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# Aerodynamic behavior of an airfoil under extreme wind conditions

Ingrid Neunaber, Caroline Braud

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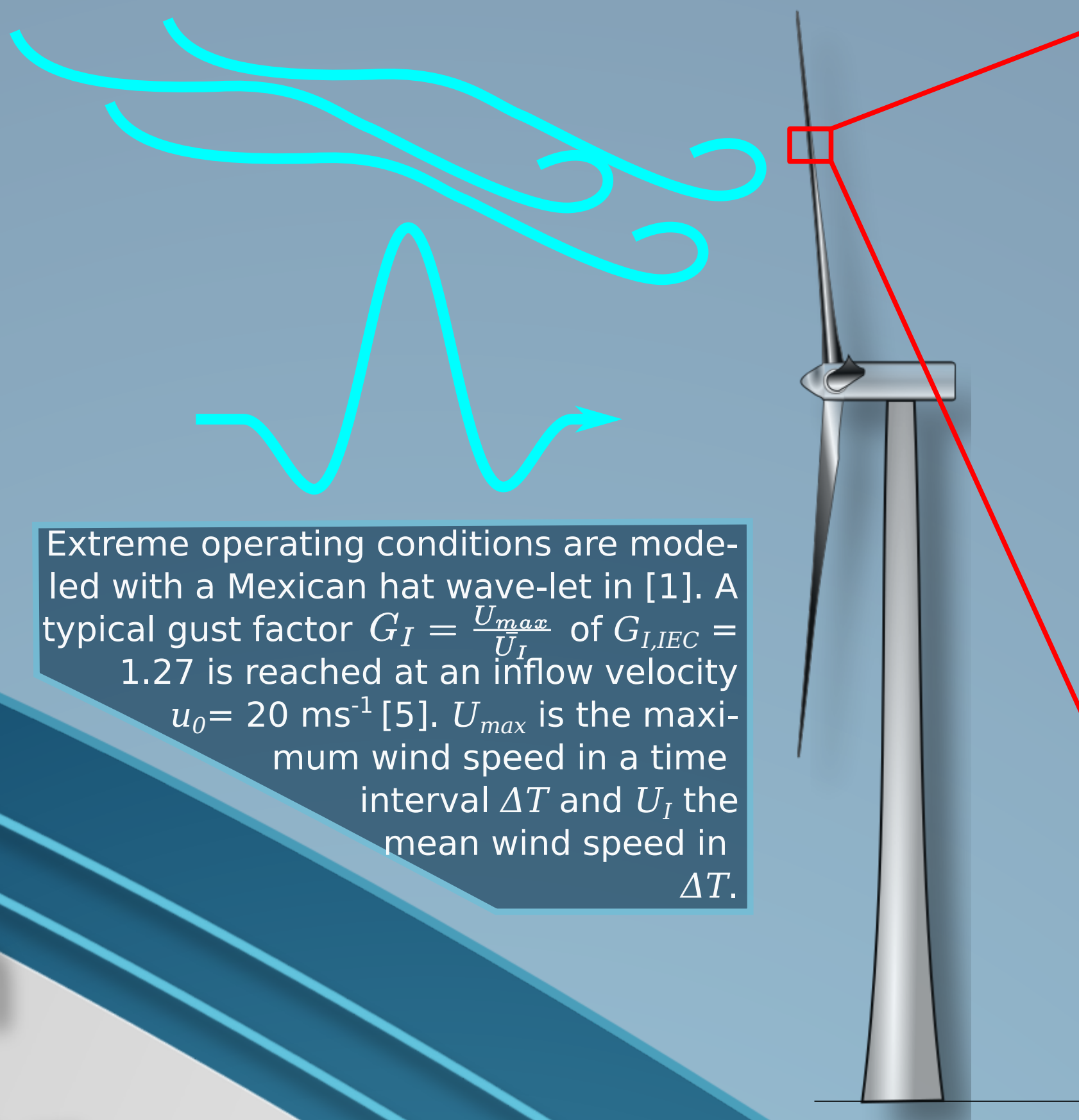
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# Motivation

- wind in the atmosphere is turbulent  $\Rightarrow$  turbulence increases loads [1]
- wind turbine safety 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



Extreme operating conditions are modeled with a Mexican hat wave-let in [1]. A typical gust factor  $G_I = \frac{U_{max}}{U_I}$  of  $G_{I,IEC} = 1.27$  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.

Example of the lift coefficient in static and dynamic inflow conditions (after [3]).

# Aerodynamic behavior of an airfoil under extreme wind conditions

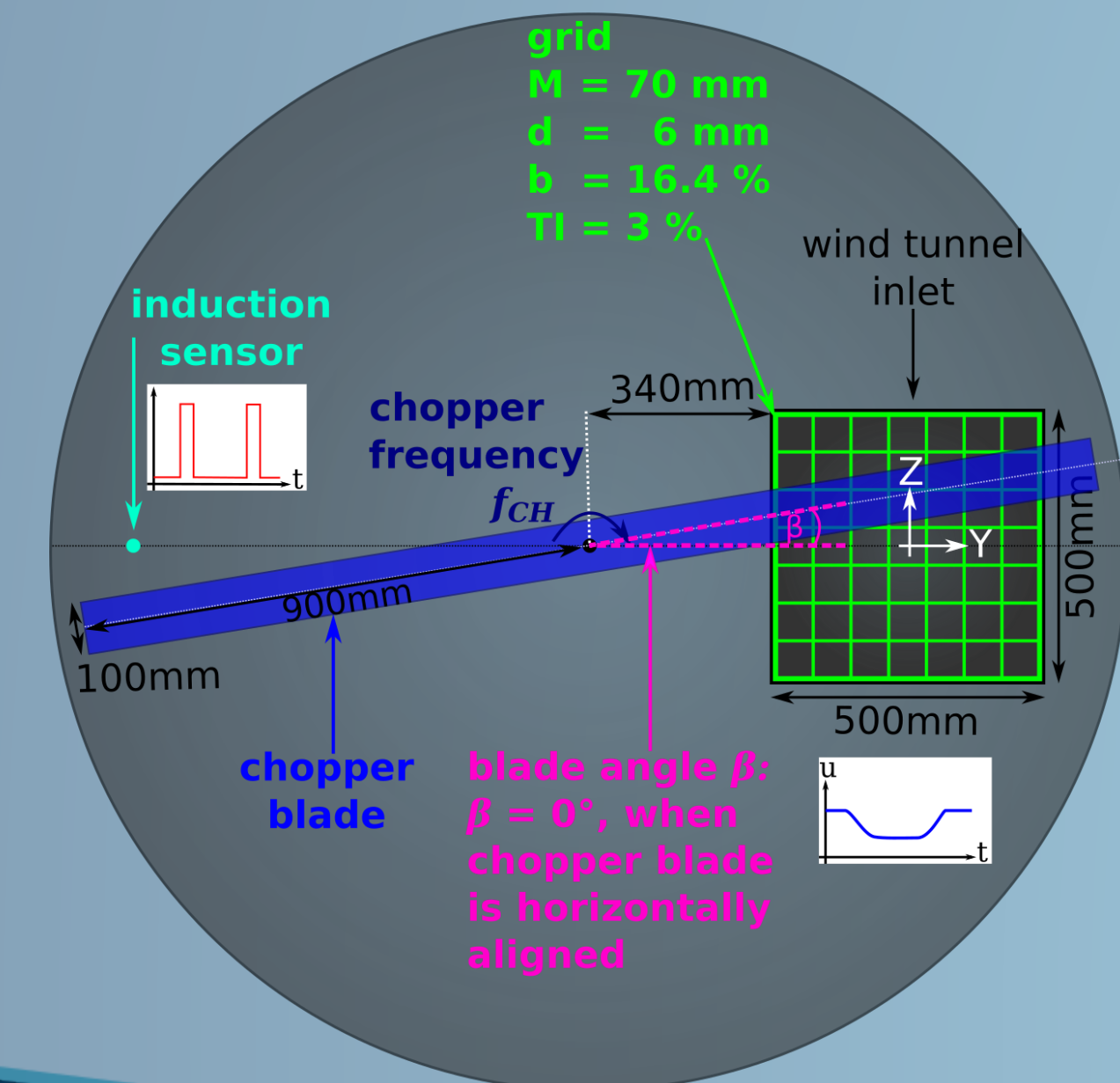
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## Setup

**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

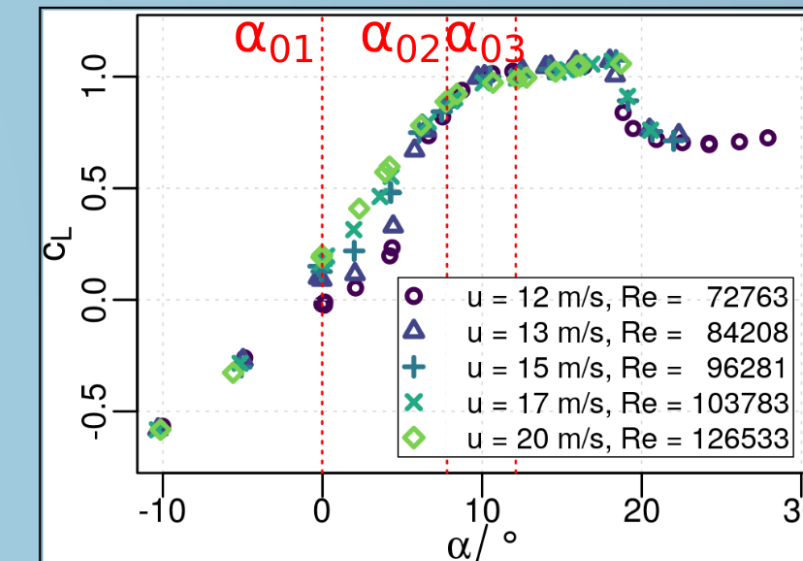
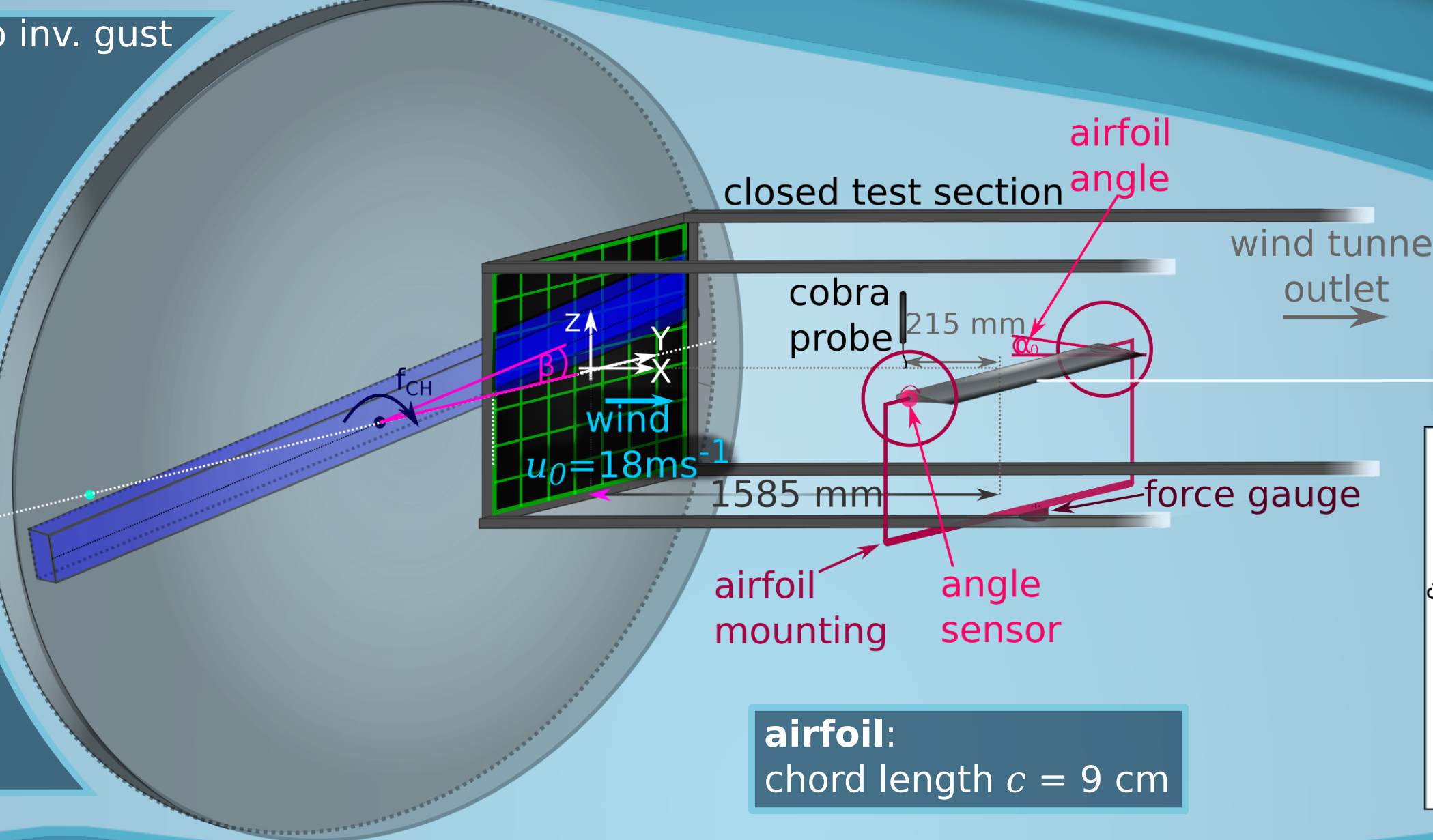


### A. Front view



### B. Setup

- Airfoil exposed to inv. gust
- 3 airfoil angles:  $\alpha_{01} = 0^\circ$ ,  $\alpha_{02} = 8^\circ$ ,  $\alpha_{03} = 12^\circ$
  - 2 chopper frequencies:  $f_{CH1} = 0.04 \text{ Hz}$  ( $t = 600 \text{ s}$ ),  $f_{CH2} = 0.4 \text{ Hz}$  ( $t = 120 \text{ s}$ )
  - inflow measured with cobra probe at  $f_s = 2.5 \text{ kHz}$
  - inflow velocity  $u_0 = 18 \text{ ms}^{-1}$

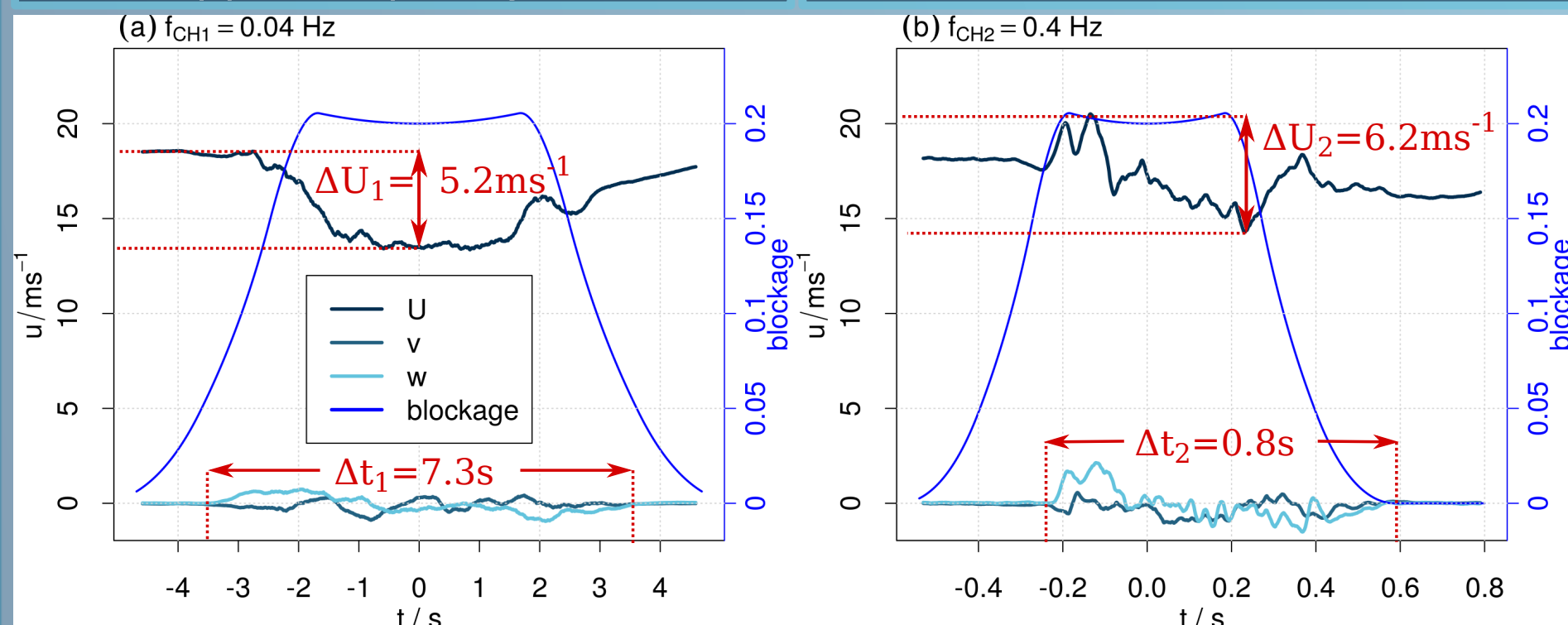


## Results: Inflow

### The inverse Gust

- large, rapid velocity deficit in  $U$  induced by chopper:  $\Delta U_1 = 5.2 \text{ ms}^{-1}$  /  $\Delta U_2 = 6.2 \text{ ms}^{-1}$
- shape of inverse gust depends on chopper frequency

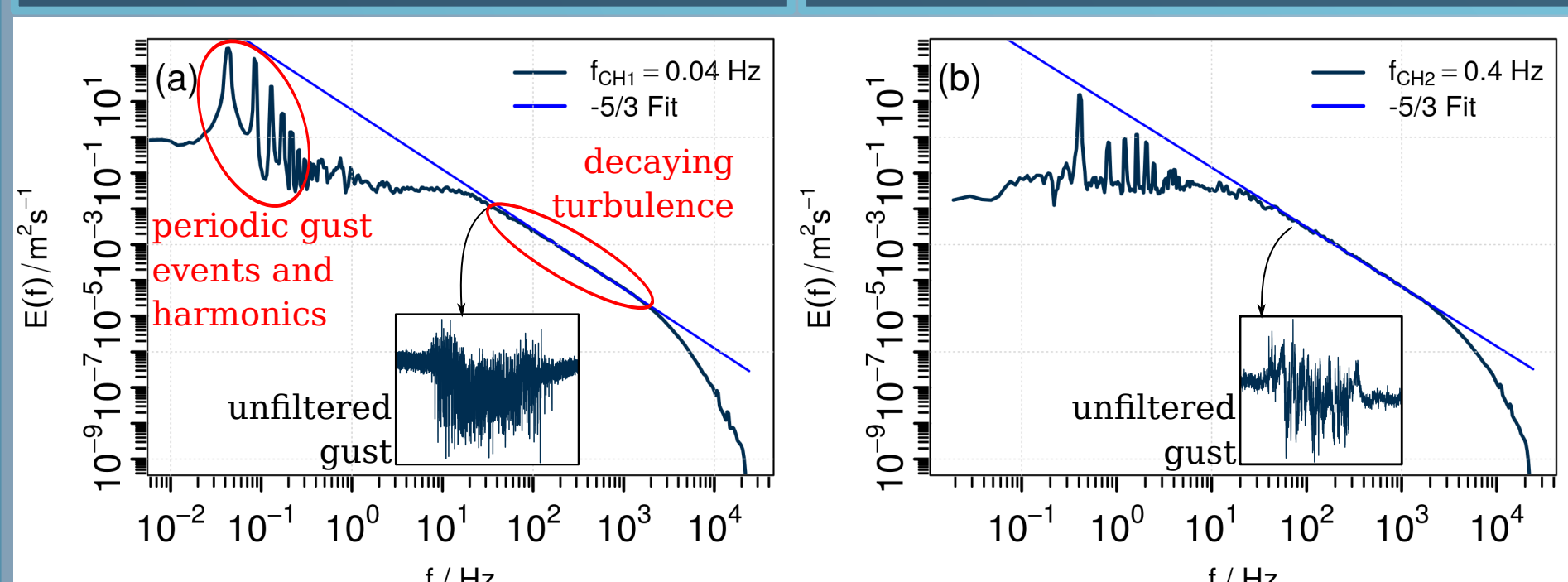
- variations in  $v$  and  $w$  component
- gust duration  $\Delta t \sim$  anti-proportional to chopper frequency:  $\Delta t \approx 7.3s(f_{CH1})$  /  $\Delta t \approx 0.8s(f_{CH2})$
- $TI \approx 17\%$  ( $f_{CH1}$ ) /  $TI \approx 13\%$  ( $f_{CH2}$ )
- $G_I \approx 1.16$  ( $f_{CH1}$ ) /  $G_I \approx 1.2$  ( $f_{CH2}$ )



### The energy spectral density

- hot-wire measurement with  $f_s = 50 \text{ kHz}$  for high resolution

- periodic gust events in time series visible as peaks with  $f_{CH}$
- turbulence in the gust decays [4]



### The mean flow field

- flow field in complete test section scanned with cobra probes
- fig.3: interpolated contour plot of

- normalized mean gust velocity
- flow inhomogeneous close to the inlet but more homogeneous downstream at airfoil position

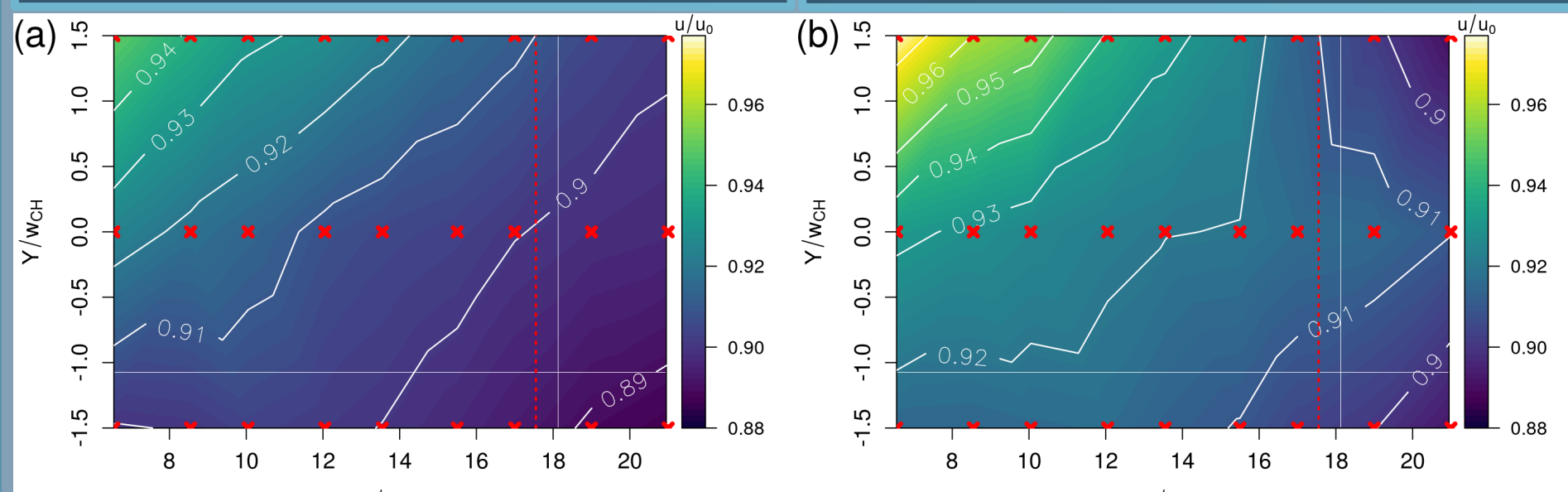
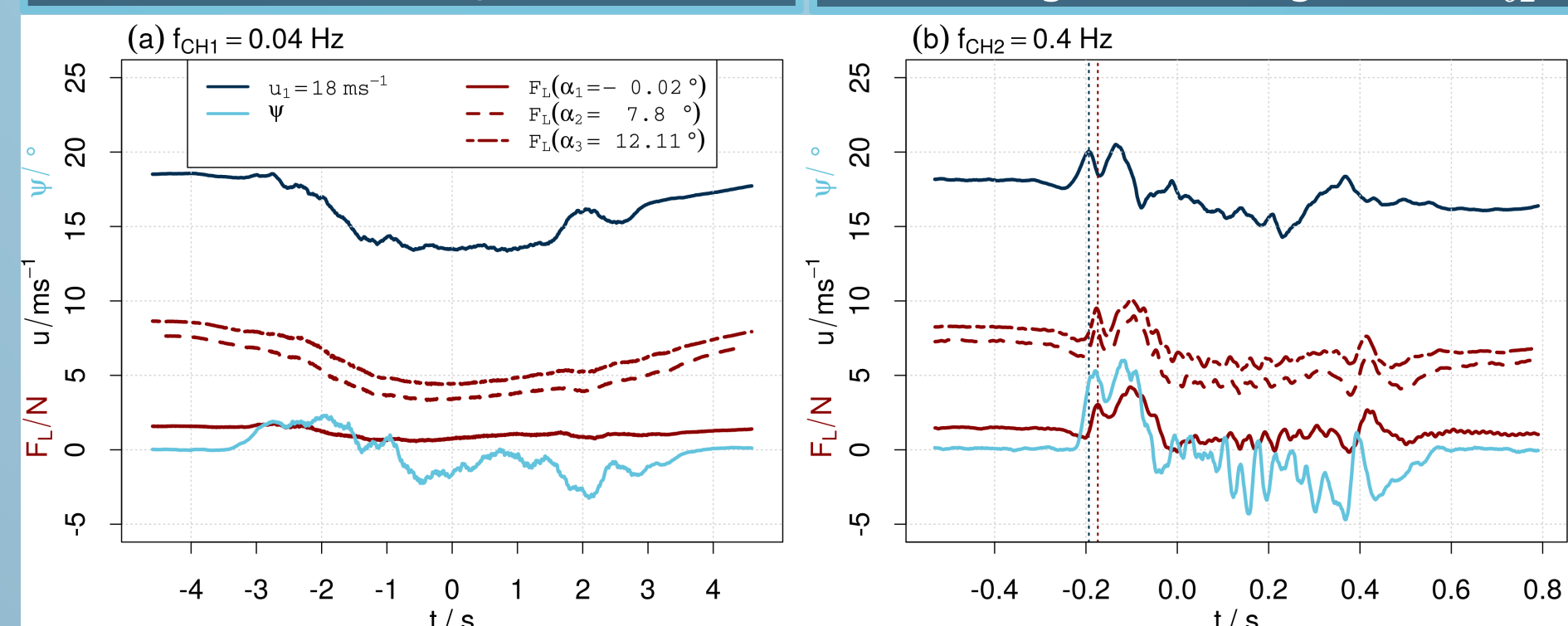


Fig. 3: Interpolated contour plot of the downstream mean gust velocity in the empty test section.  $U$  is normalized by the inflow velocity  $u_0$  along the test section for the two chopper frequencies  $f_{CH1} = 0.04 \text{ Hz}$ , (a), and  $f_{CH2} = 0.4 \text{ Hz}$ , (b). Red crosses mark the positions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

## 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  $F_L$
- lift response follows mean flow component  $U$  of the inverse gust
- small influence of  $\psi$  on  $F_L$



### 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 calculate 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  $c_L$  (-)

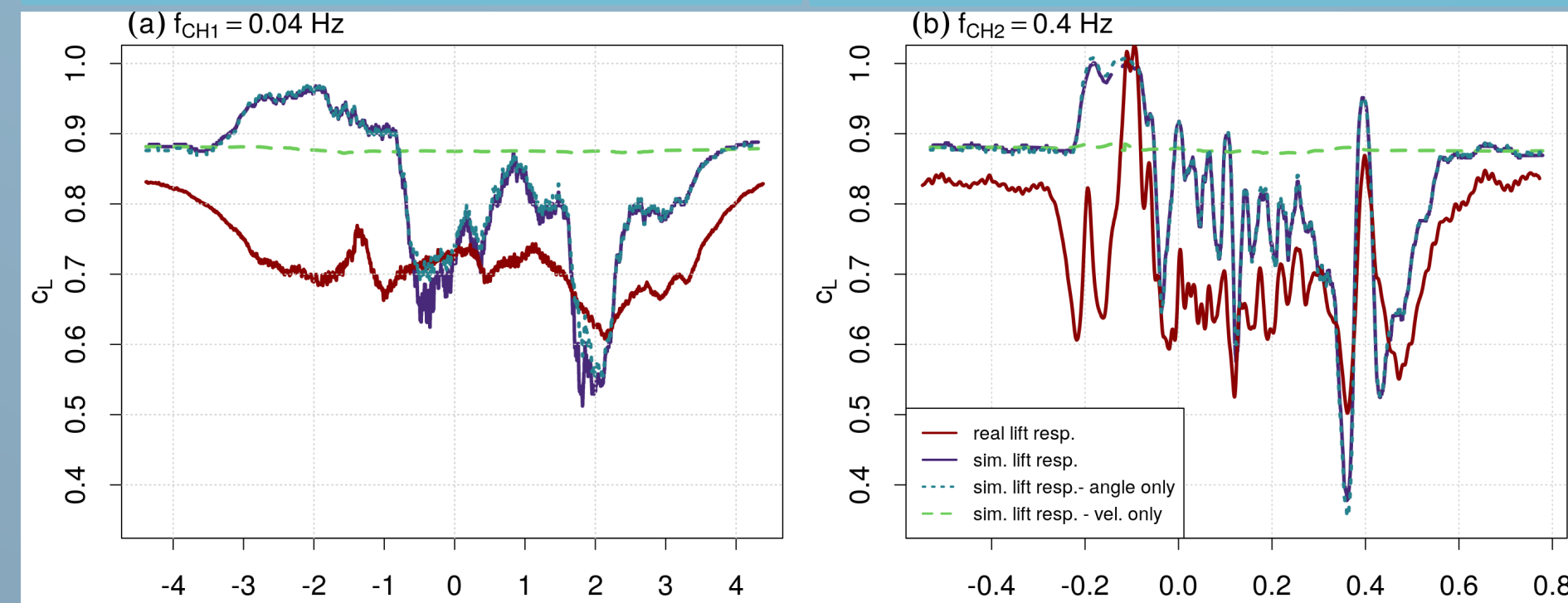


Fig. 5: Simulated and calculated lift coefficient  $c_L$  for  $\alpha_{02} = 7.8^\circ$  and  $f_{CH1} = 0.4 \text{ Hz}$ , (a), and  $f_{CH2} = 0.04 \text{ Hz}$ , (b), respectively:  $c_L$  is simulated with respect to the gust velocity and gust-induced flow pitch angle (purple), the gust-induced flow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

### The airfoil response: numbers

$\alpha_0 / ^\circ$	$f_{CH1}$	$f_{CH2}$
$\Delta U / \text{ms}^{-1}$	5.2	6.2
$\Delta \psi / ^\circ$	5.6	10.7
$\Delta F_L / N$	-0.02	1.23
	7.8	4.33
	12.11	4.26

- for  $f_{CH1}$ ,  $\Delta F_L$  is significantly smaller for  $\alpha_{01}$  than for  $\alpha_{02}$  and  $\alpha_{03}$
- for  $f_{CH2}$ ,  $\Delta F_L$  is similar for all airfoil angles but largest for  $\alpha_{02}$

## Conclusions

- 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  $5 \text{ ms}^{-1}$  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!
- 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-intrusive flow measurements (PIV) and local aerodynamic characterization

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