TOWARDS LIFE-CYCLE MANAGEMENT OF WIND TURBINES BASED ON STRUCTURAL HEALTH MONITORING

K. Smarsly[1], K. H. Law[1] and D. Hartmann[2]
[1] Department of Civil and Environmental Engineering,
Stanford University, Stanford, CA, USA
[2] Department of Civil and Environmental Engineering,
Ruhr-University Bochum, Bochum, Germany

ABSTRACT

The integration of structural health monitoring (SHM) into life-cycle management (LCM) strategies can enable wind turbine manufacturers, owners, and operators to precisely schedule maintenance work at minimum associated life-cycle costs. Monitoring data, i.e. structural, environmental, and operational data continuously collected by SHM systems, can effectively be used to capture the structural behavior of wind turbines and to reduce (epistemic) uncertainty. Both the resistance parameters of the structure and the load effects acting on the components can continuously be updated facilitating an accurate life-cycle management. This paper presents an integrated approach towards life-cycle management of wind turbines based on structural health monitoring. Information gained from a SHM system installed on a wind turbine in Germany is coupled with an online LCM system for optimum decision making with respect to operation and maintenance. The integrated LCM system presented in this paper consists of different software modules, which are installed on computers located in the wind turbine and at other, spatially distributed locations. This paper first describes the SHM system, and then presents preliminary results obtained from the online LCM system. Two case studies investigating the structural performance and the operational efficiency of the wind turbine are reported.

KEYWORDS

Life-cycle management, structural health monitoring, wind turbines, long-term monitoring, wind turbine operation and maintenance

INTRODUCTION

Renewable energy technologies, providing inexpensive, clean and safe energy, are essential to solve the global energy crisis. In many countries, wind energy is extensively supported with financial subsidies from governments to encourage the installation of next generation wind energy systems such as wind turbines and wind farms. According to the World Wind Energy Association, wind energy systems are currently used for power generation in 83 countries, 52 of which having increased their totally installed wind energy generation capacity in 2010 (WWEA 2011). In Europe, wind energy saves about €6 billion per year in avoided fuel costs that otherwise would have been needed for power production (in the form of coal, gas and oil), and avoids 106 million tons of CO_2 per year, which is equivalent to taking 25% of the cars in Europe off the road (EWEA 2010).

Cost-efficient operation and maintenance of wind turbines is a primary concern for manufacturers, owners, and operators. Unlike conventional power plants, wind turbines represent unmanned remote facilities being exposed to large numbers of load cycles that cause high mechanical stress on the structures. To ensure a reliable operation and to schedule maintenance and repair work in a cost-effective manner, it is necessary to continuously monitor and assess the structural performance, and to have a reliable estimation of the remaining lifetime of wind turbines and their components. The inherent uncertainties in load and resistance parameters impose the need for continuously updated measurement data sensed from the wind turbine. Therefore, integrated life-cycle management (LCM) strategies, coupled with structural health monitoring (SHM), that provides actual measurement data from the wind turbine, are important to enable optimal operation and maintenance of wind turbines and, eventually, to operate wind turbines beyond their original design life.

The benefits of coupling LCM strategies and SHM systems are obvious: damage can reliably be identified before it reaches critical levels; furthermore, owners and operators can be provided with detailed and accurate information on the wind turbines for decision making and for scheduling maintenance work ahead of time ("*predictive maintenance*"). The common practice in wind energy industry, however, is characterized by *reactive maintenance*, where wind turbine components are replaced or repaired after failure, or by *preventive maintenance*, where maintenance work is scheduled in regular intervals according to the specifications of the wind turbine manufacturer (Barber and Golbeck 2006). SHM can effectively capture the actual structural behavior, representing a powerful mechanism to reduce uncertainty and to calibrate structural assessment and prediction models (Okasha and Frangopol 2010, Okasha *et al.* 2010, Budelmann and Hariri 2007). Unscheduled reactive maintenance, which is about 500% more costly to conduct than scheduled maintenance (Adams *et al.* 2011), can thereby be reduced. Monitoring of load and resistance through structural and environmental parameters in tandem with monitoring of operational parameters (such as revolutions and power production) helps maximizing energy yield and minimizing the accumulated load history of the turbine. Despite such enormous potential benefits, research on how to best integrate LCM and SHM is still in its infancy and is needed (Frangopol 2011a, b).

This paper presents an integrated approach towards LCM of wind turbines based on SHM. Information gained from a SHM system installed on a wind turbine in Germany is integrated into an online LCM system in order to facilitate optimal decisions with respect to maintenance and operation, and to improve structural reliability at minimum associated life-cycle costs. This paper first describes the SHM system, and then shows two case studies presenting preliminary results obtained from the LCM system. The first case study focuses on the structural performance of the wind turbine; the second case study considers the wind turbine's operational efficiency and the life-cycle performance. The paper concludes with a brief summary and an outlook on future research.

A STRUCTURAL HEALTH MONITORING SYSTEM FOR WIND TURBINES

The reference structure, a 500 kW wind turbine located in Germany, has a rigid hub and an upwind rotor of 40 m diameter. The rotor, made of reinforced epoxy, has a swept area of 1,256 m^2 and is equipped with three synchronized blade pitch control systems. For continuously assessing the condition of the wind turbine, the SHM system is installed on the structure collecting structural, environmental, and operational data. Sensors are placed at different levels inside and outside the steel tower and on the foundation of the wind turbine. In addition, two anemometers are deployed; one is installed on top of the nacelle, the other is mounted on a telescopic mast adjacent to the wind turbine for recording wind speed, wind direction, and air temperature. Operational data, such as revolutions and power production of the wind turbine, is taken from the wind turbine machine control system.

The network of sensors, shown in Figure 1, comprises six three-dimensional accelerometers (B_1...B_6), which are mounted at five different levels on the inner surface of the wind turbine tower. The sensitivity of the accelerometers is 700 mV/g with a frequency range between 0 and 100 Hz. On the foundation of the wind turbine, three single-axis piezoelectric seismic ICP accelerometers with a sensitivity of 10,000 mV/g and a frequency range between 0 and 4,000 Hz are installed (B_7...B_9). Six inductive displacement transducers (W_1...W_6) of 5 mm range are mounted at the levels of 21 m and 42 m inside the tower. The displacement transducers are complemented by RTD surface sensors (T_1...T_6) that are capable of measuring temperature from –60 °C to +200 °C. Additional temperature sensors (T_7...T_{10}) are placed inside and outside the tower to measure temperature gradients.

Data acquisition units (DAUs) are installed in the wind turbine to collect and process the sensor data. All data sets, being sampled and digitized, are continuously forwarded from the DAUs to an on-site server for temporary storage. The on-site server, located in the maintenance room of the wind turbine, creates periodically local backups of all recorded data sets (referred to as "raw data" or "primary data"). Through a permanently installed DSL connection, the primary data is transferred to the LCM system, i.e. to a central server installed at the Institute for Computational Engineering (ICE) in Bochum, Germany.

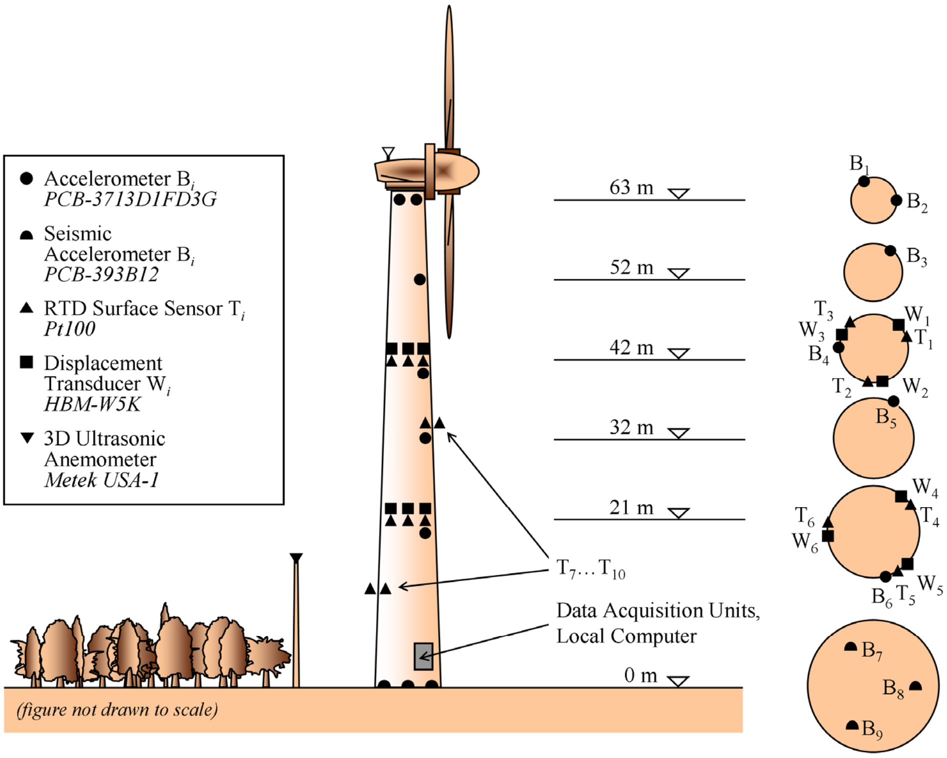


Figure 1 Instrumentation of the wind turbine

INTEGRATED LIFE-CYCLE MANAGEMENT SYSTEM

The data transmission from the SHM system (i.e. from the on-site server at the wind turbine) to the LCM system (the central server at the ICE) is automatically executed by a "Cron" job scheduler, a time-based Unix utility running on the on-site server to ensure the periodic execution of tasks according to specified time intervals. When transferring the collected primary data to the central server of the LCM system, metadata is added to provide definitions of installed sensors, DAU IDs, output specification details, date and time formats, etc. ("secondary data"). The data sets, after being synchronized, aggregated and converted, are persistently stored in a central database (also located at the ICE in Bochum), which is remotely accessible by authorized personnel. In total, the integrated LCM system consists of different modules installed and resided at spatially distributed locations,

1. a central server for automated data synchronization, data aggregation, and conversion of the primary data into secondary data being easily interpretable by human users,
2. a MySQL database for persistent storage of the data sets obtained by the SHM system,
3. RAID-based storage systems for periodic backups,
4. Internet-enabled user interfaces that provide remote access to human users and to software programs,
5. a multiagent-based diagnostic system for the self-detection of malfunctions (such as sensor breakdowns or malfunctioning data acquisition units),
6. a finite element-based model updating module providing numerical wind turbine models, which are updated using the sensor data,
7. a management module for data analysis and life-cycle management.

The following subsections will primarily focus on the management module (module 7 of the LCM system). The design and implementation of the management module are briefly described, followed by two case studies that are conducted using the management module to exemplarily illustrate the functionality and the practicability of the LCM system. For details on the other modules of the LCM system, the reader is referred to Smarsly *et al.* (2011a, b, 2012a, b), Law *et al.* (2012), Lachmann *et al.* (2009), and Hartmann *et al.* (2011).

Design and Implementation of the Management Module

Installed on a computer at the Engineering Informatics Group (EIG) at Stanford University, the management module supports the wind turbine life-cycle management through remote analyses of structural, environmental, and operational wind turbine data. To this end, the management module, written in Java, offers basic functionalities, such as regression analysis, as well as advanced functionalities based on machine learning and data mining techniques. Illustrating the architecture and the core classes of the management module, Figure 2 shows an abbreviated UML class diagram of the implementation. The architecture combines several software design patterns and architectures commonly adopted in software engineering – primarily the "three-tier model" and the "adapter pattern" (Gamma *et al.* 1995). The three-tier model, being both a software architecture and a software design pattern, ensures a concise separation of the user interface ("presentation"), the functional process logic ("controller"), and the monitoring data ("data access"). The architecture allows any of the three tiers to be upgraded, changed, or replaced independently from each other, and improves scalability, integrity and performance of the management module.

The first tier, the *presentation*, provides access to the management module and can be installed on any PC, laptop, and on Java-enabled mobile devices such as cell phones and smart phones. The *data access* tier is designed to remotely access the central database of the LCM system to request monitoring data obtained from the wind turbine. The connection to the database is realized through a programming interface based on the Java Database Connectivity (JDBC), an industry standard for database-independent connectivity between Java applications and database systems. The security of database requests and data transmissions are provided by the database system, which requires password and username as well as secure drivers to be specified when accessing the database. The third tier, the *controller*, contains specific algorithms to be used for structural as well as operational analyses and for life-cycle management of the wind turbine. As shown in Figure 2, the algorithms (e.g. fast Fourier transforms, analysis of variance, etc.) are modularly integrated into the management module in terms of adapters. Using the concept of adapters, new algorithms and existing software tools can easily be integrated into the management module.

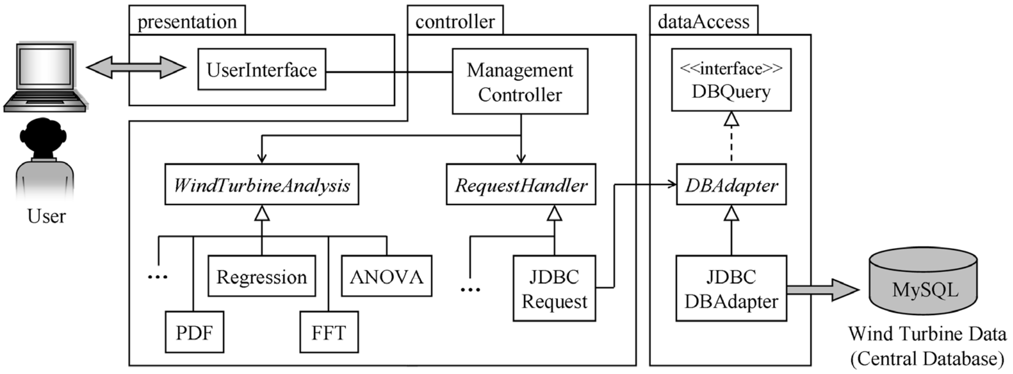


Figure 2 Architecture of the management module

Case Study: Structural Performance of the Wind Turbine

To demonstrate the functionality and the practicability of the LCM system, long-term monitoring data collected by the SHM system is analyzed using the management module. To briefly illustrate the rapid online assessment of the wind turbine's modal properties, two data sets – recorded in October 2011 and in March 2012 – are compared with respect to potential long-term changes in the structural performance. Specifically, the horizontal acceleration of the wind turbine tower, recorded by sensor B_1 at the height of 63 m (see Figure 1), is analyzed. The acceleration data represents the vibrational response of the wind turbine structure due to an unknown wind loading, which is assumed to be an approximately broadband "white" excitation (white-noise or impulse input). The example acceleration time histories are taken at similar environmental conditions, i.e. at a wind speed of about 2 m/s and a temperature of about 12 °C. Figure 3 shows the recorded acceleration responses of the wind turbine tower in October 2011 and in March 2012.

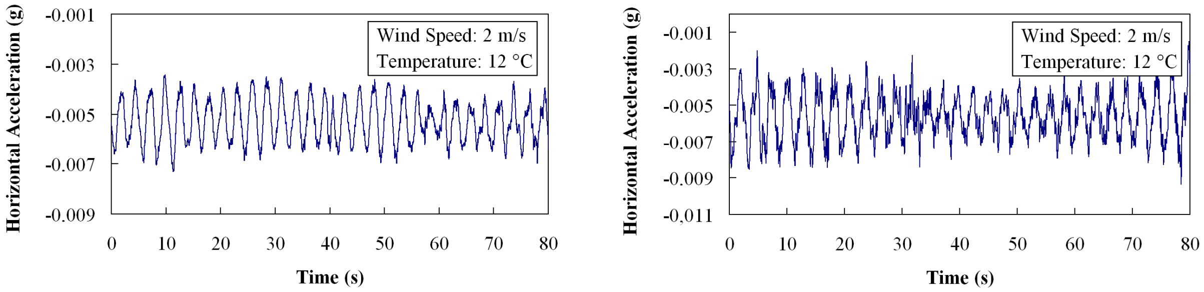


Figure 3 Example time histories of horizontal acceleration response of the wind turbine tower (sensor B_1) recorded in October 2011 (left) and March 2012 (right)

For determining the modal properties of the structure, the acceleration data is automatically transformed into the frequency domain using the Cooley-Tuckey FFT algorithm (Press 1995). The natural frequencies are then derived from the frequency spectra through peak-picking. For the given example, Figure 4 shows the calculated frequency response function of the acceleration responses recorded in October 2011. As a result of this comparison, the first natural frequencies derived from the acceleration measurements of sensor B_1 in October 2011 and in March 2012 are very close to each other. Table 1 compares the results obtained by the LCM system with calculations being made in related research projects under the supervision of the third author. The comparison calculations are based (i) on the Stochastic Subspace Identification (SSI) method, (ii) on the Enhanced Frequency Domain Decomposition (EFDD) method, and (iii) on finite element analyses of a wind turbine model (Figure 5). As shown in Table 1, the calculated natural frequencies are found to be similar, whereby the deviations are 0.3% and 2.5% (SSI) as well as 0.3% and 5.5% (EFDD). Compared with the natural frequency obtained by the FE model, the deviation is 1.3%.

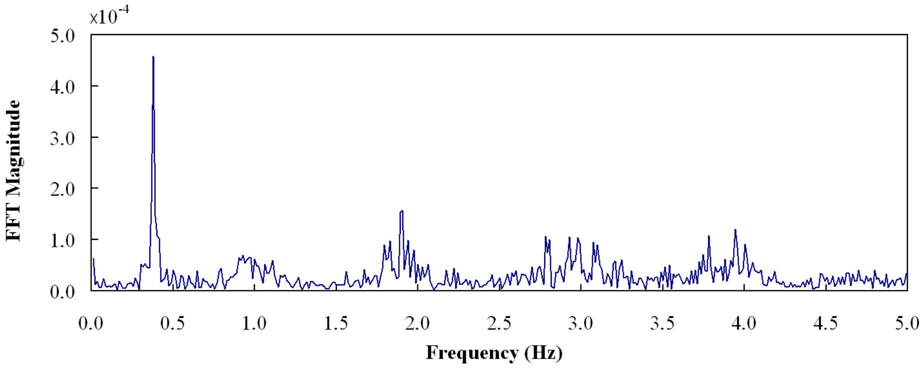
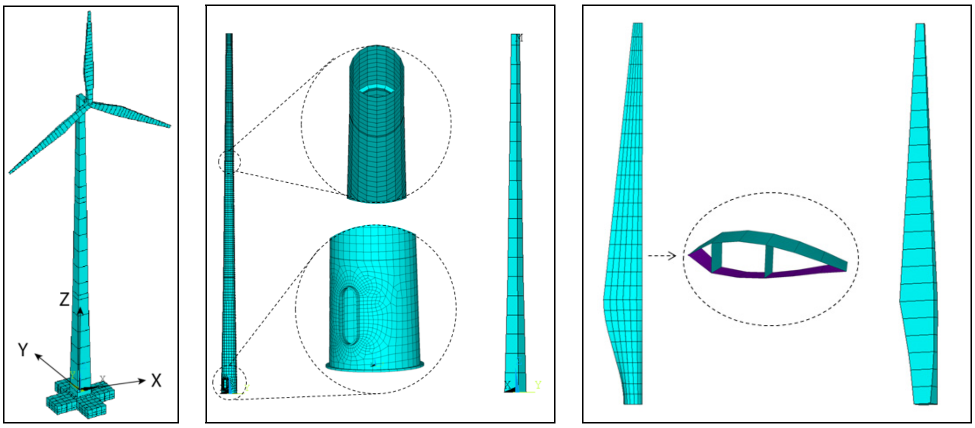


Figure 4 Frequency response function calculated by the management module (sensor B_1, October 2011)

Table 1 Calculated first modal frequencies of the wind turbine tower

	Frequency (Hz)	Deviation (%)
LCM System (Sensor B_1, March 2012)	0.37	-
LCM System (Sensor B_1, October 2011)	0.39	6.8
SSI (Liu *et al.* 2012)	0.37	0.3
SSI (Höffer *et al.* 2012)	0.38	2.5
EFDD (Liu *et al.* 2012)	0.37	0.3
EFDD (Höffer *et al.* 2012)	0.39	5.5
Finite Element Model (Leimbach *et al.* 2012)	0.36	1.3



(a) (b) (c)

Figure 5 Finite element model used for structural analyses: (a) computationally efficient, simplified model, (b) shell model and beam model of the tower, (c) shell model and beam model of the blade (Leimbach *et al.* 2012)

Case Study: Operational Efficiency and Performance of the Wind Turbine

To verify the wind turbine efficiency and to detect long-term trends in the operational behavior, environmental and operational data is analyzed online through the management module of the LCM system. The online data analyses performed can help not only to understand the operational behavior of the wind turbine, but also to validate particular measures undertaken to optimize the operational performance, to quantify energy losses that usually remain undetected (e.g. due to structural deterioration), and to minimize the costs for operation and maintenance.

Figure 6 compares the wind turbine performance over 2 years. For comparison, power curves are exemplarily constructed based on 1-month SHM data recorded in March 2010, March 2011, and March 2012. In addition, the power curve provided by the manufacturer is shown in the figure. The power curves, in detail, are calculated by the management module from the measured power output and the wind speed, and are visualized in terms of polynomial functions which fit the measured data very well ($R^2_{2010} = 0.989$, $R^2_{2011} = 0.996$, and $R^2_{2012} = 0.994$). As can be seen from Figure 6, the results demonstrate that no significant changes can be found when comparing the SHM-based power curves of 2010, 2011, and 2012. Also, the actual SHM-based power curves are found to be similar to the power curve provided by the manufacturer.

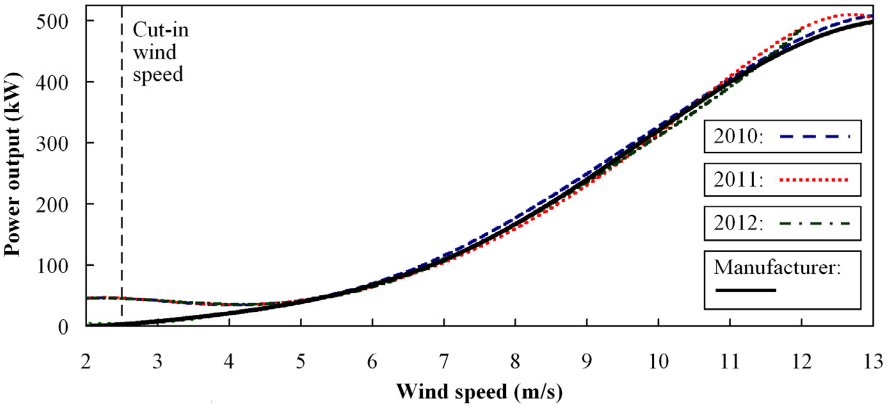


Figure 6 Power curves of the wind turbine in March 2010, 2011, and 2012 based on SHM data

The actual wind turbine efficiency is illustrated in Figure 7. Therein, the power coefficients C_P are shown as a function of the wind speed. The power coefficients, defined as the power extracted by the wind turbine relative to the power available in the wind stream, are calculated by the management module following Eq. (1):

$$C_P = \frac{P}{0.5 \rho A V^3} \tag{1}$$

where P is the produced power, ρ is the air density assuming $\rho = 1.225$ kg/m^3, V is the wind speed measured by the SHM system, and A is the swept area of the wind turbine calculated from the rotor diameter. In addition to the C_P curves, the Betz limit, representing the theoretical maximum of power efficiency, is shown in Figure 7, which implies that no wind turbine can convert more that 59.3% of the kinetic energy of the wind into mechanical energy. The efficiency of the wind turbine, as a result of this example calculation, is largest at the optimum wind speed $V = V(C_{P,max})$ that is found between $V = 7.5$ m/s and $V = 8.5$ m/s in each of the regarded time spans.

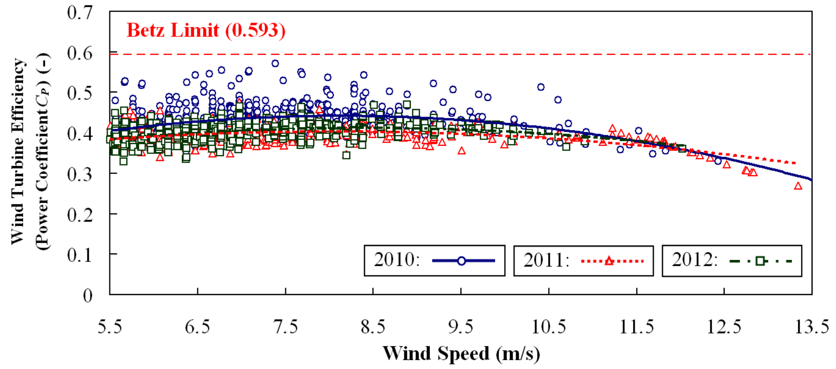


Figure 7 Wind turbine efficiency in March 2010, 2011, and 2012

It should be noted that the LCM system can be used for the verification of assumptions being made when planning and implementing wind energy projects. For example, when choosing optimal wind turbines for specific sites, several significant parameters are of importance, such as cut-in wind speed (i.e. the minimum wind speed at which the wind turbine will generate usable power) and cut-out wind speed (i.e. the wind speed at which the turbine's rated speed is exceeded so that further increases in wind speed would not lead to increased power output). Depending on the site, Weibull distributions (or Rayleigh distributions respectively) are typically used to characterize the wind speed and to estimate the power output, because actual wind speed distributions are usually not available (Celik 2004). The LCM system provides actual wind speed distributions, as shown in Figure 8 exemplarily in 50 kW intervals based on 30-minute mean values. Thereby, it is corroborated that – even when just considering the time spans exemplarily used in this case study – the 500 kW wind turbine, with a cut-in wind speed of 2.5 m/s and a cut-out wind speed between 28-34 m/s, represents an excellent choice for the given site conditions. Figure 9 shows the distribution of the power output in the regarded time spans, which corresponds, with respect to the quantities of power output and wind speed, to the mean wind speed distributions in Figure 8.

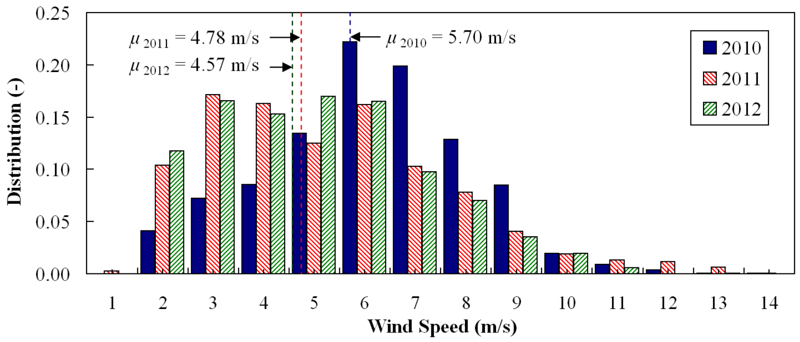


Figure 8 Mean wind speed in March 2010, 2011, and 2012

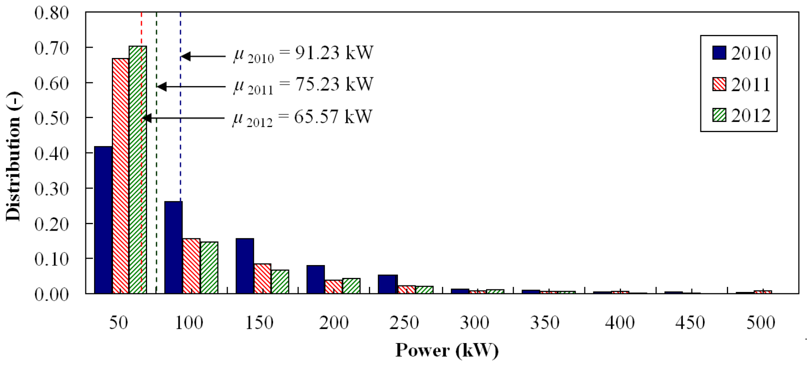


Figure 9 Generated power in March 2010, 2011, and 2012

SUMMARY AND CONCLUSIONS

An integrated life-cycle management (LCM) system for online monitoring, reliability assessment as well as optimum maintenance and inspection planning of wind turbines has been presented. Installed on a 500 kW wind turbine in Germany, a robust and modular structural health monitoring (SHM) system has been coupled with the LCM system to continuously provide and update structural, operational, and environmental data. Using the LCM system, case studies have been presented investigating the long-term structural performance and the operational efficiency of the wind turbine over 2 years. Through the case studies, the functionality and the practicability of the LCM system have exemplarily been illustrated. Moreover, the results of the case studies have revealed that (i) the monitored wind turbine is in an excellent condition and that (ii) with respect to the given site characteristics (wind speed distribution, etc.) the selected wind turbine model is an appropriate choice.

As has been demonstrated in this paper, integrating modular SHM systems into LCM strategies facilitates the understanding of the structural and operational behavior of wind turbines. Furthermore, (epistemic) uncertainties can largely be reduced because resistance parameters of the structure and load effects acting on the components are continuously updated using actual SHM data. Calculations with respect to return on investment, payback period, or cost per kilowatt hour for wind-generated power are much more precise when based on continuously updated SHM data. The integrated approach presented in this paper can help manufacturers, owners, and operators to optimize the operational performance of the wind turbines and to precisely schedule maintenance work at minimum associated life-cycle costs. Further research is needed to explore the transfer of the proposed concepts from single wind turbines to wind farms. Also, research efforts are needed to further improve the reliability and the availability of the SHM systems representing the basis for a robust and accurate life-cycle management.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the German Research Foundation (DFG) through the grants SM 281/1-1 and HA 1463/20-1. This research was also partially funded by the U.S. National Science Foundation (NSF) under grant CMMI-0824977. Any opinions, findings, conclusions or recommendations are those of the authors and do not necessarily reflect the views of the German Research Foundation and the U.S. National Science Foundation.

REFERENCES

Adams, D., White, J., Rumsey, M. and Farrar, C. (2011). "Structural health monitoring of wind turbines: method and application to a HAWT", *Wind Energy 2011*, 14, 603-623.

Barber S. and Golbeck, P. (2006). "Wind Turbine Maintenance & Condition Monitoring", *WIND ENERGY - Technology and Planning*. Online: http://www.wwindea.org/technology/ch03/en/3_4_3.html (Accessed: April 25, 2012). Bonn, Germany: WWEA.

Budelmann, H. and Hariri, K. (2007). "A structural health monitoring system for rc-/pc structures", *Life-Cycle Cost and Performance of Civil Infrastructure*. London, UK: Taylor & Francis Group.

Celik, A.N. (2004). "On the distributional parameters used in assessment of the suitability of wind speed probability density functions", *Energy Conversion and Management*, 45, 1735-1747.

Frangopol, D.M. (2011a). "Integrated Reliability-Based Life-Cycle Framework for Design, Inspection, Maintenance and Monitoring of Structures: Applications to Bridges", *Proceedings of the 53° Congresso Brasileiro do Concreto - IBRACON*. Florianópolis, Brazil, 11/2011.

Frangopol, D.M. (2011b). "Life-Cycle Performance, Management, and Optimization of Structural Systems under Uncertainty: Accomplishments and Challenges", *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, 7(6), 389-413.

Gamma, E, Helm, R., Johnson, R. and Vlissides, J. (1995). *Design Patterns: Elements of Reusable Object-Oriented Software*. Boston, MA, USA: Addison-Wesley.

Hartmann, D., Smarsly, K. and Law, K.H. (2011). "Coupling Sensor-Based Structural Health Monitoring with Finite Element Model Updating for Probabilistic Lifetime Estimation of Wind Energy Converter Structures", *The 8th International Workshop on Structural Health Monitoring 2011*. Stanford, CA, USA, 09/2011.

Höffer, R., Lachmann, S. and Hartmann, D. (2012). "Conceptual study on instrumentation for displacement-based service strength checking of wind turbines", *The 14th International Conference on Computing in Civil and Building Engineering*. Moscow, Russia, 06/2012.

Lachmann, S., Baitsch, M., Hartmann, D. and Höffer, R. (2009). “Structural lifetime prediction for wind energy converters based on health monitoring and system identification”, *The 5th European & African Conference on Wind Engineering.* Florence, Italy, 07/2009.

Law K.H., Smarsly, K. and Wang, Y. (2012). “Sensor Data Management”, *Sensor Technologies for Civil Infrastructures: Performance Assessment and Health Monitoring*. Sawston, UK: Woodhead Publishing (submitted).

Leimbach, K. R., Liu, X., Hartmann, D. and Höffer, R. (2012). “Model generation, verification, validation and updating for solving problems in structural health monitoring as well as residual lifetime estimation of wind turbines”, *The 14th International Conference on Computing in Civil and Building Engineering*. Moscow, Russia, 06/2012.

Liu, X., Leimbach, K. R., Hartmann, D. and Höffer, R. (2012). “Signal analysis using wavelets for structural damage detection applied to wind energy converters”, *The 14th International Conference on Computing in Civil and Building Engineering*. Moscow, Russia, 06/2012.

Okasha, N.M. and Frangopol, D.M. (2010): “Integration of structural health monitoring in a system performance based life-cycle bridge management framework”. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*. DOI:10.1080/15732479.2010.485726.

Okasha, N.M., Frangopol, D.M. and Orcesi, A.D. (2010). Automated finite element updating using strain data for the lifetime reliability assessment of bridges. *Reliability Engineering & System Safety*, 99(2012), pp. 139-150.

Press, W.H. (1995). *Numerical Recipes in C*, Cambridge, England: Cambridge University Press.

Smarsly, K., Law, K.H. and Hartmann, D. (2011a). “Implementation of a multiagent-based paradigm for decentralized real-time structural health monitoring”, *The 2011 ASCE Structures Congress*. Las Vegas, NV, USA, 04/2011.

Smarsly, K., Law, K.H. and Hartmann, D. (2011b). “Implementing a Multiagent-Based Self-Managing Structural Health Monitoring System on a Wind Turbine”, *The 2011 NSF Engineering Research and Innovation Conference*. Atlanta, GA, USA, 01/2011.

Smarsly, K., Law, K.H. and Hartmann, D. (2012a). “A Multiagent-Based Collaborative Framework for a Self-Managing Structural Health Monitoring System”, *Journal of Computing in Civil Engineering*, 26(1), pp. 76-89.

Smarsly, K., Hartmann, D. and Law, K.H. (2012b). “Structural Health Monitoring of Wind Turbines Observed by Autonomous Software Components – 2nd Level Monitoring”. In: *ISCCBE (International Society for Computing in Civil and Building Engineering). 14th International Conference on Computing in Civil and Building Engineering*. Moscow, Russia, 06/2012.

World Wind Energy Association – WWEA (2011). “World Wind Energy Report 2010”, *Report*. Bonn, Germany: WWEA.