Adjoint Performance Optimisation for Fan Blade Design with Efficient Structural Constraint

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Motivation

- **Objective** - optimisation methodology for fan blades to increase their efficiency while maintaining acceptable maximum stress
- **Novelty** - coupling an adjoint-based aerodynamic optimisation with a response surface based model for constraining the maximum stress on the blade

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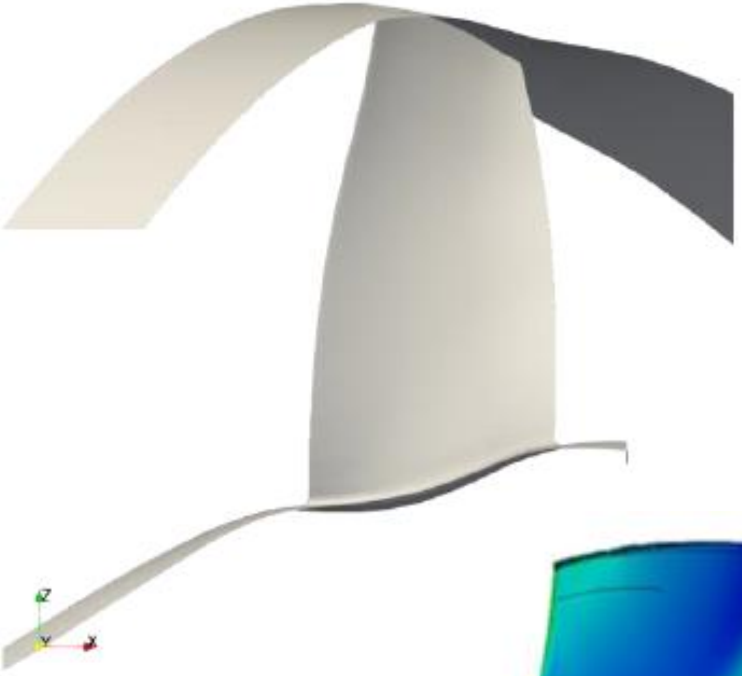
Test Case

- Rolls-Royce VITAL Fan Blade
- Representative of a modern fan
- Based on the test rig scale (a third of the engine scale)



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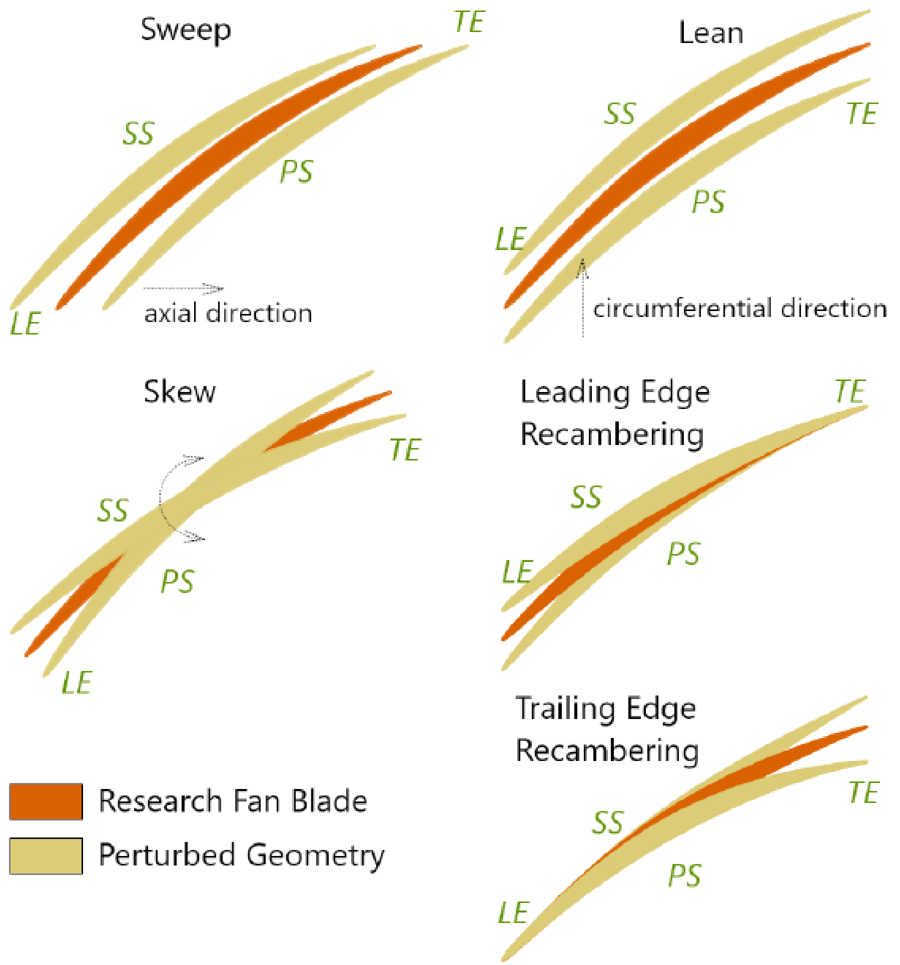
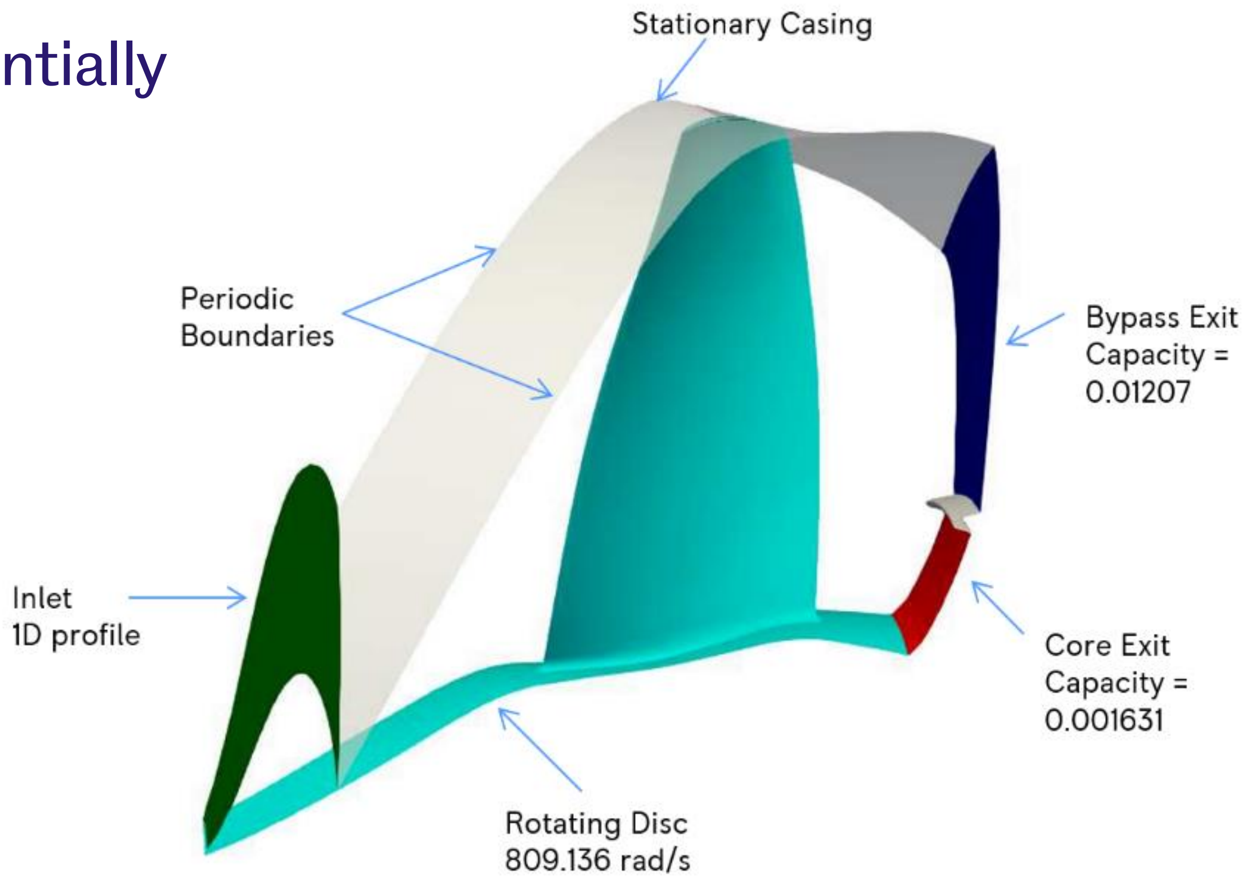
Geometry Parametrisation

- RR PADRAM's Engineering Design Parameters (EDP)
- Intuitive geometry manipulation
- Five EDPs, each controling a Degree of Freedom: Sweep, Lean, Skew, LE and TE recambering; two extra parameters: the LECA and TECA blending points
- Five blade span location: at 25%, 50%, 75%, 87.5% and 100%, based on fan blade noise production
- Smooth spanwise cubic B-spline interpolation
- A total of 35 DOFs



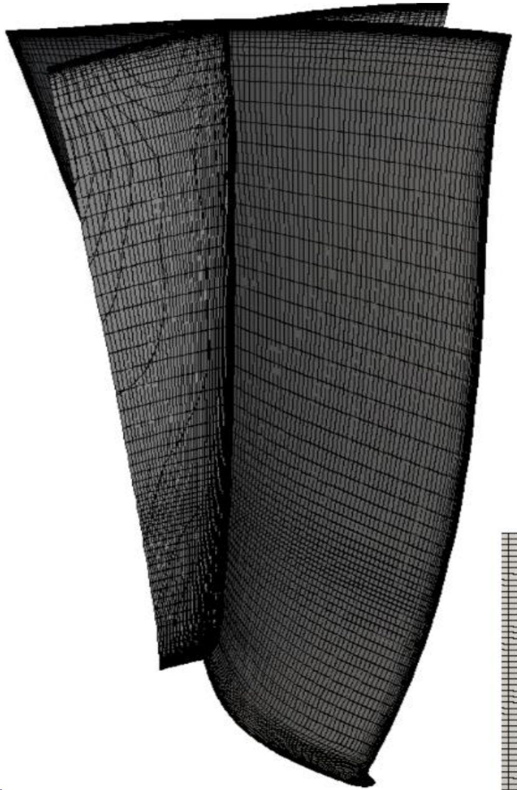
CFD Setup - Model

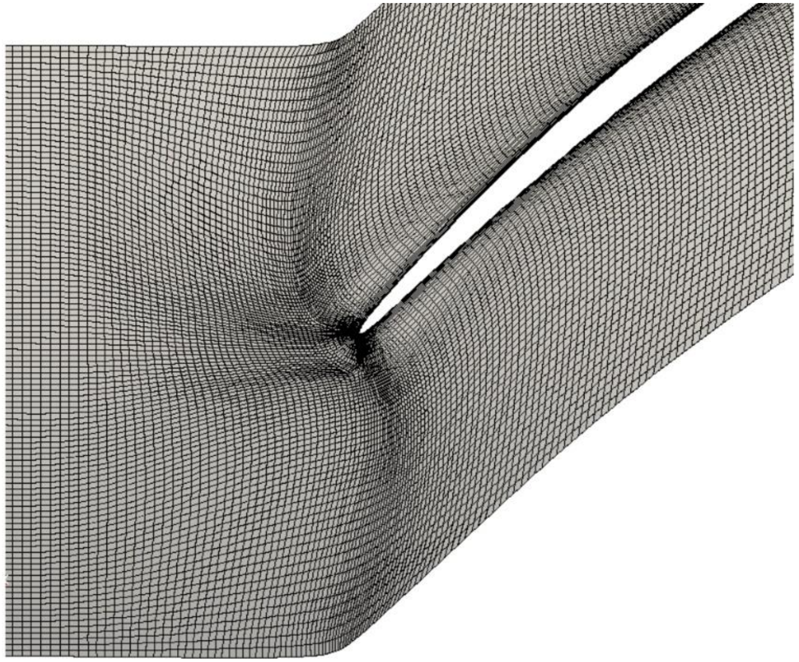
- RR CFD package, HYDRA
- Inlet boundary conditions: radial distribution of total pressure and temperature
- Outlet boundary condition: circumferentially mixed-out and radially mass-averaged capacity
- Adiabatic no-slip walls
- Rotational speed: 809.136 rad/s
- Turbulence model: Spalart-Allmaras



CFD Setup - Mesh

- Multi-block structured grids
- $y^+ \sim O(1)$
- Mesh size: approx. 6 million cells





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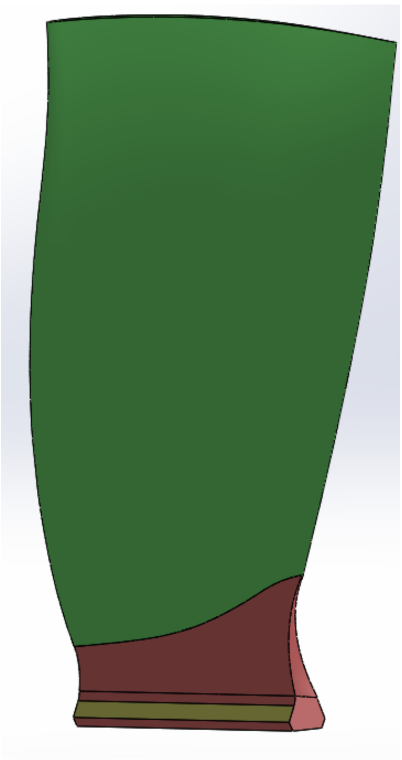
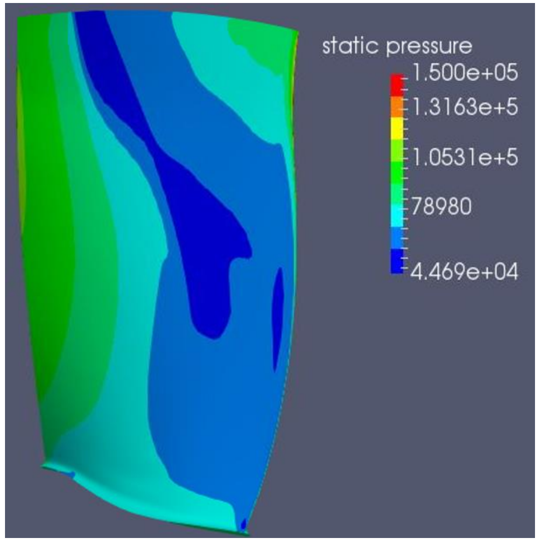
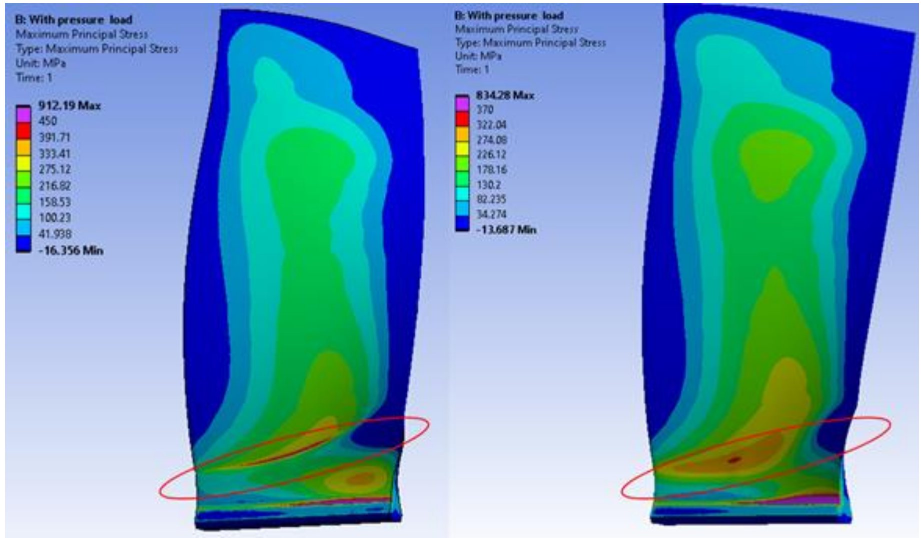
Structural Model

- The blade root was attached (red) and the yellow surfaces were fixed
- Loads: centrifugal load + integrated pressure load on the blade from CFD results
- Solid titanium alloy with yield strength 710 MPa
- The blade root ensures tangency to the aerodynamic blade shape to avoid stress concentrators
- The blade shape was preserved below 5% for smooth transition of new blade geometries







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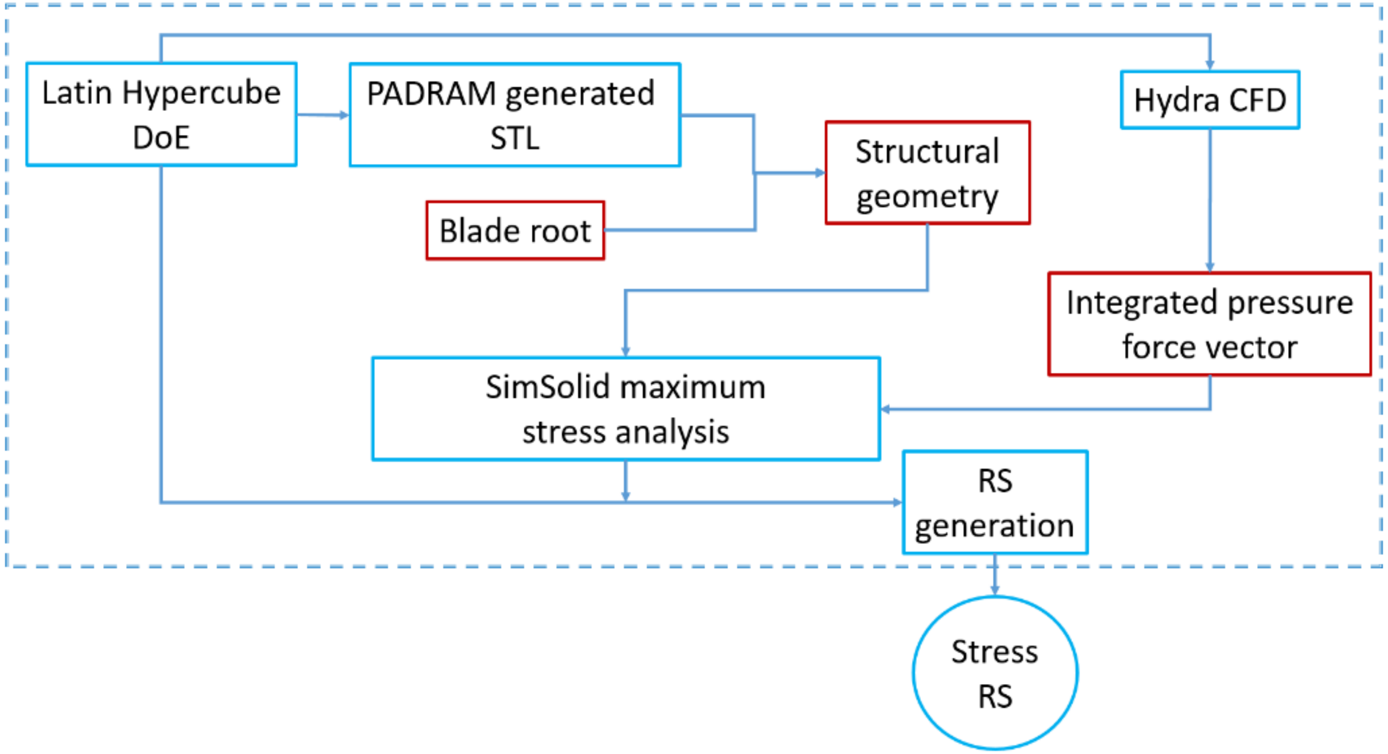
Stress Response Surface

- Latin Hypercube DoEs: 610, 900 & 2000 points
- Blade root automatically attached in SolidWorks
- Integrated pressure on the blade exported from HYDRA
- Maximum principal stress computed in SimSolid – fast meshless tool

Stress response surface generation workflow diagram



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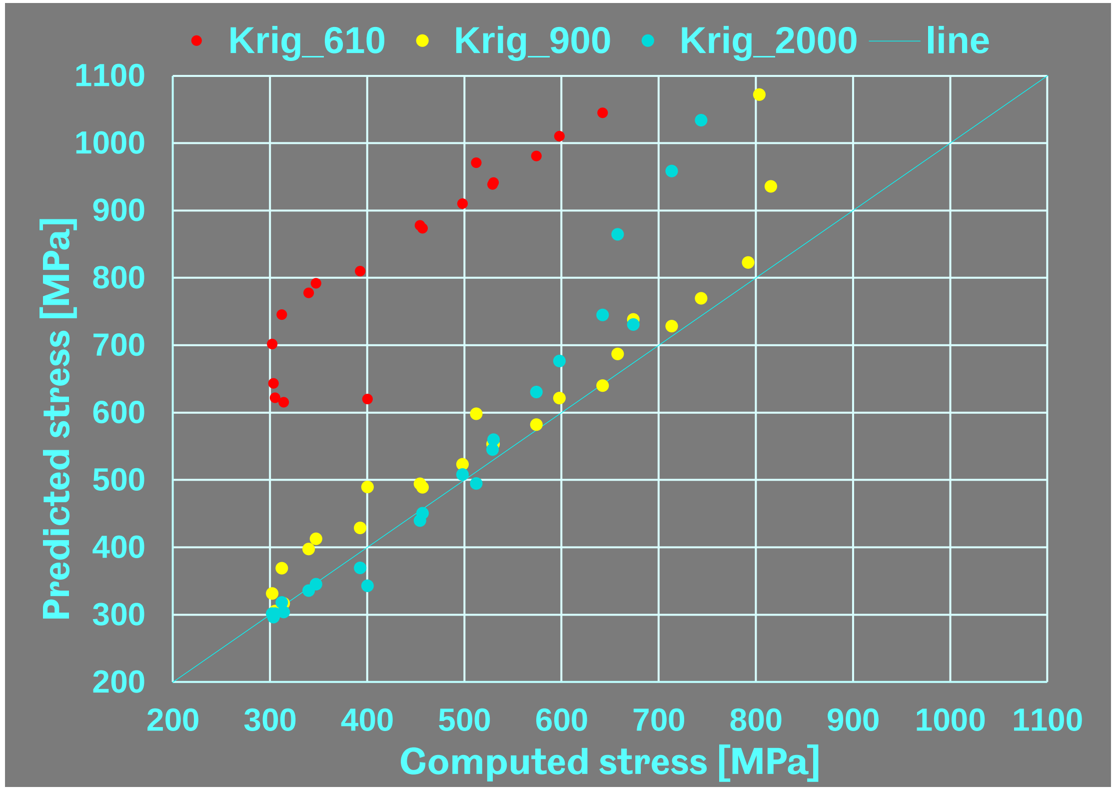
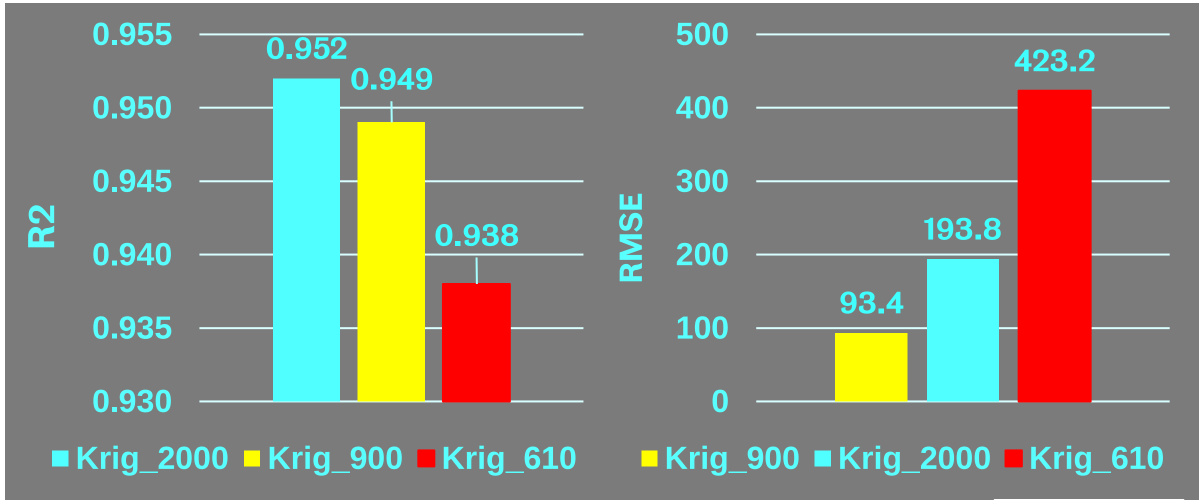
Stress Response Surface



- Response surface generated beforehand
- Tested RSMs: Kriging, Polynomial, RBF
- Region of interest: 300 – 800 MPa
- Test: 22 points resulted from an unconstrained aerodynamic optimisation
- 900 points Kriging was selected (half the RMSE and almost the same R2)



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Best results

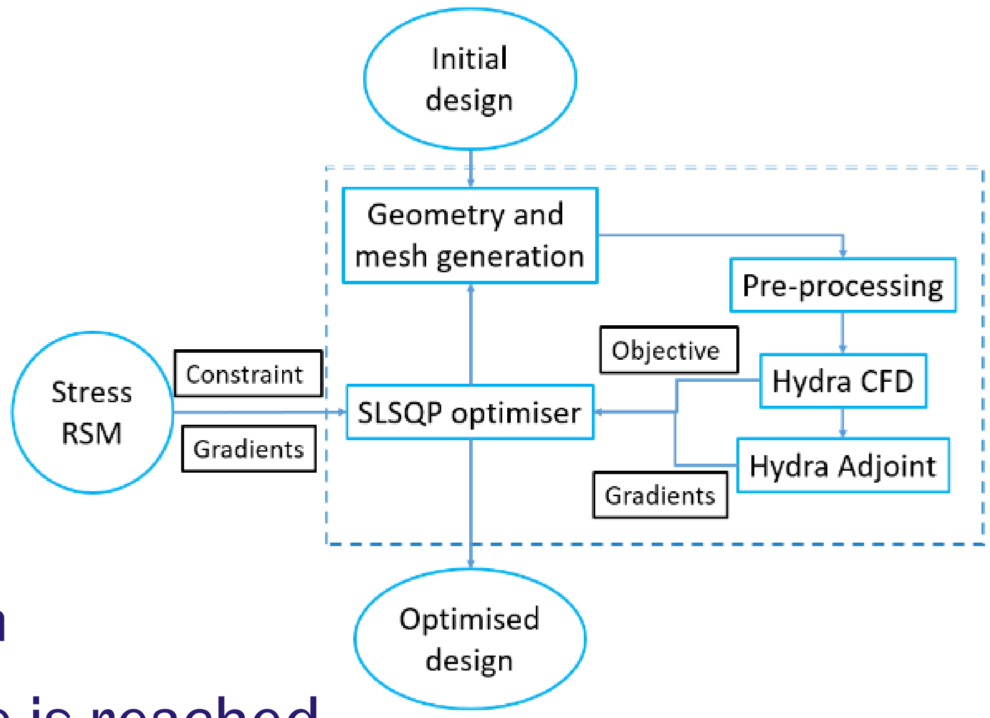
Adjoint Method

- Discrete adjoint approach in HYDRA-Adjoint
- The adjoint solver is coupled with the primal flow solver
- The computational cost does not depend on the number of design variables, but only on the objective function
- From a single adjoint solution, the sensitivity with respect to many design parameters can be computed

Optimisation Process

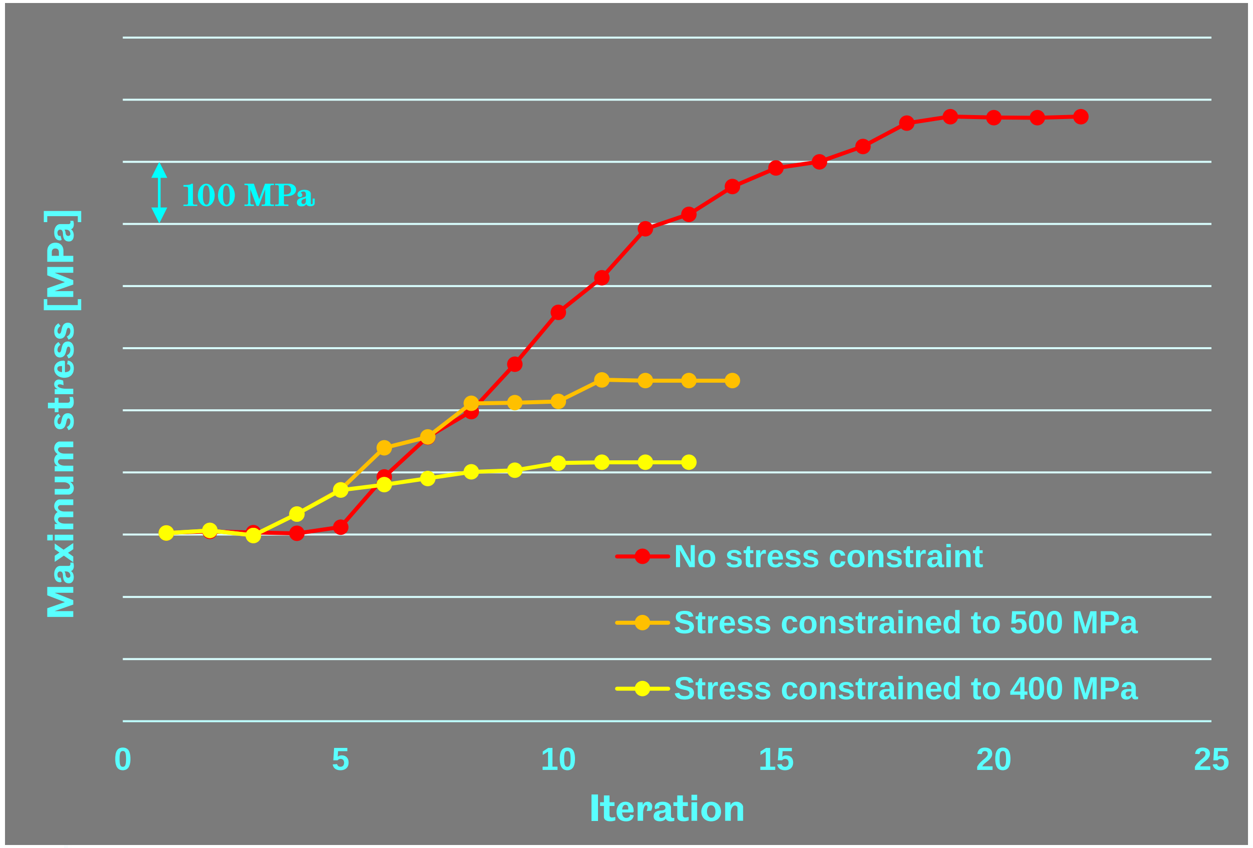
- Python - Sequential Least SQuares Programming (SLSQP) algorithm
- HYDRA CFD – Efficiency (objective function)
- RSM – Maximum stress (constraint)
- Efficiency gradients - HYDRA Adjoint
- Maximum stress gradients – finite difference
- Solving the quadratic programming problem gives a feasible direction used in the line search
- The process is then repeated until convergence is reached

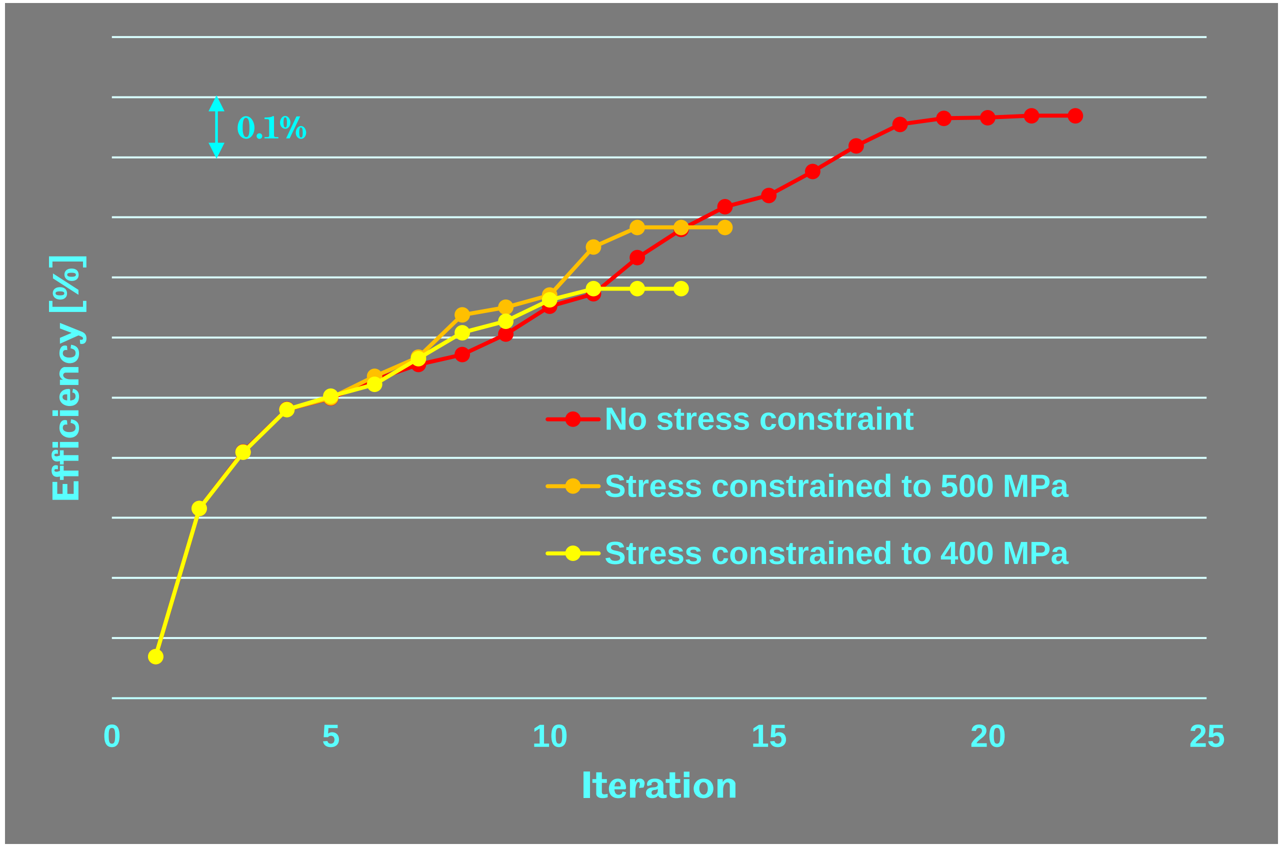
Optimisation workflow diagram



Optimisation Results

- Unconstrained and stress constrained optimisation histories for Vital fan blade
- The maximum stress was successfully constrained (to recommended 400 – 500 MPa values), but with a cost on the efficiency benefit





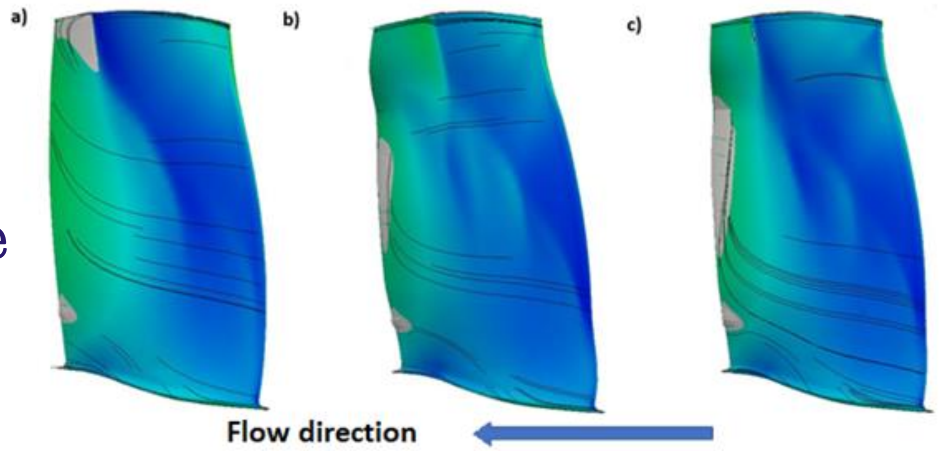
Optimisation Results

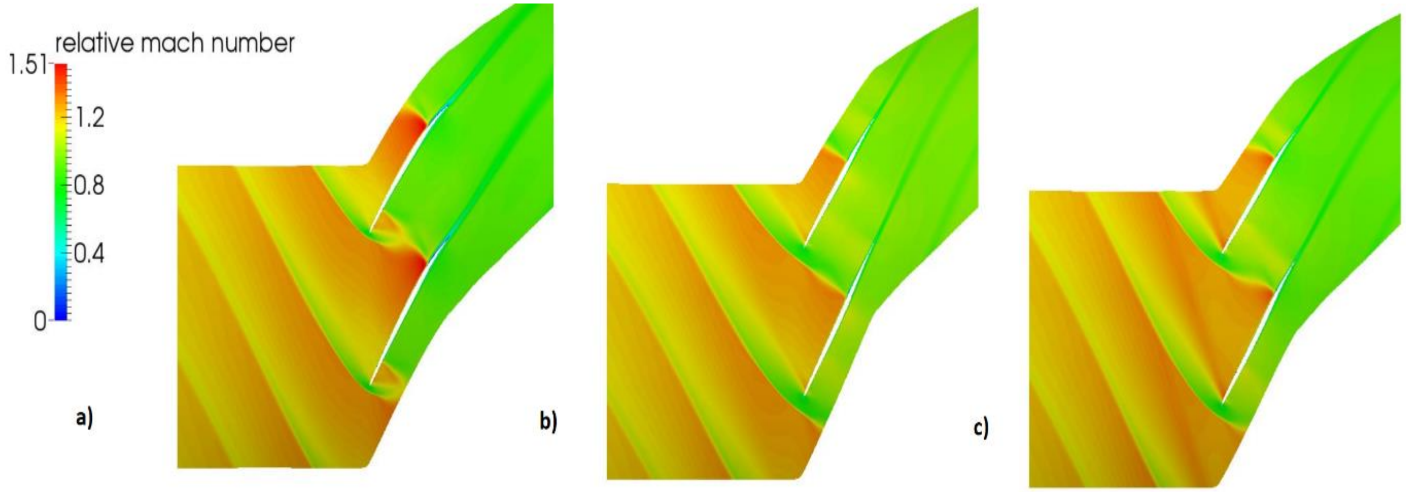
- Considerable increase in efficiency is achieved in the unconstrained optimisation (0.9%), but the maximum stress increases significantly as well, to almost 1000 MPa
- The efficiency benefit drops consistent with the imposed stress constraint, to 0.71% for 500 MPa and 0.61% for 400 MPa

Geometry	Efficiency benefit, [%]	Maximum stress, [MPa]
Datum	-	302.8
Optimal with no stress constraint	0.9	972.8
Optimal with stress constrained to 500 MPa	0.71	548.0
Optimal with stress constrained to 400 MPa	0.61	416.7

Optimal Geometry Flow Features

- Both optimum designs weaken the shock and remove the shock induced separation near the tip
- They also introduced some separation at the blade trailing edge around mid-span, more prominently for the stress constrained optimum

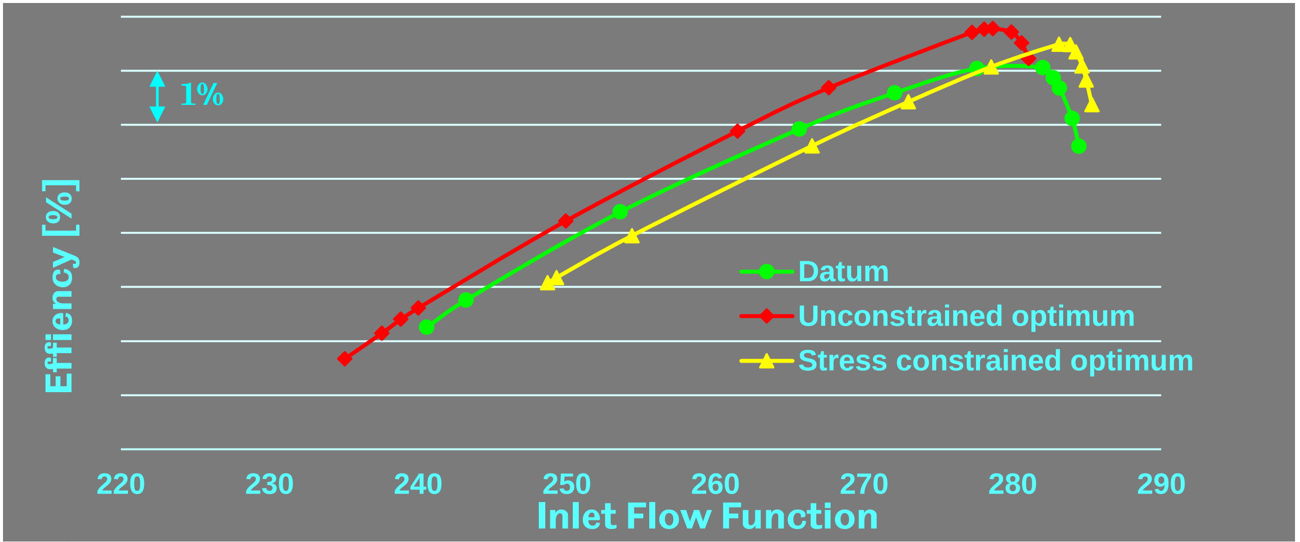


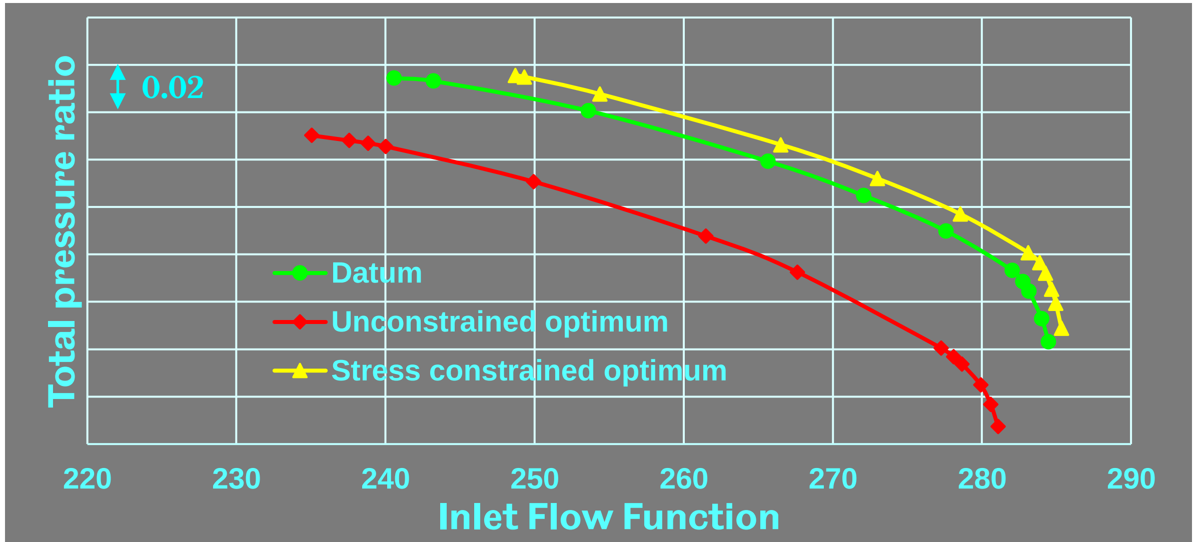


Pressure and Mach number distribution at mid span for: a)datum, b)unconstrained optimum; c)stress constrained optimum

Optimal Geometry Off Design Performance

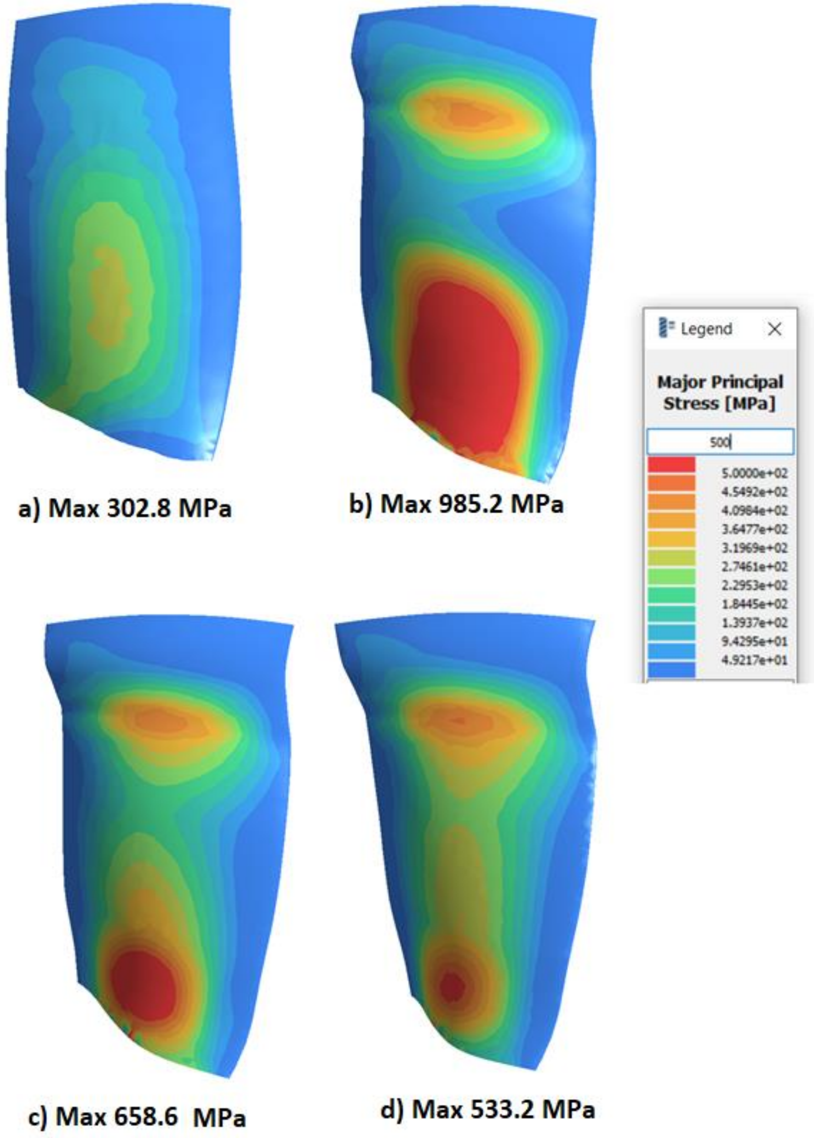
- Unconstrained optimum - better efficiency for all points and good stability margin, but the pressure ratio (PR) drops by approx. 2.2%
- Stress constrained optimum - reduced stability margin, higher efficiency in the design point region (lower for lower mass flow rates), PR increases for all points, with an average of 0.55%





Optimal Geometry Stress

- The stress distribution is similar for all optimal geometries, with a second region of increased stress
- The actual, computed values are about 25% higher than as produced from the response surface assessment
- The optimisation with the stress constraint set to 400 MPa successfully keeps the stress value close to the desired 500 MPa



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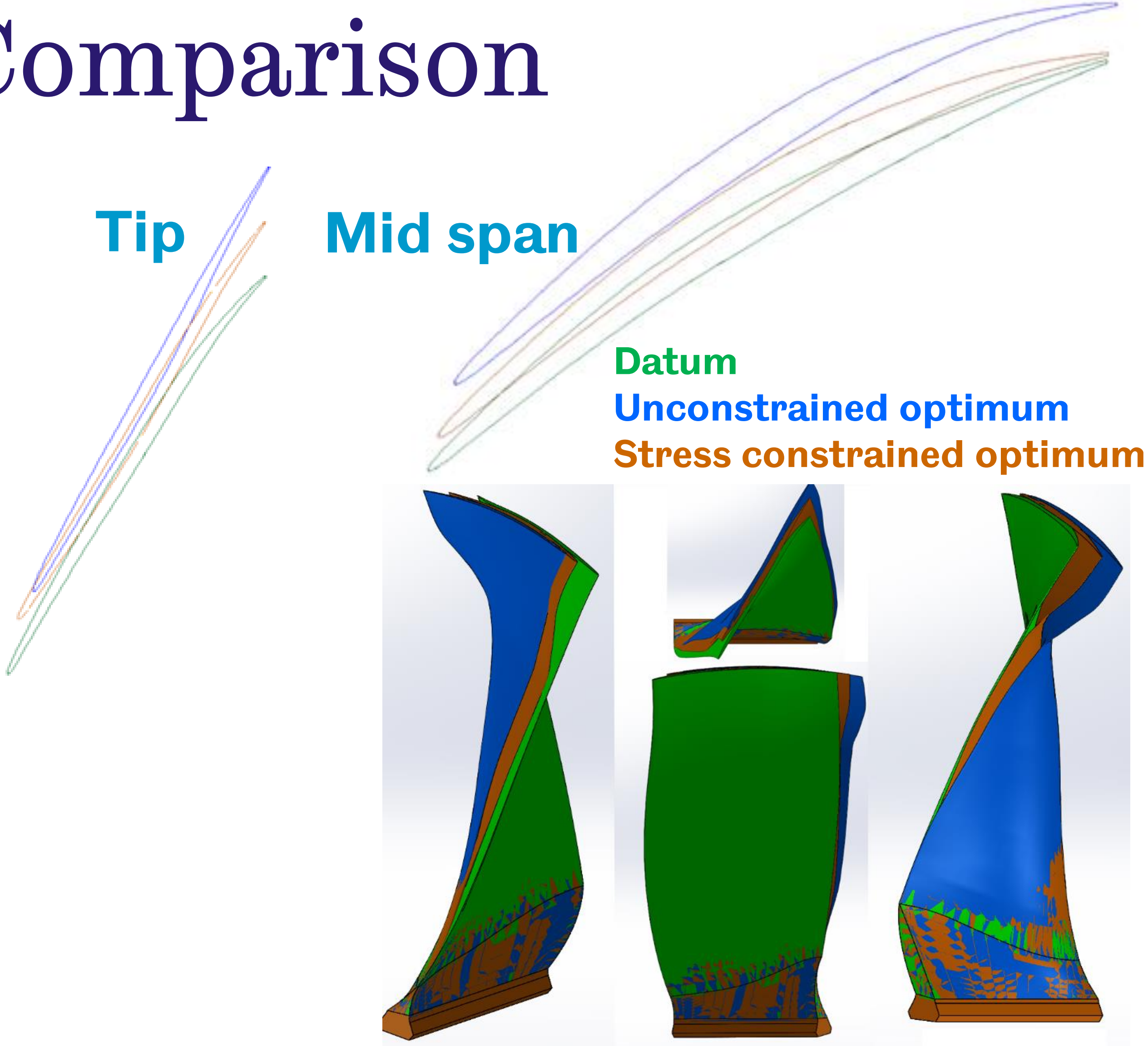
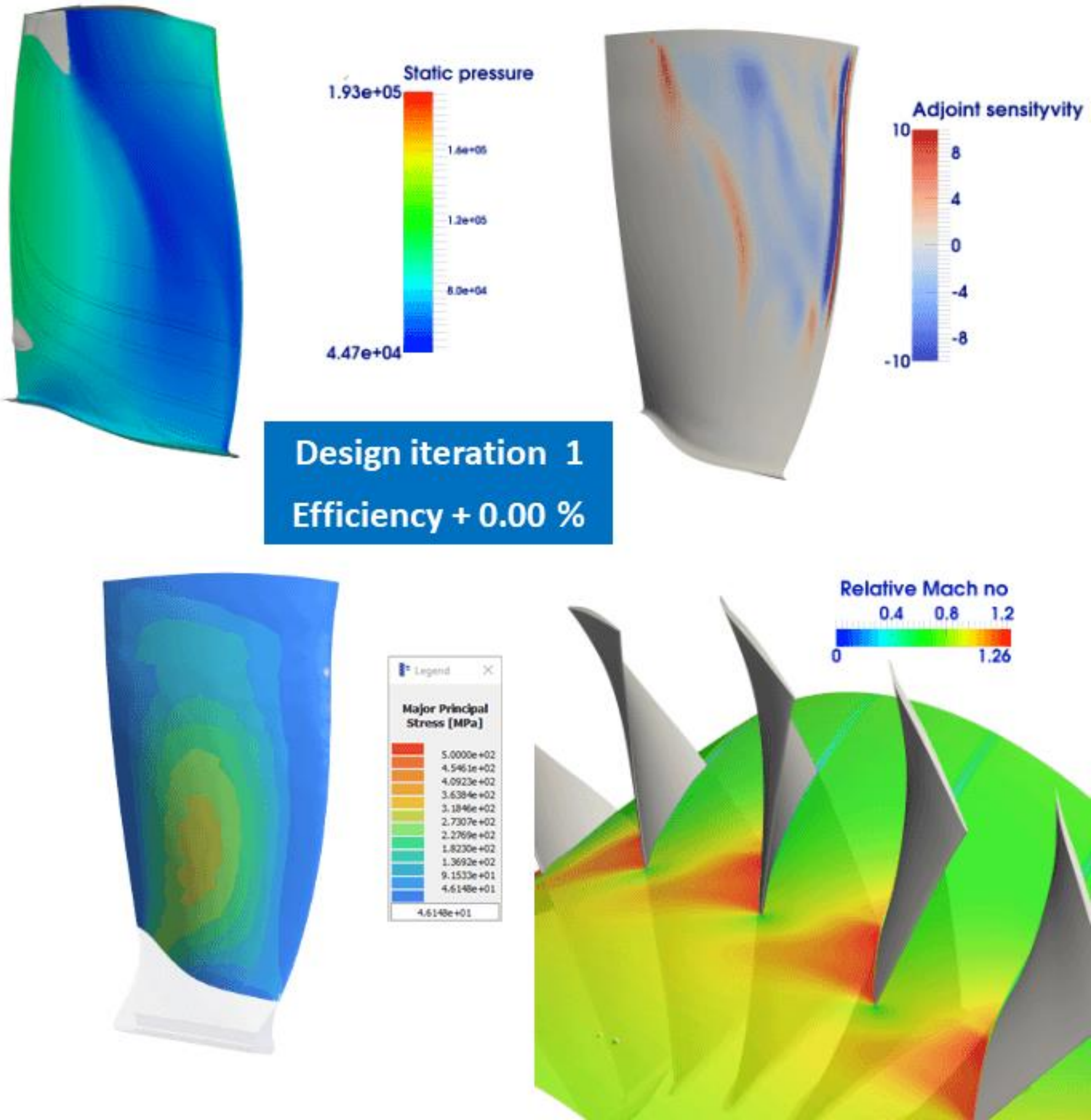
Optimal Geometry Comparison

- Both unconstrained and constrained blade profiles have a large back sweep near the tip and at mid span
- Both optima also have lean and a visible trailing edge recambering
- These geometric differences to the datum are more pronounced for the unconstrained optimum, which leads to the higher stress values



Conclusion

- The proposed MDO method has successfully and quickly led to an improved design
  - Increased aerodynamic efficiency by 0.6%
  - Maintain the stress below a specified value of 500 MPa for the VITAL fan blade
  - Results within 2 -3 days



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Conclusion

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- The method can choose to: include the blade root, consider both centrifugal and aerodynamic loads and constrain the pressure ratio
- For stability margin – the method needs to be expanded for multipoint optimisation
- For better RS accuracy: increase the number of points or use novel predictive models (coupling with Artificial Neural Networks with Active Design Subspaces is underway)

Publications

- Cuciumita, C., John, A., Qin, N., and Shahpar, S., 2021, "Structurally Constrained Aerodynamic Adjoint Optimisation of Highly Loaded Compressor Blades", ASME Paper No. GT2021-59717

- John, A., Qin, N., and Shahpar, S., 2020, "The Influence of Parameterisation Setup on the Constrained Adjoint Optimisation of Transonic Fan Blades", ASME Paper No. GT2020-15352

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Thank you for your attention!

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