Circumferential stresses
- Deterministic stresses

Lower importance

- Aperiodic stresses
  → **Generally neglected**



[Simon 2007]

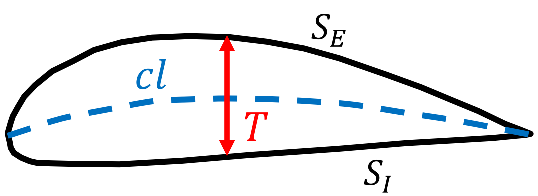
Closure models

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

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

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

- **Inviscid blade force decomposition** B_{i} :



$$\begin{cases} S_E = cl + \frac{1}{2}T \\ S_I = cl - \frac{1}{2}T \end{cases}$$

B_{i}

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

Unknown!

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

Closure models: blade forces

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

Unclosed!

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

Blade blockage B_{i1}

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

Averaged pressure

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

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

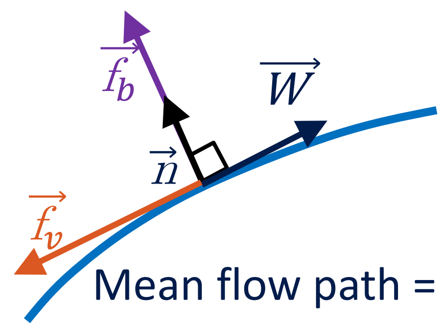
$$B_{\mathrm{i2}} = f\left(P_{S_E}, P_{S_I}\right) \qquad B_{\mathrm{v}} = f\left(\tau_{S_E}, \tau_{S_I}\right)$$

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!

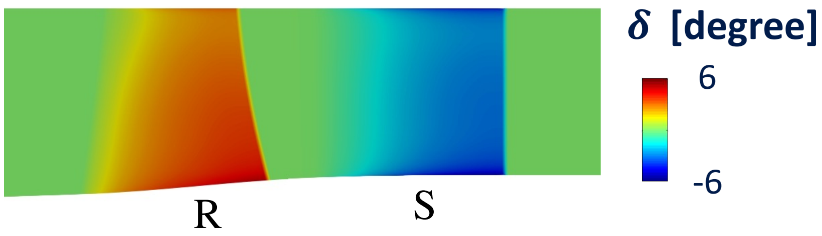


Mean flow path = $f(cl, \boldsymbol{\delta})$

Correlations for δ and ω

Deviation angle δ (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

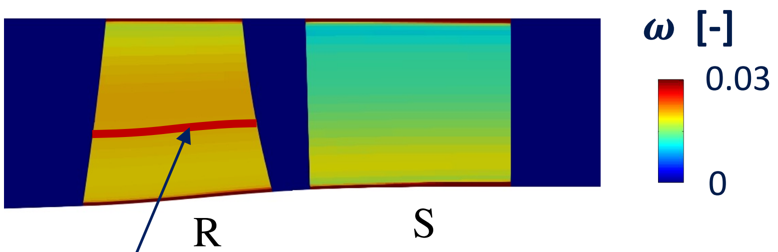


- NACA65
- C4
- Double circular arc

Loss coefficient ω (viscous blade force)

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

⚠ Profile loss only



Outline

1

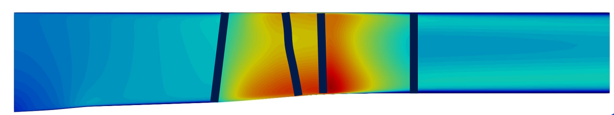
Viscous through-flow model

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

2

Application to an axial LP compressor

Application to the CME2 compressor stage



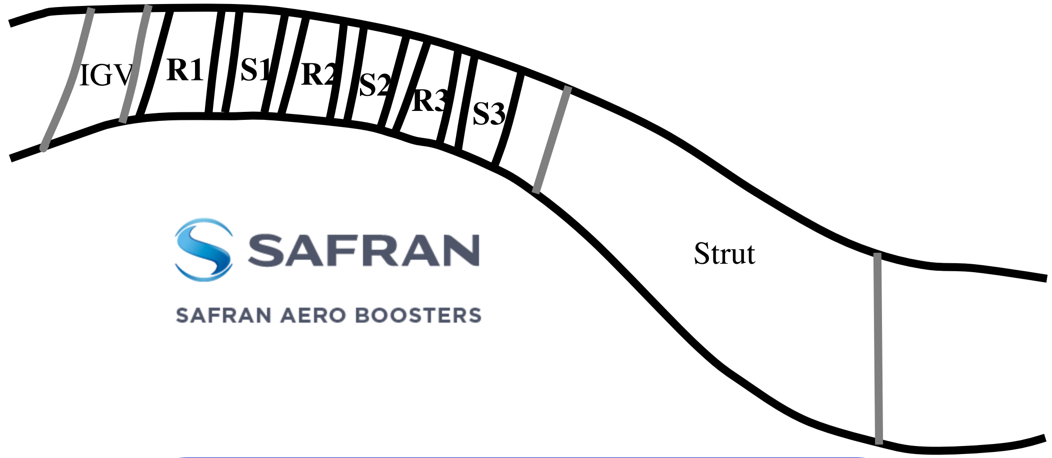
3

Geometrical variability

[SAB]

Closure model assessment

- Error quantification of closure models
- Exact correlation assumption



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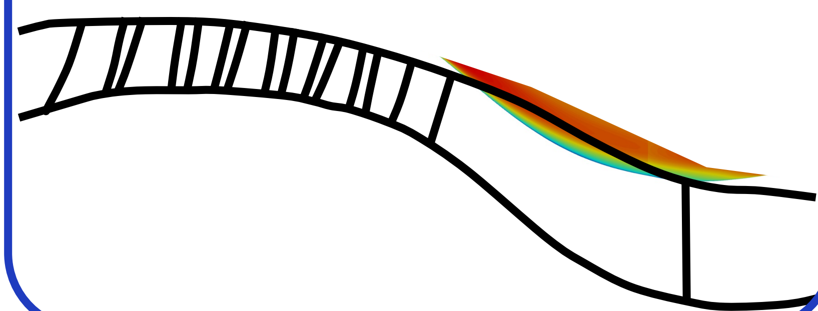
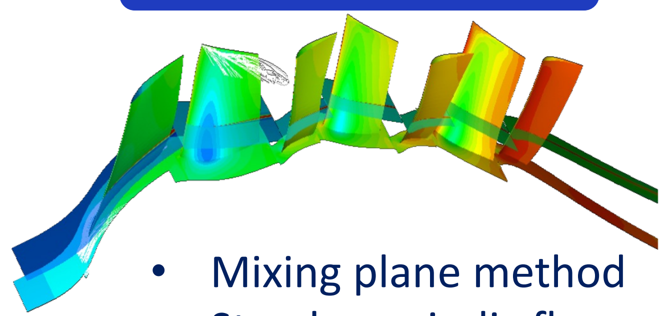
Test-case 1: low-pressure compressor

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

Through-flow (TF) simulations



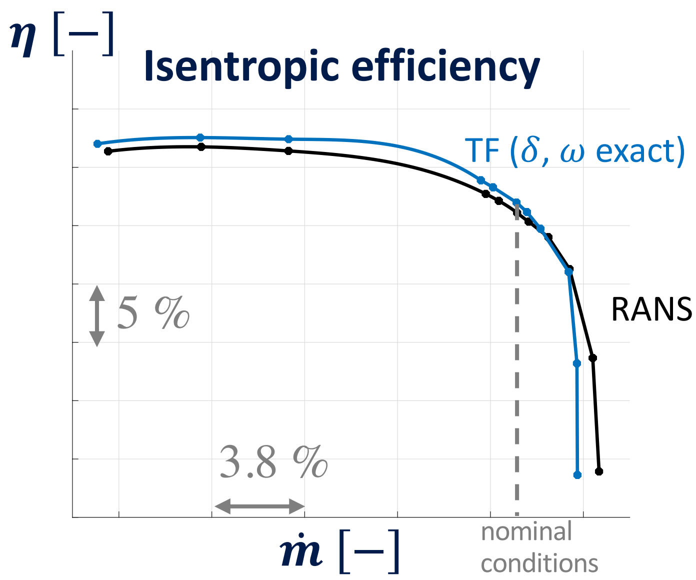
3D RANS simulations

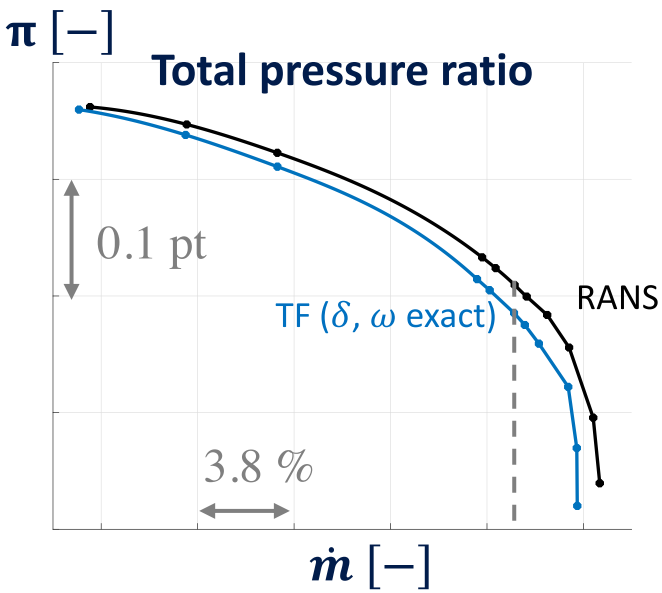


- Mixing plane method
- Steady, periodic flow

δ, ω distributions

Closure model assessment





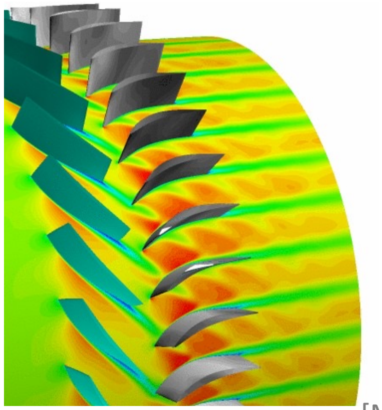
- Accurate prediction (low margin)
- More than 600 times faster (not yet optimized for speed)
- Source of errors: τ_{circ}, δ distribution, blockage assumption, turbulence model…

Model able to predict accurately performance underneath stated assumptions

But exact δ, ω unknown …

Correlations assessment

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

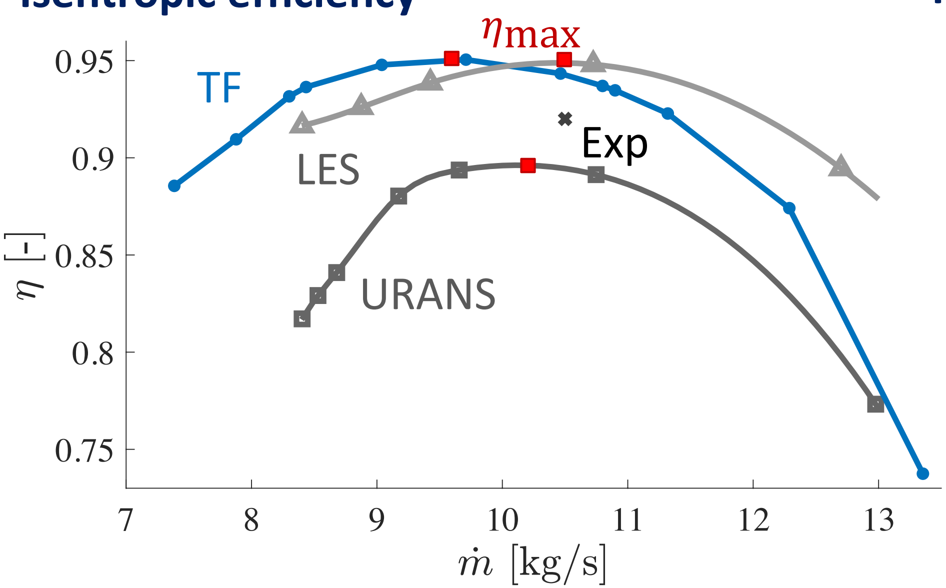


[Moreau 2019]

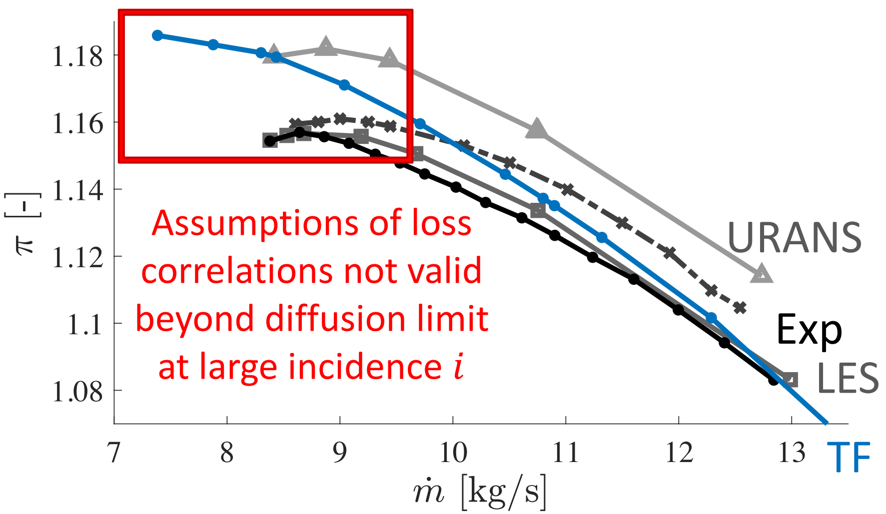
Test-case 2: CME2

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

Isentropic efficiency



Total pressure ratio



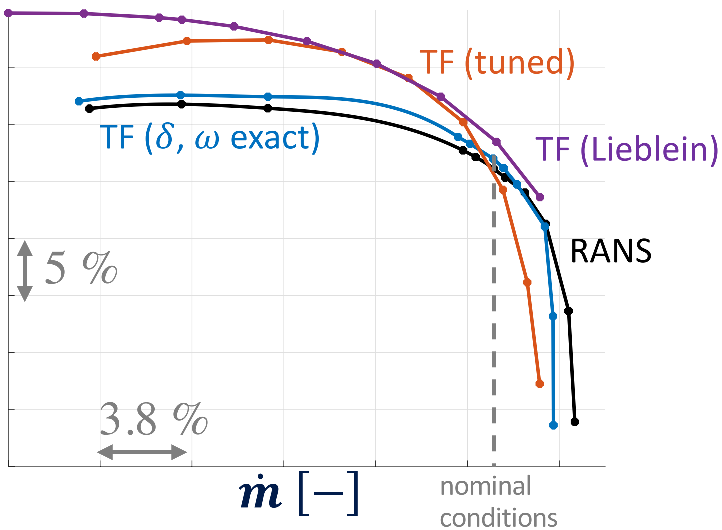
Source: [Gourdain 2015]

Correlations assessment

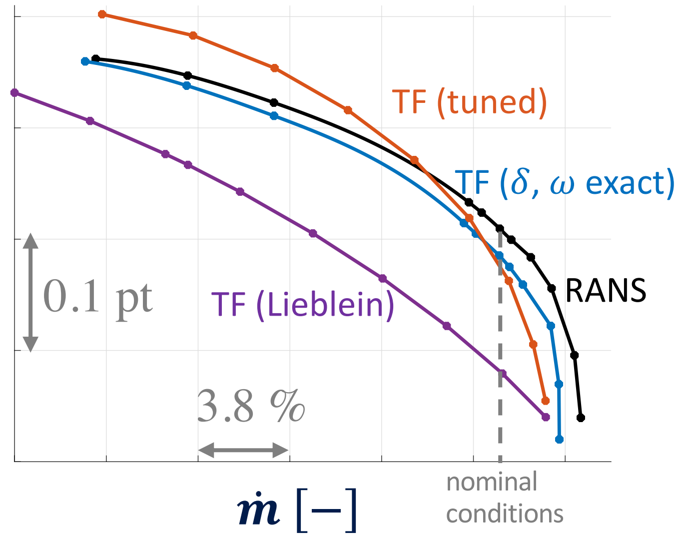
➢ Error quantification of **correlations** for $\boldsymbol{\delta}$, $\boldsymbol{\omega}$

Test-case 1: : low-pressure compressor

$\boldsymbol{\eta}$ [−] **Isentropic efficiency**



$\boldsymbol{\pi}$ [−] **Total pressure ratio**



- Rotor deviation angle correction → total pressure ratio improvement
- Mach number effect added

Strong dependence of model prediction with respect to correlation accuracy

Outline

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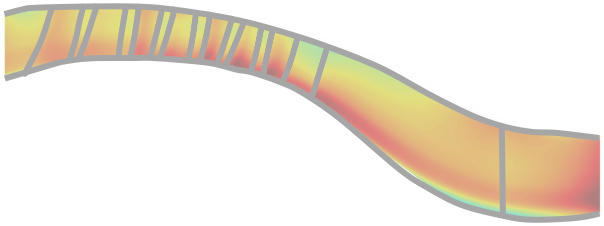
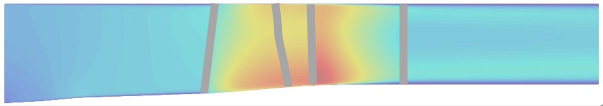
2

Application to an axial LP compressor



Application to the CME2 compressor stage



3

Geometrical variability

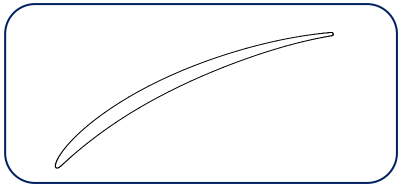
[SAB]

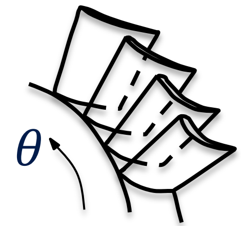
Geometry in through-flow model

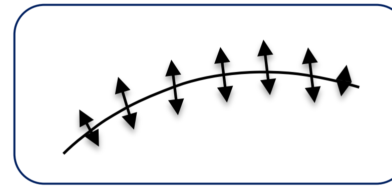
$$D_t \boldsymbol{U}(r, \theta, x, t) = \boldsymbol{G}(U, r, \theta, x, t)$$

θ −averaging

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





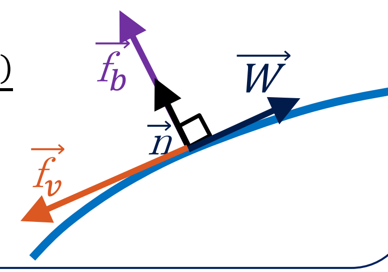


Camber Line Coordinates
&
Thickness distribution

Input

Blade forces

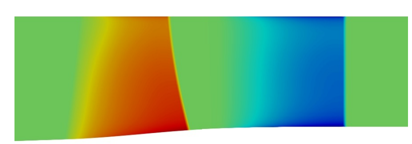
$$b = 1 - \frac{\varepsilon(x)}{s}$$



Direct impact

Correlations

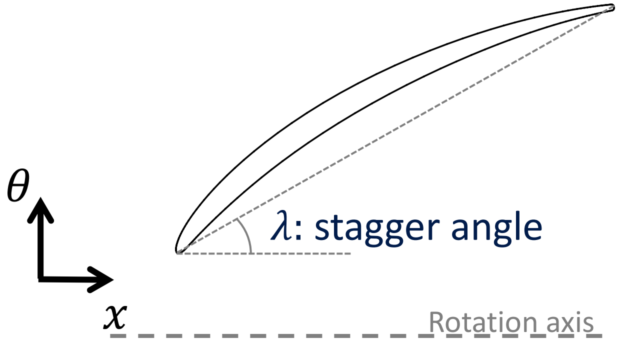
$$\delta, \omega = f(\text{geometry})$$

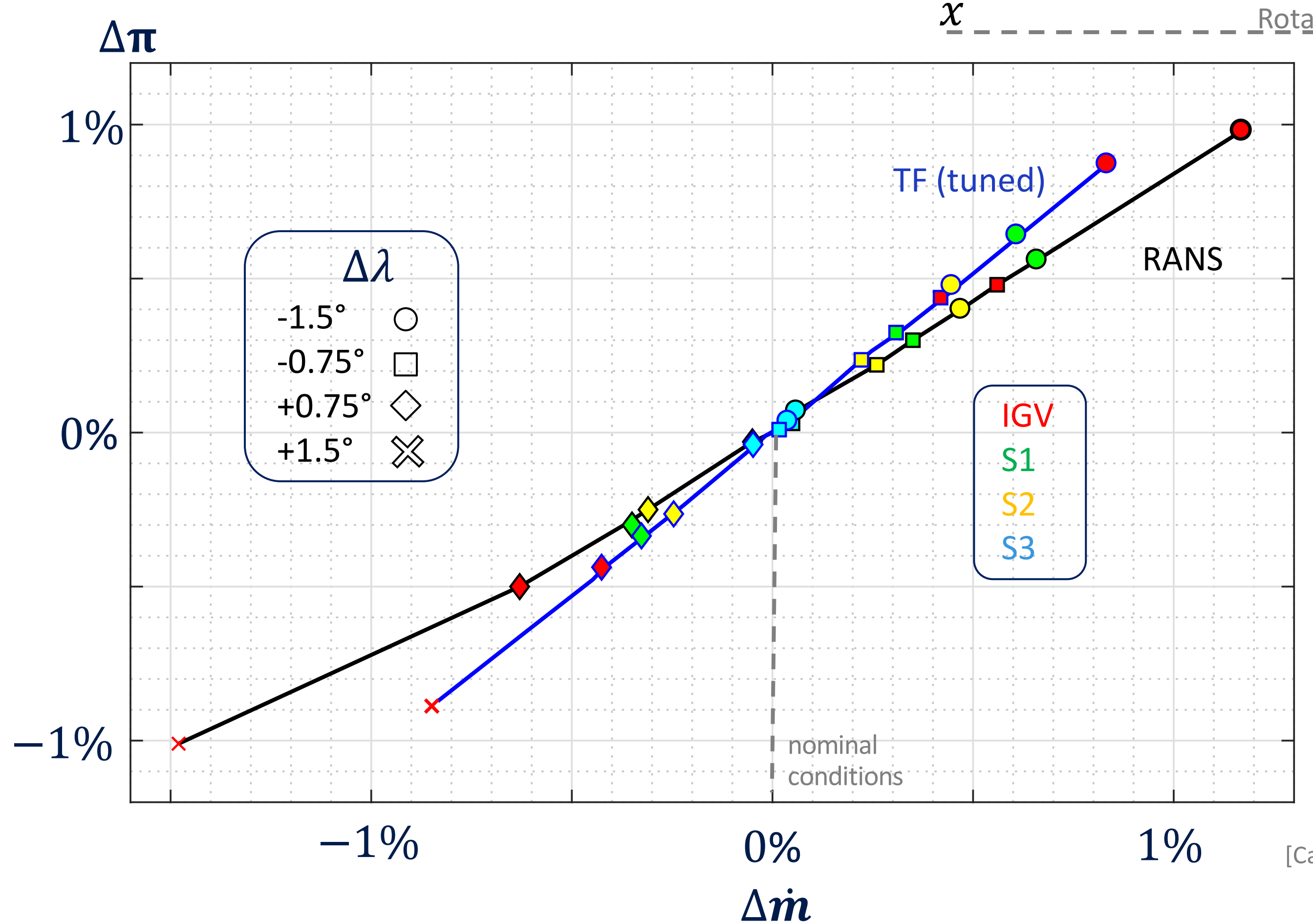


Indirect impact

Geometrical variability: stagger angle

- Direct and indirect impact
- Linear behaviour
- Propagation through downstream blades





[Camille Dufour]

Conclusion

Through- flow model

- **Low-fidelity** method
- Closures computation: **blade forces**
- Correlations: deviation angle & loss coefficient
- Strong **dependence** between performance prediction and **correlation accuracy**
- Promising approach to drastically **reduce CPU cost** compared to 3D RANS

Geometrical variability

- Direct and indirect impact
- Global good agreement for **performance variation**

Acknowledgement

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