The background features several large, overlapping, curved shapes in shades of purple, green, and blue. Interspersed among these are numerous small, yellow, triangular shapes pointing in various directions, creating a dynamic and abstract pattern.

Condition Monitoring of Wind Turbines - from CONMOW

**CREST
Loughborough University**



Contents

1. *The relationship between torque and electrical power in a wind turbine*
2. *Failure frequencies of some wind turbine mechanical components*
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1. The relationship between torque and electrical power in a wind turbine

Stator electrical power is proportional to mechanical torque applied to rotor: $P_s = T_m \omega_s$

$$n = \frac{\omega_r}{\omega_t}$$

$$\omega_s = \frac{2\pi f_s}{p}$$

$$\omega_r = (1 - s)\omega_s$$

$$P_m = T_m \omega_r$$

$$P_s = T_{em} \omega_s$$

ω_t : Turbine rotor speed

ω_r : Generator rotor speed

n : Gearbox ratio

f_s : Power supply frequency

ω_s : Synchronous speed of generator

p : Pole pairs

s : Slip

P_m : Rotor mechanical power input

T_m : Mechanical torque applied to rotor

T_{em} : Electromagnetic torque applied to the rotor by the generator

P_s : Stator electrical power

1. The relationship between torque and electrical power in a wind turbine

For a loss less generator the mechanical equation is:

$$J \frac{d\omega_r}{dt} = T_m - T_{em}$$

J : Combined rotor and wind turbine inertia coefficient In steady-state at fixed speed for a lossless generator

In steady-state at fixed speed for a lossless generator

$$T_m = T_{em}$$

$$P_m = P_s + P_r$$

$$P_r = P_m - P_s = T_m \omega_r - T_{em} \omega_s$$

$$= -T_m \left(\frac{\omega_s - \omega_r}{\omega_s} \right) \omega_s = -s T_m \omega_s$$

$$= -s P_s$$

P_r : rotor electrical power output

2. Failure frequencies of some wind turbine mechanical components

(a) Pulsating torques

General electrical expression for pulsating torques due to load variation, rotor winding defects and rotor eccentricity

$$T_p(t) = - \left[\frac{3p}{2s\omega_s} \right] \text{Re} \left\{ \left[\bar{V}_{r1} \bar{I}_{r2} - \bar{V}_{r2} \bar{I}_{r1} \right] e^{j2s\omega_s t} \right\}$$

(b) Blade-passing torque frequencies

Aero-dynamical asymmetry, e.g. unbalanced angle of attack on blades:

$1p=1\omega_t t$ oscillation.

Symmetrical rotor blades:

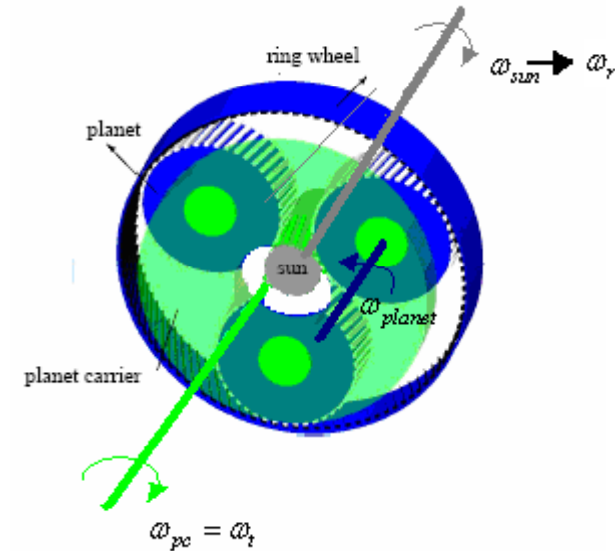
$3p=3\omega_t t$ oscillation (three times the turbine rotor angular frequency)

2. Failure frequencies of some wind turbine mechanical components

(c) Planetary gear-train torque frequencies

$$\omega_{sun} = \omega_{pc} + \frac{z_{rw}}{z_{sun}} \omega_{pc}$$

$$\omega_{planet} = \omega_{pc} - \frac{z_{rw}}{z_{planet}} \omega_{pc}$$



ω_{pc} - Actual rotational speed of planet carrier, equal to turbine rotor speed ω_t

ω_{sun} - Actual rotational speed of sun pinion

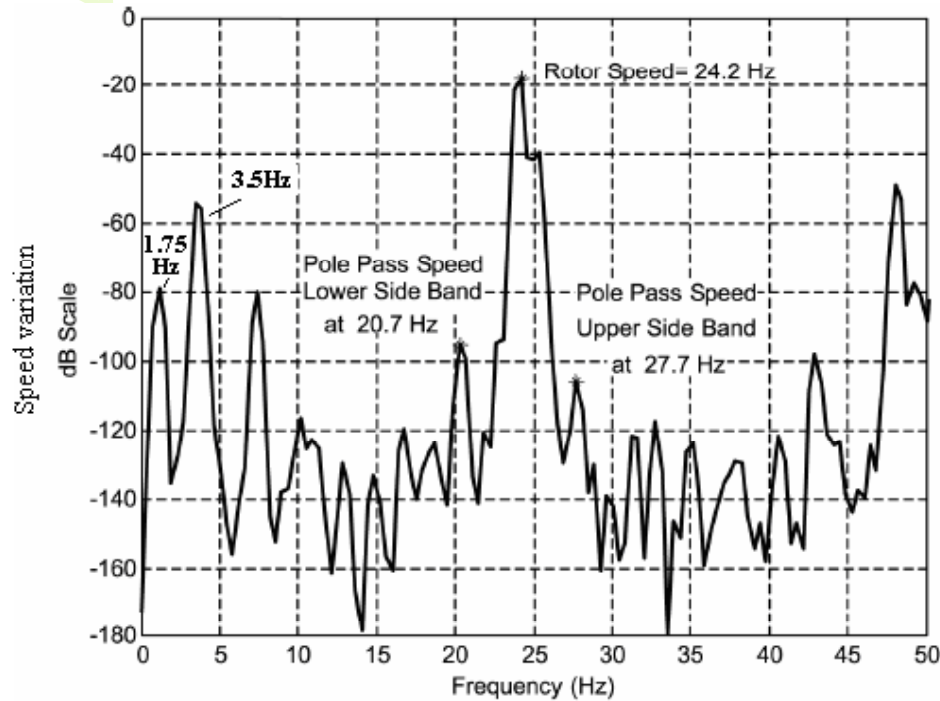
z_{rw} - Teeth number of sun pinion

z_{sun} - Teeth number of sun pinion

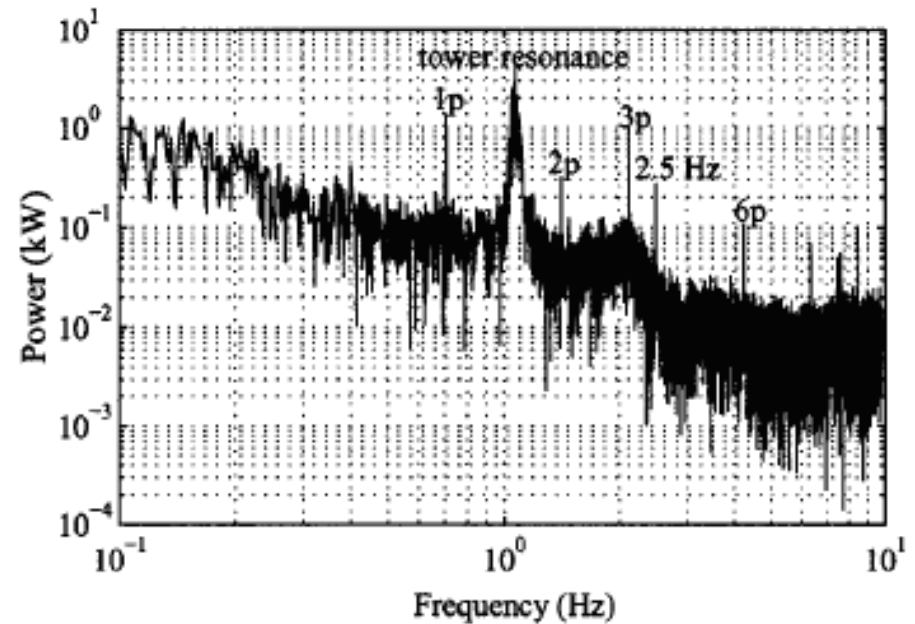
ω_{planet} - Actual rotational speed of planet carrier

z_{planet} - Teeth number of planet carrier

3. Evidence of frequency content in speed and power spectra in the literature



Induction motor speed variation signal of instantaneous angular speed (Ben Sasi et al, 2004)



Wind turbine power (Thiringer, T et al.)

4. Application to wind turbine signals

Morlet wavelet transform

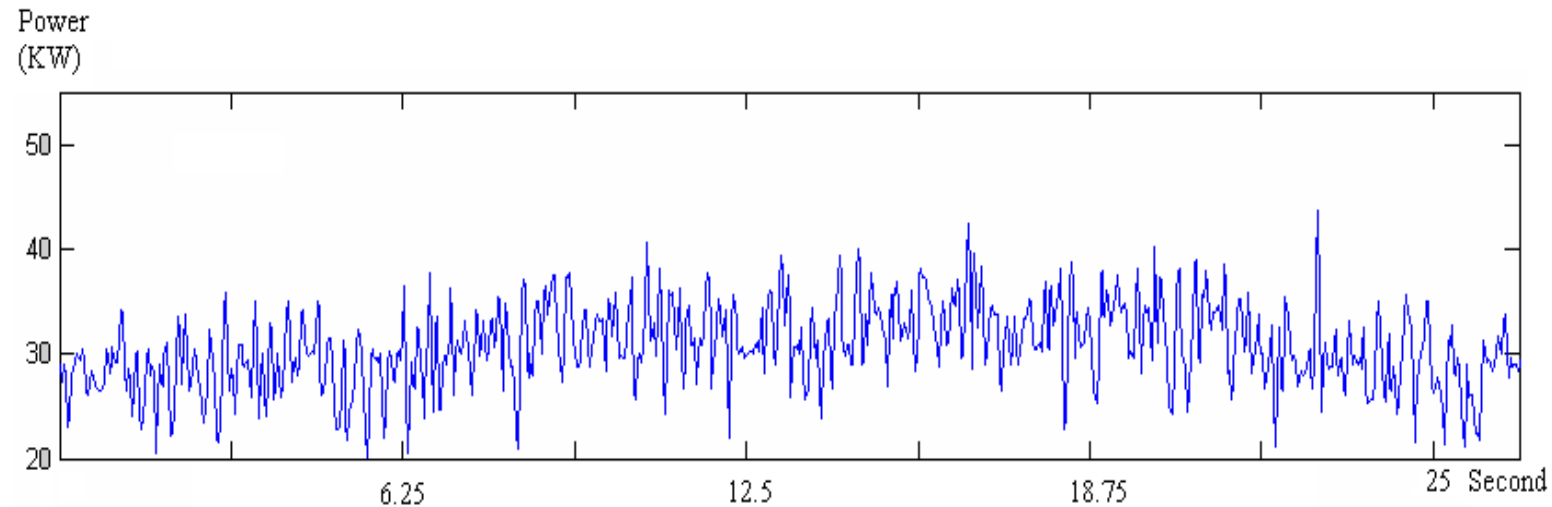


Figure 1. Power data from Nordex Turbine

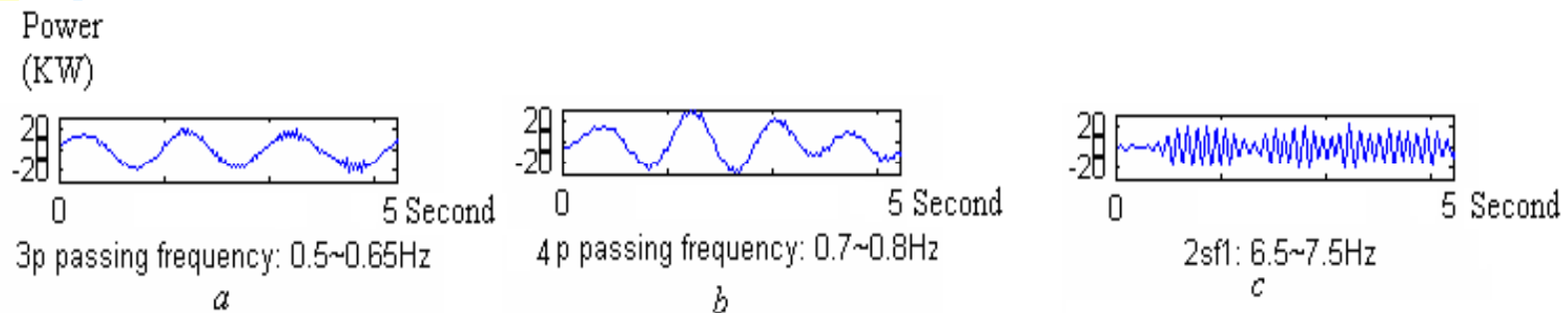
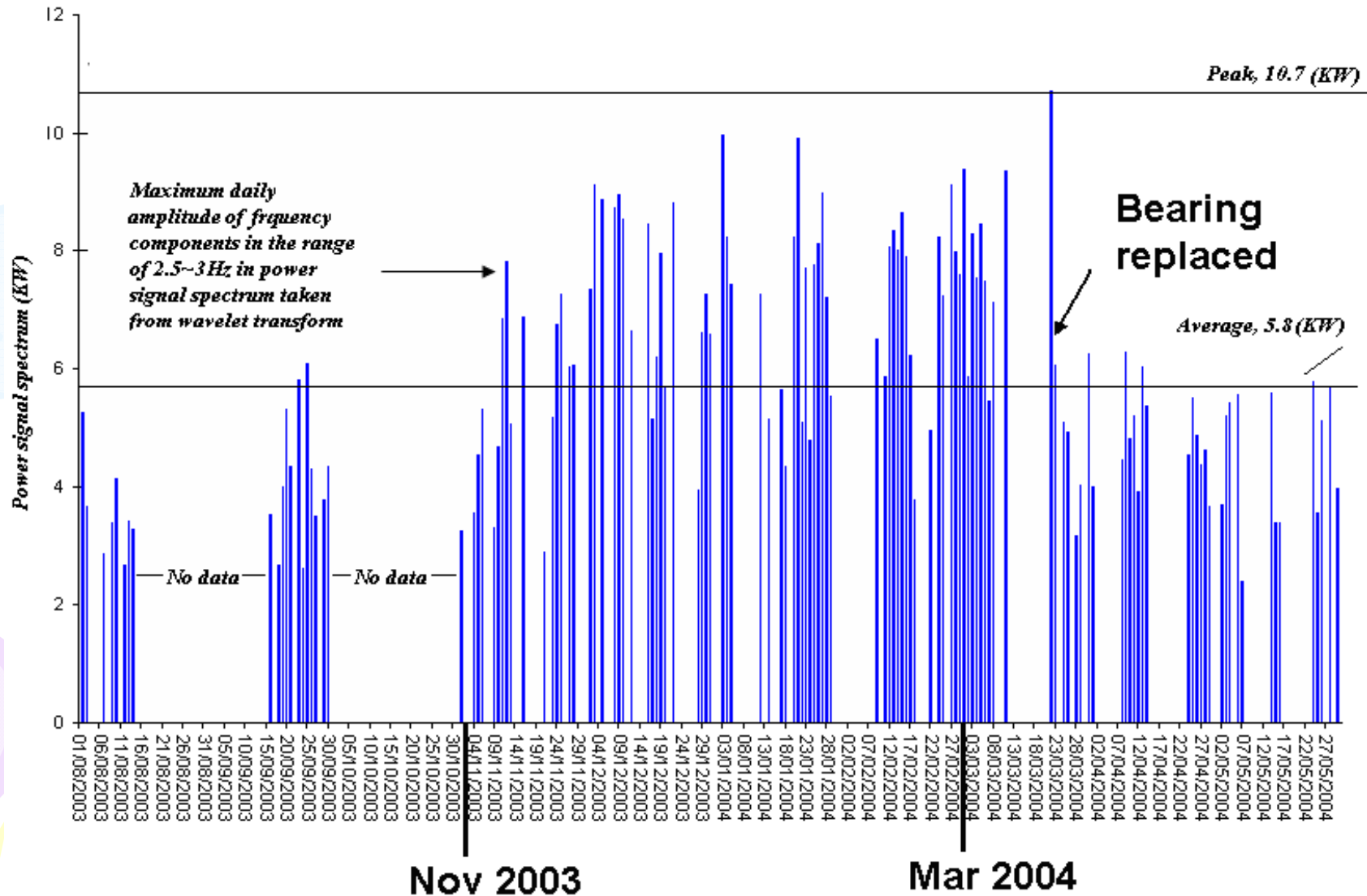


Figure 2. Vibration signals due to failure modes extracted from power data using Morlet wavelet transform

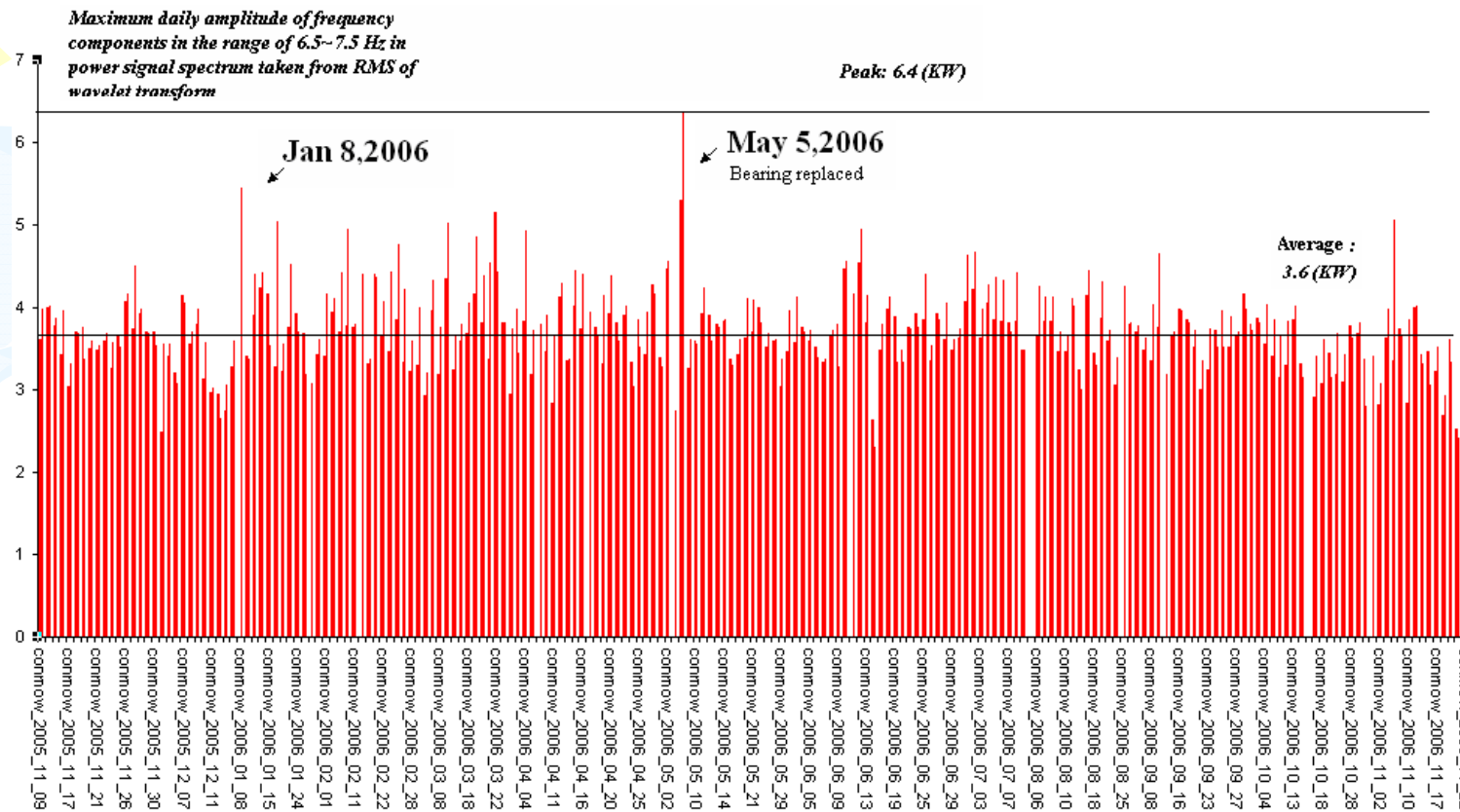
4. Application to wind turbine signals

Daily 2s frequency components of turbine spectrum of power
(i) GE turbine at Zoetermeer, South Holland



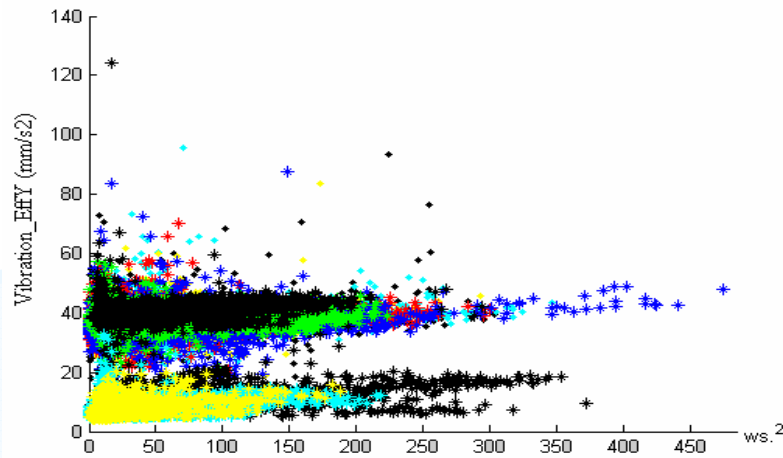
4. Application to wind turbine signals

Daily 2s frequency components in turbine spectrum of power
(ii) Nordex turbine 8 at Wieringermeer, Holland

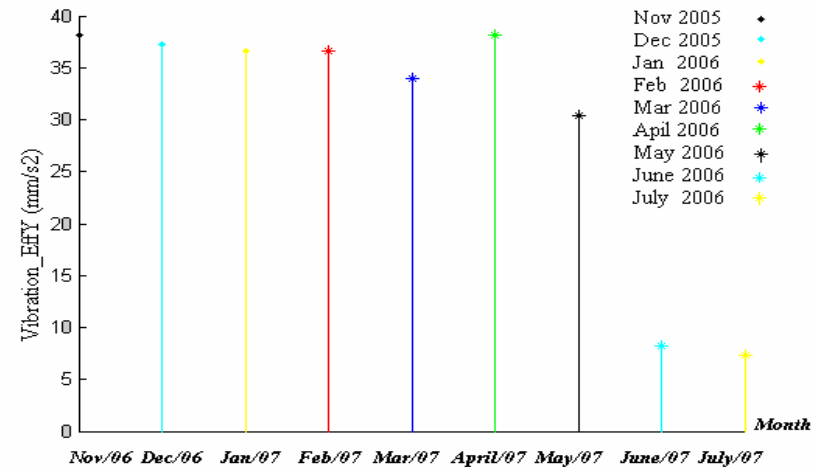


5. Statistical data analysis of nacelle lateral vibrations

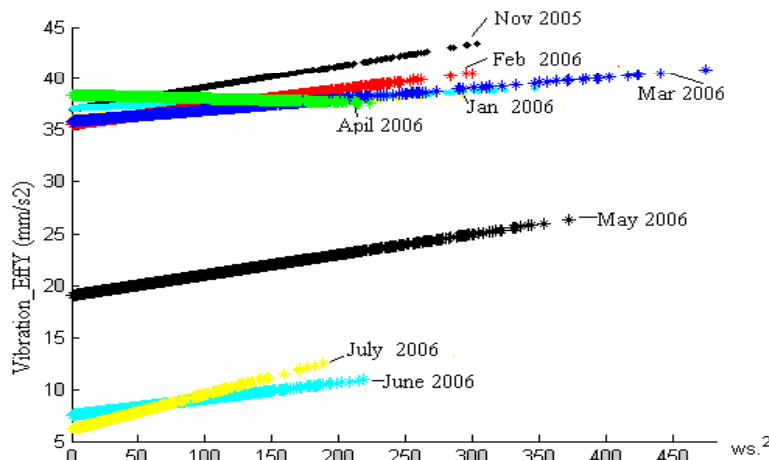
Nordex turbine 8 at Wieringermeer, Holland



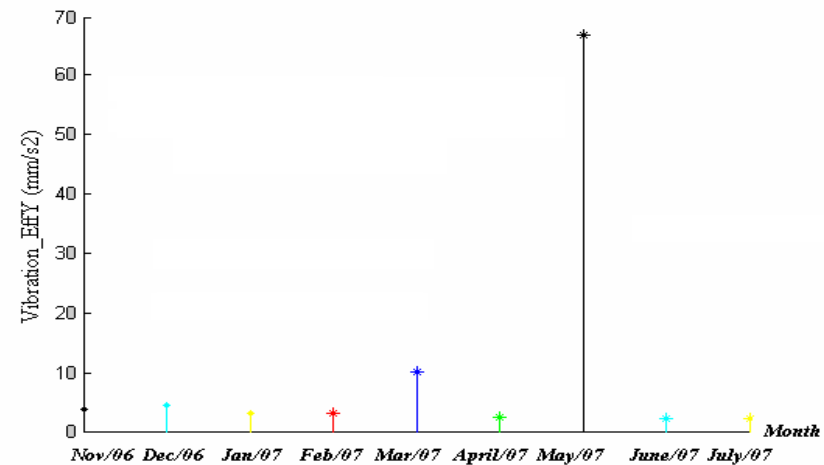
(a) Raw vibration data from nacelle lateral accelerometer



(b) Mean of raw vibration data



(c) Statistical filtering of raw vibration data



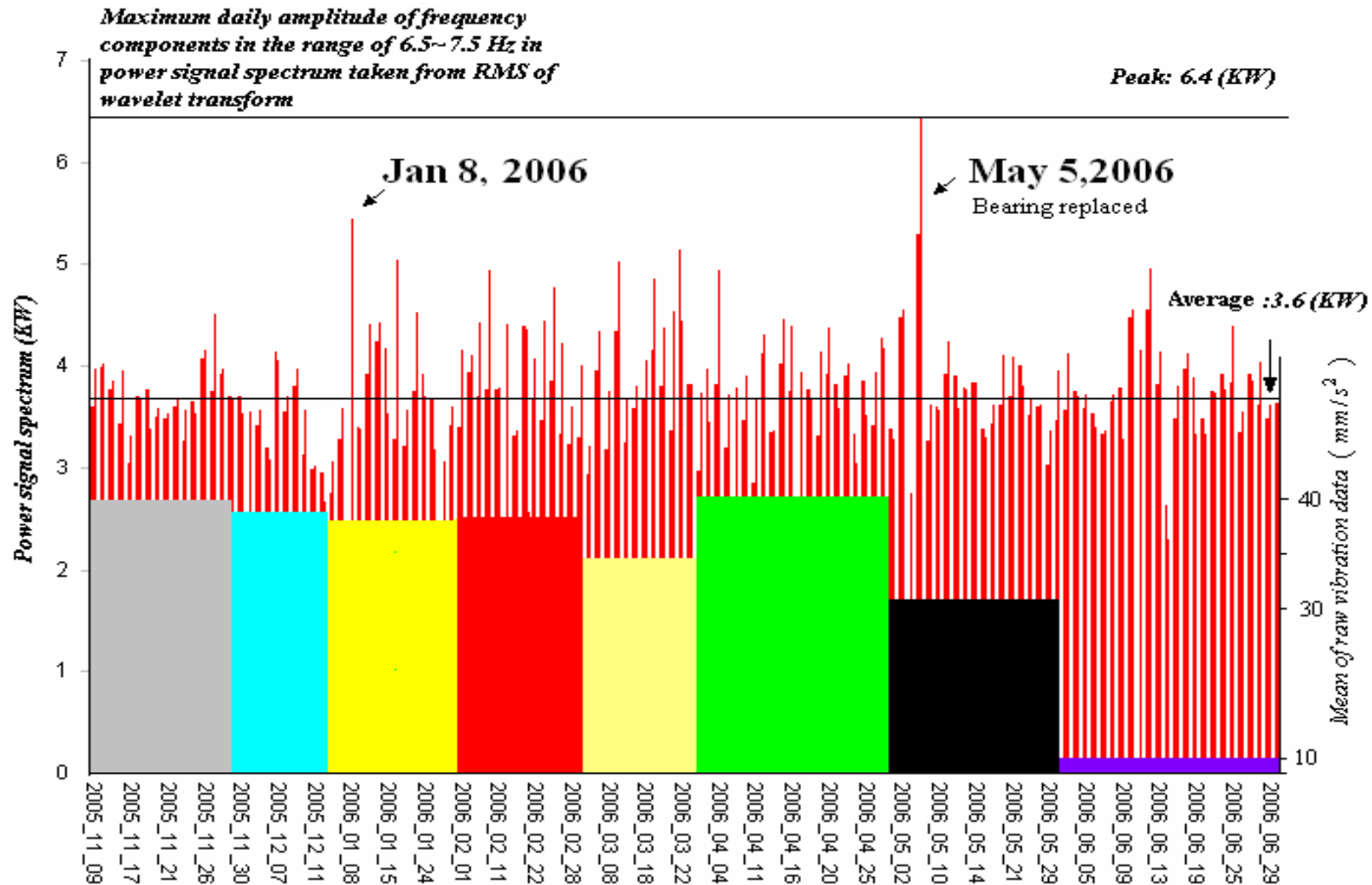
(d) Standard deviations of raw vibration data

High nacelle lateral vibration caused by generator misalignment

4 & 5. Both Methods

Daily frequency components in turbine power signal spectrum
With superimposed, nacelle lateral vibrations

Nordex turbine 8 at Wieringermeer, Holland

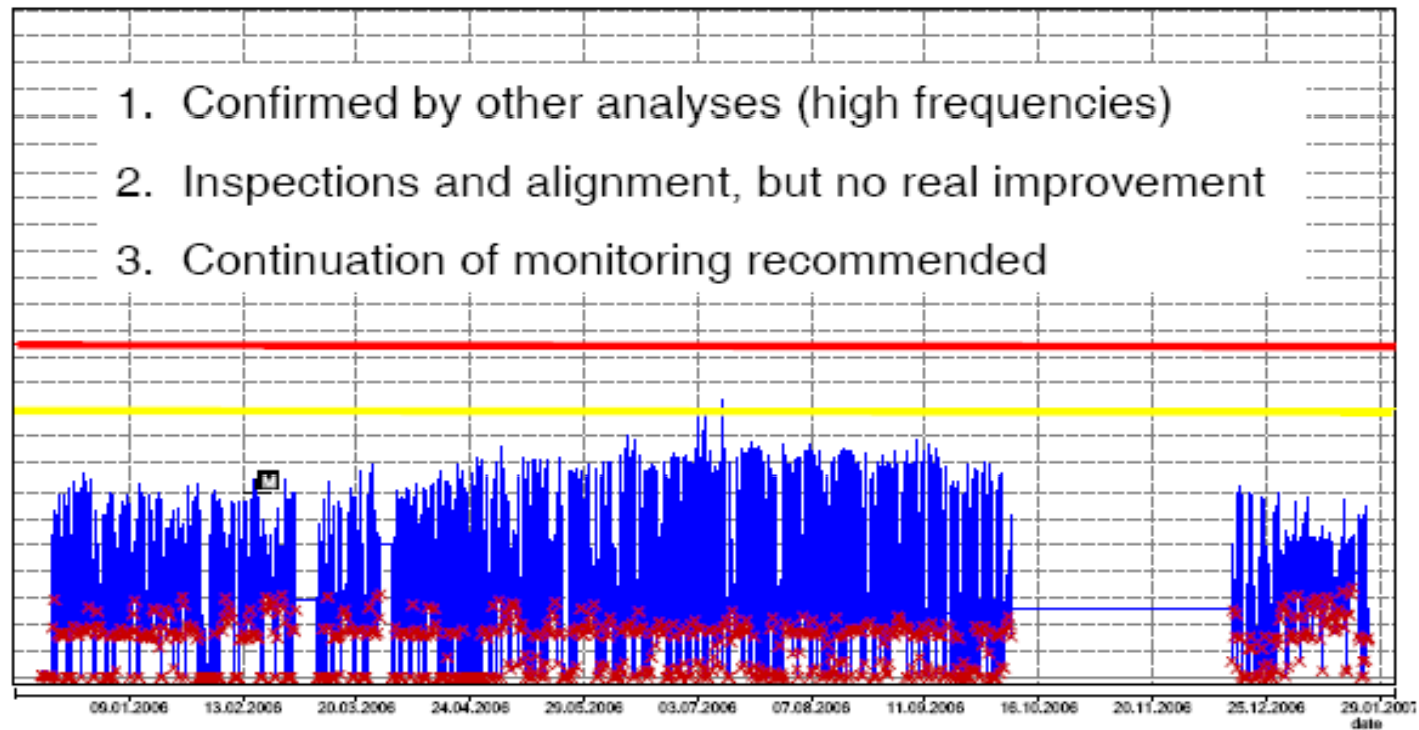


5. Comparison with other data

Vibration measurements from Prüftechnik GmbH
Nordex turbine 8 at Wieringermeer, Holland



Results: High vibration level generator (Turbine 8)



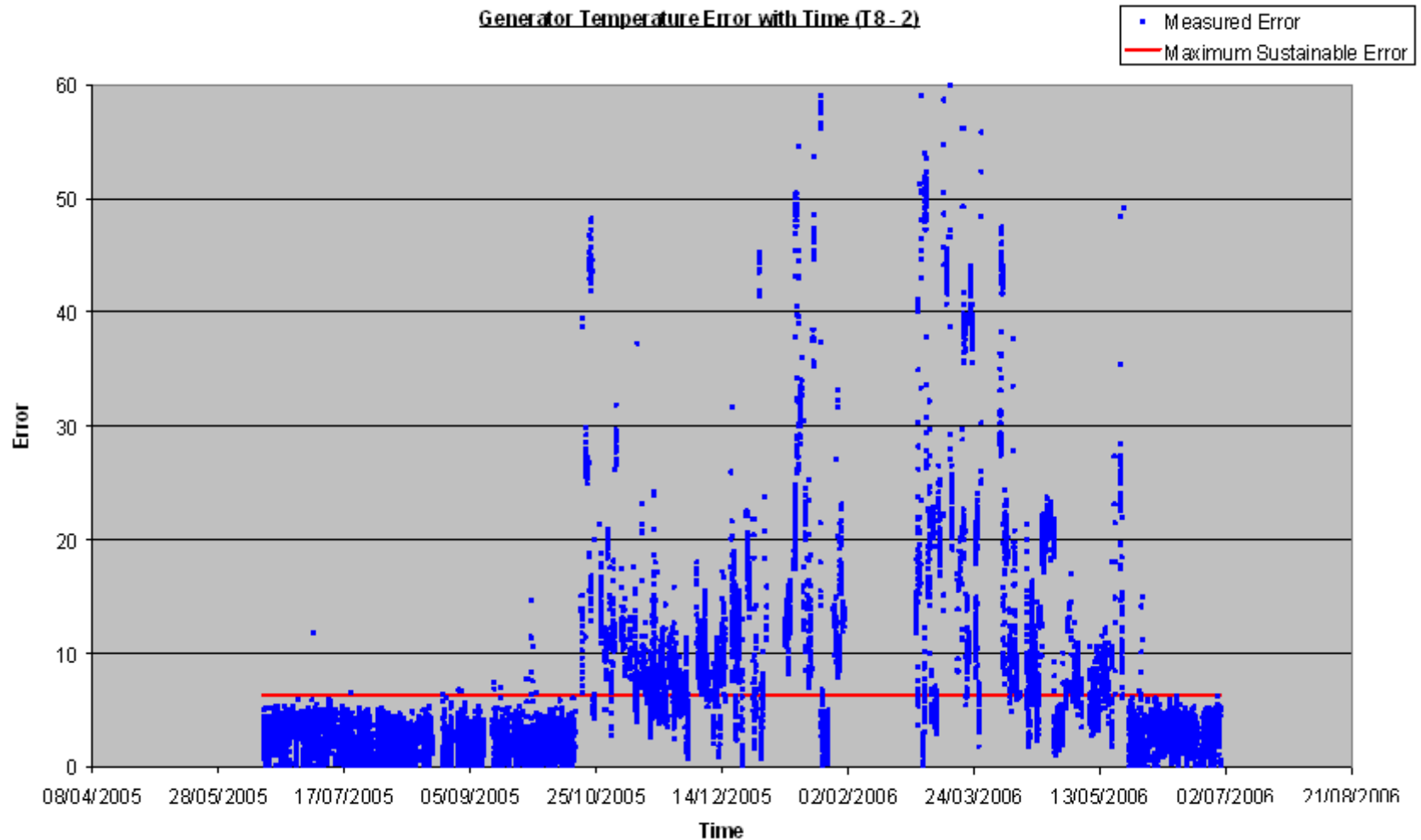
5. *Comparison with other data*

Generator bearing temperature error

from long-term trend with time

Nordex turbine 8 at Wieringermeer, Holland

Generator Temperature Error with Time (T8 - 2)





6. *Conclusions*

- Electrical power can be used for condition monitoring of variable-speed wind turbines, see Jefferies and Infield.
- Power amplitude transformed by a Morlet wavelet provides 2s vibration information relevant to generator failure modes in both time and frequency domain.
- Monthly mean model results of nacelle lateral vibration signal are a useful additional signal for condition monitoring.



7. Potential topics for research and development

- *Investigation on vibration information of wind turbine failure modes in both frequency and time domain, e.g. spectrum of other wind turbine elements and relationship between physical parameters of wind turbines.*
- *Experimental proof of the frequency component theory for the turbine power presented*
- *Develop commercial software to incorporate Morlet wavelet transforms into the condition monitoring of turbine power signal.*
- *Develop the monthly mean analysis, demonstrated here, into a daily mean analysis to improve detection problems (See a recently developed example from Hagshaw Hill wind farm, e.g. daily_power_curve_monitoring.camrec)*



Acknowledgements

We would like to acknowledge the invaluable assistance of Professor Prof. Peter Tavner and Mr Michael Wilkinson for information and discussion.