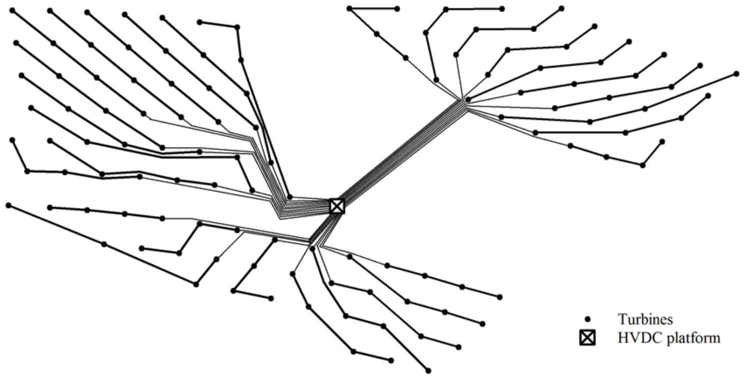
Linear Models for the Dynamic Analysis of Wind Turbines and Wind Power Plants

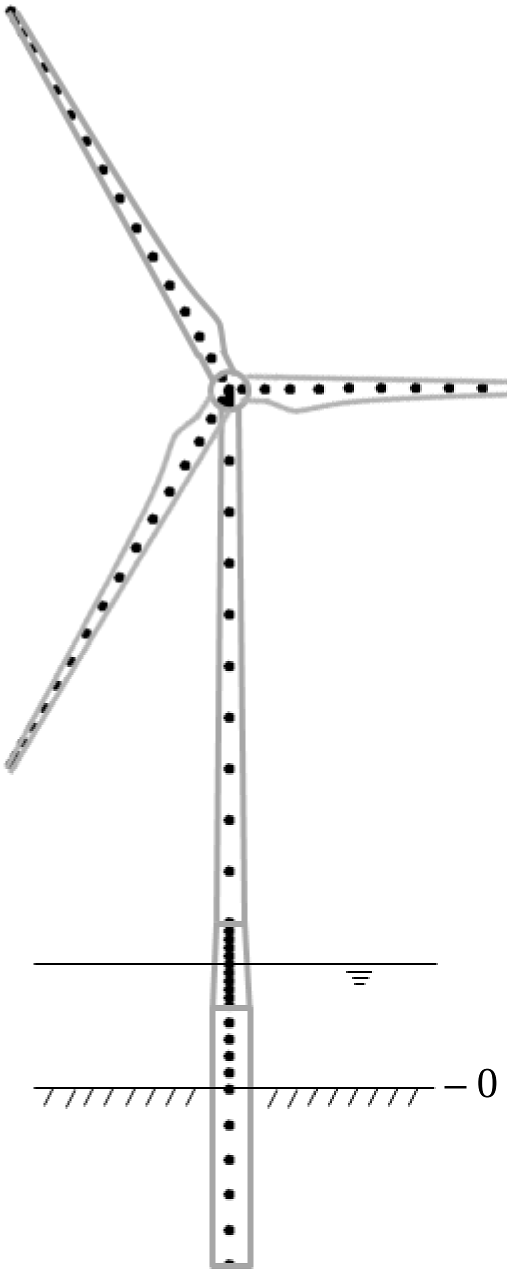
Karl Merz
SINTEF Energy Research
February 4, 2015

Contributors:
Lene Eliassen, Statkraft
Olimpo Anaya-Lara, U. Strathclyde and SINTEF Energy Research
John Olav Tande, SINTEF Energy Research

DTU 10 MW wind turbine (+ NOWITECH 10 MW nacelle), offshore foundation



Tower +40 to +145 m
Stiffened w.r.t. onshore design
approx. 900 tonnes



Transition piece +20 to +40 m
approx. 600 tonnes

30 m water depth

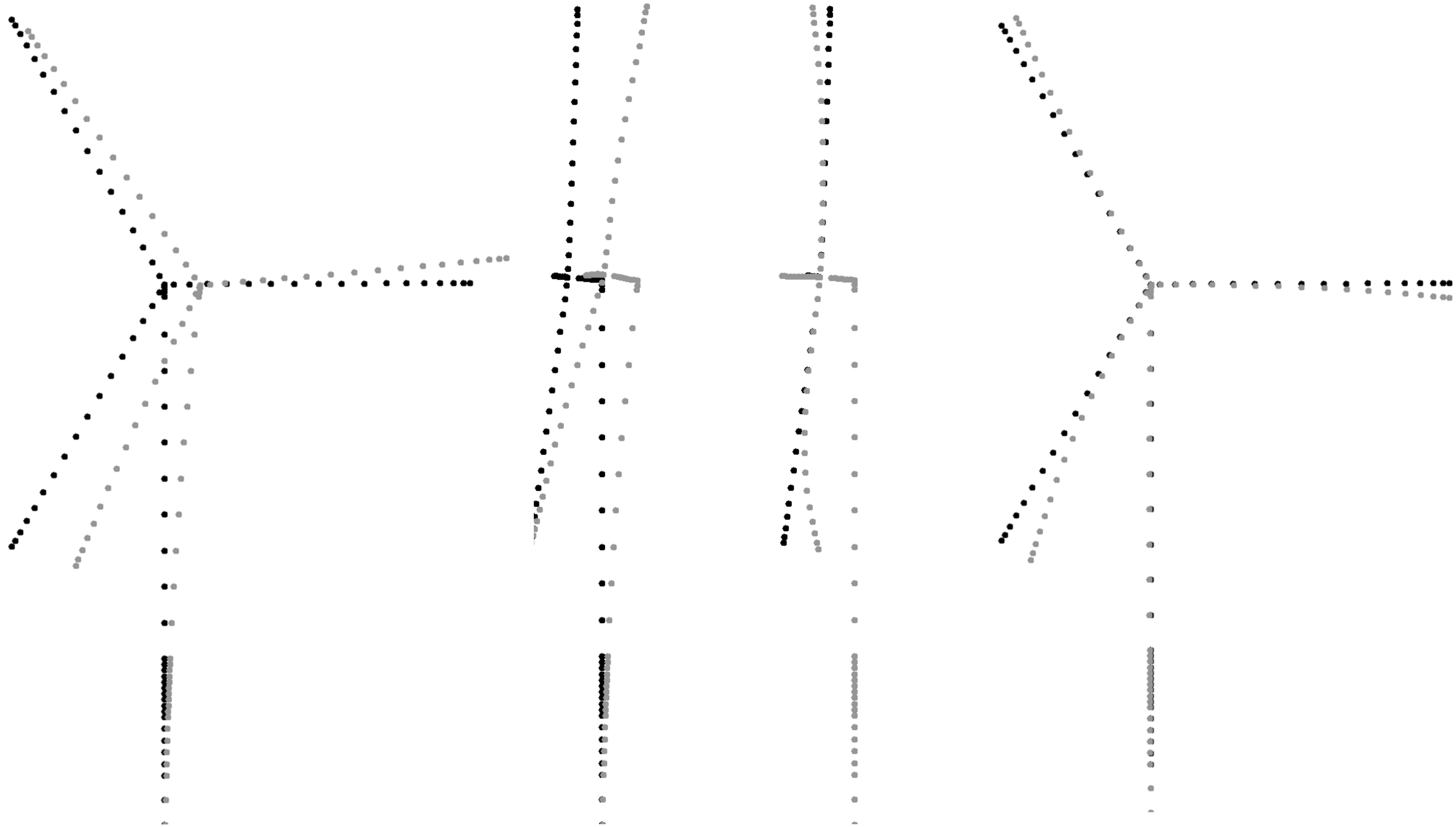
Monopile, -42 m to +20 m
9 m diameter
approx. 1500 tonnes

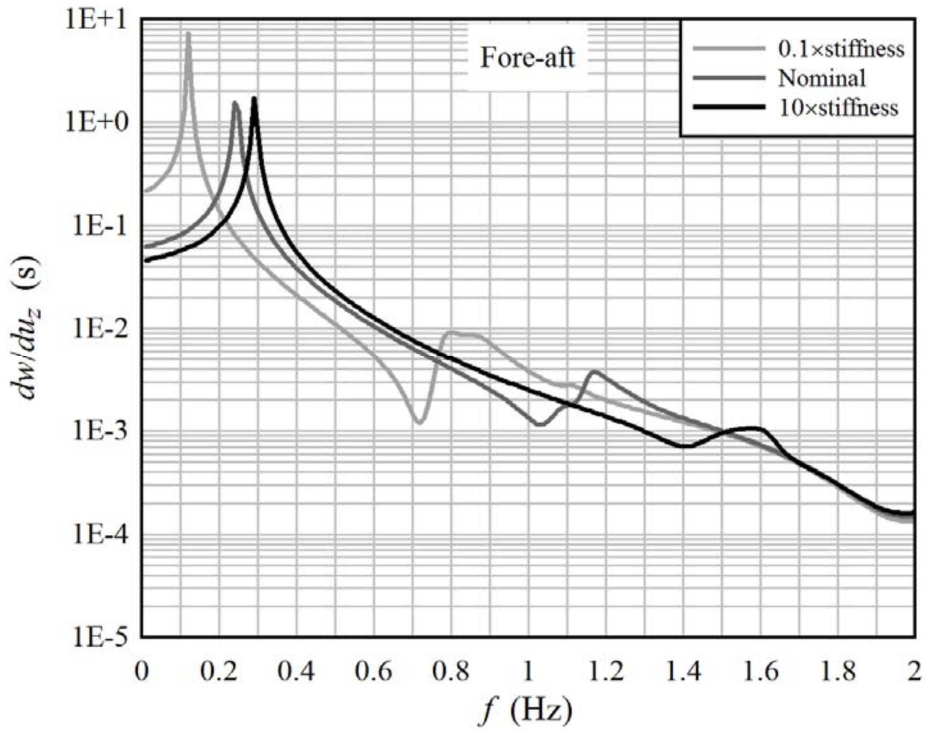
Dogger Bank seabed profile

$$\mathbf{T}_B^{\psi}\mathbf{L}\mathbf{T}_{\psi}^{B}\frac{d\mathbf{x}^{\psi}}{dt} = \left(\mathbf{T}_B^{\psi}\mathbf{A}\mathbf{T}_{\psi}^{B} - \Omega\mathbf{T}_B^{\psi}\mathbf{L}\frac{\partial\mathbf{T}_{\psi}^{B}}{\partial\psi}\right)\mathbf{x}^{\psi} + \mathbf{T}_B^{\psi}\mathbf{B}\mathbf{u}$$

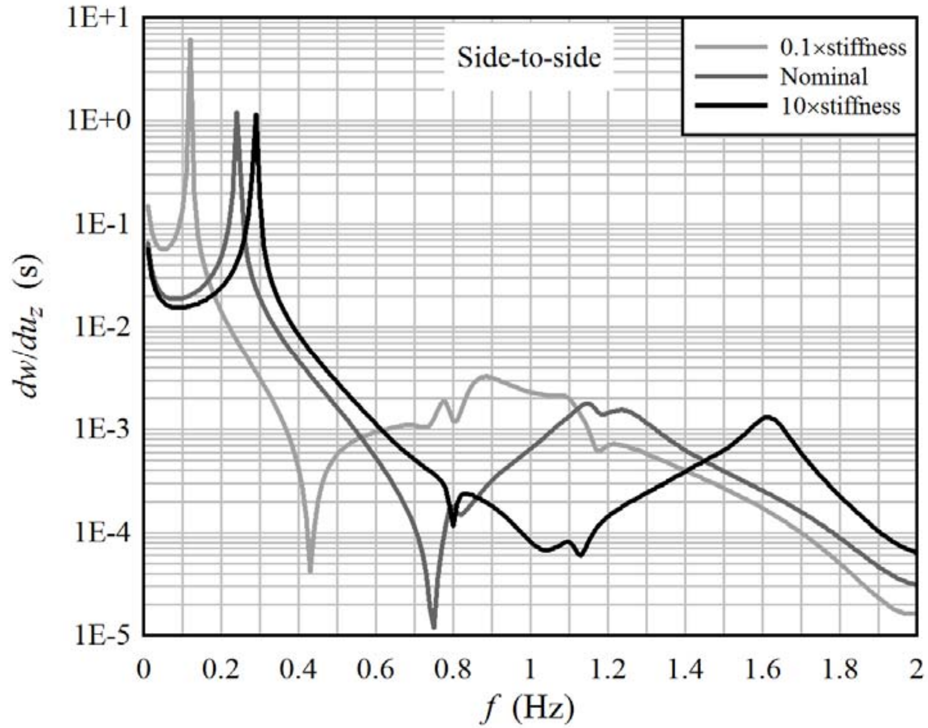
$$\mathbf{y}^{\psi} = \mathbf{T}_{B,y}^{\psi}\mathbf{C}\mathbf{T}_{\psi,x}^{B}\mathbf{x}^{\psi} + \mathbf{T}_{B,y}^{\psi}\mathbf{D}\mathbf{u}$$

$$\begin{bmatrix} \mathbf{T}_{\psi}^{B} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}\mathbf{T}_{\psi}^{B} \end{bmatrix}\frac{d}{dt}\begin{bmatrix} \mathbf{q}_1^{\psi} \\ \mathbf{q}_2^{\psi} \end{bmatrix} = \begin{bmatrix} -\Omega\dfrac{\partial\mathbf{T}_{\psi}^{B}}{\partial\psi} & \mathbf{T}_{\psi}^{B} \\ -\mathbf{K}\mathbf{T}_{\psi}^{B} & -\mathbf{C}\mathbf{T}_{\psi}^{B} - \Omega\mathbf{M}\dfrac{\partial\mathbf{T}_{\psi}^{B}}{\partial\psi} \end{bmatrix}\begin{bmatrix} \mathbf{q}_1^{\psi} \\ \mathbf{q}_2^{\psi} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \Delta\mathbf{F} \end{bmatrix}$$



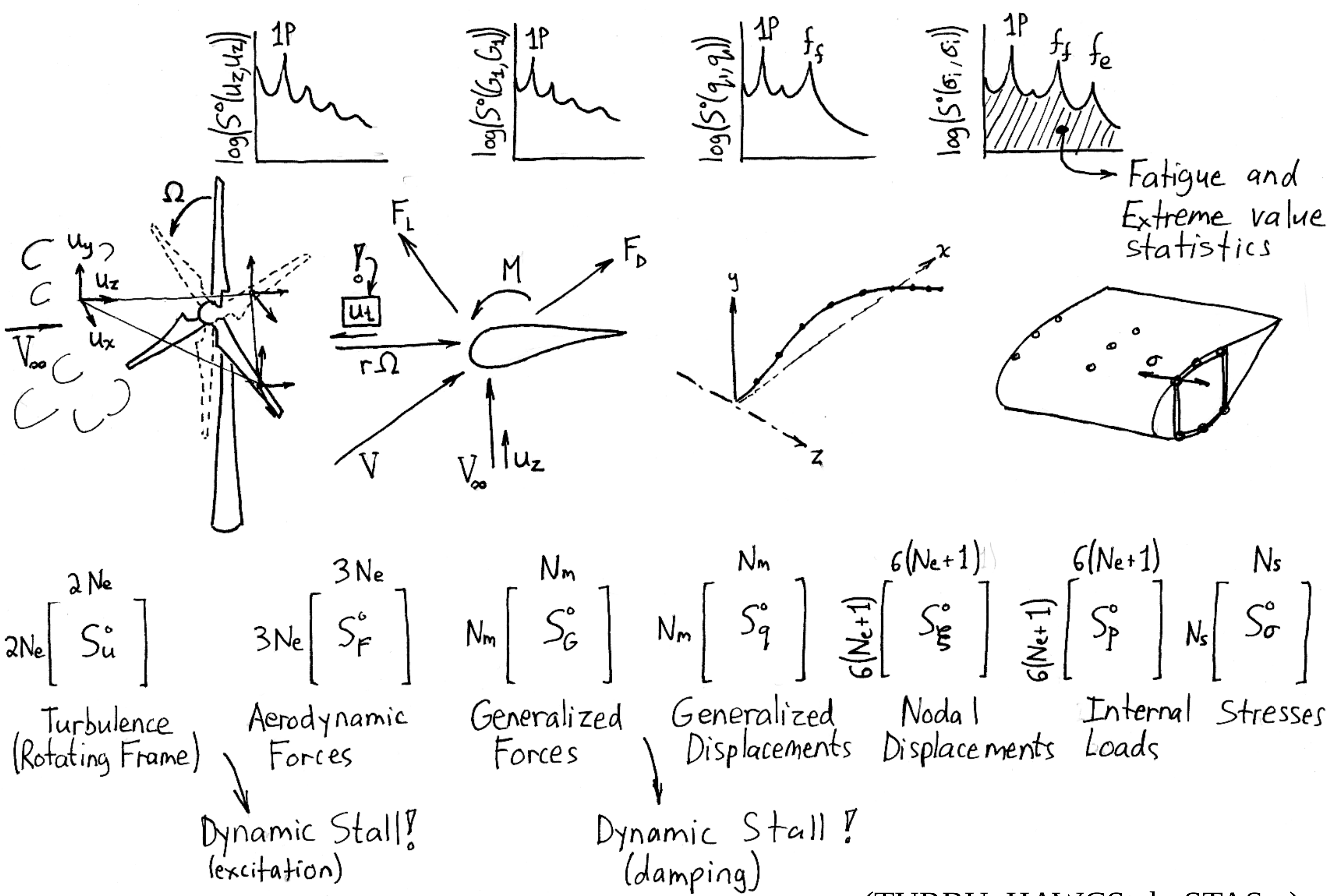


Fore-aft
0.1×stiffness
Nominal
10×stiffness
1E+1
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
dw/du_z (s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
f (Hz)



Side-to-side
0.1×stiffness
Nominal
10×stiffness
1E+1
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
dw/du_z (s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
f (Hz)

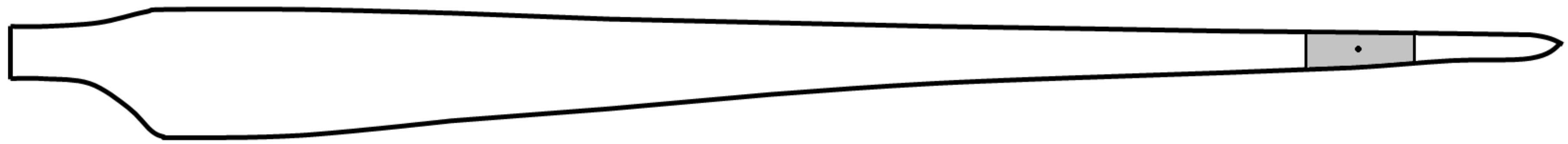
Frequency-domain analysis

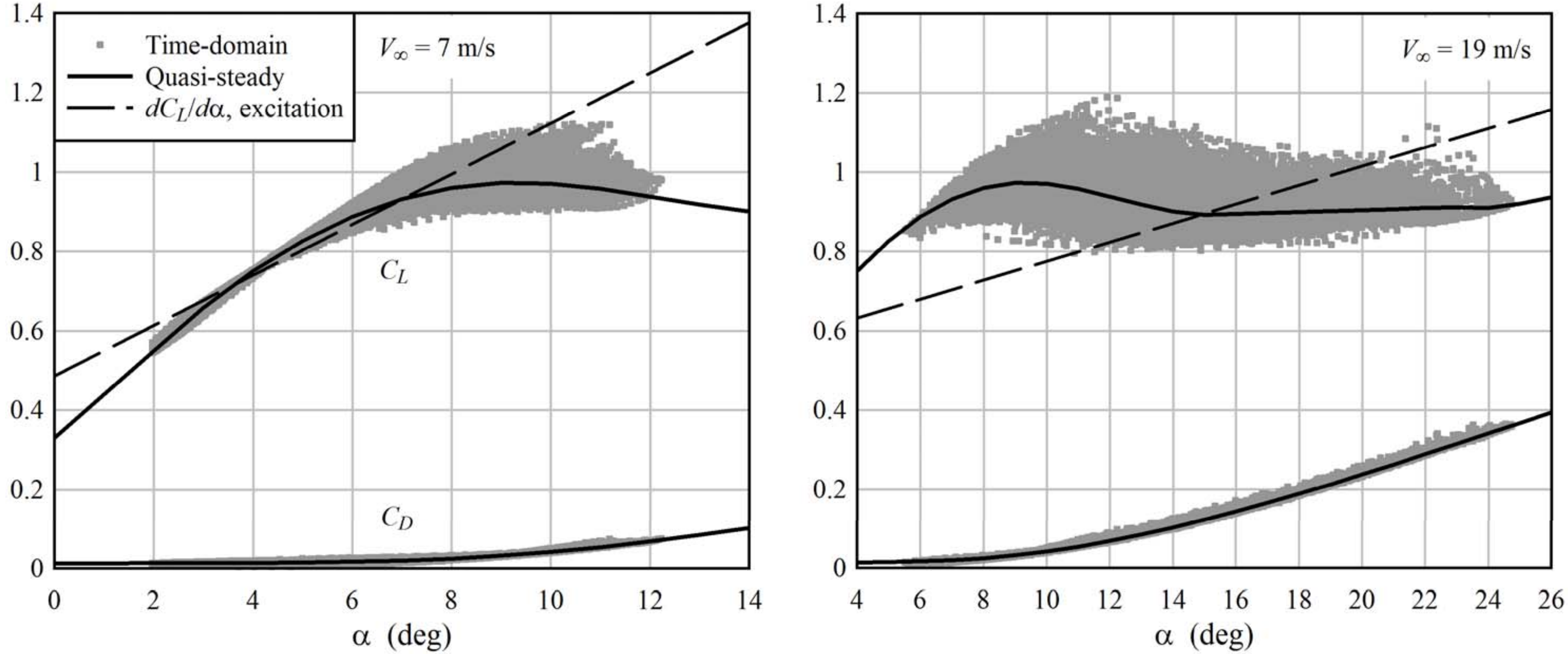


(TURBU, HAWCStab, STAS...)

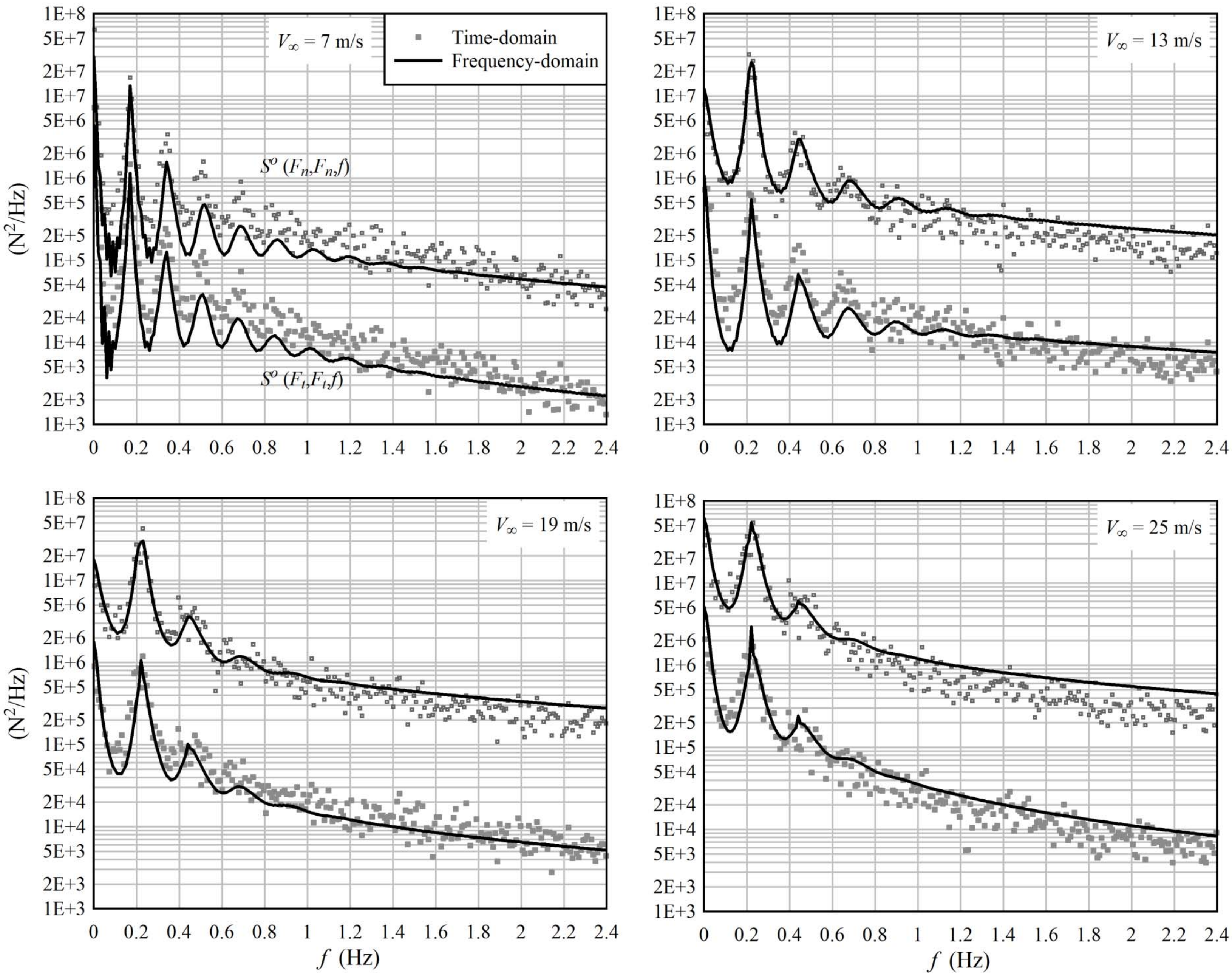
State of a representative outboard airfoil section

Time-domain: FAST/AeroDyn with Leishman-Beddoes dynamic stall

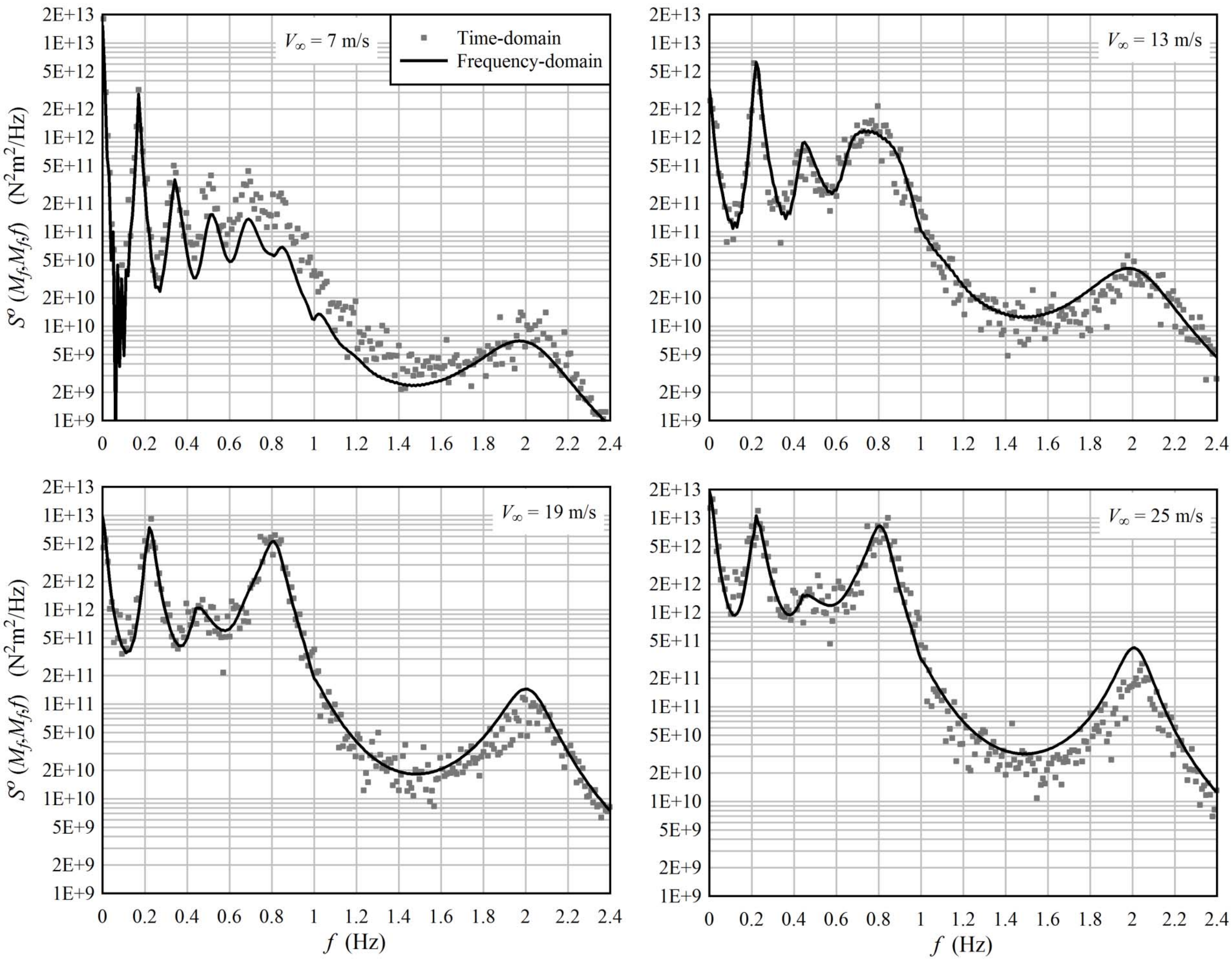




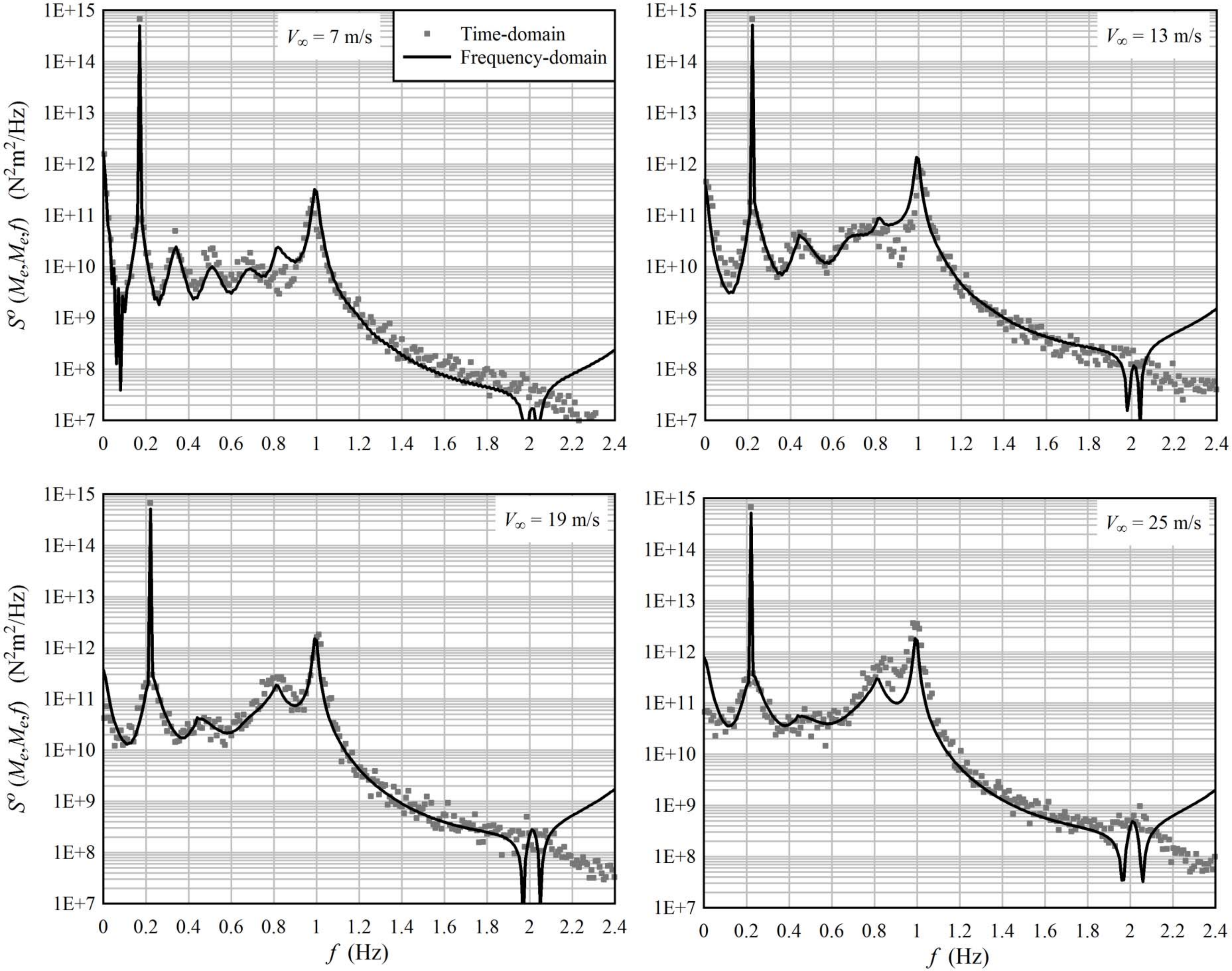
Normal and in-plane aerodynamic loads for an outboard element



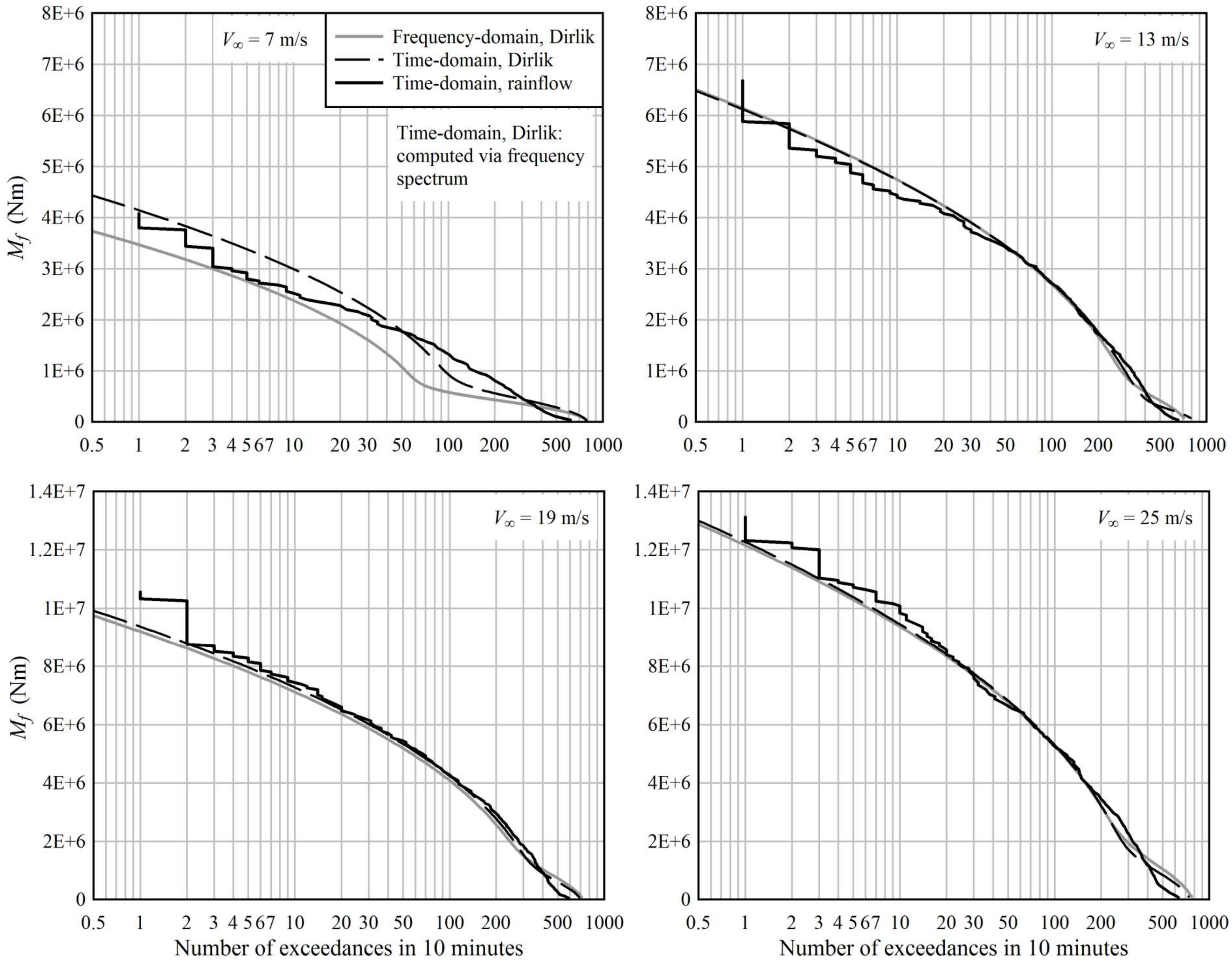
Flapwise blade root bending moments



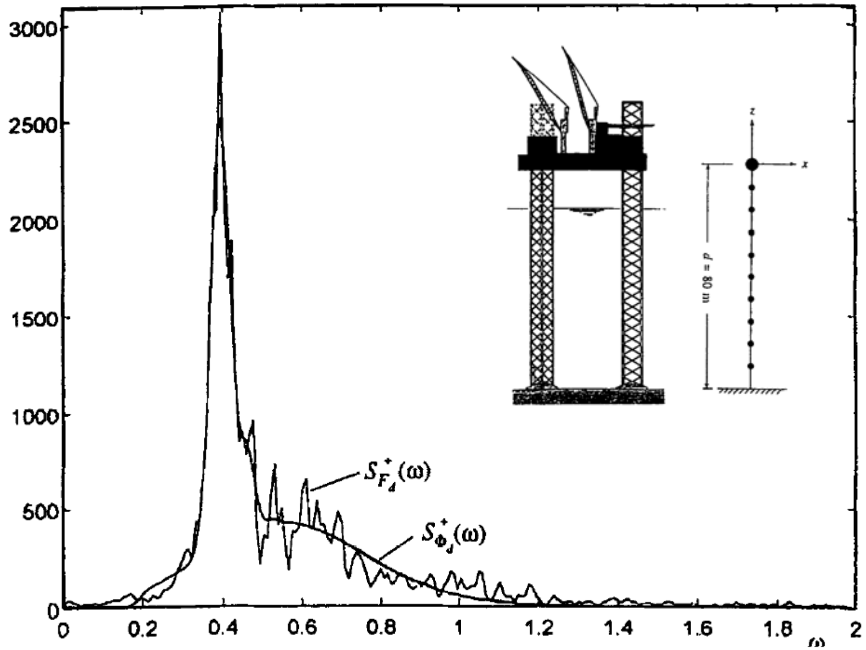
Edgewise blade root bending moments

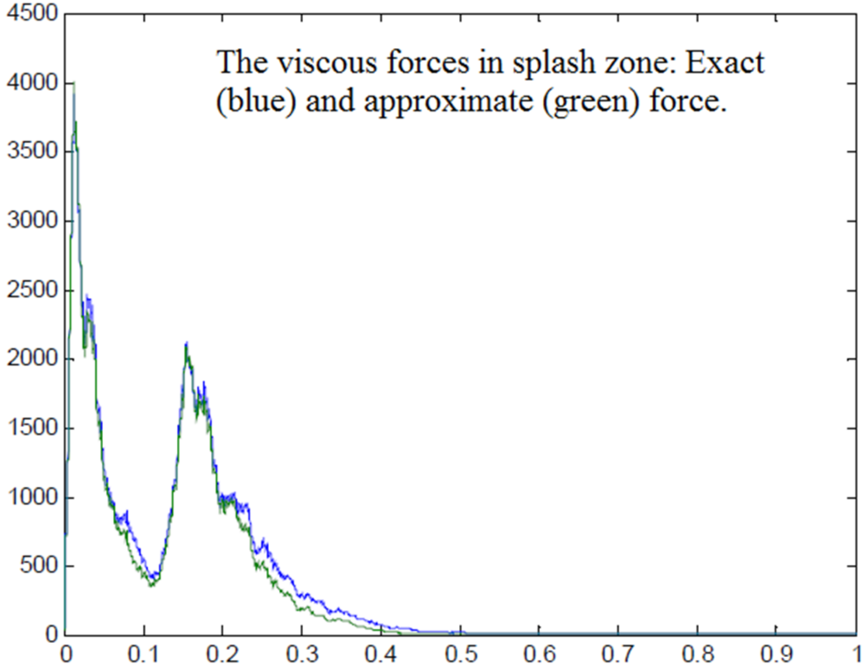


Flapwise blade root bending moment fatigue cycles



Wave forces can be linearized stochastically





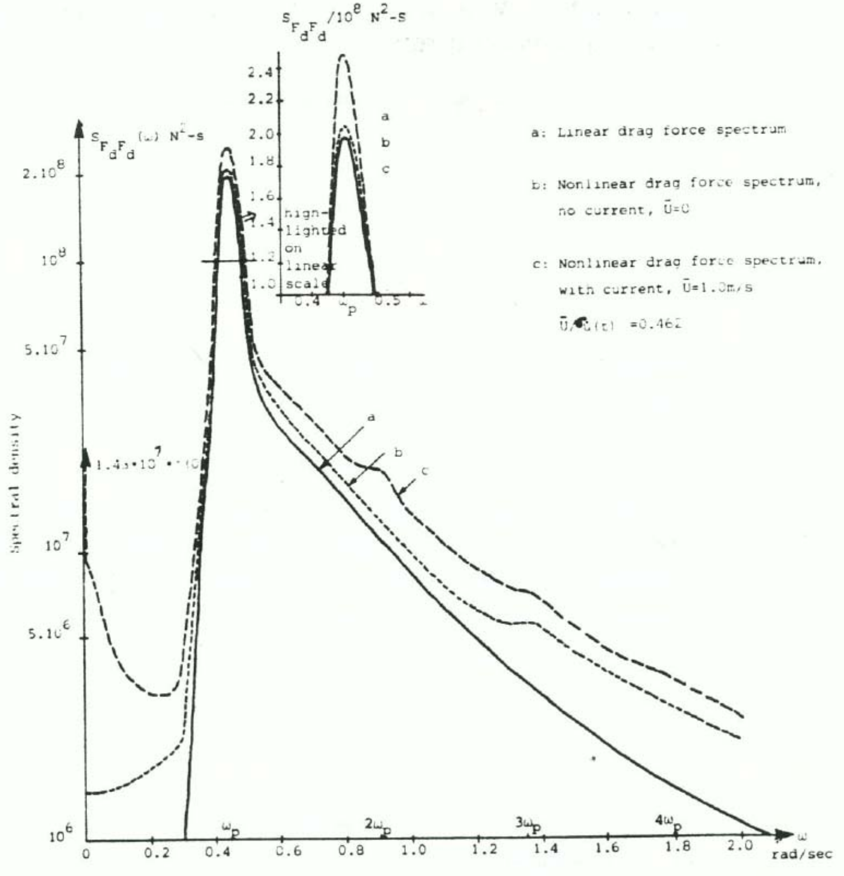
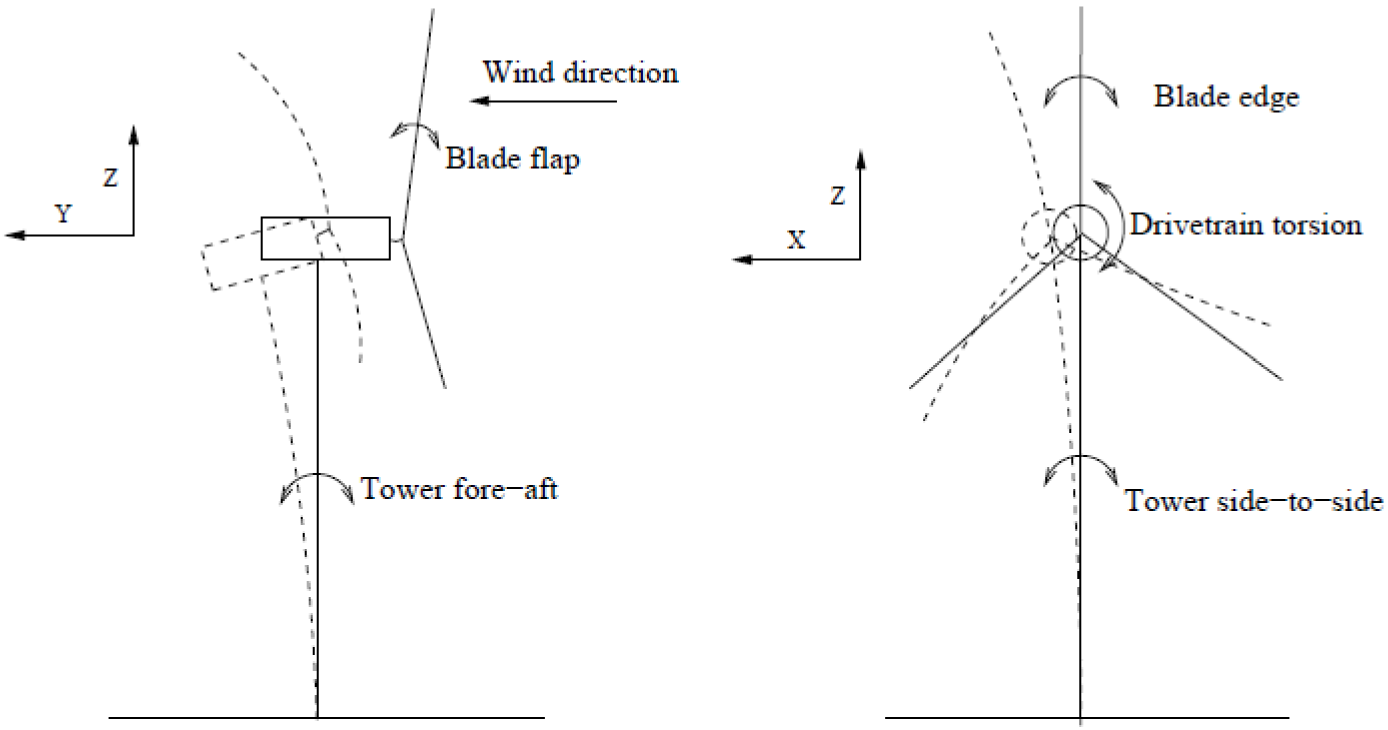


Figure 8. Spectral density function for drag force in the case of a Jonswap state state. $\omega_p = 0.45\,rad/s$, $\gamma = 7$, $\alpha = 0.015$

Upper left: Naess A; Pisano AA; Frequency domain analysis of dynamic response of drag dominated offshore structures; Applied Ocean Research 19 (1997) 251-262. Lower left: Lie H; Kaasen KE; Viscous drift forces on semis in irregular seas – a frequency domain approach; Proceedings OMAE 2008. Above: Gudmestad OT; Connor JJ; Linearization methods and the influence of current on the nonlinear hydrodynamic drag force; Applied Ocean Research 5 (1983) 184-194.

Large wind turbine – degrees of freedom



- It is desirable to use the turbine controller to minimise blade and tower oscillations, and gearbox vibrations

Source: S. Suryanarayanan

Load mitigation control loops

Objectives:

- ►Minimise gearbox vibrations – shaft torsional oscillations
- ►Minimise tower oscillations

Modified baseline controller:

- ► Additional control loops (tuned filters, mainly), in the generator-torque control loop
- ► Still collective blade-pitch control (CPC)
- ► Feedback signals: generator speed, tower displacements (fore-aft, side-to-side), gearbox torque (not typically available)

Load mitigation control loops

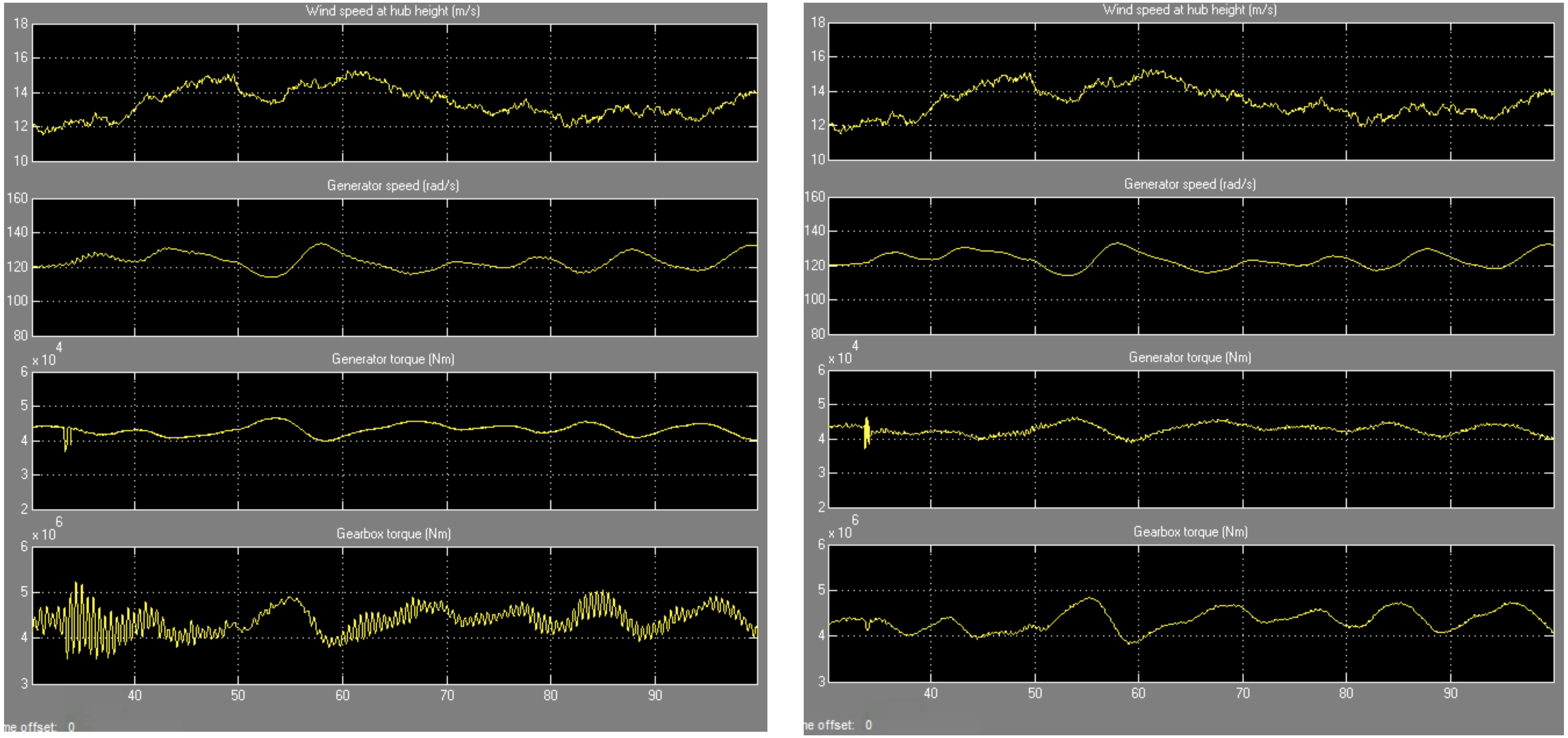
- 5MW NREL baseline controller in Simulink plus control loop to minimise gearbox vibrations

Wind profile

Gen speed

Gen torque

Gearbox torque

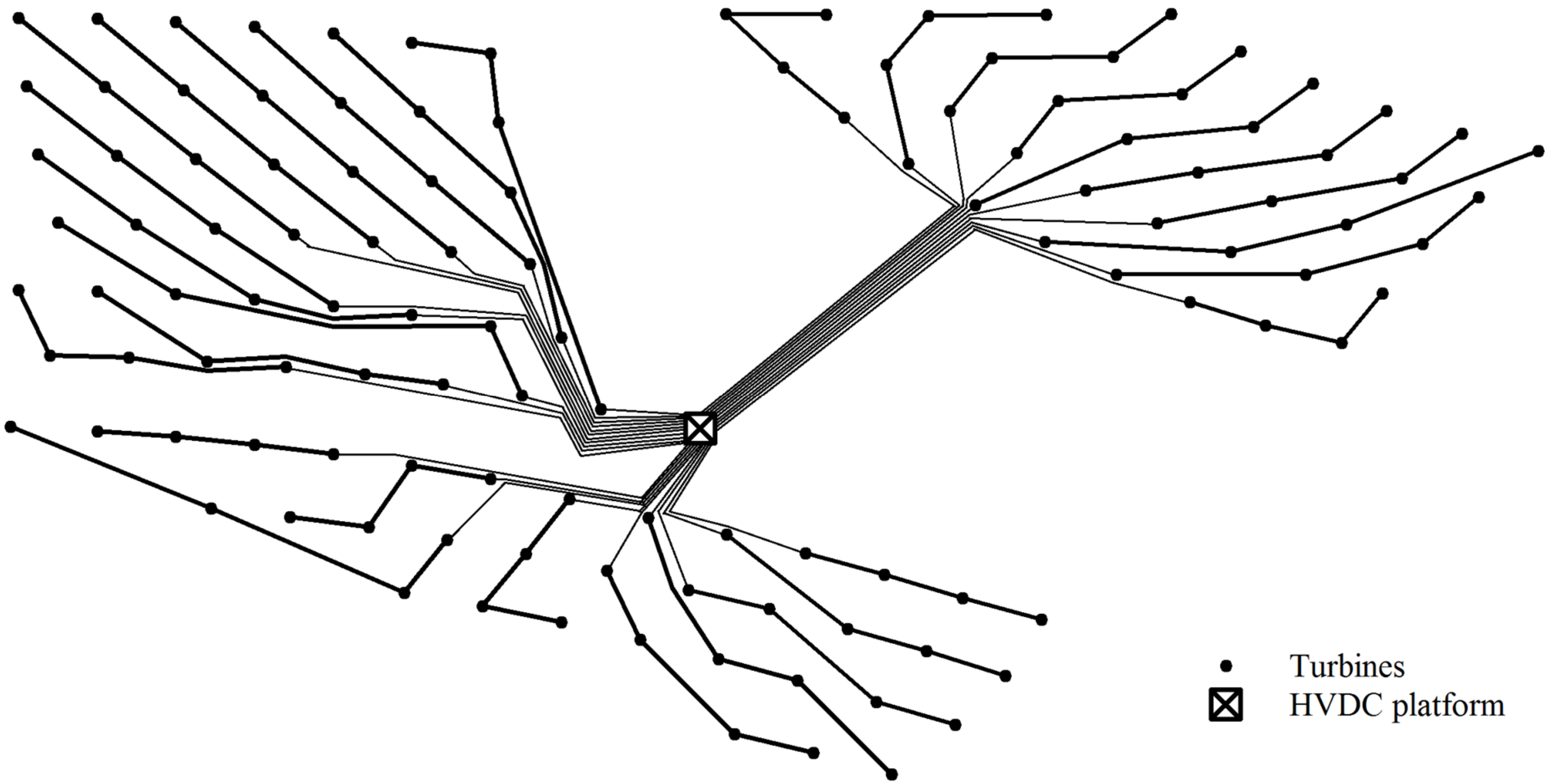


Responses without and with gearbox vibration control loop mitigation

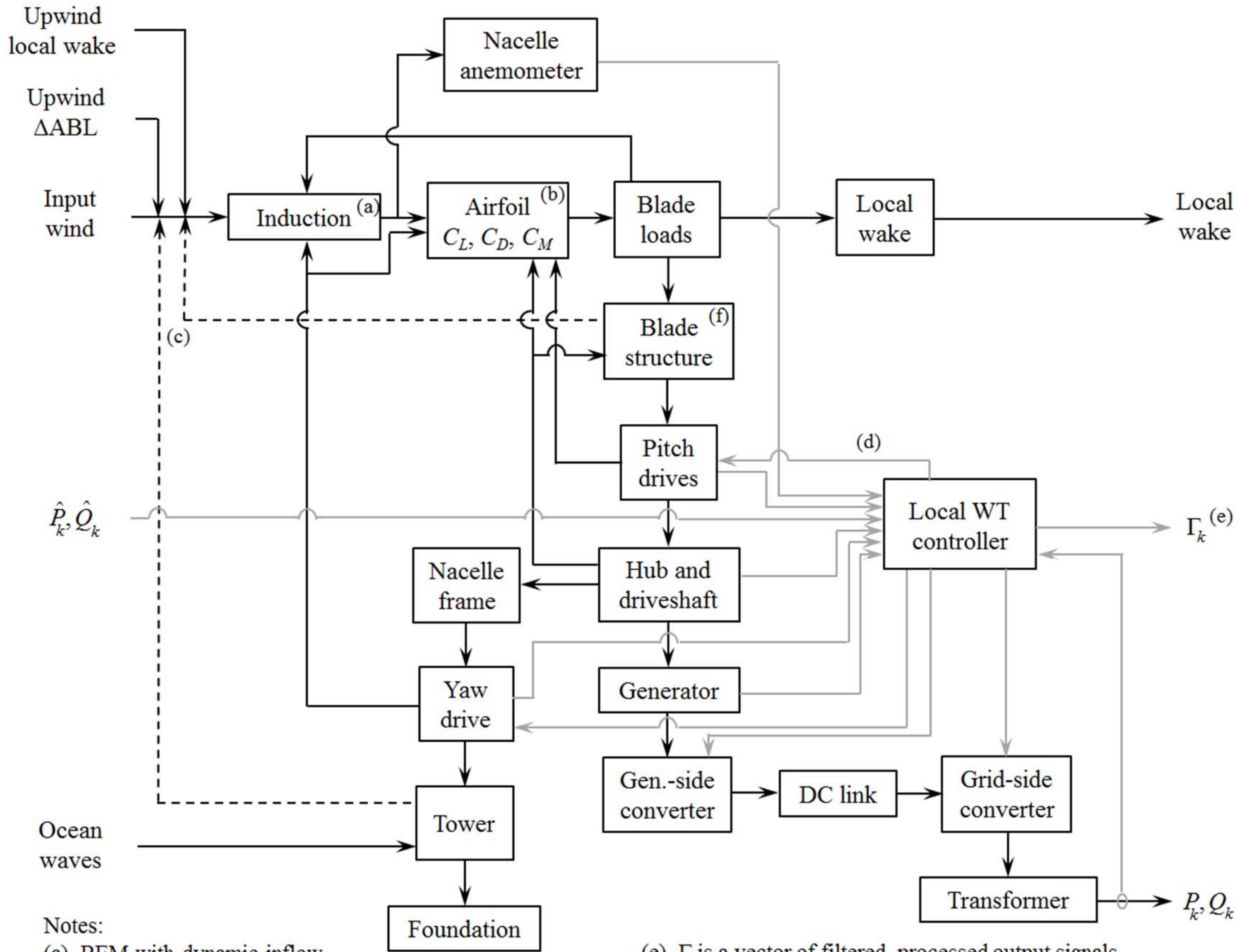
For illustration purposes only

How do load mitigation control actions integrate with wind power plant control actions?

A GW-scale wind power plant



A state-space model of a wind farm



Notes:

(a) BEM with dynamic inflow

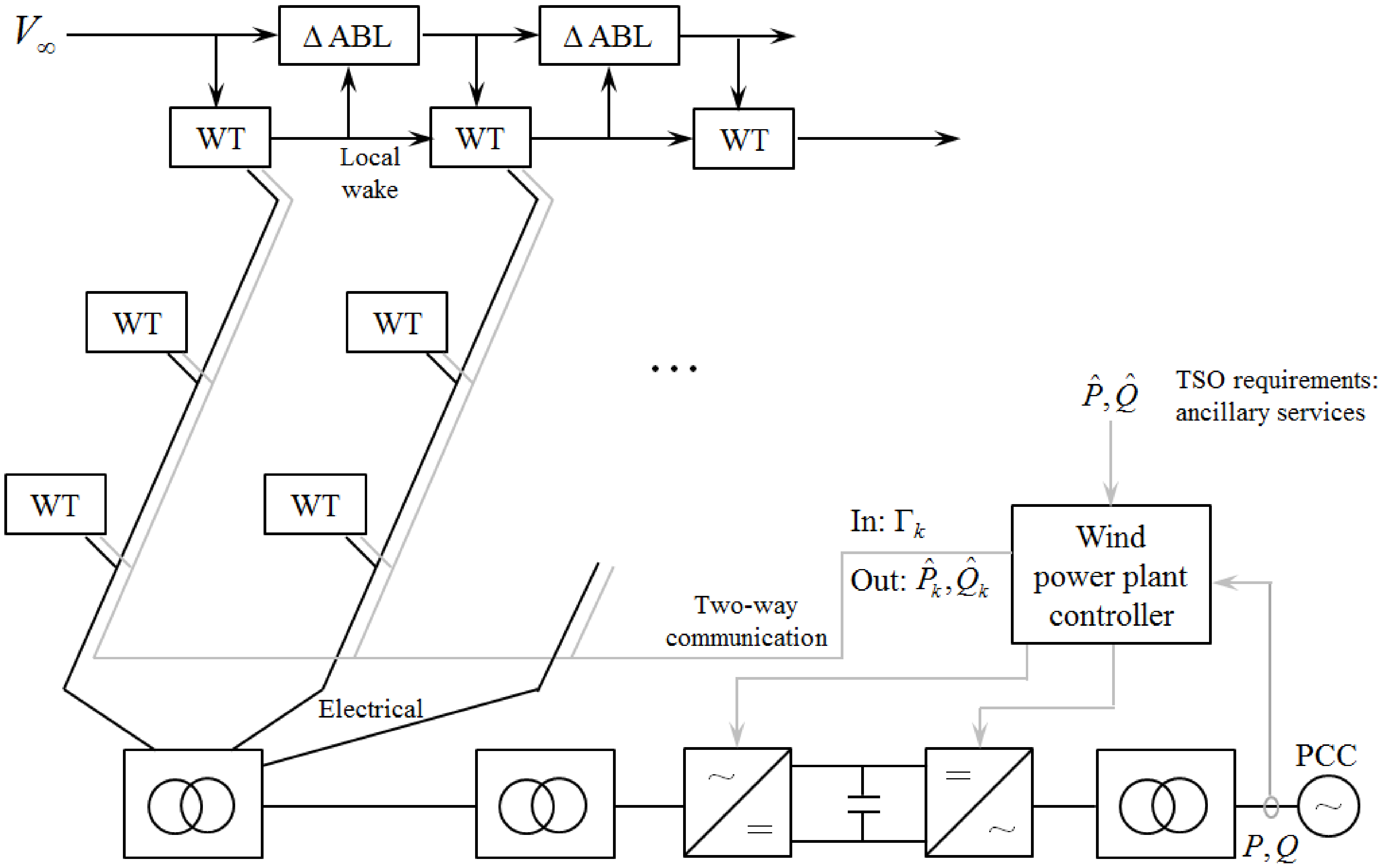
(b) Dynamic stall, Øye type model

(c) Aerodynamic damping, may be linearized and computed independently

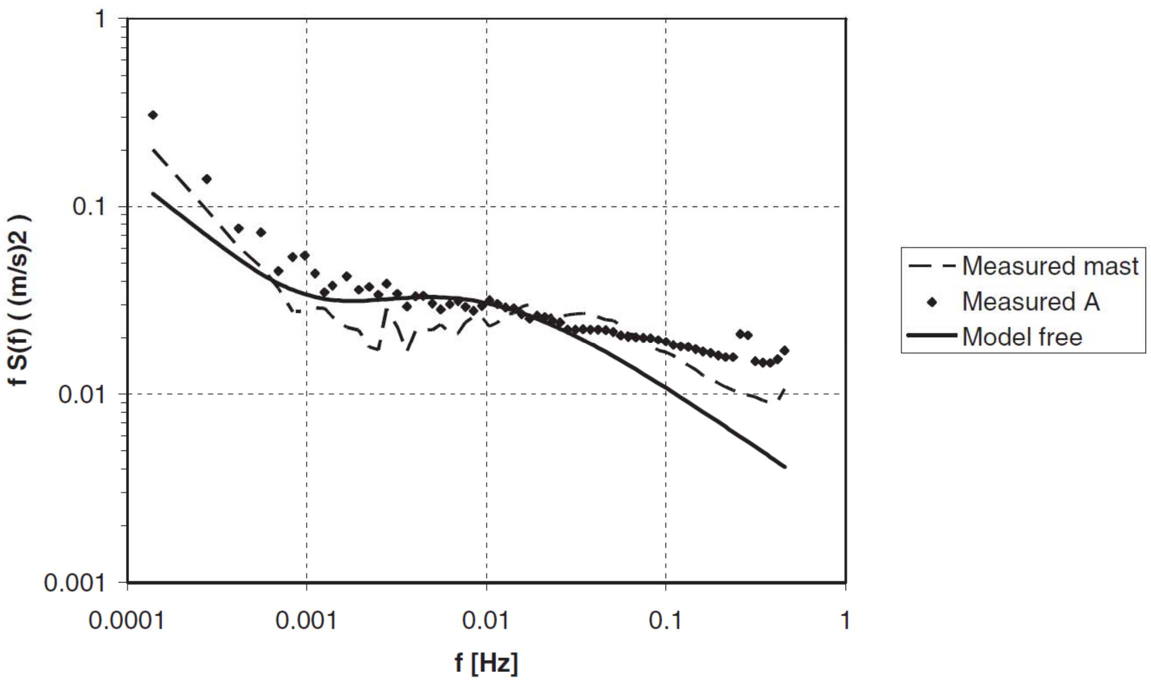
(d) Black lines: physical connection. Grey: communication.

(e) Γ is a vector of filtered, processed output signals.

(f) Additional load, strain, or acceleration sensors could be installed in any of the mechanical components and fed to the local controller for active damping or inclusion in the output signal vector Γ.


V_∞
Δ ABL
Δ ABL
WT
WT
WT
Local wake
WT
WT
WT
WT
• • •
$\hat{P}, \hat{Q}$
TSO requirements: ancillary services
In: Γ_k
Out: $\hat{P}_k, \hat{Q}_k$
Wind power plant controller
Two-way communication
Electrical
PCC
P, Q

Spectral wind field models at the plant scale



Sørensen P, *et al*. Modelling of power fluctuations from large offshore wind farms. Wind Energy 11 (2008) 29-43.

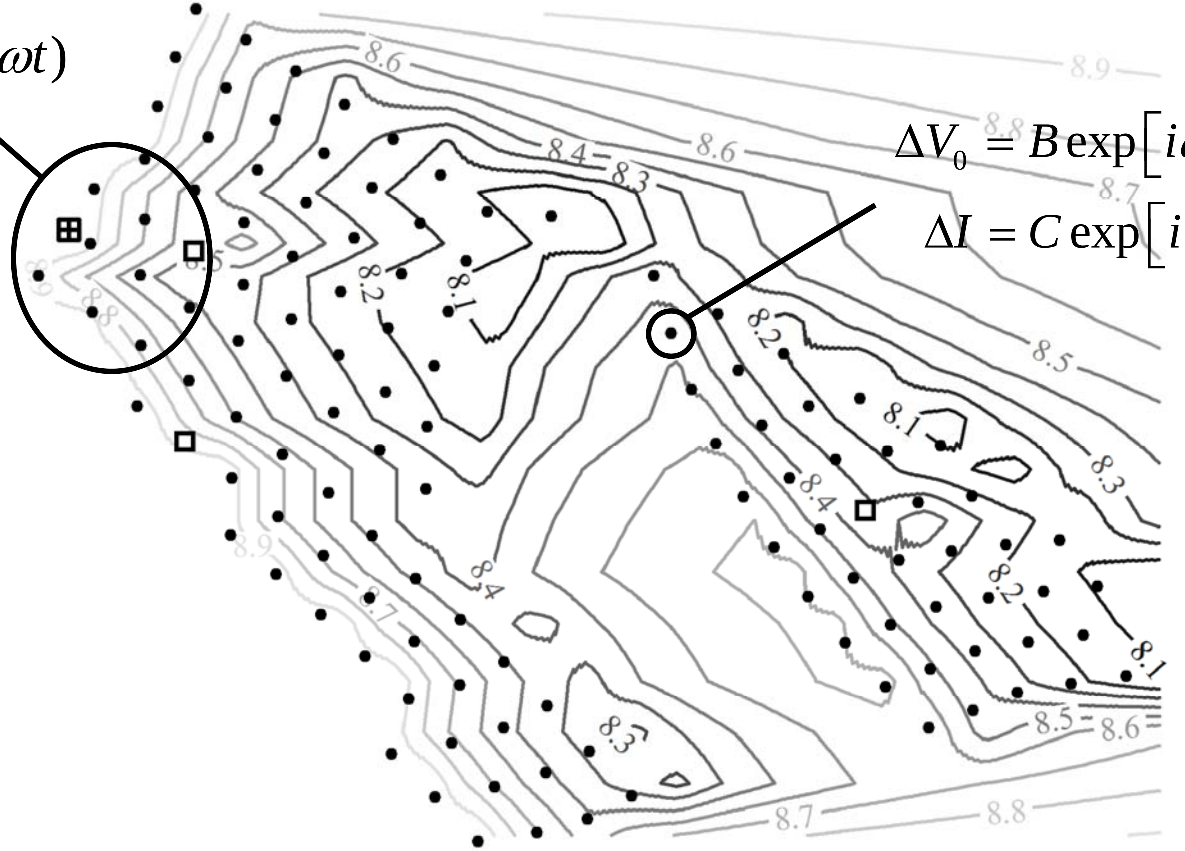
$$S_{LF}(f) = (\alpha V_\infty)^2 \frac{H/V_\infty}{\left(\frac{H}{V_\infty} f\right)^{5/3} \left(1 + 100 \frac{H}{V_\infty} f\right)} \Rightarrow \int_0^{f_1} S_{LF}\, df = \infty ?$$

Influence of control actions on the atmospheric boundary layer

$$\Delta\beta = A\exp(i\omega t)$$

$$\Delta V_0 = B\exp\left[i\omega\left(t-\alpha\right)\right]?$$

$$\Delta I = C\exp\left[i\omega\left(t-\beta\right)\right]?$$



Within the normal operating range of a wind turbine, can the perturbations be represented by a diffusion function, ideally a linear differential equation?

A relevant experiment: