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PERFORMANCE COMPARISON OF CONTROL SCHEMES FOR VARIABLE-SPEED PITCH-REGULATED WIND TURBINES

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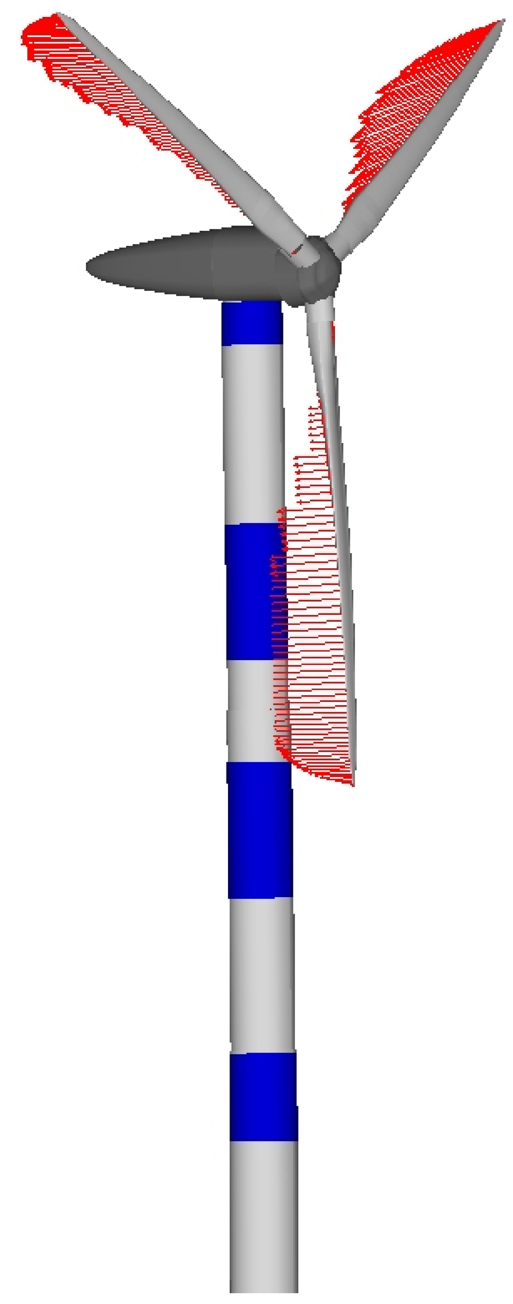


GOAL

Compare performance of different control laws:

- Optimized wind-scheduled PID
- Wind-scheduled LQR based on linearization of reference model
- Non-linear model adaptive controller based on Direct Transcription (DT)
- Reference Augmented Predictive Control (RAPC)

WIND TURBINE MODEL

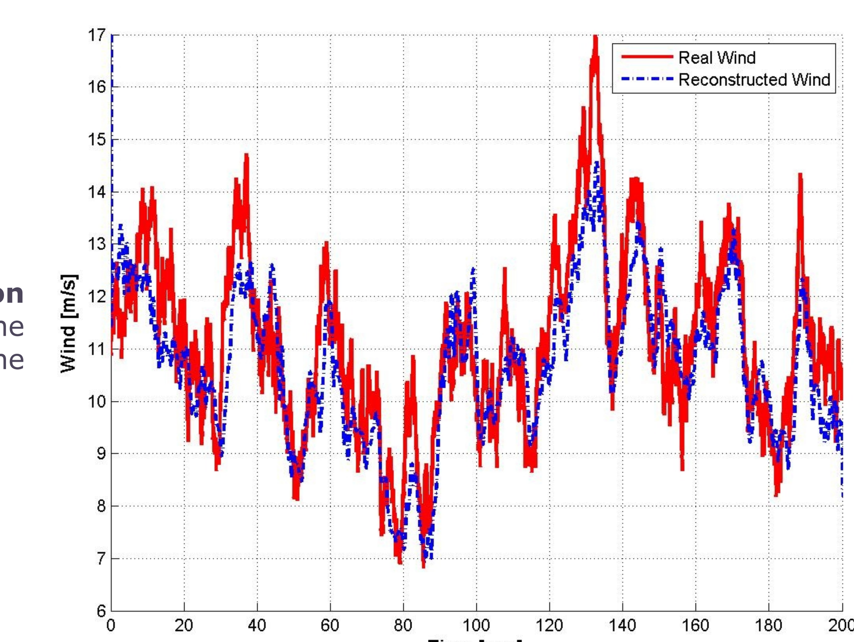
- Detailed multibody finite element model with axial-bending-shear-torsion deformable geometrically exact non-linear beam elements for blades and tower, actuator and sensor models, generator model, mechanical losses
- Aerodynamics: lifting lines with Pitts-Peters inflow model, IEC wind models, von Karman turbulence, tower shadow and wind shear

WIND OBSERVER

Need wind estimate for wind-scheduled PID and model based controllers:

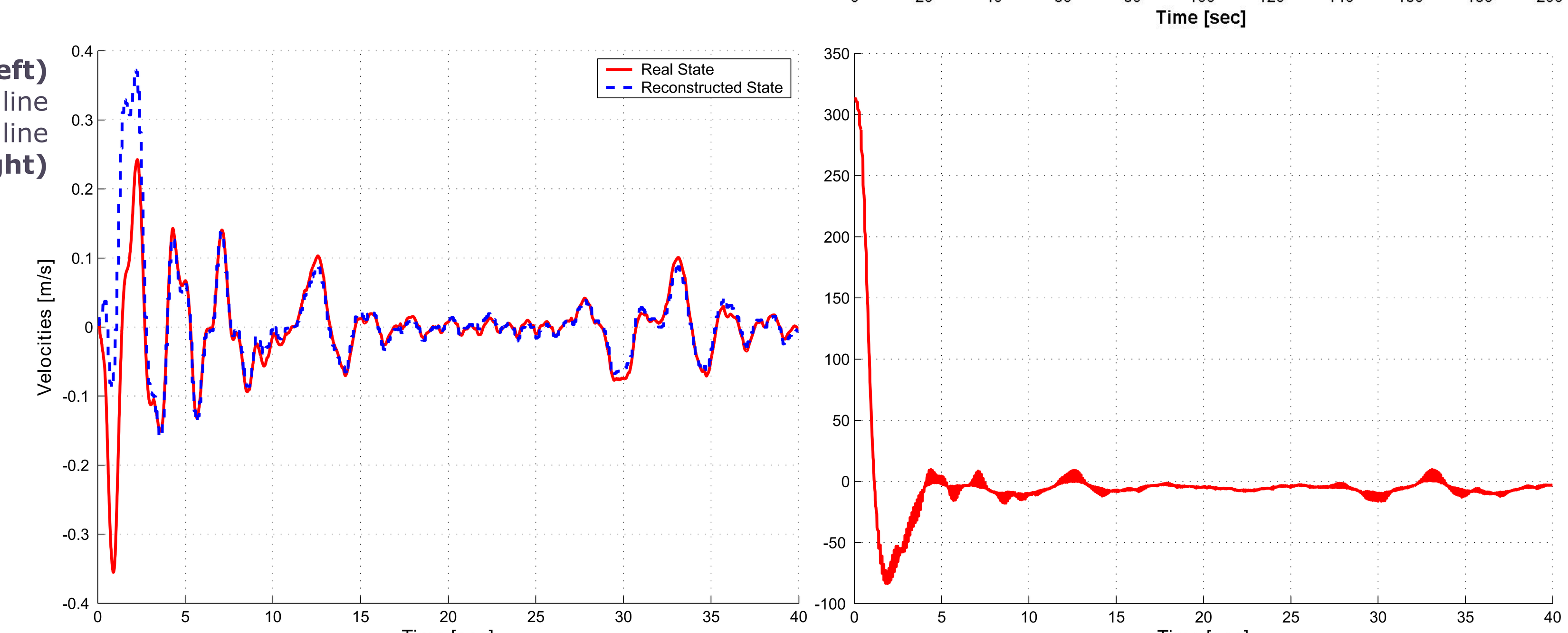
- Avoid use of anemometer: rotor wake disturbance, nacelle interference
- Reconstruct wind using rotor speed and blade pitch measurements
- Model based Kalman observer:
  - Predict wind based on spectral density model
  - Correct by enforcing satisfaction of rotor torque balance equation

Kalman wind estimation
Actual wind: solid line
Reconstruction: dashed line



TURBINE STATE OBSERVER

Tower tip velocity (left)
Actual state: solid line
Reconstruction: dashed line
Displacement error (right)



Need estimate of tower tip velocity for model based controllers:

- Predict tower tip displacement/velocity by integrating measurement of nacelle accelerometer
- Compute tower modal amplitude from strain-gage reading
- Kalman filter: correct accelerometer-based prediction using strain-gage-based displacement measure

MODEL BASED PREDICTIVE CONTROLLERS

ALL: reference wind turbine model for drive-train, tower fore-aft and pitch actuator dynamics

LQR: wind-scheduled output-feedback based on linearized reduced model

Prediction optimal control problem:

$$\min_{\boldsymbol{u},\boldsymbol{x},\boldsymbol{y}} \; J = \int_{t_0}^{t_0+T_p} L(\boldsymbol{y},\boldsymbol{u})\,\mathrm{d}t$$

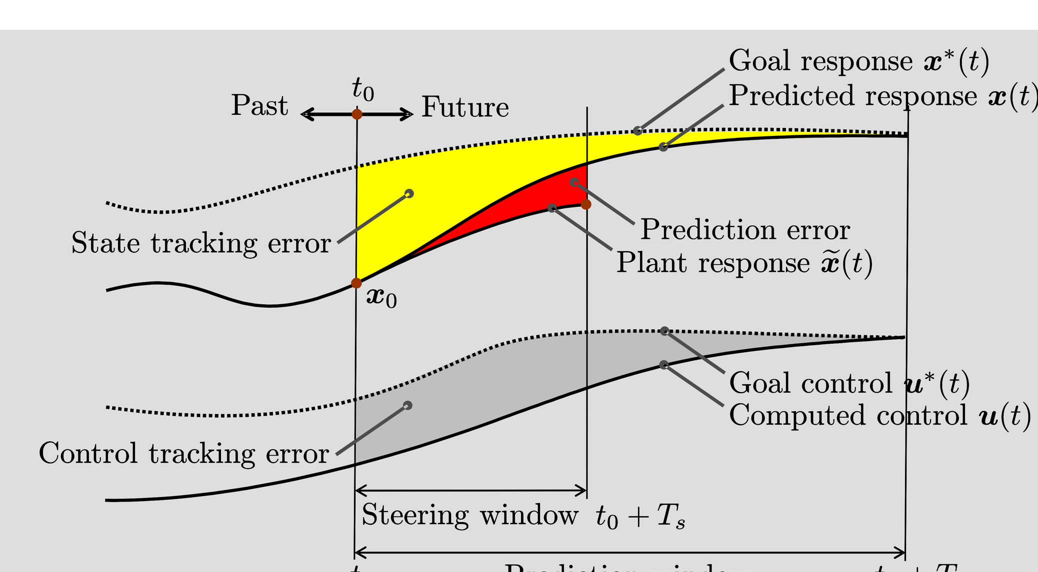
$$\text{s.t.:}\; \boldsymbol{f}(\dot{\boldsymbol{x}},\boldsymbol{x},\boldsymbol{u}) = 0 \quad t \in [t_0, t_0+T_p]$$

$$\boldsymbol{x}(t_0) = \boldsymbol{x}_0$$

$$\boldsymbol{y} = \boldsymbol{g}(\boldsymbol{x}) \quad t \in [t_0, t_0+T_p]$$

with cost:

$$L(\boldsymbol{y},\boldsymbol{u}) = (\boldsymbol{y}-\boldsymbol{y}^*)^T \boldsymbol{Q} (\boldsymbol{y}-\boldsymbol{y}^*) + (\boldsymbol{u}-\boldsymbol{u}^*)^T \boldsymbol{R} (\boldsymbol{u}-\boldsymbol{u}^*)$$



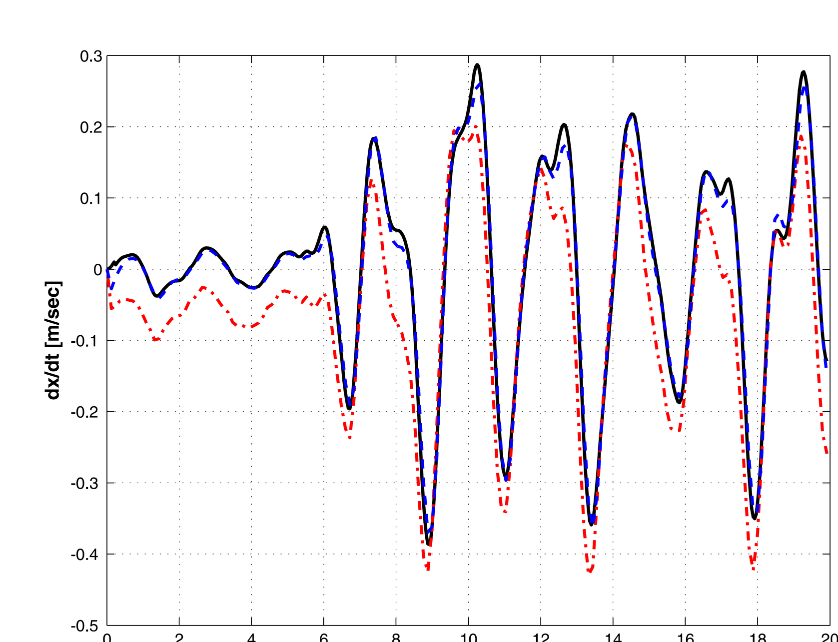
DIRECT TRANSCRIPTION: (Bottasso et al. 2006)

- Non-linear adaptive reduced model:
  - Augment reference model with unknown defect **d**: $\boldsymbol{f}_{\text{ref}}(\dot{\boldsymbol{x}},\boldsymbol{x},\boldsymbol{u}) = \boldsymbol{d}(\boldsymbol{x},\boldsymbol{u}), \quad \boldsymbol{d}(\boldsymbol{y},\boldsymbol{u}) = \boldsymbol{d}_p(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}_m) + \boldsymbol{\varepsilon}$
  - Approximate **d** using single hidden layer neural network: $\boldsymbol{d}_p(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}_m) = \boldsymbol{W}_m{}^T \boldsymbol{\sigma}(\boldsymbol{V}_m{}^T \boldsymbol{i} + \boldsymbol{a}_m) + \boldsymbol{b}_m$
- Turn optimal control pb. into parameter optimization pb. by time discretization
- Solve resulting non-linear programming pb. by sequential quadratic programming

REFERENCE AUGMENTED PREDICTIVE CONTROL (RAPC): (Bottasso et al. 2007)

- Adaptive control and adaptive model, no pre-training, fast adaption
- Adaptive control:
  - Reference control solution (LQR) augmented with neural element
  - Identify neural parameters to ensure that total control satisfies optimal control pb.

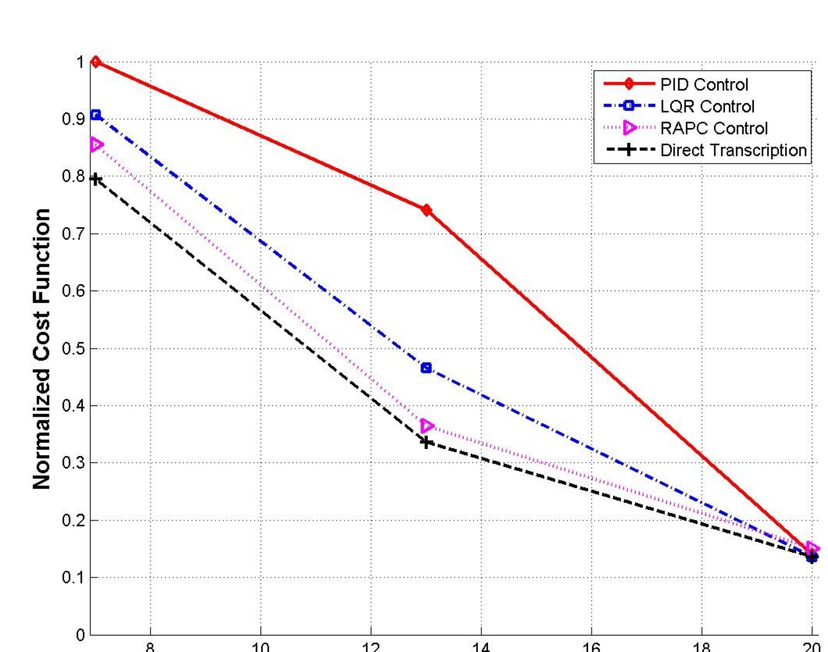
Effect of model adaption on tower fore-aft speed
Plant: solid line
Reference model: dash-dotted line
Neural augmented reference: dashed line



RESULTS

Comparison of performance in turbulent wind with ice accretion on blades and cold air

- Direct transcription is best, but cannot guarantee hard real-time schedule
- RAPC has good performance and fixed operation count



OUTLOOK

- Implementation and porting on PC-104 embedded hardware
- Test in the field on 1.5MW wind turbine