Wind Energy Systems Engineering Workshop 2024

Wind turbine flap technology development – from laboratory to full scale testing

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- with major contributions from DTU colleagues and our co-workers at SGRE led by Alejandro Gomez Gonzalez

Outline

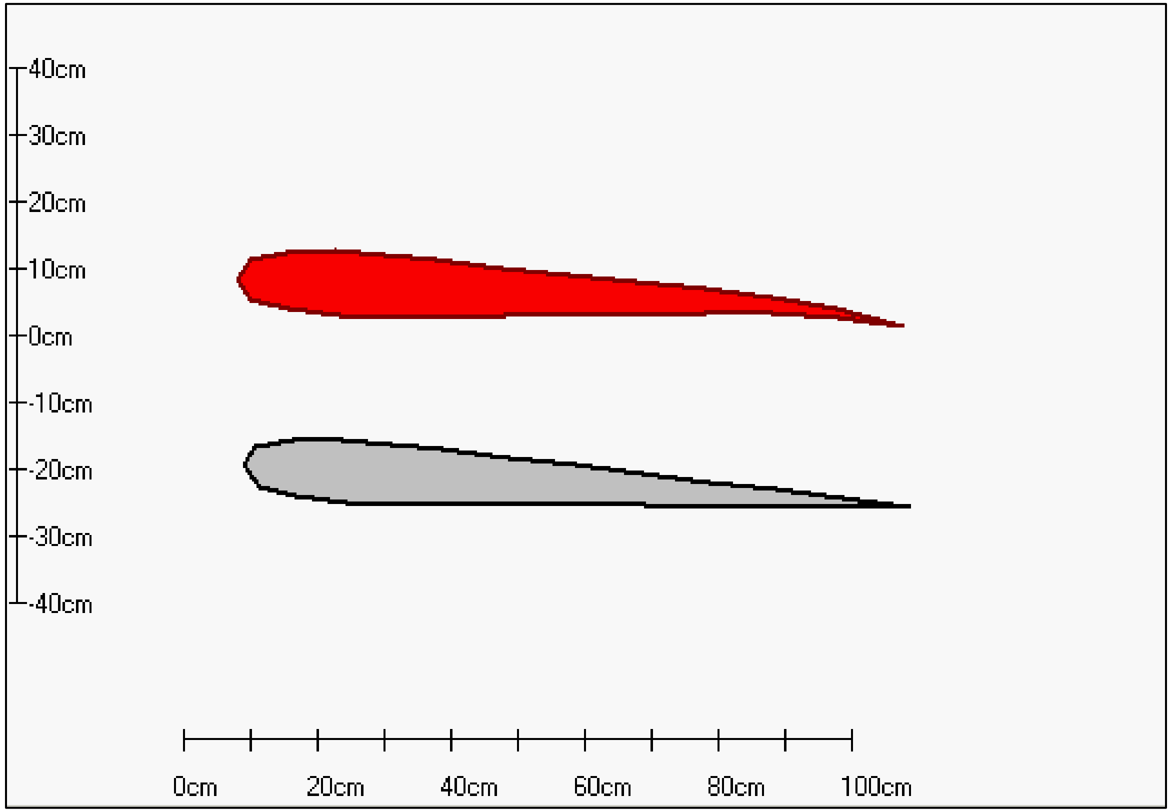
- Introduction
- Development track
- The researched flap technology and methods
- Full scale tests and measurements
- Conclusions and outlook

Introduction

Introduction

- the motivation for flap technology

Morphing trailing edge counteract disturbances from turbulent inflow



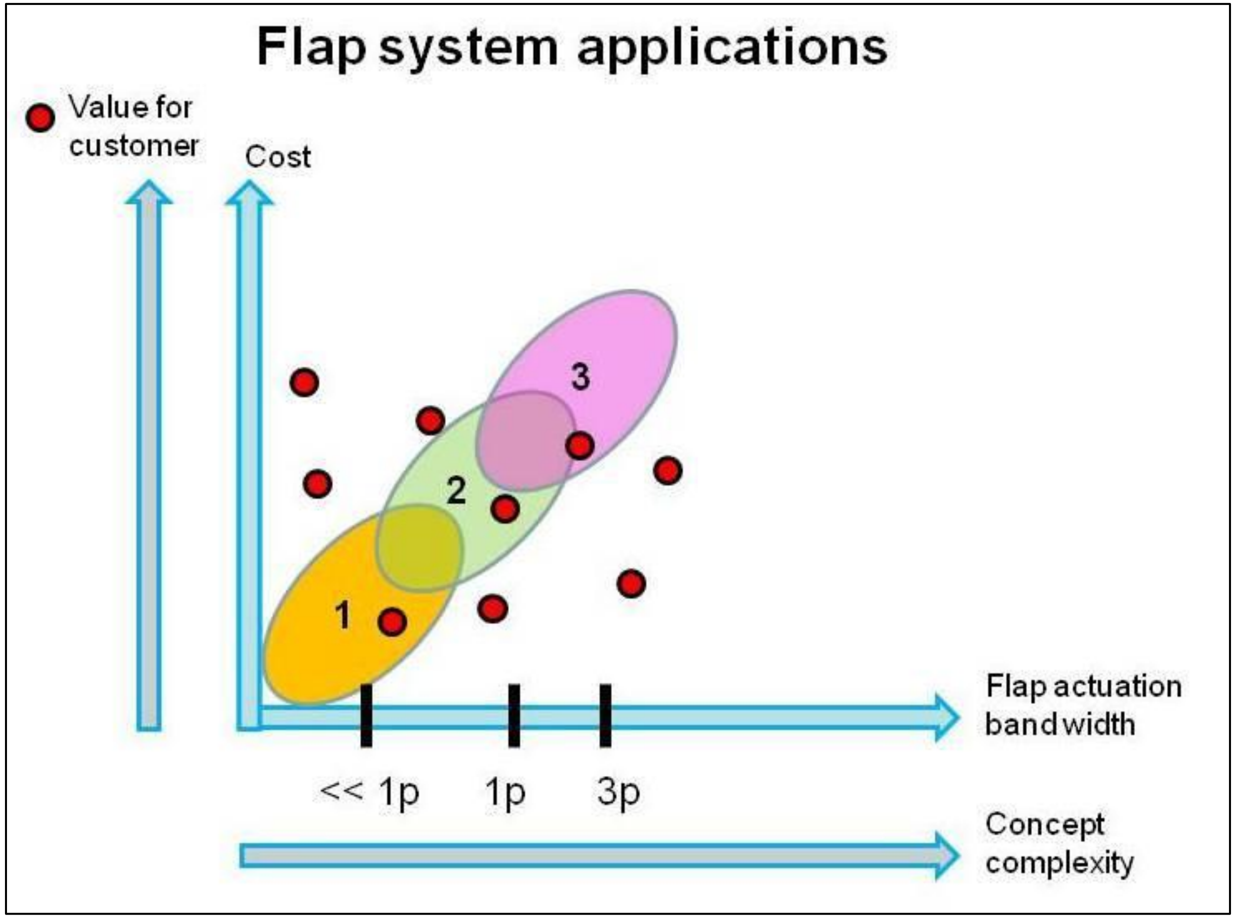
Flaps add a **third control option** to the traditional rotor speed and pitch control

Wind Turbine control

- Rotor speed
  - aero loading $f_{rs}(r) \approx (r\,\Omega)^2$
- Pitch
  - aero loading $f_p(r) \approx k\, p_{ang}$
- Flap
  - aero loading $f_{fl}(r) \approx k_{fl}\;\; fl_{ang}(r)$

But limitations in the real world

- bandwidth of the flap actuation
- amplitude limits
- non-optimal control inputs
- cost of the technology
- robustness



Strong requirements from the wind turbine industry to the technology

- ❑ robust and reliable (25 years lifetime)
- ❑ no metal parts
- ❑ no electronics
- ❑ no mechanical parts
- ❑ scalable to large blade sizes (+100m)

piezzo electric actuators in wind tunnel exp. 2007

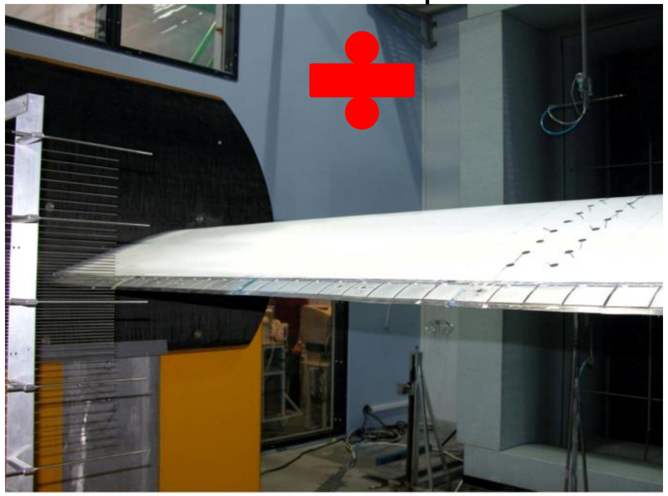


FIGURE C.2 THE TEST SECTION WITH THE TEST STAND AND THE WAKE RAKE DOWNSTREAM OF THE AIRFOIL SECTION.

Use flap technology from aircraft ?

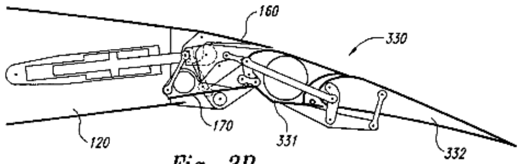


Fig. 3B

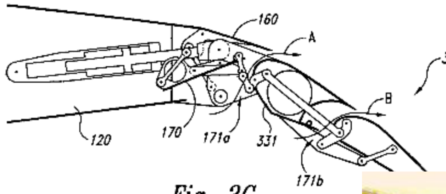
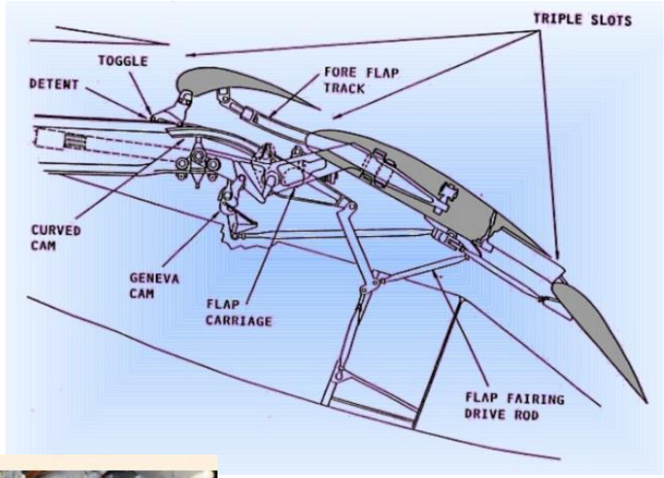


Fig. 3C

Too complex



Development track

Development of flap technology, numerical tools and experimental facilities, 2007 to 2022

Background 2007

- In the period up to 2007 a considerable work on **developing tools for analysis** of the **potentials of smart technology** and in particular flap technology had been carried out
- Overall the **analyses showed promising potentials** for load reduction and **increased AEP** were found
- However, **no real, scalable technology was developed at that time**

Development

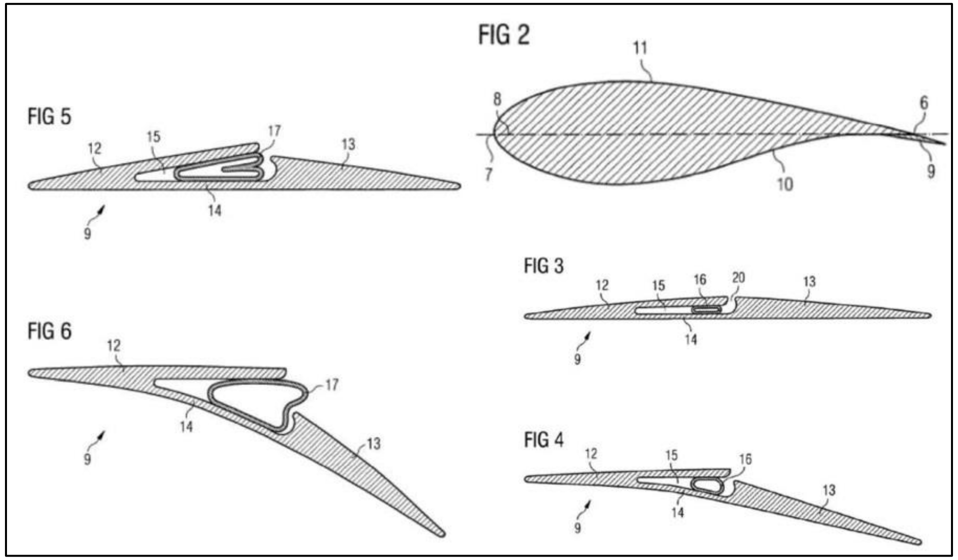
- 2007 – GAP funding — DTU (Risø) – patent filed on a concept
- 2009 – 2nd GAP funding — DTU (Risø)
- 2010-2015 Induflap (EUDP funding) — DTU, Rehau, AVN
- 2015-2018 Induflap2 (EUDP funding) — DTU, Siemens, Rehau
- 2019-2022 VIAs (EUDP funding) — SGRE, DTU, Rehau
- 2024-2027 FAR (EUDP funding) — SGRE, DTU

The researched flap technology and development activities

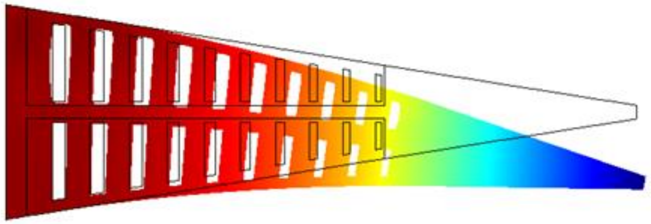
Two main flap design tracks followed
- add/on and fully integrated

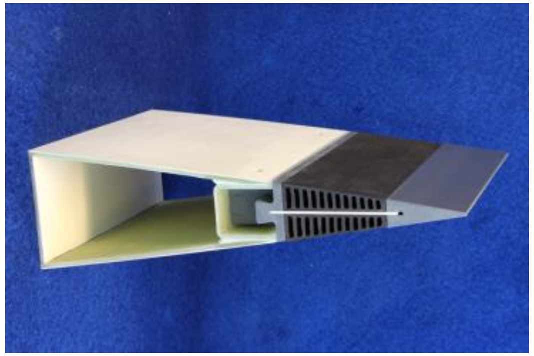
- a flap in an elastic material
- pneumatically activated
- two main concepts

add/on flap



internal voids
full morphing TE

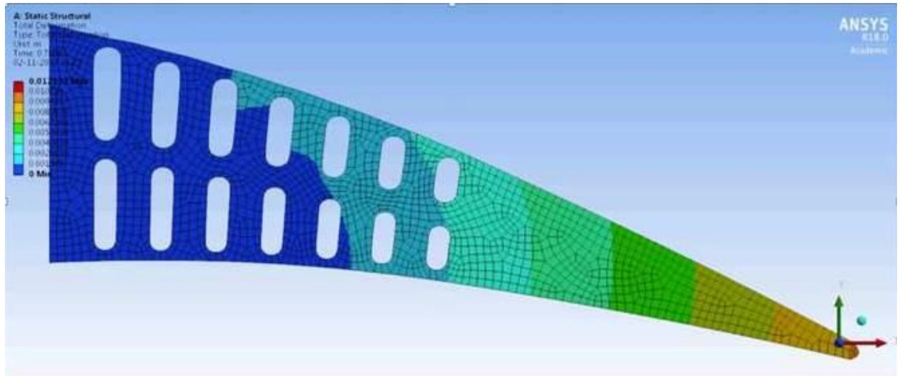


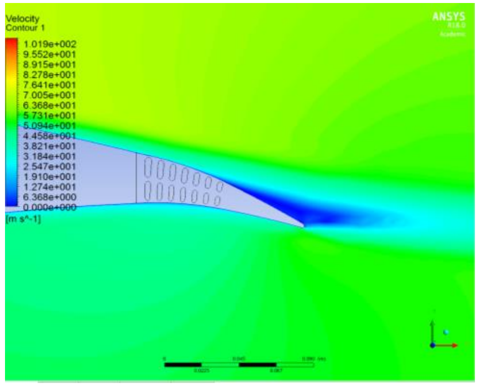


FEM – FSI optimization – the integrated flap

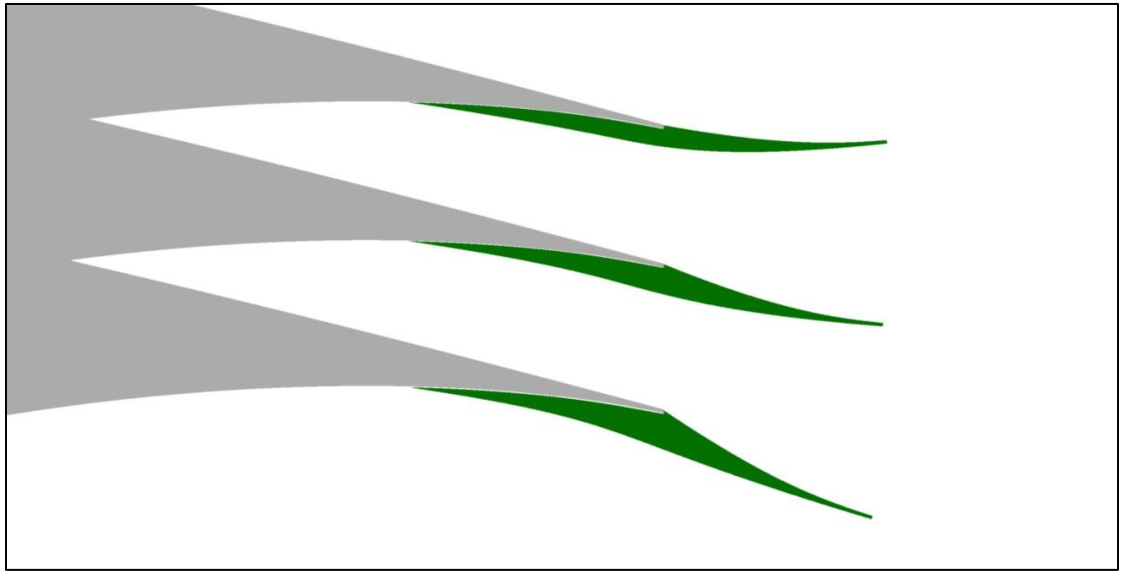
- Design variables: voids position/size
- Response: Cl, Cd, safety factor
- Optimization with Multi-Objective Genetic Algorithm (max(Cl), min(Cd), SF≥1.5

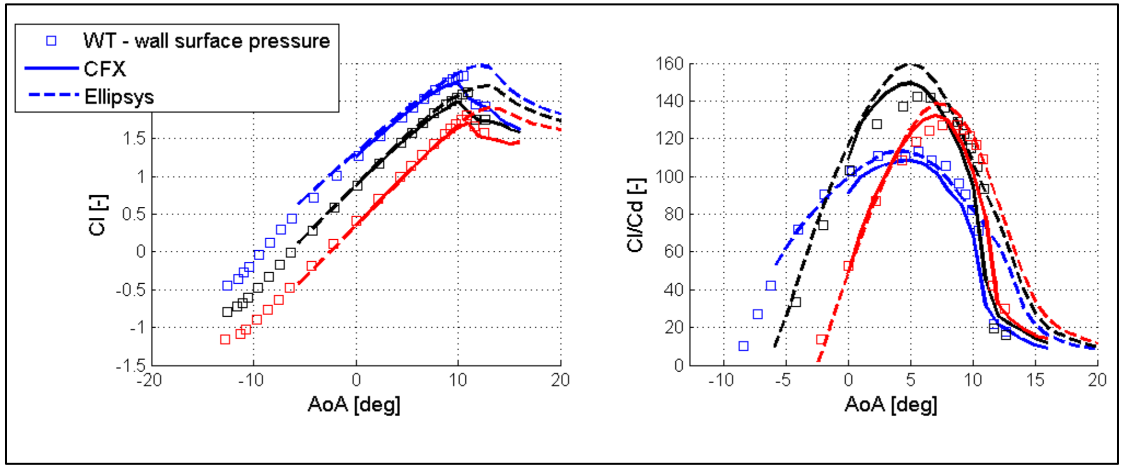
	DX [mm]	DW [mm]	DH [mm]	delta [deg]	SF [-]	δCl [-]	δ(Cl/Cd) [%]
FEM	7	3	9	7.9	2.9	-	-
FSI	6.94	2.72	8.98	6.9	3.1	0.22	-12%

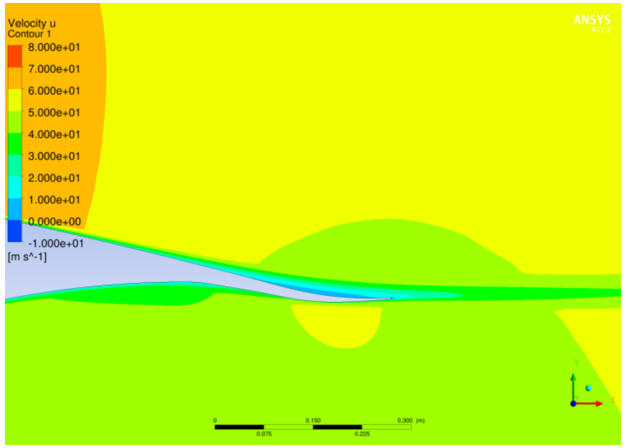


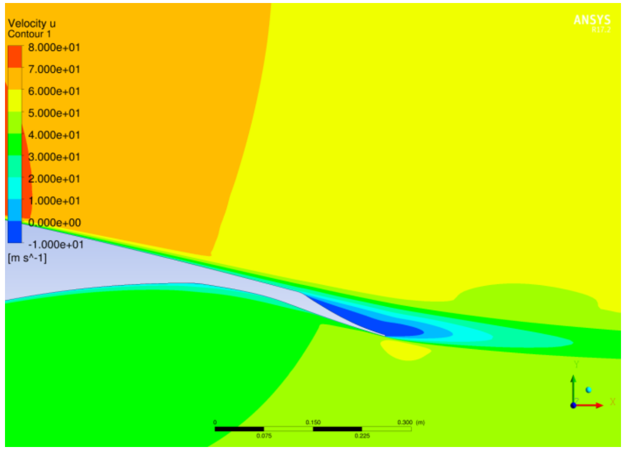


Wind tunnel tests – CFD computations – add/on flap



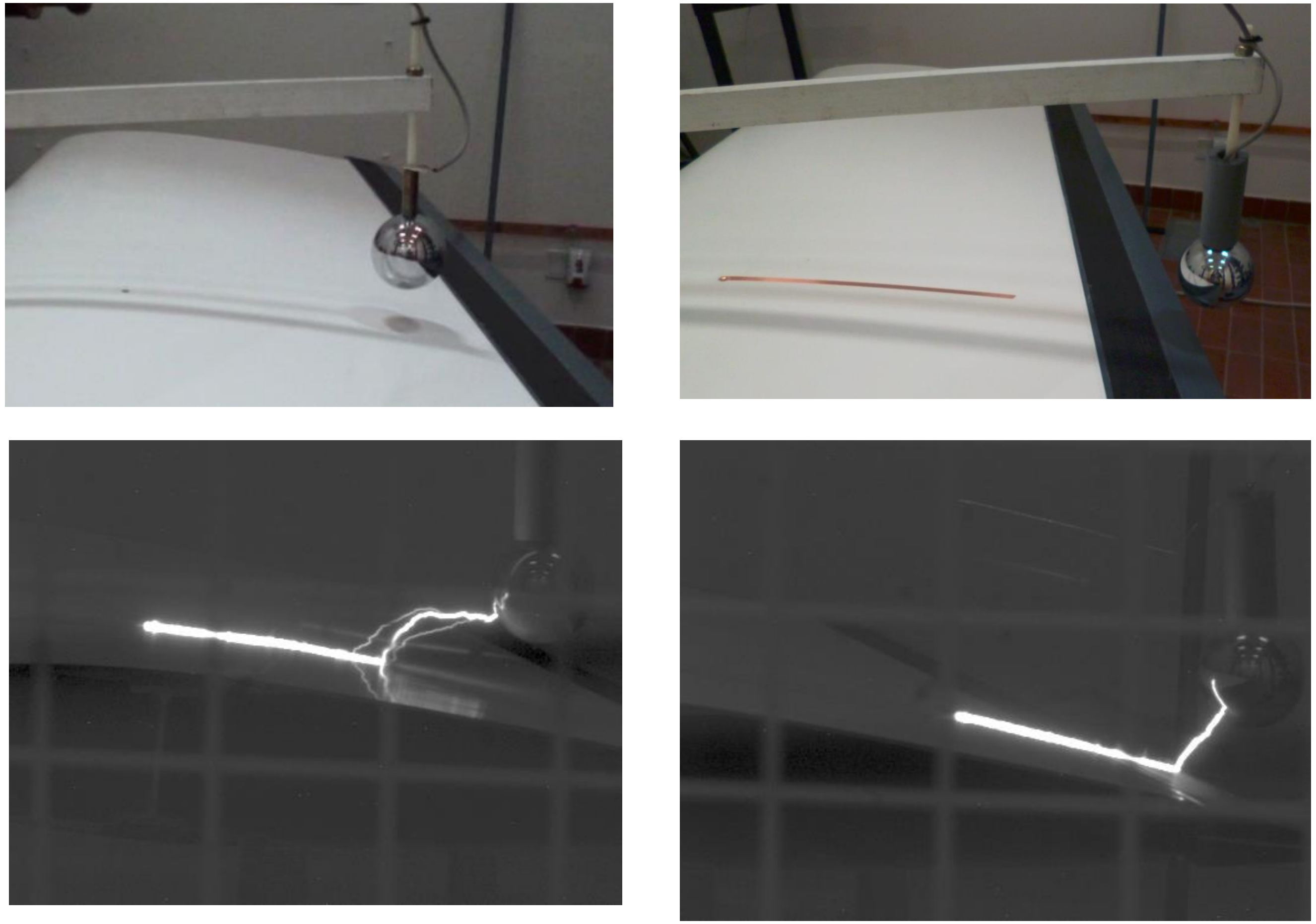






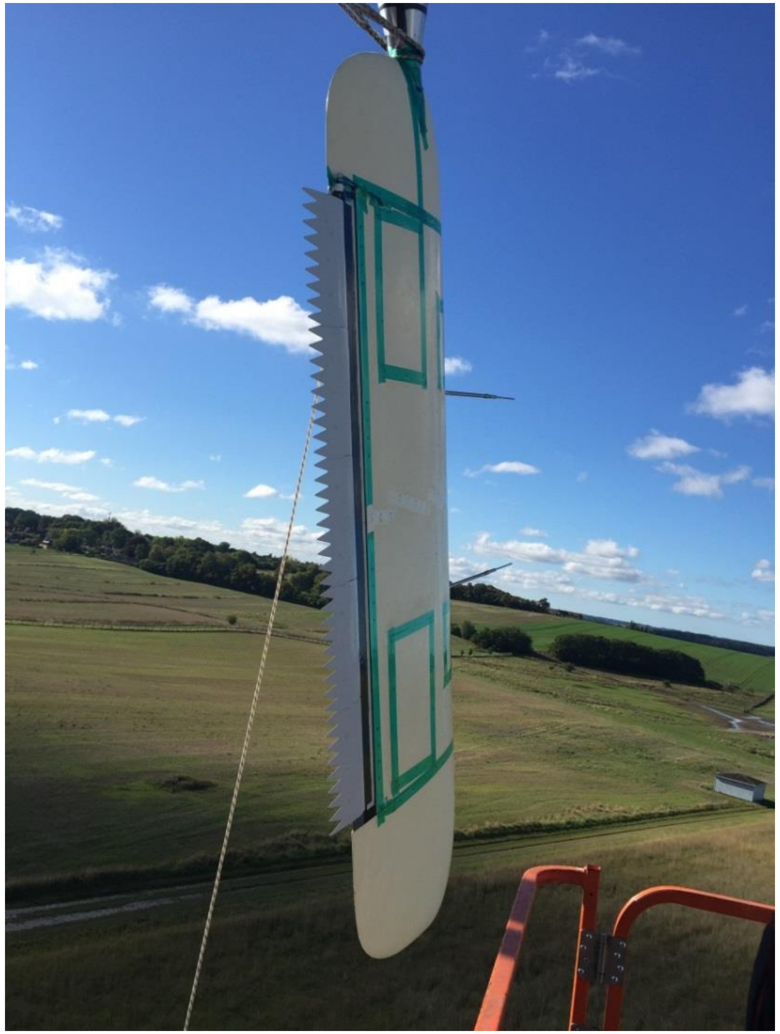
Testing for lightning damage

The Santoprene flap material showed a higher withstand voltage in tracking tests than GFRP



Flap testing on the rotating rig

Inaugurated in 2015



Full scale tests and measurements

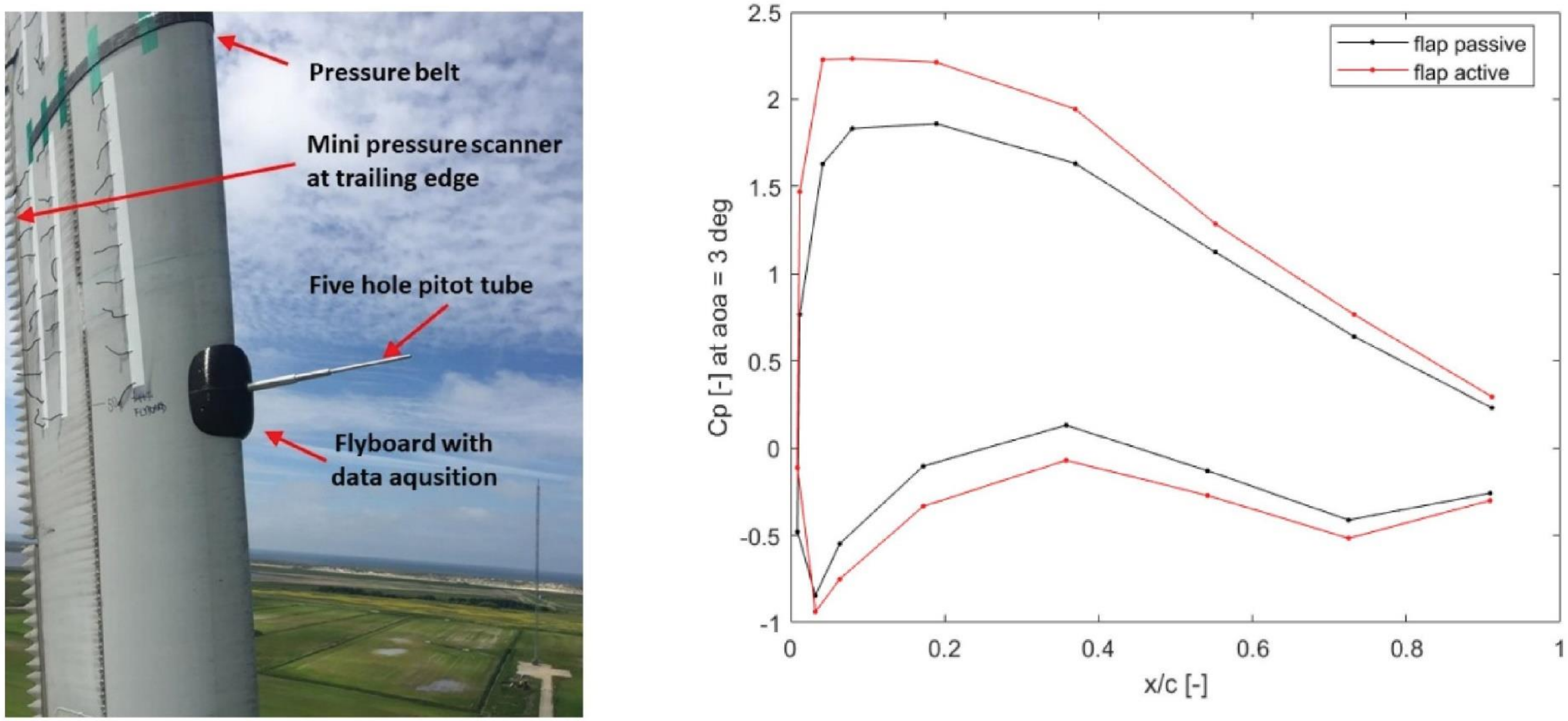
Four full scale tests carried out over 4 years

	Phase 1	Phase 2
Date	Oct 2017 - June 2018	Dec 2018 - June 2019
Turbine	SWT-4.0-130	SWT-4.0-130
AFS revision	FT008rev9	FT008rev10
AFS actuation	discretely adjustable	continuously adjustable
Validation type	on-off cycles	on-off cycles
Location on blade	47.5 - 62.5 m	42.5 - 62.5 m
Other tests	Flow visualization	None
	Phase 3	**Phase 4**
Date	June 2020 - June 2021	July 2021 - Aug 2022
Turbine	SG-4.3-120 DD	SG-4.3-120 DD
AFS revision	FT008rev10	FT008rev10
AFS actuation	continuously adjustable	continuously adjustable (faster)
Validation type	on-off cycles, cyclic 1P	on-off cycles, cyclic 1P
Location on blade	38.0 - 58.0 m	38.0 - 58.0 m
Other tests	Inflow sensor and pressure belt	Inflow sensor, pressure belt, and wake-rake

Table 1: Campaign information

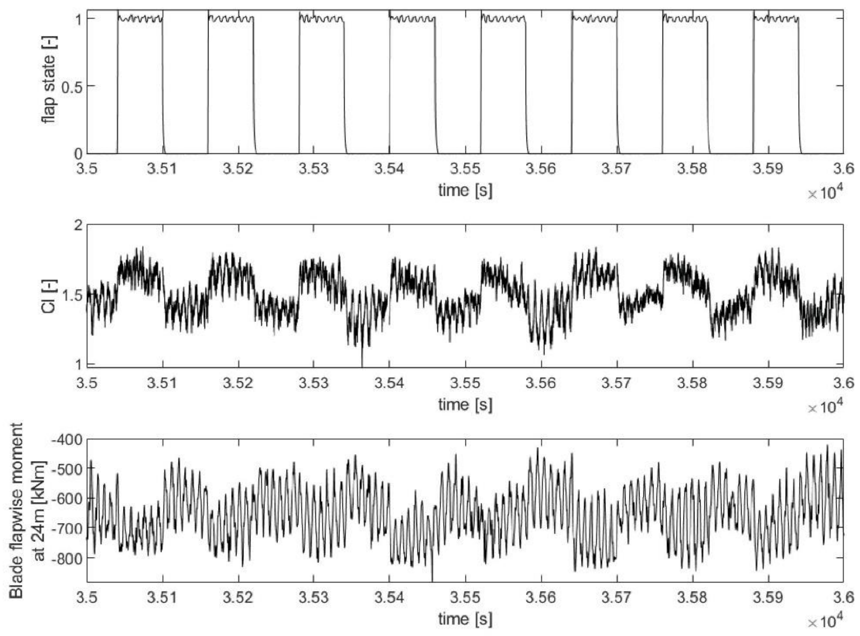
Phase 3 - test in June 2021

- measurements with a pressure belt and inflow sensor

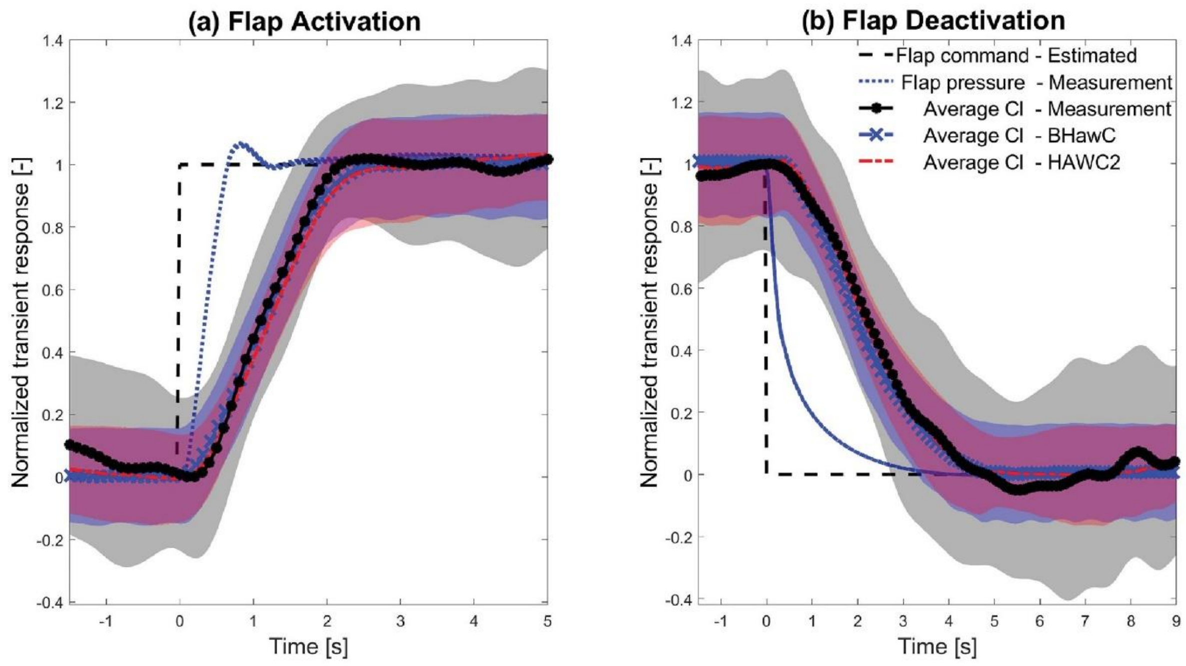


(a) Flyboard setup (b) Exemplary pressure distribution obtained from pressure belt

The measurements with the pressure belt and inflow sensor used to tune the flap response models

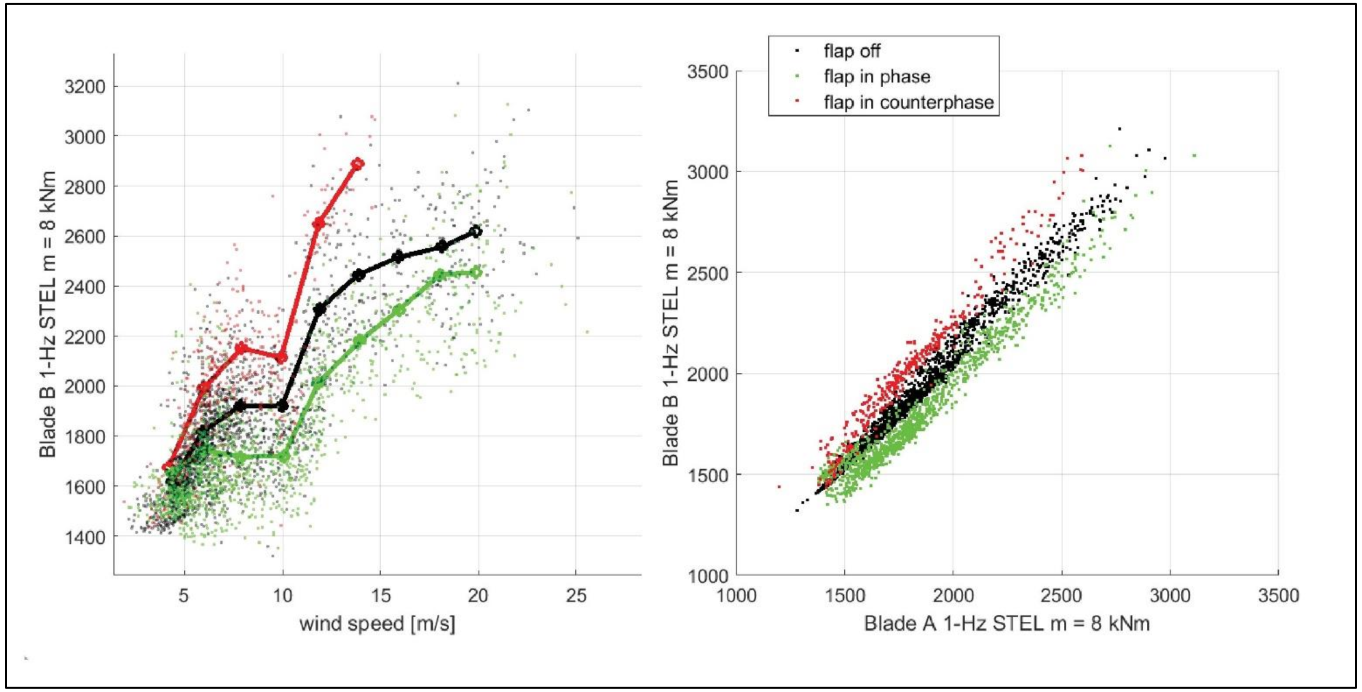


Measured aerodynamic and aeroelastic flap response for 60 sec swap on/off of the flap

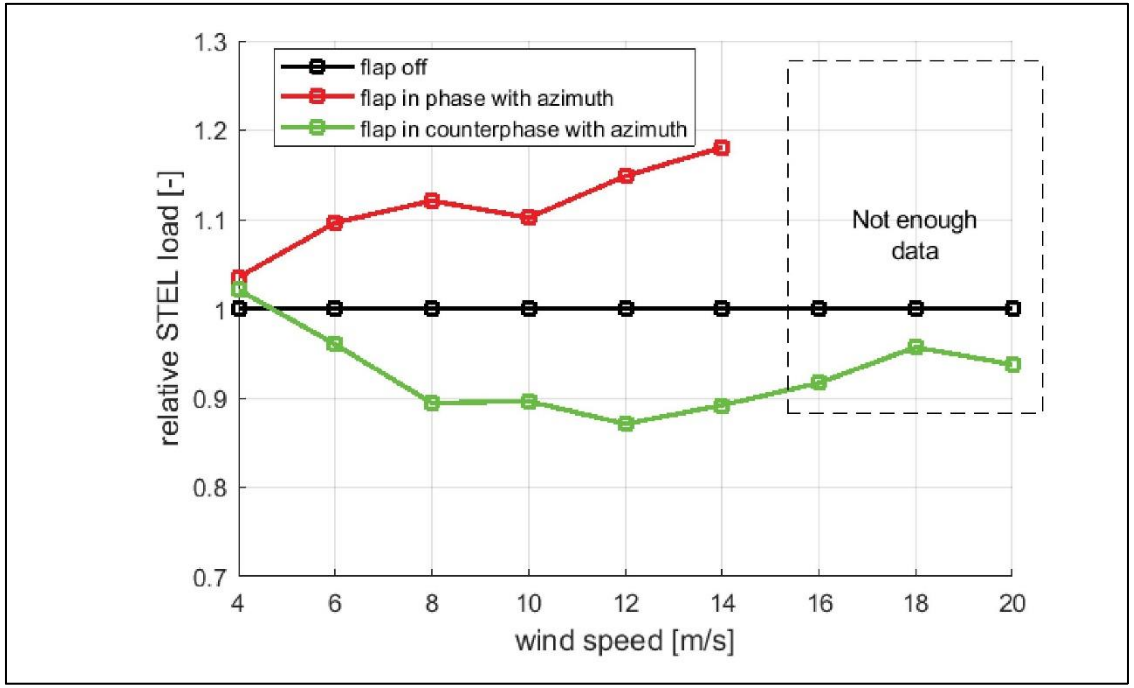


Measured data used to tune and validate the flap response models in the aeroelastic codes BhawC and HAWC2

Measured short term (10 min) equivalent loads (STEL) with cyclic control of the flaps



Left: 10-min 1Hz fatigue equivalent of root flapwise bending moment. Right: blade-2-blade fatigue comparison



Binned relative short term equivalent loads function of wind speed

Conclusions

- A complete **development line (experimental and computational)** for flap technology from prototype to full scale has been developed in cooperation with two industrial partners

- Close **collaboration between academia and industry** has been essential for the achievements and enabled by the **funding from EUDP**

- **Four full scale campaigns** carried out with control ranging from steady flaps, swap on/off to cyclic control

- **Advanced measurements with pressure belts and inflow sensors** in two of the campaigns have been essential for detailed model tuning and validation of the flap models in the aeroelastic codes

Outlook

The project **"Flow Adaptive Rotor" (FAR)** is carried out over the next 2½ years. It has three main objectives:

- The development and demonstration of **advanced load reduction methods** using **directly information from the turbulent atmospheric flow** (so-called flow-based control strategies) and active flow control devices like flaps
- The development and demonstration of **advanced and robust flow measurement systems** for rotor blades (inflow and pressure belt measurements)
- Experimental investigations with **pressure belts and inflow measurements** of **complex flow situations** which are of high relevance for the design of modern large wind turbine rotors.

Acknowledgement

The funding from **EUDP** to the projects INDUFLAP, INDUFLAP2, VIA´s and FAR is greatly acknowledged

References

- Gonzales, Alejandro Gomez, Peder B. Enevoldsen, Andrea Gamberini, Athanasios Barlas, and Helge Aa. Madsen. 2023. “Operational Experience during a Four Year Test Program of Active Flaps on a Wind Turbine Blade.” X Eccomas Thematic Conference on Smart Structures and Materials (Smart 2023), 850–65.
- Gomez Gonzalez, A., P. Enevoldsen, T.K. Barlas, and H. Aa Madsen. 2022. “Test of an Active Flap System on a 4.3 MW Wind Turbine.” Journal of Physics. Conference Series 2265 (3): 032016. https://doi.org/10.1088/1742-6596/2265/3/032016.
- Gonzalez, A. Gomez, P. Enevoldsen, T.K. Barlas, H. Aa. Madsen, and A. S. Olsen. 2020. “Consolidated Results of the Laboratory and Full Scale Field Validation of an Active Flap System.” Journal of Physics: Conference Series 1618 (5): 052024. https://doi.org/10.1088/1742-6596/1618/5/052024
- Gomez Gonzalez, Alejandro, Peder B. Enevoldsen, Athanasios Barlas, and Helge A. Madsen. 2021. “Field Test of an Active Flap System on a Full-Scale Wind Turbine.” Wind Energy Science 6 (1): 33–43. https://doi.org/10.5194/wes-6-33-2021.
- Madsen, H. Aa, T. Barlas, A. Fischer, A.S. Olsen, and A. Gomez Gonzalez. 2022. “Inflow and Pressure Measurements on a Full Scale Turbine with a Pressure Belt and a Five Hole Pitot Tube.” Journal of Physics. Conference Series 2265 (2): 022096. https://doi.org/10.1088/1742-6596/2265/2/022096.
- Barlas, T. K., and G. A.M. van Kuik. 2010. “Review of State of the Art in Smart Rotor Control Research for Wind Turbines.” Progress in Aerospace Sciences 46 (1): 1–27. https://doi.org/10.1016/j.paerosci.2009.08.002.
- Gamberini, Andrea, Thanasis Barlas, Alejandro Gomez Gonzalez, and Helge Aagaard Madsen. 2024. “Validation of Aeroelastic Dynamic Model of Active Trailing Edge Flap System Tested on a 4.3 MW Wind Turbine.” Wind Energy Science 9 (5): 1229–49. https://doi.org/10.5194/wes-9-1229-2024.
- Gamberini, Andrea. 2023. “Aeroelastic Model Field Validation and Performance State Estimation of Wind Turbine Active Flaps.” DTU Wind and Energy Systems. https://doi.org/10.11581/DTU.00000290.
- Aagaard Madsen, Helge, Athanasios Barlas, and Tom Løgstrup Andersen. 2015. “A Morphing Trailing Edge Flap System for Wind Turbine Blades.” Proceedings of the 7th Eccomas Thematic Conference on Smart Structures and Materials (Smart 2015).
- Aagaard Madsen, Helge, Athanasios Barlas, and Tom Løgstrup Andersen. 2015. “Testing of a New Morphing Trailing Edge Flap System on a Novel Outdoor Rotating Test Rig.” Scientific Proceedings. Ewea Annual Conference and Exhibition 2015, 26–30.

Thank you for your attention

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