VINK-Virtual Integrated Compressor Demonstrator

FT2016
2016-10-11

Outline

- Background
- Method of attack
- Design process
- Selected results
- Ongoing work
- Summary

Background

- Over the past few decades the efficiency of the compressors in turbofan engines has been continuously improved through usage of the modern three-dimensional design techniques for compressor blades and vanes.

- The potential further improvements could be achieved if the interaction between different compressor components is being optimized from the engine system perspective

Motivation

- For the aerospace applications the weight and size of the engine has a major impact on fuel consumption →future compression systems have to be made compact, with parts closely integrated to each other

- The ability to assess complex dynamic processes is being challenged since the various parts cannot be considered isolated from each other.

- Usage of the light materials and thin walls means that the traditional conservative design methods are no longer appropriate

Purpose

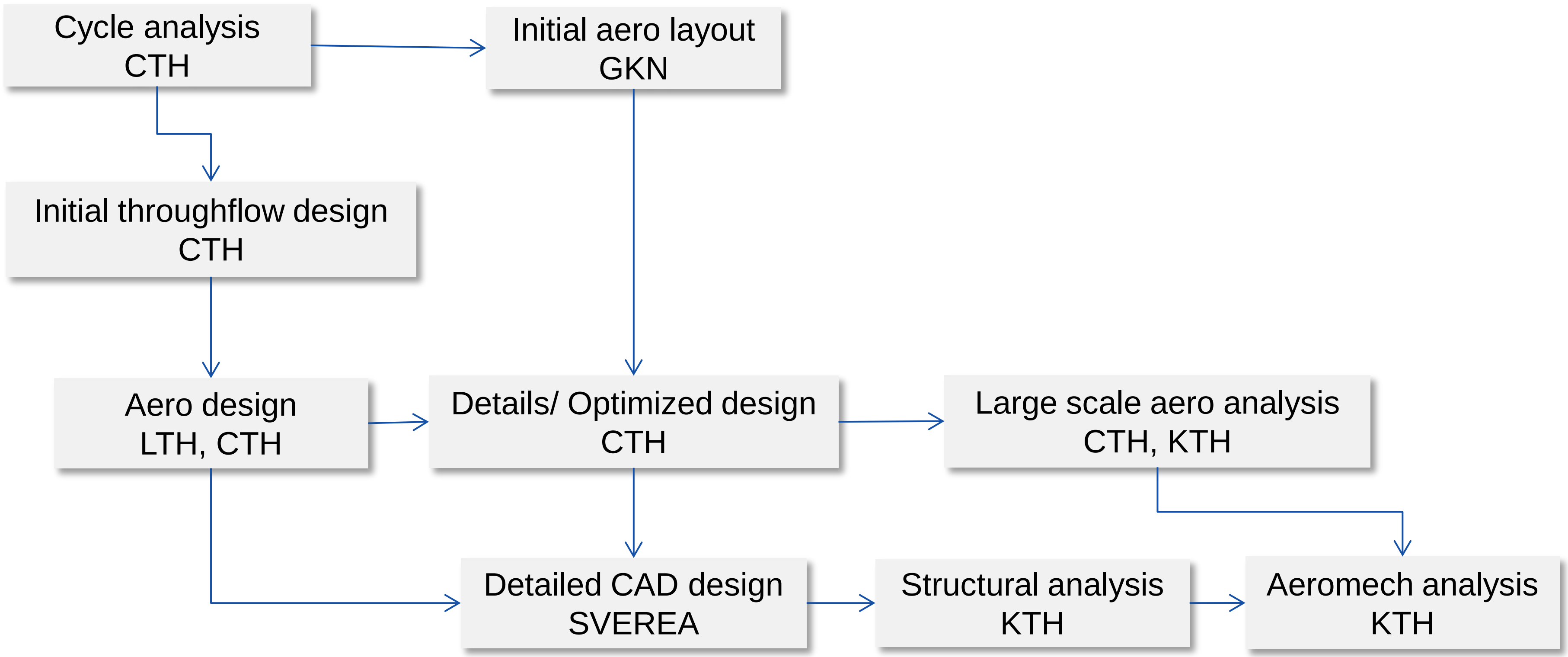
- VINK project has been initiated to address this complex interaction in the design chain of a high speed booster including a LPC, an intermediate duct containing support struts and a bleed system.

- The project aims at:
  - Application and interconnection of the state-of-the-art virtual tools and methods (both commercial and in-house tools)
  - Defining the design rules for confident aerodynamic design of a highly efficient low pressure compressor
  - Develop open designs that can be used for detailed research and as reference for improvements

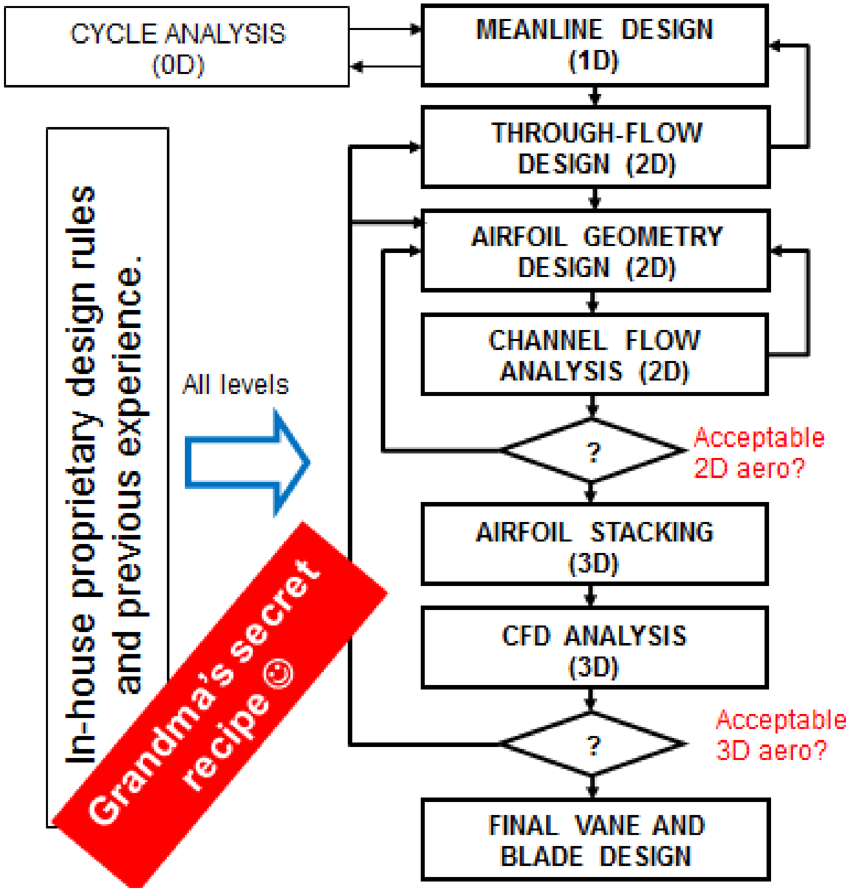
Project background

- VINK : NFFP6 Vinnova funded project
- Started Nov 2014, duration 2 years
- Partners involved: GKN Aerospace (project leader), Chalmers University, LTH, SWEREA and KTH

Project workflow



Aero design process



Reduced order through-flow (p_0 and α distributions,). Inputs like: angles, loading, reaction, intra stage swirl, diffusion factors, deHaller number, etc.

- Include hub-to-shroud variation
- Axi-symmetric, non “free-vortex”

- Design individual airfoil sections
- Profile family, DCA, CDA, Arbitrary, Bezier, …

Evaluate blade surface Mach numbers and diffusion factors. Determine optimum surface contours by iterating with airfoil geometry program.

Engine assumption

- Pre-defined airframe & thrust requirements → suitable engine performance data → basic conceptual design → definition of the component and stage interfaces

- Geared turbofan architecture; 120+ inch fan

- Airframe set of requirements:
  - twin aisle, 2 engines aircraft
  - Number of passengers 250
  - Range capability: 6500 NM
  - cruise Mach number: 0.82,
  - Thrust Class: 70klb thrust (static condition)

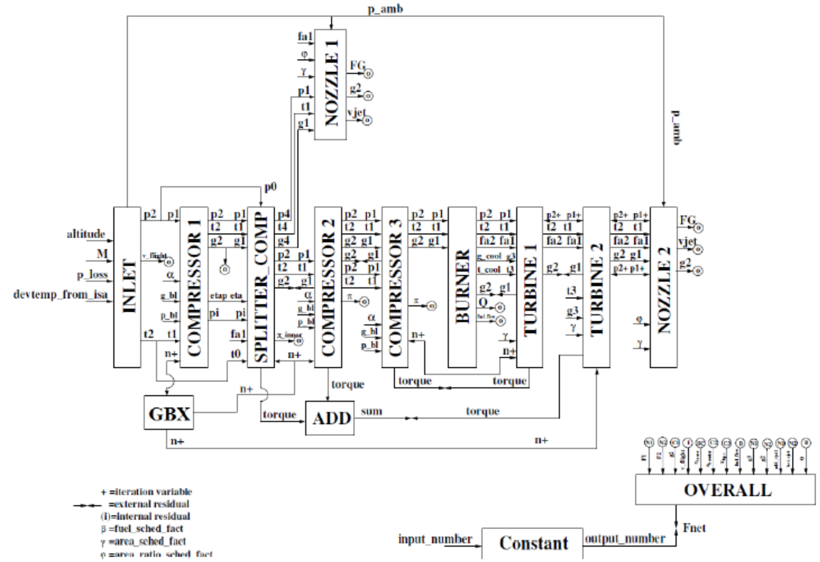
Engine performance

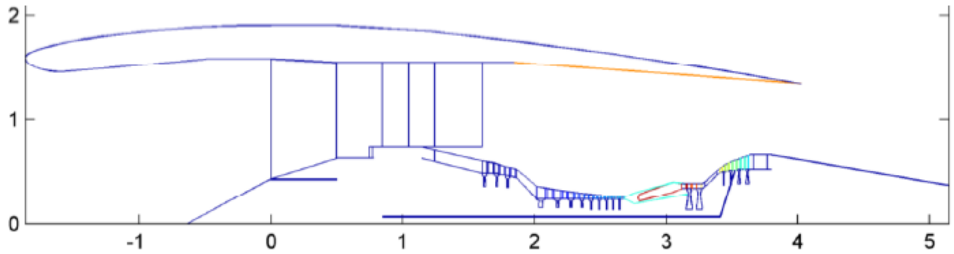
- Engine performance to define booster boundary conditions

- Data computed based on Chalmers in-house tool GESTPAN

- Initial conceptual design based on performance data:

  1(Fan) 3(IPC) 10(HPC) 2(HPT) 4(LPT)





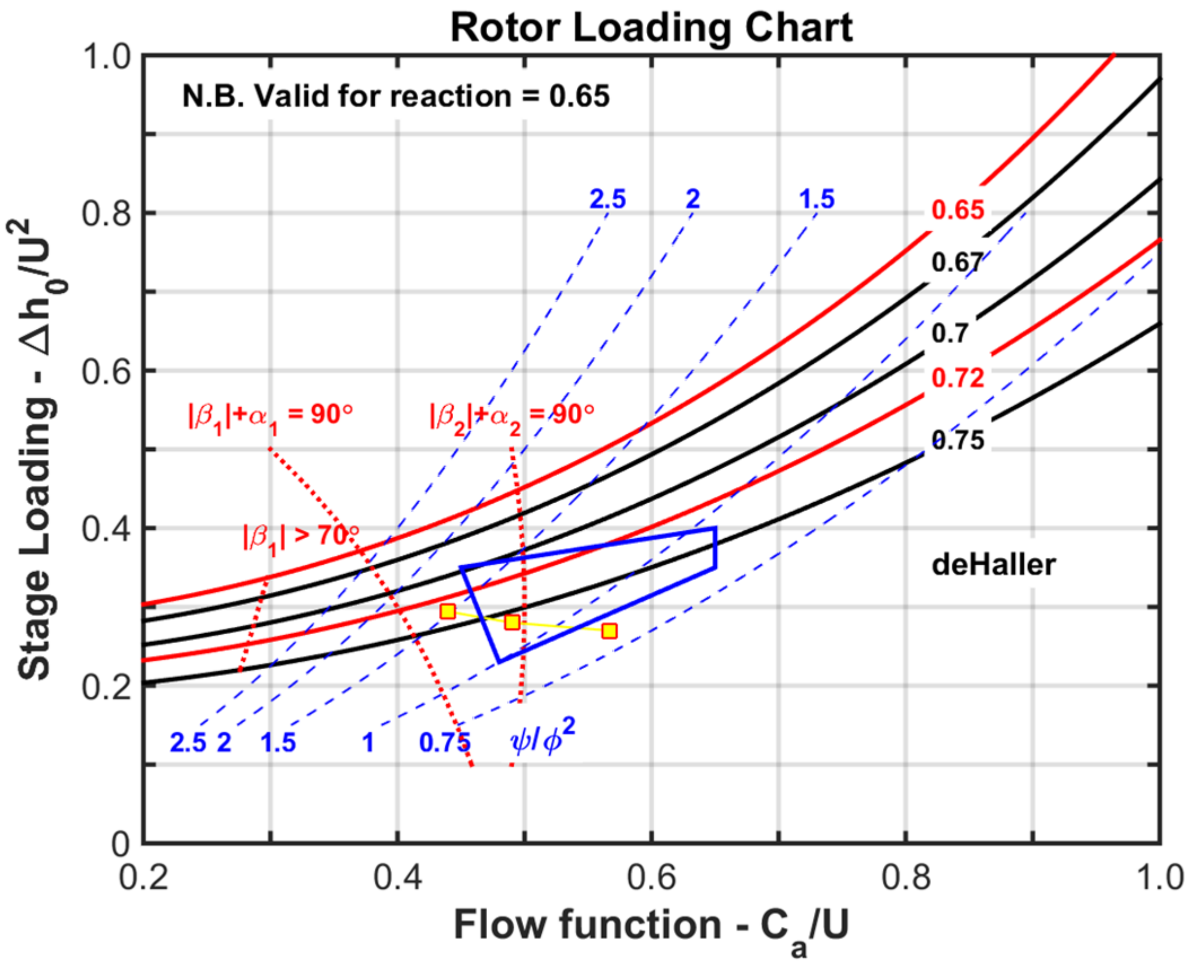
Basic IPC performance

- The top-of-climb condition selected to define basic performance of the high speed booster

# stages	3			
	UNIT	Take-off	Top-of-climb	Cruise
W23	kg/s	91,25	42,68	37,31
T23	K	329,83	282,4	265,7
P23	kPa	133,45	47,9	45,92
P24	kPa	292,5	119,7	109,36
T24	K	418,5	376,3	347,8
xni		6114	6242	5789

- Output: corner points (radius, axial coordinate)

1D design- Stage loading chart

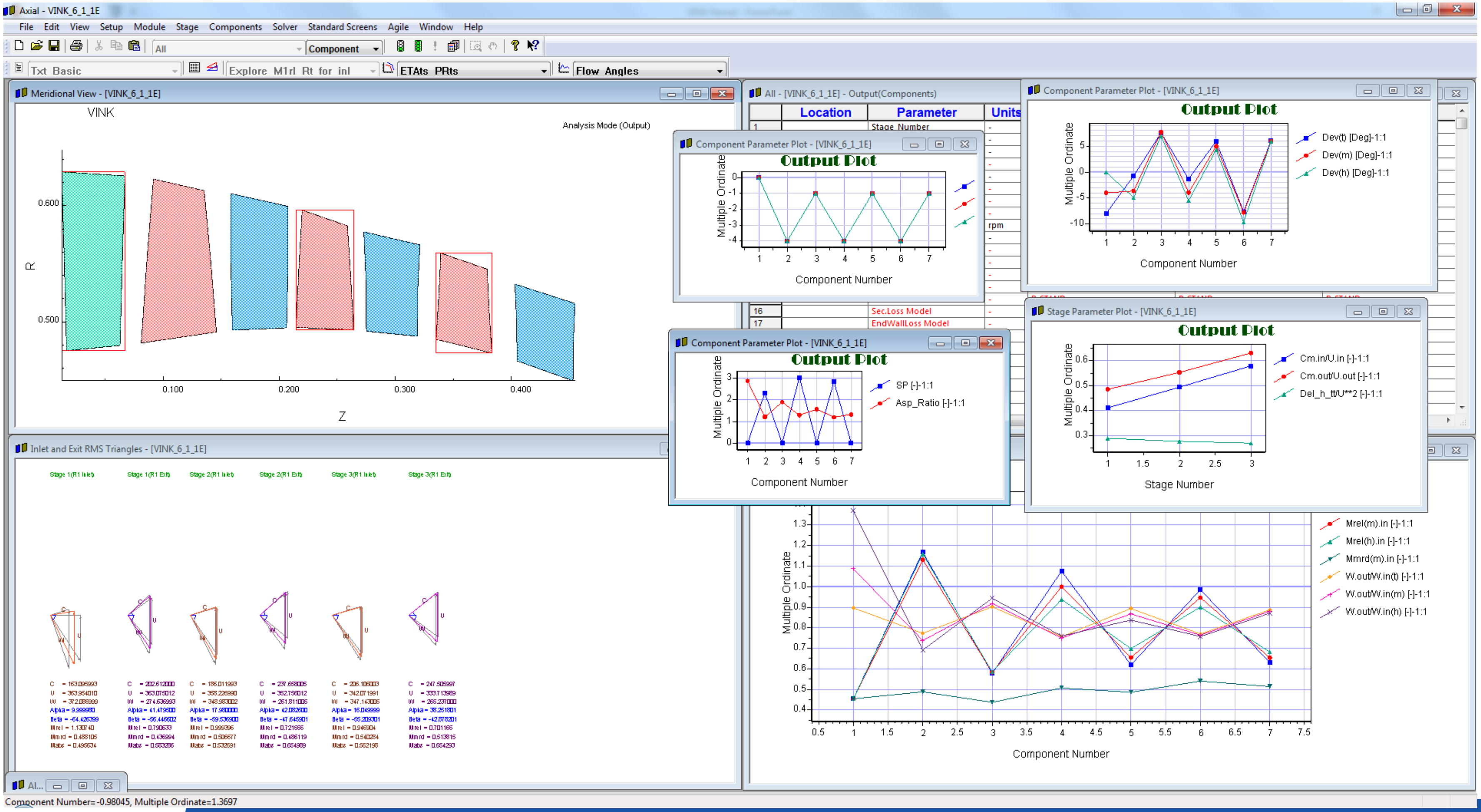


$$\psi = \frac{\Delta h_0}{U^2}$$

$$\varphi = \frac{C_m}{U}$$

$$\sigma = \frac{\psi}{\varphi^2}$$

Reduced-order throughflow design (Axial)



Radial equilibrium equation – old school?

$$C_m \frac{dC_m}{dl} = \underbrace{\sin(\phi-\gamma) C_m \frac{\partial C_m}{\partial m}}_{(a)} + \underbrace{\cos(\phi-\gamma)\frac{C_m^2}{r_c}}_{(b)} - \underbrace{\frac{C_\theta}{r}\frac{d(r\cdot C_\theta)}{dl}}_{(c)} + \underbrace{\frac{dh_0}{dl}}_{(d)} - T\underbrace{\frac{ds}{dl}}_{(e)} - \underbrace{\sin(\phi-\gamma)F_m}_{(f)} - \underbrace{\cos(\phi-\gamma)F_n}_{(g)}$$

(a) convective acceleration in meridional direction

(b) streamline curvature (SCM)

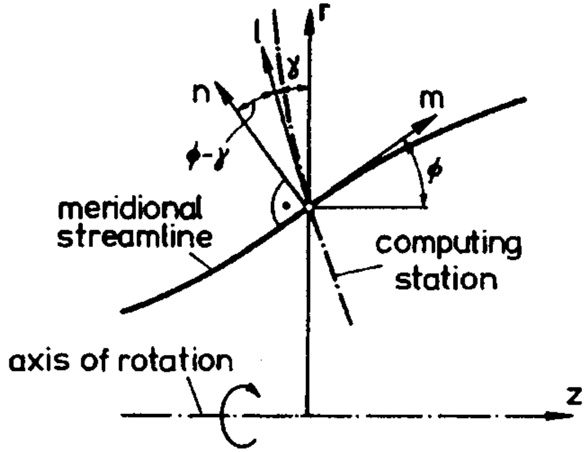
(c) angular momentum

(d) work gradient

(e) entropy gradient (losses)

(f) body force (meridional direction)

(g) body force that is normal to the streamline (blade force)

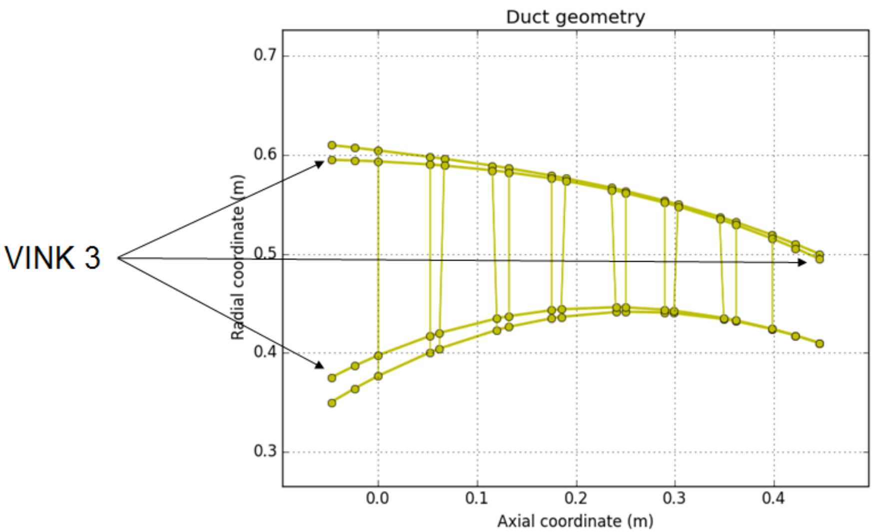


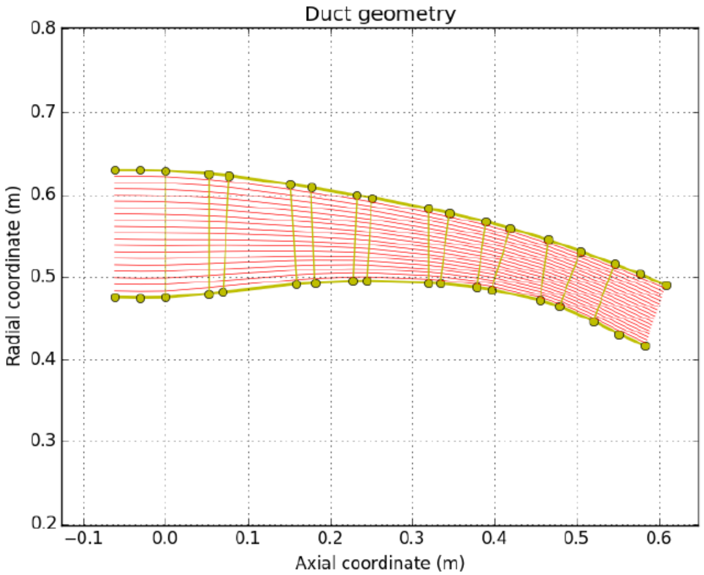
Terms (a), (b), (d), (e), (f) and (g) are considered to be equal to zero in the “simplified radial equilibrium equation” SRE.

The SCM-equation is still the back-bone in all turbomachinery design!

Throughflow based design (SC90c)

- Six design iterations to optimize compressor

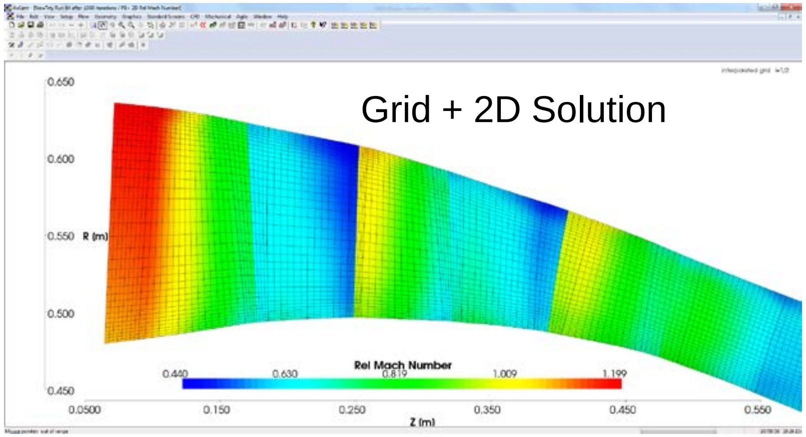




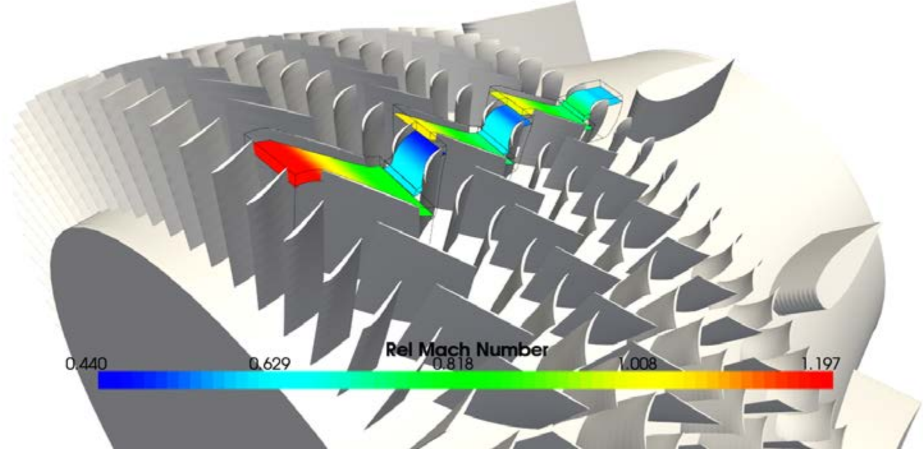
VINK6

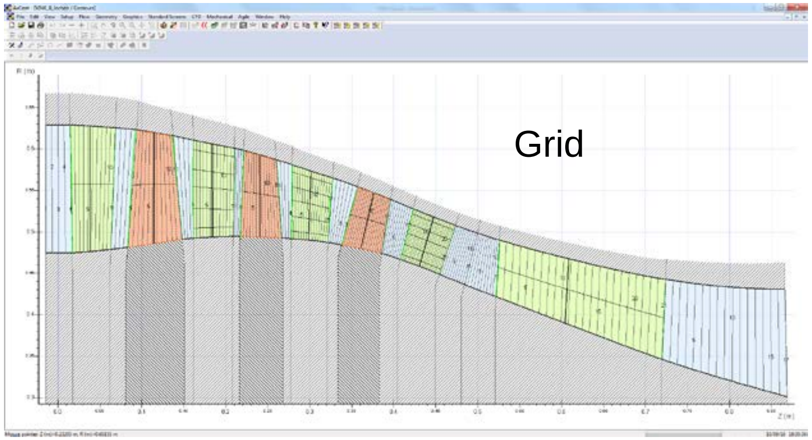
ψ_{R1}	0.299	φ_{R1}	0.477	π_{R1}	1.516	α_{IGV}, α_{S1}	(18,10,0), (18,18,18)	$M_{tip,rel,R1}$	1.192
ψ_{R2}	0.284	φ_{R2}	0.432	π_{R2}	1.410	α_{S2}	(20,20,20)	$M_{tip,rel,R2}$	1.082
ψ_{R3}	0.273	φ_{R3}	0.515	π_{R3}	1.312	α_{S3}	(0,0,0)	$M_{tip,rel,R3}$	0.971

Throughflow design – time marching (AxCent)

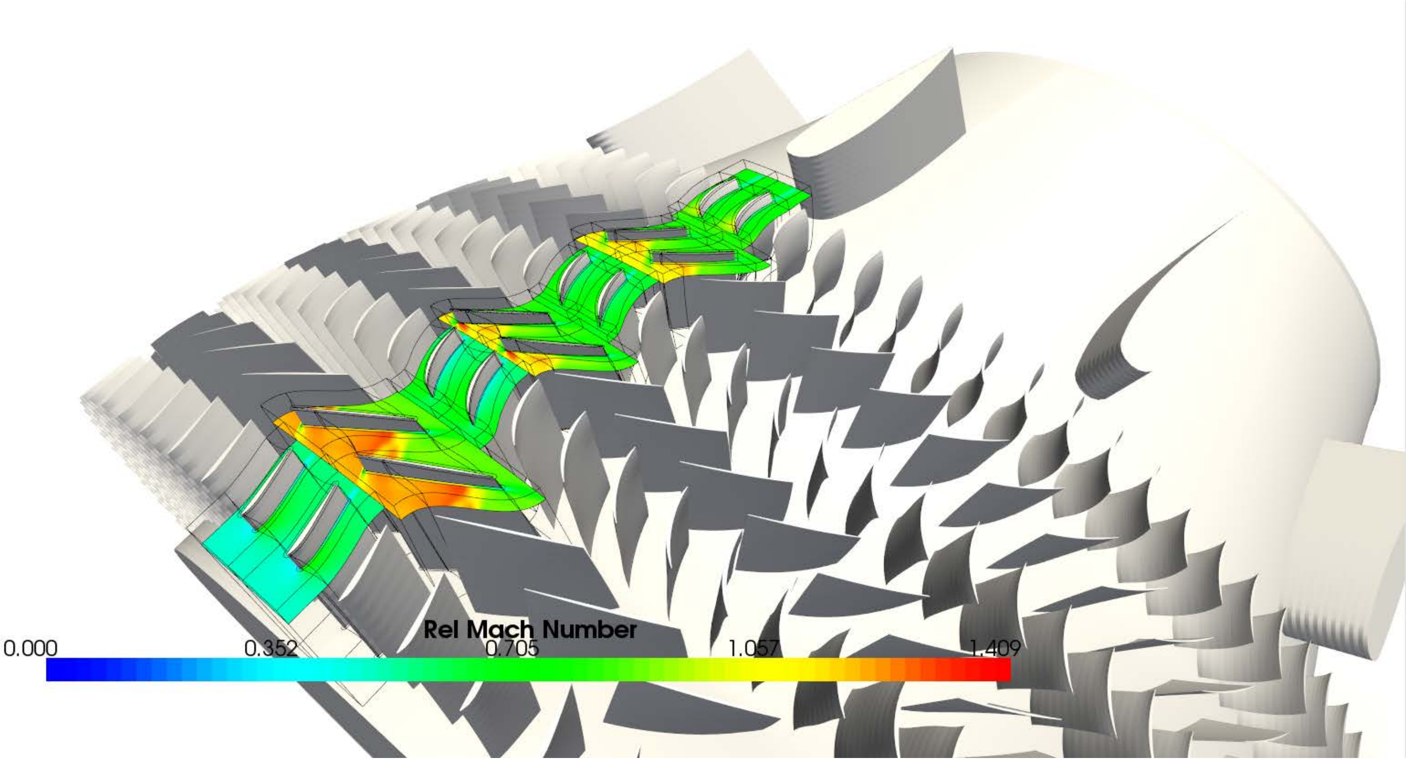


2D Solution in full geometry

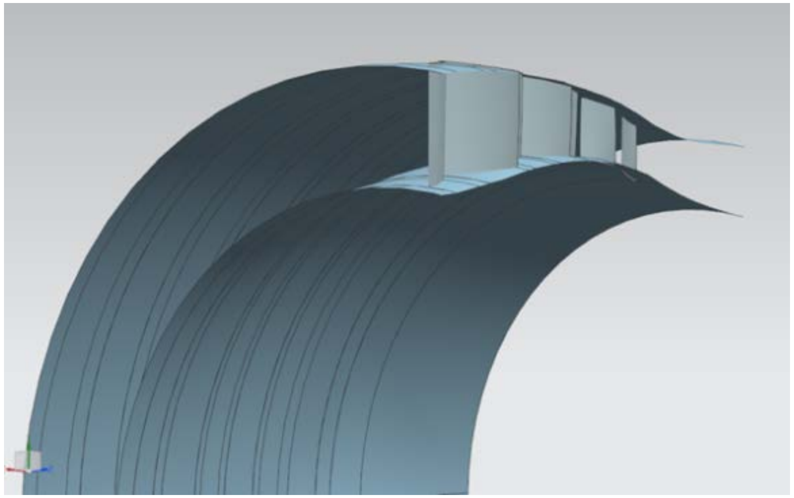


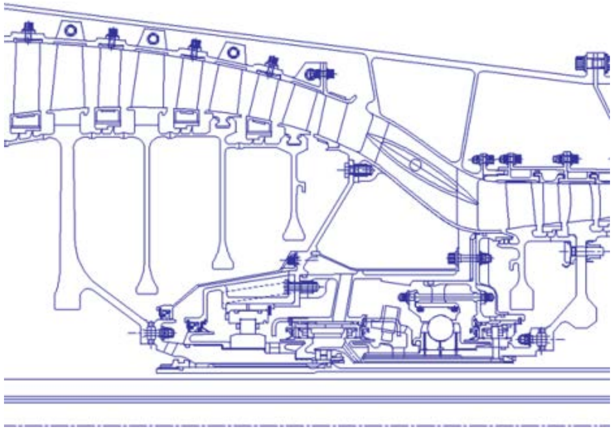


Full 3D design (AxCent)



Detailed CAD design

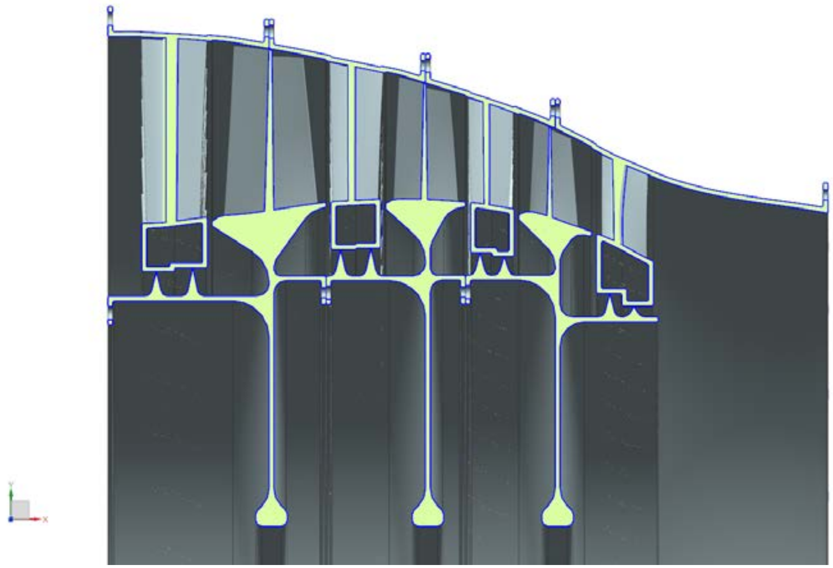


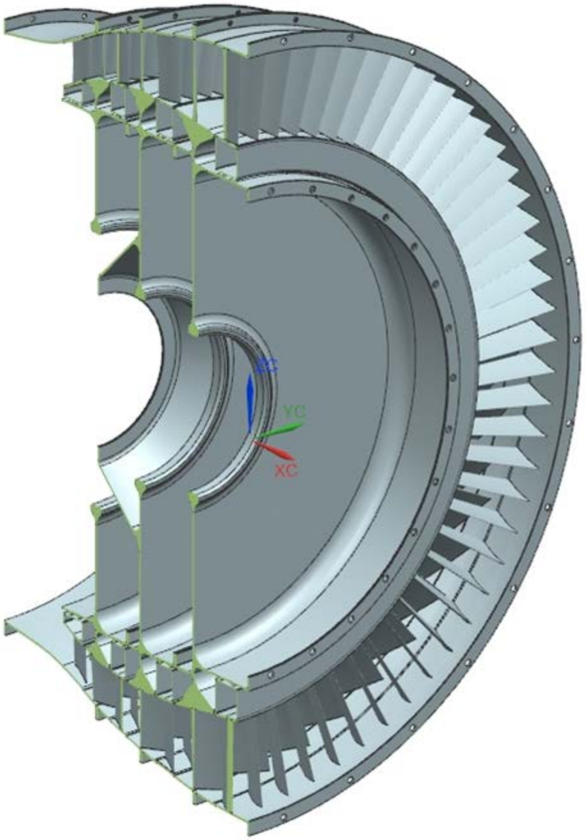


Input: 3d aero surfaces (blade, gas channel geometry) and blade count in each stage

Other geometry features are based on previous designs and technical experience

Compressor layout CAD

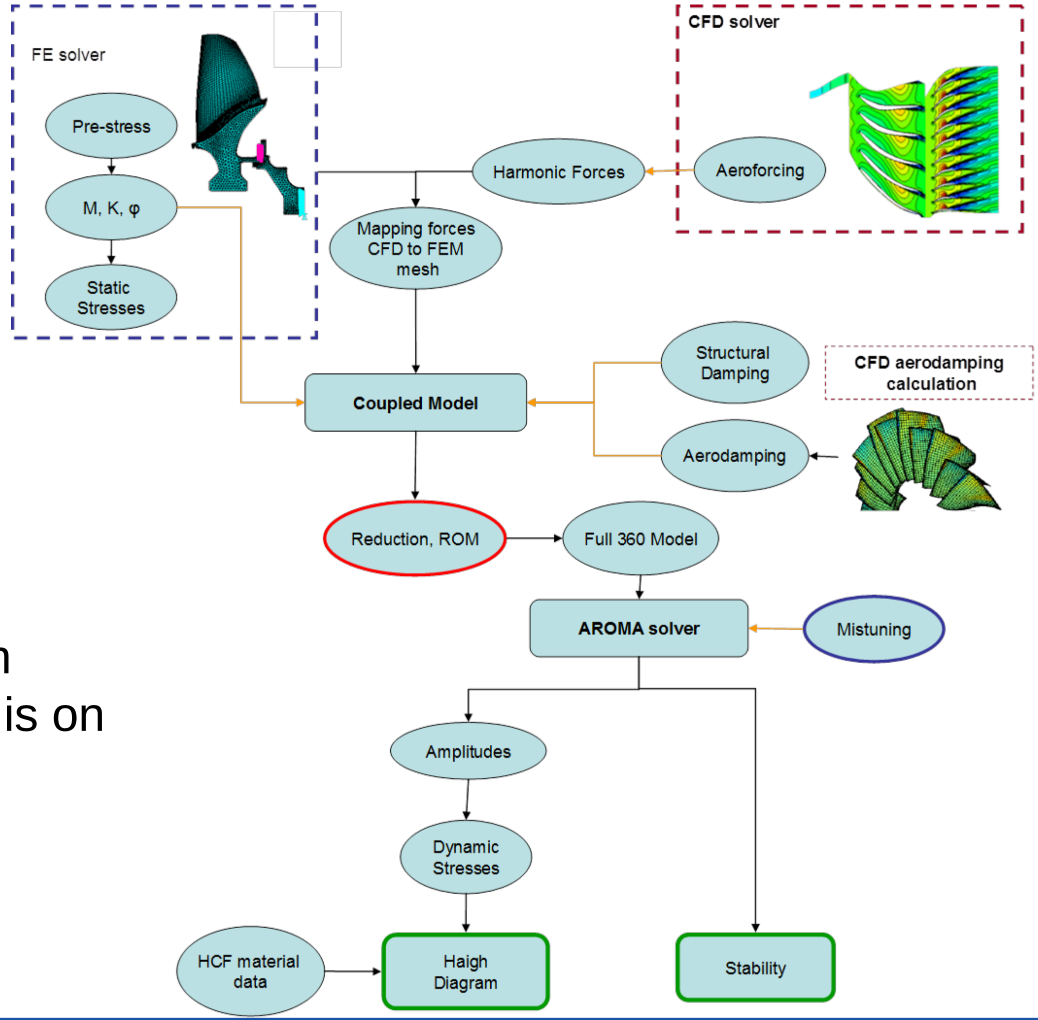




Aeromechanical analysis

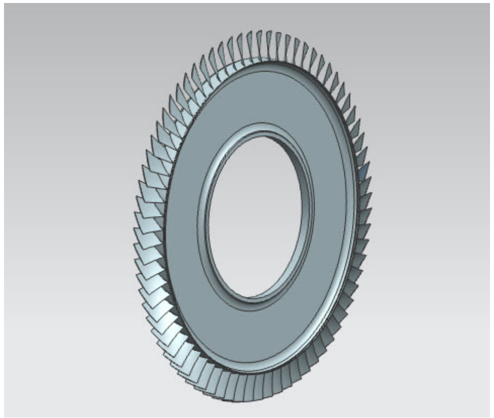
AROMA tool (KTH)

Analysis Chain

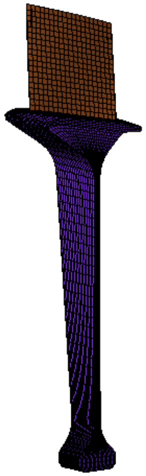


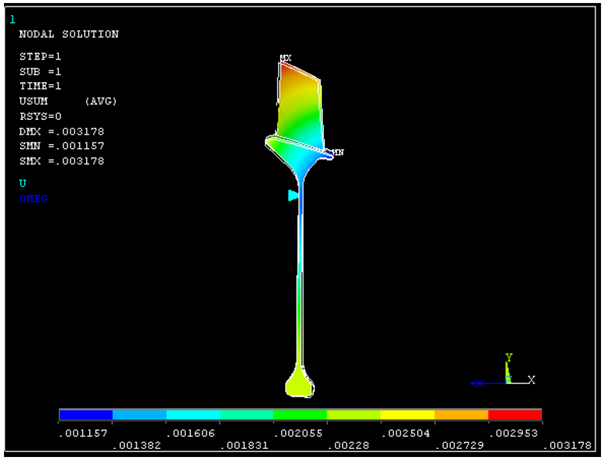
- Focus of the aeromech analysis in this project is on the rear stage of the booster

Rotor 3 blisk

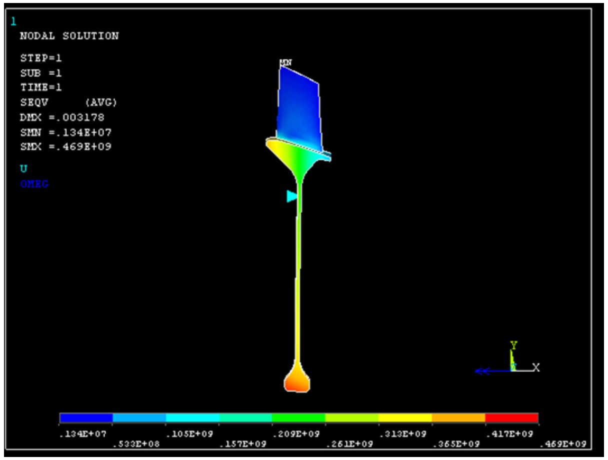


Cyclic symmetric analysis





Static displacement

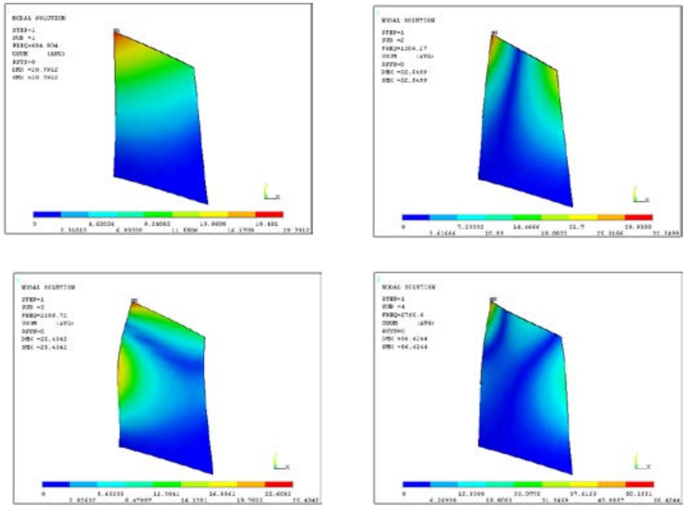


Von Mises stress

@ 6242rpm

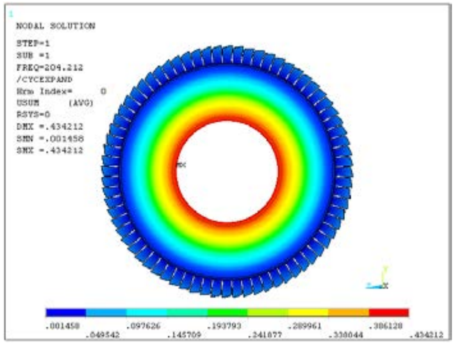
R3 modal analysis

Blade only

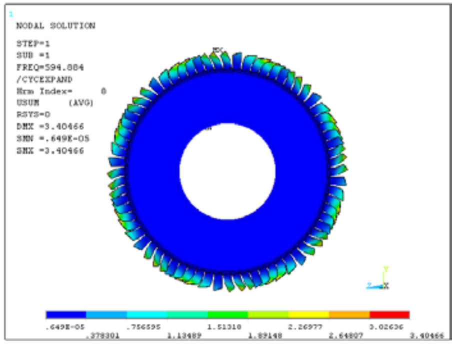


SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	604.80	1	1	1
2	1304.3	1	2	2
3	2188.7	1	3	3
4	2760.6	1	4	4
5	3504.5	1	5	5
6	4505.6	1	6	6
7	5125.8	1	7	7
8	5679.1	1	8	8
9	6672.3	1	9	9
10	7125.3	1	10	10
11	7563.1	1	11	11
12	7972.0	1	12	12
13	9089.4	1	13	13
14	9539.0	1	14	14

Blade+disk

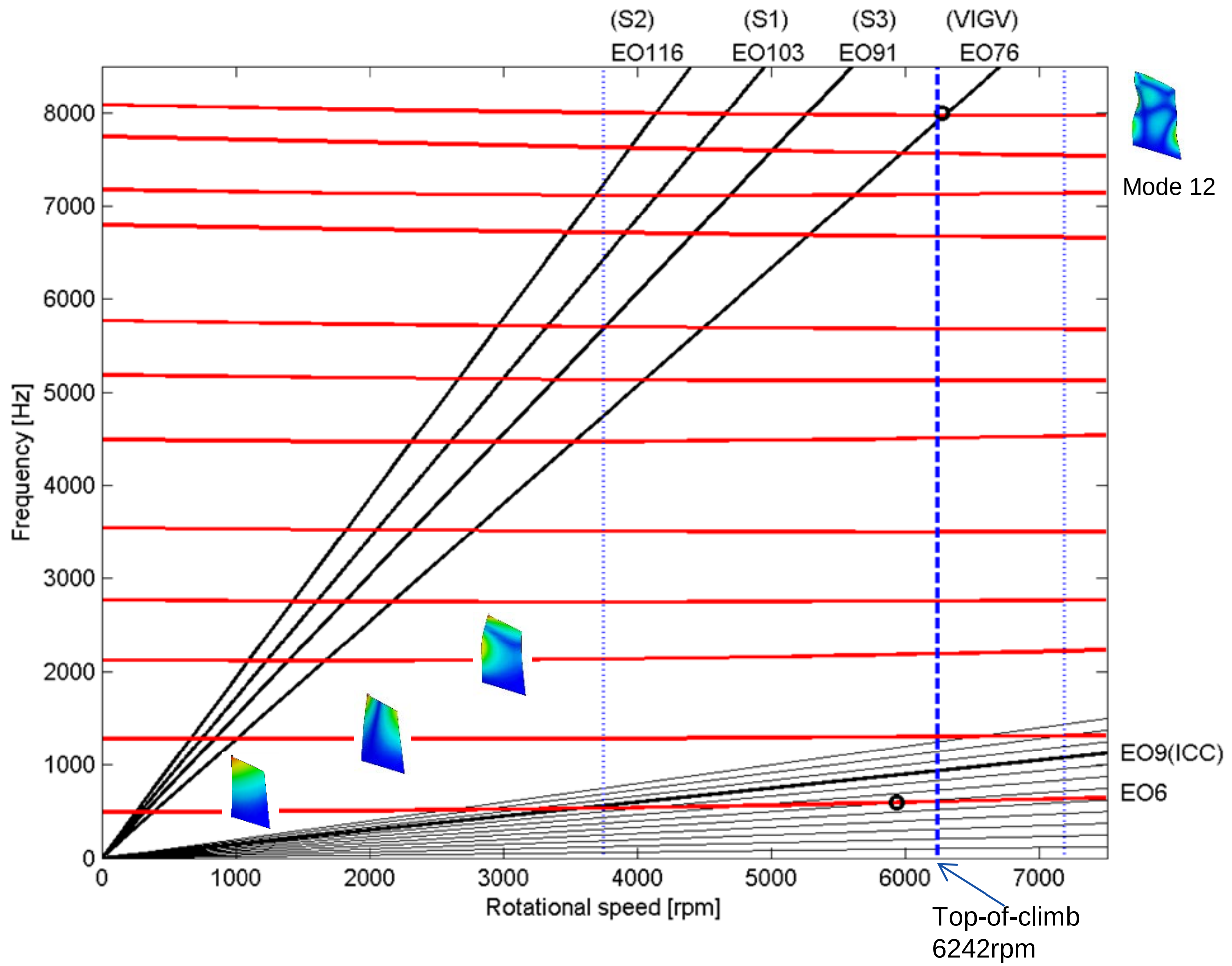


Mode 1, ND0

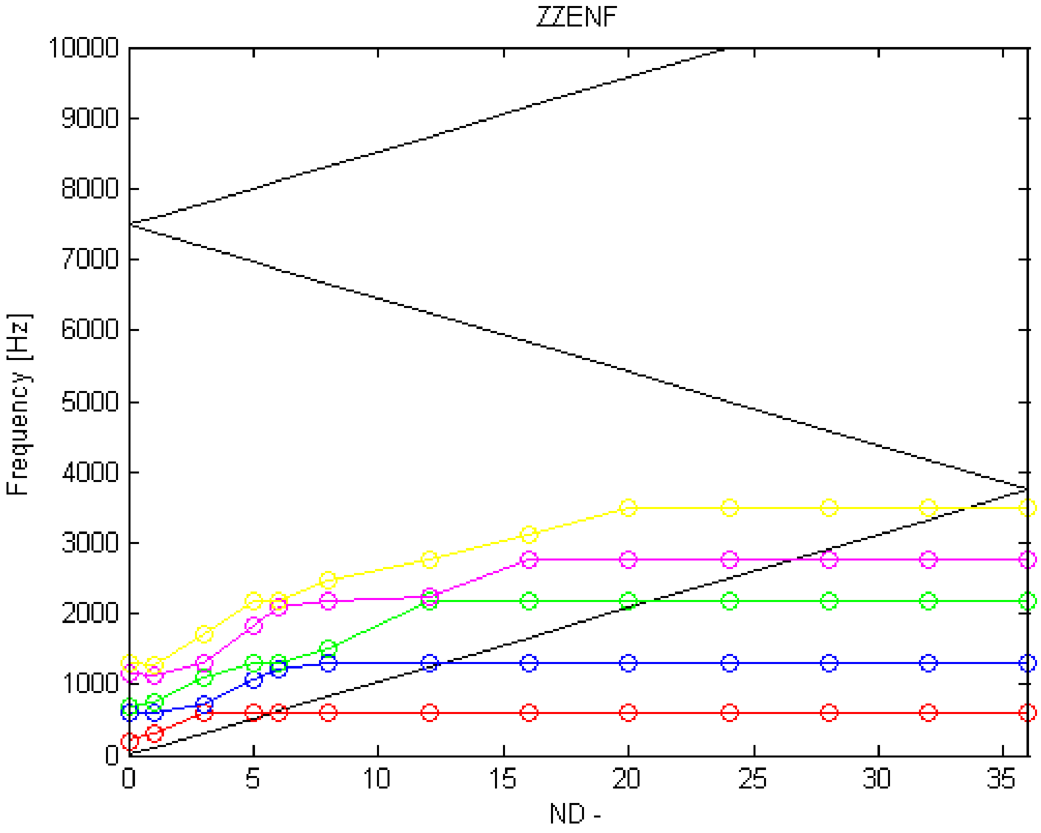


Mode 1, ND8

Campbell diagram R3



R3 ZZENF diagram



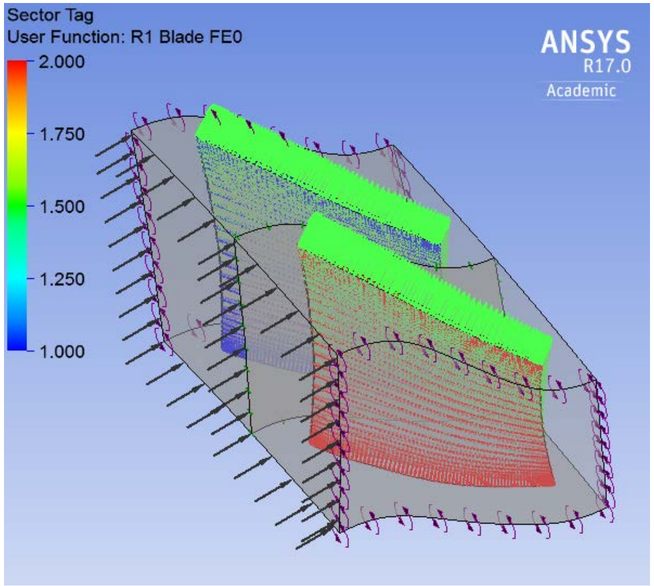
Aerodamping predictions

- Aerodamping simulations in Ansys CFX v17, using Fourier Transformation method
- Transient simulation initialized by a steady state solution (rotor domain)

$$W_{aero} = -\int_A \pi h \cdot \hat{n} p_i dA$$ Aerodynamic work

$$\Xi = \frac{-W_{aero}}{\pi b \alpha^2 c^2 (p_0 - p_1)}$$ Aerodynamic damping coefficient

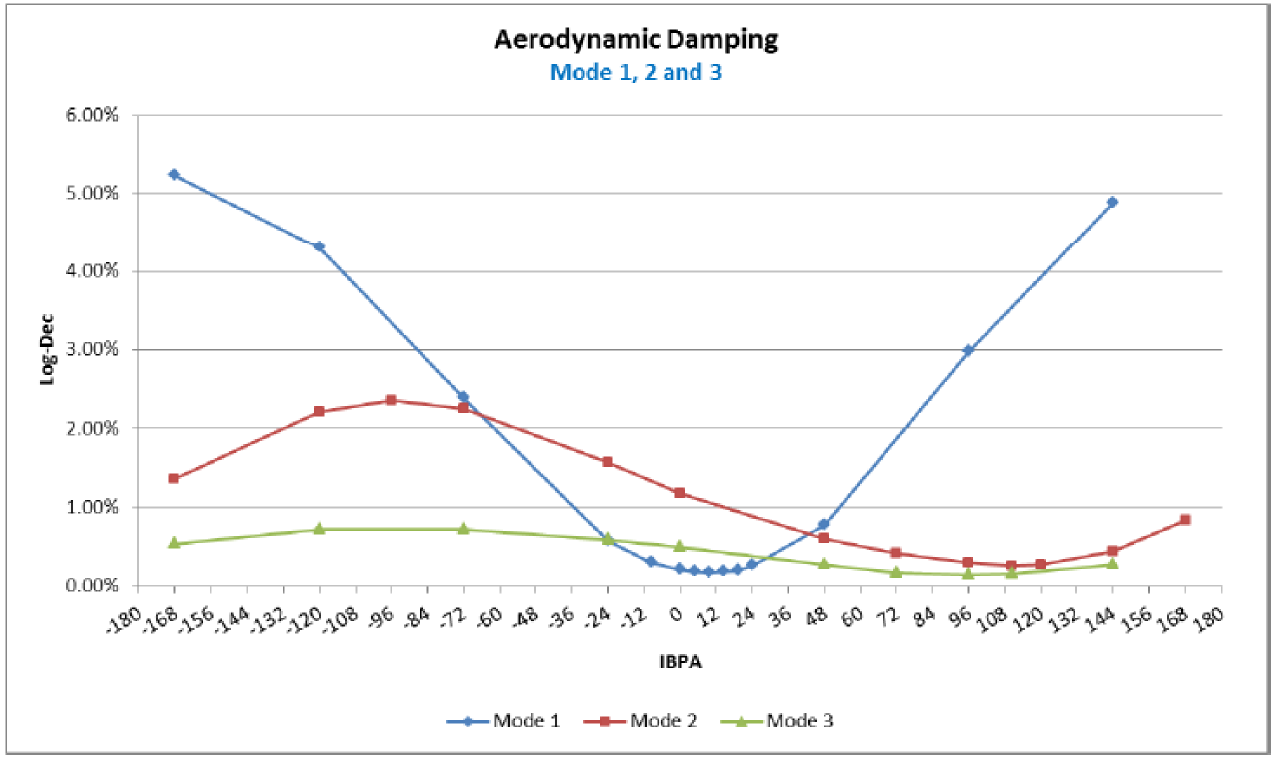
$$\delta = -W_{aero} / 2KE_{max}$$ Logarithmic decrement



The negative value of aerodynamic damping implies unstable condition → flutter

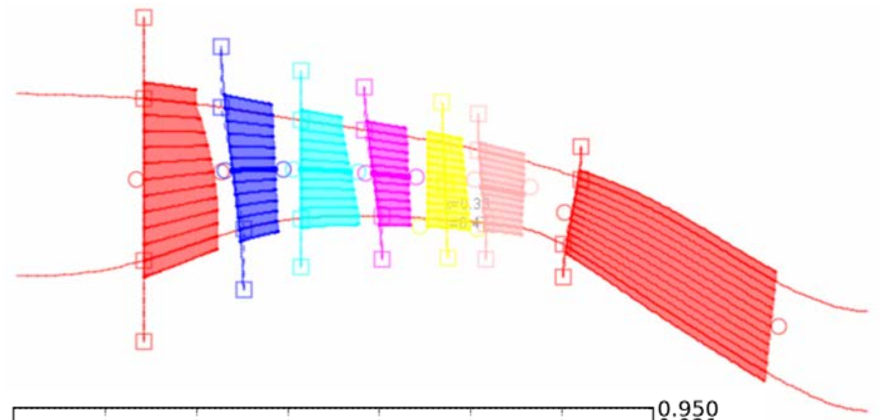
Aerodamping curve R3

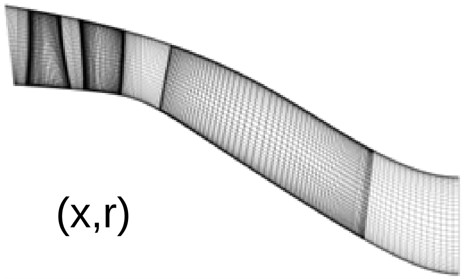
	Modal Frequency (Hz)	*Reduced Frequency* $k = 2\pi fc/U$
Mode 1	589.5	0.59
Mode 2	1472.7	1.46
Mode 3	1999.2	1.99

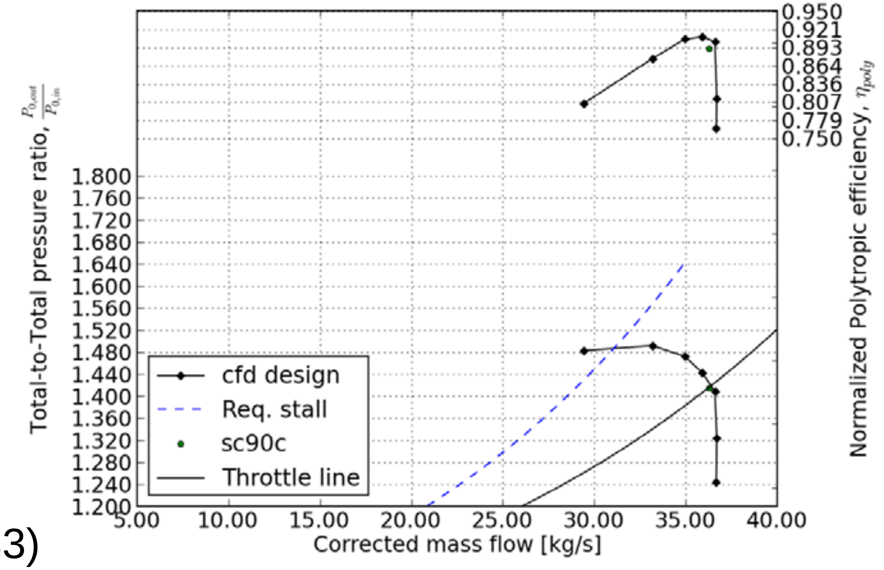


Rear stage & IMC

- 3D CFD design of the rear stage with IMC done by GKN





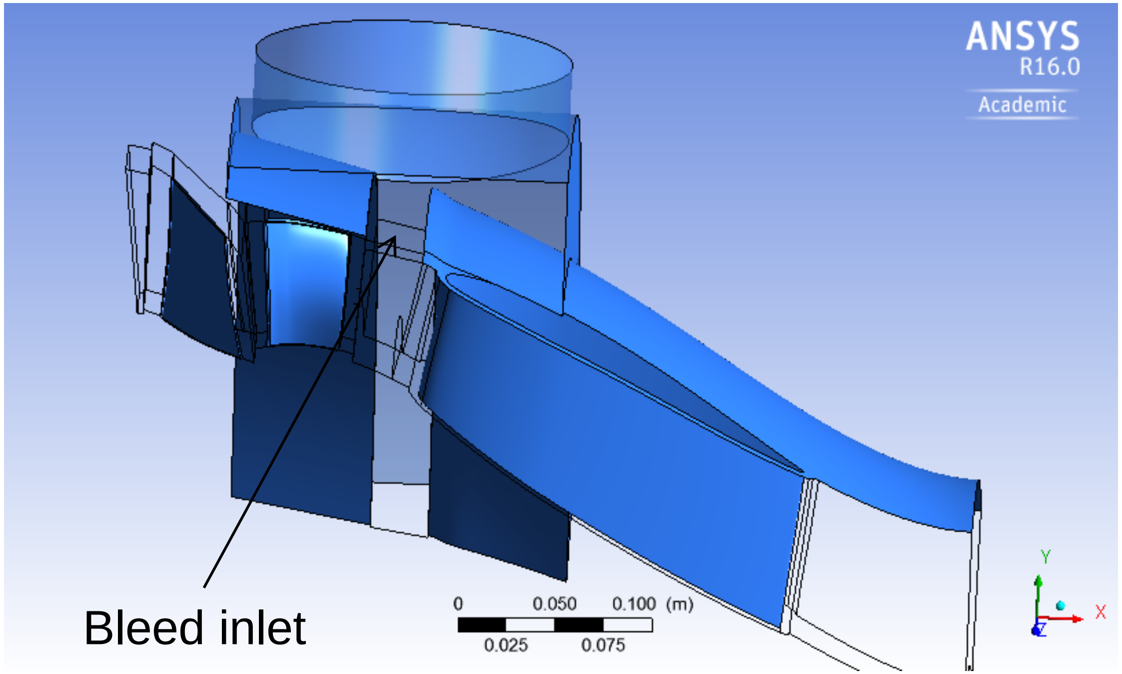


Compressor map (R3-S3)

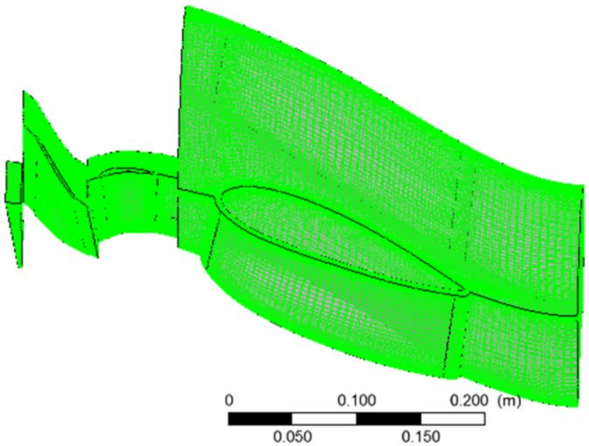
Bleed system

Bleed opening added between S3 and ICC

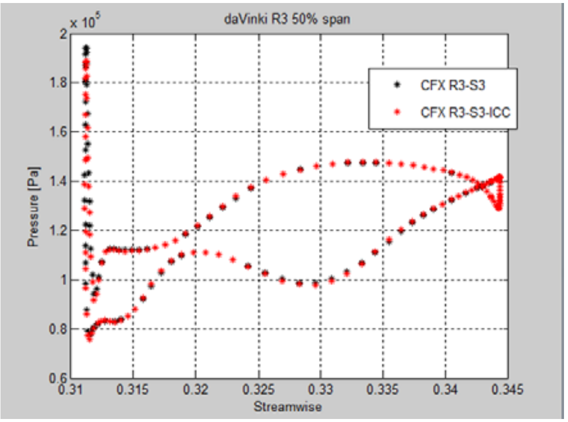
→ To asses impact of the bleed channel on the performance

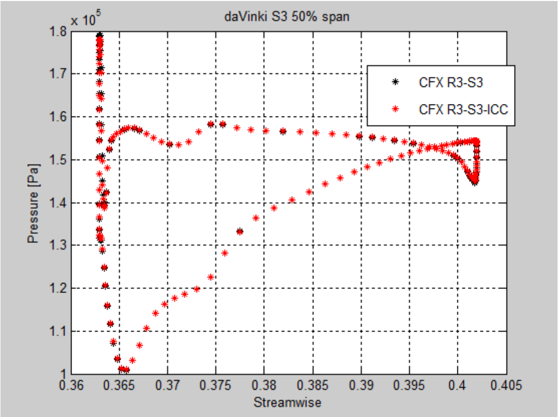


Steady state stage aerodynamics



Stage modelled in CFX
(single passage, mixing plane at interfaces, periodic boundaries)

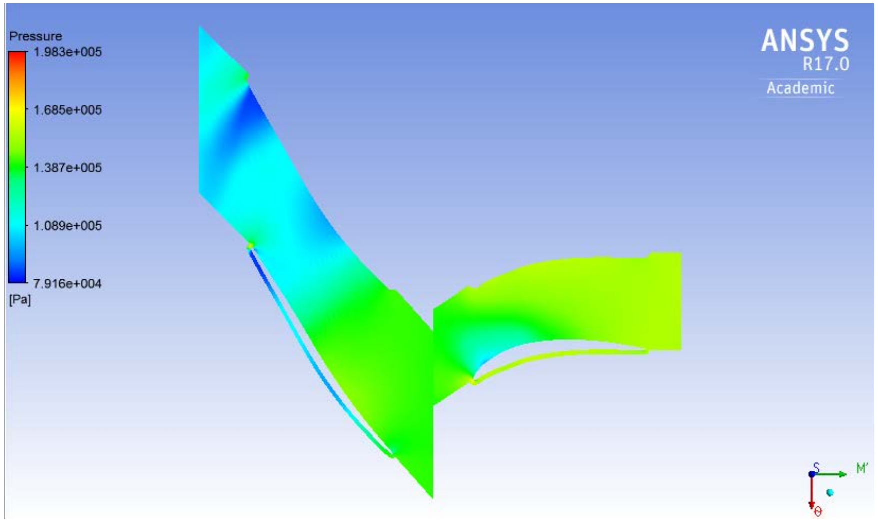




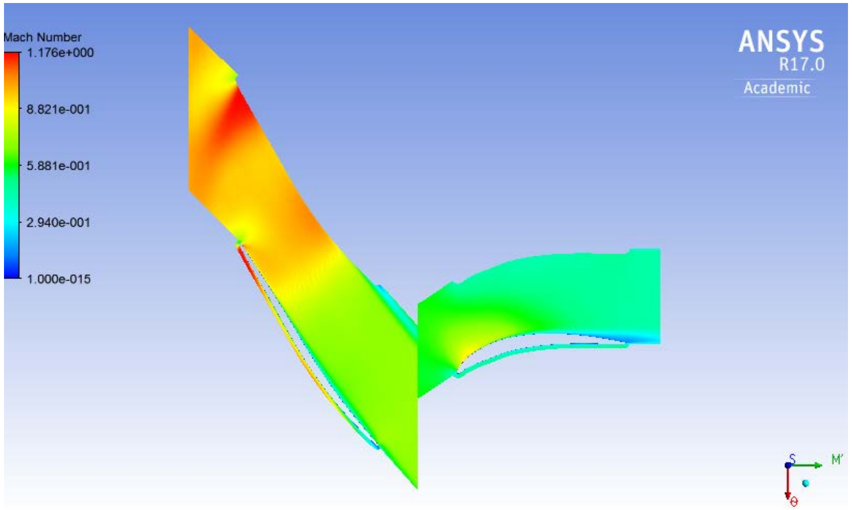
R3

Blade loadings

Steady state stage aerodynamics



Static pressure at midspan (blade-to-blade)



Mach number at midspan (blade-to-blade)

Unsteady aerodynamic simulations

- To assess the blade row interaction and unsteady aerodynamic forces, transient simulations have to be performed

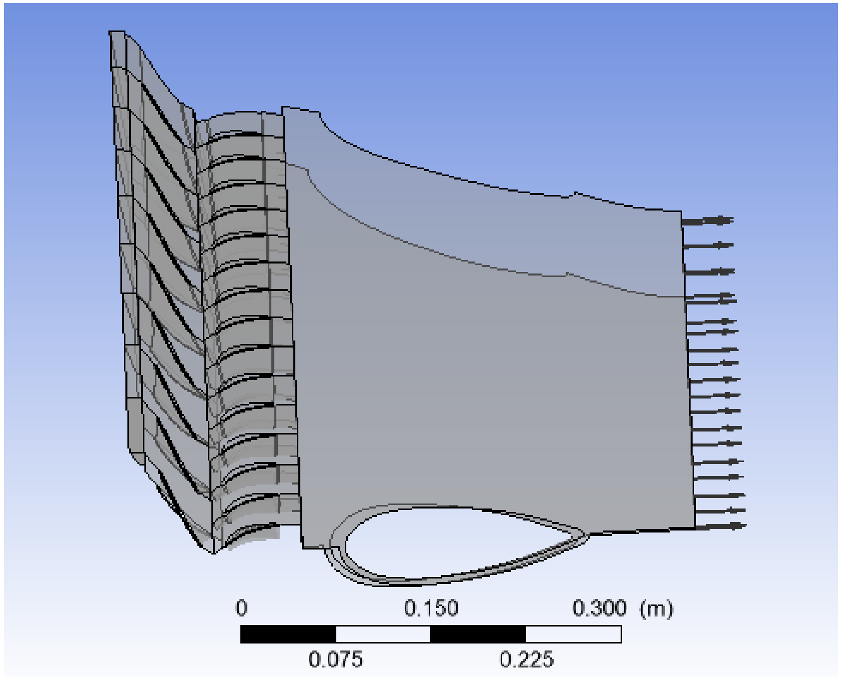
Scaling method
(to achieve equal pitch)

domain	**R3**	**S3**	**IMC**
Full annulus	75	130	9
Sector 40deg	8	14	1

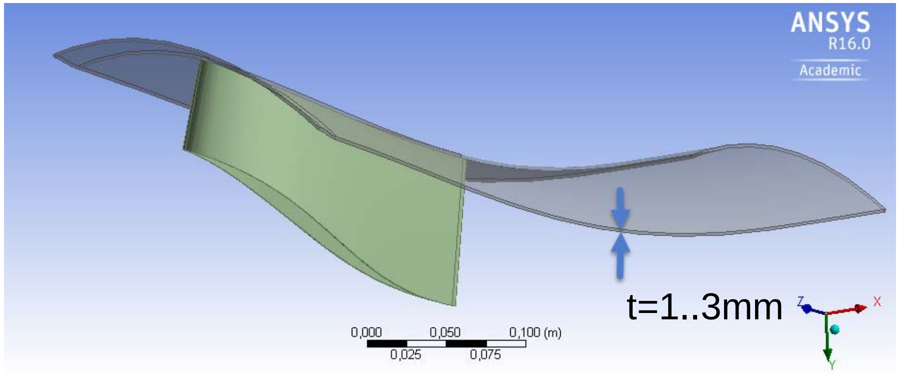
S3 : 130 → 126

R3 : 75 → 72

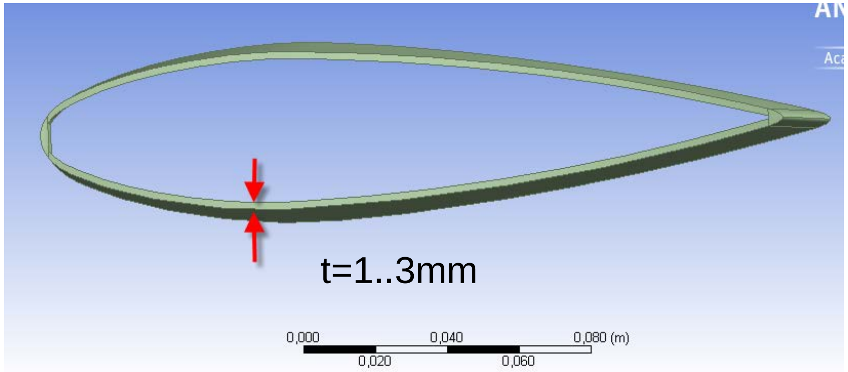
BCR : 1.73 → 1.75

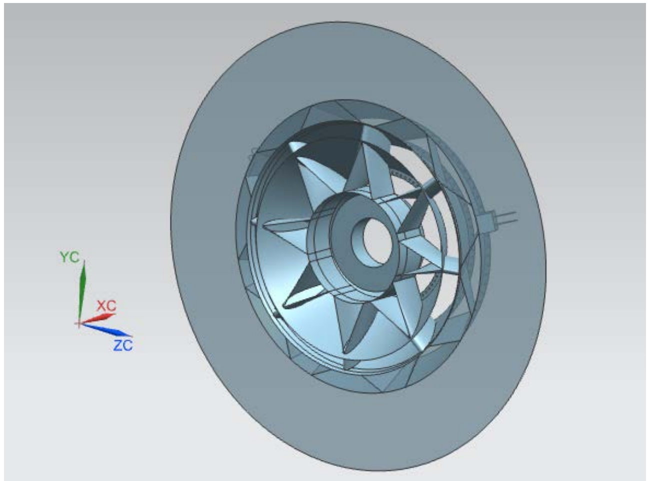


Structural analysis of IMC duct



- Varying strut panel wall & casing wall thickness t=1-3mm
- Different materials: Ti-6Al-4V, Al 7075, carbon-fiber composite





Near term work

- Aerodynamic optimization of the stages
- Off -design operating point (approach with 30% bleed air)
- Aerodamping simulations with linearized solver (LUFT)
- Unsteady aerodynamic simulations of the rear stage (including bleed box) → potential effects on R3, forcing on S3 and strut, unsteady aero forces on the “bleed lip”
- Aeromech analysis of the IMC duct and struts

Summary

- Design process of a three stage high speed booster intended for a geared engine architecture has been presented

- The platform and methods established in the project enables further detailed research in respective areas and can be used a reference for improvements

- A strong collaboration between has been established the partners (industry and academia) to conduct future national and international research and demonstrator projects.