ADiSS– Aerodynamic Damping in Separated Flow

Project summary

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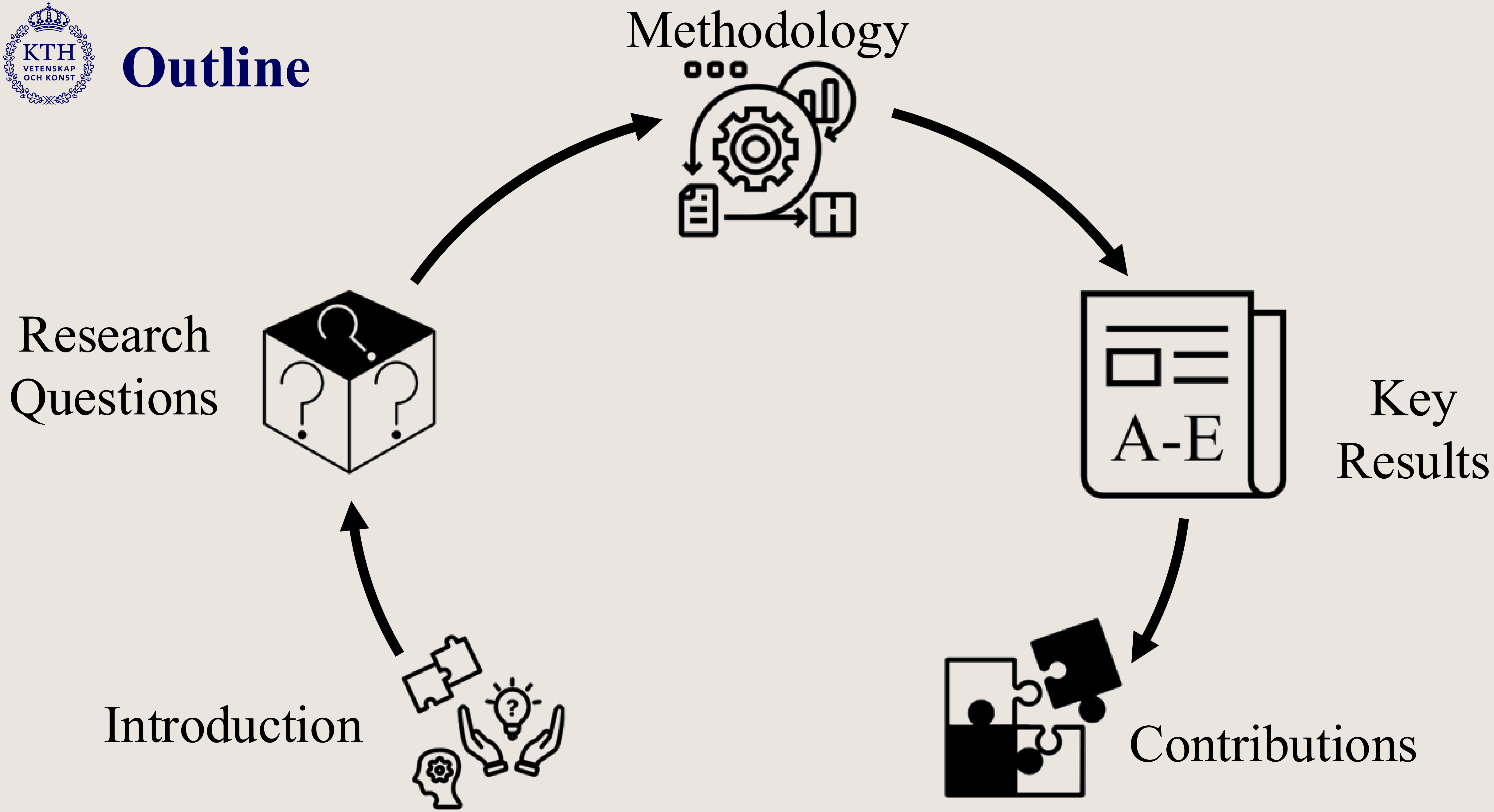
Presentation material prepared by Carlos Tavera Guerrero

FT2025

Outline



Introduction

Research Questions

Methodology

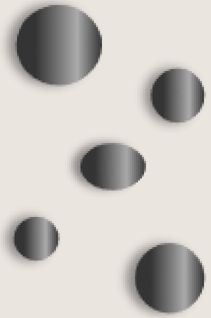
Key Results

A-E

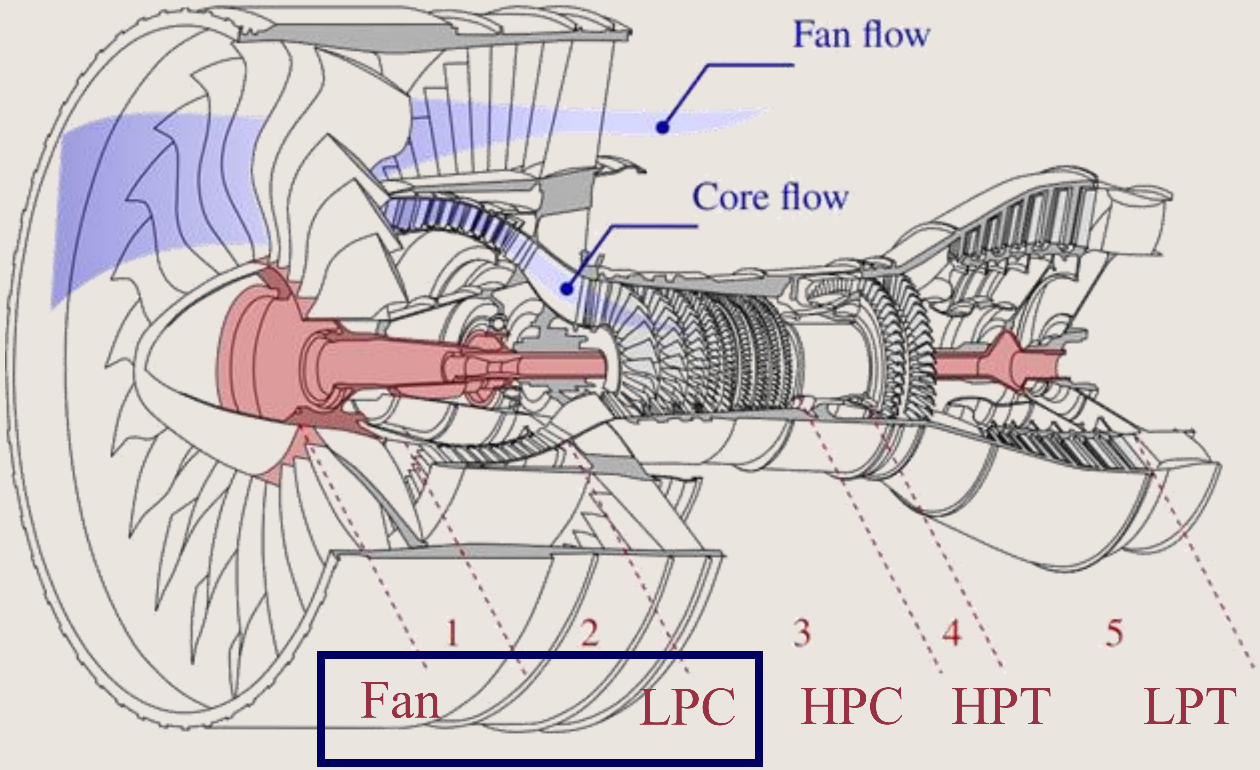
Contributions

Introduction-Erosion

Foreign objects e.g. sand grains, hail, water droplets



Different sizes, concentrations, material, etc

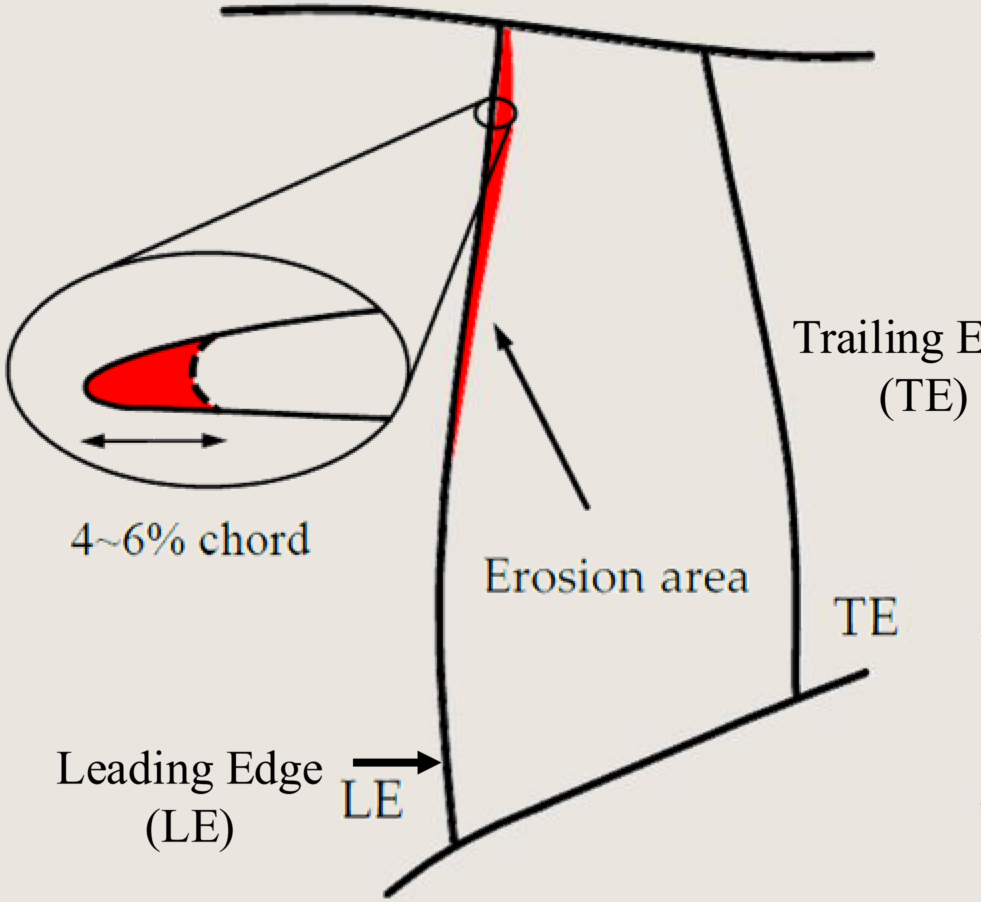


Inherent interaction with atmospheric conditions that drive erosion mechanisms

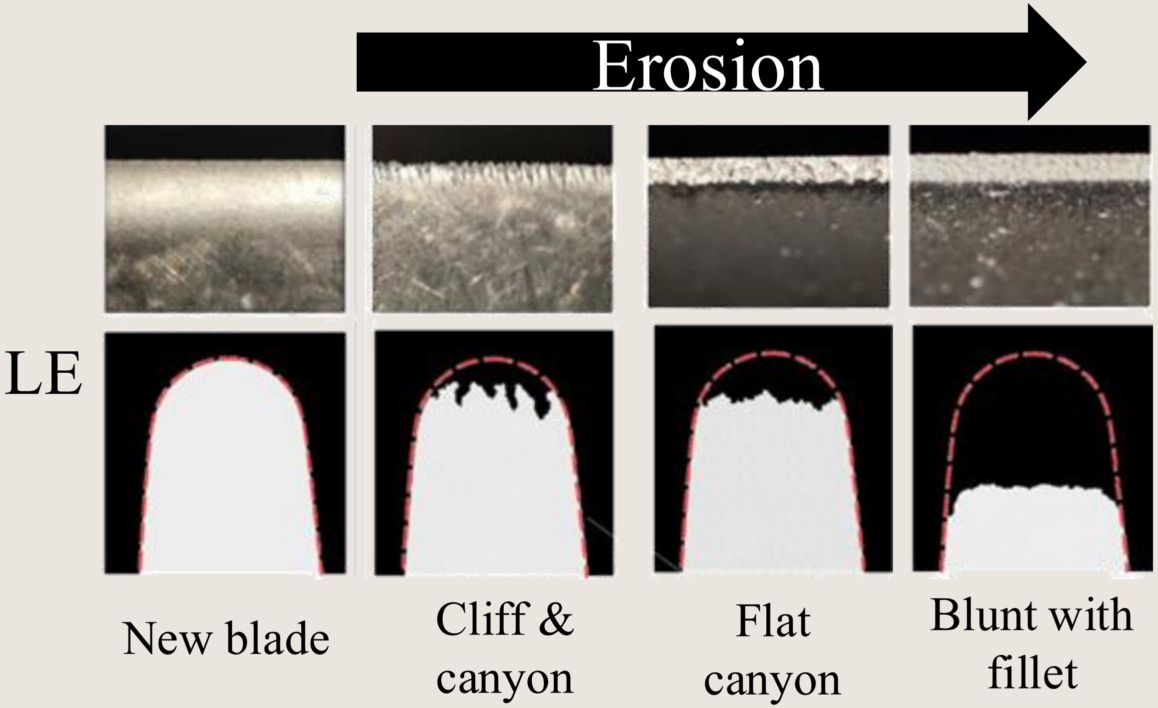
N. Salvat, “Modeling of shaft precessional motions induced by unilateral and frictional blade/casing contacts in aircraft engines,” Ph.D. dissertation, Nov. 2015.

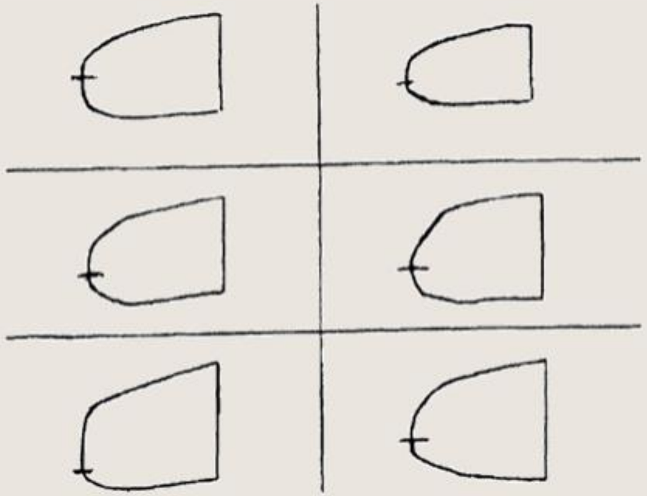
Introduction - Erosion

Fan meridional view

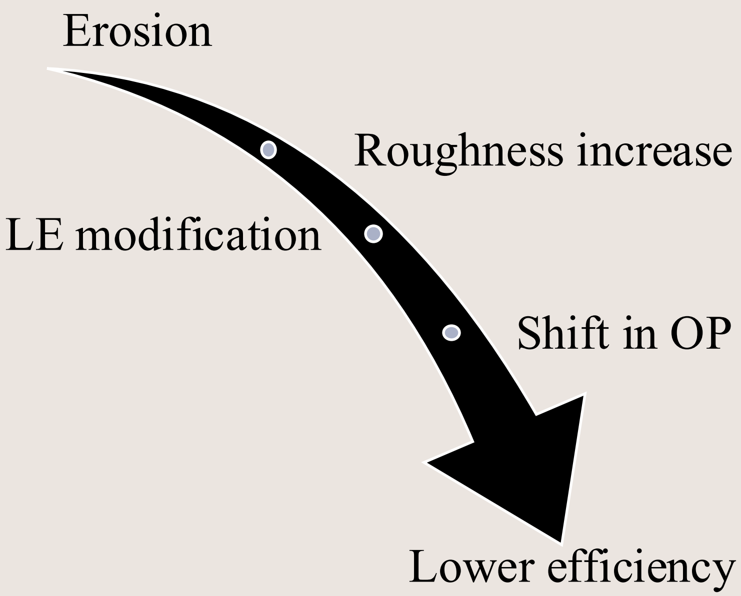


4~6% in the fan while 1% is more common in the compressor





Variety of LE contours



Erosion

Roughness increase

LE modification

Shift in OP

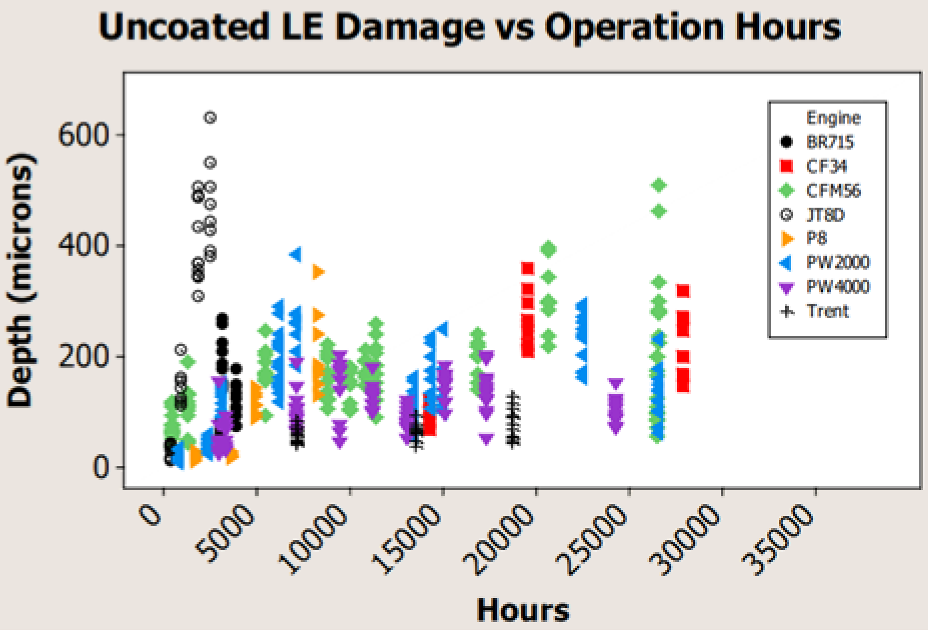
Lower efficiency

Images modified from: Shi, L., et al. (2023). A review on leading-edge erosion morphology and performance degradation of aero-engine fan and compressor blades. *Energies*, *16*(7), 3068.

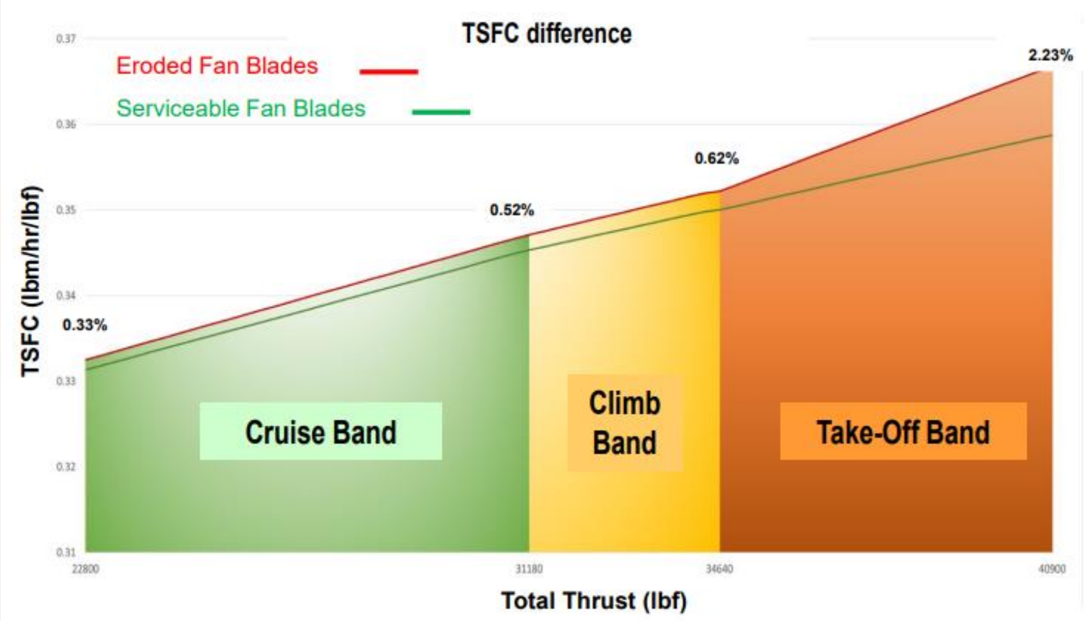
Introduction - Erosion

Can LE erosion influence aeroelastic instabilities?

Images from: Delta TechOps (DTO), GKN Aerospace, MDS Coating, America's Phenix, Inc. (2024), Leading Edge Protective Coating Against Fluid and Particulate Erosion for Turbofan Blades. https://www.faa.gov/sites/faa.gov/files/May-2024-Americas-Phenix-Briefing.pdf



Microscale damage

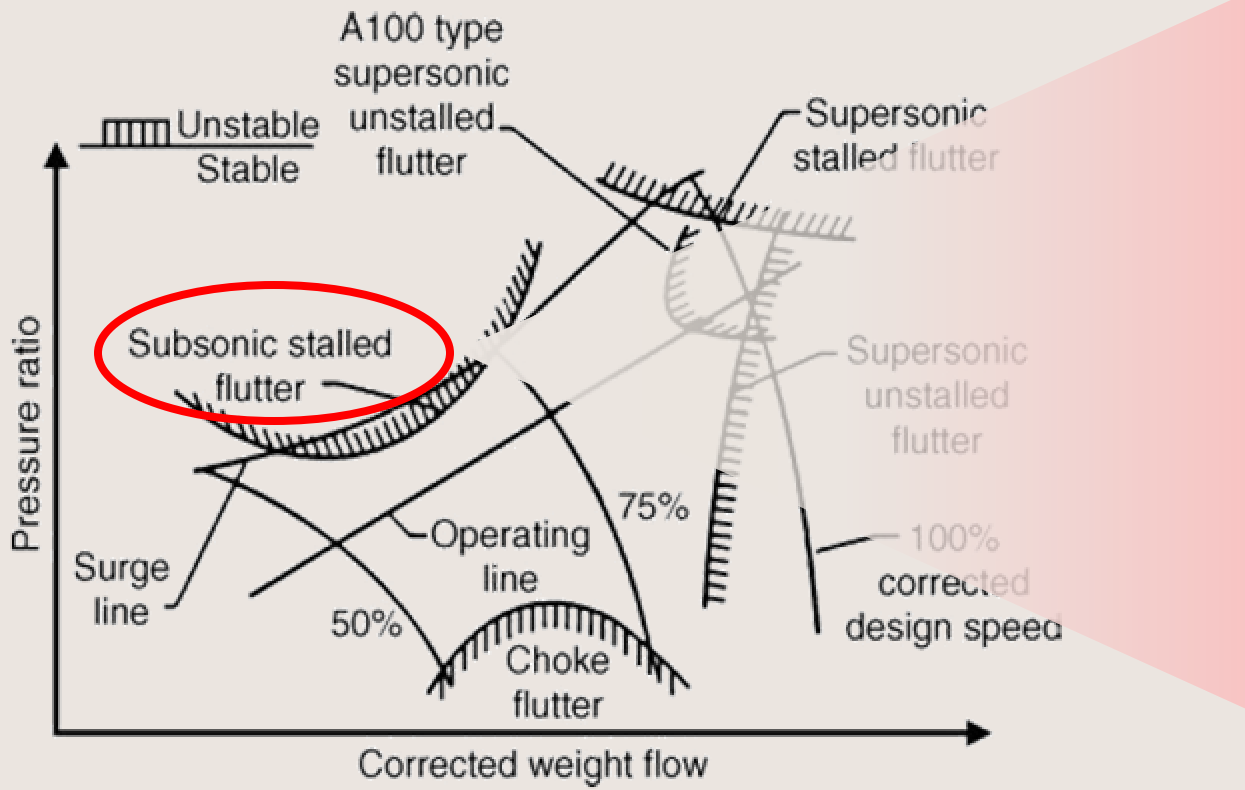


More fuel burn, larger operating costs, and higher environmental impact

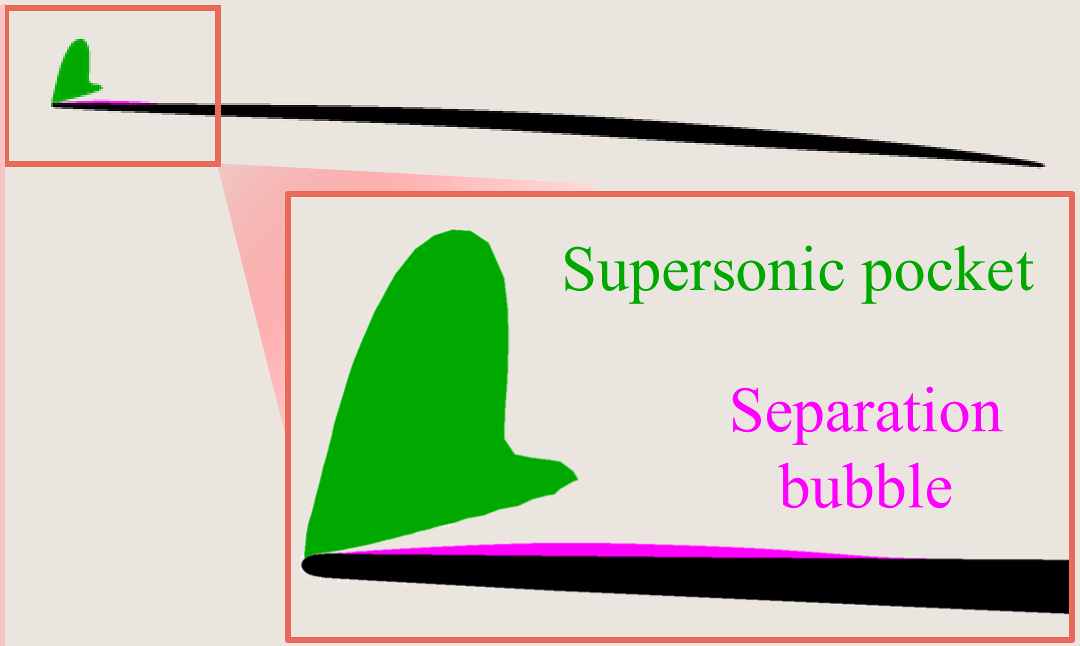
Macroscale consequences

Introduction - Compressor aeromechanics

Flow direction



Region of interest (part-speed)

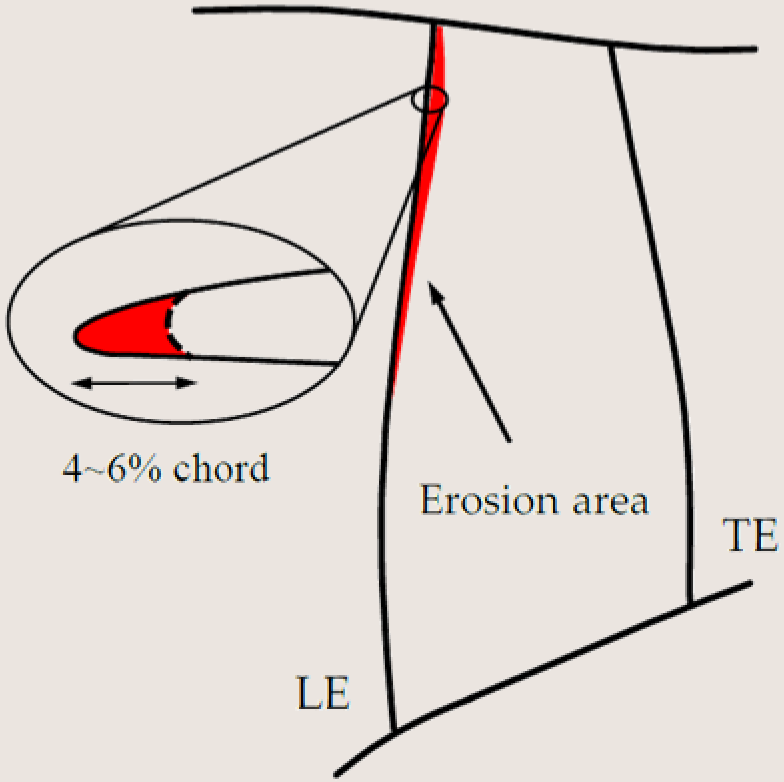


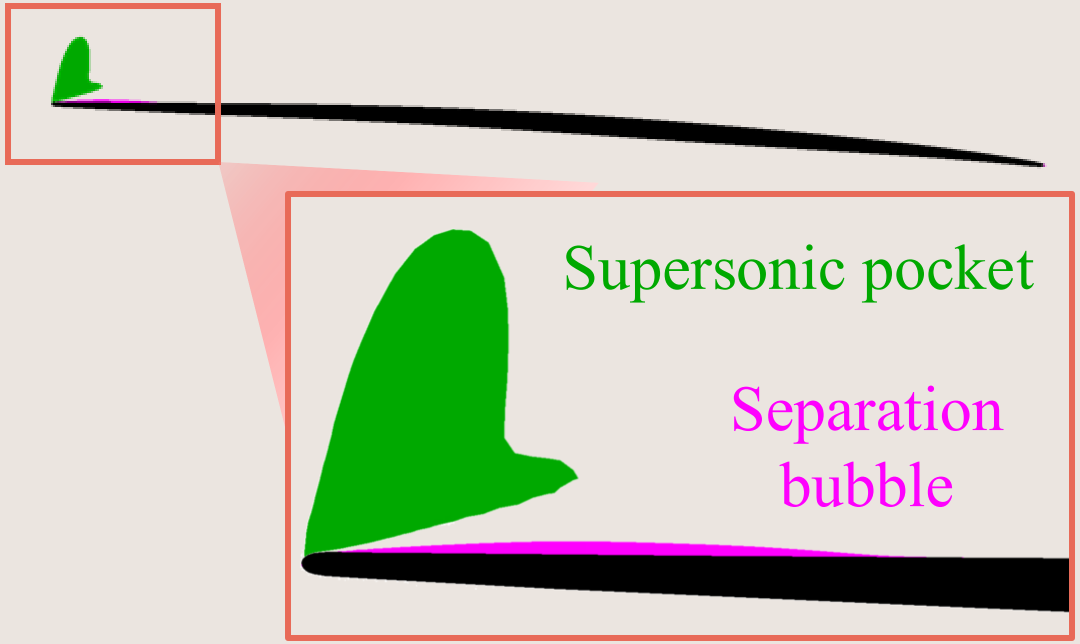
Shock-induced separation mechanism

Bendiksen, O., Kielb, R. E., & Hall, K. C. (2010). Turbomachinery aeroelasticity. *Encyclopedia of Aerospace Engineering*.

Introduction – Research Window

LE Erosion + **Aeromechanics** = Sparse or non-existent in the available literature





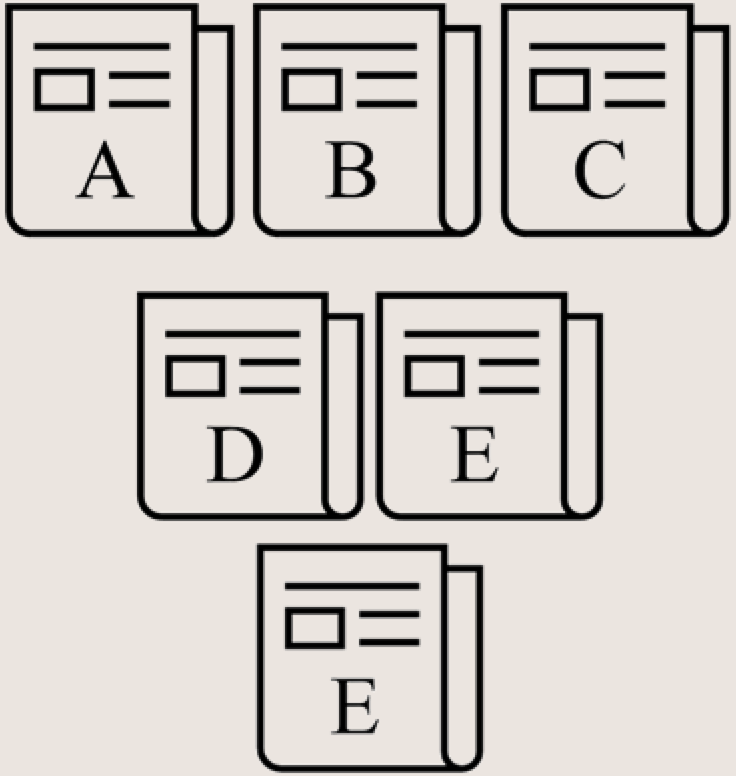
Goal: Identify the effect of leading-edge erosion mechanisms on the aeroelastic response of transonic compressors → Transonic Linear Cascade (TLC)

Research Questions

RQ1 How well do **numerical methods** compare **to experimental data** when predicting **the reattachment line** and **aeroelastic response** in a shock-induced separation mechanism?

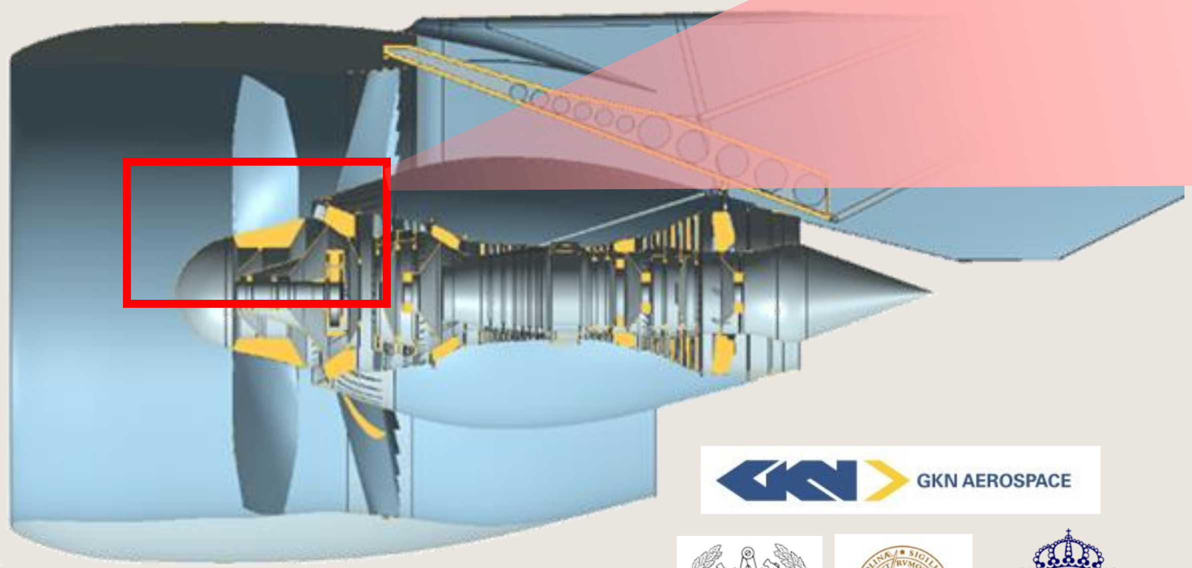
RQ2 What is the **contribution** of **roughness** in the **aerodynamic damping** and **aeroelastic response**?

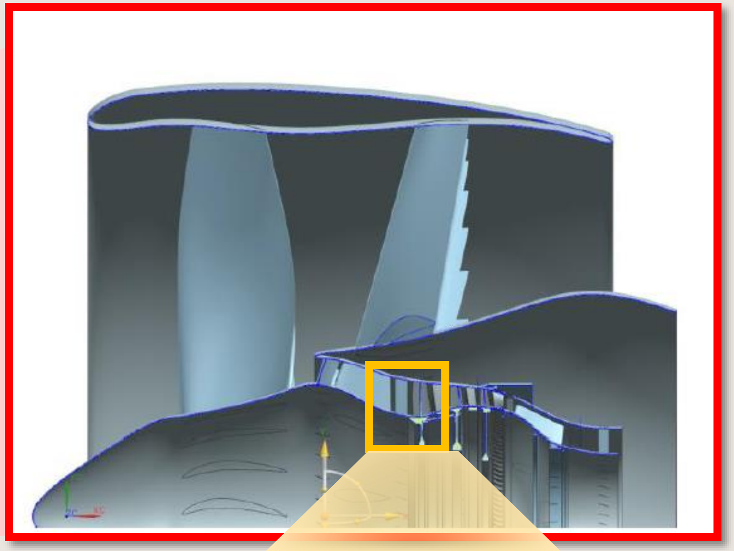
RQ3 How does the **eroded leading edge** mechanism affect the **aeroelastic response** in a shock-induced separation mechanism?



Methodology – VINK LPC R1

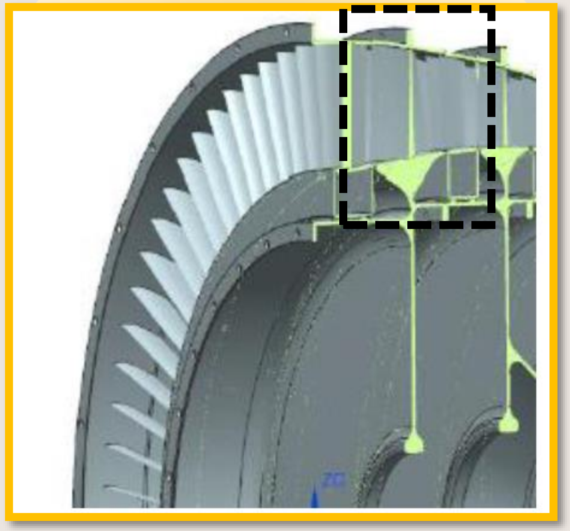
RM400 engine





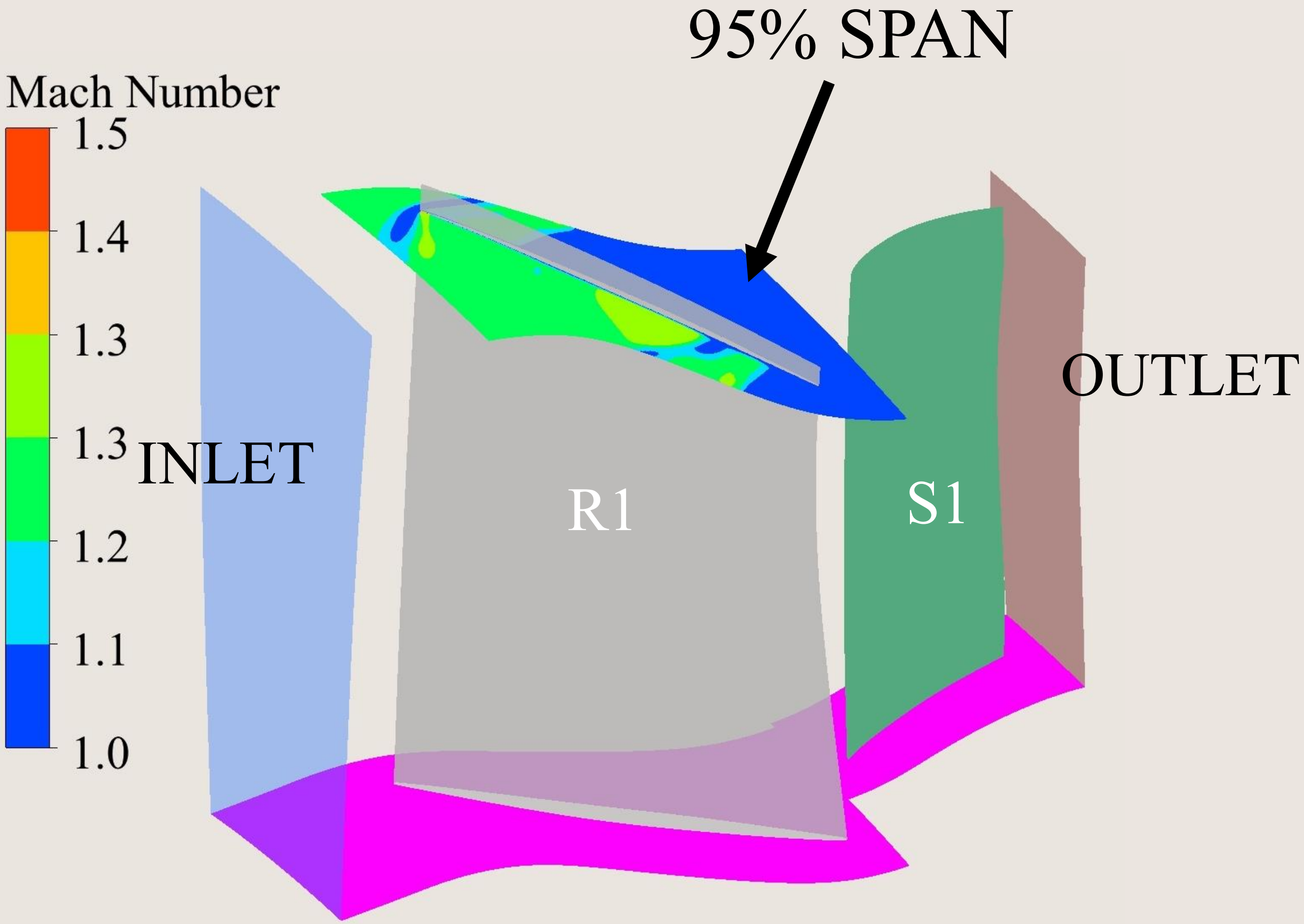
NFFP 6-8

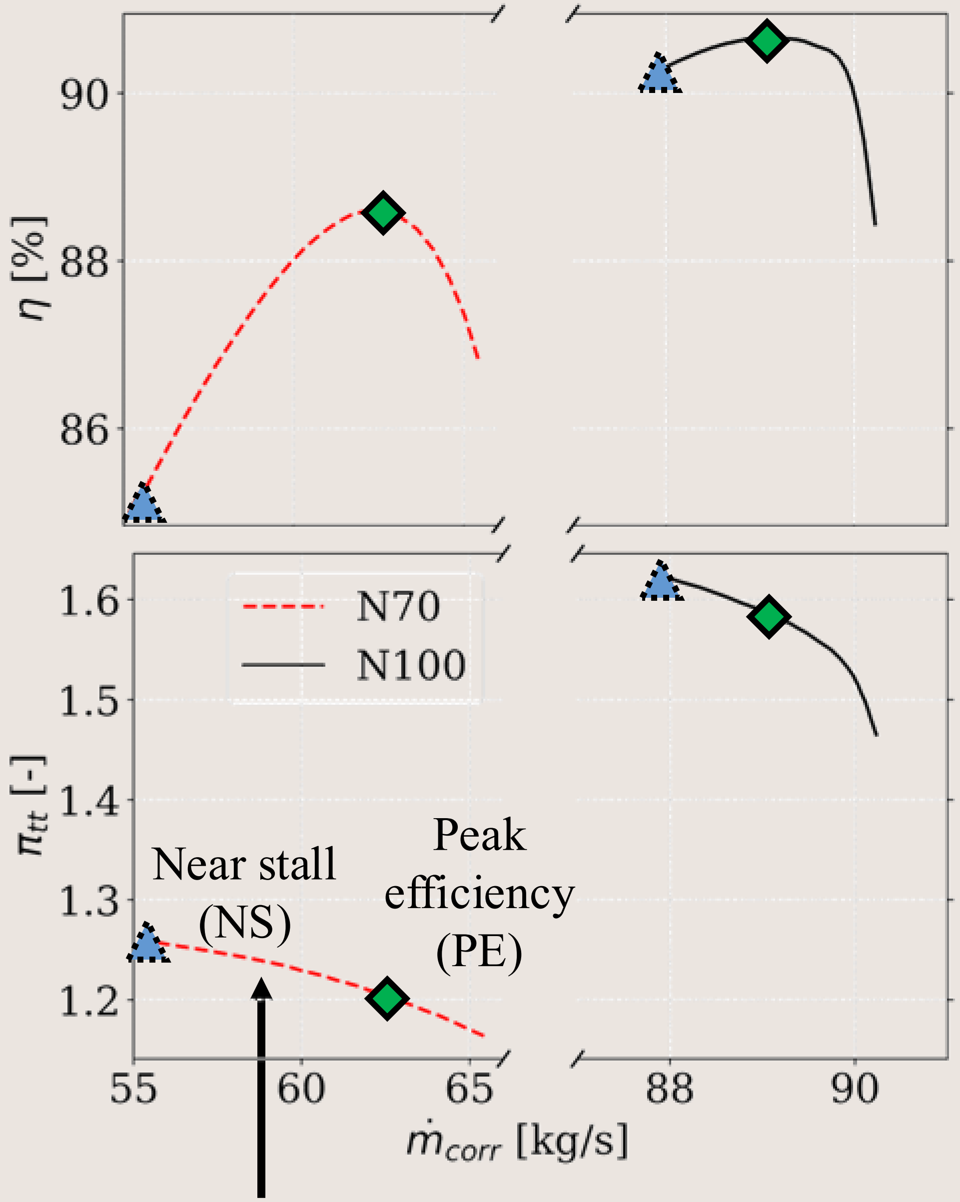
VINK
LPC R1



Lejon, M., Grönstedt, T., Glodic, N., Petrie-Repar, P., Genrup, M., & Mann, A. (2017, June). Multidisciplinary design of a three-stage high-speed booster. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 50794, p. V02BT41A037). American Society of Mechanical Engineers.

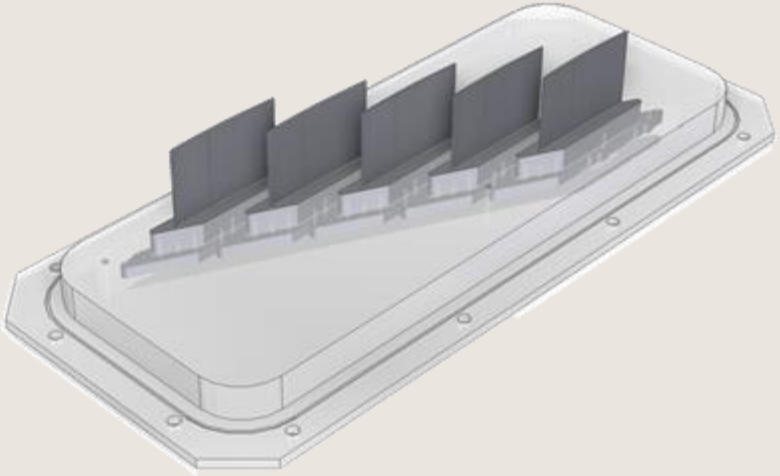
Methodology – VINK LPC R1

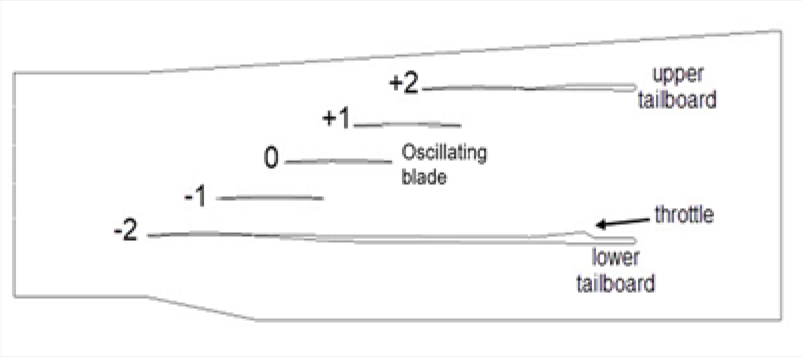




Speed line and operating points of interest

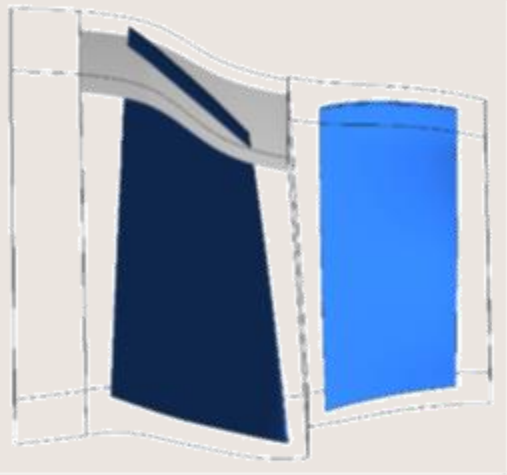
Methodology – Cascade blade profiles

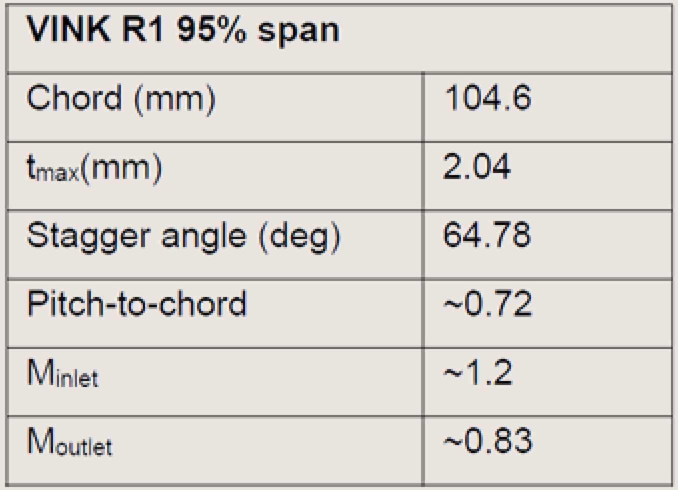




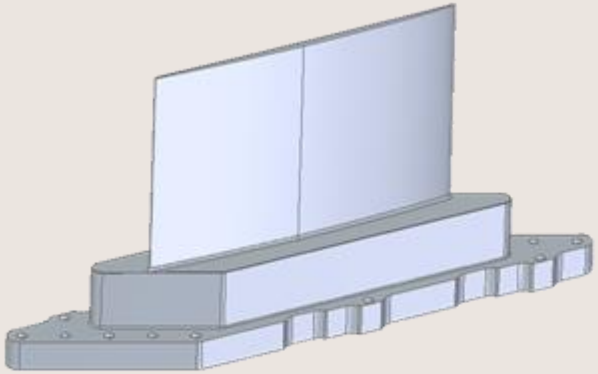
Cascade is operated in influence coefficient mode

Reference compressor rotor blade profile VINK R1





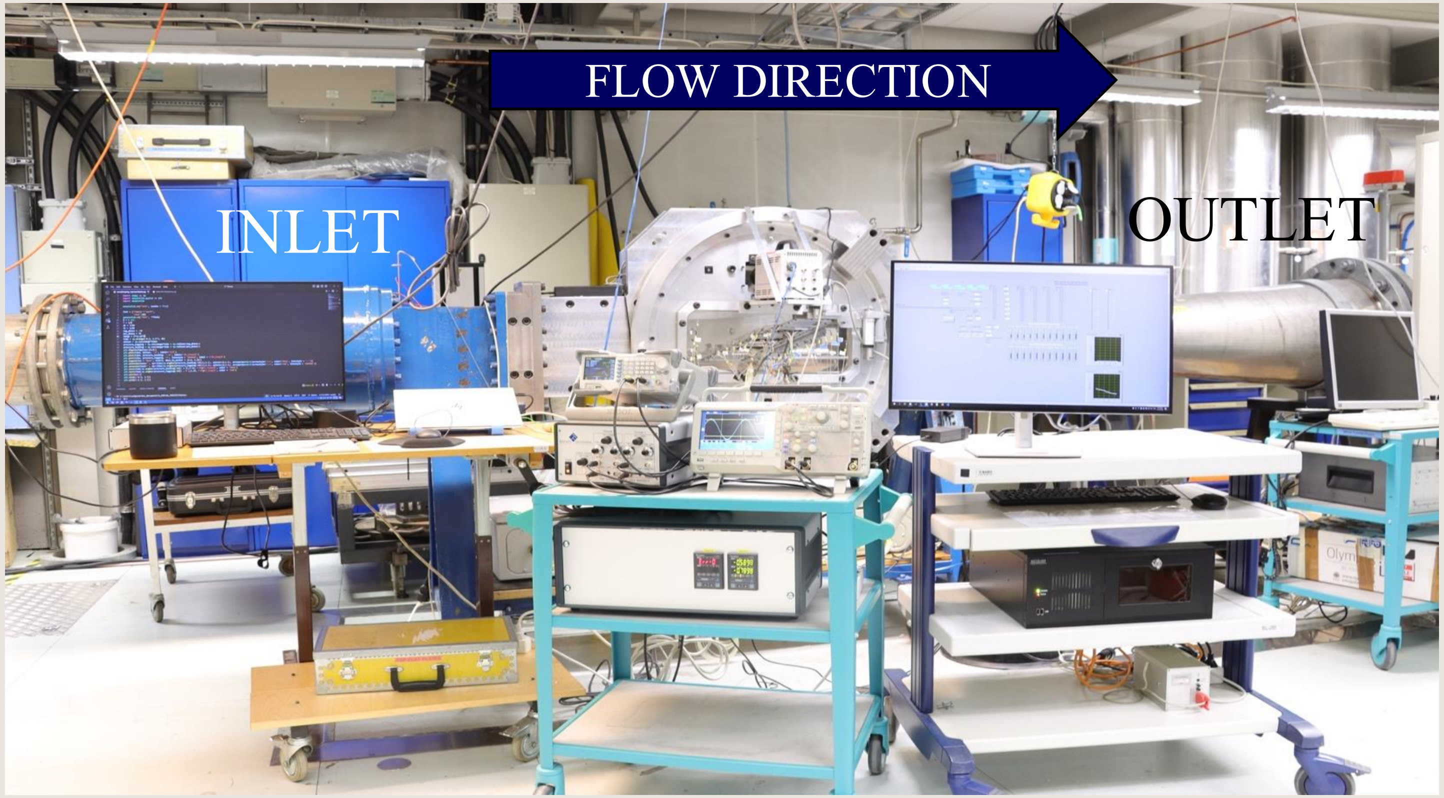
VINK R1 95% span	
Chord (mm)	104.6
t_{max}(mm)	2.04
Stagger angle (deg)	64.78
Pitch-to-chord	~0.72
M_{inlet}	~1.2
M_{outlet}	~0.83



TLC blade is a prismatic extrusion, blade height 70mm

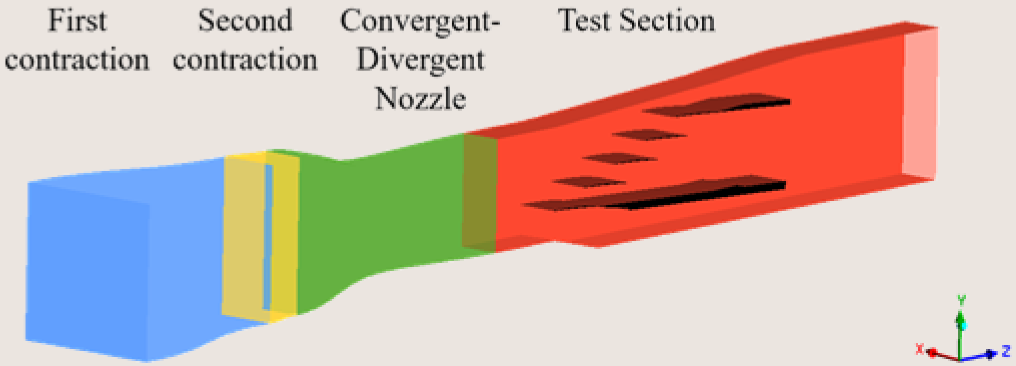
Methodology - Overview

Experimental campaigns



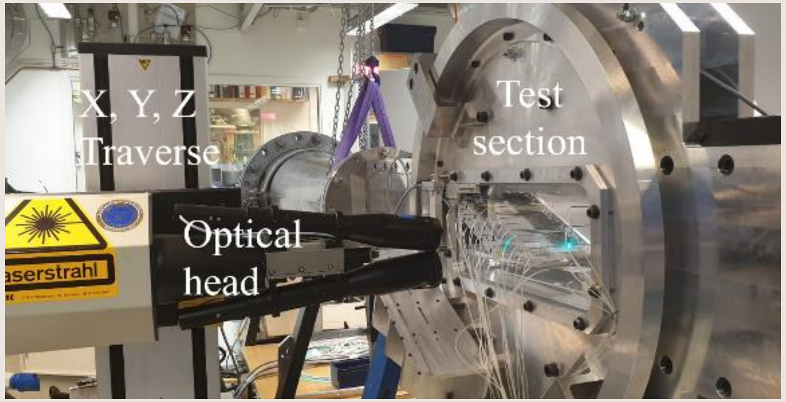
Transonic Linear Cascade at KTH

Numerical analysis



Methodology – Test section instrumentation

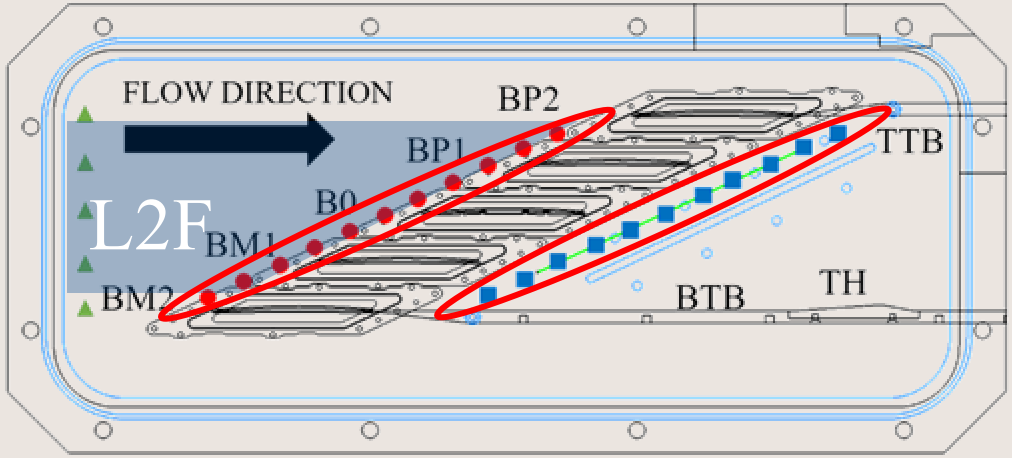
Inlet and upstream location



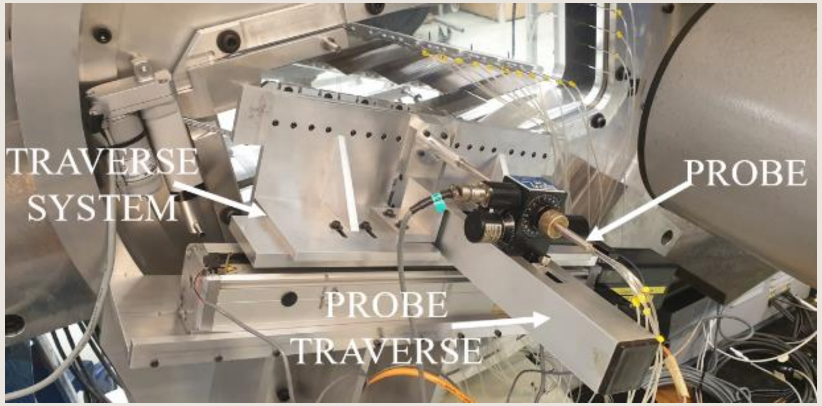
L2F → Velocity field, flow angle

Upstream and downstream locations

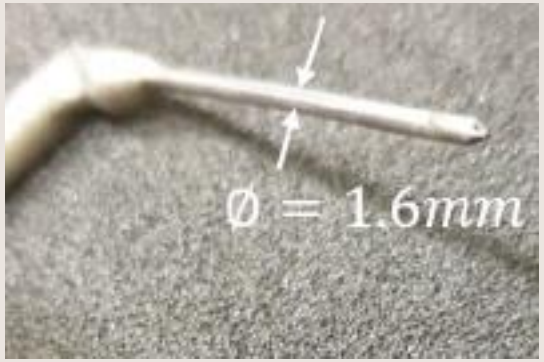
Pressure taps → M_{iso}



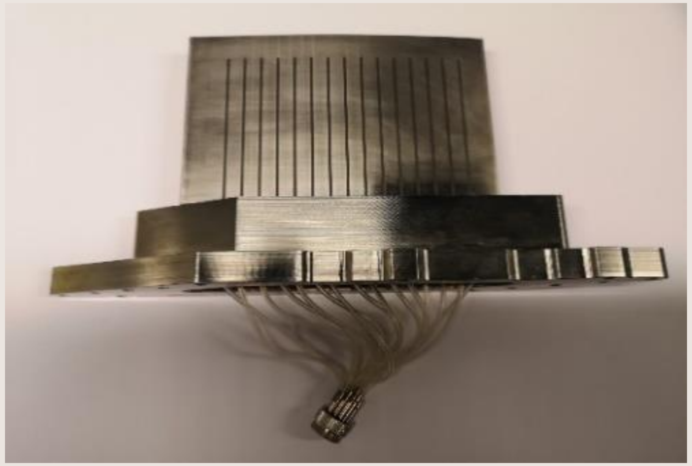
Downstream location

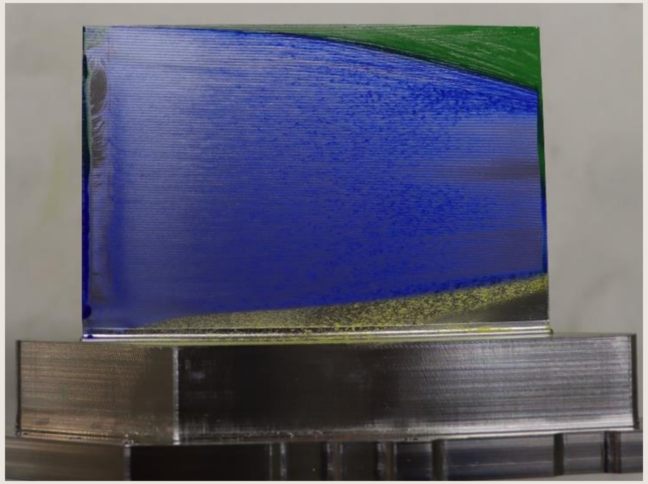


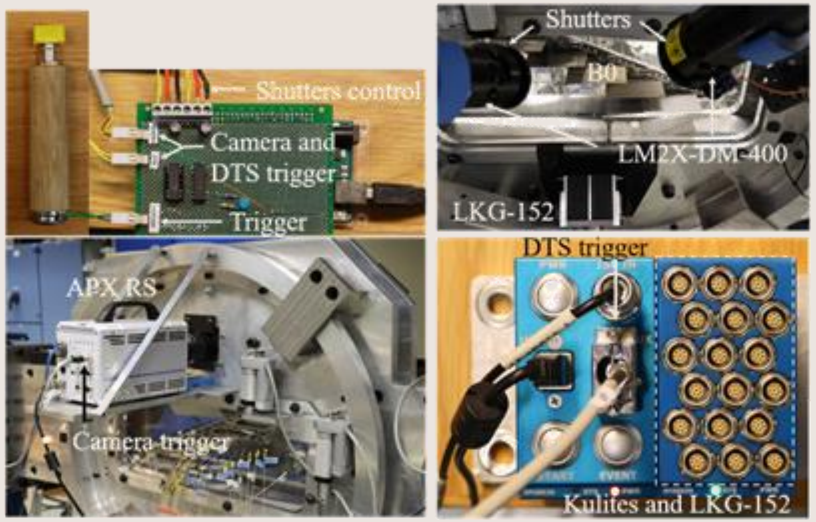
Five-hole probe → Downstream flow properties (calibration & reconstruction)



Methodology– Blades instrumentation

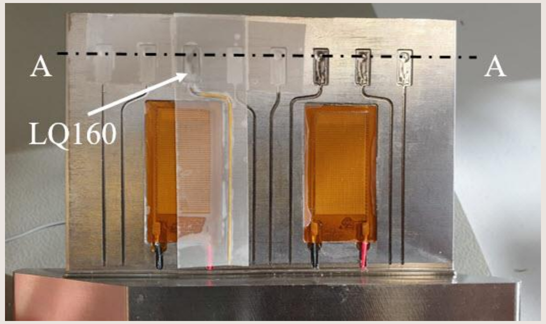




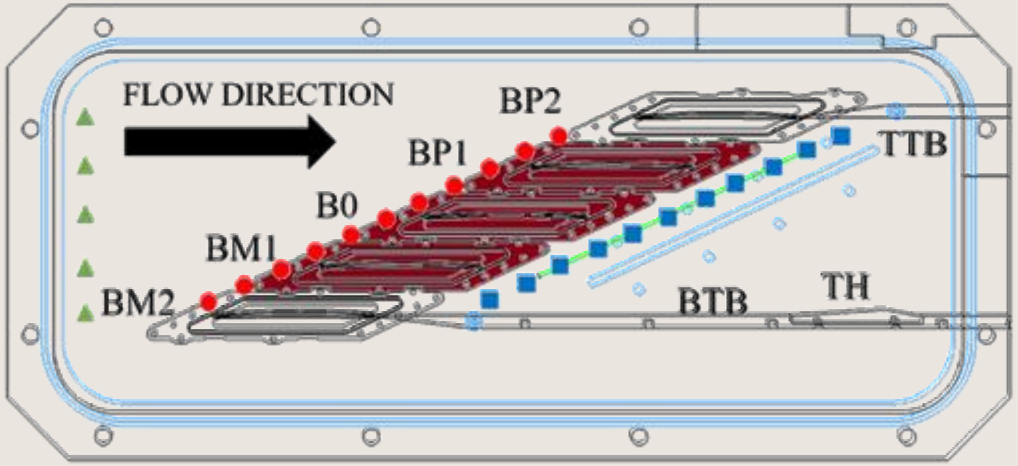


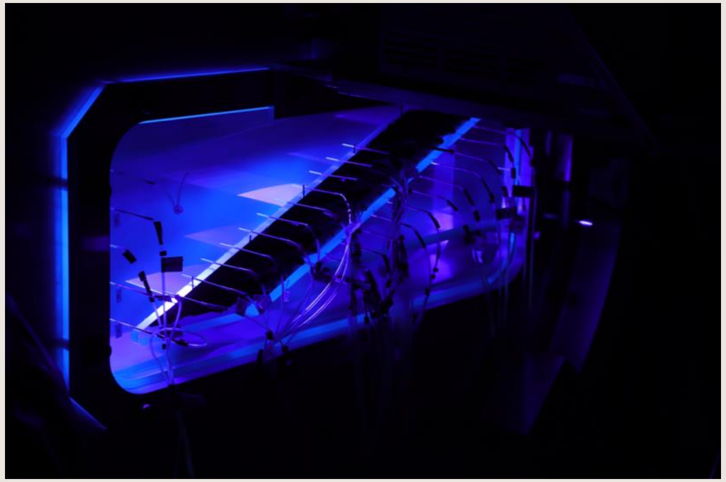
Pressure taps → Blade loading

Flow visualization → Reattachment line



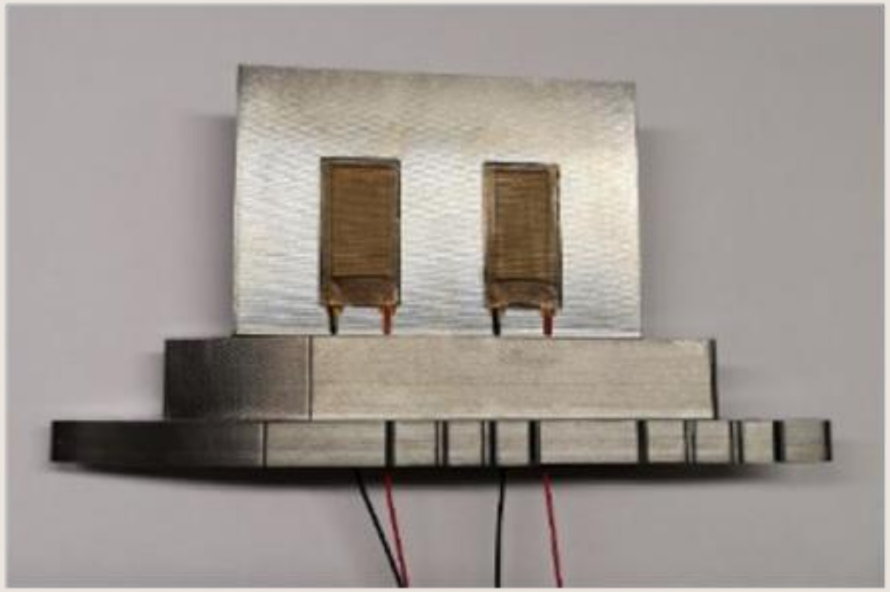
Kulites on 85% span
→ Unsteady response



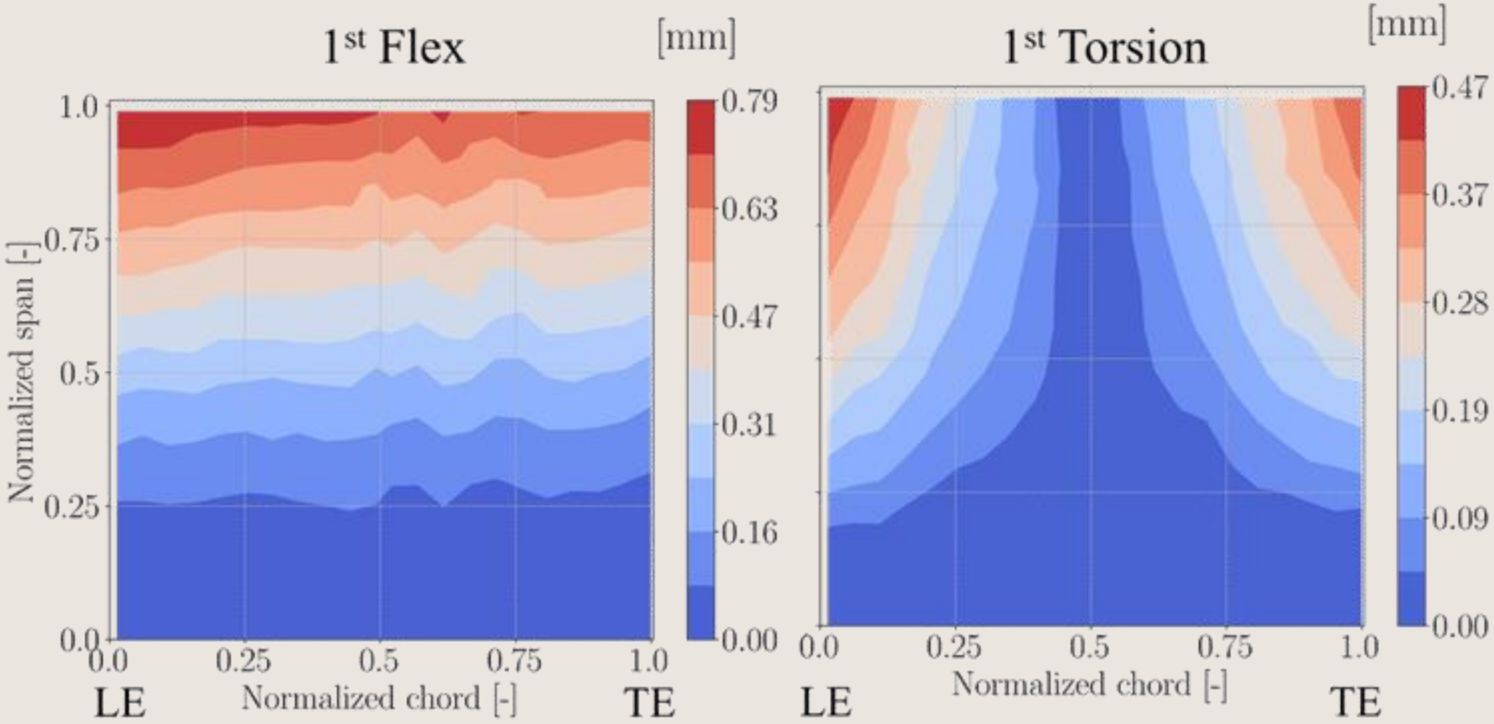


PSP → B0 SS M_{iso}

Methodology – Blade oscillation mechanism

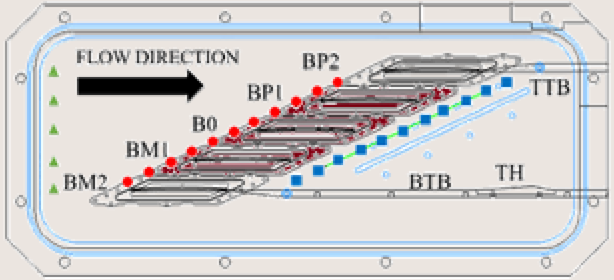


Measured vibration amplitude of the first two modes



The blade 0 vibration is induced by means of two MFC P1 type (M-2814-P1) piezoelectric actuator elements
Supplied with continuous voltage signal in form of a sinus wave, max input voltage ±500V

Methodology – Test objects definition

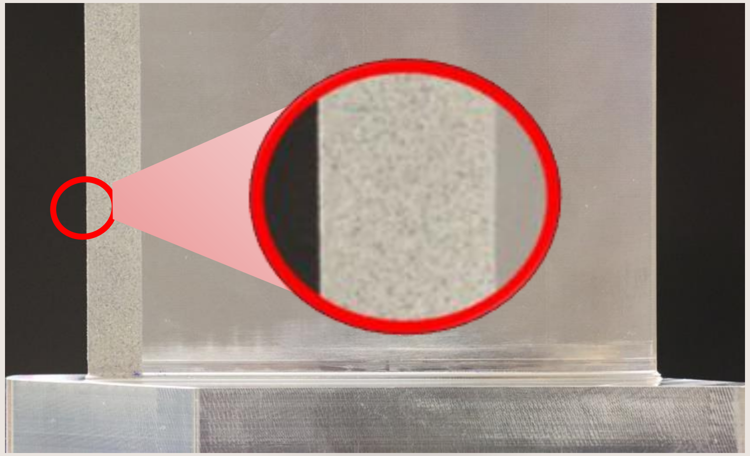


Modifications are done in BM1, B0, and BP1

New blade

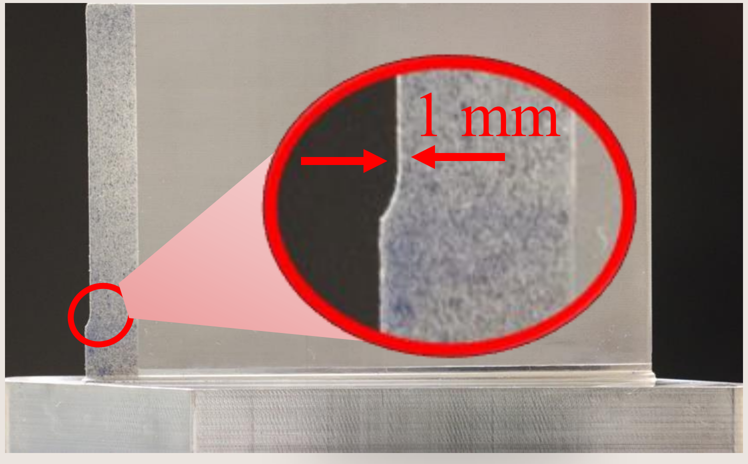
Smooth

Early stage of erosion



Rough

Last stage of erosion

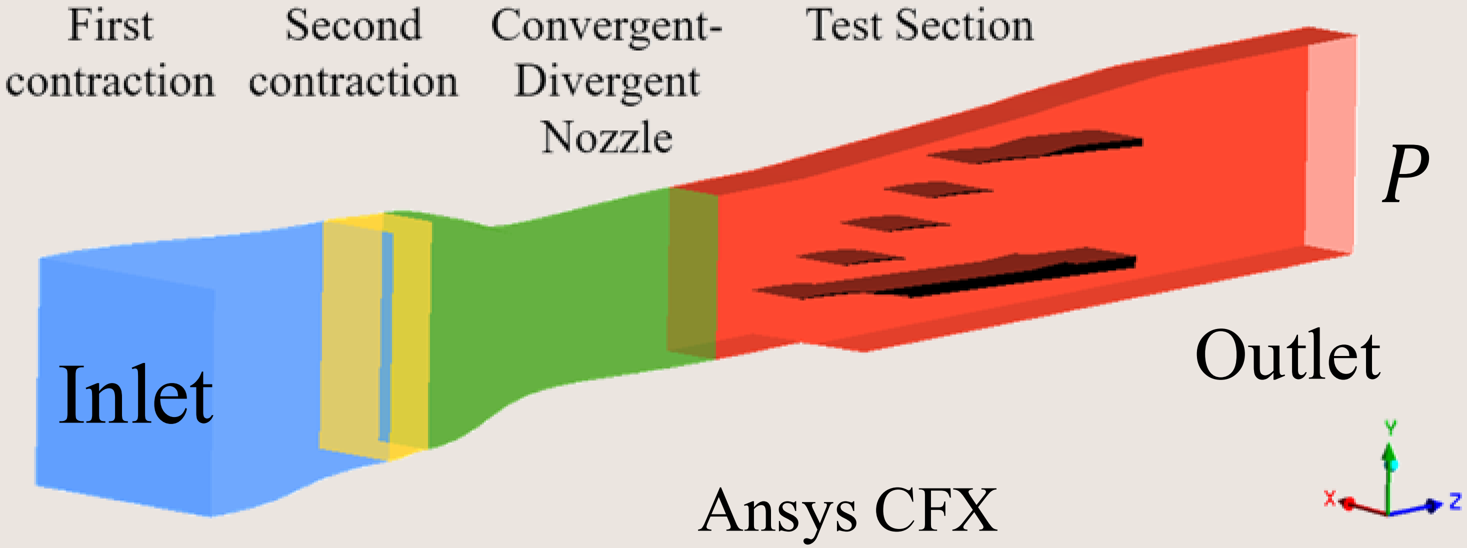


Eroded

Methodology- Numerical Overview

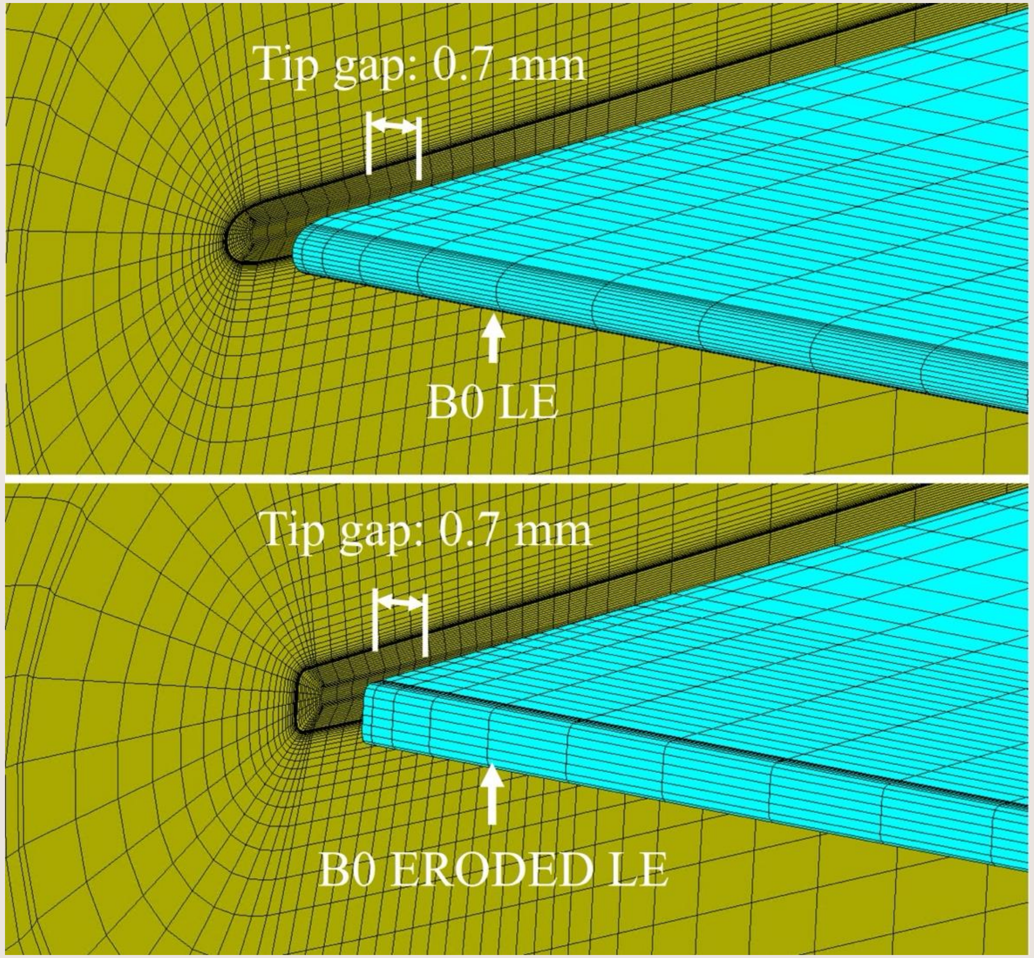
$$\Pi = \frac{P_0}{P}$$

Represents the experimental setup



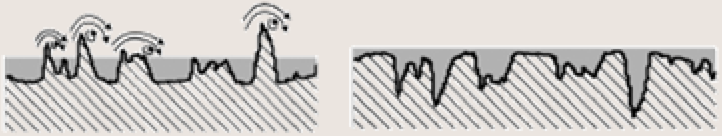
Ansys CFX
≈12 M elements
$y^+ < 2$
SST with Reattachment Modification

LE modelling



Methodology- Numerical Overview

Real surface

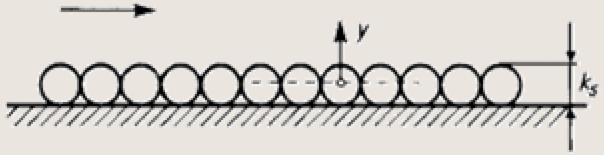


Positive skew (peak dominated)

Negative skew (valley dominated)

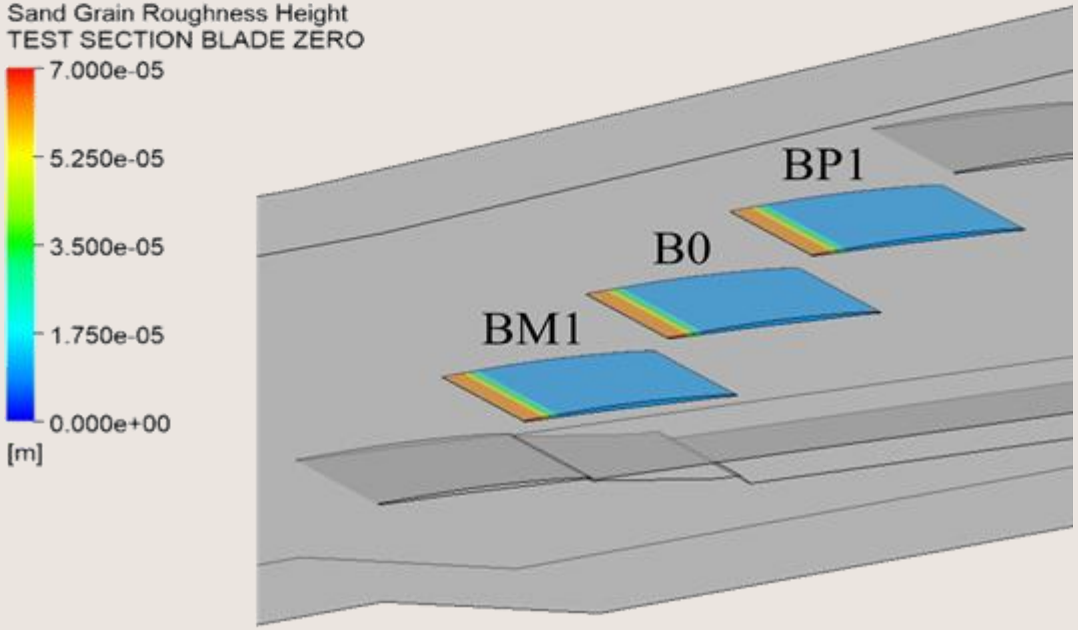
Colebrook

Equivalent sand-grain roughness (k_s)



Packed sand-grain

Nikuradse



Numerical roughness mimic experimental setup

$$\boldsymbol{k_s} = 8.9\ \boldsymbol{R_a} \longleftarrow \text{Measured}$$

$k_s \approx 63\ \mu m$ Icing method (Colebrook)

Non-physical length scale

$$k_s^+ = \frac{\boxed{k_s} u_\tau}{\nu}$$

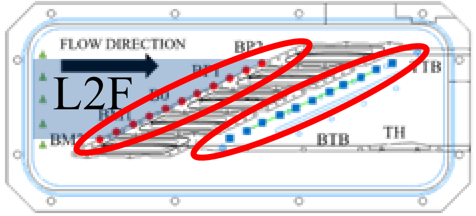
k_s^+	**Wall regime**
$0 < k_s^+ \leq 5$	Hydraulically Smooth
$5 < k_s^+ \leq 70$	Transitional
$70 < k_s^+$	Fully Rough

Schlichting, H., & Gersten, K. (2016). *Boundary-layer theory*. springer.

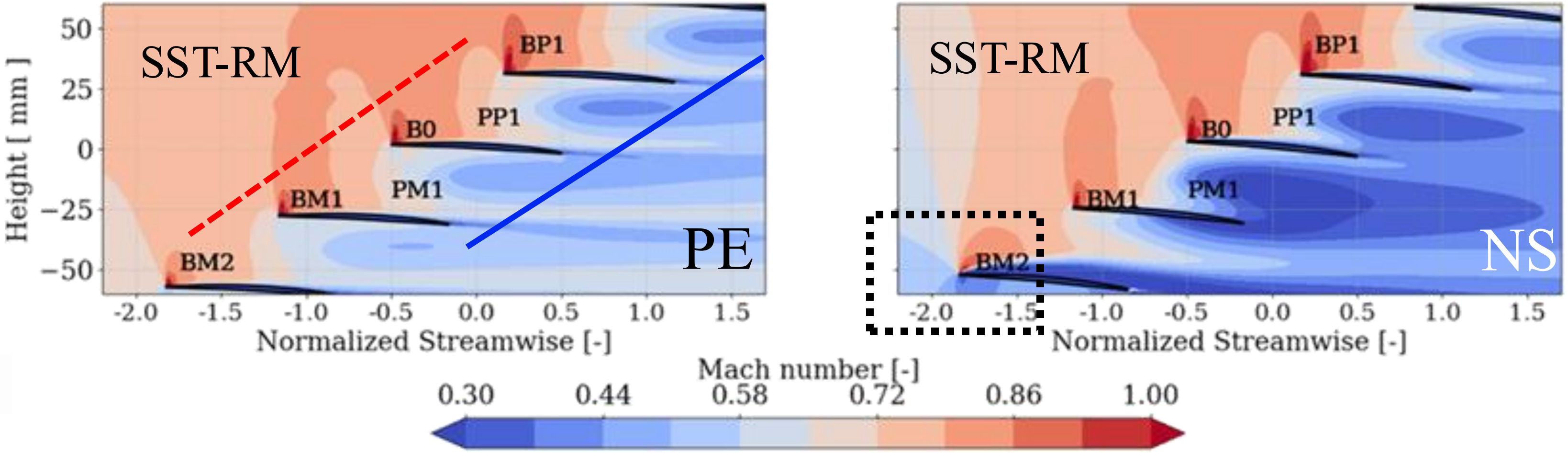
Goodhand, M. N., Walton, K., Blunt, L., Lung, H. W., Miller, R. J., & Marsden, R. (2016). The limitations of using "Ra" to describe surface roughness. Journal of Turbomachinery.

Schäffler, A. (1980). Experimental and analytical investigation of the effects of Reynolds number and blade surface roughness on multistage axial flow compressors.

Nominal Cascade – Operating point

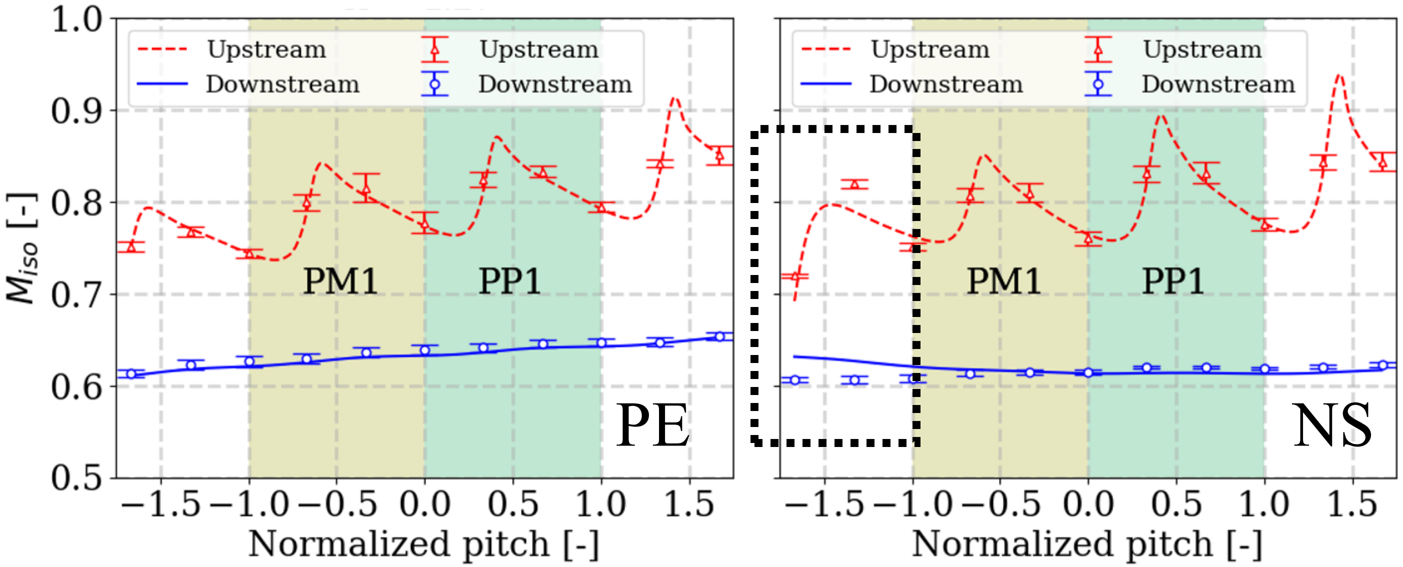


Two operational points, **1% tip gap**, representing VINK LPC R1: PE ($\Pi = 1.29$) and NS ($\Pi = 1.25$).

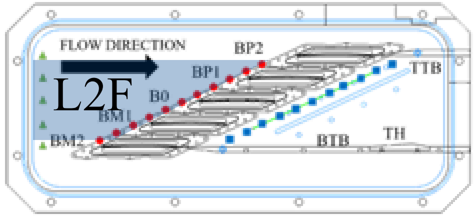


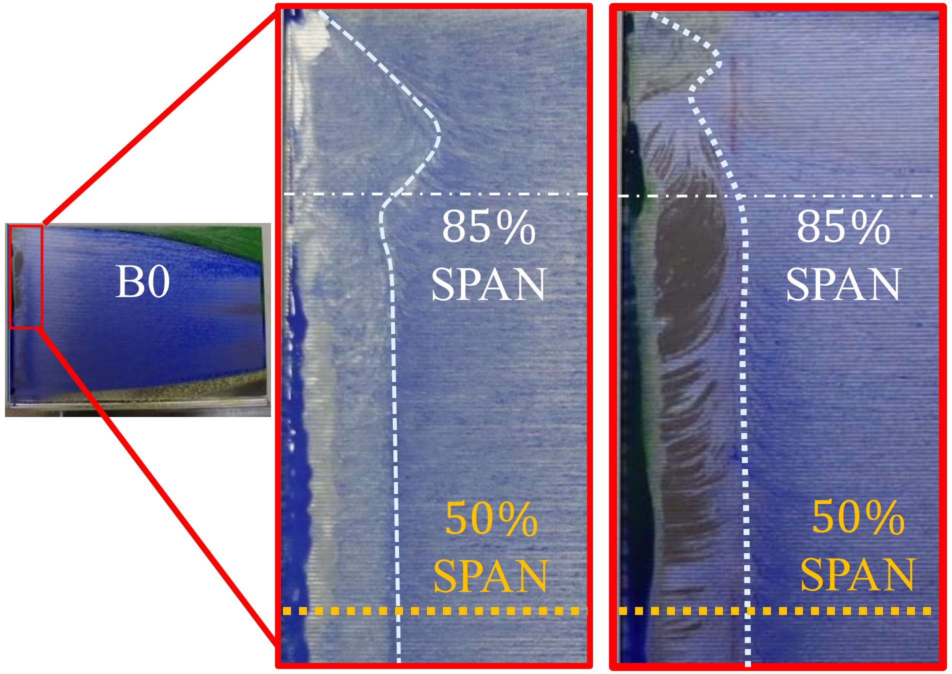
The upstream and downstream conditions at both operating points are captured by the numerical model

Largest difference at NS ($\Pi = 1.25$), influenced by BM2 and bottom bypass.



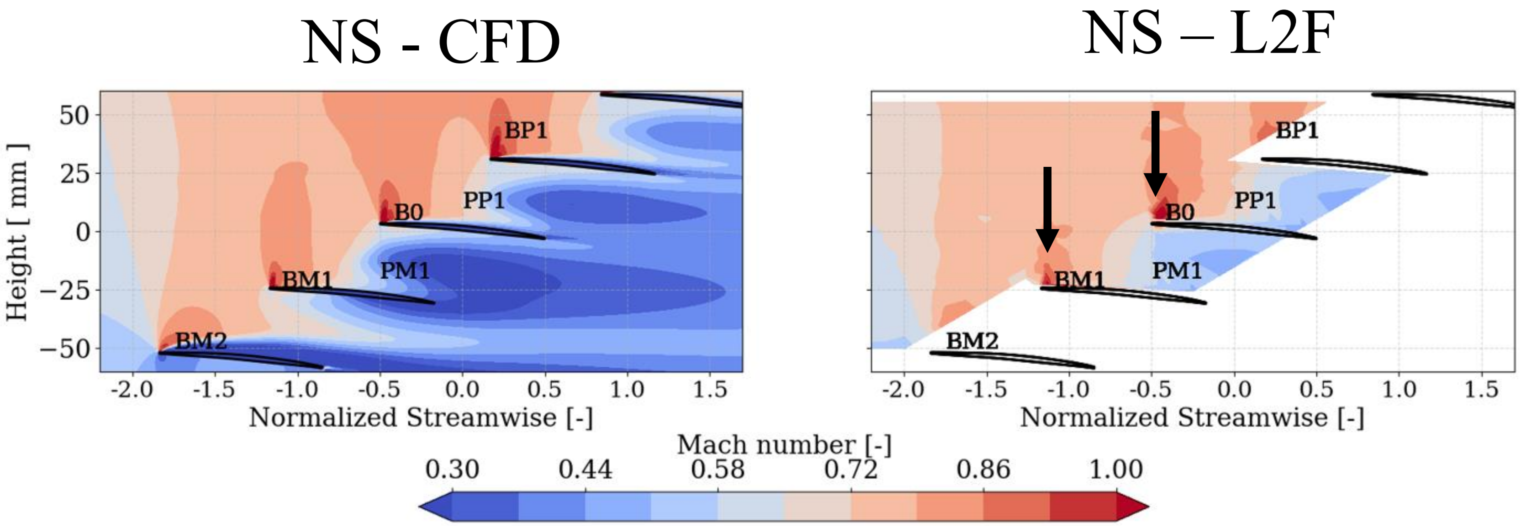
Nominal Cascade – Reattachment location





PE $(\Pi = 1.29)$

NS $(\Pi = 1.25)$


NS - CFD

NS – L2F

Blade	$\Pi = 1.29$ EXP [mm]	$\Pi = 1.29$ CFD [mm]	$\Pi = 1.25$ EXP [mm]	$\Pi = 1.25$ CFD [mm]
BM1	7.1 ±0.2	6.2	7.8 ±0.2	6.8
B0	5.8 ±0.2	5.6	7.1 ±0.2	7.5
BP1	7.3 ±0.2	6.9	8.5 ±0.2	8.8

Comparison at 50% span

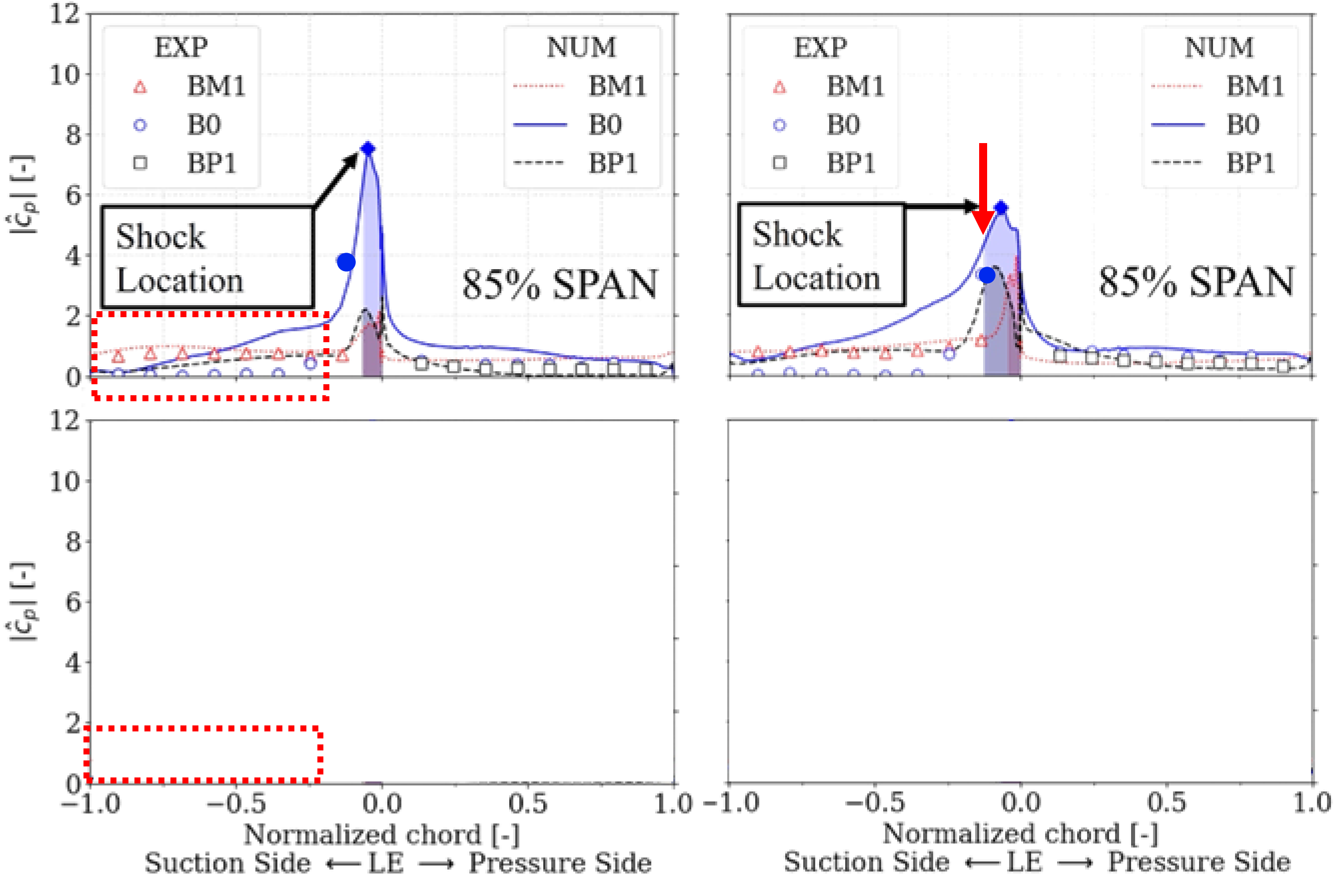
Flow visualization confirmed the separation bubble and reattachment line

CFD and Exp reattachment line in alignment, std $\pm 0.7\ mm$

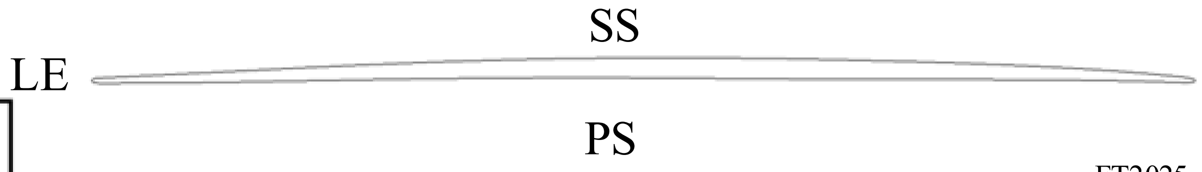
L2F measurements confirmed a shock-induced separation

Nominal Cascade – Aeroelastic response

$$|\hat{c}_p| = \frac{(|\hat{P}| - |\hat{P}_{vacuum}|)c_{ref}}{A_{rms}P_{ref}}$$


PE
($\Pi = 1.29$)

NS
($\Pi = 1.25$)



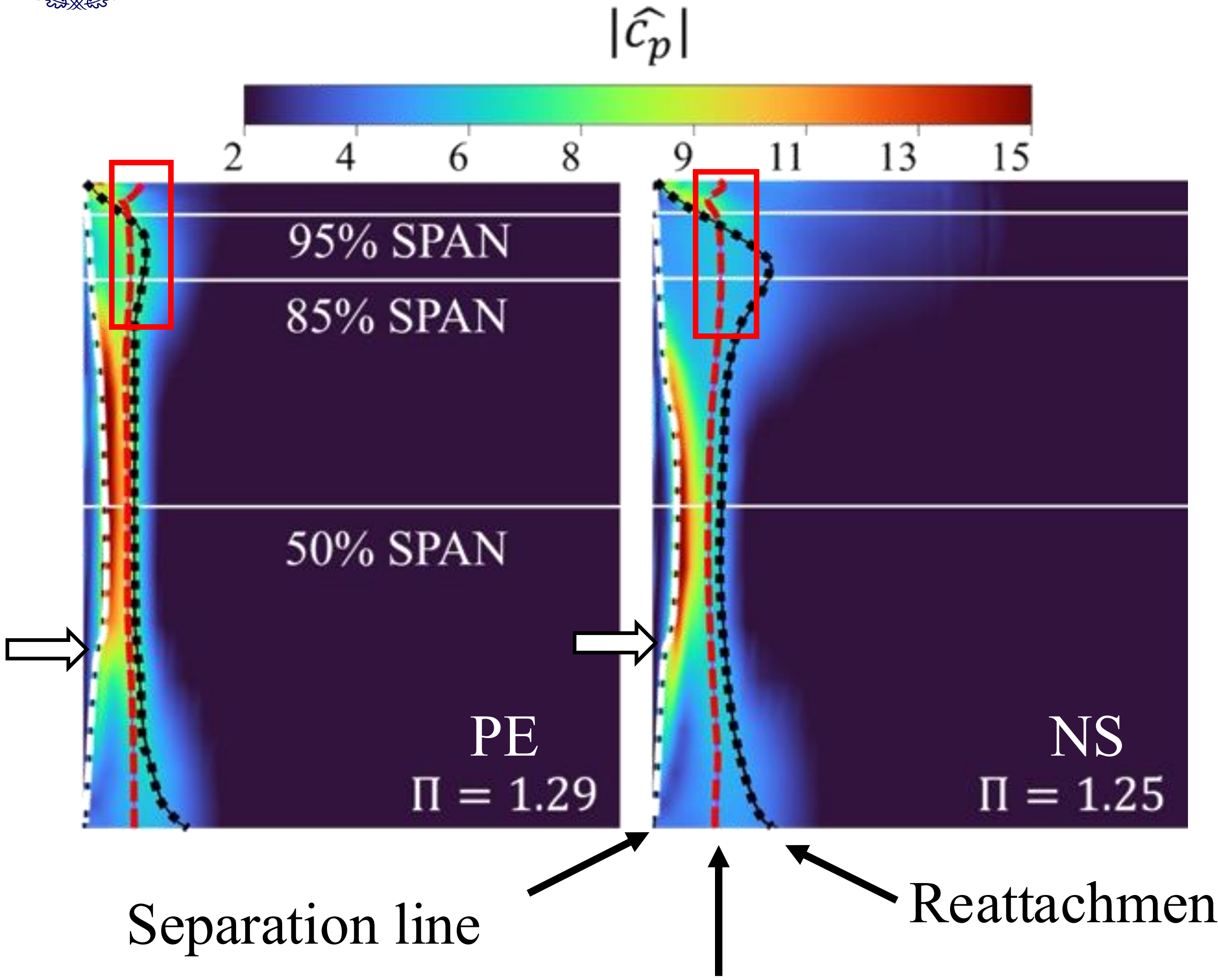
At 85% span:

- Shock dominates the aeroelastic response
- Reattachment location appears to not contribute to $|\hat{c}_p|$
- Fast decrease of unsteady pressure from EXP
- CFD overprediction of $|\hat{c}_p|$ downstream of the shock

At 50% span:

- CFD overprediction might not be driven by near wall effects
- The maximum amplitude is not at the shock location. Apparent shock-separation onset interaction

Nominal Cascade – CFD B0 Aeroelastic response



Separation line

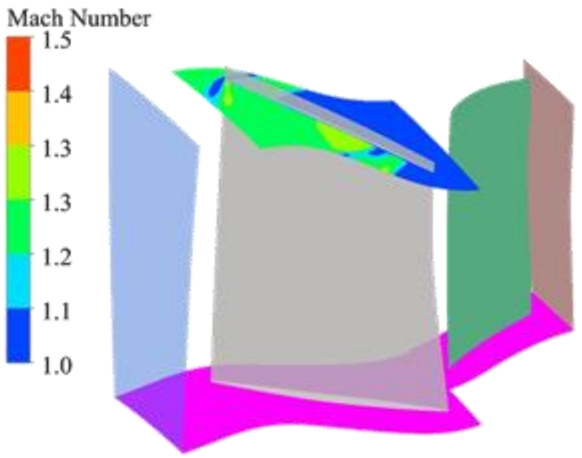
Shock location

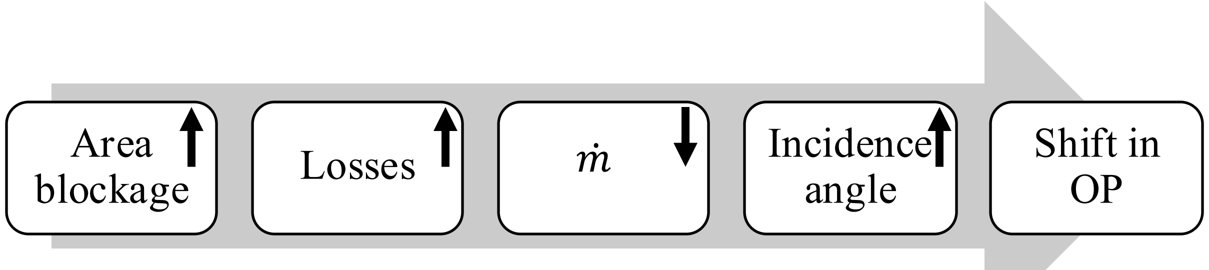
Reattachment line

Unsteady pressure peak driven by an interaction of the shock and the separation onset. Lower amplitude at NS, as the shock is moved downstream

Towards the tip the response is dominated by the shock wave location and end wall mechanisms

VINK LPC R1 - k_s influence on operating point

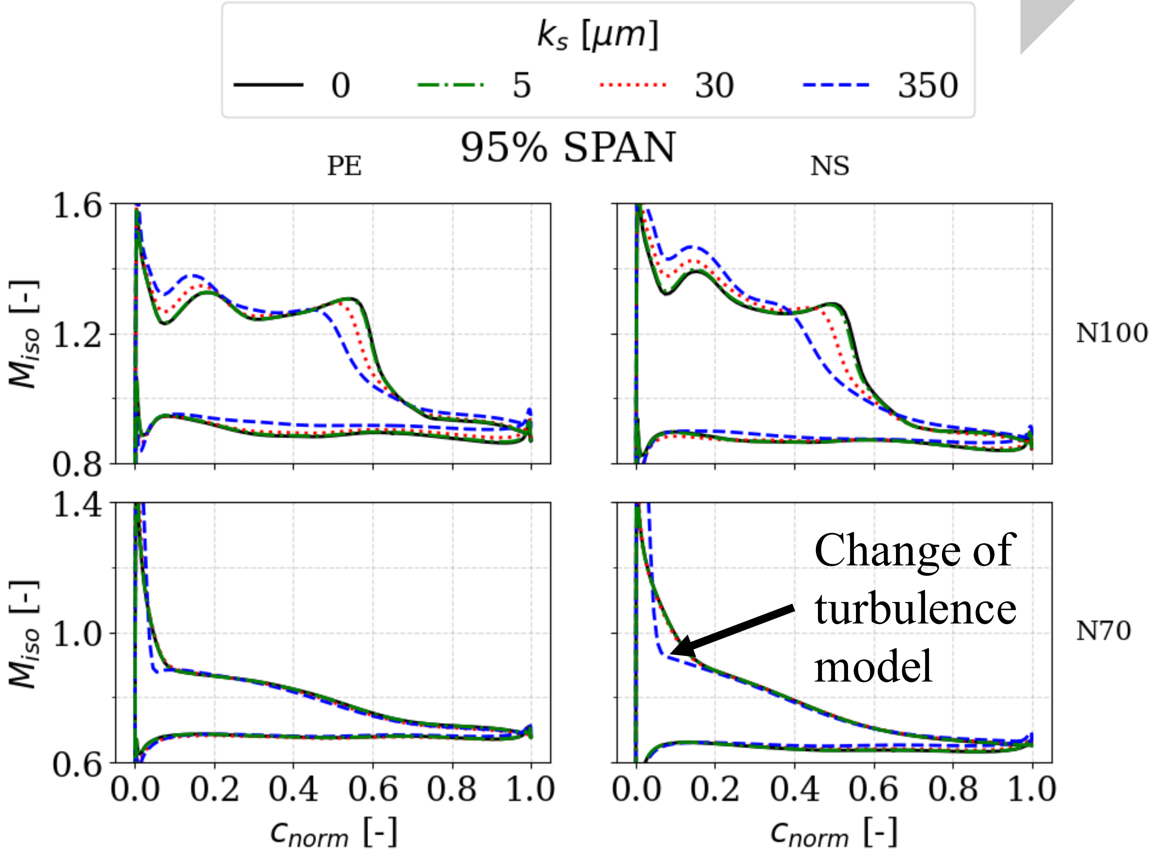




Area blockage ↑ → Losses ↑ → $\dot{m}$ ↓ → Incidence angle ↑ → Shift in OP

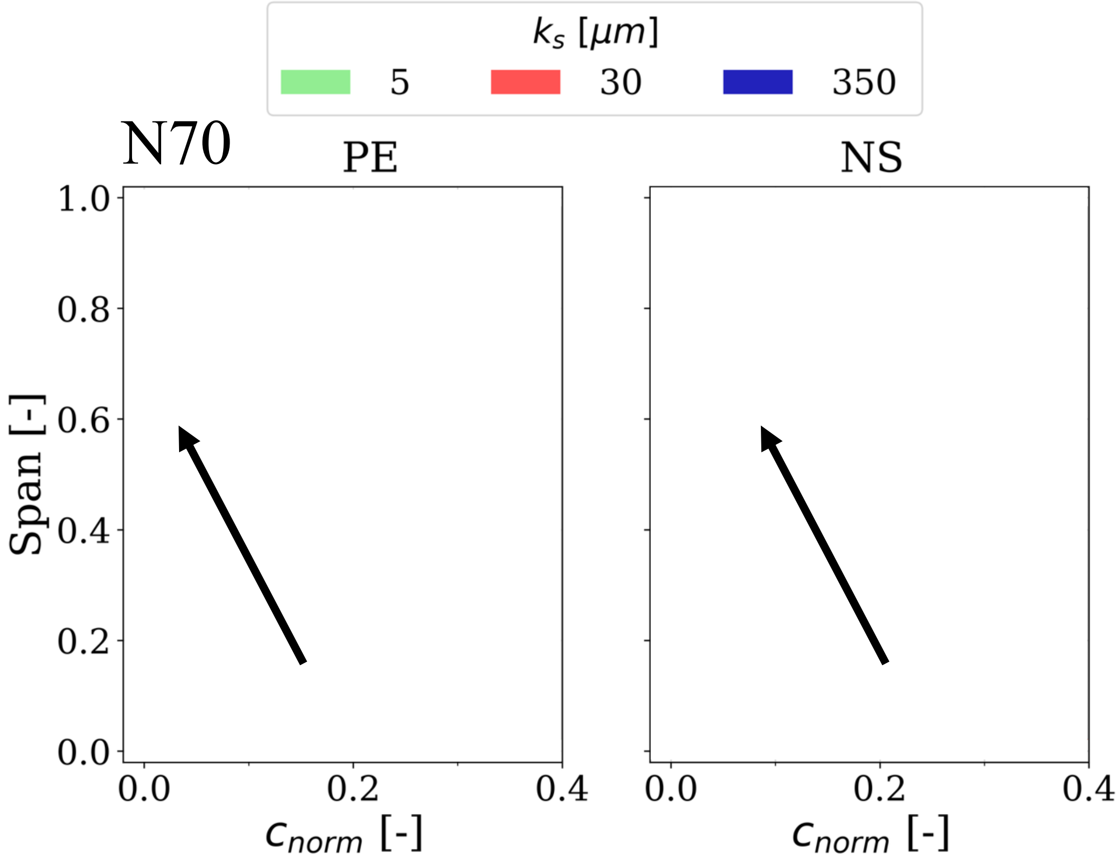
Roughness **(via Nikuradse)** applied to the entire blade and for different wall regimes

Wall regime	k_s [μm]
Smooth	0
Hydraulically Smooth	5
Transitional	30
Fully Rough	350



Change of turbulence model

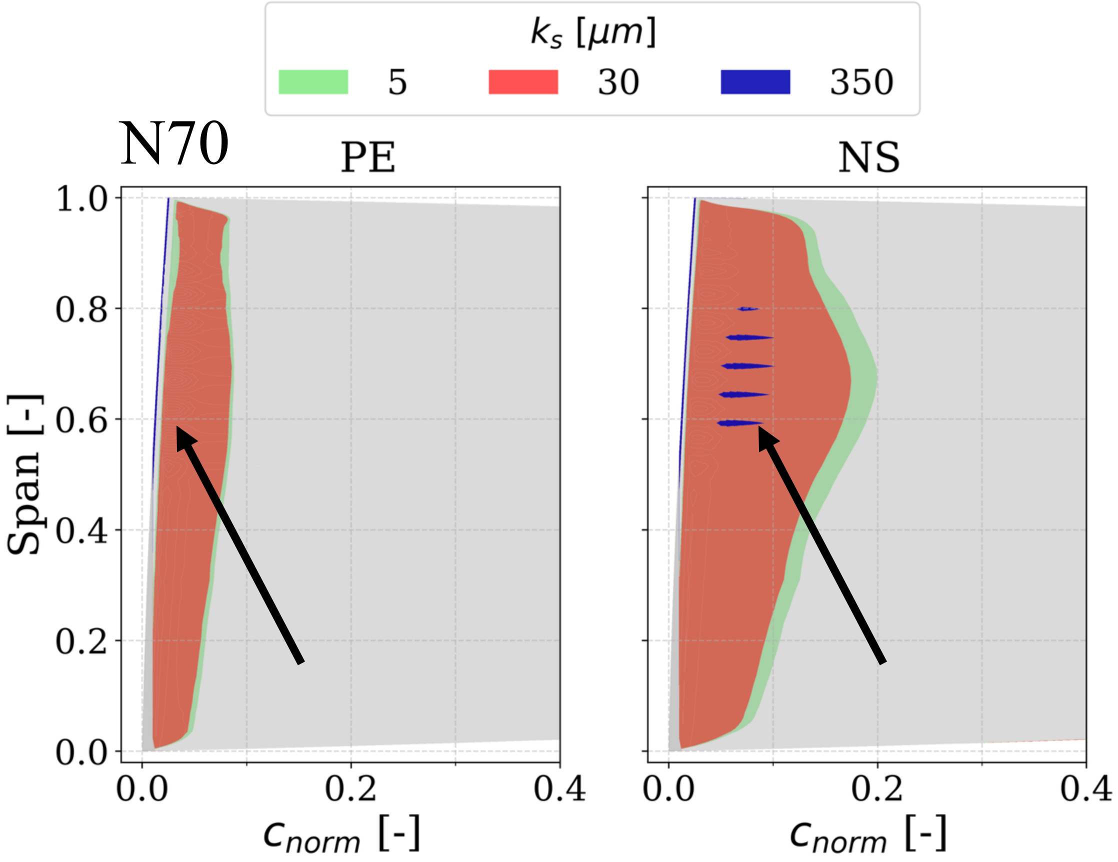
VINK LPC R1 - k_s influence on separated area



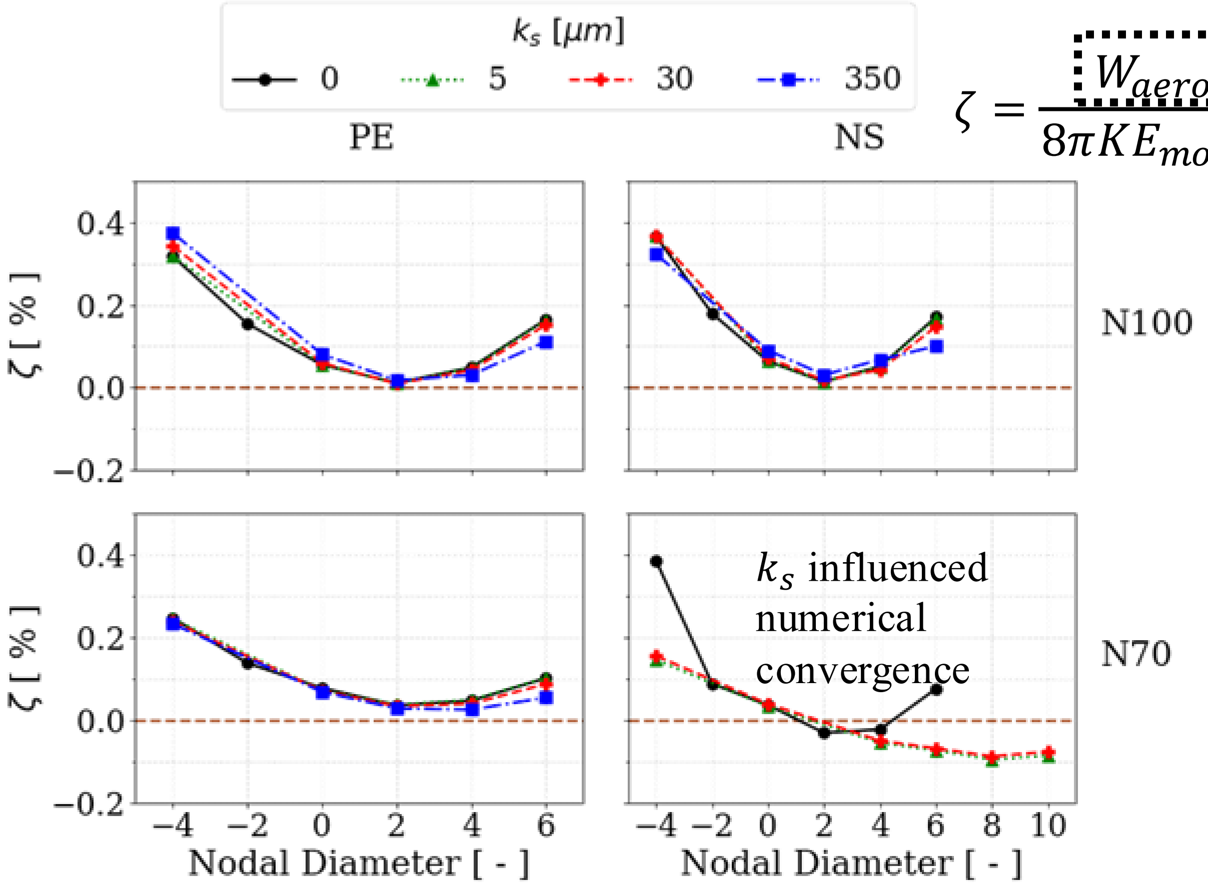
Separated areas are reduced due to an increase in roughness

Nikuradse wall modelling could not predict separated regions at fully rough regime

VINK LPC R1 - k_s influence on aerodamping



$$\zeta = \frac{\boxed{W_{aero}}}{8\pi K E_{mode}}$$



Separated areas are reduced due to an increase in roughness

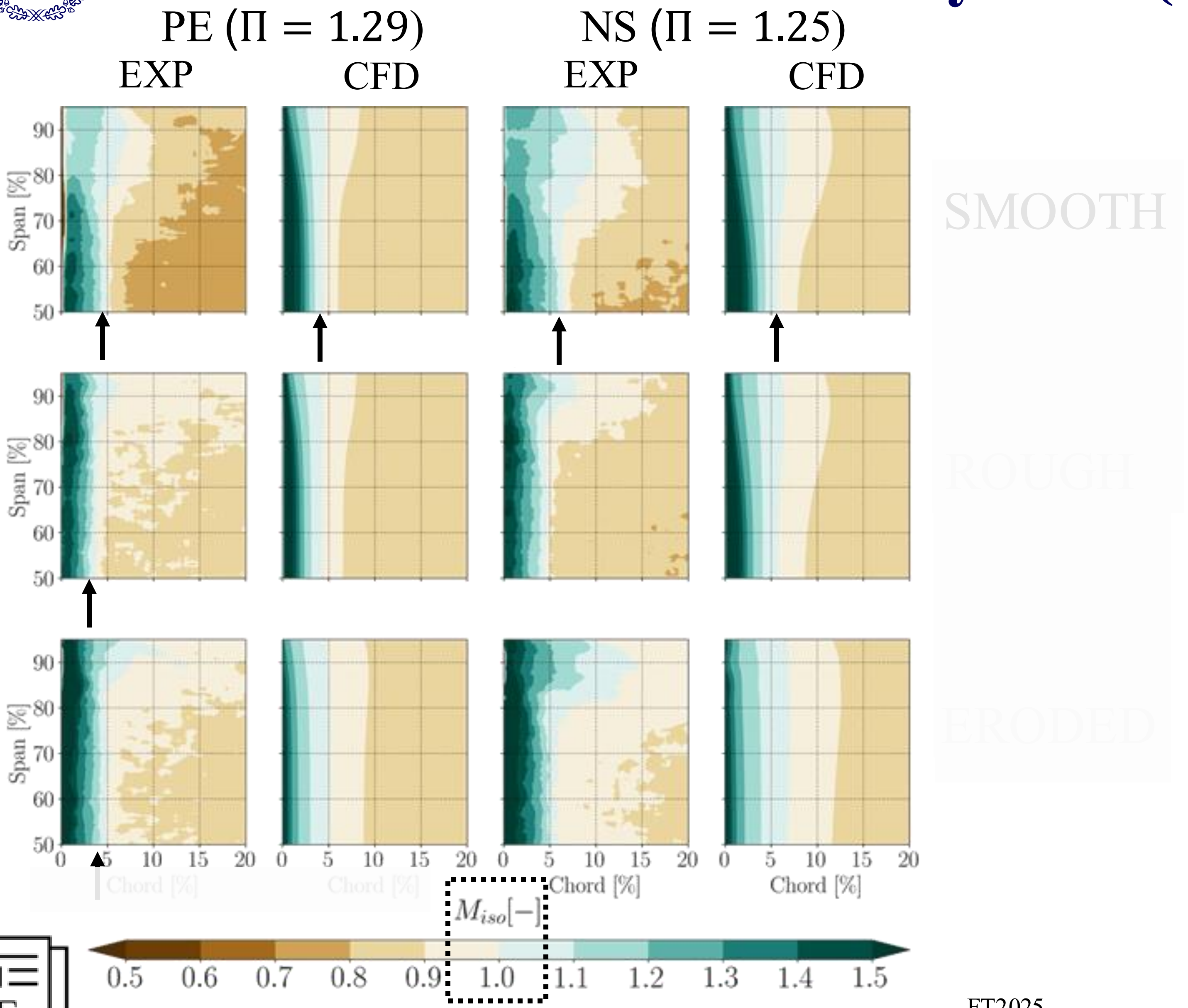
Nikuradse wall modelling could not predict separated regions at fully rough regime

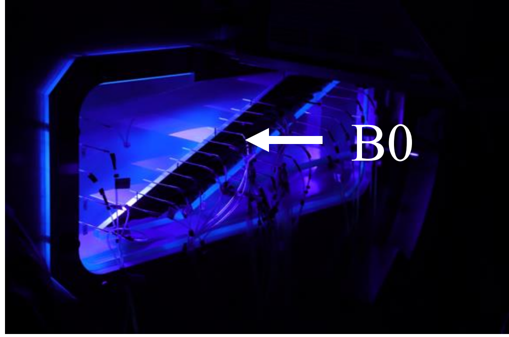
Roughness does not modify the least stable ND

Roughness produced no general trend on ζ

N70 showed convergence issues at NS

LE eroded cascade – Steady aero (PSP B0 M_{iso})





Roughness reduces the supersonic pocket extension, while in the eroded case it increases. The supersonic region extends at the tip in both cases

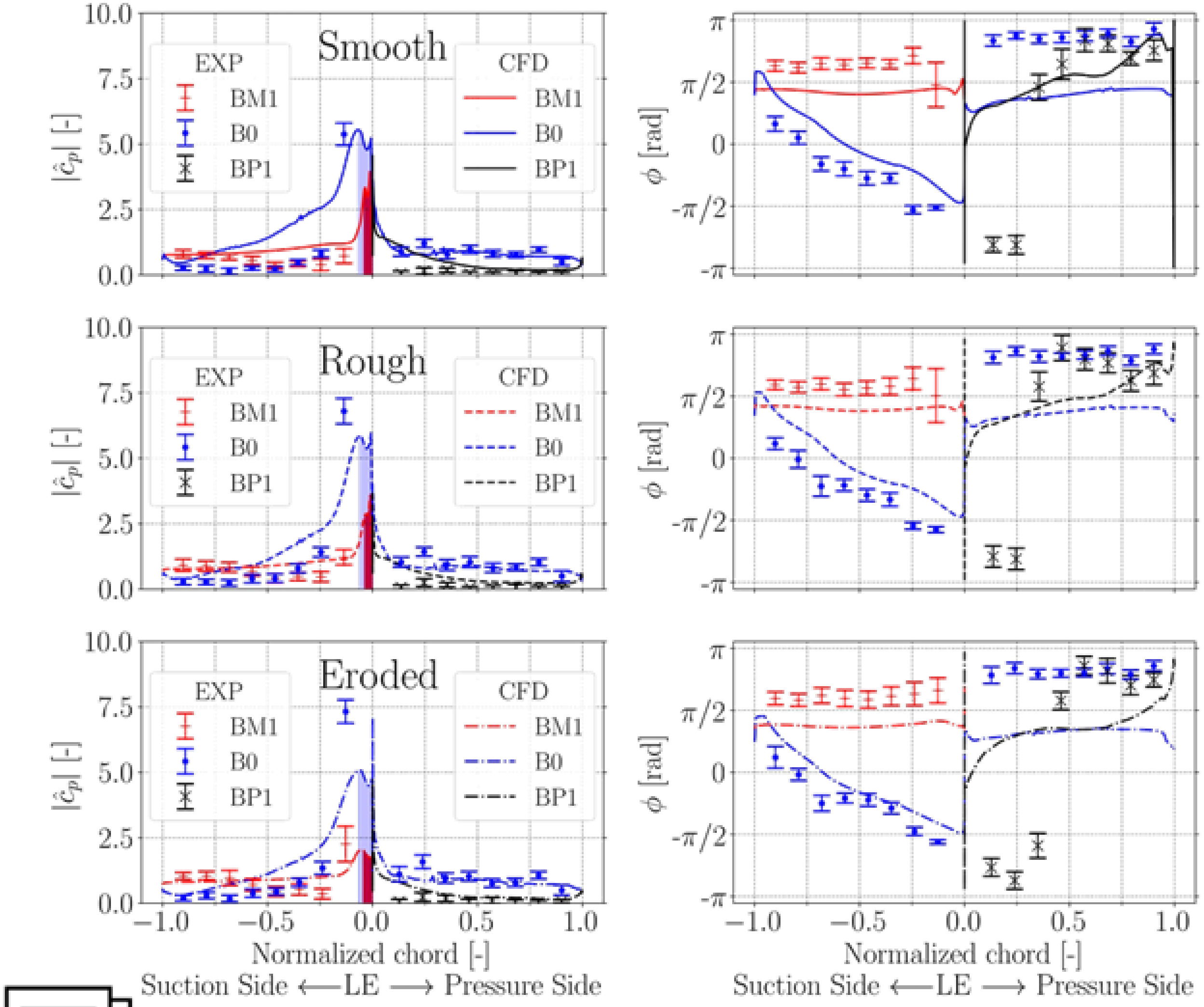
CFD does not predict significant changes in the pressure field due to roughness **(Icing model)**

In the eroded case, there is a qualitative mismatch at the LE high-pressure gradient (exp vs. CFD)

A larger extension of the supersonic regions is observed at higher incidence for both methods. Overall qualitative mismatch.

LE eroded cascade– Aeroelastic Response

NS (Π = 1.25) at 85% span



SMOOTH

ROUGH

ERODED

The phase remains fairly unaffected due to erosion and roughness. Aeroelastic response is driven by steady-state aerodynamics

Num: The maximum amplitude is located at the shock. Exp: Largest amplitude slightly shifted from the shock location

Rough: The experimental data shows an amplitude increase of 26%, while it numerically remains unchanged.

Eroded: The experimental data shows an amplitude increase of 36%, while numerically it decreases by 8%

Contributions

A B C

RQ1 How well do **numerical methods** compare **to experimental data** when predicting **the reattachment line** and **aeroelastic response** in a shock-induced separation mechanism?

- In the cascade, the SST with reattachment modification (RM) model showed closer agreement with experimental data. SST RM set as the reference turbulence model.
- The aeroelastic response for the smooth case showed that, at both operating points (PE and NS), CFD appears to overpredict the harmonic pressure coefficient amplitude downstream of the shock.
- At the measurement plane, the numerical results indicate that the aeroelastic response is driven by the shock wave location. At midspan, the shock interacts with the separation line, while the reattachment line does not appear to have a direct correlation to the aeroelastic response.

Contributions

D E

RQ2 What is the **contribution of roughness** in the **aerodynamic damping** and **aeroelastic response**?

- **In VINK LPC R1:**
    - Roughness affects the operating point, modifying the blade loading but at part speed differences are negligible for hydraulically smooth and transition wall regimes.
    - Reduction of separated areas due to roughness had a negligible effect on the aerodynamic damping. Roughness affects the aerodynamic damping but with no general trend.
- Roughness wall modeling based on Nikuradse showed limitations at fully rough regimes in VINK LPC R1 and in the TLC at the transition regime. Icing modeling based on Colebrook is recommended.
- **In the cascade:**
    - Experimental data showed an increase of harmonic pressure coefficient amplitude of 22% and 26% at Π=1.29 & 1.25. The increase might be associated with a stronger steady shock (via PSP) near the leading edge.
    - At 85% span, numerical data showed negligible differences when roughness was included. At midspan, an interaction appears to exist between the rough wall modeling and the separation line.

Contributions

RQ3 How does the **eroded leading edge** mechanism affect the **aeroelastic response** in a shock-induced separation mechanism?

- The isentropic Mach number increases with larger supersonic extension w.r.t smooth and rough cases. Numerical results predict a weaker and localized Mach number at the leading edge

- The eroded case, showed an increase of 36% in the harmonic pressure coefficient amplitude w.r.t. smooth case at both operating points, while CFD predicts a reduction of 24% and 8% at $\Pi=1.29$ & 1.25.

- Experimental results confirmed the numerical prediction of a fairly unchanged phase lag between the blade motion and unsteady pressure.

List of Publications

- **Paper A:** Glodic, N., Tavera Guerrero, C., & Gutierrez, M. (2020). Blade oscillation mechanism for aerodynamic damping measurements at high reduced frequencies. E3S Web Conf.Volume 345, 2022XXV Biennial Symposium on Measuring Techniques in Turbomachinery (MTT 2020), 345 https://doi.org/10.1051/e3sconf/202234503002

- **Paper B:** Tavera Guerrero, C., Glodic, N., & Groth, P. (2022). Validation of Steady-State Aerodynamics in a Transonic Linear Cascade at Near Stall Conditions. Proceedings of the ASME Turbo Expo. Presented at the ASME Turbo Expo 2022:Turbomachinery Technical Conference and Exposition, GT 2022, 13-17 June 2022, Rotterdam, Netherlands. https://doi.org/10.1115/GT2022-81346

- **Paper C**: Tavera Guerrero, C., Glodic, N., Gutierrez Salas, M., & Mårtenson, H., Aeroelastic Response in an Oscillating Transonic Cascade - An Experimental and Numerical Approach, International Journal of Turbomachinery Propulsion and Power IJTPP, Special issue from (ISUAAAT16). Int. J. Turbomach. Propuls. Power 2025, 10(2), 7; https://doi.org/10.3390/ijtpp10020007

List of Publications

- **Paper D**: Tavera Guerrero, C., Gutierrez, M., Glodic, N., & Deshpande, S. (2024). Numerical Surface Roughness Influence on the Aerodamping of an Axial Transonic Compressor at Nominal Speed and Part-speed. Proceedings ASME Turbo Expo 2024: Turbomachinery Technical Conference and Exposition, GT 2024. June 24-28, 2024, London, United Kingdom. https://doi.org/10.1115/GT2024-125215

- **Paper E**: Tavera Guerrero, C., Gutierrez Salas, M., & Glodic, N., Leading Edge Erosion Influence on the Aeroelastic Response in an Oscillating Transonic Linear Compressor Cascade, International Journal of Turbomachinery Propulsion and Power IJTPP, *Draft version, under review process*