

### Aerodynamic behavior of an airfoil under extreme wind conditions

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## Motivation

- wind in the atmosphere is turbulent  $\Rightarrow$  turbulence increases loads [1] wind turbine savety and durability guaranteed by design requirements from IEC-61400-1 norm: extreme wind conditions are accounted for [2] interaction between complex, rapid flow structures and the rotor blade is not well understood: aerodynamic behavior of an airfoil is highly dependent on dynamic variations of the angle of attack between the flow and the blade

Look at the

🕴 video here!

Aerodynamic behavior of an airfoil under extreme wind

B. Setup

- 3 airfoil angles:

- 2 chopper fre-

 $f_{CH1} = 0.04$  Hz

 $f_{CH2} = 0.4$  Hz

 $\alpha_{01} = 0^{\circ}$ 

 $\alpha_{02} = 8^{\circ}$ 

 $\alpha_{03} = 12^{\circ}$ 

quencies:

(t = 600 s)

(t = 120 s)

inflow mea-

sured with

 $u_0 = 18 \text{ ms}^{-1}$ 

cobra probe

at  $f_{S} = 2.5$  kHz

- inflow velocity

Airfoil exposed to inv. gust

Extreme operating conditions are modeled with a Mexican hat wave-let in [1]. A typical gust factor  $G_I = \frac{U_{max}}{I_T}$  of  $G_{LIEC} = 1$ 1.27 is reached at an inflow velocity  $u_0 = 20 \text{ ms}^{-1}$  [5].  $U_{max}$  is the maximum wind speed in a time interval  $\Delta T$  and  $U_I$  the mean wind speed in  $\Delta T$ .



A: regular inflow The flow is attached to the airfoil and the wind turbine operates normally. The control can account for changes in the inflow.



**B:** gust A sudden change in the inflow velocity, i. e. a **gust**, causes a sudden change in the angle of attack at the rotor blade which leads to an overshoot in lift due to dynamic stall and results in high loads. Control mechanisms do not operate fast enough to avoid this.



**Objectives** 

- introduce a setup capable of producing strong,

## Setup

### The Chopper

Strong, rapid flow perturbations are generated by a rotating bar that cuts through the inlet of the wind tunnel [4]. Turbulence is added by a regular grid

### A. Front view



# conditions

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Å

### airfoil closed test section angle wind tunnel outlet cobra probe<sup>215</sup> mm wind $u_0 = 18 \text{ms}$ <u>--</u> force gauge 1585 mm 0.5 airfoil angle 0.0 sensor mounting -0.5 airfoil:

chord length c = 9 cm

### rapid flow variations while also including turbulence - characterize the flow generated by this setup expose an airfoil to the inflow and investigate the impact of extreme flow variations on the lift response of the airfoil

Conclusions

°°° ° °

u = 12 m/s, Re = 72763

u = 13 m/s, Re = 84208 u = 15 m/s, Re = 96281

u = 17 m/s, Re = 103783

u = 20 m/s, Re = 126533

### **Results: Inflow**



## **Results: Airfoil**

The airfoil response fig. 4 shows the response of the phase-averaged, smoothed lift force  $F_L$  to the gust for the three airfoil angles, the inflow velocity and the flow pitch angle  $\psi$  $\Rightarrow$  angle of attack:  $\alpha = \alpha_0 + \psi$ the higher  $\alpha_0$ , the higher  $F_I$ lift response follows mean flow component U of the inverse gust for both chopper frequencies - small influence of  $\psi$  on  $F_L$ 

10 10

ß

'n



**Fig. 4**: Airfoil's lift response to the gust: The gust velocity (dark petrol), the gust-induced flow pitch angle  $\psi$  (light petrol) and the lift force response for the three airfoil angles  $-0.02^{\circ}$ ,  $7.8^{\circ}$  and  $12.11^{\circ}$  (red, different line types) are plotted for  $f_{CH1} = 0.04$  Hz, (a), and  $f_{CH2} = 0.4$  Hz, (b).

Main results

be constant

- the simulated  $c_L$  response is

determined by change of  $\alpha$ 

- with respect to only U,  $c_L$  would

- the simulated and measured  $c_{I}$ 

tude but differ significantly in

namic effects present

are in the same order of magni-

case of  $f_{CH1} \Rightarrow$  dynamic aerody-

- for the rapidly changing flow of

Simulated airfoil response further investigation of the influence of U and  $\psi$  on the lift response of the airfoil - interpolated surface fit of  $c_L(\alpha,$  $u_0$ ) (cf. setup) used to calculace *expected* response of  $c_L$  to gust figure 5: influence of U and  $\psi$ can be separated by calculating  $c_L$  with respect to U (- -),  $\psi$  (- -), and both U and  $\psi$  (—) for  $\alpha_{02}$ - additionally: measured  $c_L$ (—)

6.2 arDelta U /  $ms^{ extsf{-1}}$ 5.2  $\Delta \psi$  / ° 10.7 5.6 4.38 -0.02 1.23  $\Delta F_L / N$ 5.32 7.8 4.33 4.26 4.38 12.11 for  $f_{CH1}$ ,  $\Delta F_L$  is significantly smaller for  $\alpha_{01}$  than for  $\alpha_{02}$  and  $\alpha_{03}$ 

The airfoil response: numbers

 $f_{CH1}$ 

 $f_{CH2}$ 

 $\alpha_0$  / °

- the **response of the airfoil** to the gust
- appears to be mainly determined by mean velocity
- a comparison with the simulated gust response shows that dynamic effects that cannot be explained by the static lift curve are present
- in the **future**, we plan to
  - further customize the setup to also generate increasing gusts
- investigate the dynamic effects using non-instrusive flow measurements (PIV) and local aerodynamic characterization

## Sources

- [1] Frandsen S (2007) Turbulence and turbulence generated structural loading in wind turbine clusters, Phd thesis, DTU - Risø National Laboratory
- [2] IEC 61400-1-4 (2019) Wind energy generation systems Part 1: Design requirements, Report, International Electrotechnical Commission

- lift coefficient  $c_L$ 

 $\alpha_{01}$   $\alpha_{02}\alpha_{03}$ 

-10

-new setup for generation of complex, strong, turbulent flow changes for aerodynamic investigations presented: the *chopper* 

- 2 different chopper frequencies investigated
- main flow features include
- rapid strong inverse gust
- decaying turbulence within gust (cf. [4])
- changes of the mean velocity of over 5 ms<sup>-1</sup> in less than 2s ( $f_{CH1}$ ) / 0.4s ( $f_{CH2}$ )
- variation of v and w flow component during gust  $\Rightarrow$  dynamic angle of attack changes investigatable!

**Fig. 2**: Energy spectral density of the stream-wise velocity component measured with a hot-wire 21.5 cm in front of the airfoil ( $\alpha_{02} = 7.8^{\circ}$ ) for the two chopper frequencies  $f_{CH1} =$ 0.04 Hz, (a), and  $f_{CH2} = 0.4$  Hz, (b).

f / Hz

f / Hz



Fig. 3: Interpolated contour plot of the downstream mean gust velocity in the empty test section. U is normalized by the inflow velocity  $u_0$  along the test section for the two chopper frequencies  $f_{CH1} = 0.04$  Hz, (a), and  $f_{CH2} = 0.4$  Hz, (b). Red crosses mark the positions of the cobra probe, the red dashed line the position of the leading edge of the airfoil.



**Fig. 5**:Simulated and calculated lift coefficient  $c_L$  for  $\alpha_{02} = 7.8^{\circ}$  and  $f_{CH1} = 0.4$  Hz, (a), and  $f_{CH2} = 0.04$  Hz, (b), respectively:  $c_L$  is simulated with respect to the gust velocity and gust-induced flow pitch angle (purple), the gust-induced flow pitch angle only (turquois, dotted), and the velocity only (green, dashed).

[3] Choudhry A, Leknys R, Arjomandi M and Kelso R (2014) An insight into the dynamic stall lift characteristics, *Experimental Thermal and Fluid* Science **58** 

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