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MULTI-DISCIPLINARY MULTI-OBJECTIVE DESIGN OPTIMIZATION OF A CENTRIFUGAL COMPRESSOR IMPELLER

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- Introduction
- Advantages of Inverse design for 3D multi-objective optimization
- Compressor Test CaseNoise model
- Results
- CFD Analysis
- Conclusions

Typical Design Requirements for Centrifugal Compressors

- High pressure ratio
- High efficiency
- Wide stable operating range
- Low cost
- High reliability despite being subjected to vibration and flow excitation (especially Turbochargers).

Hence centrifugal compressor aero/mechanical design is subjected to one of the most complicated multi-objective/multi-point design requirements in turbomachinery **requiring use of large part of design space.**

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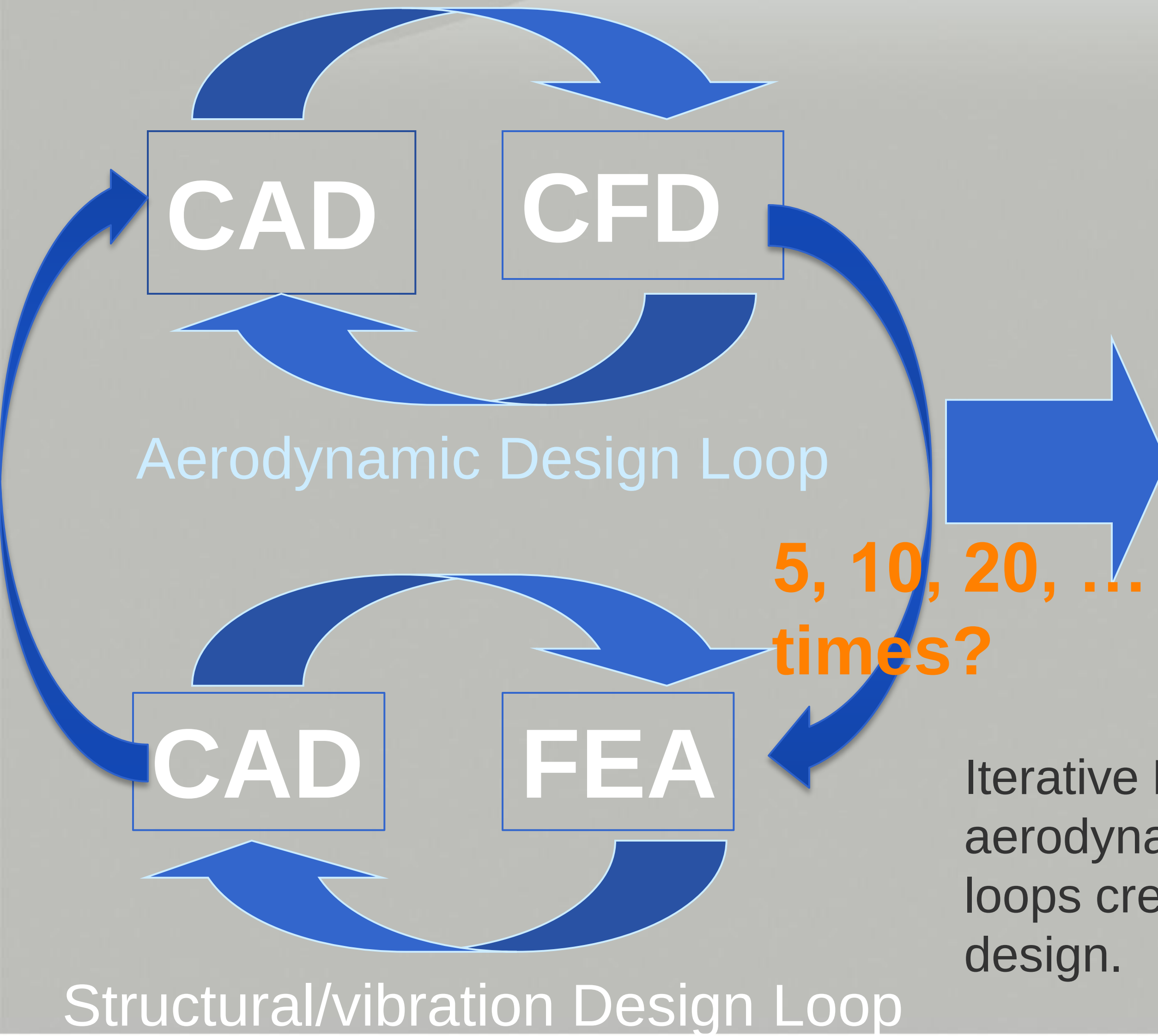
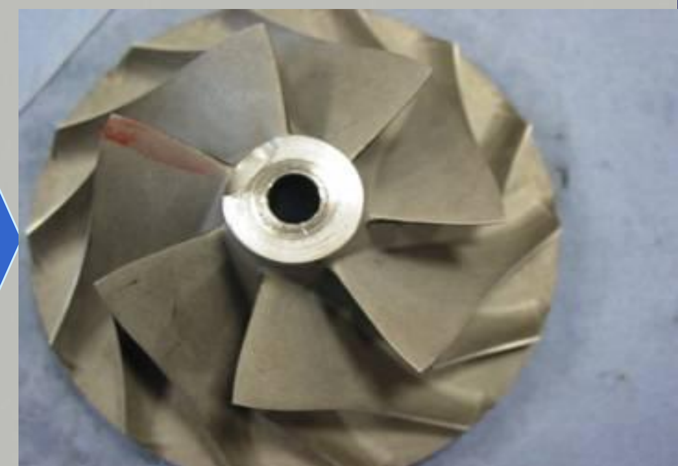
Conventional Aero/Mechanical Design

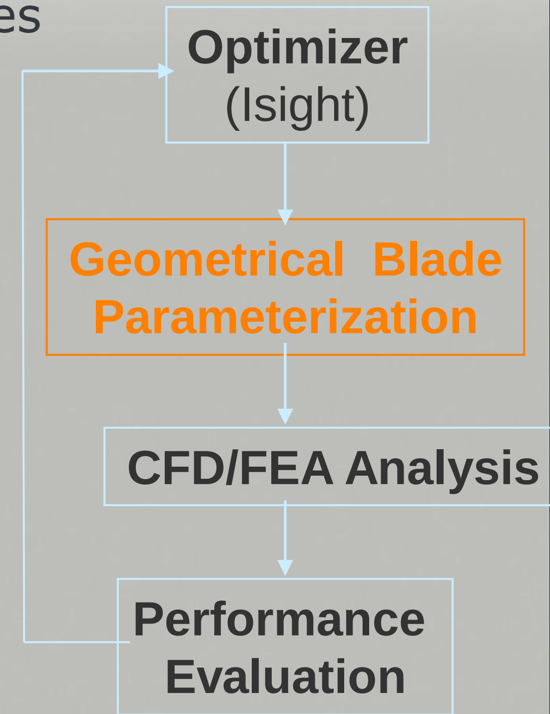




Iterative Process and separate aerodynamic and Structural design loops create major bottlenecks in design.

Conventional Automatic Optimization

- Conventional automatic design optimization strategies based on blade geometry parameterization.



Advantages:

- Reduction of man cost
- Systematic design methodology

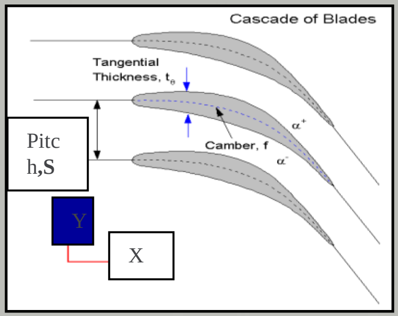
Drawbacks:

- High computational cost
- Large number of design parameters for 3D
- Weak Non-linear relationship between geometrical design parameters and aerodynamic performance
- Difficulty to derive a general know-how
- Design constraints (design mass flow rate, work coefficient, etc

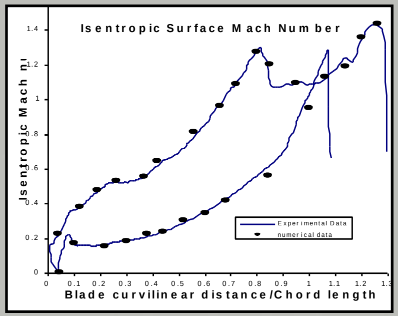
MOST OF DRAWBACKS ARE RELATED TO THE BLADE PARAMETERIZATION

Inverse Design Method

Conventional (Direct) Approach

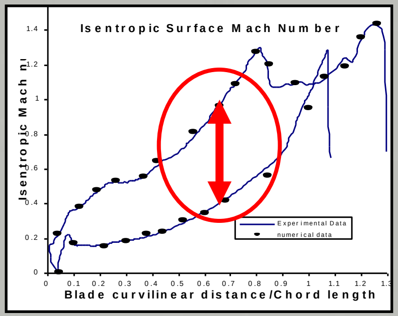


Geometry is Specified

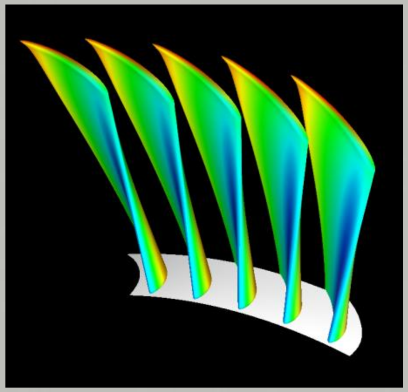


Aerodynamic performance

Inverse Design



Aerodynamic Performance (blade loading)



3D Geometry

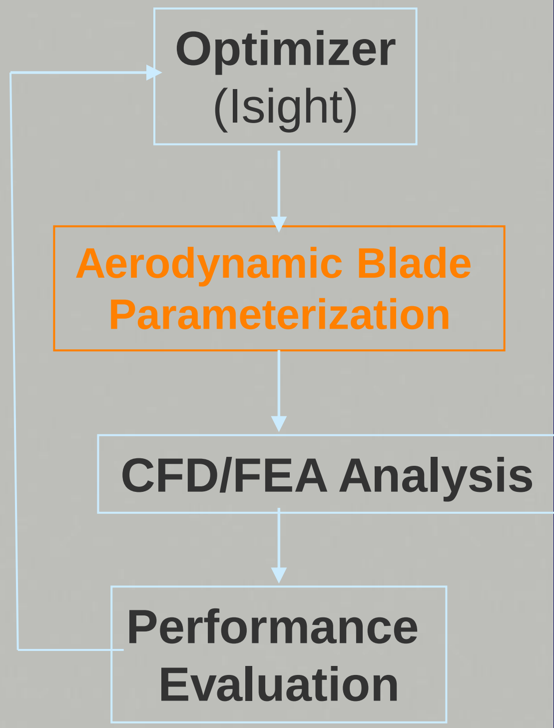
Direct Control

- 3D flow is extremely complex, so with **Direct Approach** it is difficult to exploit flow analysis results into the design process
- **Inverse Design** allows designers to control the parameters that directly affect performance

Automatic Optimization based on Inverse Design Parameterization

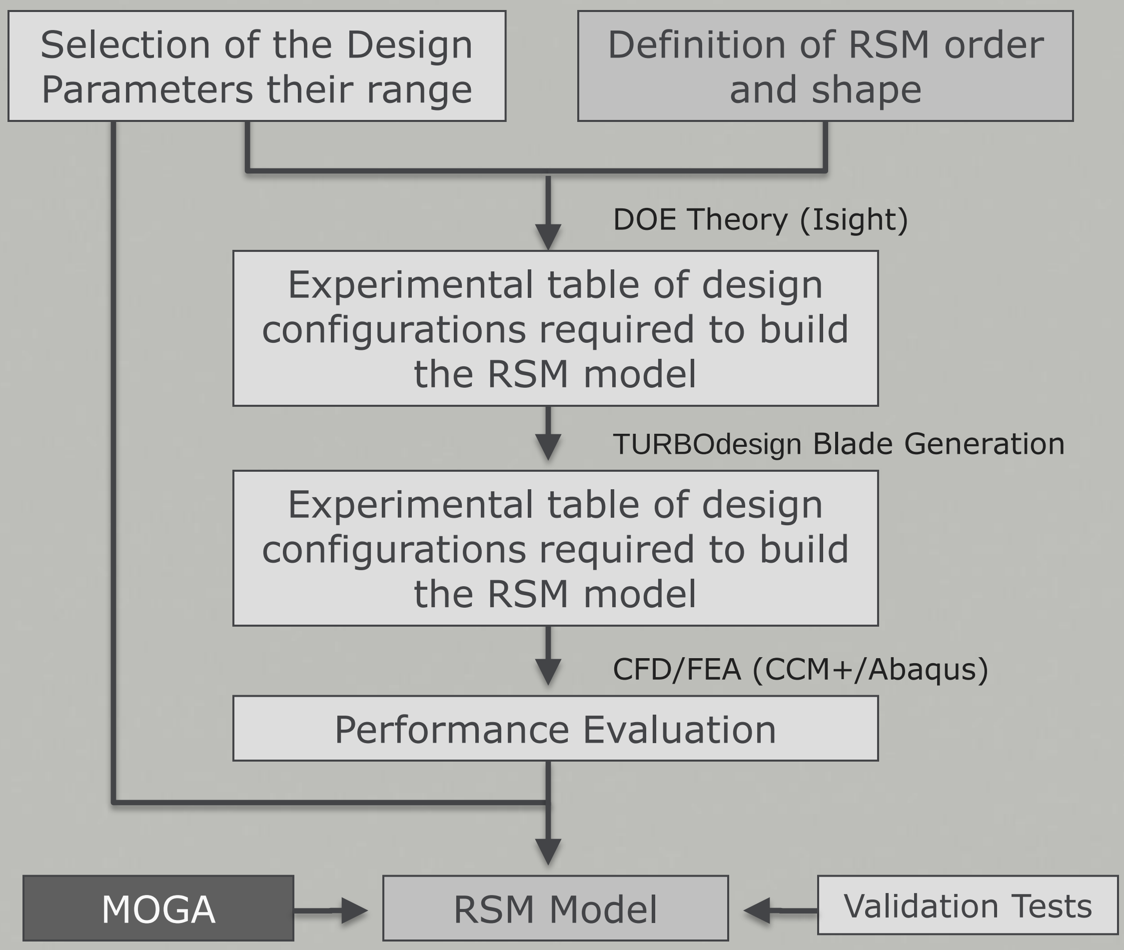
Advantages of a blade parameterization based on Inverse Design:

- ✓ A lower number of input parameters is required to describe the blade geometry.
- ✓ The design specifications (mass flow rate, work input coefficient) are automatically satisfied
- ✓ The objective function Y=F(Xi) correlating the input parameters to the output performance has a simpler mathematical expression
- ✓ Results of optimum solution can be easily exploited for similar design problems



Optimization Strategy Based on

Inverse Design+DoE + RSM+MOGA



Ideal method for multi-point / multi-objective design

Main Advantages of IDOE strategy:

- ✓ Low computational cost
- ✓ Computational time not related to the number of performance parameters
- ✓ Easy sensitivity analysis
- ✓ Fast MOGA optimization on RSM
- ✓ Inverse design parameterization ensures good accuracy of the approximation

Baseline Compressor

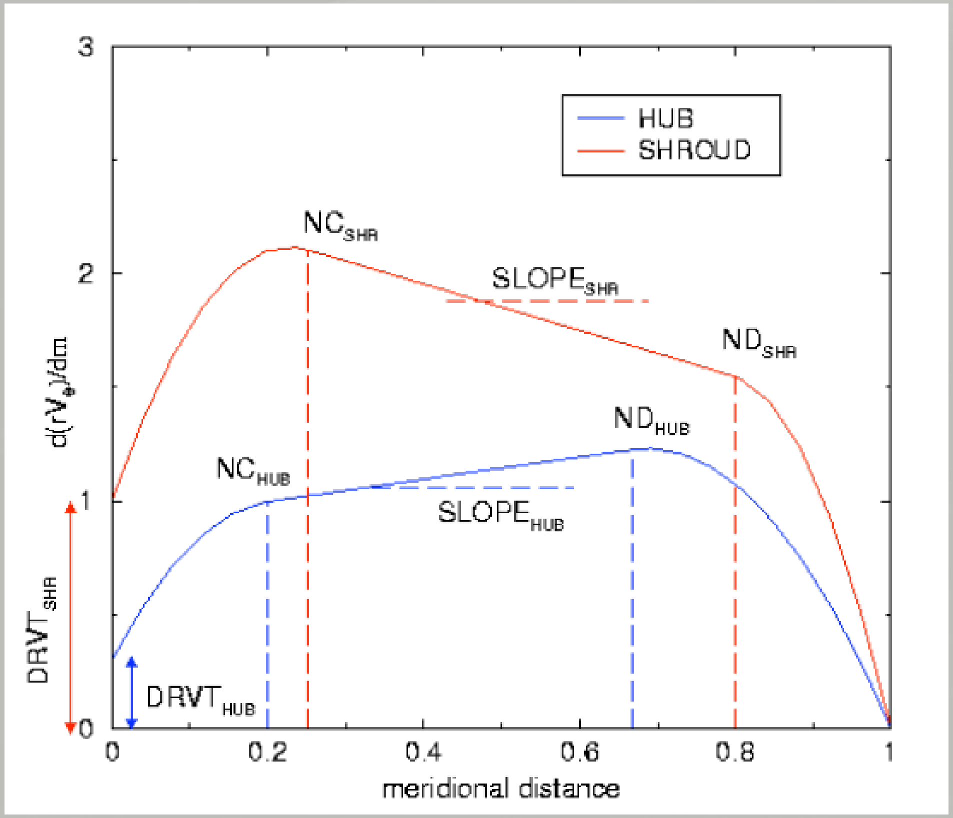
Impeller	Baseline Impeller
Shaft speed	N=14000 rpm
Design flow	5.31 kg/s
Impeller Tip radius	r2=200 mm
Rotor Tip speed	U2=293m/s
Pressure Ratio	Pt_{12}=2.1
Blade number	20 Full blades

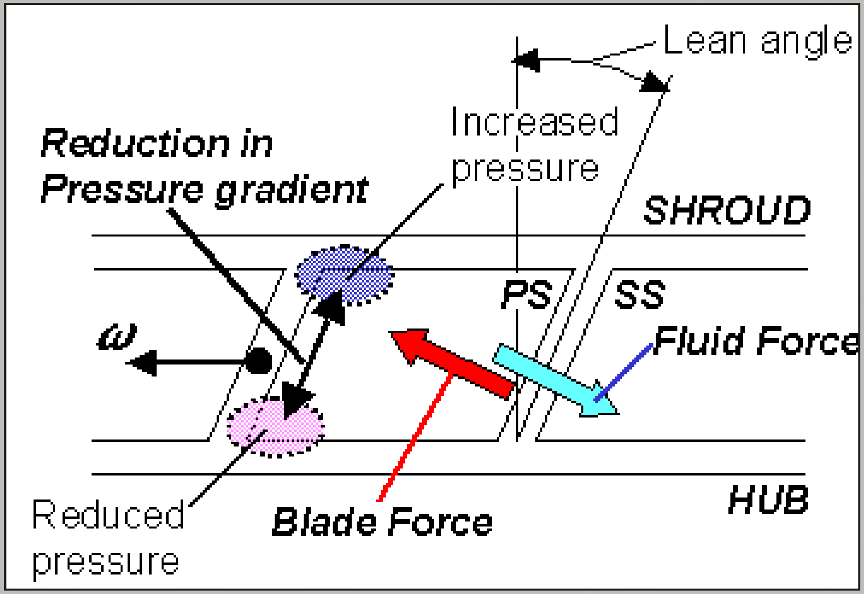
Baseline Impeller is the impeller used by Eckardt at DLR Cologne for LDV measurements

Material Property (Aluminium Alloy):

- Density: 2.7e-09 Ton/mm^3
- Young's Modulus: 7000 MPa
- Poisson's ratio: 0.35
- Thermal Expansion: 2.31e-5 mm/mm

Basic Design Parameters in TURBOdesign1





Blade loading

Stacking

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Design and Performance Parameters

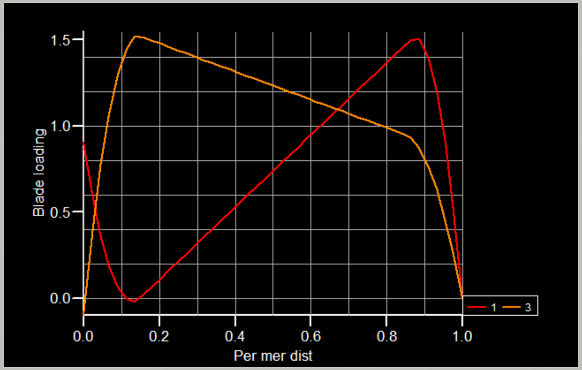
Design Parameters

Parameter	Range	No of Parameters
$SLOPE_{HUB}$	0.5 to 3	1
$SLOPE_{SHR}$	-1.2 to 1.5	1
$DRVT_{HUB}$	0 to 0.9	1
Stacking value (wrap angle)	-5 deg to + 10 deg	1

A DOE table generated by Isight Latin Hypercube was used consisting of 22 configurations.

Performance Parameters

Parameters	Operating Point
T-T Efficiency	Design point (Qd)
T-T Efficiency	85% of Qd
Choke & Stall Flow rate	
Peak Stress	Design Flow



Range of loading Parameters

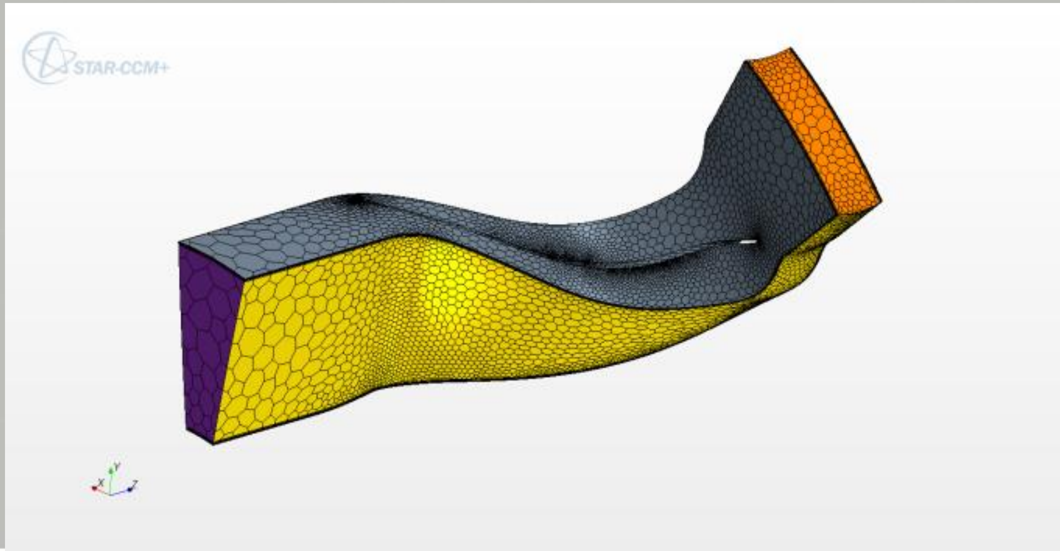
Impeller Geometries

Large variation in geometry of impeller is achieved with only 4 design parameters

CFD Analysis by CCM+

TurboWizard input, and polyhedral automeshing

- ~400k cells per blade passage, low-y+ wall resolution
- Inlet Stagnation pressure, outlet pressure/target mass flow
- Full performance curve for 14000RPM speed line
- 22 designs – over 200 CFD calculations



FEA Interface

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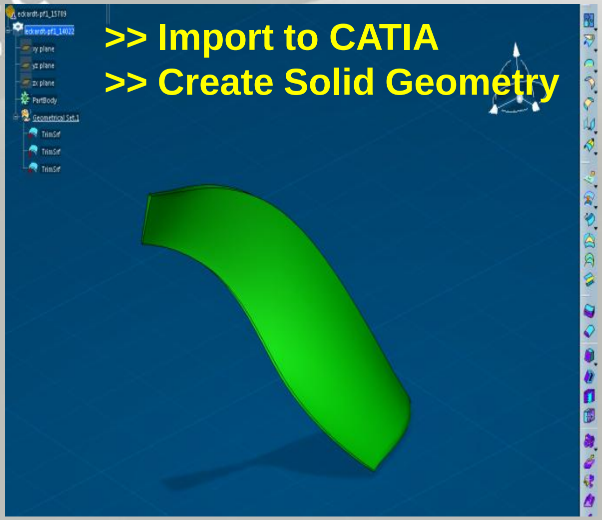
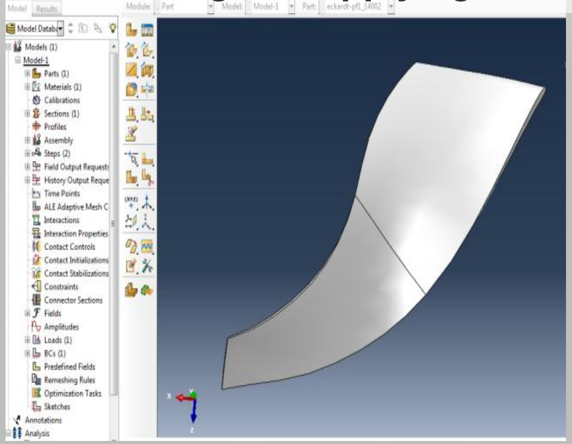
IGES file from TURBOdesign1

>> Import to CATIA
>> Create Solid Geometry

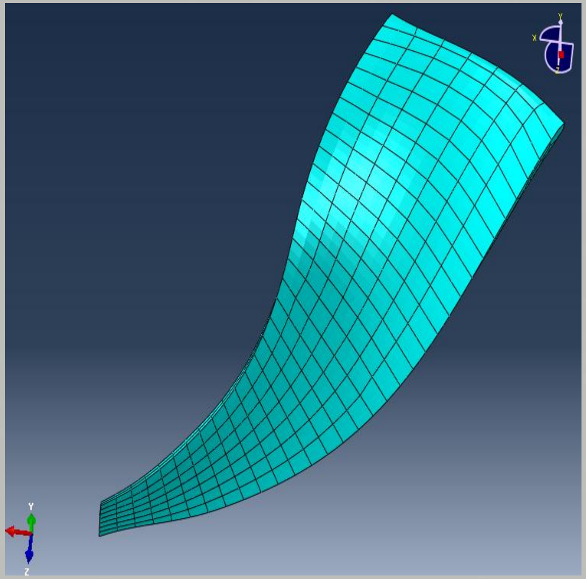


>> Import to Abaqus/CAE
>> Meshing and Applying B.C.



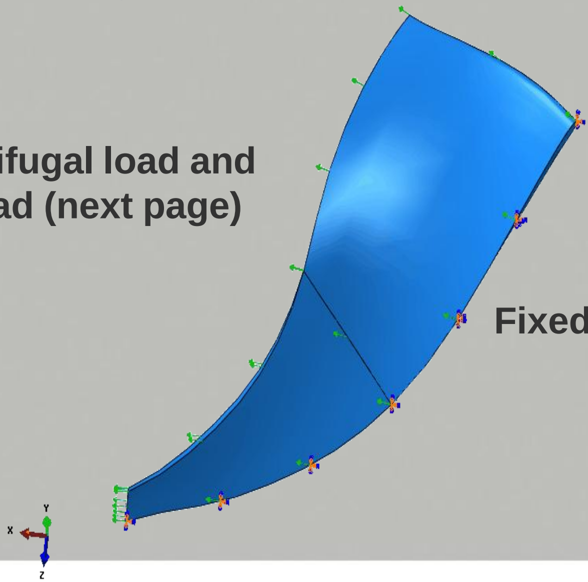
Boundary Condition

Meshing



C3D20R solid element is used.
8K ~ 12K DOFs

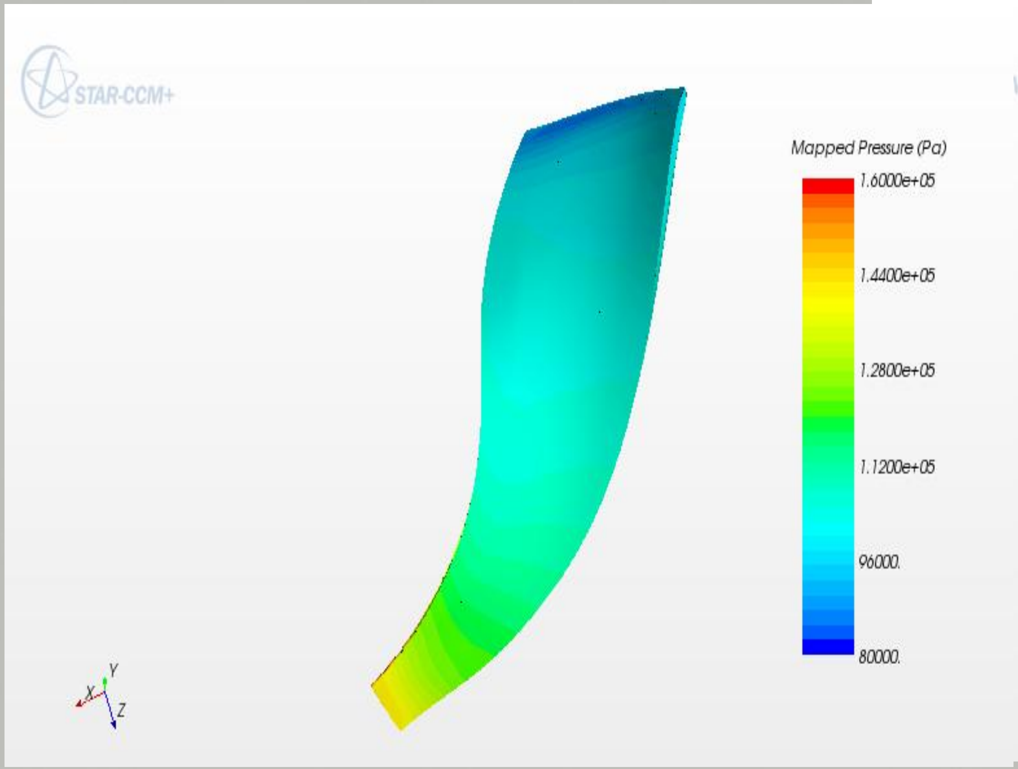
Apply centrifugal load and pressure load (next page)



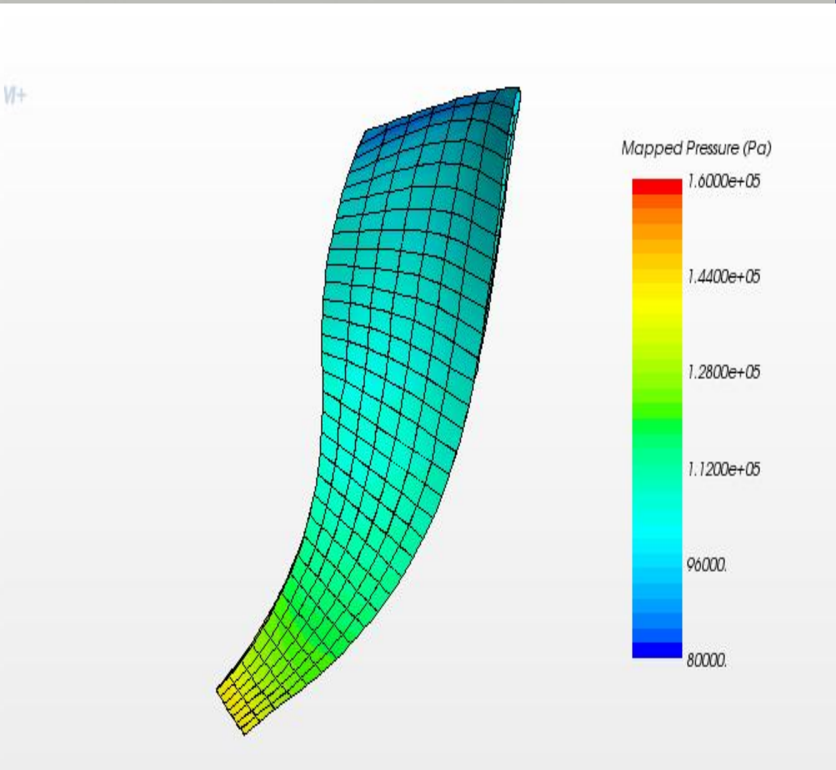
Fixed on disk side

Pressure Mapping in STAR-CCM+

- Abaqus input file extracted directly from STAR-CCM+ is used for pressure load.

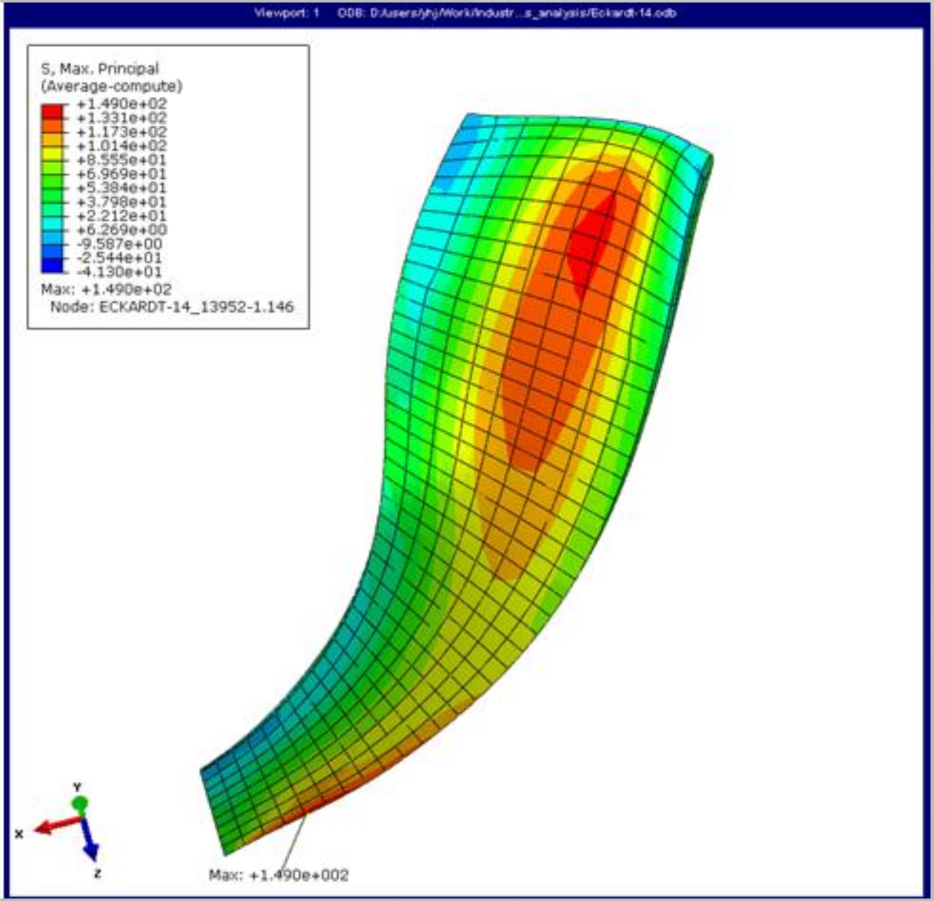


Pressure in CFD model

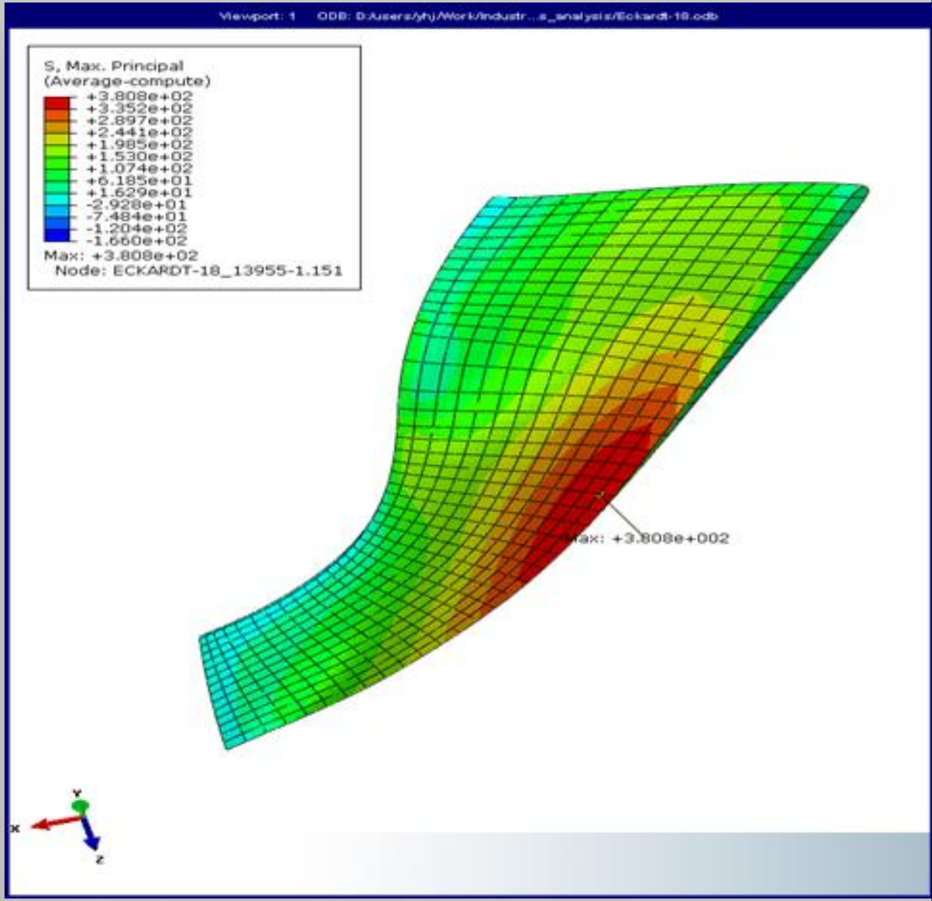


Pressure in Abaqus model

Typical FEA Results



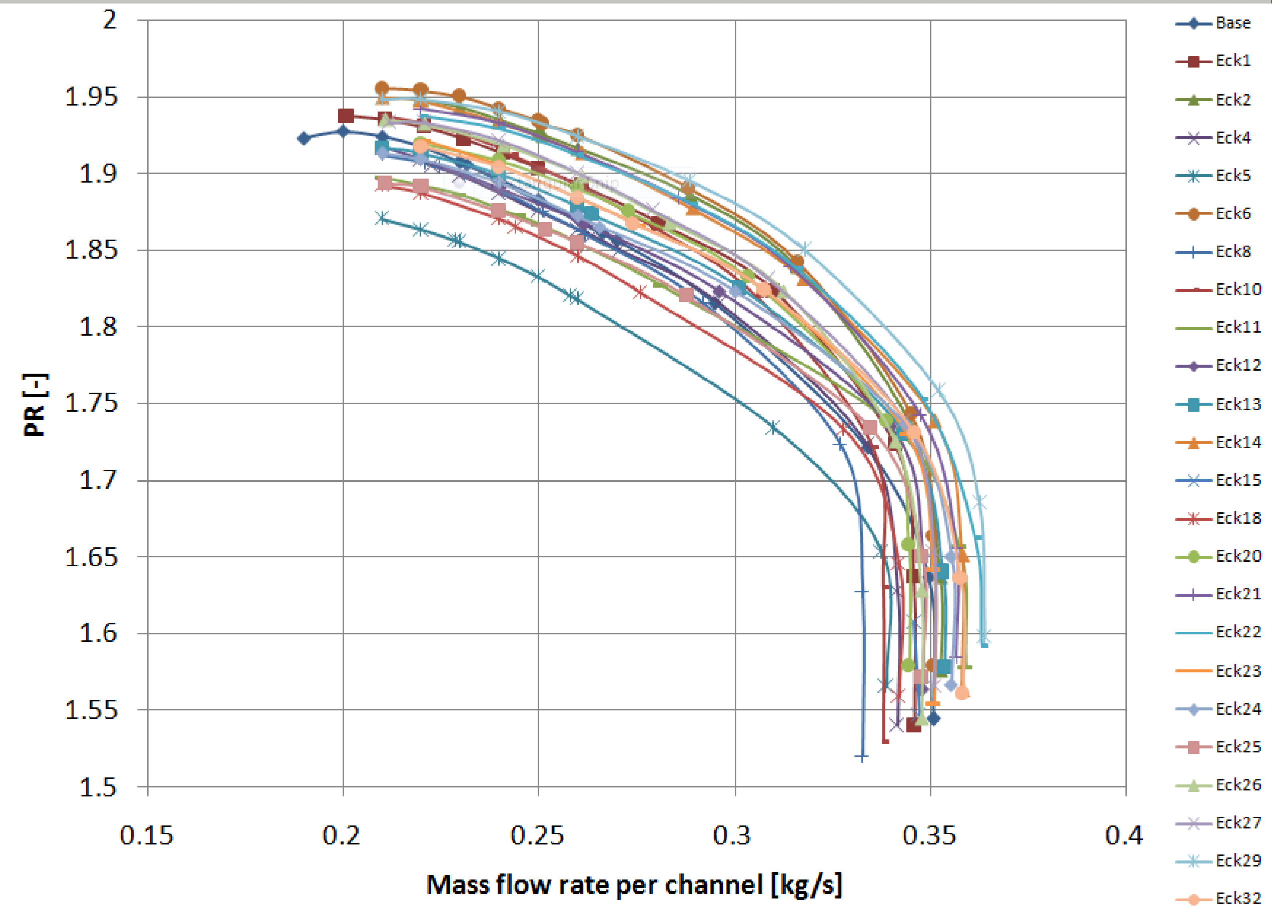
Impeller 14



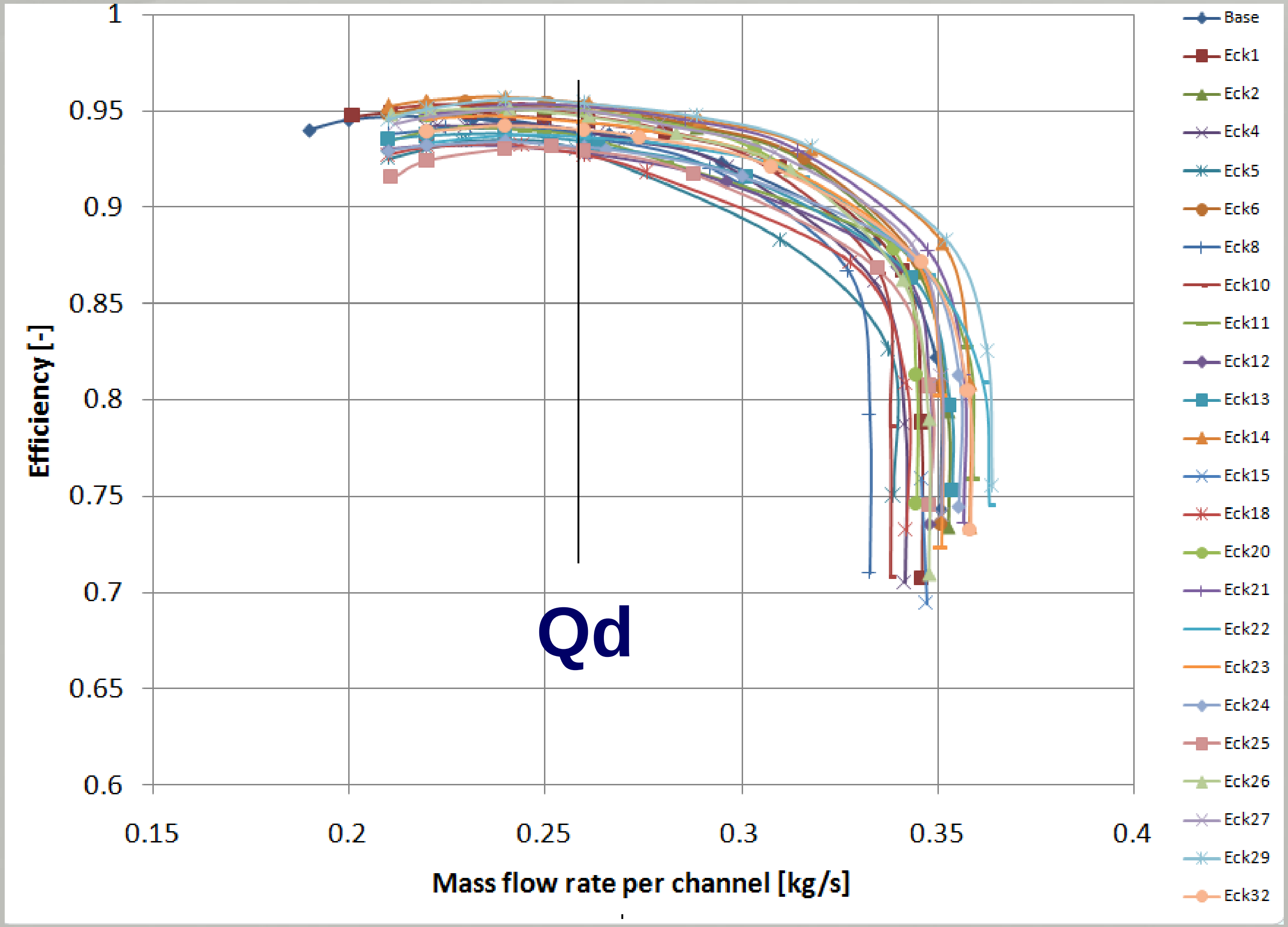
Impeller 16

CFD Results for DoE Table

- ✓ Using TUBOdesign1 for blade parametrization ensures that resulting pressure ratio is very close to baseline.
- ✓Changes in PR are related directly to efficiency changes. Specific work is maintained in TURBOdesign1
- ✓Interesting to see so many different impeller designs meeting the duty points



CFD Results DoE Table



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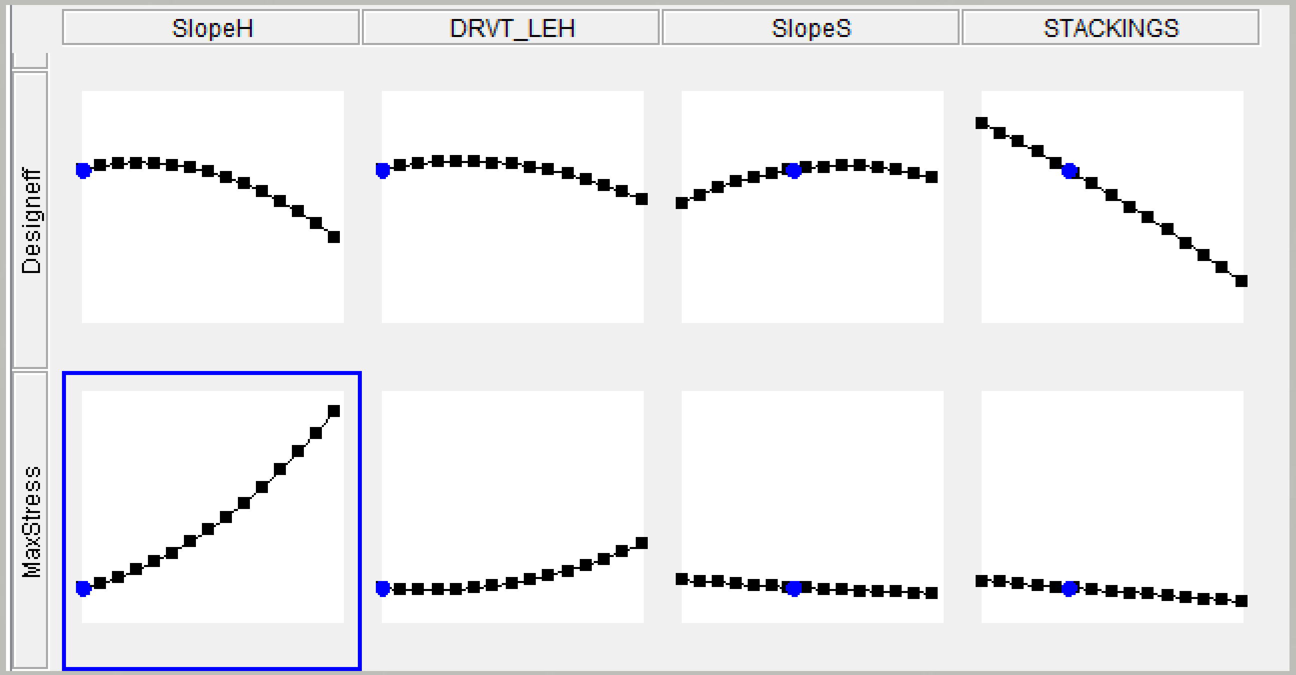
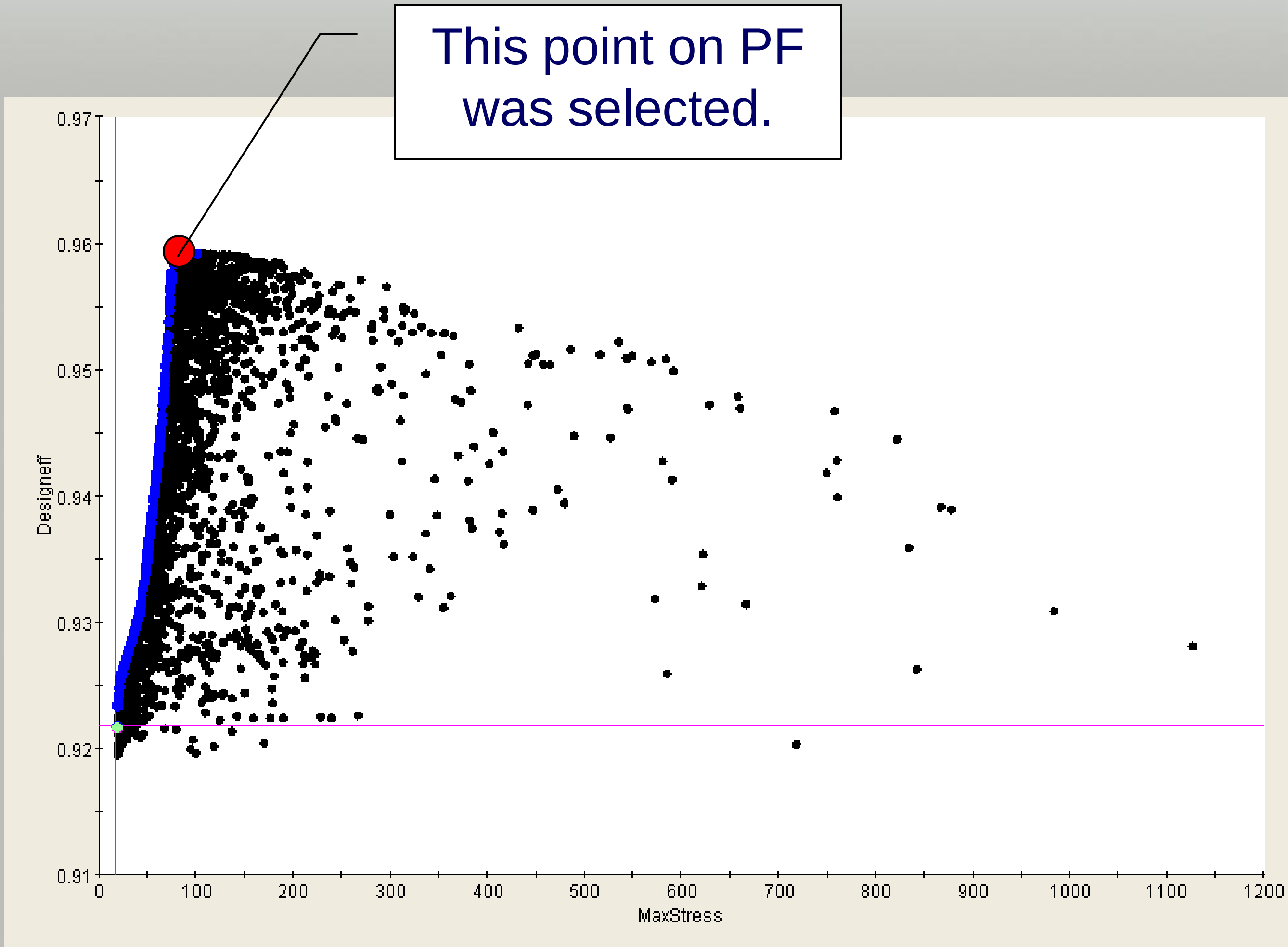
Response Surface Model & Sensitivity

Results from DoE table were used to create a Quadratic Response Surface using Isight. Acceptable values of R2 apart from efficiency at stall.

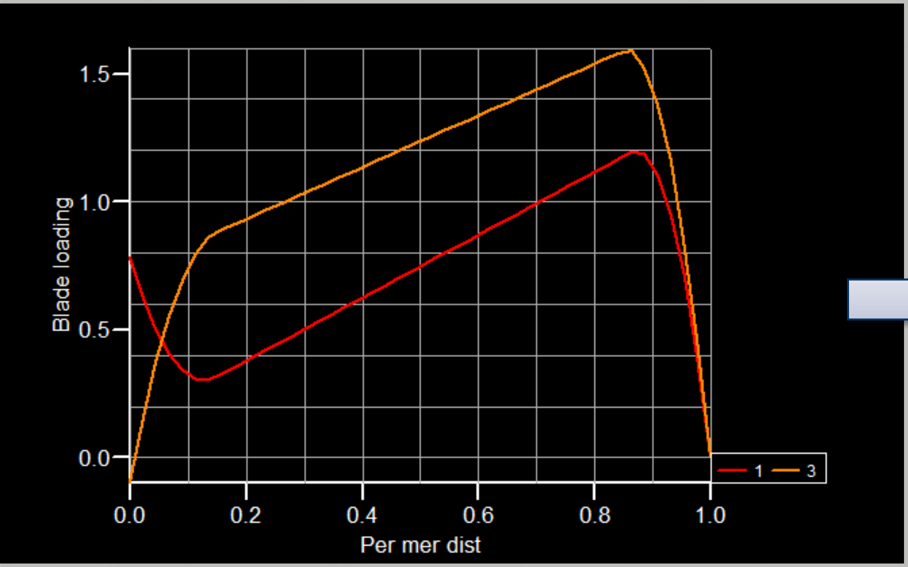


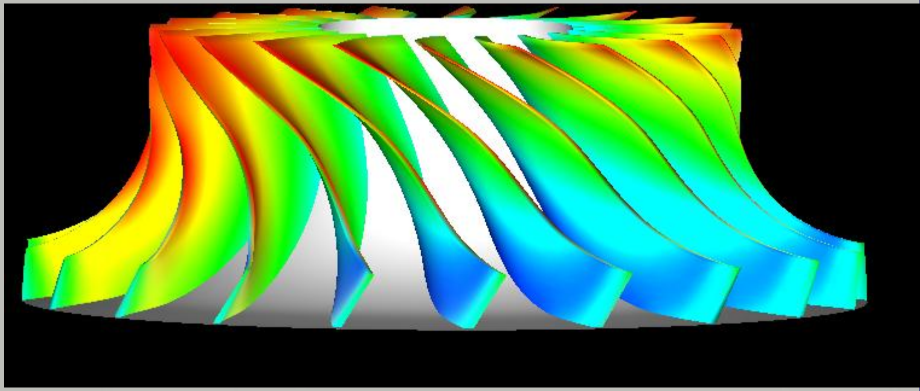
MOGA on RSM

- Isight was used to run MOGA (NSGAII) on the RSM.
- Constraint was placed on throat area to match the choke margin of Baseline.



Optimized geometry





Optimized Blade loading

Optimized Blade Shape

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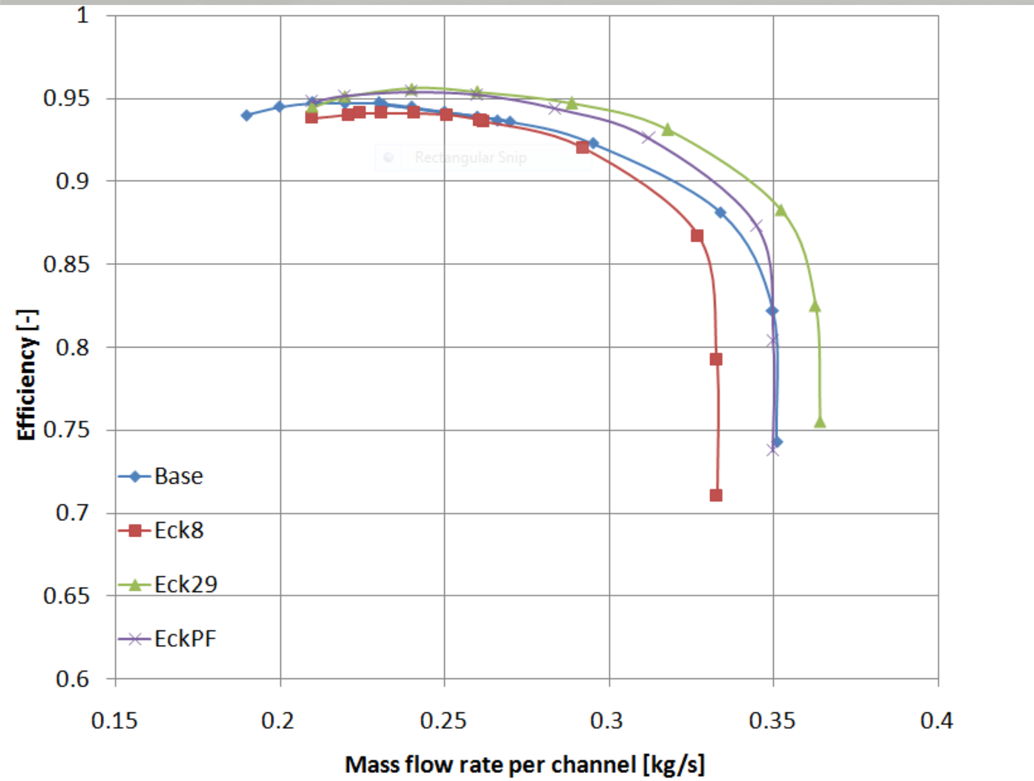
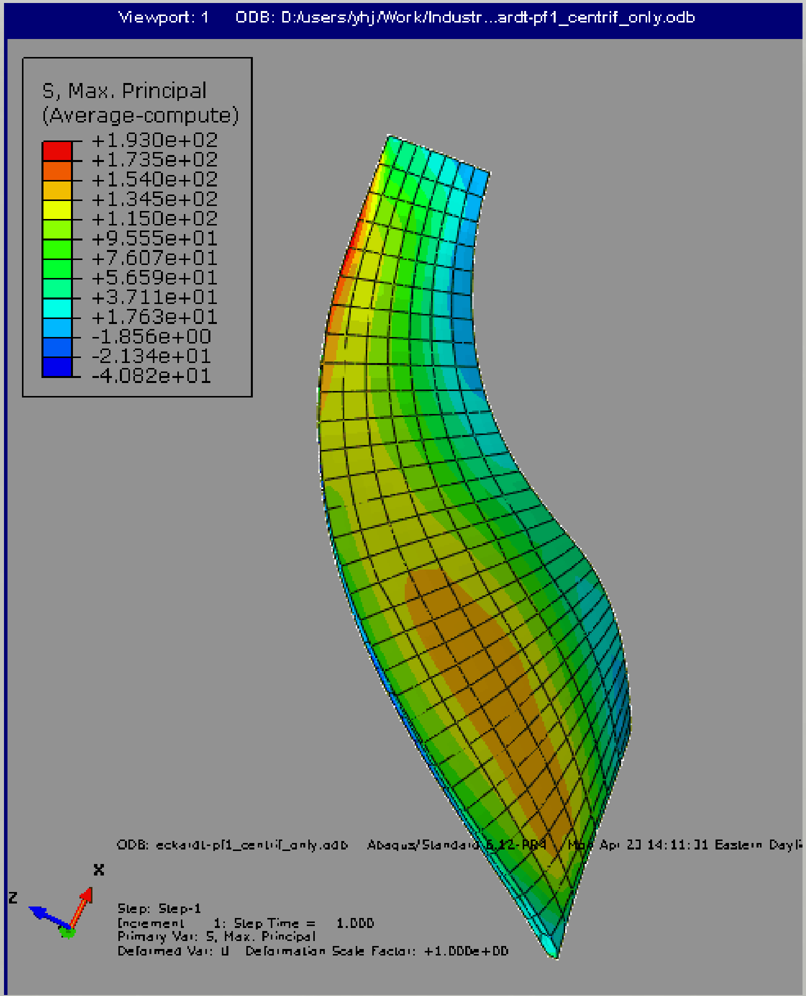
Results for Optimized Design





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Conclusion

- 3D inverse design based blade parametrization provides an ideal approach for multi-objective/multi-point optimization
- Using 4 design parameters and 22 Geometrical configurations accurate Response Surface was created for efficiency and stress.
- By running a MOGA on the Response Surface a Pareto front showing trade off between efficiency and stress was obtained.
- The proposed optimization strategy can be used for exploring the design space for finding design know-how that satisfy multi-point/multi-disciplinary/multi-objective requirements.

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Thank you

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