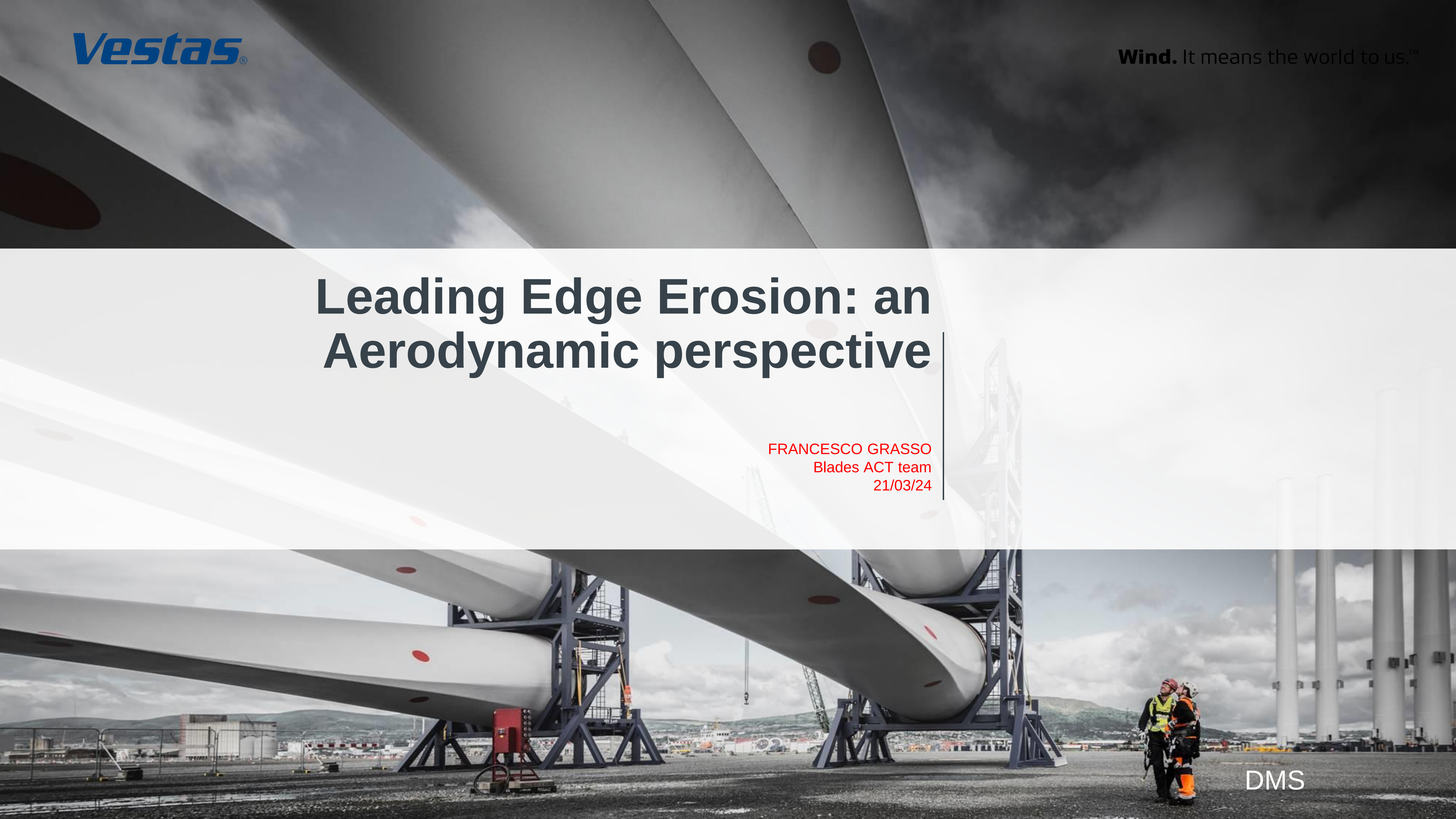
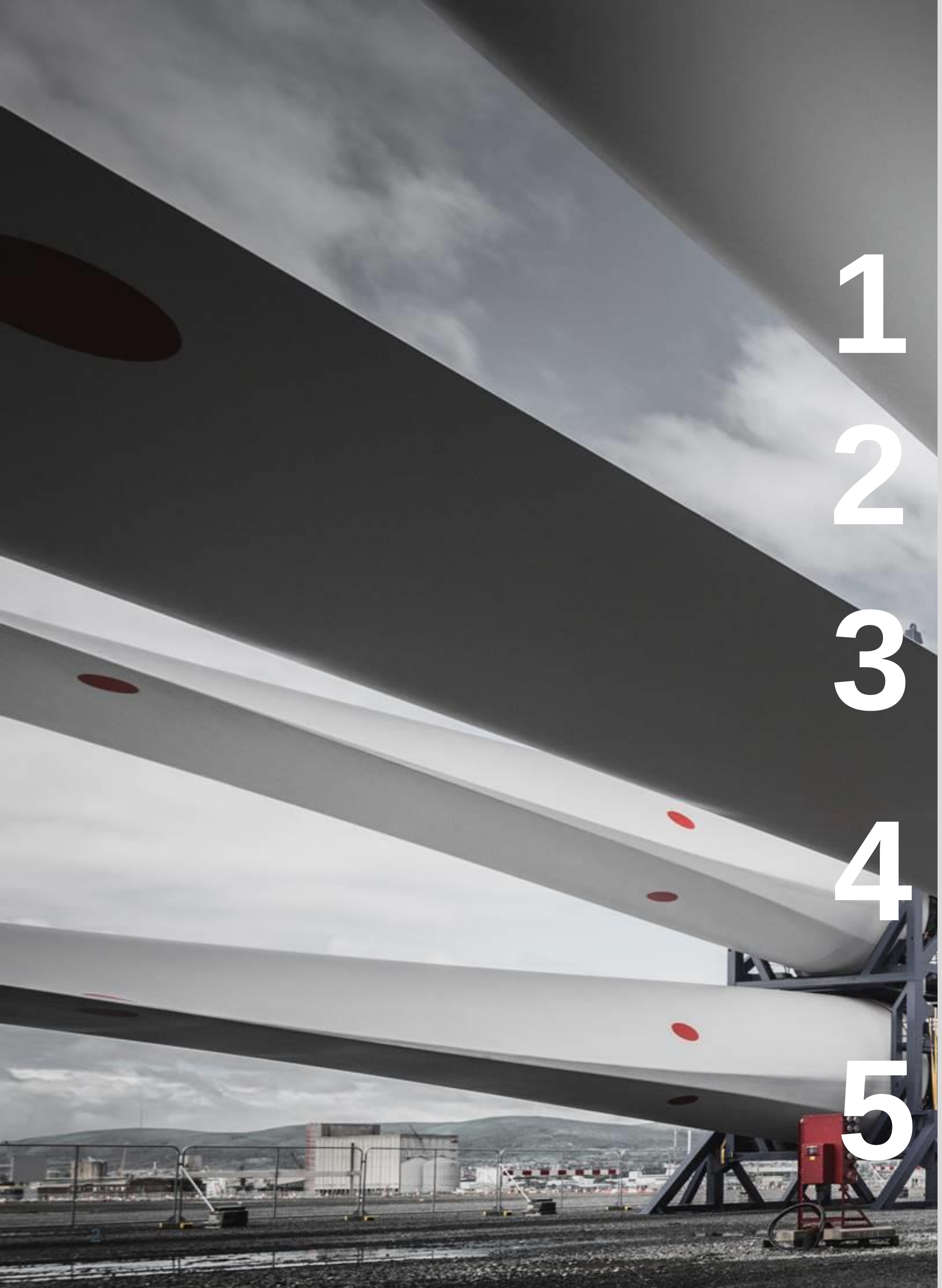


Leading Edge Erosion: an Aerodynamic perspective

FRANCESCO GRASSO
Blades ACT team
21/03/24

DMS



1 Introduction

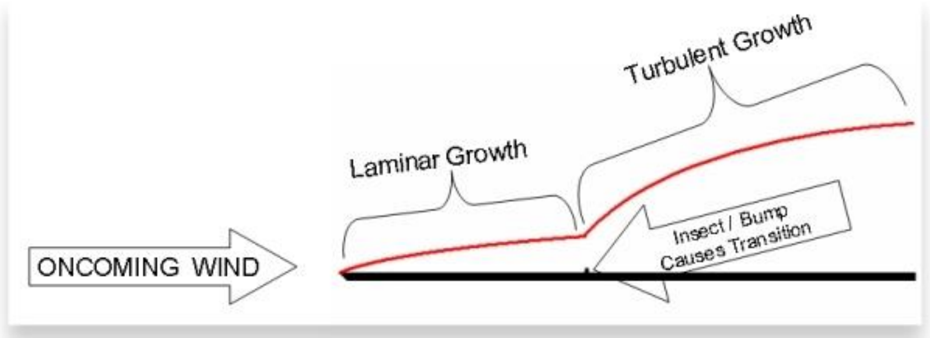
2 LE erosion aerodynamic modelling

3 LEP solutions

4 LE erosion mitigation by aerodynamic design

5 Conclusions

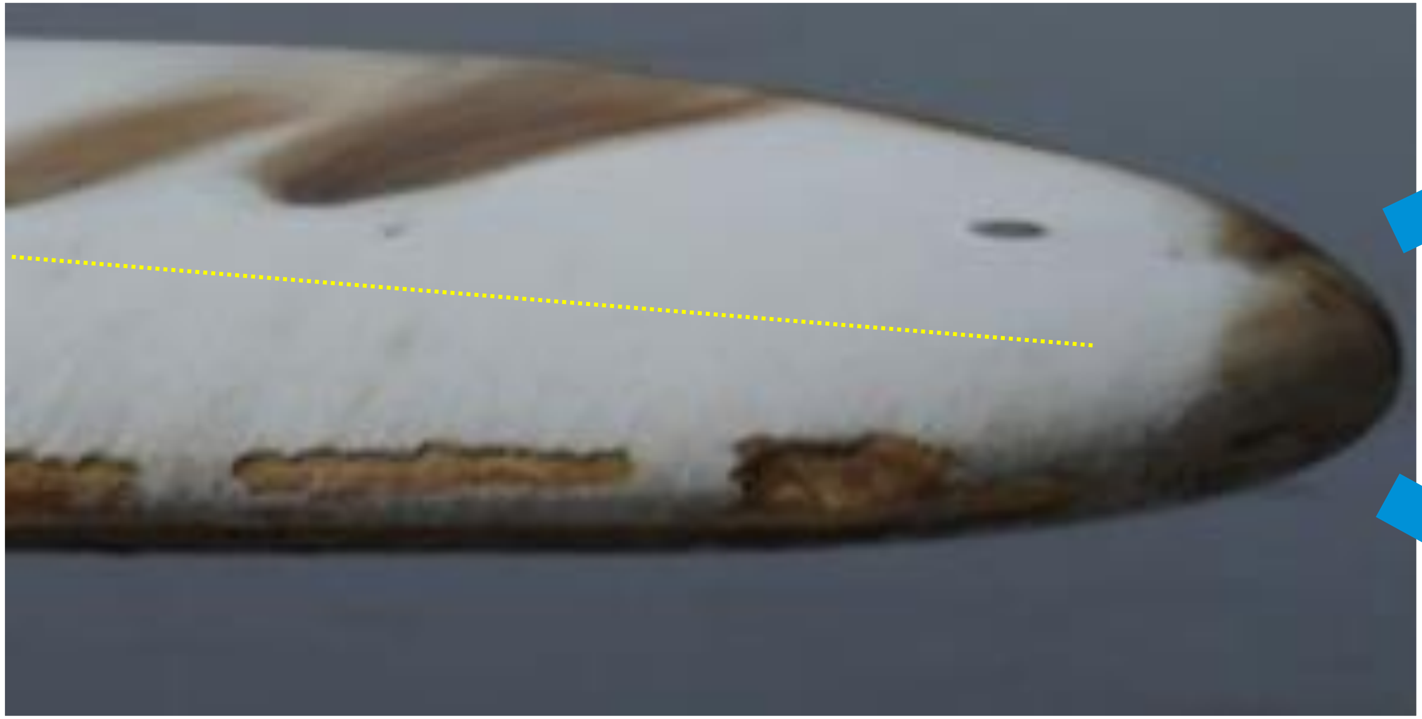
1. Introduction – why aerodynamics cares?

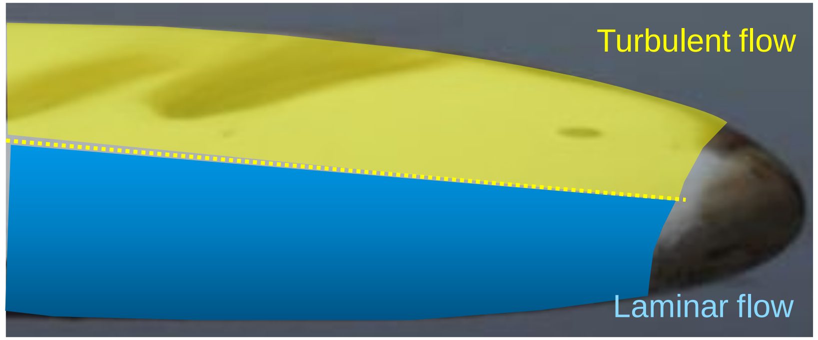


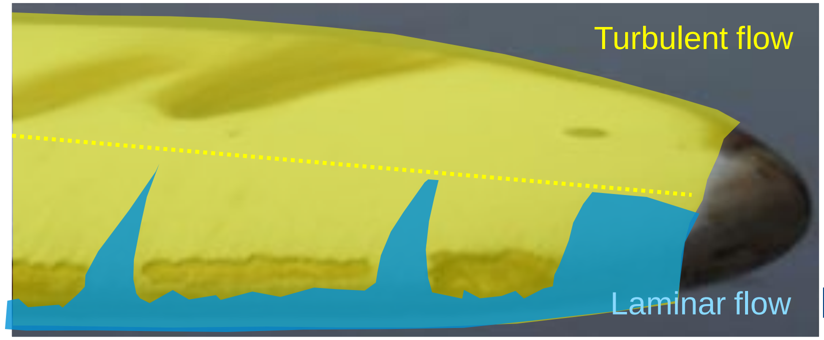
The flow around the blade has a laminar region and a turbulent region

Generally, turbulent flow generates larger drag

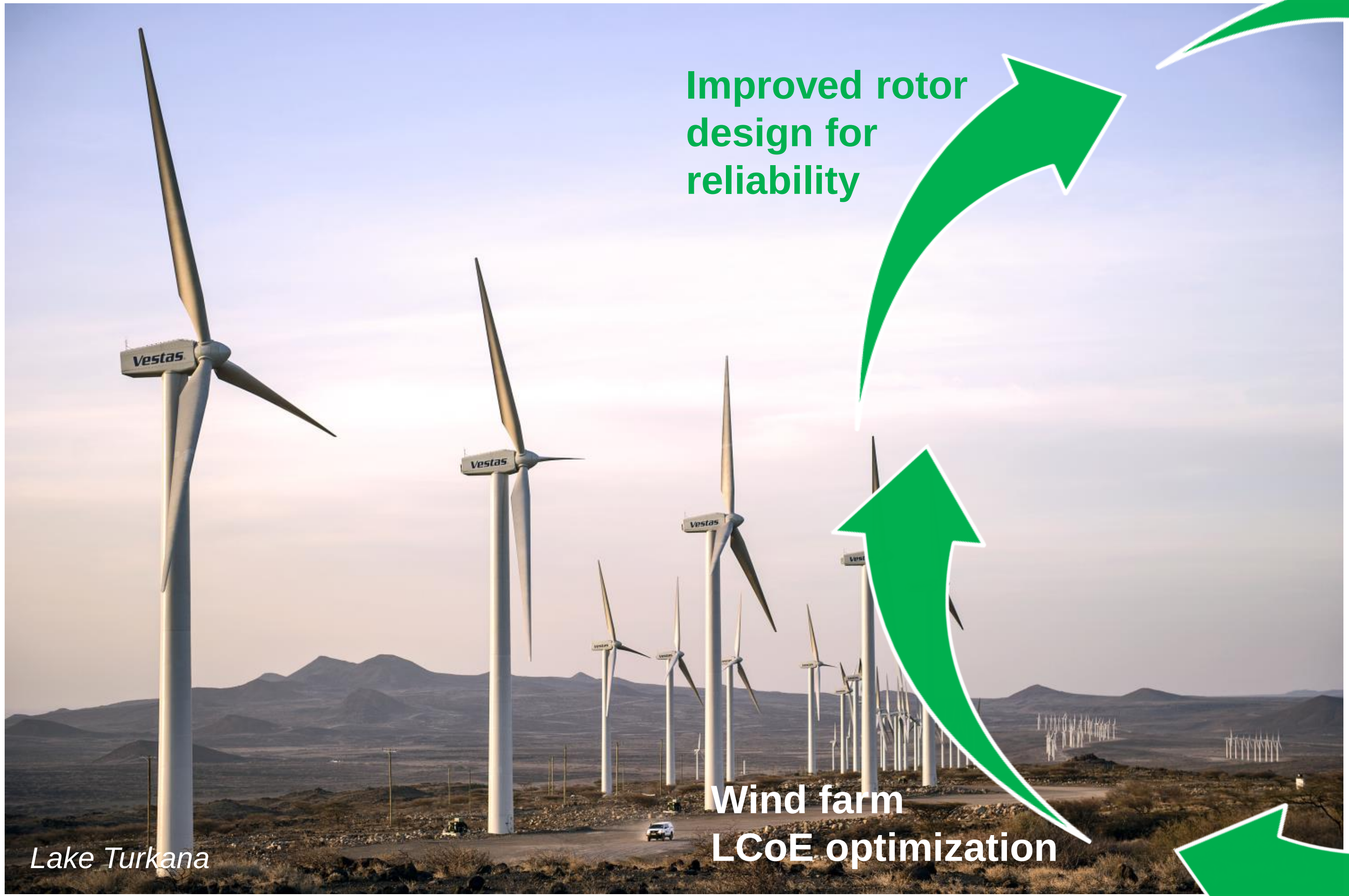
Geometrical imperfections might introduce early transition to turbulent and so, additional drag AND NOISE





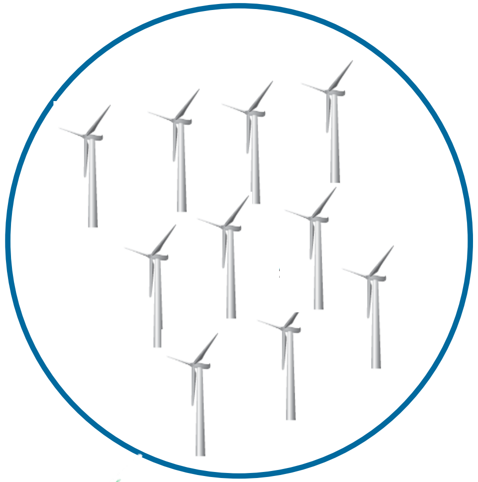


1. Introduction – what we want to achieve at the end?



Improved rotor design for reliability

- Blade characteristics
- Actual blade surface condition
- Site/Environment conditions



Holistic predictive model:
- Costs
- AEP
- Noise
- Material durability

Maintenance strategy optimization

- Maintenance support planning
- Tailored maintenance solution

Wind farm LCoE optimization

Classification: Public

Vestas

2. LEE aerodynamic modelling – general aspects

Approach	Pro	Cons
Semi-empirical	• No/little computational effort	• Lot of data needed to build the model
2D/3D Panel code	• Low computational effort • Simple usage	• Geometrical limitations in describing eroded shape • Need of data for validation
2D/3D CFD	• More general in regards of model restrictions	• Very expensive in computational resources • Need of data for validation
AI/machine learning	• Low computational effort • No model-limited	• Very expensive in training the model • Need of data for validation and training

Regardless of the approach, **experimental data** and **robust LE erosion classification system** are needed

Classification: Public

Vestas

2. LEE aerodynamic modelling – standardise LE erosion categories

Vestas joined **IEA task46** and **LERCAT** initiatives to collaborate with other Institutions in the Wind Community and advance together the state of art

Task 46 | IEA Wind TCP (iea-wind.org)

LERcat - DTU Wind and Energy Systems

Classification system details	Source						
	Vestas	Sandia	IEA task46	LM	SGRE	UIUC	EURAMET
Blade/aerofoil based system	Combined blade/aerofoil	Combined blade/aerofoil	aerofoil	aerofoil	aerofoil	aerofoil	aerofoil
Blade level scenarios	6	4	Same as Sandia TBC	NA	NA	NA	NA
Aerofoil level severity grades	5	4	5	3	4	9	5
Aerodynamic impact metric	Drop on aerofoil Cl, Cd, Cm, L/D	Drop on aerofoil Cl, Cd, Cm, L/D	Power reduction	Drop on aerofoil Cl, Cd, Cm, L/D	Aerofoil L/D drop	Drop on aerofoil Cl, Cd, Cm, L/D	Aerofoil L/D drop
Aerodynamic data source	Wind tunnel	Wind tunnel	Same as Sandia TBC + Power Simulation TBC	Wind tunnel	NA	Wind tunnel	Wind tunnel
Aerofoils tested	NACA 63_3-418, Vestas aerofoils	NACA 63_3-418, S825	Same as Sandia TBC	DU00-w-212	NA	DU96-w-180	NACA 63_3-418
Reynolds number [million]	Up to 3 for Vestas aerofoils, up to 5 for NACA 63_3-418	2 for S825, 2.4 for NACA 63_3-418	Same as Sandia TBC	3, 6	NA	Up to 1.85	Up to 7
Technique to reproduce erosion on wind tunnel model	LE erosion masks	LE erosion reproduction	Same as Sandia TBC	3D printed LE based-on RET tests	NA	Contaminated LE	sandpaper

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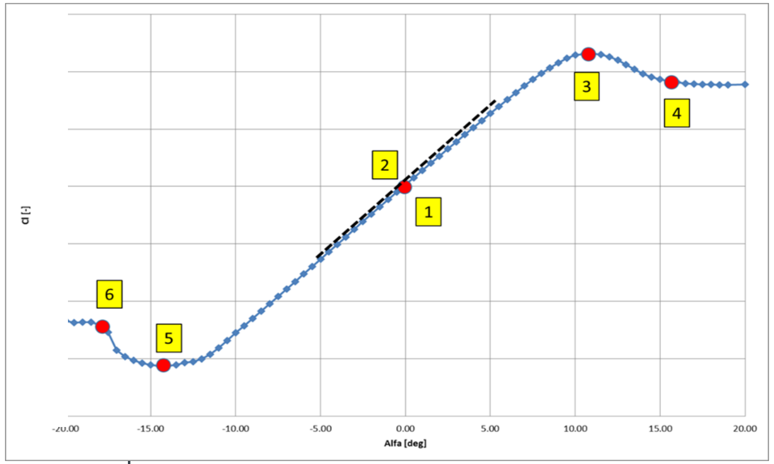
2. LEE aerodynamic modelling – reverse LE erosion categories

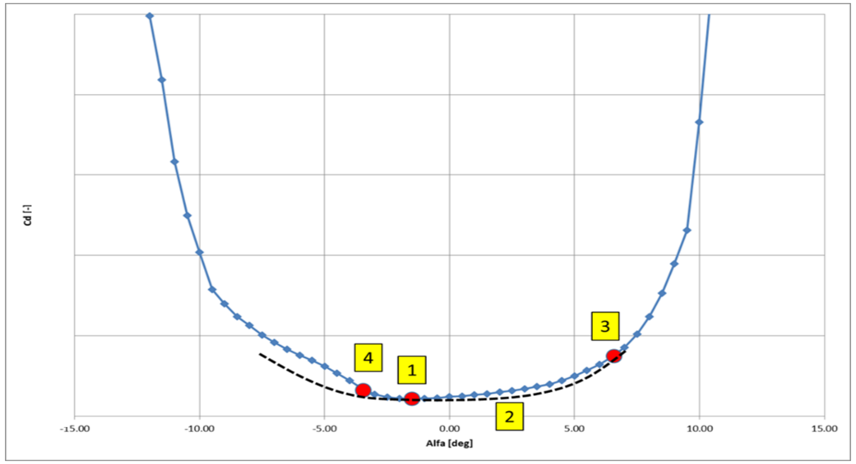
Would it be possible to build a LE erosion classification system based on available wind tunnel data, as kind or reverse approach?

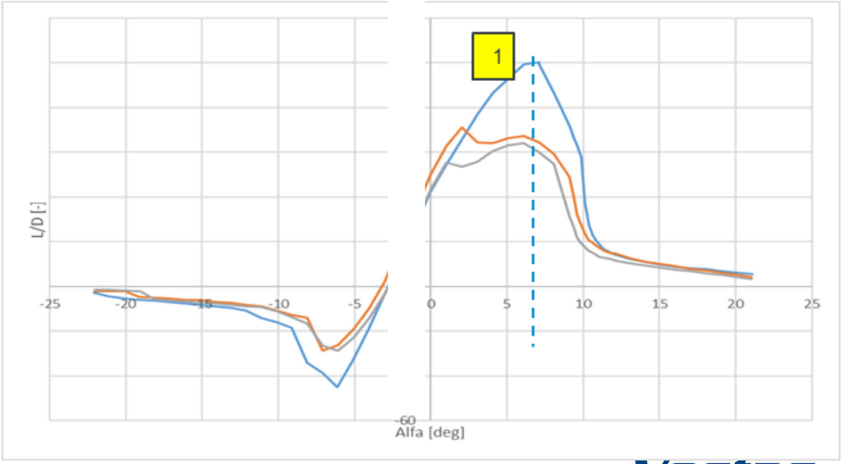
Source	Dataset	Aerofoil	Data Re number									
			1	1.2	1.5	1.75	2	2.2	3	4	5	6
Vestas		Vestas aerofoils		x		x	x	x	x		x	
Sandia		NACA 63_3-418 S814			x		x		x	x		
IRPwind		NACA 63_3-418	x				x		x			
DTU	**LERWTB**	NACA 63_3-418							x		x	x
	Stuttgart	NACA 63_3-418							x			
LM		DU00-w-212 LM aerofoil							x			x
UIUC		DU96-w-180	x		x		x					

Few questions:

- Different aerofoils have been used. Would be the trends applicable to all?
- LE erosion in wind tunnel is emulated in different ways. Which one is more appropriate? Are the results compatible?
- The data are measured in wide Re number range. Which one to use? Would the trends be consistent?
- Different parameters could be used as reference. Which ones are more appropriate? Would the trends be very sensitive to this choice?
- How the parameters should be tracked?







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2. LEE aerodynamic modelling – reverse LE erosion categories

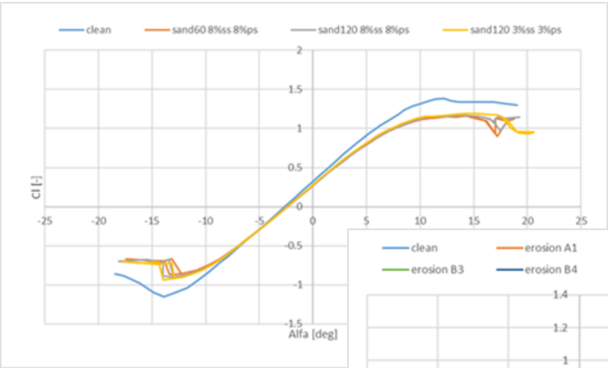
Few attempts…

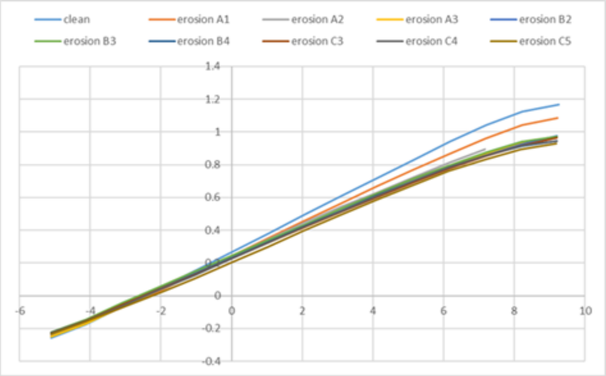
Partner	Erosion range																	
Vestas				1 1.254	2 1.414		3 1.607	4 1.698								5 2.287		
Sandia	100 3 1.04	100 9 1.1		100 15 1.25		140 3 1.58	200 3 1.62	eroded 1.69										
IRPwind										P240 4-4 1.84		P240 8-8 1.92		P240 15-15 2.044				
													P80 4-4 1.98		P80 8-8 2.13		P80 15-15 2.34	
														P40 4-4 2.01		P40 8-8 2.21		P40 15-15 2.45
DTU Stuttgart data											120 3ss 3ps 1.885			120 8ss 8ps 2.047	60 8ss 8ps 2.147			
DTU PLC data (LERWTB)						P400 1.56	P120 1.61		P40 1.76									
LM			erosion 1.175	heavy erosion 1.253														

Classification based on minimum drag

Partner	Erosion range				
Vestas	1 0.945	2 0.889	3 0.827	4 0.818	5 0.808
Sandia					
DTU Stuttgart data					
DTU PLC data (LERWTB)					
LM	ersoion 0.948	heavy erosion 0.898			

Classification based on stall AOA





Classification based on maximum L/D

Partner	Erosion range																		
Vestas						1 -43.5	2 -47.6	3 -53.3				4 -57.7							5 -75.3
Sandia	100 3 -25	100 9 -28.3	100 15 -33.8	140 3 -39.1	200 3 -41.9							eroded -57.5							
IRPwind									P240 4-4 -54.8		P240 8-8 -56.9		P240 15-15 -59.4		P80 8-8 -63		P80 15-15 -65.9		
													P80 4-4 -60.4	P40 4-4 -61.7		P40 8-8 -64.3		P40 15-15 -67.6	
DTU Stuttgart data										120 3ss 3ps -55.9			120 8ss 8ps -60.2		60 8ss 8ps -62.4				
DTU PLC data (LERWTB)						P400 -43.1		P120 -53.6					P40 -59.5						
LM			erosion -31.8				heavy erosion -47.7												

Vestas

2. LEE aerodynamic modelling – reverse LE erosion categories

Few decisions:

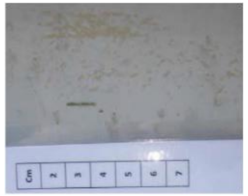
1. L/D has been selected as parameter:
    - It is directly related to the rotor AEP
    - It combines together drag and lift. The first being more sensitive at low angle of attack, the latter at high angle of attack so that the L/D combination is more balanced parameter.

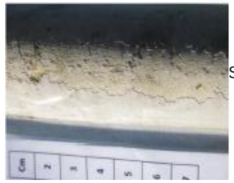
2. L/D max has been preferred in this study, although L/D at different operative point could be preferrable

3. Percentage drops have been used to have more general trends

4. 3 million Re data have been used since more data were available. However, the checks at different values show resemblant values

Partner	Erosion levels																		
	roughness		1				2	3				4					5		
	L/D drop<30%		30% <L/D drop <44%				44% <L/D drop <52%	52% <L/D drop <57%				57% <L/D drop <65%					L/D drop > 65%		
Vestas						1 -43.5	2 -47.6	3 -53.3				4 -57.7							5 -75.3
Sandia	100 3 -25	100 9 -28.3	100 15 -33.8	140 3 -39.1	200 3 -41.9							eroded -57.5							
IRPwind									P240 4-4 -54.8		P240 8-8 -56.9		P240 15-15 -59.4		P80 8-8 -63		P80 15-15 -65.9		
IRPwind													P80 4-4 -60.4	P40 4-4 -61.7		P40 8-8 -64.3		P40 15-15 -67.6	
DTU Stuttgart data										120 3ss 3ps -55.9			120 8ss 8ps -60.2		60 8ss 8ps -62.4				
DTU PLC data (LERWTB)						P400 -43.1		P120 -53.6					P40 -59.5						
LM			erosion -31.8				heavy erosion -47.7												





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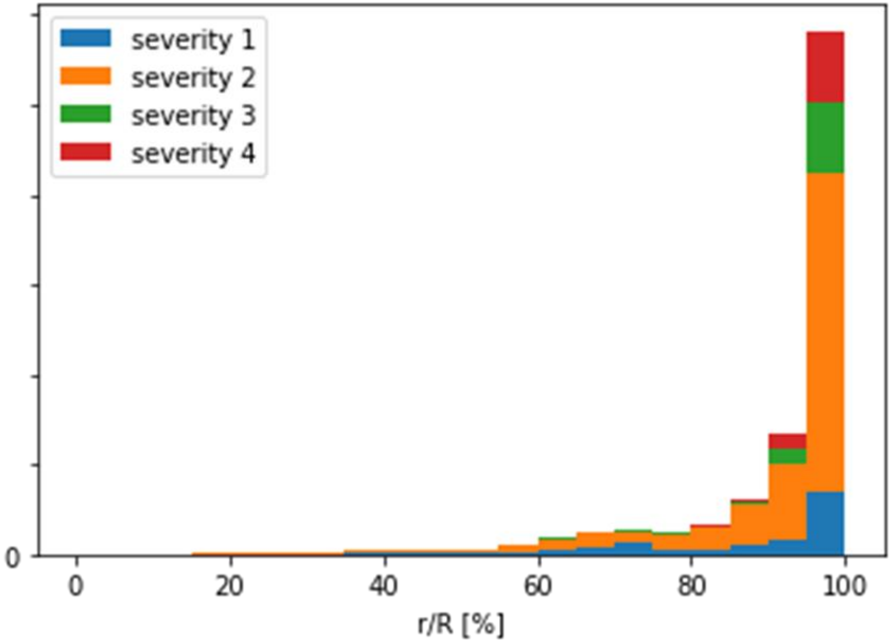
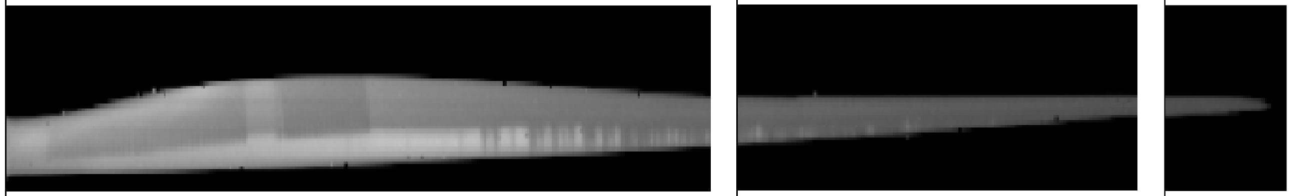
2. LEE aerodynamic modelling – 5MW test case

Normally, the blades do not appear uniformly eroded. So, the erosion levels identified should be combined to provide a blade-level scenario before the AEP impact can be evaluated.



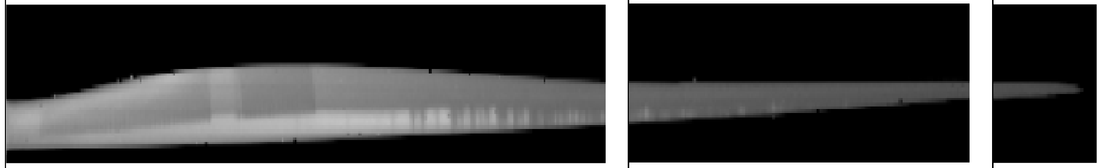


Blade erosion scenario	r/R < 60%	60% - 90%	>90%
	Aerofoil erosion severity level		
0	0	0	0
A	0	0	1
B	0	1	1
C	0	1	2
D	0	2	2
E	0	2	3
F	0	2	4

Aerofoil erosion level	Average L/D drop [%]
1	37
2	48
3	54.5
4	61

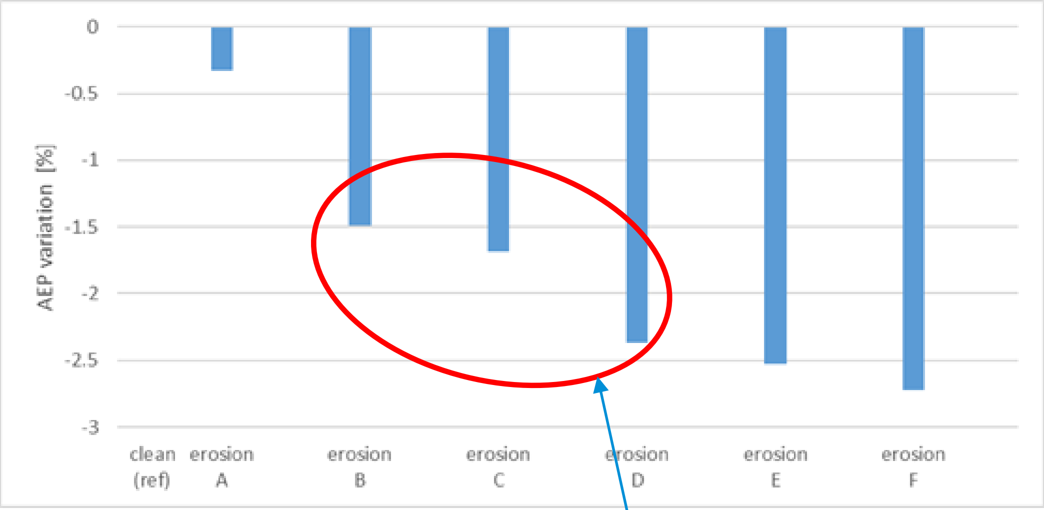
2. LEE aerodynamic modelling – 5MW test case

Blade erosion scenario	r/R < 60%	60% - 90%	>90%



Blade erosion scenario	Aerofoil erosion severity level		
	r/R < 60%	60% - 90%	>90%
0	0	0	0
A	0	0	1
B	0	1	1
C	0	1	2
D	0	2	2
E	0	2	3
F	0	2	4

Configuration	Aerofoil erosion severity level		AEP delta
	60% < r/R < 90%	r/R > 90%	[%]
clean (ref)	-	-	-
erosion A	-	1 37% L/D drop	-0.3
erosion B	1 37% L/D drop	1 37% L/D drop	-1.5
erosion C	1 37% L/D drop	2 48% L/D drop	-1.7
erosion D	2 48% L/D drop	2 48% L/D drop	-2.4
erosion E	2 48% L/D drop	3 54.5% L/D drop	-2.5
erosion F	2 48% L/D drop	3 61% L/D drop	-2.7

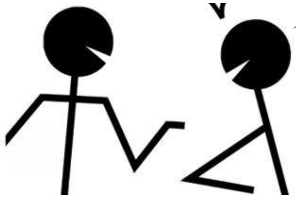


The correlation helps identifying best maintenance moment

The exercise shows the connection between rotor level and aerofoil level losses

The AEP impact cannot be measured so must be small

- Is your asset still profitable?
- What about the noise?



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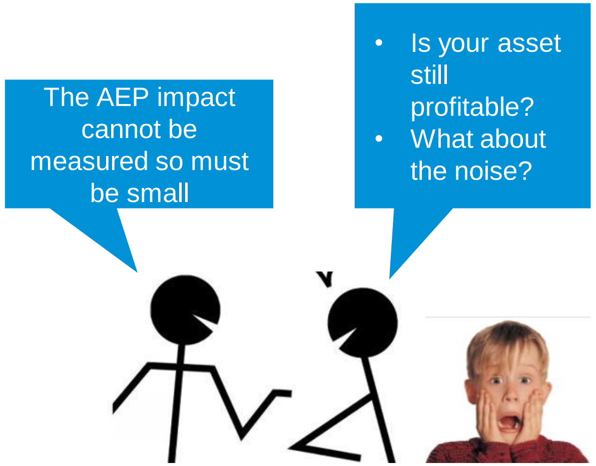
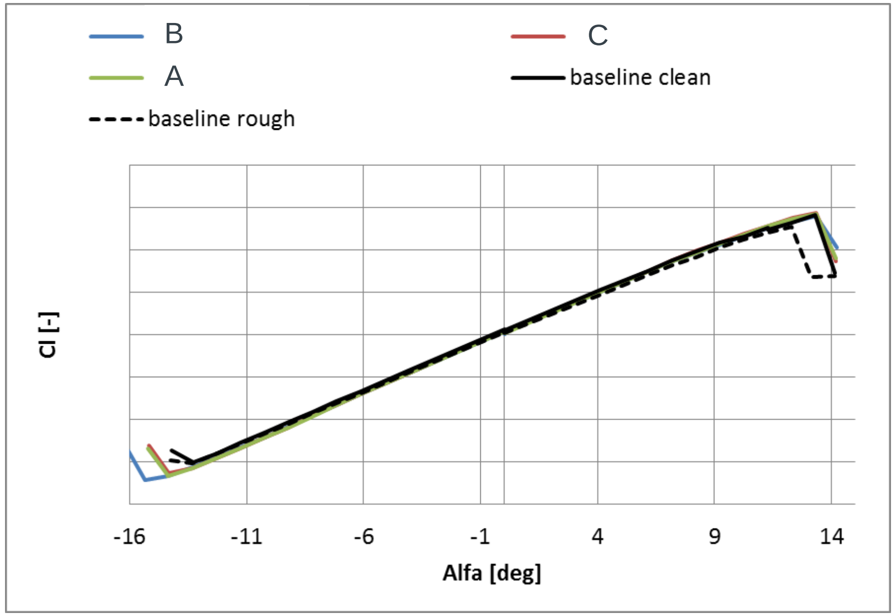
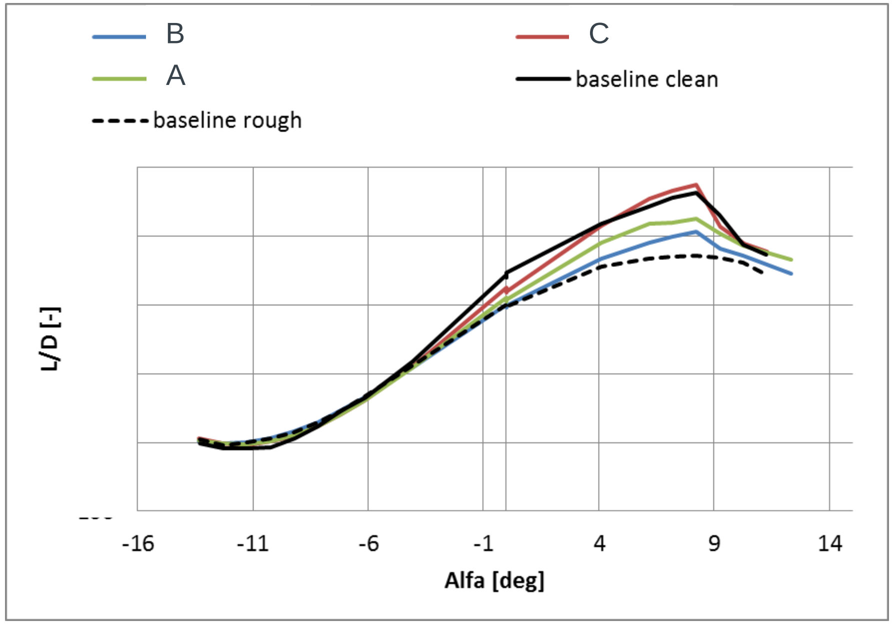
3. LEP solutions – ~~aerodynamic~~ multidisciplinary challenges

- Several solutions are available on the market such as paints, tapes, shields. With different effectiveness and different costs, they appear to mitigate erosion issues from material point of view.
- However, manufacturing quality is key to make sure they also work from aerodynamic point of view.
- The aerodynamic LE erosion classification will help selecting the best LEP solution for each site/climate. For this however, an aerodynamic model for the LEP is needed.

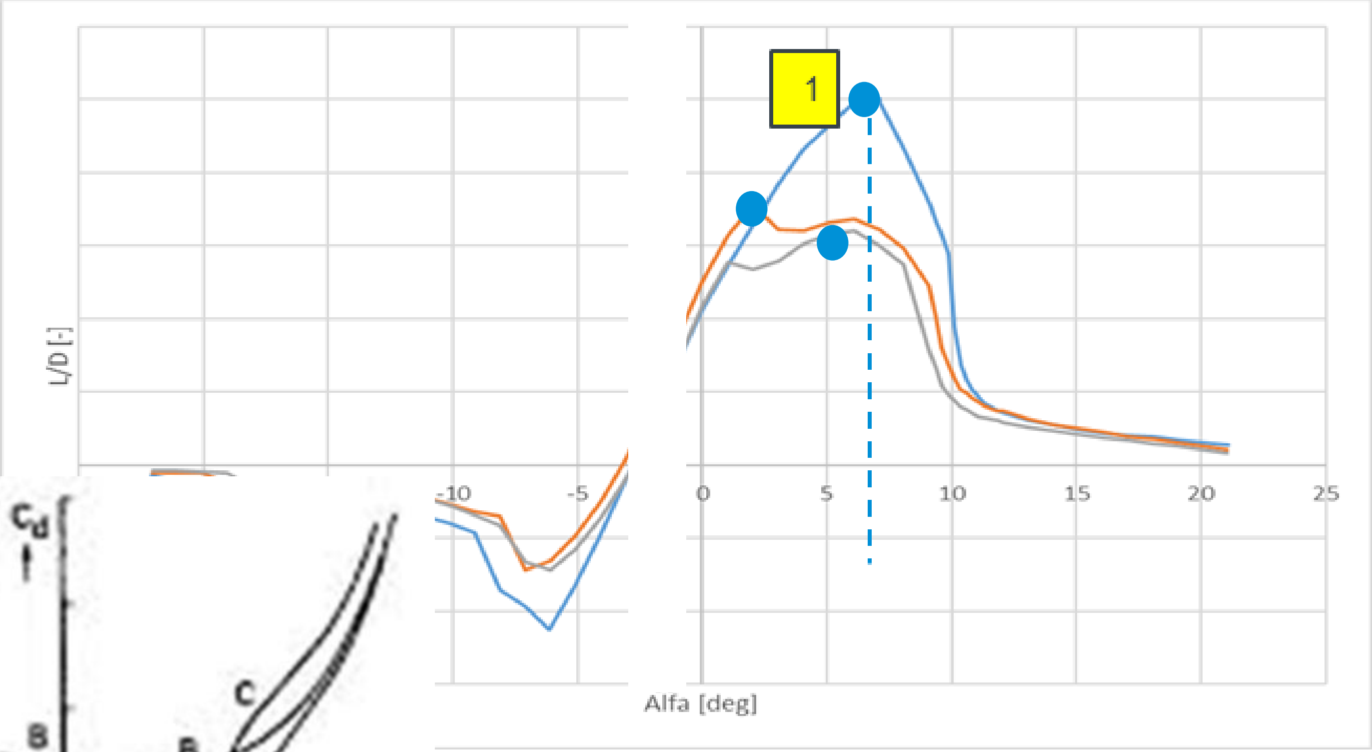


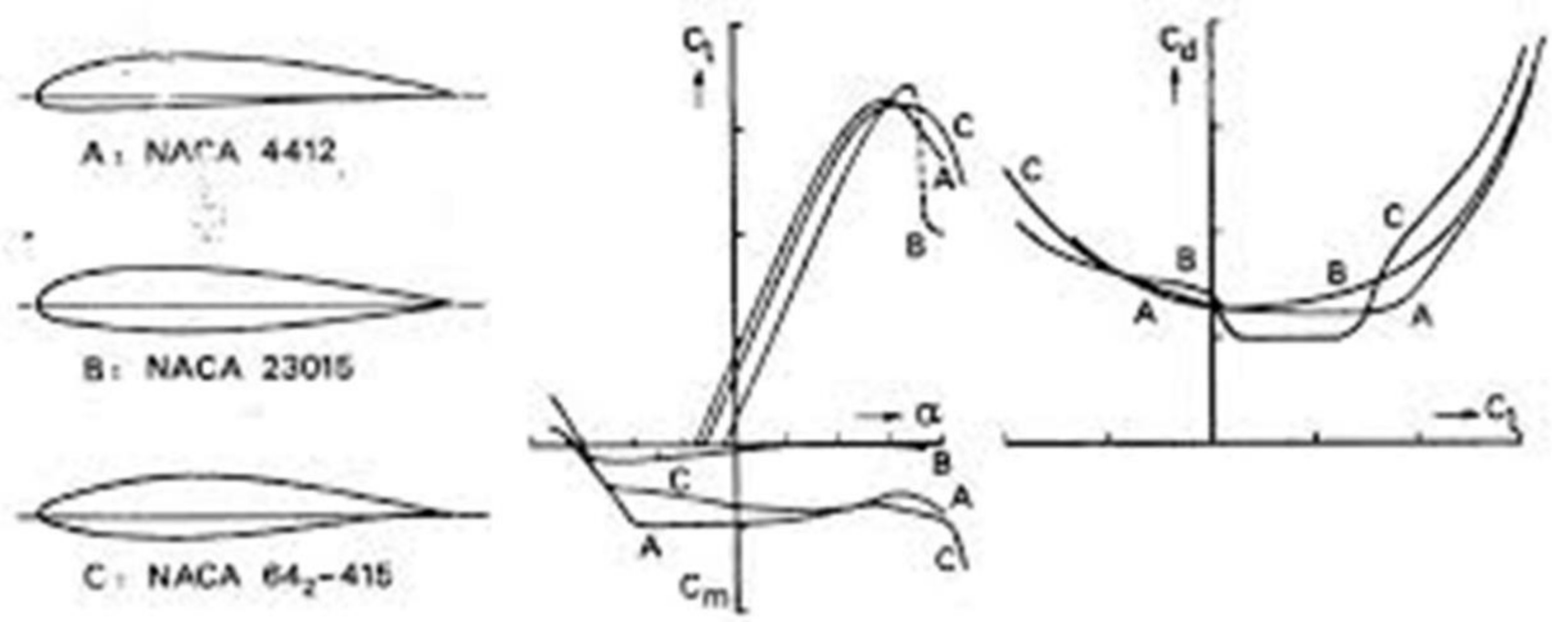




4. LE erosion mitigation by smarter aerodynamic design

- LEE and LEP modelling capability could be used to mitigate their impact by tailored aerofoil selection/design and/or blade shape optimization





5. Conclusions

- LE erosion plays critical role in wind Industry as it affects the overall performance of the rotor.
- Proper LEE modelling including aerodynamics and acoustic impact, would allow the introduction of optimal maintenance strategies and would help selecting the most effective LEP solution
- Multidisciplinary approach and early selection of the LEP solution would help developing the rotor technology strategy in more effective way to obtain robust performance against erosion

Q&A

18 September 2024

Vestas