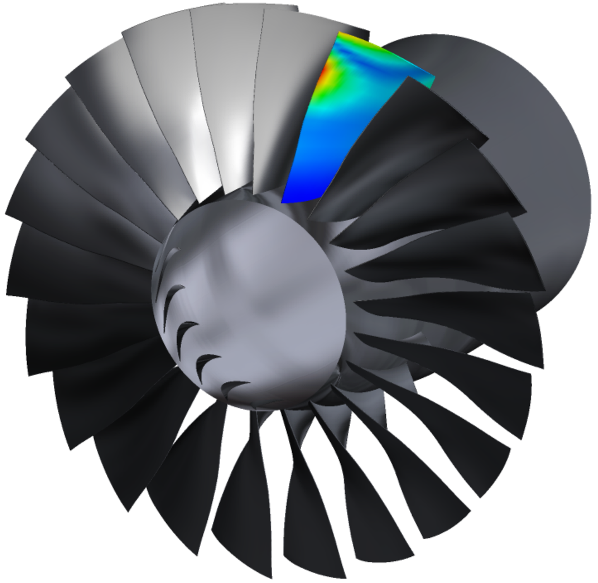
Adjoint 3D Aeroelastic Turbomachinery Optimization using Harmonic Balance

Current developments and future perspective

Nitish Anand, Matteo Pini and Piero Colonna.

Propulsion and Power, TU Delft.

1st SU2 Conference, Online, 2020.

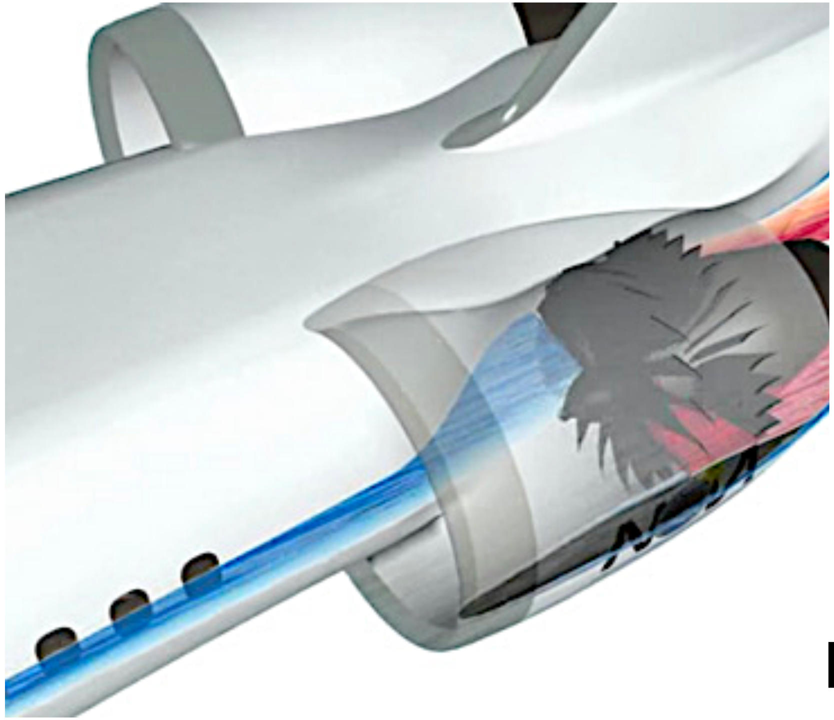


12th June 2020

Scope of Research

MDO of next-gen turbomachines

Boundary Layer Ingestion Fans



Highly loaded turbines
(reusable rockets)

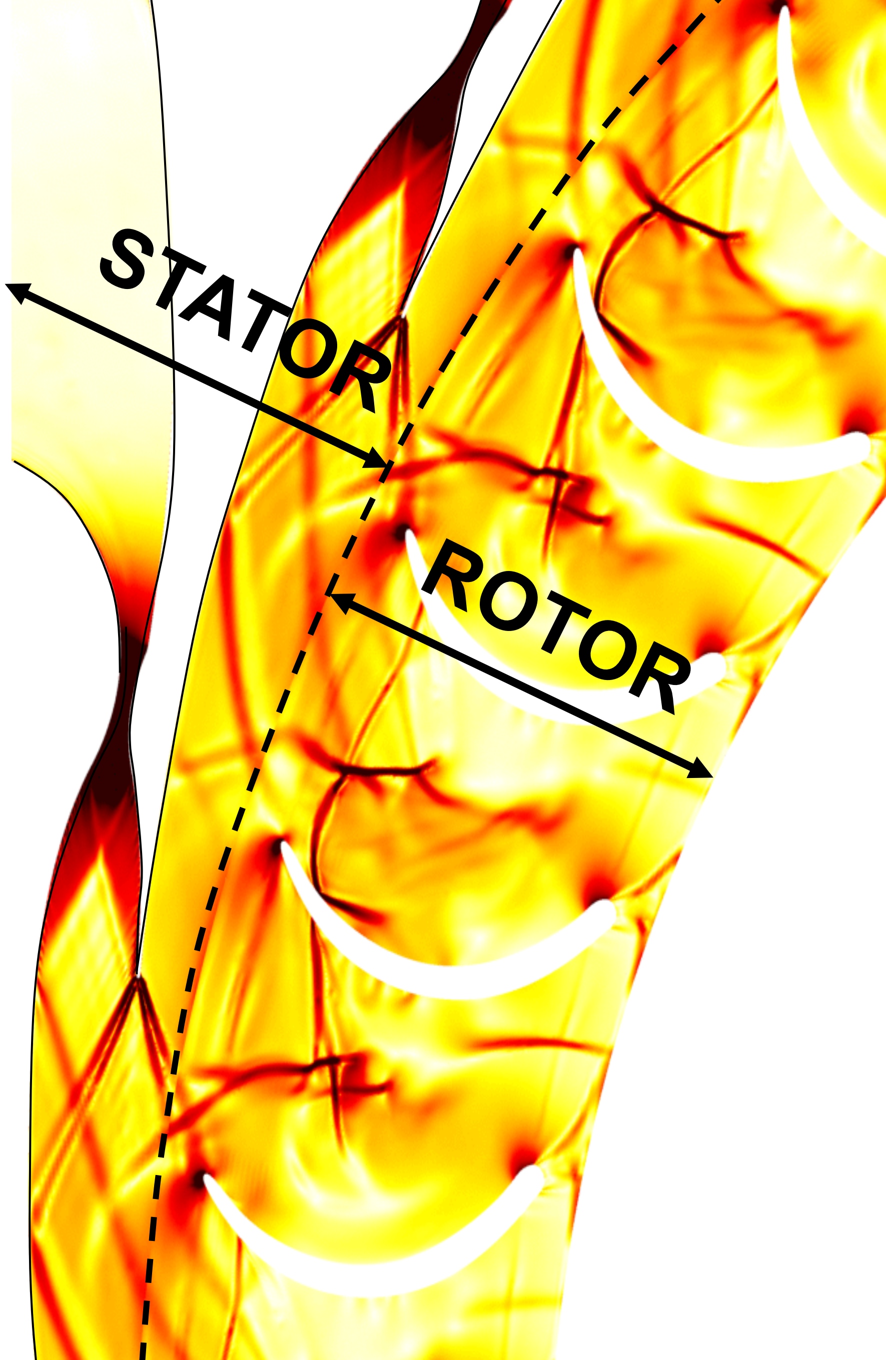
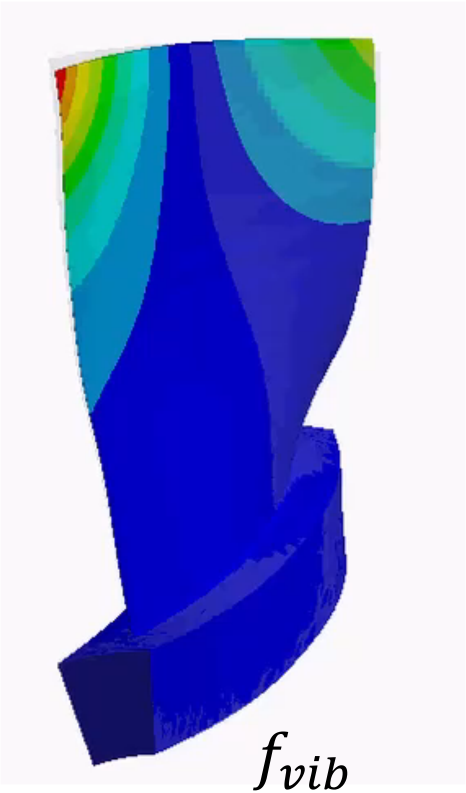
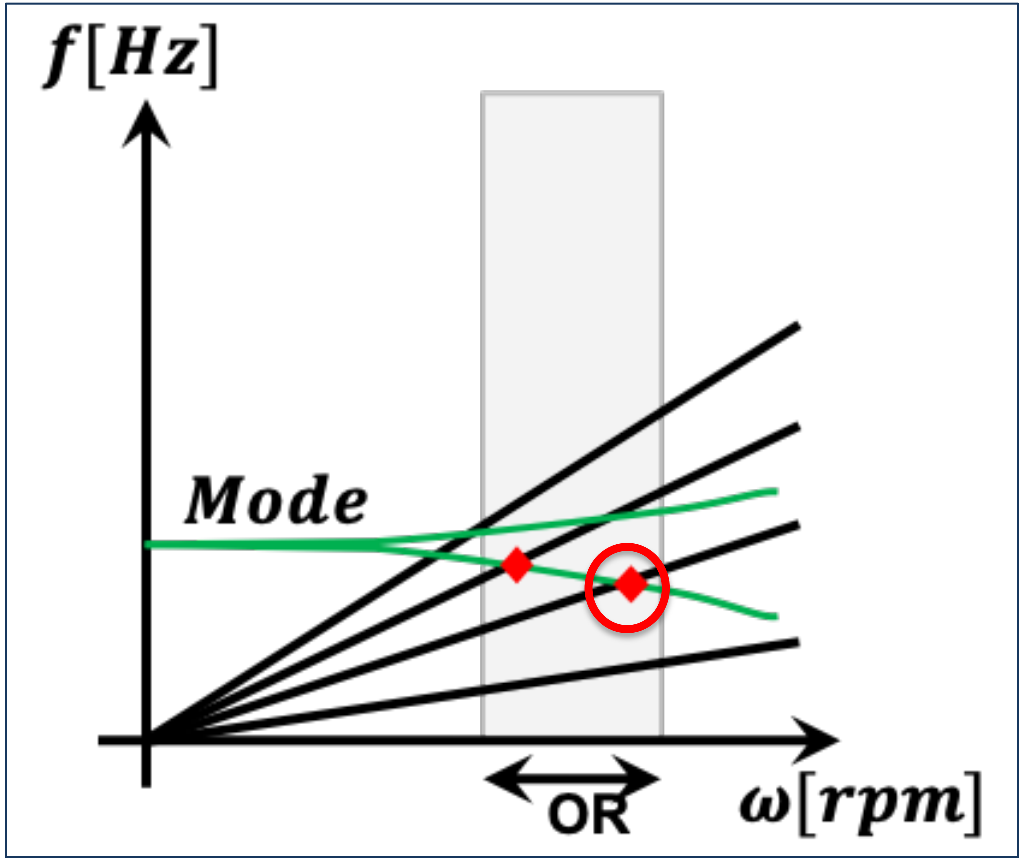
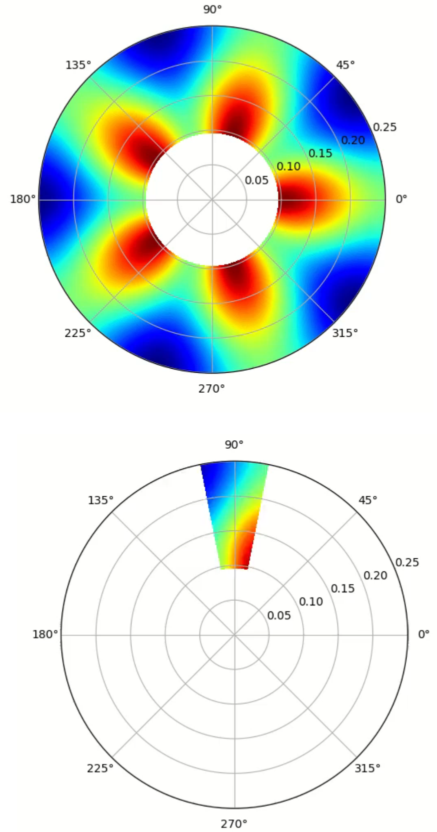


Image Reference: N. Anand, MSc Thesis 2016 (TU-Delft), Onera.fr

Forced Response Due to Unsteady Inflow



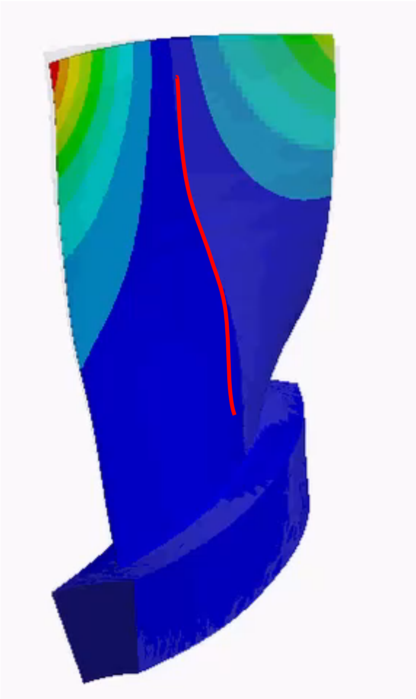




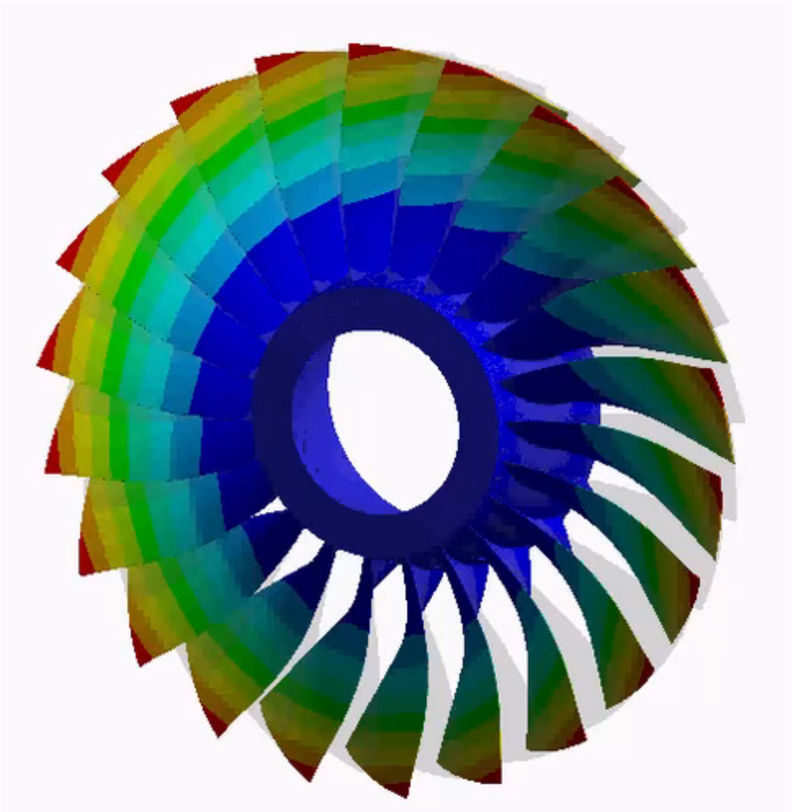
Necessary Condition

$$f_{vib} = f_{blade\ passing}$$

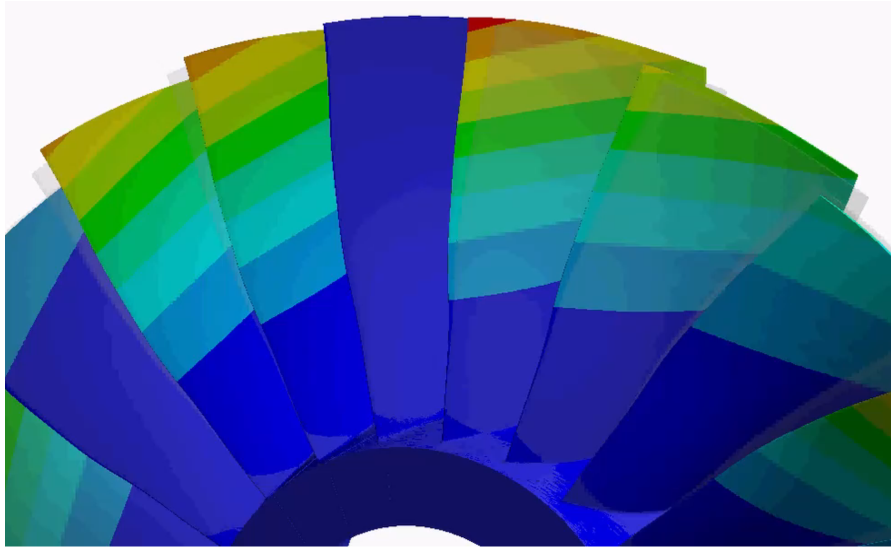
Turbomachinery Vibration



Blade Mode



Disk Mode



Blisk Mode

(R. S. de Oliveira, MSc Thesis 2020, TU-Delft)

Our Main Goal(s) with SU2

- Efficient aero-elastic analysis/design method using ROMs (harmonic-balance)
- Applicability to variety of turbomachines
  - Transonic fan/propeller with/without BLI
  - High-speed turbines and compressors

ROM: reduced-order model

Forced Response Analysis

Identification of resonant conditions

1. Campbell diagram
2. Interference diagram

$$\omega_{exc} = \omega_k$$

Computation of aerodynamic forcing and damping

3. Aero forcing

$$\vec{\phi}_k^T \vec{F}_{exc}$$

$$\vec{F}_{aero}(t) = \vec{F}_{dist}(t) + \vec{F}_{motion}(t)$$

4. Aero damping

$$\xi_k$$

$$\vec{F}_{aero}(t) = \vec{F}_{dist}(t) + \vec{F}_{motion}(t)$$

Structural integrity analysis

5. Forced response

$$\vec{\sigma}_{alt}$$

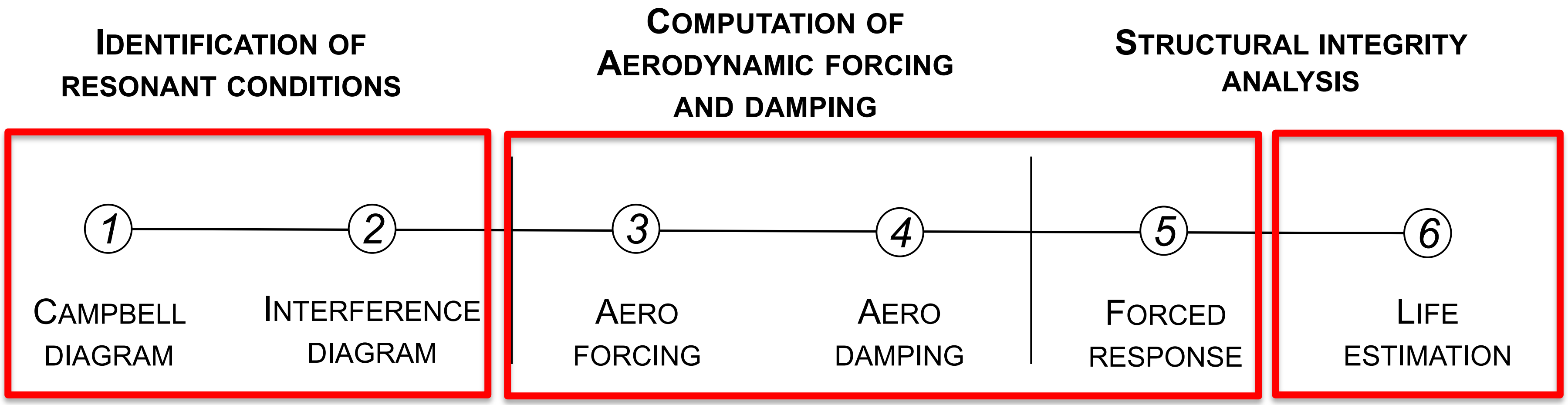
$$\vec{\sigma}_{static}$$

6. Life estimation

Are structural stresses inside safety limits regarding fatigue?

(R. S. de Oliveira, MSc Thesis 2020)

Forced Response Analysis



Assumption:

- Natural frequency of the blade does not change with shape.

Design:

- Energy Method Based Approach

w_f w_d

Analysis:

- Post-process Life using a FEM tool.

(R. S. de Oliveira, MSc Thesis 2020)

Technical Approach

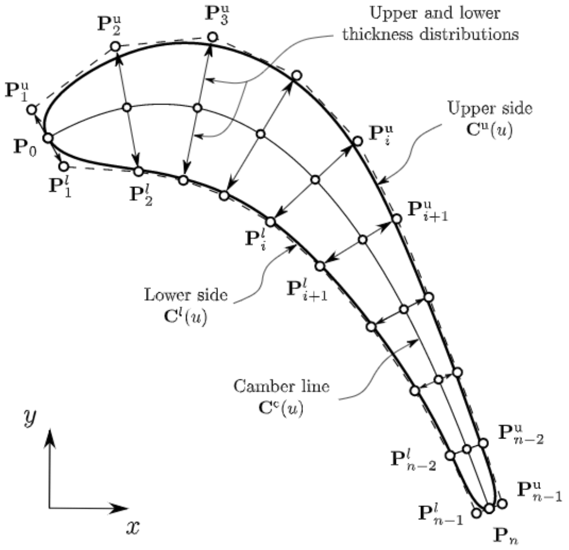
- *Energy Method* for aero-elastic analysis
  - *Primal computational Cost* → 2 x URANS (=HB) simulation
  - *Adjoint computation Cost* → ~3 x URANS (=HB)
- Geometry Parametrization → CAD-Based (coupled to SU2)

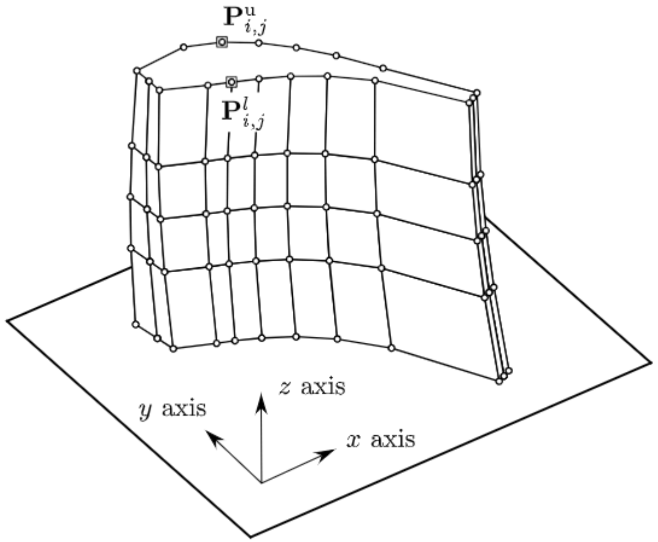
SU2 code

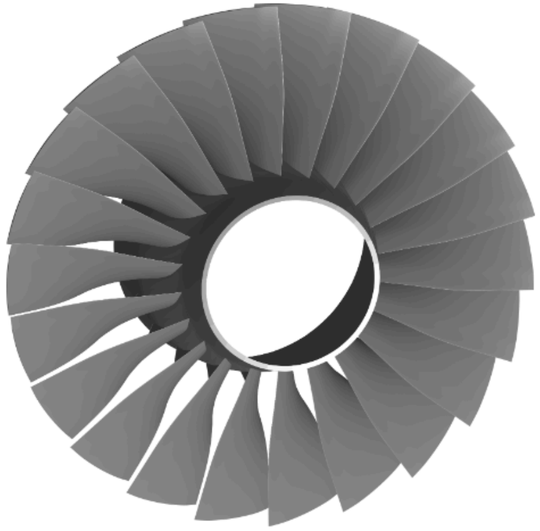
ParaBlade
A python based blade parametrization tool

HB-based Aeroelastic Design Chain – 1

$\boldsymbol{\alpha}$ → **Surface Deformation**: $\mathbf{X}_{\text{surf}} = \mathcal{S}(\boldsymbol{\alpha})$ → **Volume Deformation**: $\mathbf{X}_{\text{vol}} = \mathcal{V}(\mathbf{X}_{\text{surf}})$ → **Grid Movement**: $\mathbf{X}_{\text{vol},t} = \mathcal{G}(\mathbf{X}_{\text{vol}})$ → **Flow Solver**: $\mathbf{U}_t = \mathcal{F}(\mathbf{U}_t, \mathbf{X}_{\text{vol},t})$ → $\mathcal{J}$

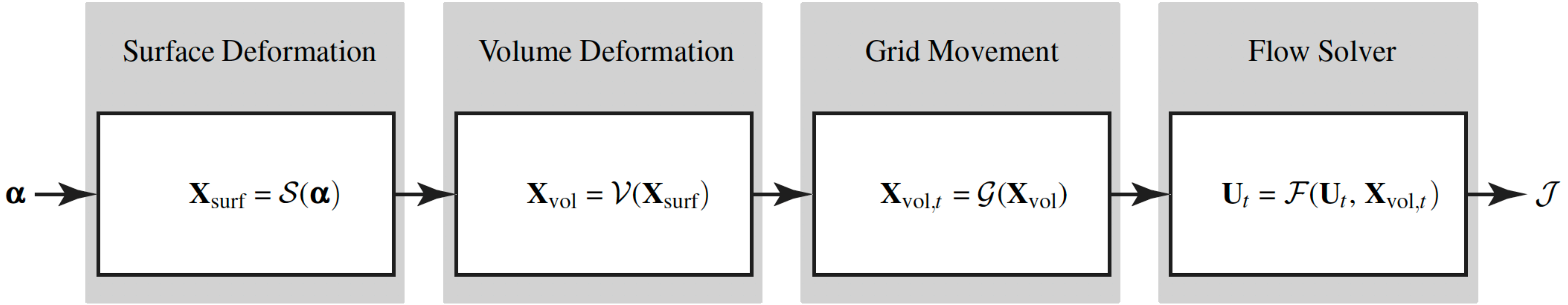






(Anand et. al, TurboExpo 2020 & Agromayor et. al, Under Review)

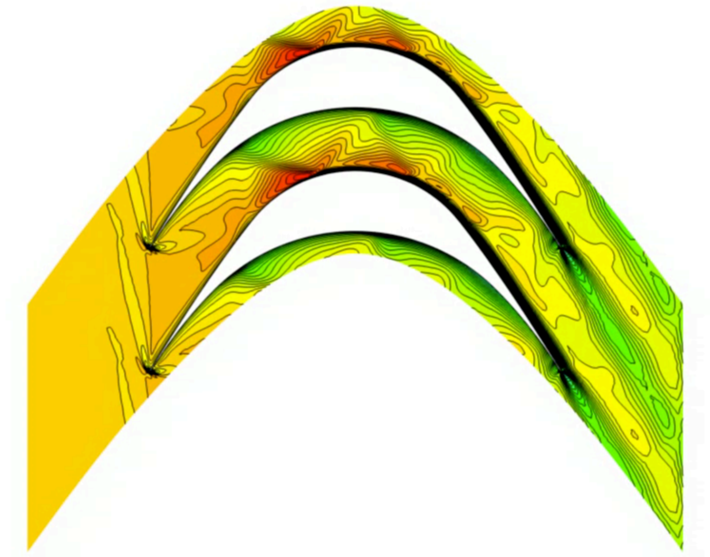
HB-based Aeroelastic Design Chain – 2



Grid Movement Formulation

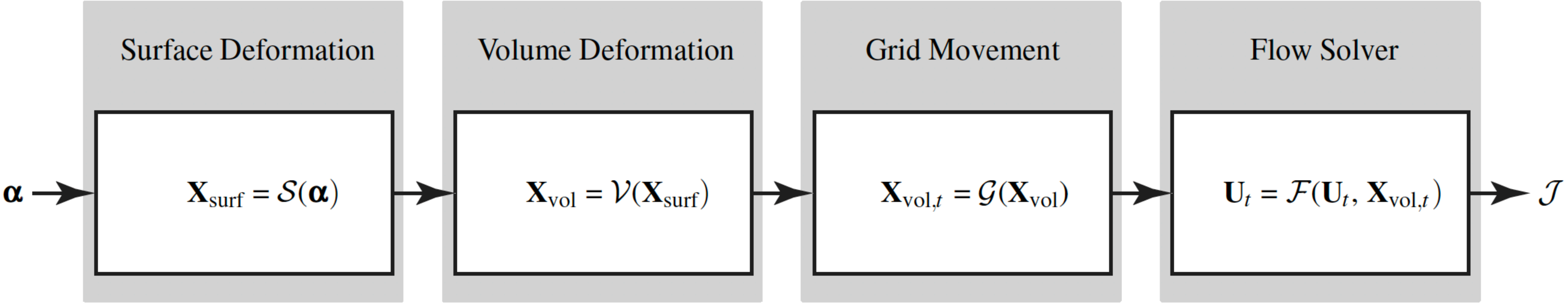
$$\mathbf{K}\Delta\mathbf{X}^k_{\text{vol},t} = \mathbf{T}\Delta\mathbf{X}^k_{\text{surf,pitch},t},$$

$$\mathbf{X}^k_{\text{vol},t} = \mathcal{G}\left(\mathbf{X}_{\text{vol}}\right) = \mathbf{X}^k_{\text{vol}} + \Delta\mathbf{X}^k_{\text{vol},t}.$$



(Anand et. al, TurboExpo 2020)

HB-based Aeroelastic Design Chain – 3



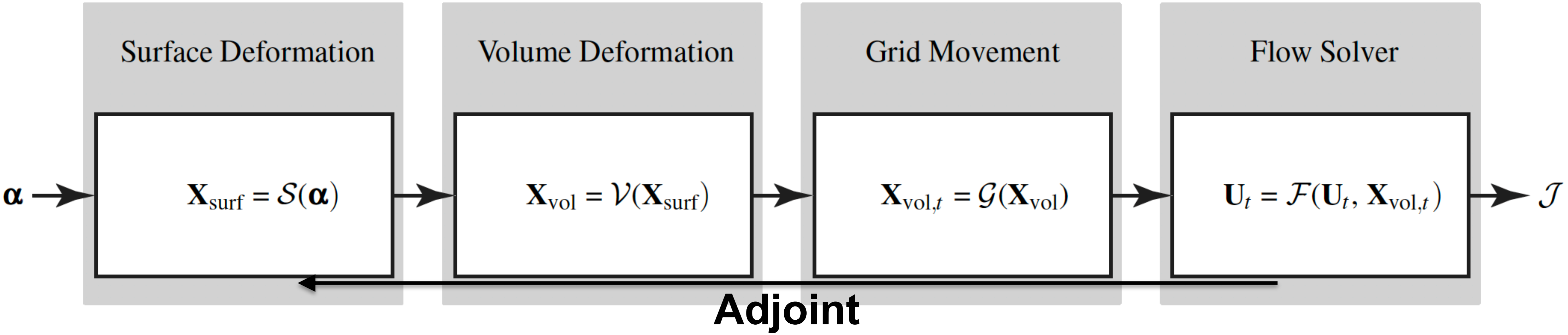
Harmonic Balance Formulation

$$\left(\frac{\Omega I}{\Delta t} + \mathbf{J}\right) \Delta \mathbf{U}_n = -\tilde{\mathcal{R}}_n\left(\mathbf{U}^q, \mathbf{U}^{q-1}\right), \qquad n = 0, 1, \ldots, N-1$$

$$\tilde{\mathcal{R}}_n\left(\mathbf{U}^q, \mathbf{U}^{q-1}\right) = \mathcal{R}_n\left(\mathbf{U}^q\right) + \Omega \sum_{i=0}^{N-1} H_{n,i} \Delta \mathbf{U}_i + \Omega \sum_{i=0}^{N-1} H_{n,i} \mathbf{U}_i^q .$$

(Anand et. al, TurboExpo 2020)

HB-based Aeroelastic Design Chain – 4



Adjoint Problem

$$\begin{aligned}
\min_{\alpha} \quad & \mathcal{J}\left(\mathbf{U}_n(\boldsymbol{\alpha}), \mathbf{X}_{\mathrm{vol},n}(\boldsymbol{\alpha})\right), \\
\text{s.t.} \quad & \mathbf{U}_n(\boldsymbol{\alpha}) = \mathcal{F}_n\left(\mathbf{U}(\boldsymbol{\alpha}), \mathbf{X}_{\mathrm{vol}}(\boldsymbol{\alpha})\right), \\
& \mathbf{X}_{\mathrm{vol},n}(\boldsymbol{\alpha}) = \mathcal{M}_n(\boldsymbol{\alpha}) = \mathcal{G}\left(\mathcal{V}\left(\mathcal{S}(\boldsymbol{\alpha})\right)\right),
\end{aligned}$$

Adjoint Equations

$$\bar{\mathbf{U}}_n = \frac{\partial \mathcal{J}}{\partial \mathbf{U}_n}^{\mathrm{T}} + \sum_{i=0}^{N-1} \frac{\partial \mathcal{F}_i}{\partial \mathbf{U}_n}^{\mathrm{T}} \bar{\mathbf{U}}_i,$$

$$\bar{\mathbf{X}}_n = \frac{\partial \mathcal{J}}{\partial \mathbf{X}_n}^{\mathrm{T}} + \frac{\partial \mathcal{F}_n}{\partial \mathbf{X}_n}^{\mathrm{T}} \bar{\mathbf{U}}_n,$$

$$\frac{d\mathcal{M}_n}{d\boldsymbol{\alpha}} = \frac{d\mathbf{X}_{\mathrm{vol},n}}{d\mathbf{X}_{\mathrm{vol}}} \frac{d\mathbf{X}_{\mathrm{vol}}}{d\mathbf{X}_{\mathrm{surf}}} \frac{d\mathbf{X}_{\mathrm{surf}}}{d\boldsymbol{\alpha}},$$

TU Delft

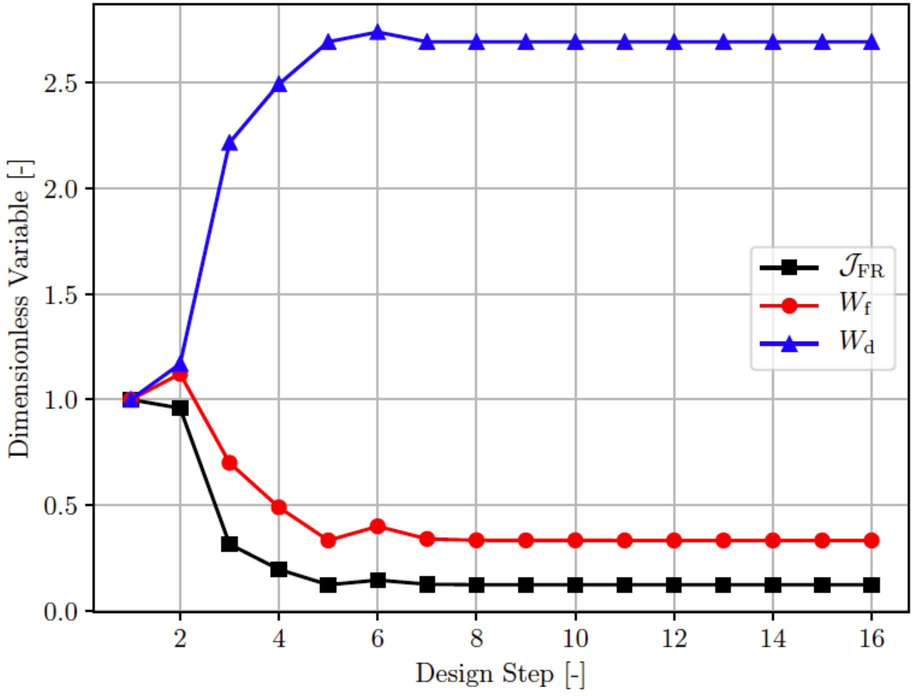
(Anand et. al, TurboExpo 2020)

Current Status of Implementation

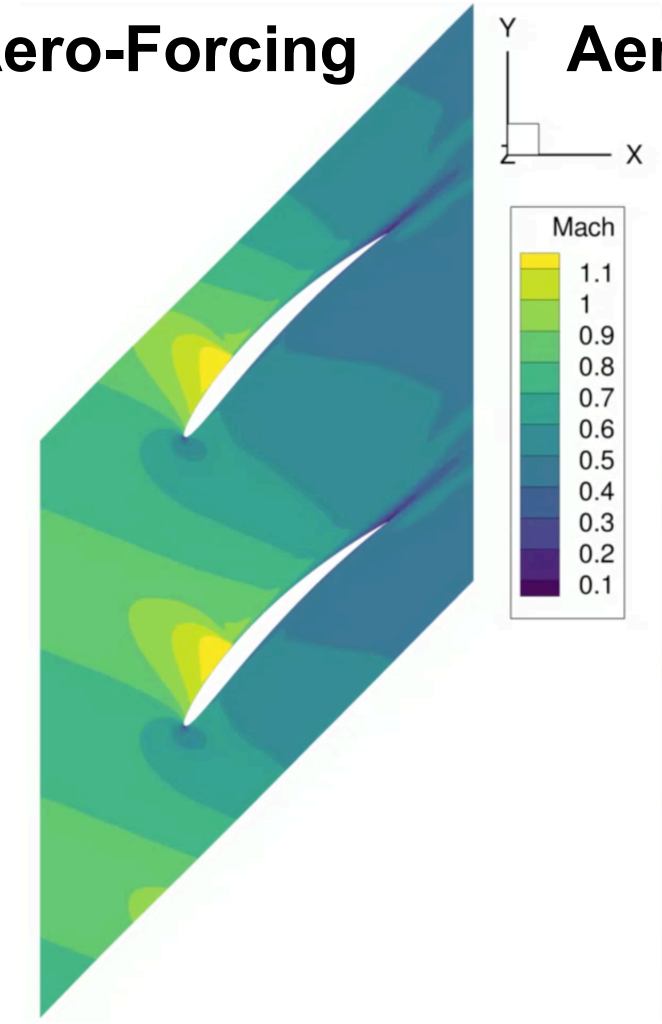
- Multi-frequency, harmonic balance method with deforming grid.
- Multi-zone, MP and HB, optimization using CAD-Based method.
- SU2 Branch:github.com/arubino/SU2/tree/feature_3D_turbo_aeroelasticity
- ParaBlade: github.com/NAnand-TUD/parablade/tree/master

TU Delft

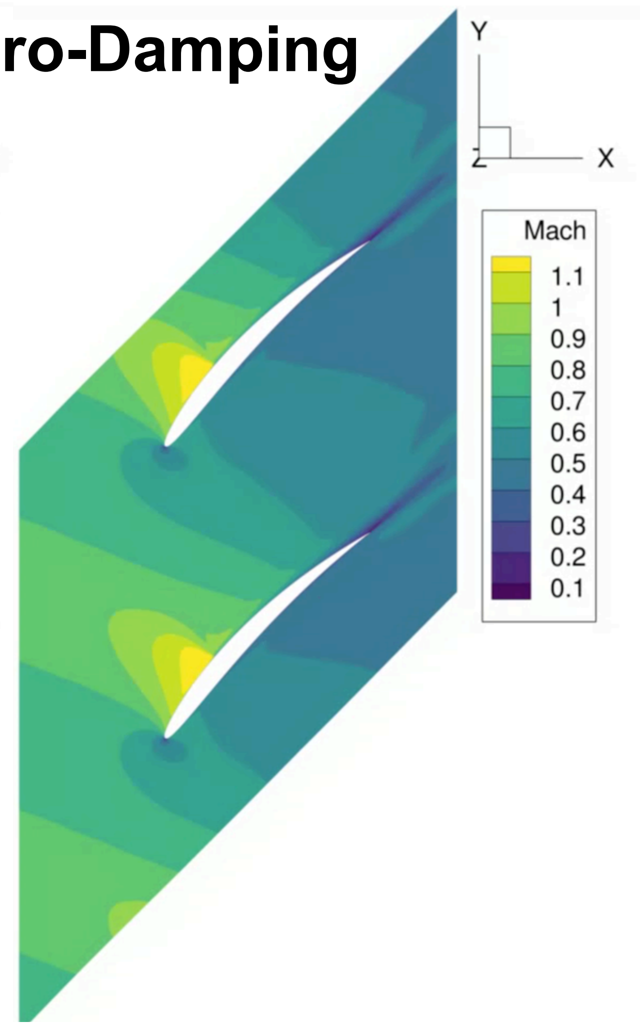
Example 1: FR Minimization in Compressor



Aero-Forcing



Aero-Damping

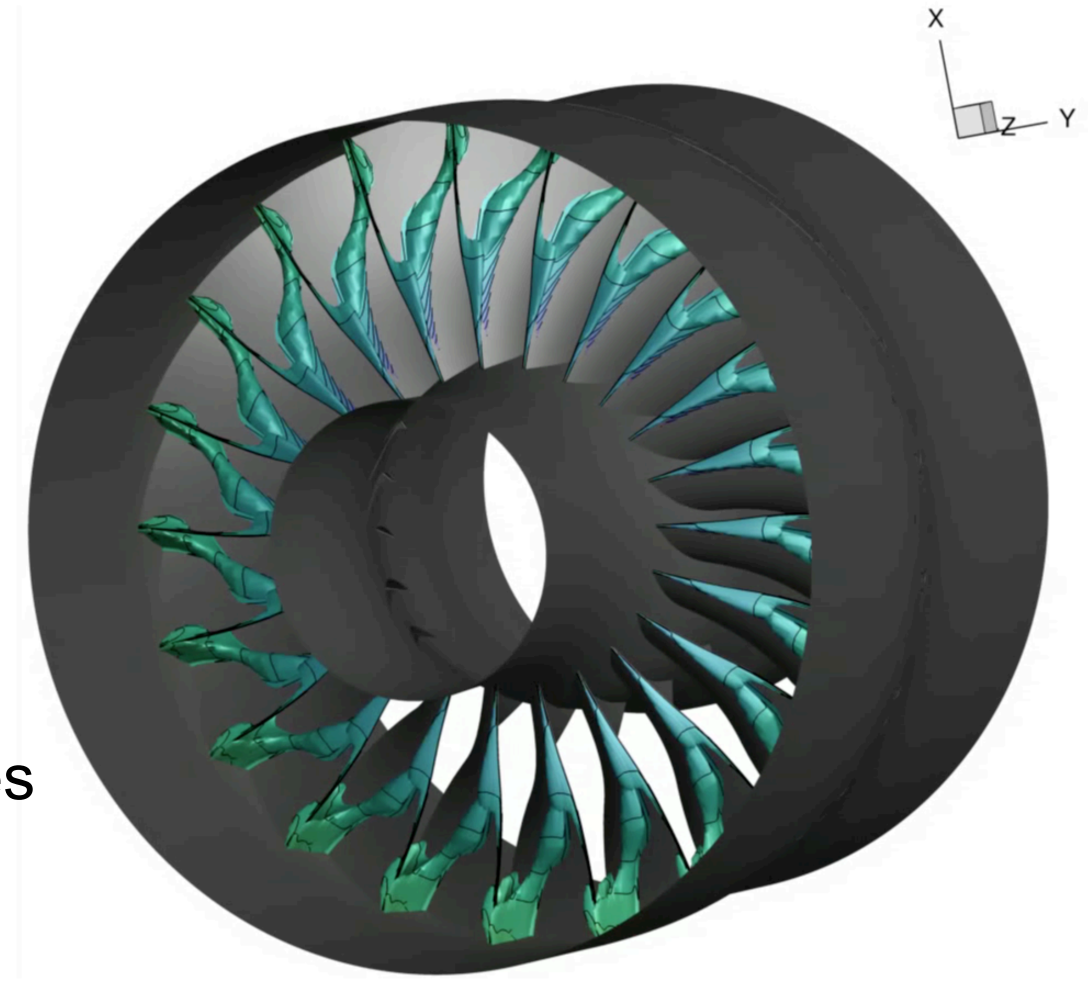


(Anand et. al, TurboExpo 2020)

Example 2: FR Minimization in NASA R67

Vibrating NASA R67

- CAD-Based Parametrization
- Deforming Grid (External File)
- Harmonic Balance + Adjoint
- Computational cost: 36h in 20cores
- Results available soon…



Future Perspectives

- Improve flow solver robustness → merge with develop
- 3D-FSI design with CAD → in progress
- CAD-based design for multi-zone (stator/rotor) problems → In progress
- More test cases/validation/lots of optimization…

Thank you for your attention…!!!
Questions ?

Email: n.anand@tudelft.nl