The preliminary design of a Low Transonic Fan made of composite material, test article of an innovative WT test campaign to measure aerodynamic, aeroelastic and aeroacoustics advances in UHBR Turbofan engines

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Project Objectives

- To perform a **literature review** of the main issues affecting composite **UHBR** engine fans;
- To **design a low-transonic fan** typical of a future large aircraft UHBR engine, in terms of aerodynamic shaping as well as structural design and analysis to make sure the test article can safely go close to aerodynamic and aeroelastic instabilities in an expected way during WT operations;
- To **design** the test article(s);
- To **manufacture** the test article(s);
- To **instrument** test articles and rigs;
- To perform **experimental tests** including fan instabilities due to off-design operation and inlet distortion;
- To perform a **final experimental-numerical assessment** for calibrating and validating numerical models;
- To provide **open access** to all the produced **models, data and documents** for other institutions for in-house developed methods validation, with the objective to establish an "open test-case" for the whole European scientific community, unique in the engine fans landscape.

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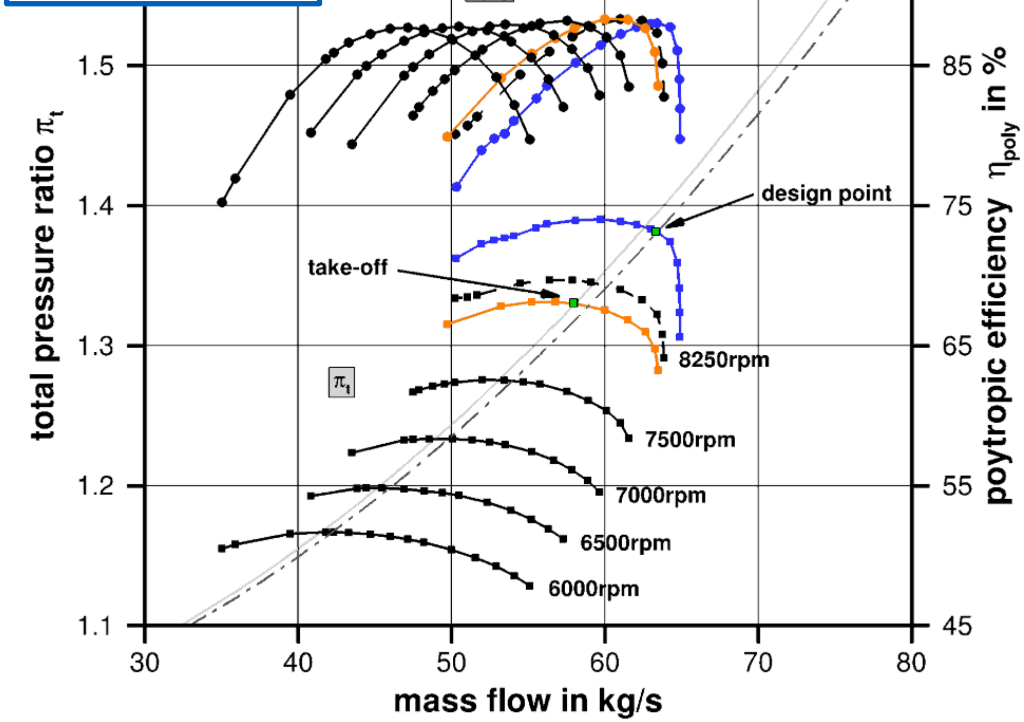
Project Partners

- **IBK →** Project Coordination, support to Low Transonic Fan (LTF) aeroelastic design, test article design Leader and manufacture responsible
- **TUBS →** requirements management, LTF aerodynamic design and scaling approach, rig modification and instrumentation, management of WT tests
- **LUH →** LTF aeroelastic and aeroacoustic design, support to WT test measurements, pre/ post-test predictions
- **DREAM →** Support to LTF design and post-test predictions (CFD)
- **ADC →** Manufacture and instrumentation of test article, support to WT tests

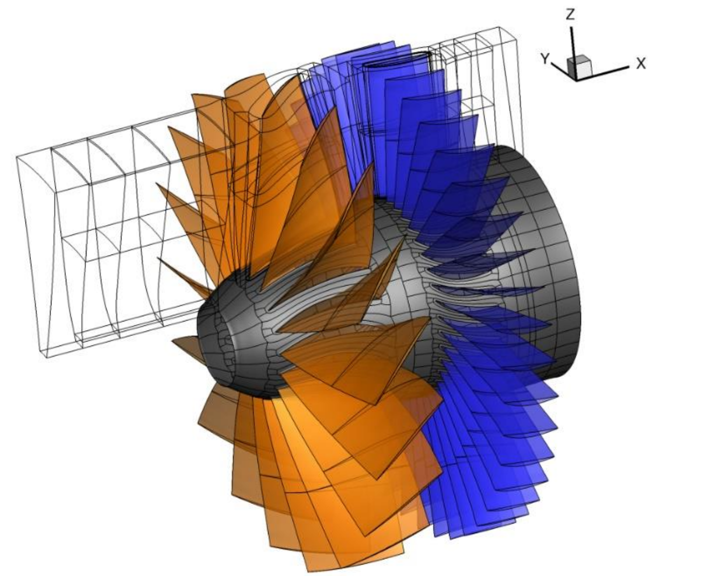
Aerodynamic Design, status after SRR

- Fan stage with a scaling factor of 1:3.3; 18 rotor blades and 40 stator blades
- Restrictions due to manufacturability and rig installation
- $SM_{cruise} = 12.1\%$ and $SM_{takeoff} = 11.5\%$ (target: $SM > 11\%$)

$$SM = 1 - \frac{\pi_{t,DP}}{\pi_{t,SL}} \frac{\dot{m}_{SL}}{\dot{m}_{DP}}$$



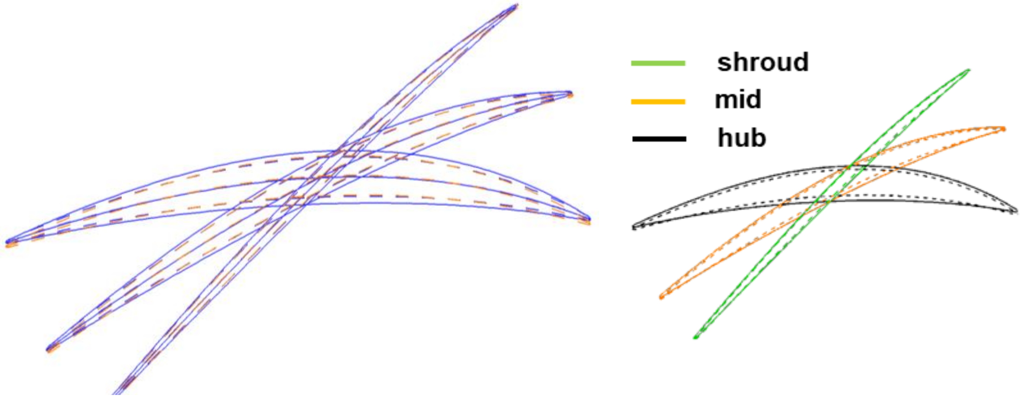
	mass flow	total pressure ratio	poly. efficiency
Design target	63.4 kg/s	1.37	89.2%
Case 132	63.4 kg/s	1.38 (+0.7%)	89.3% (+0.1%)



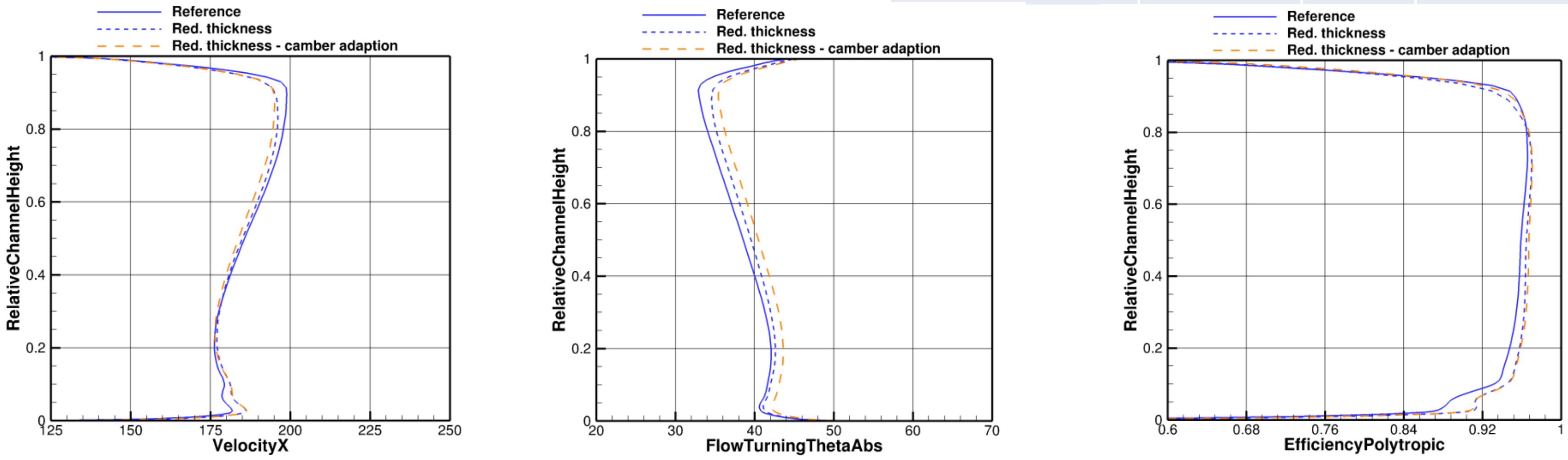
Aerodynamic Design, new blade geometry

- **Thickness of rotor blade reduced to 75%**
- **Reduction driven by structural design reqs.**

New Fan Design

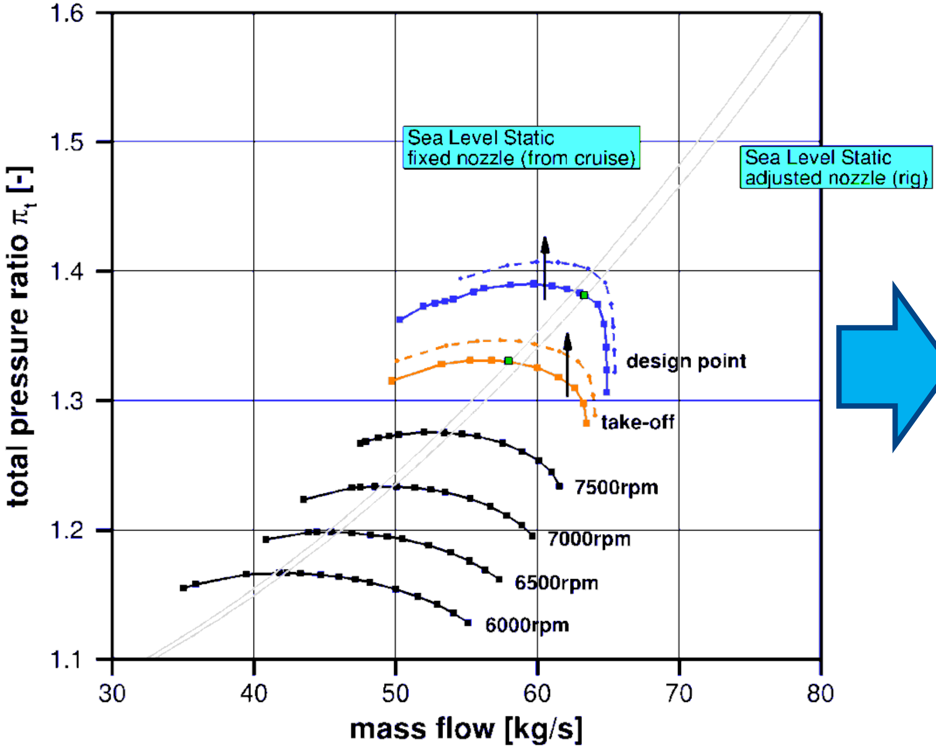


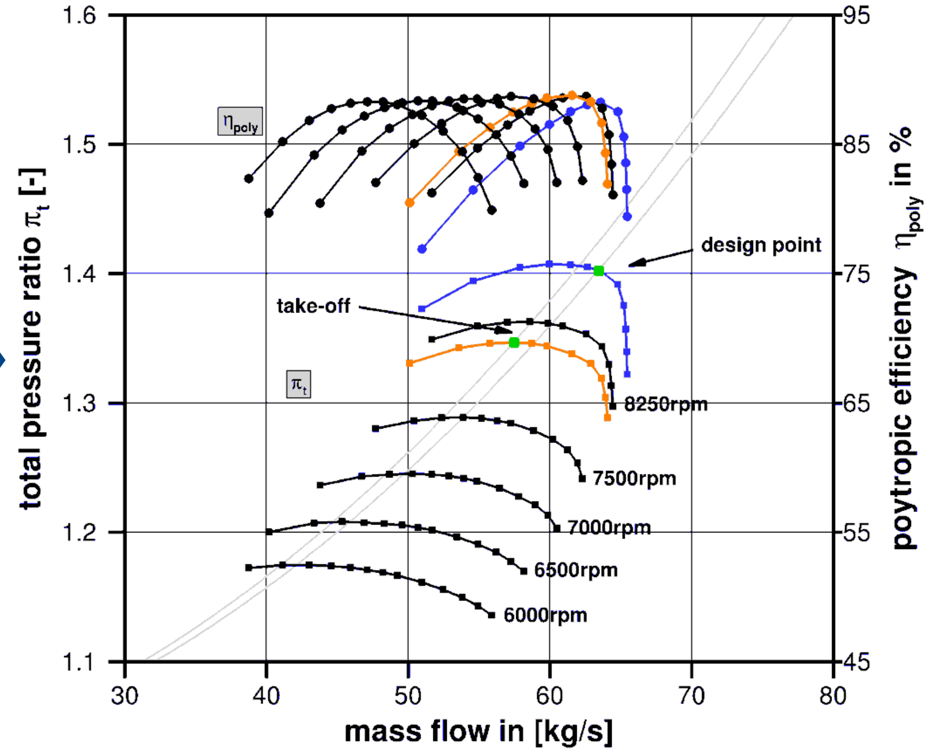
	$\dot{m}$ [$^{kg}/_{s}$]	π [-]	η_{poly} [%]
Design target	63.4	1.37	89.2
Reference	63.4	1.38	89.3
Thin blade	63.4	1.37	87.6
Thin blade C.A.	63.4	1.40	88.2



Aerodynamic Design, speed lines

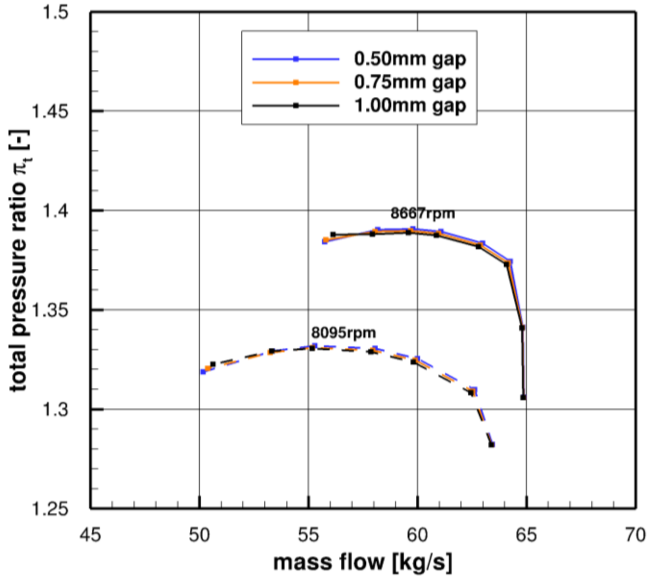
- **Speed lines of the fan stage get shifted to higher total pressure ratios**
- **Only slight change towards higher mass flows**

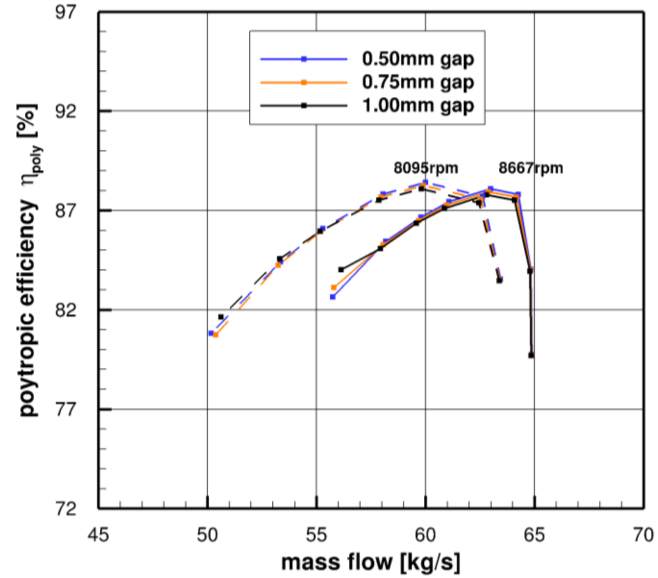




Aerodynamic design, tip gap sensitivity

- Investigation of tip gap **sensitivity to predict influence of blade elongation**
- Throttle lines for **0.5 mm, 0.75 mm and 1 mm tip gap**, at design speed (8667rpm) and take-off (8095rpm)





- Total pressure ratio and polytropic efficiency drop linearly with increasing tip gap size → **Increase in tip gap of 1% ~ -1.5% efficiency**
- best **compromise** with mechanical design requirements found with **a gap of 0.75 mm**

Structural design, drivers and requirements

Usual blade design

- No flutter wanted
- High amount of 0° plies for high bending stiffness
- ±45° plies on the outside for torsional stiffness
- Typically above the 2P-line in the Campbell diagramm

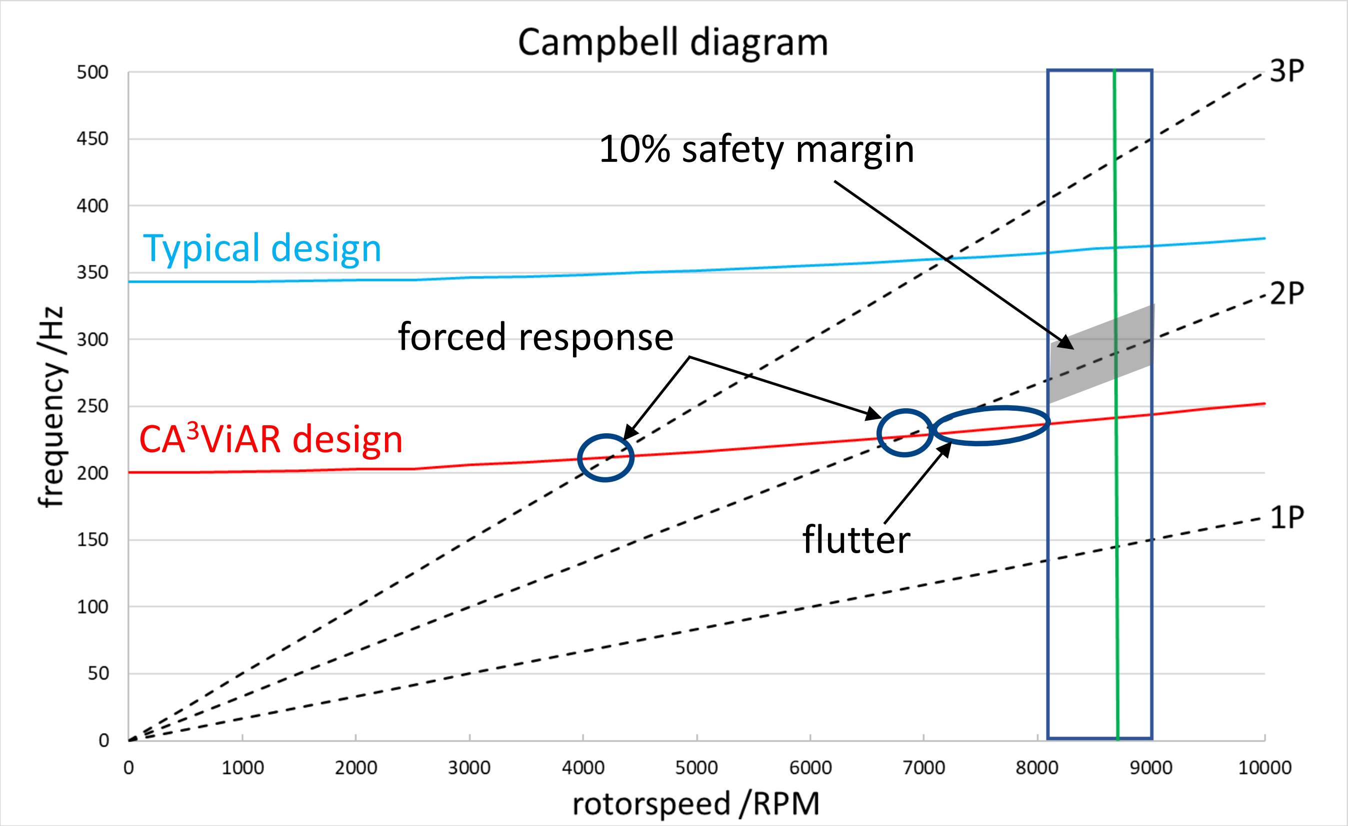
CA3ViAR blade design

- Flutter wanted at special conditions (specific massflow and IBPA)
- No flutter at design conditions
- Blade has to be tailored to specific Eigenfrequency for the first bending mode
- Twist-to-plunge (T2P) ratio needs to stay above specific value
- Below the 2P-line in the Campbell diagramm

Design possibilities

Eigenfrequency ↓:
- Young's Modulus of fibre ↓
- Fibre volume fraction ↓
- Substitution of 0° plies by 90° plies (other angles increase torsional stiffness too much – T2P ratio ↓)

T2P ratio ↑:
- Young's Modulus of matrix ↓ (reduces shear modulus of plies)
- Substitution of ±45° plies by ±60° plies (higher angle = lower torsional stiffness)



For flutter additional condition requirements are needed:
- Low massflow
- Specific IBPA (interblade phase angle)

Identification of interesting Eigenfrequency and T2P area

Target Eigenfrequency

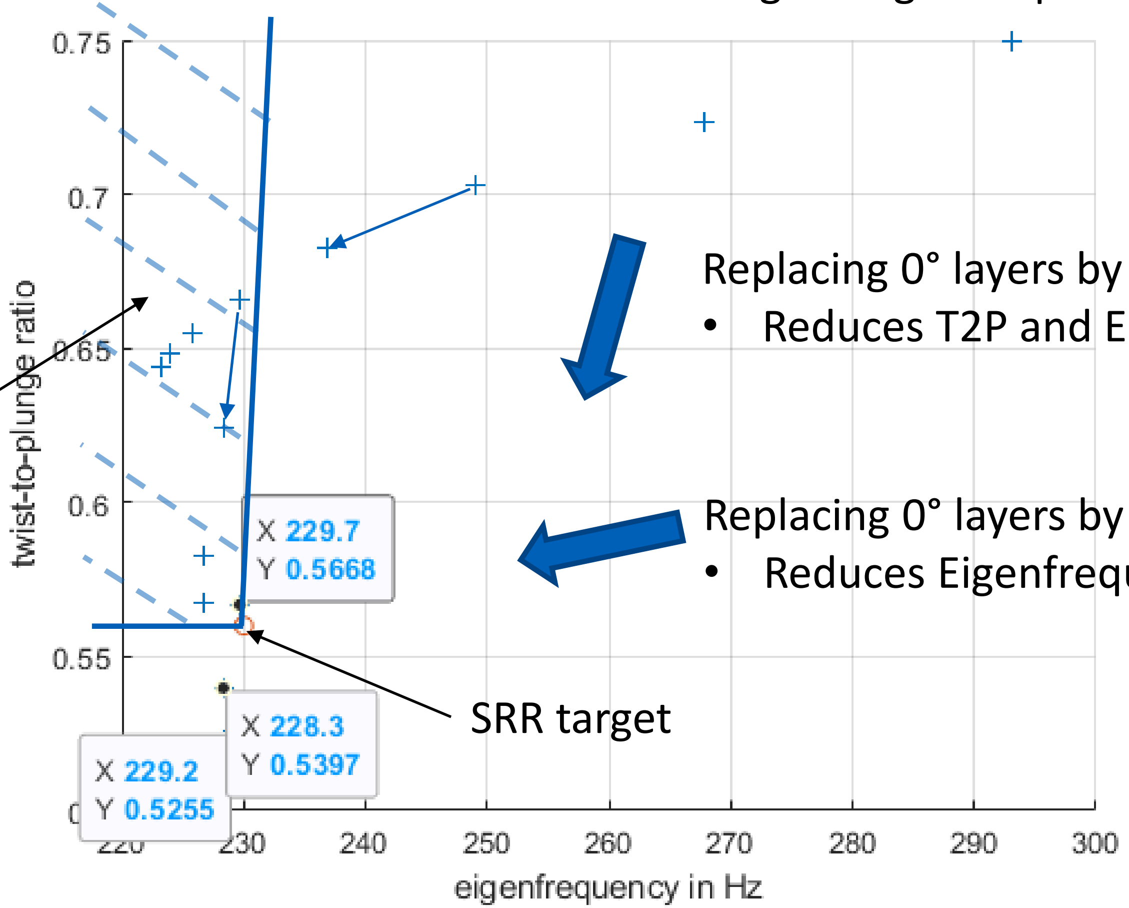
- 230Hz at 7500RPM

Target Twist-to-plunge ratio

- 0.56 at 7500RPM

Increased T2P allows flutter at higher Eigenfrequencies

Interesting area



Replacing 0° layers by ±45°/ ±60°layers

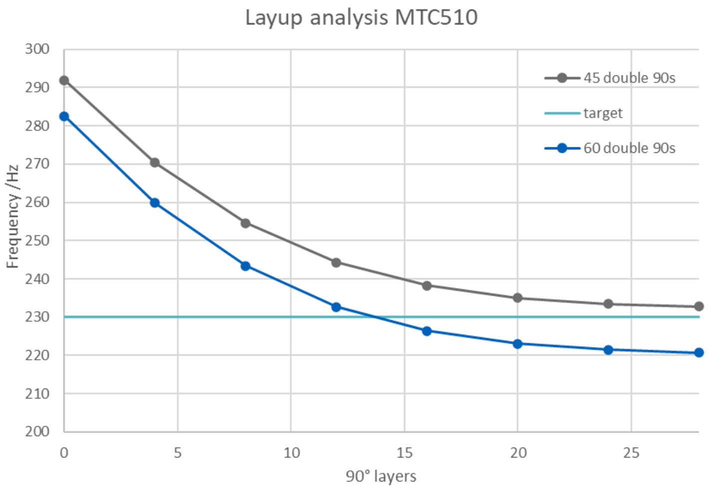
- Reduces T2P and Eigenfrequency

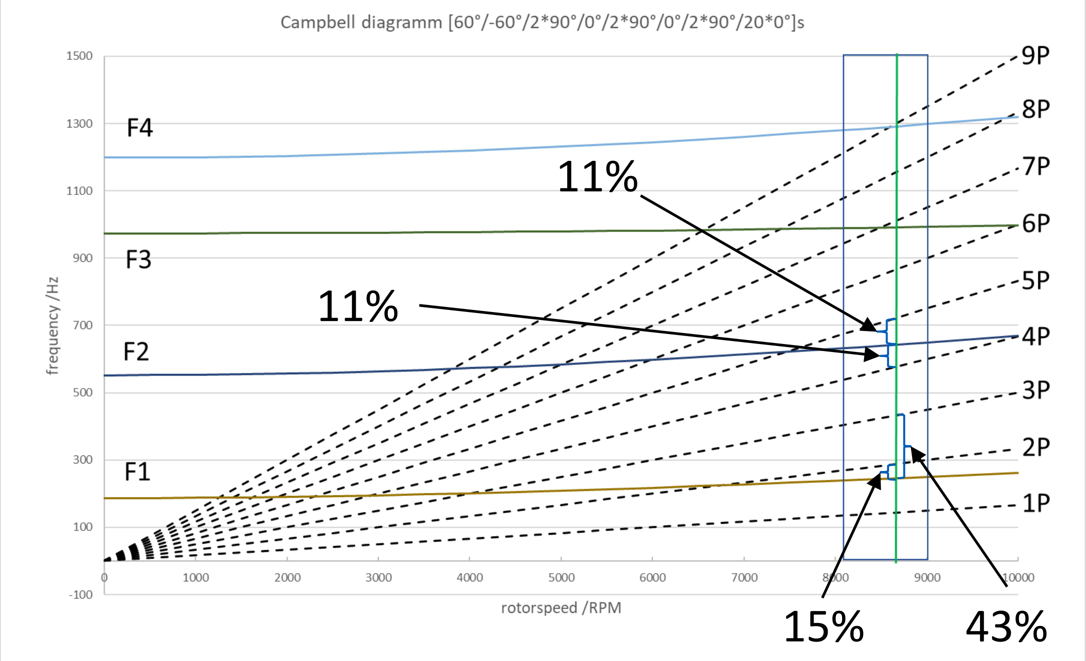
Replacing 0° layers by 90°layers

- Reduces Eigenfrequency, T2P slightly

SRR target

Sensitivity analysis on layup and Campbell diagram





Operational safety

- Campbell diagramm used to ensure safe operation at design conditions
- Areas of forced response can also be identified
- Safety requirements according to NASA CR-174992 are met for design layup
- Robust design (distance to 1P line larger than distance to 2P line)

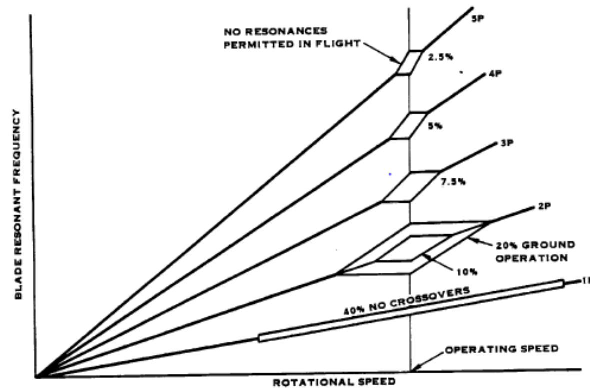
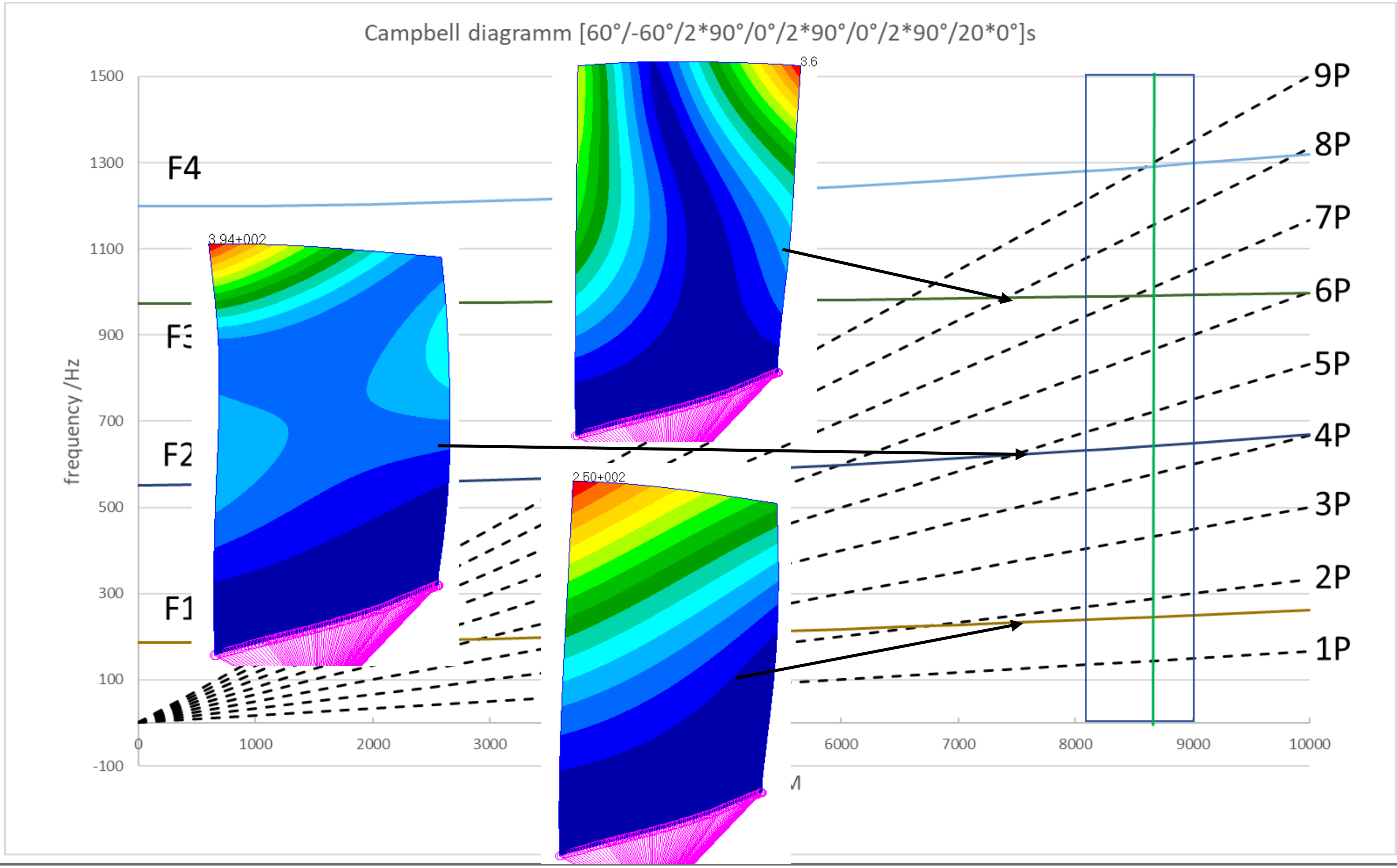


FIGURE 5.13 BLADE DESIGN FREQUENCY CRITERIA

[NASA CR-174992 – Large scale prop-fan structural design study]

Natural modes

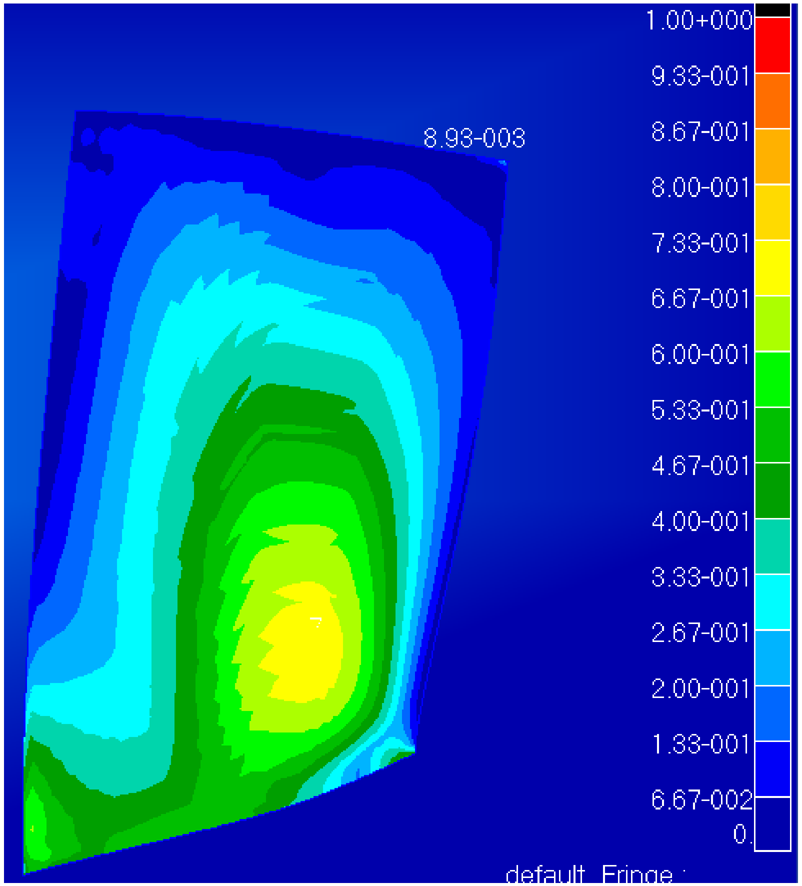


Static stress analysis, Target Layup, Design condition

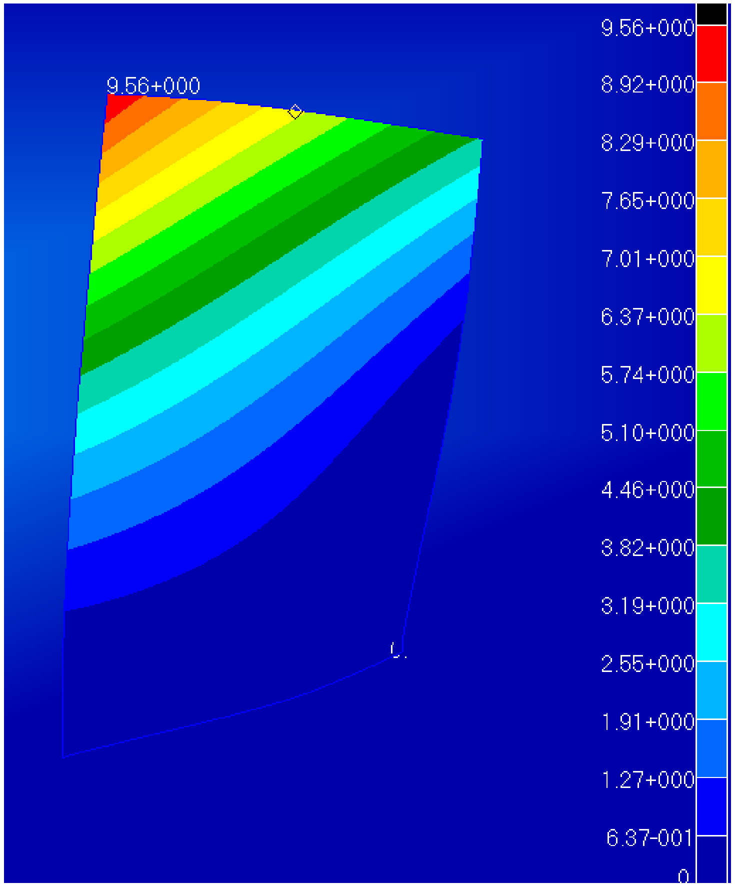
LF = 2.5 max. failure index = 0.732

Knockdown factor = 1.3

$$F(\sigma_{ij}) = \left(\frac{1}{R_{11}^{+}} - \frac{1}{R_{11}^{-}}\right)\sigma_{11} + \left(\frac{1}{R_{22}^{+}} - \frac{1}{R_{22}^{-}}\right)\sigma_{22} + \frac{1}{R_{11}^{+}R_{11}^{-}}\sigma_{11}^{2} + \frac{1}{R_{22}^{+}R_{22}^{-}}\sigma_{22}^{2} + \frac{2F_{12}^{*}}{\sqrt{R_{11}^{+}R_{11}^{-}R_{22}^{+}R_{22}^{-}}}\sigma_{11}\sigma_{22} + \frac{\tau_{12}^{2}}{R_{12}^{2}}$$



LF = 1 displacements



Fatigue analysis

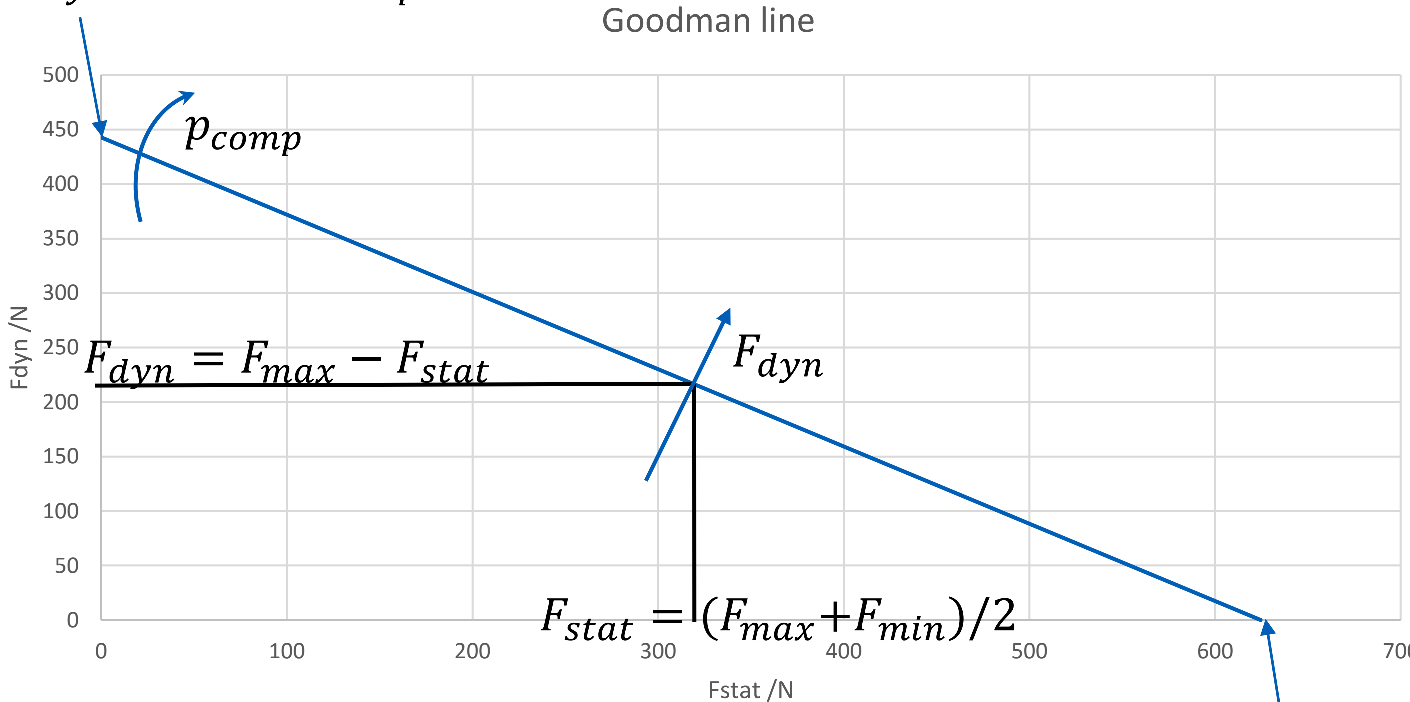
Fatigue load condition

- Delta-loads due to non-axial symmetric operating conditions of the fan, e.g. in case of rotating stall/ cross-wind scenarios
  - Max. pressure ratio vs. choke point
- Derived from maximum and minimum load occurring to the blade in those conditions
- Load factor = 1 and knockdown factor = 1.3 used for fatigue analysis
- Beneficial loads scaled in opposite direction
- Effect of fatigue taken into account by reducing the material performance $\mathbf{p}_{\mathbf{comp}}$ in relation to the expected amount of cycles
- Low cycle fatigue considered by reducing material performance further

Goodman chart – creating static equivalent loads

p_{comp} is the performance of the composite material after a certain amount of cycles (e.g. 10^6 cycles p_{comp} ~ 0.9; 10^8 cycles p_{comp} ~ 0.7)

$$F_{dyn,eq} = F_{dyn} + F_{stat} \cdot p_{comp}$$



$$F_{stat,eq} = F_{dyn,eq} / p_{comp}$$

Tsai-Wu criterion

Combined material degradation Low cycle + high clycle Fatigue

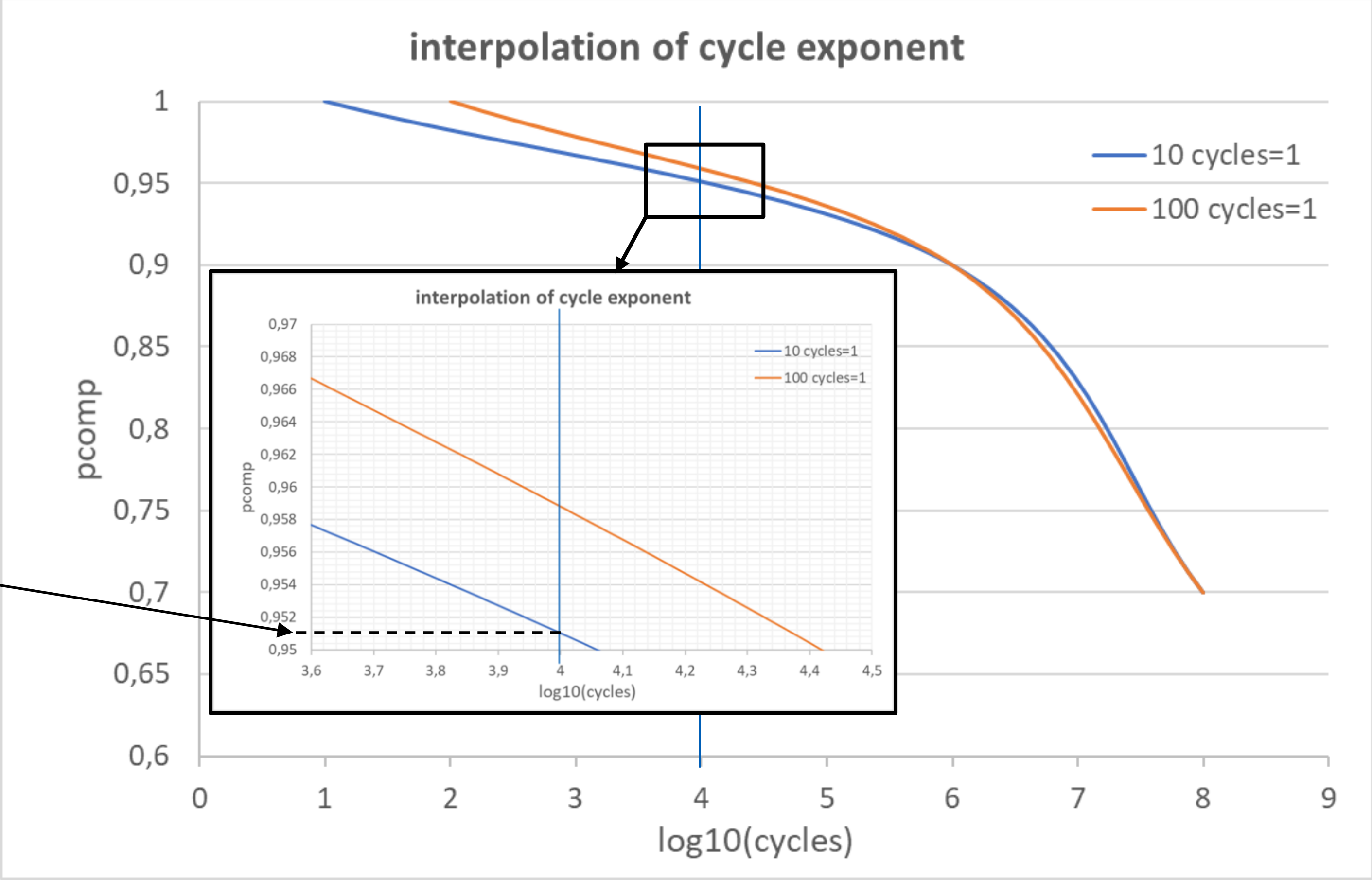
High cycle fatigue (flutter analysis):

p_{comp} for 10^8 cycles = 0.7

Low cycle fatigue (turning on and off):

p_{comp} for 10 cycles = 1

- Zero damage
- Interpolation:
- p_{comp} 10^4 = 0.951



Combined p_{comp} (Accumulated damage)

$$1 - \sum_{i=1}^{k} 1 - p_{comp,i} = p_{comp,c} = 1 - 0.049 - 0.3 = \mathbf{0.651}$$

Low cycle reduction

high cycle reduction

Failure index calculation for Fatigue

Load component (Fx, Fy, Fz, Mx, My, Mz) max. pressure ratio -> F_{max}

Load component (Fx, Fy, Fz, Mx, My, Mz) choke point -> F_{min}

fatigue cycles

combined material degradation $\mathbf{p}_{comp}$

$$F_{static} = (F_{max} + F_{min})/2$$

$$F_{dynamic} = F_{max} - F_{static}$$

$$F_{dyn,eq} = F_{static} \cdot p_{comp} + F_{dynamic}$$

$$F_{stat,eq} = F_{dyn,eq}/p_{comp}$$

For all load components on all span stations

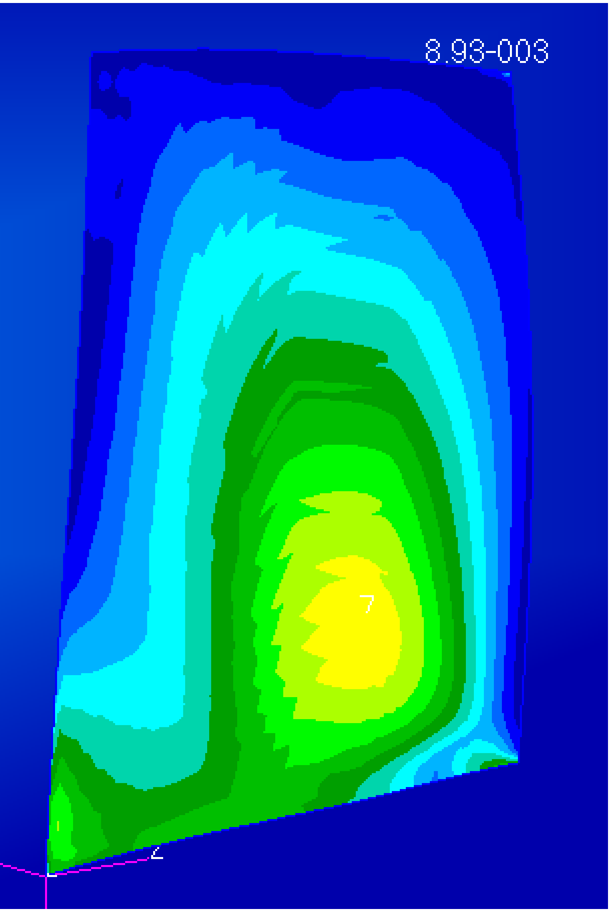
Fatigue Loads

FE Model

Failure index (Tsai-Wu-criterion)

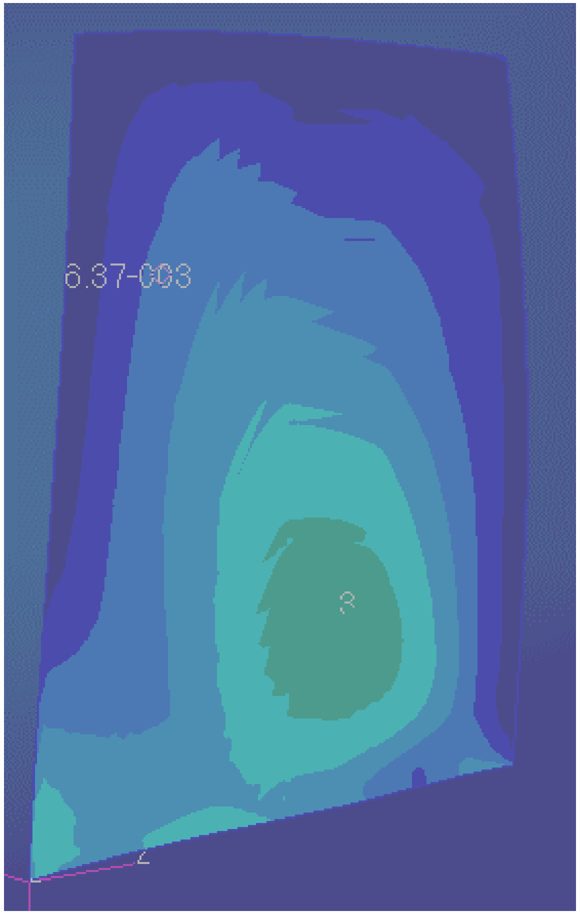
Failure index, fatigue analysis

LF = 2.5 (static design loads)
Knockdown factor = 1.3



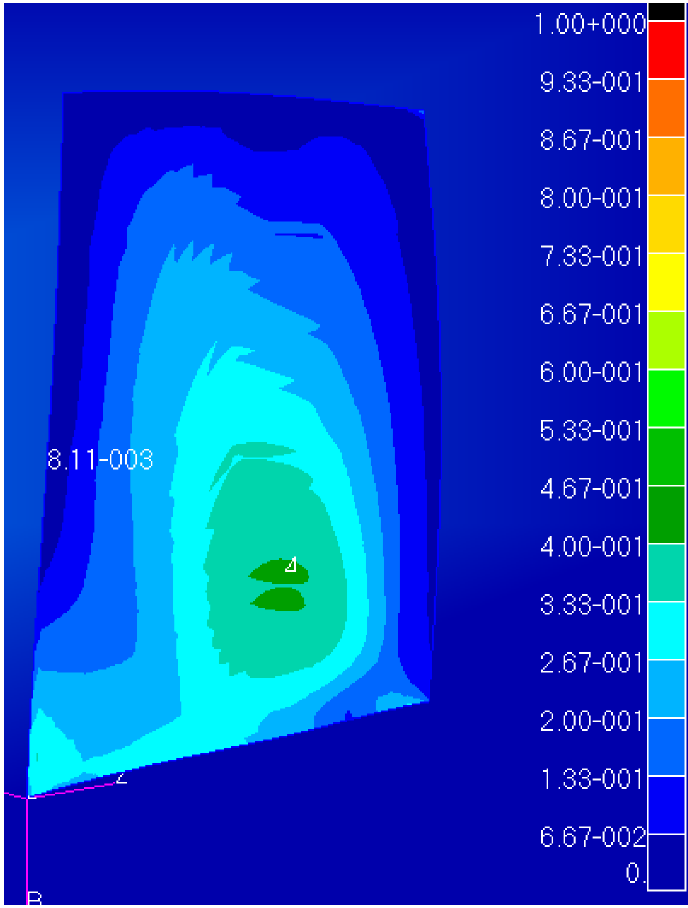
max. failure index = 0.732

LF = 1 (static loads)
Knockdown factor = 1.3



max. failure index = 0.386

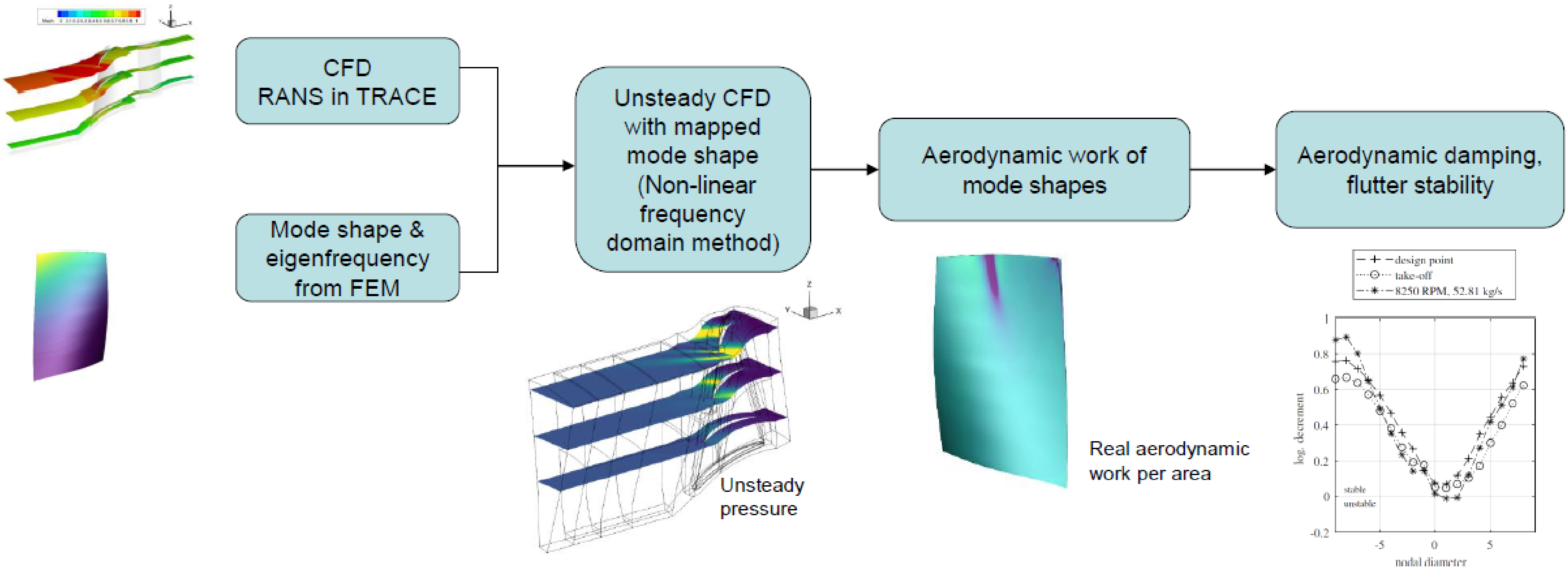
Fatigue loads:
Knockdown factor = 1.3



max. failure index = 0.417

Aeroelastics, High-fidelity flutter analysis

Flutter simulation with TRACE Harmonic Balance:



Rotor-only Simulation

- Direct restart of 3D-simulations from aerodynamic design
- Understanding of rotor blade behaviour
- Fast analysis of layup variation on the blade only damping

Coupled Intake Simulation

- Quantify intake reflections on aerodynamic damping
- Compare different intake lengths
- Required for final layup decision

Aeroelastic analysis and reqs. for PDR

Performed parameter study and analysed different layups and their influence on the **rotor-only aerodynamic damping**:

1. Mode 1 with ND 1 and ND 2 prone to flutter.
2. Reduction of eigenfrequency and increase of twist-to-plunge ratio to trigger flutter.
3. High aerodynamic damping for Mode 1 with $|ND| > 2$.
4. Layup with **eigenfrequency** of 230 Hz and **twist-to-plunge ratio** of 0.56 at 7500 RPM is **unstable** at throttled fan condition at rotational speeds above 7500 RPM.

Variation of the intake length to manipulate the influence of intake reflection.

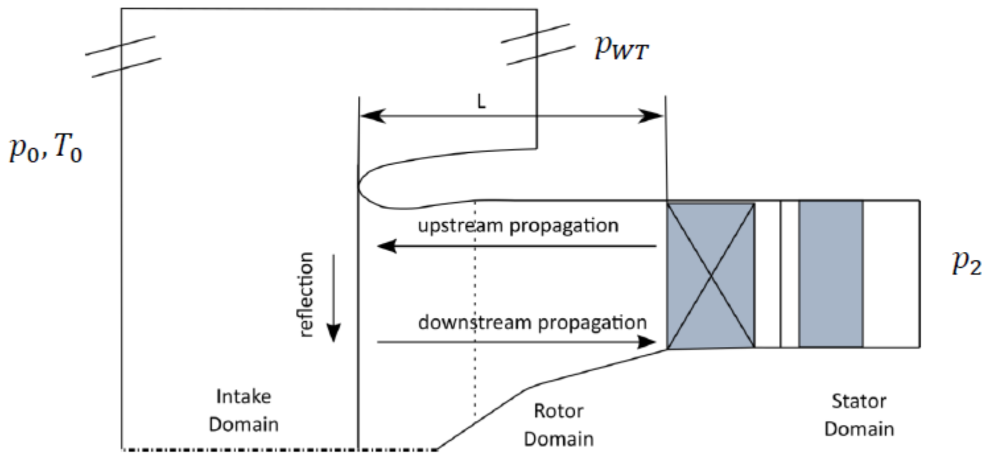
Aim for the PDR:

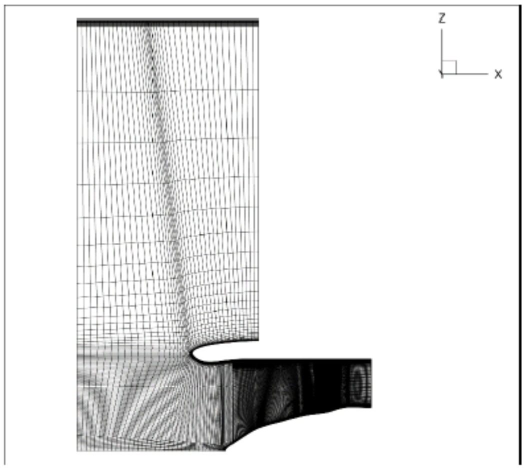
- **Quantify** the effect on the aerodynamic damping of the **intake reflection** and different intake length.
- Find a structural blade design that is:
  - **Stable** on the **working line** with all intakes.
  - **Unstable** at **throttled** fan condition.
  - Within the **safety constrains** (e.g. failure index, 10% distance to 2. EO).
- Simulate **fan stability map** for modes prone to flutter.

Intake effect on flutter, numerical scheme

Coupled intake + rotor simulation – Numerical Setup

Wind tunnel and nacelle added to **resolve reflections** of the upstream traveling waves at the intake lip.

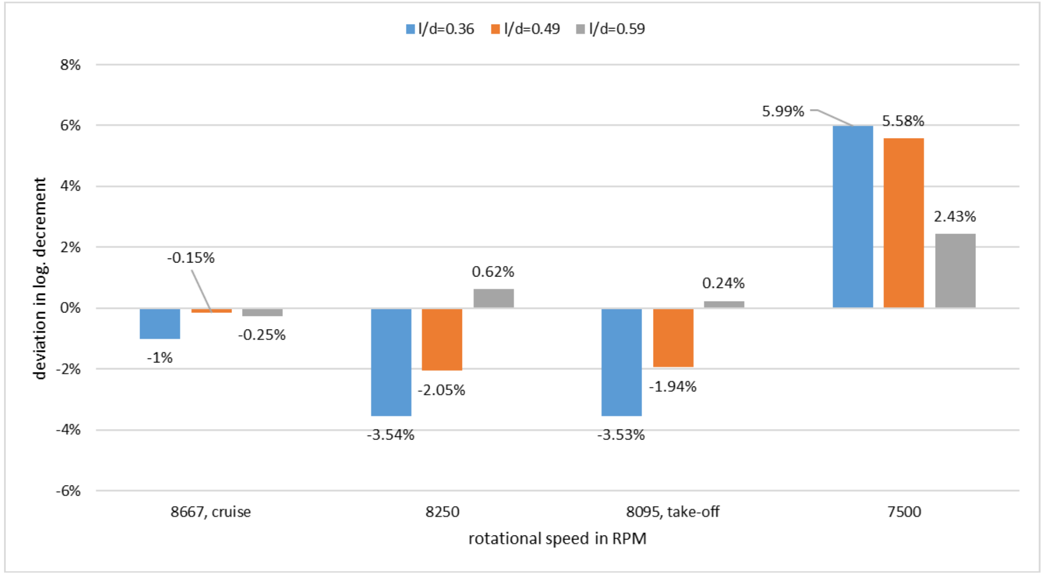




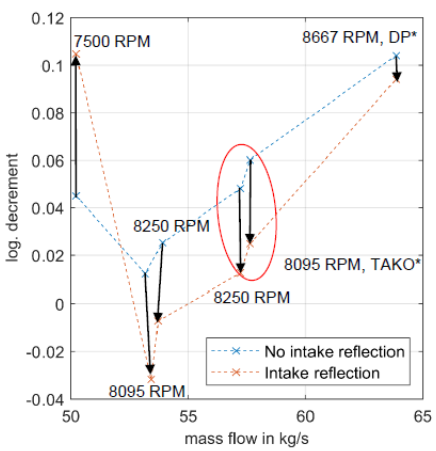
Simulation domain:
- AutoGrid (Rotor, Stator) and ANSYS ICEM (Intake)
- 6.8 million nodes
- Ambient condition at wind tunnel inlet
- Constant stat. pressure at wind tunnel outlet
- Intake + Rotor + Stator resolved with 1st harmonic
- 20 cells per wavelength for max. frequency
- $y^+ \approx 1$

Setup parameters:
- $k{-}\omega$ Turbulence model
- $\gamma{-}Re_{\Theta t}$ Transition model
- Mean flow (0th harmonic) and the 1st harmonic of the blade vibration frequency
- Low-Reynolds wall treatment
- Mixing plane as interface
- 0.1 mm vibration amplitude

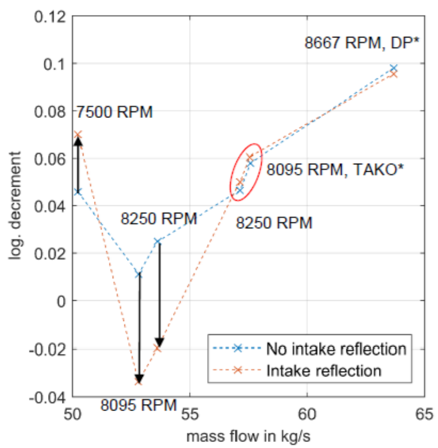
Intake lenght effect on ND 2, detail of short intake



Short intake $\frac{L}{D} = 0.36$, ND 2



Long intake $\frac{L}{D} = 0.59$, ND 2



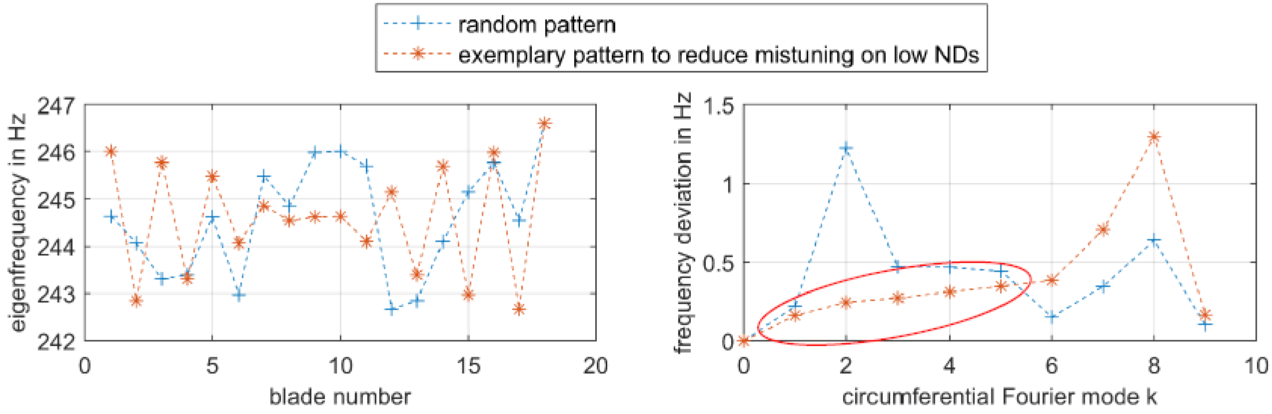
Structural damping and mistuning on natural frequencies

Mechanical damping and mistuning are counteracting the flutter instability.

- The blade foot will be designed to reduce the expected mechanical damping.
- Target for low scatter in eigenfrequency during blade manufacturing.
- Distribution of the blades in the disk to reduce effect of mistuning on low NDs, which are prone to flutter.

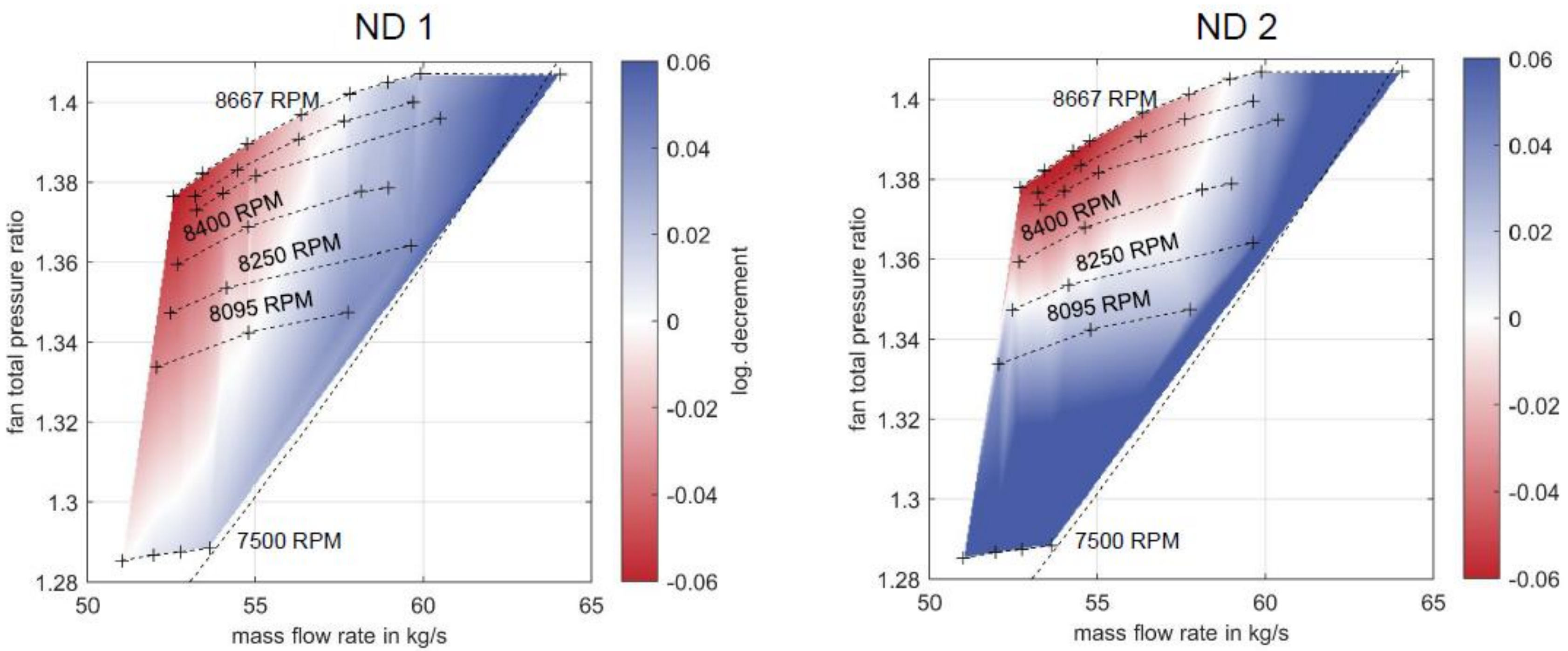
Assumption of isolated mode pairs (e.g. $\pm$ND2) average the aerodynamic damping with increasing mistuning amplitude, Martel et al., 2018 (DOI: 10.1115/1.2720503).
For multiple active modes, the coupling and averaging is between all the active modes.

Idea: Use a pattern distribution to reduce the deviation in eigenfrequency of low order NDs.



Flutter simulation to iterate final layup

Flutter map with short intake for Mode 1, ND 1 & ND 2 of layup MTC510 4x60° 12x90°:



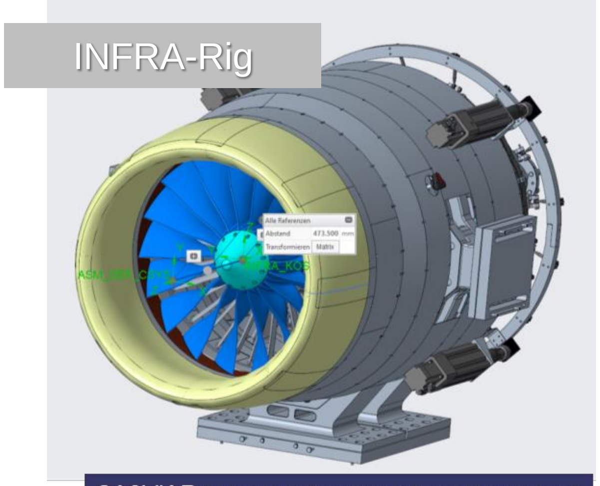
- Large unstable areas for ND 1 and ND 2 for throttled fan conditions.
- Sufficient flutter margin to the working line for ND 1 and ND 2.
- Both NDs have their most unstable condition at 8667 RPM and reduced mass flow rates.

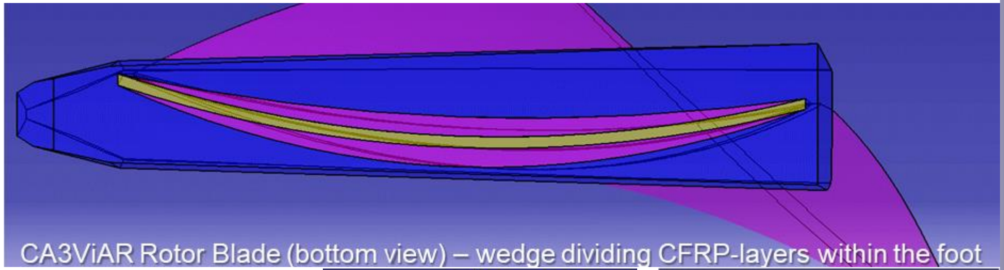
Preliminary mechanical design

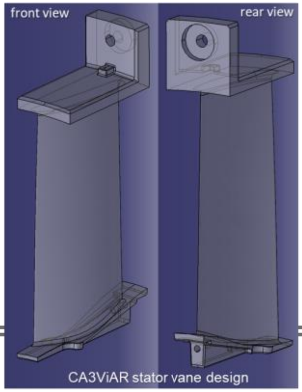
The CA3ViAR new rotor and stator stages will be assembled to the same rig used for the INFRA project, which featured a blisk design for its rotor stage.

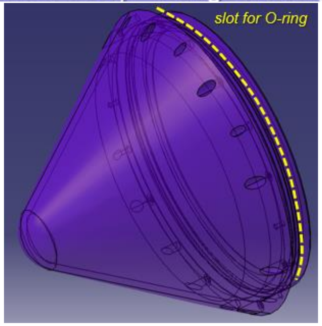
An important requirement is to reuse as many interfaces (and parts) of the existing rig as possible (e.g. rotor shaft for the rotor stage), to minimize design and manufacturing efforts and therefore costs

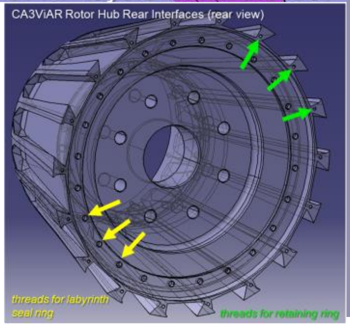
The design approach is to use a slotted rotor hub and rotor blades including a dovetail-like foot design.

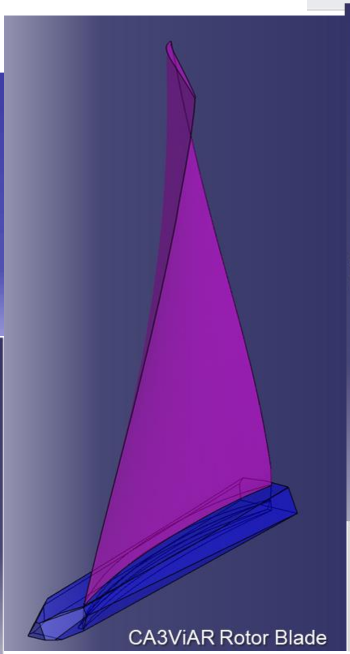


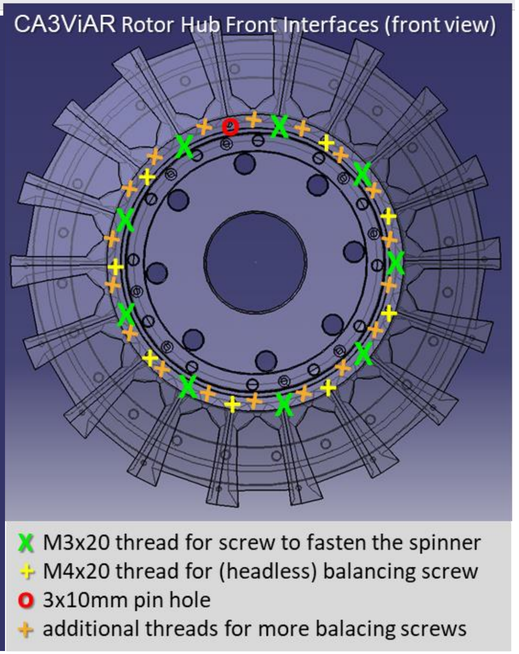










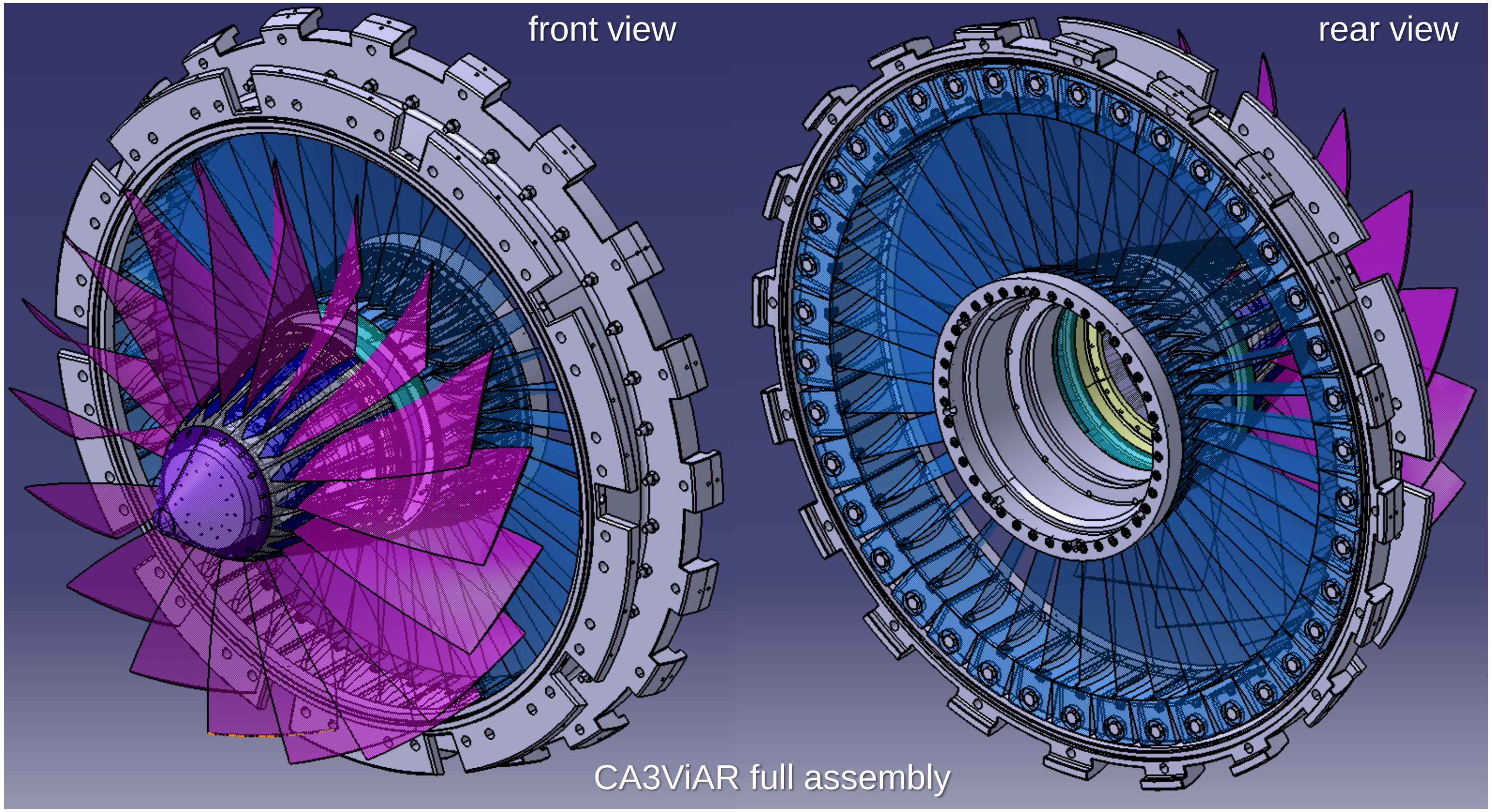


CA3ViAR PDR - Mechanical Design

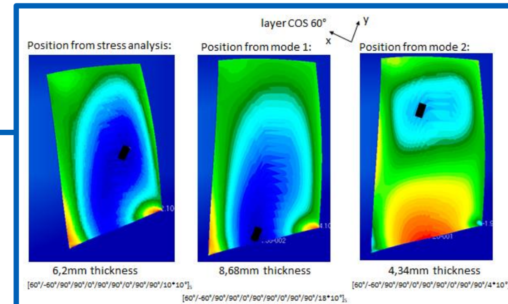
CA3ViAR Rig

Full Assembly

The picture shows the full assembly including all newly designed parts.



CA3ViAR PDR - Mechanical Design



FE and modal analysis

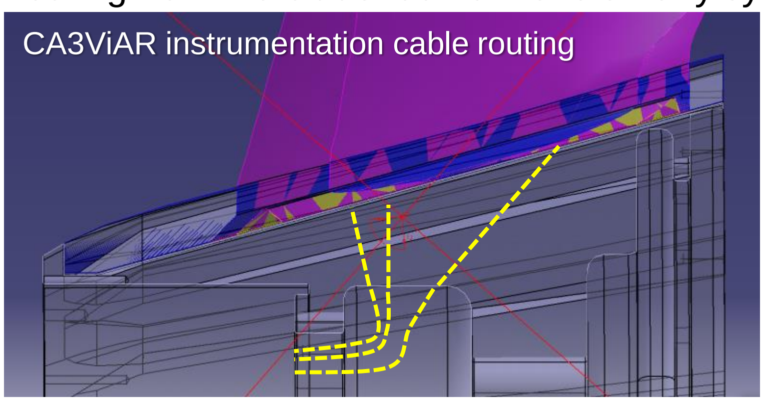
CA3ViAR Rotor Design

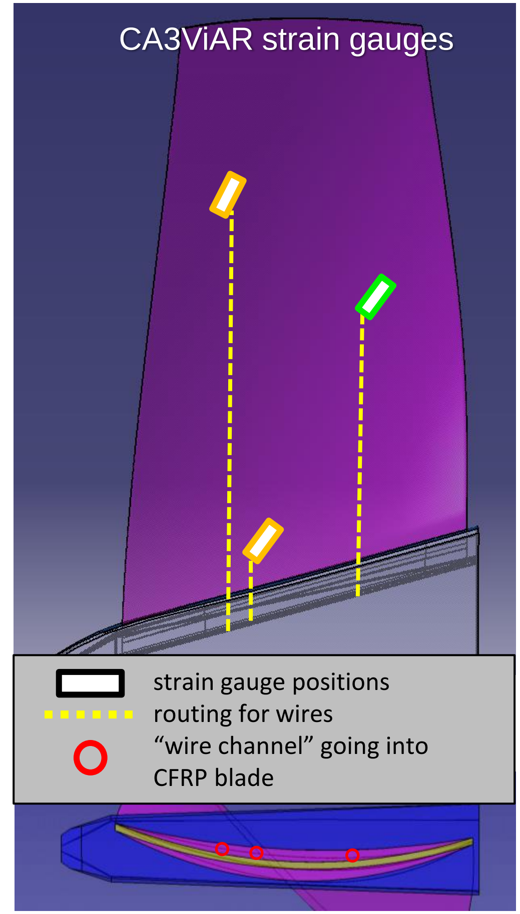
Instrumentation – Strain Gauges

According to FE calculations, SG positions were identified in most critical areas.

- Every blade is instrumented with one **SG** to monitor maximum stress
- Six blades will be instrumented with two additional **SG's** to detect the modal participation of the 1st & 2nd natural modes
- Different SG-installation strategies are under investigation (co-cured on surface or fully embedded, secondary bonding), with the aim to ensure feasible sensor installation, maximize reliability and minimize the impact on aerodynamic performance
- More details are given in the presentation by ADCO

The sketch in the figure below shows that there is enough space available on the hub for cable routing from the blade foot to the telemetry system





Strain gauges positions and instrumentation breadboard

Considerations:

- Same material as for the final blades.

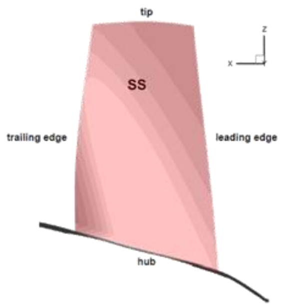
(MTC510 prepreg already ordered for trials)

- Representative thickness and layup
- Assess options for SGs

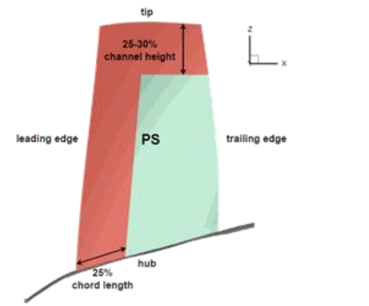
Breadboard Specimen:

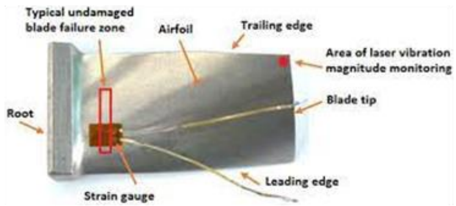
Trial Plates, made of CFRP

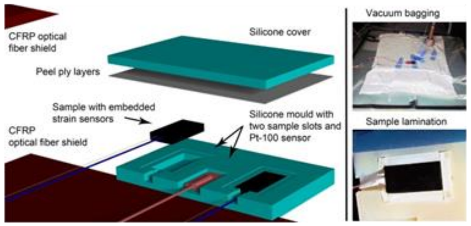
- Suction surface (SS) is a keep out zone



- Pressure surface (PS) has a green zone for strain gauges







Options for installation

	Routing	SG
Option 1	External	Surface
Option 2	Embedded	Surface
Option 3	Just inside the surface (groove)	Surface
Option 4	Embedded	Embedded

Surface/ embedded case study – Measuring equipment

Align the trial tests with real test

Bridge

3 wires

Bridge

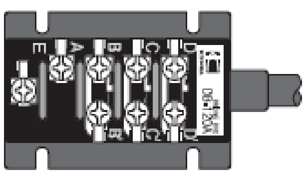
Bridge

Datalogger (Signal conditioner -Dynamic strain amplifier)

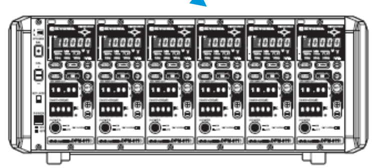
Analog to digital converter

PC

Quarter bridge



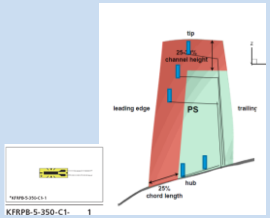
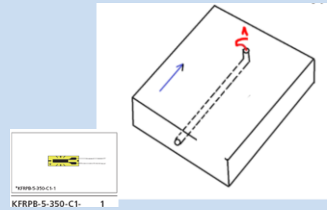
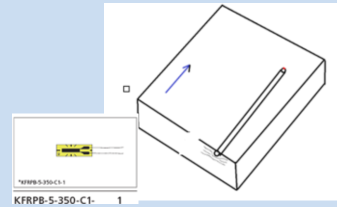
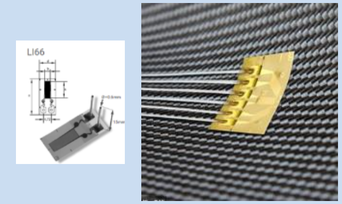
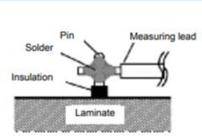
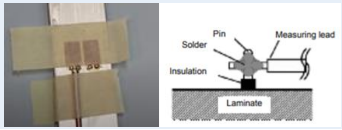
Bridge Box



Strain Amplifiers
DPM-900 Series

The selection of SG resistance must be verified by the available Amplifier

Plate Trial testing and SG placement options

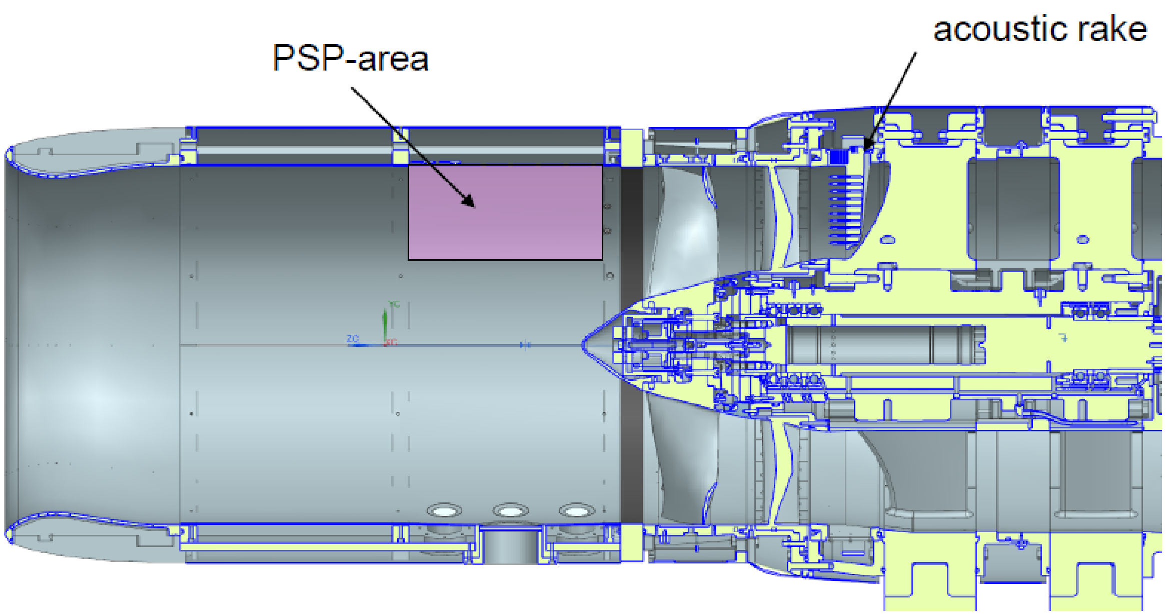
Characteristic	Option 1	Option 2	Option 3	Option 4
Option Figure				
Strain gauge type	Resistance : basic (350 Ω) CTE: 1.0E-06/K Voltage Excitation: 5-10 V	Resistance : basic (350 Ω) CTE: 1.0E-06/K Voltage Excitation: 5-10 V	Resistance : basic (350 Ω) CTE: 1.0E-06/K Voltage Excitation: 5-10 V	Resistance : basic (350 Ω) CTE: 0.5 E-06/K Voltage Excitation: Max 2.5 V
Wiring/Rooting	3 Wires Φ0.2 polyester lead wire (-196 deg Celc< T< +200 deg) 1.5Ω/m Max strain value: 50000 µm/m	3 Wires Φ0.2 polyester lead wire (-196 deg Celc< T< +200 deg) 1.5Ω/m Max strain value: 50000 µm/m	3 Wires Φ0.2 polyester lead wire (-196 deg Celc< T< +200 deg) 1.5Ω/m Max strain value: 50000 µm/m	3 Wires Φ0.2 polyester lead wire (-196 deg Celc< T< +200 deg) 1.5Ω/m Max strain value: 50000 µm/m
Adhesive	Z70 is recommended	Z70 is recommended for SG Wiring is consolidated with CFRP plies	Z70 is recommended for SG Wiring is consolidated with CFRP plies	Z70 is recommended for SG Wiring is consolidated with CFRP plies
Coating	SG250 for general mechanical protection	SG250 for general mechanical protection	SG250 for general mechanical protection	SG250 for general mechanical protection
Connection-SG/ wiring	Soldering ends 	Through soldering pin 	Soldering ends 	Combined 

Summary of instrumentation demonstration test

Sample No.	Test scope	Parameters	Support equipment
Coupon plate 1: Specimen: 3 / 200x 30x 4 1 SG surface/ routing external	-Functional test: a) SG/ wiring resistance b) Dimensional check of the assembly	- Thin wire soldering	1) MGSE for the plate support 2) Arduino Wheatstone bridge for voltage excitation
Coupon plate 2 : Specimen: 3 / 200x 30x 4 1 SG surface/ routing embedded	Functional test: a) SG/ wiring resistance b) Wiring interruption (possible) c) Insulation of 'soldering node'	- Soldering option-coating spray insulation - Curing process for wiring.	
Coupon plate 3 : Specimen: 3 / 200x 30x 4 1 SG surface/ routing surface (groove)	Functional test: a) SG/ wiring resistance b) Wiring interruption (possible) c) Dimensional check of the assembly d) Insulation of 'soldering node'	- Soldering options insulation-coating spray insulation - Curing process for wiring.	
Coupon 4 : Specimen : 3 / 200x 30x 4 1 SG embedded / routing embedded	Functional test: a) SG/ wiring resistance b) Wiring interruption (possible) c) Insulation of the SG pins	- Soldering options insulation-coating spray insulation - Curing process for SG/wiring.	

Aeroacoustics

- Design an **aocustic rake** to measure tonal noise from rotor-stator interactions **behind the stator**.
  - Full radial mode analysis (RMA) up to 3rd blade passing frequency (BPF).
  - Compare acoustic modes with numeric simulation.
- Design an **extended PSP*-Intake** to measure tonal noise propagating **upstream of the rotor**.
  - Spatial measurement of sound pressure at intake duct wall up to 5 kHz.
  - Analyse pressure distribution and compare it to numerical simulation.

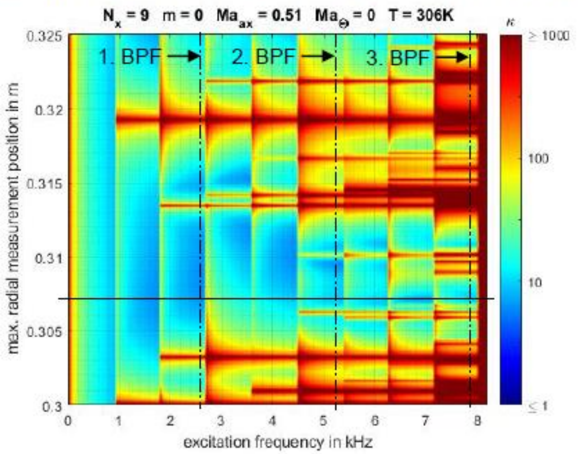


*pressure-sensitive paint

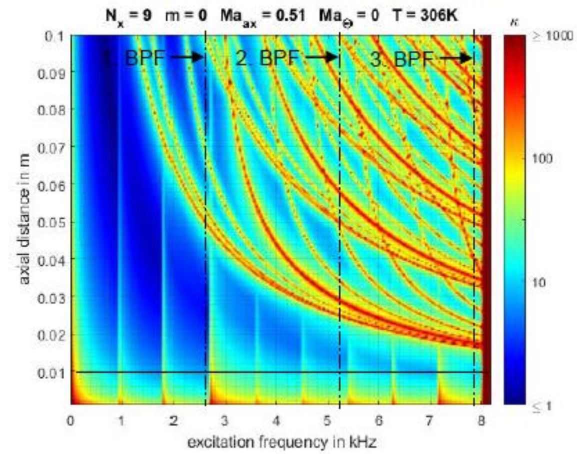
Design and Optimization of the aeroacoustic rake

- 9 measurement sensors per rake, 2 rake on different axial positions → **18 measurement sensors required.**

Variation of radial measurement position



Variation of axial distance

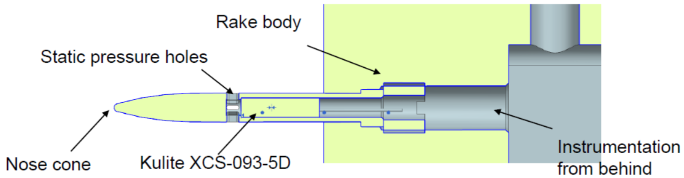


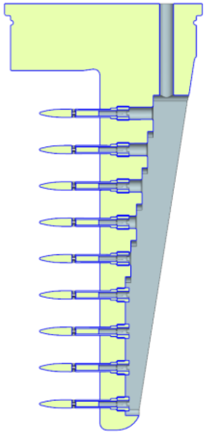
Source: GRAS

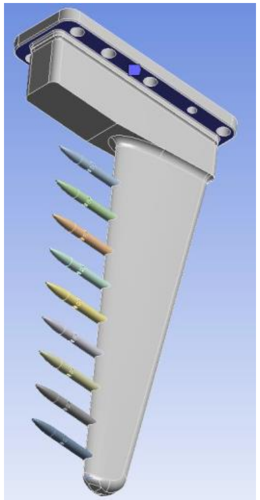
Distribution of <u>9 sensors between 0.307 m and 0.185 m</u> channel height with good condition number.

<u>Axial distance of 0.01 m</u> as a compromise between condition number and available space.

Estimation of the **expected pressure amplitudes** due to rotor-stator interactions (RSI) with **CAA simulation** at design point (8667 RPM and 63.4 kg/s mass flow rate).







Ongoing activities and way forward

- **Refinement of aeroshape and layup** to cope with an unexpected behaviour of the blade tip under load (unwanted small negative radial displacement).
  This is now being faced by
  - Thickness adaption
  - Introduction of lean angle
- As a consequence, further check of aeroelastic performance and stator vane aerodynamic design are ongoing
- **Completion of detail design including demonstration tests** to decide on instrumentation cable routing → **CDR** and start of manufacture
- Test article **Manufacture** and rig modification
- **Test Campaign** execution (PTF) and post-test analysis and calibration of numerical methods

Q&A

https://www.ca3viar-project.eu/

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