LOAD MONITOR 2

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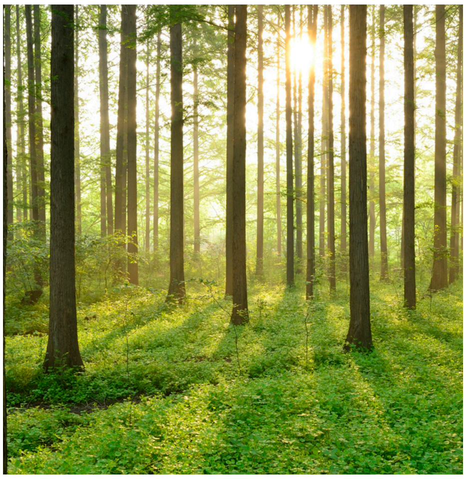

VINDFORSK

Energiforsk

Load Monitor 2

Measuring and modeling vibrations and loads on wind turbines

Part 2: Concepts for monitoring loads on towers and foundations

INGEMAR CARLÉN

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Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Förord

LoadMonitor – Mätning och modellering av vibrationer och laster på vindkraftverk" är ett projekt finansierat av Energiforsk och Energimyndigheten genom programmet Vindforsk IV.

Projektets övergripande mål är att öka kunskapen om hur turbinlaster och turbinprestanda påverkas av svenska klimat-, skogs och terrängförhållanden.

Med hjälp av nacellemonterad lidar, SCADA systemet och ett egenutvecklat vibrationsmätningssystem har man dels undersökt kopplingen mellan den ostörda vinden och vibrationer i nacellen (del 1) och dels hur man på ett kostnadseffektivt sätt kan mäta laster i strukturen (del 2). Sist men inte minst har man genom projektet fått möjlighet att validera en strömningsmodell över skog som är av stort värde då en stor del av den svenska vindkraften är placerad i skog.

Projektet har utförts av Kjeller Vindteknikk, Uppsala Universitet campus Gotland och Teknikgruppen med stöd av Stena Renewable.

Göran Dalén

Ordförande, Vindforsk IV

Sammanfattning

Merparten av alla vindkraftverk som installeras idag är utrustade med olika typer av övervakningssystem vars syfte är att tidigt upptäcka om en del eller en komponent är i behov av service eller måste bytas ut. Om dessa behov identifieras i god tid så kan man effektivare planera underhåll och undvika kostsamma skador. Dessa system är i allmänhet inte fullt utvecklade när det gäller att bedöma risken för framtida skador beroende på särskilda vind-förhållanden på platsen, eller på att vindkraftverkets styrsystem inte är optimalt inställda.

Ett sätt att bättre förstå vilka belastningar ett specifikt verk utsätts för, är att övervaka lastnivåer i huvudkomponenter som rotor, drivlina, torn och fundament. Direkta mätningar av laster med traditionella metoder är komplicerade och kostsamma, varför sådana görs endast i samband med särskilda undersökningar. Ett intressant alternativ är därför att försöka beräkna approximativa lastnivåer med hjälp av signaler som regelmässigt samlas in från varje verk via SCADA. Denna rapport beskriver metoder att med god noggrannhet approximera lastvariationer i torn och fundament, med utgångspunkt från generatoreffekt samt maskinhusets accelerationer i två riktningar. Resultaten bygger på såväl aeroelastiska simuleringar, som på mätningar från ett vindkraftverk i skogsterräng.

Eftersom vibrationsmätningar med tillräcklig upplösning sällan varit tillgängliga via SCADA förrän helt nyligen, så diskuteras här även metoder och system för att utföra kompletterande mätningar av accelerationer i nacellen. Systemen bygger på modern accelerometerteknik med digital kommunikation, samt små robusta sk. *enkortsdatorer.* För några alternativ presenteras även kopplingsschema, mönsterkortsdesign samt källkod.

Summary

A majority of the wind turbines that are being installed today are equipped with monitoring systems in order to facilitate early detection of component wear or system malfunction. The collected information is very useful for efficient planning of service actions, and as a basis for decision regarding component replacement. However, these systems are generally not designed to collect data useful when assessing remaining component lifetime, depending on the site conditions or non-optimal control system configuration.

One way to better understand the loading conditions for a specific wind turbine is to monitor the load levels in major components such as the rotor, drive train, tower or foundation. Direct load measurements are generally complex and costly, why these are conducted only to support specific investigations. An attractive alternative is then to try to derive approximate load signals from the SCADA data that is collected and stored on a regular basis.

The present study aims to describe methods to calculate approximate time histories of loads on tower and foundation, based on high resolution power and vibration data. The results are based on time domain aeroelastic simulations, as well as on direct measurement from a wind turbine operating at a forested Swedish inland site.

Since nacelle acceleration signals of sufficient resolution are rarely available through SCADA, various design options for portable vibration measurement systems were are explored. The main idea is to base the design on modern sensitive microelectromechanical components connected to standard single board computers via serial communication. Schematics, circuit board layouts and source code for some designs are presented.

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1 Introduction

Monitoring of wind turbines and wind farms has become a strong focus area in recent years. The main target is to reduce operational costs by improving the planning of maintenance, and to detect possible signs of degradation before a complete failure of a specific component. Another reason to ensure high quality of the various sources high frequency streaming wind farm data, and to spend time on advanced signal processing, is the possibility to identify and turbines that are underperforming.

In addition to the information collected by Condition Monitoring Systems (CMS) and Structural Health Monitoring (SHM) systems, a wind farm operator can chose to collect and store data that can be used for Load Monitoring. These sets of identified data can then be used for relative comparisons, where estimated component loads can be compared between different turbines in a wind farm, or with turbines of similar type in any other farm. Depending on the availability of technical information, a comparison with certified load spectra may be performed.

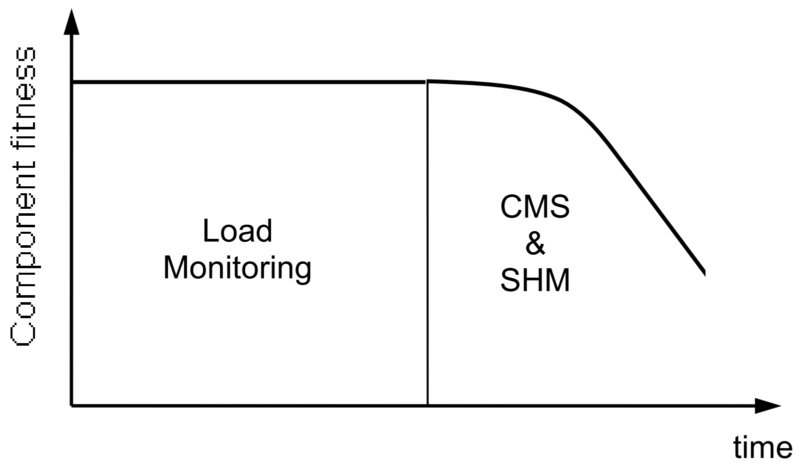

Figure 1-1. The life of a wind turbine component

A wind farm is by many owners regarded as an asset among others in an investment portfolio. This means that it can be traded on the market based on reasons behind individual investment strategies. A potential buyer then have to conduct a thorough investigation of the actual farm, including full survey of the overall turbine conditions, and ultimately try to define the number of years of profitable operation that can be expected. In cases where the remaining life time of main components cannot be properly assessed, this will be treated as a considerable risk in the total asset evaluation, and the price tag should be adjusted accordingly.

In the present study, Load Monitoring of wind turbine towers and foundations will be in focus. The underlying work will be based on results from aeroelastic load simulations, as well as analyses of high quality load measurements from a Swedish test site. Finally, autonomous measurement systems for flexible measurements of nacelle vibrations are developed and discussed.

2 Aeroelastic load simulations

Time domain aero-hydro-servo-elastic system simulations have during the past 30 years formed the core of modern wind turbine design and R&D activities. The dynamic equations describing the mechanical behaviour/interactions of subsystems and the influences from the environment (air/water flow, gravity) can today be conveniently solved by advanced time stepping numerical schemes. Software tools for wind turbine system simulation have mainly been developed by universities, research institutes and wind energy consultants, and there have been several international benchmark- and collaboration projects targeting this development [1][2].

Teknikgruppen have since 1982 continuously developed the aeroelastic code Vidyn [3], which has over the years been used within numerous commercial and R&D projects. In the present study Vidyn was used to initially explore the relations between standard wind turbine SCADA signals (~1 Hz), and the corresponding dynamic loads one tower and foundation.

Since the conclusions of the initial investigation are not expected to depend on turbine size, but should apply to any 3-bladed model with tubular tower, variable speed, pitch control, and fixed yaw system, the popular NREL 5 MW benchmark turbine was here chosen [4].

In order to sufficiently cover the wind speed range from cut-in to rated wind speed, seven 10 min turbulent wind fields were simulated (5-11 m/s , IEC turbulence class B [5]).

Table 1. Turbulence parameters (Kaimal model) for the 7 wind field simulations.

Case/seed	U	σ_u	σ_v	σ_w	L_u	L_v	L_w
1	5	1.31	1.05	0.65	340.2	113.4	27.7
2	6	1.41	1.13	0.71	340.2	113.4	27.7
3	7	1.52	1.22	0.76	340.2	113.4	27.7
4	8	1.62	1.30	0.81	340.2	113.4	27.7
5	9	1.73	1.38	0.86	340.2	113.4	27.7
6	10	1.83	1.47	0.92	340.2	113.4	27.7
7	11	1.94	1.55	0.97	340.2	113.4	27.7

The turbulent wind fields where used to run a corresponding set of Vidyn simulations, where loads, vibrations etc. was written to results files. The time series of electrical power and tower bottom for-aft bending moment respectively (7x10 min), where then processed to a set of 70 1min averages, presented in Figure 2-1. A fitted 2nd order polynomial was then used to map power to tower bending moment, and the results for mean wind speeds 6 m/s and 9 m/s respectively are shown in Figure 2-2 and Figure 2-3.

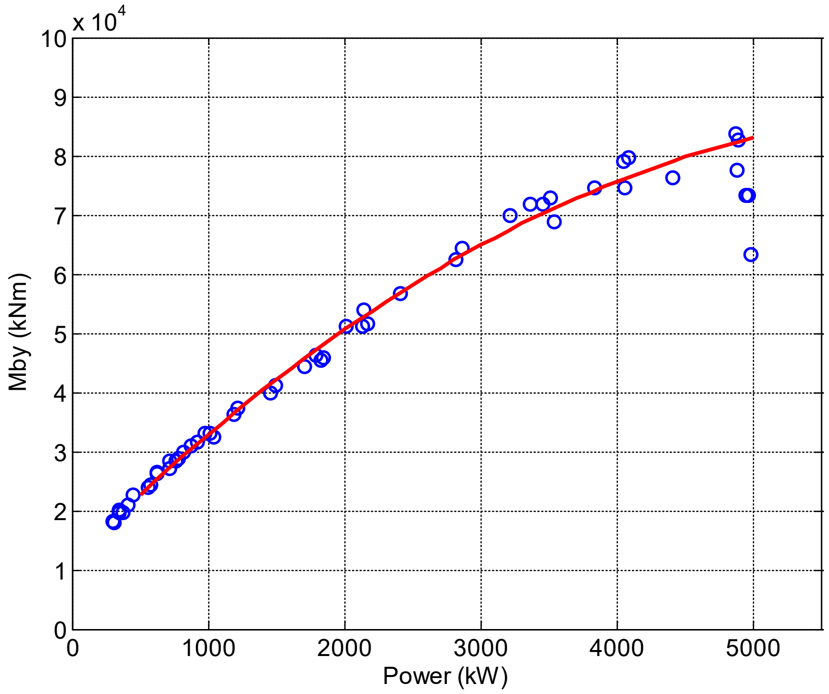

Figure 2-1. Simulated tower bottom for-aft bending moment vs. electrical power (1min averages) together with a 2nd order polynomial fit valid for situations below rated power.

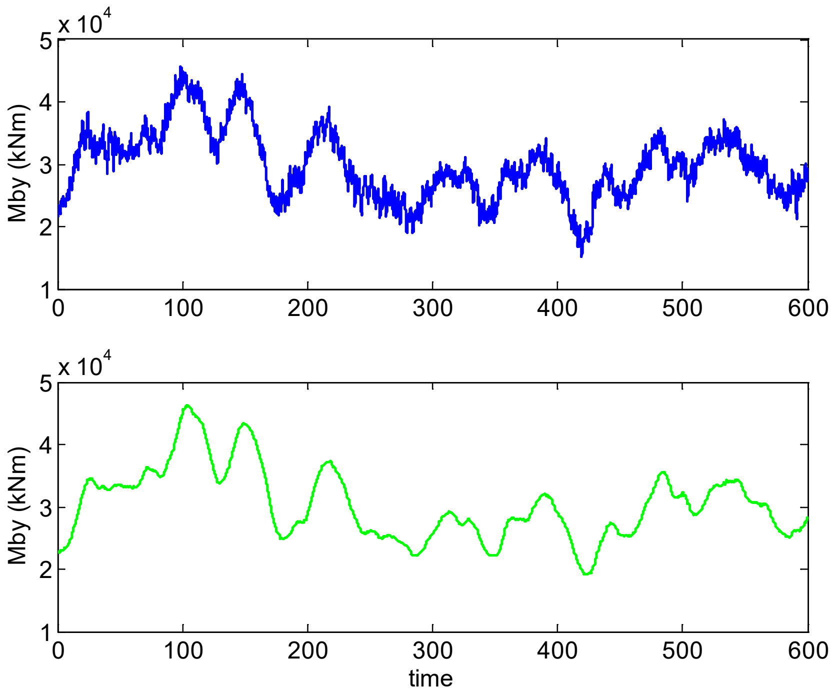

Figure 2-2. Tower bottom for-aft bending moments (blue) simulated, and (green) approximated from electrical power (6 m/s mean wind)

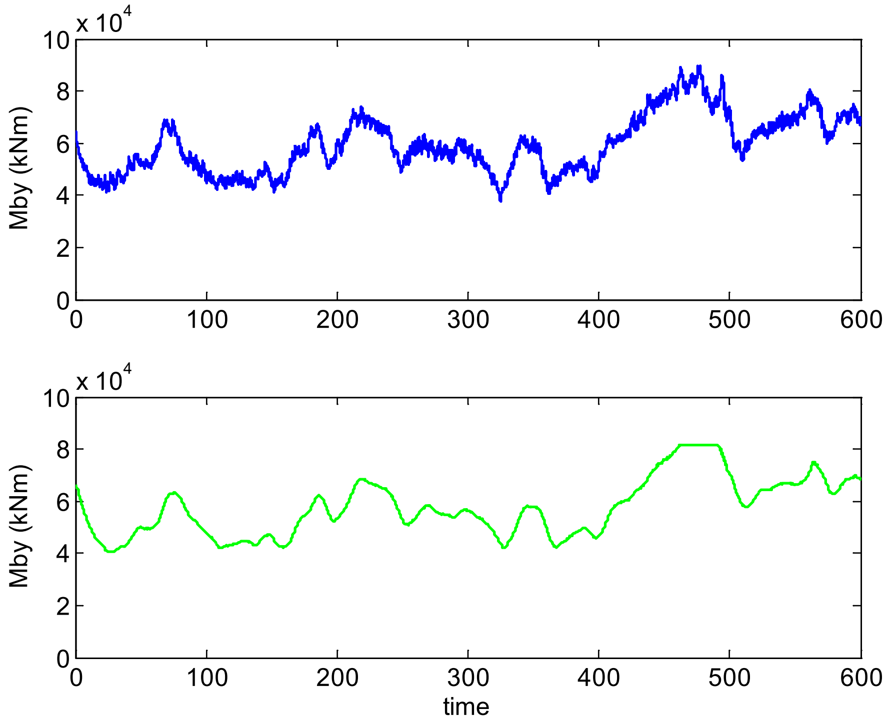

Figure 2-3. Tower bottom for-aft bending moments (blue) simulated, and (green) approximated from electrical power (9 m/s mean wind)

It is seen that the power signal can be used to successfully approximate the for-aft tower bottom bending moment for wind speeds below rated wind speed. The larger load cycles caused by rotor thrust variations due to large scale turbulence, is clearly captured, while the high frequency variations are absent. One can either argue that the small load variations will lead to stress cycles blow the fatigue endurance limit of welded joints or reinforcement members, or try to add those as well from other sources.

In Figure 2-3 it is also seen that the approximated load signal is flattened out at the higher peaks due to pitch control actions in order to remain at rated power. The consequences of pitch control will be discussed in the next section.

3 Load and SCADA measurements at the Ryningsnäs test site

During 2009, Vattenfall did field measurements on two Nordex N90 wind turbines near Ryningsnäs in the south-east of Sweden. The experimental work, which was done in collaboration with Energy Research Centre of the Netherlands (ECN), comprised load measurements (tower, main shaft and blades) on both turbines, and wind measurement in a 120 m met mast erected nearby.

An important difference between the two turbines was the tower heights, 80 m and 100 m respectively. The campaign continued for ~13 months, and produced the first full data set for turbines operating over the Scandinavian pine forest.

Figure 3-1. The Ryningsnäs wind farm seen from the air.

In a similar way as for the aeroelastic simulations discussed in the previous section, a set of 1min averages of power and for-aft tower bottom bending moments was created. For this task data corresponding to a couple of days were used (south-west sector, varying wind speeds, the N90-100 turbine). The fitted relations (3rd order polynomial + stepwise linear) are shown in Figure 3-2. In this case the rotor thrust is compared (tower bottom bending moment divided by tower height). The result is here similar to what was seen in Figure 2-1,

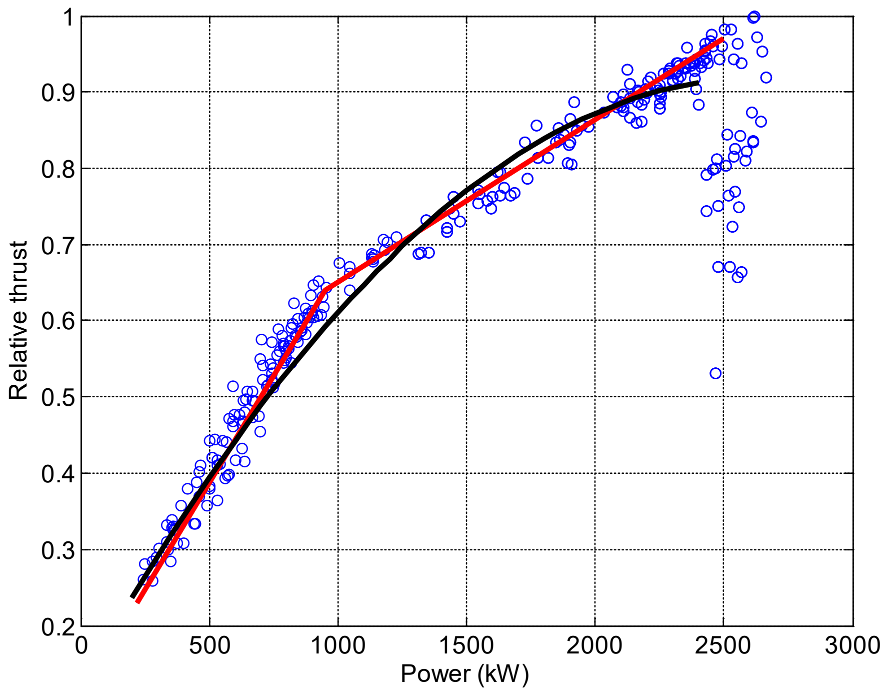

Figure 3-2. Measured tower bottom for-aft bending moment vs. electrical power (1min averages)

For the measured data the goal is now to find also a relation between nacelle vibrations and tower base bending moments. The first step is then to take a look at the side-side motion of the tower. In the upper plots of Figure 3-3, tower bottom side-side bending moments are compared to lateral nacelle vibrations. Some common content can here be identified, but after applying a band-pass filter (± 8% around the tower resonance frequency), the signal patterns become more or less identical (lower plots). The main difference between the filtered and unfiltered bending moments can now be identified as the rotor torque. The procedure is then to identify the constant that maps the filtered lateral nacelle acceleration on to the torque-less side-side tower bottom bending moment, and then add the rotor torque on top. For the high frequency content of the approximated for-aft tower base bending moment, the same constant can be applied. In practice there is here also dynamic content originating from the rotor dynamics, but in the current context they are believed to be of minor importance.

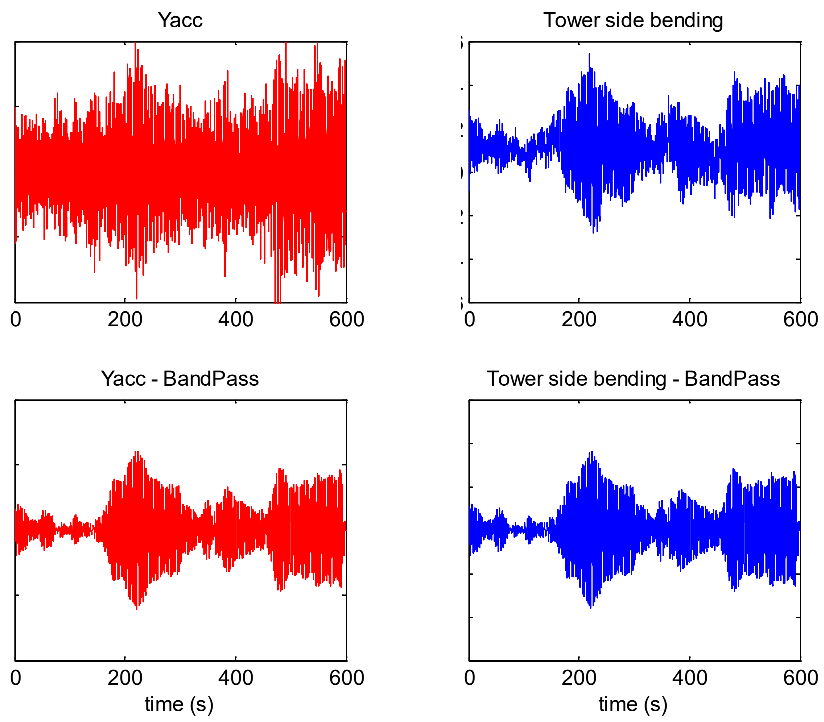

Figure 3-3. Lateral nacelle acceleration and tower base side-side bending moment before (above) and after (below) applying a band-pass filter.

The developed procedures to derive approximate tower loads from SCADA power and nacelle vibration signals were subsequently compared with sequences of measured data from the N90-100 turbine. The results are presented in Figure 3-4 Figure 3-7. In order to account for the consequences of blade pitching on the rotor thrust force, a simple two parameter model (-k1*pitch^k2) was here fitted to the measurements.

As a conclusion from the comparisons between the measured and approximated tower loads presented above, rather detailed monitoring of tower and foundation loads is possible, given that the data needed is available. Here SCADA power of ~1 Hz will be sufficient, but in order to succeed with the band-pass filtering, nacelle vibration signals should have a resolution of 15-20 times the tower frequency (e.g. 2.5 – 5 Hz).

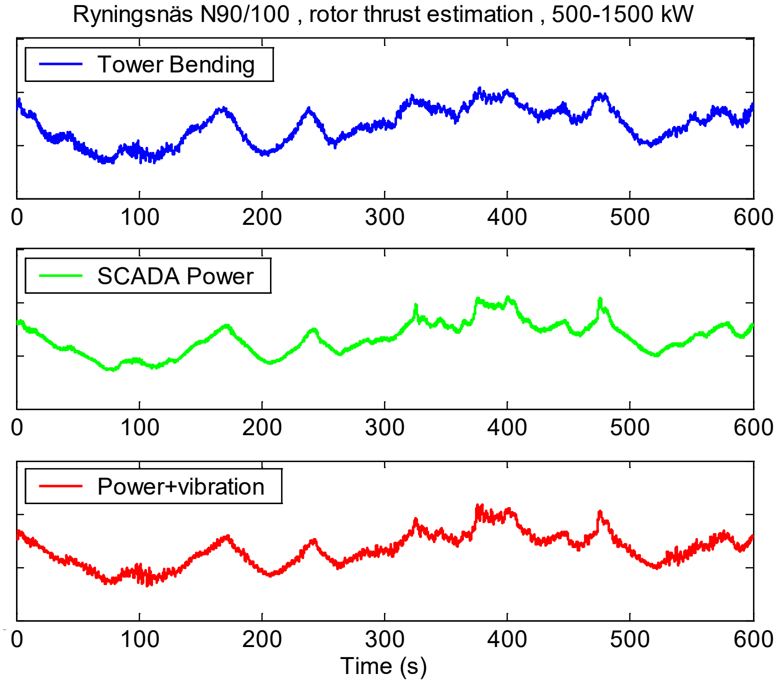

Figure 3-4. Measured rotor thrust compared with approximated signals (in two steps – 500-1500 kW)

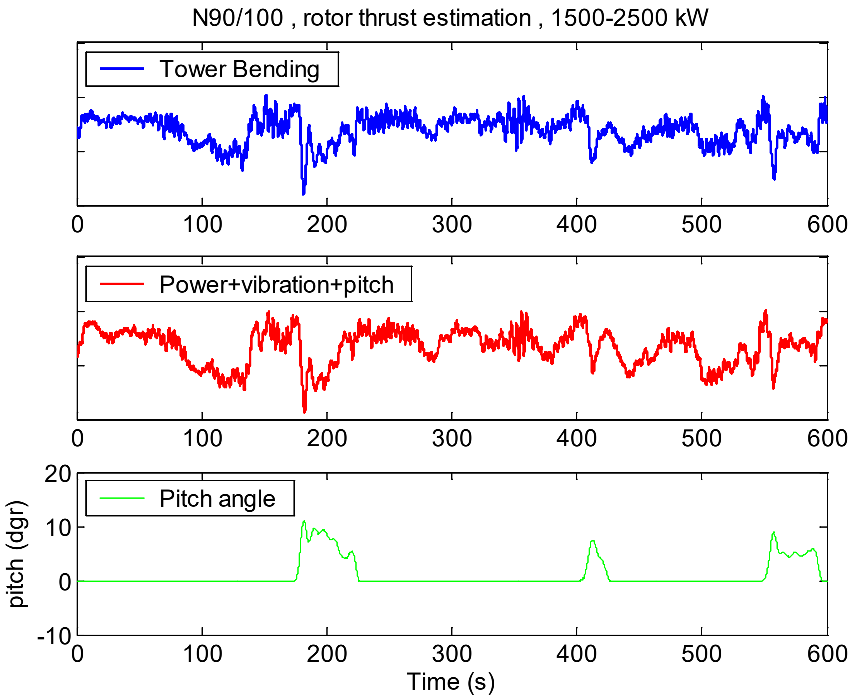

Figure 3-5. Measured rotor thrust compared with approximated signal (with pitch angle – 1500-2500 kW).

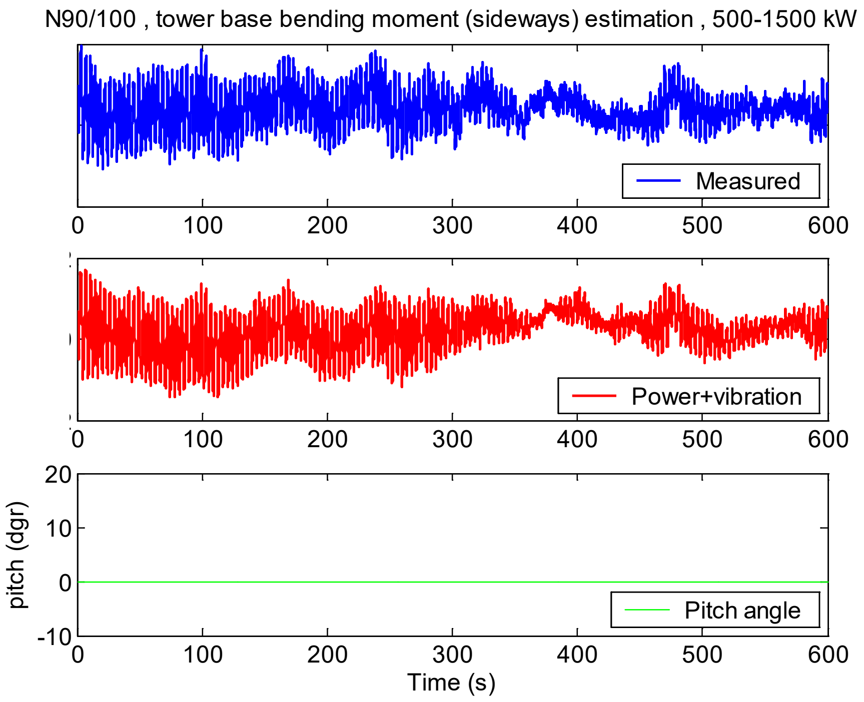

Figure 3-6. Measured side-side tower base bending moment compared with approximated signal (with pitch angle - 500-1500 kW)

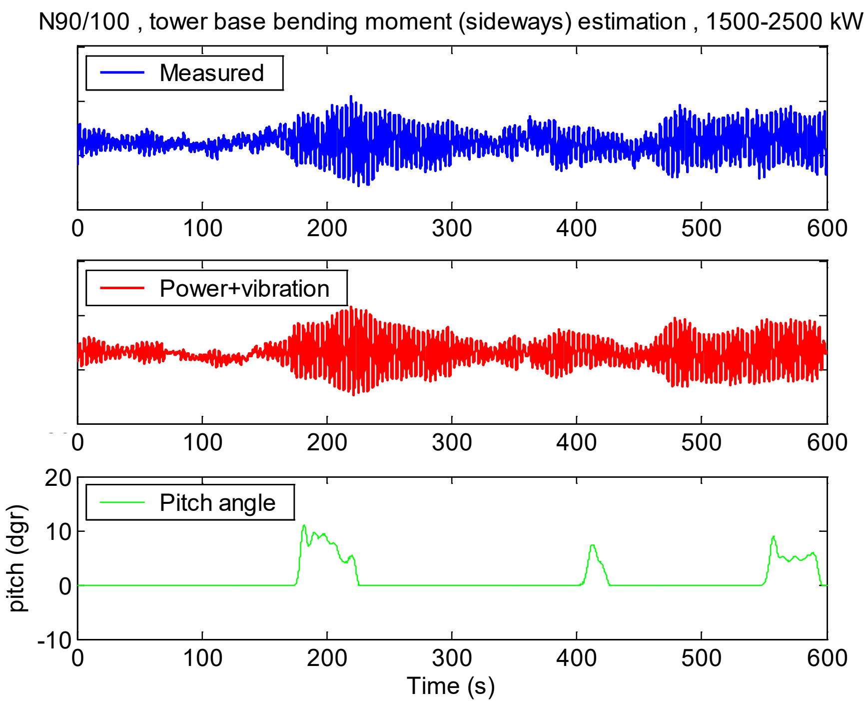

Figure 3-7. Measured side-side tower base bending moment compared with approximated signal (with pitch angle - 1500-2500 kW)

4 Concepts for vibration measurements

Traditionally wind turbine nacelle vibrations are measured using so called servo accelerometers that are screwed to the nacelle main frame. The tower top vibration signals are then used for various purposes in the safety system and control system respectively. However, accelerations of any useful resolution are rarely available through the standard SCADA interface. In case a detailed turbine investigation requires nacelle vibrations to be measured, then additional measurement systems are costly and the corresponding system design and installation work require trained personnel.

In this case, the availability of an autonomous compact system that is easy to install, will lower the threshold to actually complete a measurement campaign. If logger and sensor can be accommodated in a small robust cabinet, with just a low voltage power cable to be attached, then the installation could be performed by an ordinary service technician doing scheduled routine work.

For this purpose, the servo accelerometer is not suitable due to the size and requirement for special purpose (odd voltage) stabilized power supply. In addition the servo accelerometers are expensive and may need regular service if moved around.

There has been a rapid development of Microelectromechanical components (MEMS) that can measure very small acceleration levels at low frequencies. In parallel, the development of wind turbines towards larger sizes also means new requirements on the sensors used. After scanning the world market for a MEMS sensor suitable to measure nacelle accelerations of a modern wind turbine, the choice finally fell on the SCA103T-D04 from Murata. The main features that was taken into account here were: a) analogue as well as digital data communication (serial – SPI), b) a small footprint for convenient circuit board design, c) a sufficient resolution (<0.1 mg), d) linear characteristics down to 0 Hz (DC), e) standard low demand 5V power supply.

4-1. A standard servo accelerometer (left) and the SCA103T-D04 uni-axial accelerometer/inclinometer.

A first test of the SCA103T-D04 as dual axis nacelle accelerometer was a 7 months campaign in a wind turbine at a Swedish inland site **[6]**. This initial setup was based around a standard Campbell CR1000 analogue logger. This test indicated very good reliability and sufficient resolution/sensitivity. However, as described in the data sheets, the sensor suffers from some internal dynamics around 11 Hz, which means that it is not suitable when frequencies above ~5-6 Hz are of interest.

Electronic components as the SCA103T-D04 are designed to work with standard low demand power supplies and established communication protocols, which make them suitable for integration with small single-board computers, such as the Raspberry PI (developed by the Raspberry PI foundation). A big internet community as well as the availability of well tested software libraries, here made the PI computer the choice for the initial development of a portable nacelle vibration measurement device.

The PI can communicate with the SCA103T-D04 via the SPI protocol, and for this purpose, a conceptual logger software was here developed using the Python programming language (see listing in Appendix A).

Since the Raspberry PI uses 3.3 V for SPI communication, two level-shifters are here included to lift the voltage up to 5 V as required by the SCA103T-D04. The schematic of the PI-based design is shown in Figure 4-3.

The final step is then to develop a circuit board layout that can fit the connections and geometry of the single board computer, ultimately forming a sandwich style design. This task was here completed through combining the EDA software (Electronic Design Automation) KiCad (schematics), and the PCB tool (Printed Circuit Board) Xpedition. The result is a two layer compact board that fits exactly the mounting footprint and the pin connection of the Raspberry board (see Figure 4-2 and Figure 4-4)

Xpedition can write production files so even small number of units can be ordered from different companies (on line service) for quick delivery and to a reasonable cost per board. However, ordering complete boards (with components – soldered) will probably require a larger number of units.

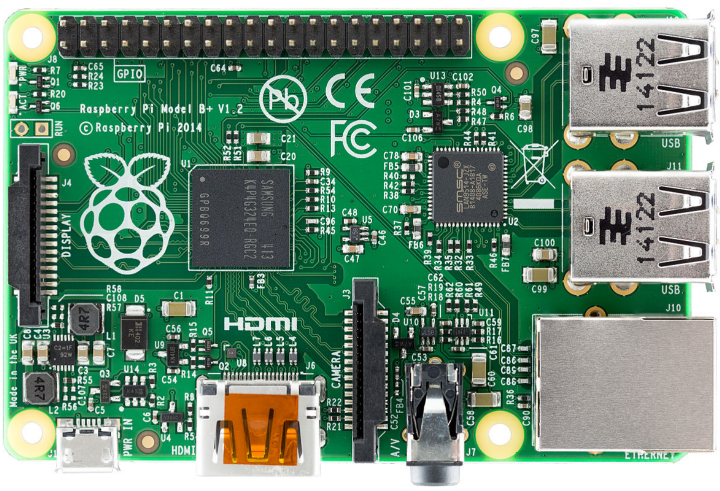

Figure 4-2. The raspberry PI single-board computer.

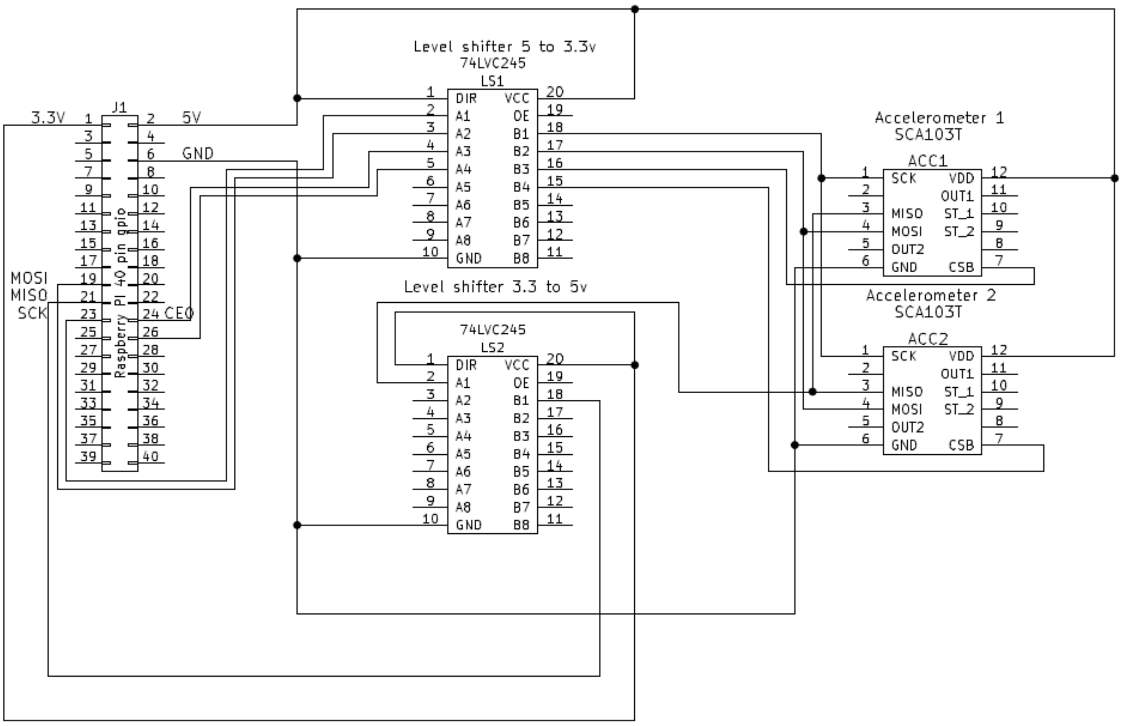

Figure 4-3. Schematic of the Raspberry/SCA103T-D04 design

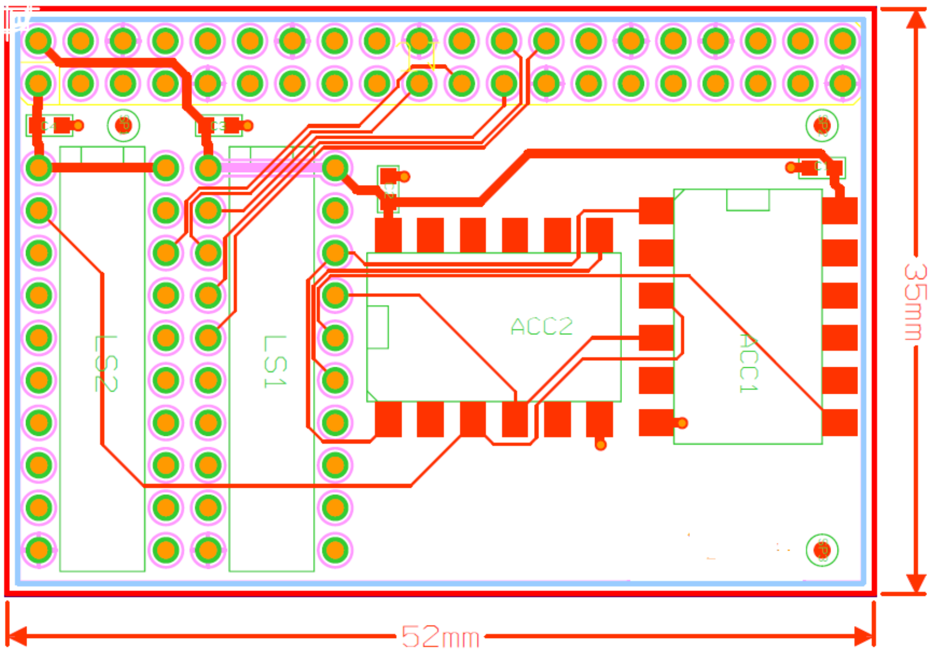

Figure 4-4. Principal dual layer Raspberry circuit board design based on the schematic in Figure 4-3 .

An alternative choice for a single board computer may here be the Arduino UNO. Arduino is a company which manufactures small microcontrollers that are distributed as *open source hardware*. This open architecture has resulted in a large and active user community, together with many companies designing and selling hardware that fit to the different Arduino models. Here the Arduino UNO board was tested due to the possibility to end up with a very simple design. The UNO can here handle the serial communication at 5V, and therefor level shifters are not needed.

The Arduino programming language is based on C/C++ syntax and links to many useful software libraries. Use of the UNO for a similar application as presented for the Raspberry PI above might face a restriction in sampling frequency (limited to 30-50 Hz) depending on the storage hardware used. Sample code to set up serial communication with the SCA103T-D04 in the same way as for the Raspberry PI, is presented in Appendix B, and the corresponding schematic is shown in Figure 4-6.

A very recent candidate to optionally replace the PI or the UNO, is the Onion Omega2. The Omega2 is a tiny but powerful Linux computer that has less than ¼ of the size of the Raspberry PI. The very small footprint makes the Omega2 a very interesting candidate when very compact system designs are desirable. Serial communication through SPI can here be achieved using Python code very similar to the solution presented for the Raspberry PI.

All the system designs discussed above will in operation have a very small power consumption. However, since 220V is usually available in the nacelle, the charging and handling of batteries is not worth the extra dimension of independence they bring.

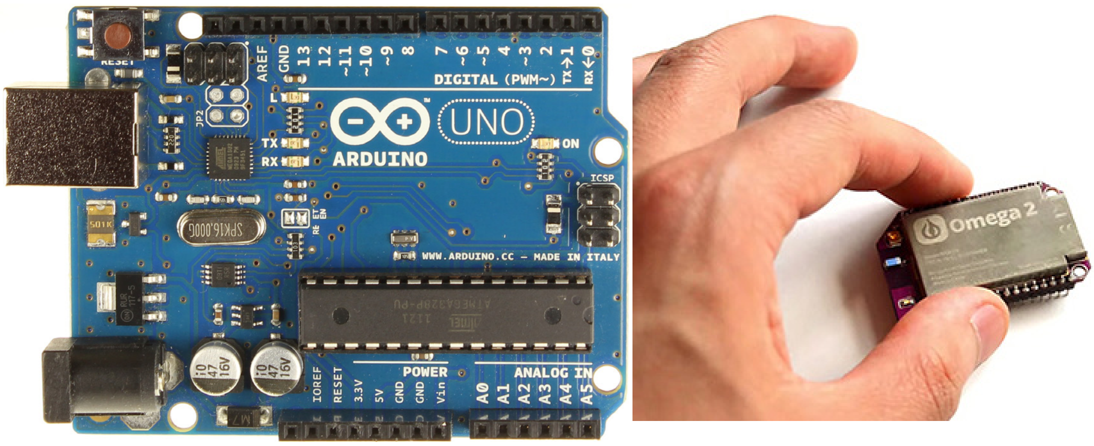

Figure 4-5. Arduino UNO and Onion Omega2 microcontroller boards

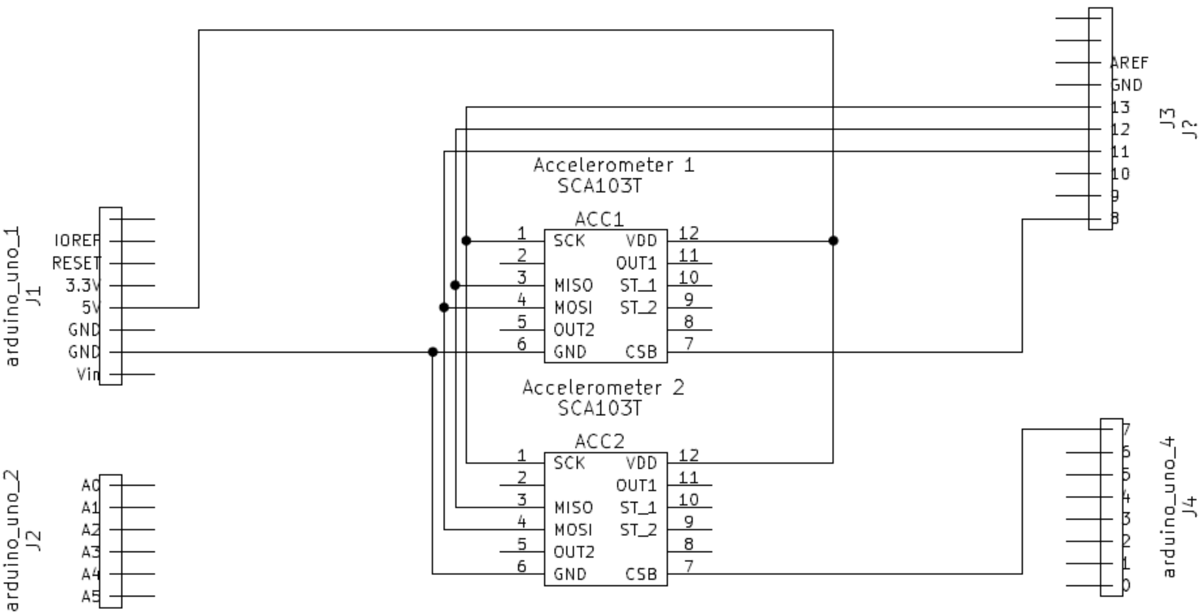

Figure 4-6. Schematic of the Arduino/SCA103T-D04 design

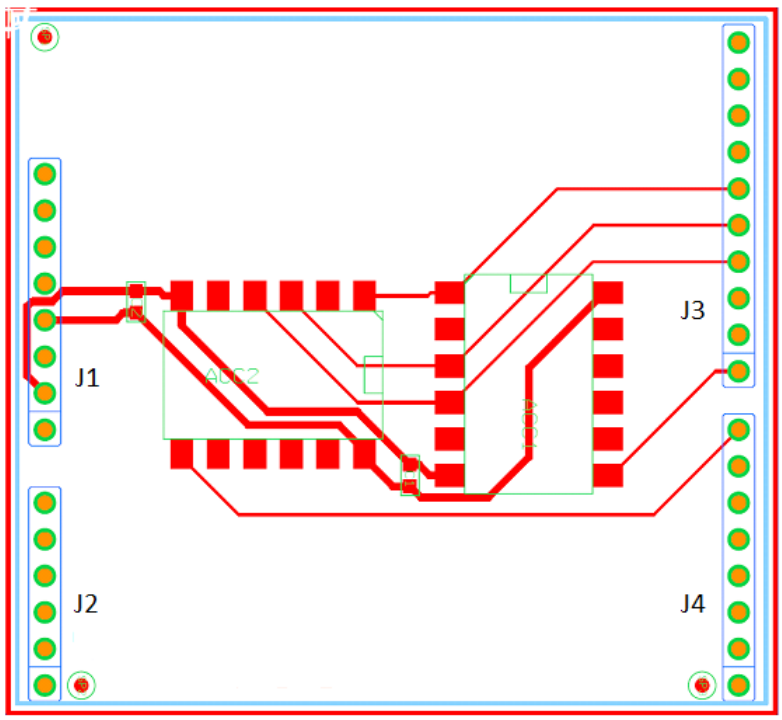

Figure 4-7. Principal single layer Arduino circuit board design based on the schematic in Figure 4-6 .

5 Conclusions

Monitoring of wind turbine fatigue load levels can to some extent be accomplished by processing high frequency SCADA data, such as active power and nacelle vibrations. In the present study focus was set on tower and foundation, but there are more advanced approaches that can be used for other components/cross-sections such as blades, drive train and nacelle main frame. It is here tempting to try methods based on Artificial Neural Networks or similar, but the additional complexity might make them hard to implement in existing monitoring software. Here regression based methodologies are believed to be more robust, simpler to describe and more straight-forward to code.

By extending measurements of nacelle motions to include nacelle roll and pitch angles, there is a potential to also address rotor blade out-of-plane and main bearing loads. Motion Reference Units (MRU's) capable of resolving the very small nacelle rotations of a wind turbine are today available on the market, and it is likely a matter of time before this type of sensors have become common components of wind turbine monitoring systems.

The rapid development of modular small computer systems together with advanced electronic components/sensors and powerful software libraries, will likely push the boundaries of what type of signals that can be experimentally explored for the continuous development of wind turbine monitoring systems. All enhancements of existing data sets are also very valuable for different types of model validation.

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Appendix A: Raspberry source code

Python code to communicate with the SCA103T-D04 and store data to a chosen type of storage device (here a SD card):

```
#!/usr/bin/env python

import spidev
import time
import datetime
import os

spi1=spidev.SpiDev()
spi2=spidev.SpiDev()
spi1.open(0,0)
spi2.open(0,1)

time0 = time.time()
date = datetime.datetime.now()

fname_first = "/root/" + os.uname()[1] + "_rawdata_" \
+ date.strftime("%Y-%m-%dT%H:%M:%S") + ".dat"

tid0 = time.time()

first_run=True
first_file=True

fname=""

while True:

  d1=spi1.xfer([0b00010000, 0x0, 0x0])
  d2=spi1.xfer([0b00010001, 0x0, 0x0])

  x=( d1[1] << 8 ) + d1[2] >> 5
  y=( d2[1] << 8 ) + d2[2] >> 5

  a1=(x-y)/6554.0
  d1=spi2.xfer([0b00010000, 0x0, 0x0])
  d2=spi2.xfer([0b00010001, 0x0, 0x0])

  x=( d1[1] << 8 ) + d1[2] >> 5
  y=( d2[1] << 8 ) + d2[2] >> 5
  a2=(x-y)/6554.0

  time1 = time.time()

  elap = time1-time0

  time0 = time1

  dstr="%10.5f" % elap + "\t" + "%10.5f" % a1 \
  + "\t" + "%10.5f" % a2

  fname_old=fname
  fname = "/home/test/" + os.uname()[1] + "_rawdata_" \
  + "%4.4i" % date.year + "-" + "%2.2i" % date.month \
  + "-" + "%2.2i" %         date.day + "T" \
  + "%2.2i" % date.hour +  ":00:00.dat"
```

```
if fname == fname_old:
  if first_file:
    f = open(fname_first,"a")
  else:
    f = open(fname,"a")
else:
  if first_file:
    f = open(fname_first,"w")
  else:
    f = open(fname,"w")

  f.write("%site_name:'"+os.uname()[1]+"'"+"\n")
  f.write("%timezone:'" \
  + file("/etc/timezone").read().split("\n")[0] \
  + "'"+"\n")

f.write(dstr + "\n")
f.close()
print dstr
```

Appendix B: Arduino source code

Arduiono code to communicate with the SCA103T-D04 and store data to a chosen type of storage device (here a SD card):

```
#include <SPI.h>
#include <Wire.h>
#include <SD.h>

#define ECHO_TO_SERIAL   1 // echo data to serial port
#define WAIT_TO_START    0 // Wait for serial input in setup()

#define LOG_INTERVAL  25 // mills between entries (reduce to
take more/faster data)
#define SYNC_INTERVAL 25 // mills between calls to flush() - to
write data to the card

const int chipSelect = 10;

const int cs1=7;
const int cs2=8;

unsigned long t1;
unsigned long t2;
unsigned long dt;

void setup() {

Serial.begin(57600);
SPI.begin();
SPI.setClockDivider(SPI_CLOCK_DIV64);


pinMode(cs1,OUTPUT);
pinMode(cs2,OUTPUT);

digitalWrite(cs1,HIGH);
digitalWrite(cs2,HIGH);
```

LOAD MONITOR 2

Procedures for monitoring of wind turbine loads has recently been identified as important complement to the Condition Monitoring Systems , which today are delivered as standard components in most wind farm projects. The load information produced is important for the understanding of differences in the inflow conditions at different turbine locations within a wind farm, and adds to the understanding regarding the suitability of turbines certified within the optional IEC wind turbine classes.

Well organised load data also adds to the asset value in when e.g. remaining life time will be assessed, in case a wind farm is sold as an asset from an investment portfolio.

Here robust methods for the monitoring of loads on towers and foundations are presented. The approach relies on ordinary SCADA data, as well as on high frequency nacelle vibration signals. Until very recently, vibration data has rarely been available through the standard SCADA interface, but this situation is gradually changing.

In order to facilitate load monitoring in existing wind farms, small portable systems for the measurement of nacelle accelerations are here discussed. For two different designs, circuit boards are developed, and conceptual source code is submitted.

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