Towards robust control design for active flow control on wind turbine blades
first results based on numerical simulations

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Active flow control on wind turbine blades session - 29 August - 12:00-12:25
Objectives

- Robust control tools for active feedback control of the air flow on turbine blades
- Linear transfer functions representing approximately some dynamics
- Heuristic (or better) design of low order controllers
- Robust analysis of the feedback loop with respect to modeling uncertainties

- Cooperation with Caroline Braud & Emmanuel Guilmineau
- Choice of a blade profile & actuators/sensors
- Discussion about expected phenomena and objectives
- 1st tests on numerical simulations of the flow
- 2nd tests on a physical benchmark
Numerical experiments without and with constant air blowing

\[ C_\mu = 0 \]

\[ C_\mu = 0.055 \]

\[ f_{C_\mu=0} = 97.3408 \text{Hz} \]

\[ f_{C_\mu=0.055} = 102.7487 \text{Hz} \]

Increased steady-state and amplitude
Proposed linear model

- Oscillator at $f_{C\mu}$ Hz

- Actuation $C_\mu$ to $k_{C\mu}$

- Upstream air flow $V_0$

- Wake

- Air pressure at point $p$: $P_p$

- $k_{0p}$

- $k_{p}$

- $\tau_p$

- $\hat{k}_p$

- $\hat{\tau}_p$

- $V_0$ actuation

- $P_p$ air pressure at point $p$

- Blue part is repeated for each points where air pressure is measured

- $k_{C\mu}$ and $k_{0p}$ identified using steady-state values

- $\tau_p$ identified using phase shift of sinusoids at frequency $f_{C\mu}$

- $\tau_p \simeq \hat{\tau}_p$ assumed similar because almost colocated

- $k_p$ and $\hat{k}_p$ identified using amplitude of sinusoids at frequency $f_{C\mu}$

- All parameters should be considered as uncertain (modeling and identification errors)

- Model at one operating point (e.g., one pitch angle $\alpha = 0$)

- Linear parameter-varying (LPV) could be considered to go further

- Choice of 1st order transfer functions coherent with experiments by Braud&Jaunet

- Model takes into account only dynamics at low frequencies (from 0 to $f_{C\mu} \simeq 100$Hz)
Proposed control problem

- Goal 1: Make the system asymptotically stable (wake will converge to zero)
  - Could be achieved by appropriate feedback control: \( u(t) = H(y(t)) \)

- Goal 2: Keep lift at prescribed achievable level
  - Control should contain integrator

- Goal 3: Attenuate influences of \( \Delta V_0 \) and wake on lift
  - Can be evaluated by the \( H_\infty \) norm of the transfer from \( \Delta V_0 \) to \( z \)

- Properties should be robust to modeling, uncertainties, noise & saturation
Choice of a simple control structure

- $y$: sum of 2 measures, upstream + close to wake  
  $$y = P_{131683} + P_{168671}$$

- upstream: contains mostly information about $\Delta V_0$
- downstream: contains mostly information about wake

- PI control  
  $$u(t) = K_P \hat{\epsilon}(t) + K_I \int_0^\infty \hat{\epsilon}(\tau) d\tau$$

- with Anti-Windup  
  $$\hat{\epsilon} = \epsilon - \frac{k_a}{\tau_a s + 1}(C_\mu - u)$$

- Hand-tuned parameters  
  $$K_P = 10^{-2}, K_I = -200, k_a = 10, \tau_a = 10^{-5}$$
Open loop simulations with linear model

- **OFF/ON actuator** \( C_\mu(t \in [0, 0.25]) = 0 \) \( C_\mu(t \in [0.25, 0.5]) = 0.055 \)
- **\( \Delta V_0 \)** periodic positive and negative steps (5\% variation of \( V_0 \))

\[
P_p(t) \quad y(t) \quad \text{wake}
\]
Closed loop simulations with linear model

- Requested 'lift' \( y_c(t \in [0, 0.25]) = -1.04 \quad y_c(t \in [0.25, 0.5]) = -1.46 \)
- Same \( \Delta V_0 \), noise=0

\[
\begin{align*}
\Delta V_0 &= 0 \\
u(t) &\quad y(t) &\quad \text{wake}
\end{align*}
\]
Closed loop simulations with linear model

- Requested 'lift' \( y_c(t \in [0, 0.25]) = -1.04 \) \( y_c(t \in [0.25, 0.5]) = -1.46 \)
- Same \( \Delta V_0 \), noise \( \neq 0 \)

\[
\begin{align*}
\text{u(t)} & \\
\text{y(t)} & \\
\text{wake} &
\end{align*}
\]
Robustness of closed-loop

\( \gamma = H_\infty \) performance of transfer \( \Delta V_0 \rightarrow z \)

- (A) If no uncertainties on parameters
- (B) Constant uncertainties: 10% on \( \tau \), 5% on \( f_{C\mu} \), 20% on \( k_{C\mu} \)
- (C) Time varying uncertainties: 10% on \( \tau \), 5% on \( f_{C\mu} \), 20% on \( k_{C\mu} \)

\[ V_0 \]

upstream air flow

actuation \( C_\mu \)

\[ k_{C\mu} \]

Oscillator at \( f_{C\mu} \) Hz

wake

\[ \frac{k}{\tau s + 1} \]

\[ \frac{k}{\tau s + 1} \]

weighted sum of pressures

\[ W_1 \]

\[ W_2(s) \]

\[ z \]

performance

\[ P \]

vector of measured air pressures at several points

\[ \epsilon \]

error

\[ y_c \]

requested value

\[ u \]

control signal

\[ k_0 \]

\[ P \]

\[ 0.055 \]

\[ H \]

Values computed using R-Romuloc toolbox

\[ \gamma(A) = 0.4153 \quad , \quad \gamma(B) \leq 0.4279 \quad , \quad \gamma(C) \leq 0.4563 \]

- Values computed using R-Romuloc toolbox
Conclusions

▲ Simple control strategy based on existing actuators/sensors
▲ Data obtained from numerical experiments
▲ Encouraging simulations and robustness assessments

▼ Need for validation on closed-loop numerical experiments
▼ Need for validation on physical experiments
▼ Physical sensors may not be efficient enough (noise + ?)
▼ Actuators may not be efficient enough (saturation + PWM + ?)

■ Easily hand-tuned control
  ● Structured control tools (Hifoo, hinfstruct,...) could do better

■ Current study for one operating point ($\alpha = 0$, one wind speed, etc.)
  ● Need for parameter-varying control, or adaptive control