Frequency-weighted MPC of Trailing Edge Flaps. Tests on a V27.

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Outline

• Trailing Edge Flaps
  - Background
  - Motivation

• Model Predictive Control
  - Design Model (Blade model)
  - Frequency weighted control

• Results
  - Simulations
  - Field tests

• Conclusions
Why use Trailing Edge Flaps?

Wind turbulence
Wind shear
Wake of another turbine
Tower shadow
Yaw misalignment
Wind slope

Loads in all parts of the wind turbine
Why use Trailing Edge Flaps?

Today’s solution: Individual Pitch Control (IPC)
• Each blade can pitch individually
• Power control and load reduction
• But slow actuation due to the inertia of the blade (mass > 6 tons)

Up to 28% load reduction [1]

Trailing Edge Flaps (TEF)
• Controls the flow locally (more efficient)
• High actuation frequency

Up to 60% load reduction [2]

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System – V27

V27 Vestas turbine:
- located at Risø DTU
- 27 m diameter
- 225 kW nominal power
- 3 independent flaps on one blade
- extra sensors
Design Model – Blade Model

- A modal model is used: the blade is modelled by its first $N_m$ mode shapes

\[ u_z(x,t) = \sum_{i=1}^{N_m} g_i(t)u_z^i(t) \]
\[ u_y(x,t) = \sum_{i=1}^{N_m} g_i(t)u_y^i(t) \]

- Newton’s 2\textsuperscript{nd} law is applied for each mode shape

\[ M_{g_i}\ddot{g}_i + C_{g_i}\dot{g}_i + K_{g_i}g_i = F_{g_i}(g_j, \dot{g}_j, \beta, V, \omega, \varphi...) \]
Design Model – Blade Model

\[ M_{g_i} \ddot{g}_i + C_{g_i} \dot{g}_i + K_{g_i} g_i = F_{g_i} (g_j, \dot{g}_j, \beta, V, \varphi...) \]

\[
\begin{aligned}
X_{k+1} &= AX_k + B U_k + G V_k \\
Y_k &= C X_k \\
Z_k &= C_m X_k
\end{aligned}
\]

flap moment
Design Model – Blade Model

![Graph of Normalised gain vs. Normalised frequency](image)

![Graph of Phase vs. Normalised frequency](image)

Legend:
- **Blue**: Flex - Stiff turbine
- **Red**: Flex - Flexible turbine
- **Black**: Linear model
MPC – a frequency problem

Time series and PSD of the blade root flap moment

Blade root flap moment PSD [-]

Frequency [-]

0 20 40 60 80 100 120 140 160 180 200

Time [s]
MPC – Cost on the outputs

System

\[
\begin{aligned}
X_{k+1} &= AX_k + BU_k + GV_k \\
Y_k &= CX_k
\end{aligned}
\]

Predicted outputs

\[
\begin{bmatrix}
Y_1 \\
Y_2 \\
\vdots \\
Y_N
\end{bmatrix} =
\begin{bmatrix}
CA \\
CA^2 \\
\vdots \\
CA^N
\end{bmatrix} X_0 +
\begin{bmatrix}
CB & 0 & \cdots & 0 \\
CAB & CB & 0 & \vdots \\
\vdots & \ddots & CB & 0 \\
CA^{N-1}B & \cdots & CB
\end{bmatrix}
\begin{bmatrix}
U_0 \\
U_1 \\
\vdots \\
U_{N-1}
\end{bmatrix} +
\begin{bmatrix}
CG & 0 & \cdots & 0 \\
CAG & CG & 0 & \vdots \\
\vdots & \ddots & CG & 0 \\
CA^{N-1}G & \cdots & CG
\end{bmatrix}
\begin{bmatrix}
V_0 \\
V_1 \\
\vdots \\
V_{N-1}
\end{bmatrix}
\]

\[Y = \Phi X_0 + \Gamma U + \Gamma_d V\]

Cost on the predicted outputs

\[\Phi_y = \frac{1}{2} (Y - R)'Q_y (Y - R)\]
Frequency weighted MPC – Cost on filtered outputs

Blade root flap moment PSD [-]

1P 2P 3P 1st flapwise 1st edgewise

Frequency [-]

output [-]

output set point filtered output

Time [-]
Frequency weighted MPC – Cost on filtered outputs

Output filter
\[
\begin{aligned}
X_{k+1}^y &= A_y X_k^y + B_y Y_k \\
\tilde{Y}_k &= C_y X_k^y + D_y Y_k
\end{aligned}
\]

Predicted filtered outputs
\[
\begin{bmatrix}
\tilde{Y}_1 \\
\tilde{Y}_2 \\
\vdots \\
\tilde{Y}_N
\end{bmatrix} =
\begin{bmatrix}
C_y \\
C_y A_y \\
\vdots \\
C_y A_y^{N-1}
\end{bmatrix}
X_0^y +
\begin{bmatrix}
D_y & 0 & \cdots & 0 \\
C_y B_y & D_y & 0 & \vdots \\
\vdots & \ddots & \ddots & D_y \\
C_y A_y^{N-2} B_y & \cdots & C_y B_y & D_y
\end{bmatrix}
\begin{bmatrix}
Y_1 \\
Y_2 \\
\vdots \\
Y_N
\end{bmatrix}
\]

\[\tilde{Y} = \Phi_y X_0^y + \Gamma_y Y \quad \text{and} \quad Y = \Phi X_0 + \Gamma U + \Gamma_d V\]

Cost on the predicted filtered outputs
\[
\Phi_{\tilde{Y}} = \frac{1}{2} (\tilde{Y} - R)' Q_{\tilde{Y}} (\tilde{Y} - R) = \frac{1}{2} U' H U + g' U + c
\]
Frequency weighted MPC – Cost on zero-phase filtered outputs
MPC – Frequency weighted control – Cost on ZPF outputs

\[ \Phi_{\tilde{Y}} = \frac{1}{2} (\tilde{Y} - R)' Q_{\tilde{Y}} (\tilde{Y} - R) = \ldots = \frac{1}{2} U' H U + g' U + c \]
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Simulation code – Flex5

- Flex5, developed by DTU Mechanical Engineering.
- Blade Element Momentum (BEM) model
- Blades and tower are flexible
- Engineering models:
  - Tip correction
  - Dynamic wake
- Dynamic stall model from Risø DTU [3]
- Quadratic Program solver from the university of Leuven, Belgium [4]

Simulations

![Graph showing normalized flap BRM spectral density](image)

![Graph showing normalized TEF angle spectral density](image)

Legend:
- Red: Baseline
- Green: Low order filter
- Blue: High order filter
Simulations – zero-phase filters

![Graph showing normalized flap BRM spectral density and normalized TEF angle spectral density for different filters.]
Field tests

- MPC with costs on zero-phase filtered inputs and outputs
- Focus on the 1P and 2P loads
- No pitch position sensor
- Only one working trailing edge flap

- 38 minute test including:
  - 10 2-minute tests with active trailing edge flaps
  - 9 2-minute tests with fixed trailing edge flaps
Field tests

![Graph showing normalized flap BRM spectral density and TEF angle spectral density over a normalized frequency range of 0.5 to 5.]

- Blue line: Active trailing edge flaps
- Red line: Trailing edge flaps fixed
Field tests

In average: 13.8% load reduction
Field tests – system identification

System identification from Thanasis Barlas, based on TU Delft work.
Conclusions

- A model predictive control has been designed in order to alleviate blade root loads with emphasize on given load frequencies.

- Costs on zero-phase filtered inputs and output increase the performance of the MPC.

- Field test showed load reduction: more tests needed to confirm the fatigue load reduction!

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Thank you for your attention