Coupling Sensor-Based Structural Health Monitoring with Finite Element Model Updating for Probabilistic Lifetime Estimation of Wind Energy Converter Structures

D. HARTMANN, K. SMARSLY and K. H. LAW

ABSTRACT

The worldwide demand for green energy systems is evident. In this context, wind energy converters will play a paramount role. Extending the service life of a wind energy converter translates into significant economic savings as well as ecological earnings. New opportunities for the management and operation of the wind energy converters make it beneficial to know the structural condition and the remaining life span of wind energy converters at each point in time during their operation. This paper presents the implementation of an integrated framework for probabilistic lifetime estimation of wind energy converter structures coupling sensor-based structural health monitoring with finite element model updating.

INTRODUCTION

The Fukushima disaster in Japan, in March 2011, has caused a dramatic change in the thinking with respect to the future energy supply. As a consequence, a massive demand for green energy systems becomes apparent. In this context, wind energy converters play a paramount role. New giant off-shore as well as new large-scale on-shore wind energy converters are being erected. Likewise, existing wind energy converters are being replaced by more powerful systems with taller shafts and larger rotor blades.

One question for renewable wind energy systems is, how the operating costs and utility charges should be bored by the customers. To answer this question, it is indispensible to know the remaining life span of the wind energy converters at each point in time during their operation. This paper presents an integrated framework that brings together (i) sensor-based structural health monitoring (SHM) systems, (ii) model updating and system identification methodology, and (iii) reliability analyses and probabilistic lifetime estimation. This integrated concept opens new opportunities for the management and operation of wind energy converters.

Dietrich Hartmann, Department of Civil and Environmental Engineering, Ruhr-University Bochum, Bochum, Germany
Kay Smarsly and Kincho H. Law, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA

A SHM SYSTEM FOR WIND ENERGY CONVERTER STRUCTURES

A SHM system is installed on an wind energy converter located in Germany, which is used as a reference structure for validating the proposed concept. The SHM system consists of two subsystems: an on-site hardware system and a decentralized software system that are designed to monitor the structural conditions and operations of the wind energy converter (Fig. 1).

On-Site Hardware System

The *on-site hardware system*, consisting of sensors, data acquisition units and a computer installed in the wind energy converter, is designed to continuously collect measurement data from the wind energy converter. As shown in Fig. 1, six three-dimensional accelerometers, type PCB-3713D1FD3G, are placed in selected locations on five different levels inside the shaft of the wind energy converter. In addition, three single-axis piezoelectric seismic accelerometers are mounted on the foundation of the structure. Furthermore, a network of six inductive displacement transducers is installed at two levels inside the shaft. The displacement transducers are complemented by resistance temperature detectors to account for temperature influences on the transducers. Additional temperature sensors are placed inside and outside the shaft to measure temperature gradients. For gauging wind speed and directions, an ultrasonic anemometer is mounted on a telescopic mast adjacent to the wind energy converter.

To collect and process sensor data, two types of data acquisition units (DAUs) are installed. For recording temperature data, three 4-channel Picotech RTD input modules PT-104 are deployed. Data handling of accelerations and displacements is carried out by means of four Spider8 measuring units. The sampled and digitized data sets are temporarily stored in the local computer placed inside the wind energy converter. Using a permanently installed DSL connection, the data sets are periodically forwarded to the database system for persistent storage and access.
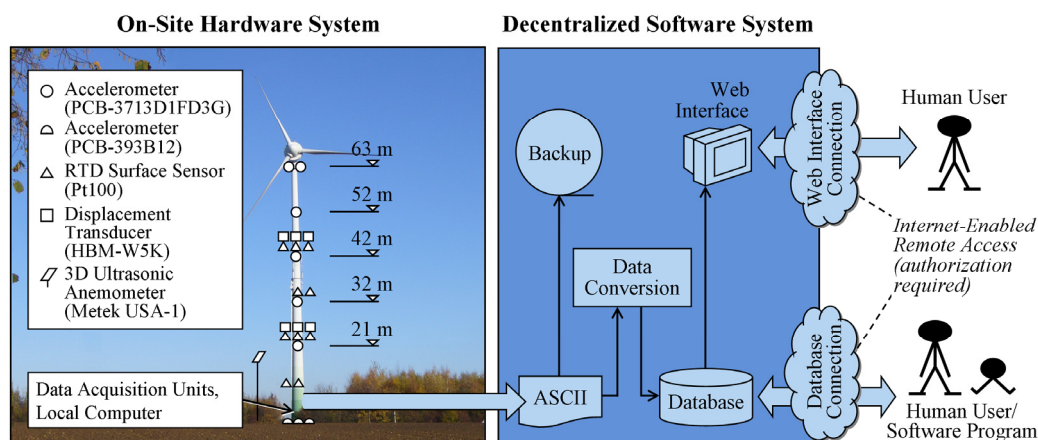

Fig. 1. Overview of the SHM system.

A Decentralized Software System

The *software system*, which is remotely connected to the hardware system, is designed (i) to persistently store the measuring data collected by the hardware

system and (ii) to provide remote access to the data sets for use by both human users and software programs. A modular, flexible and robust multi-agent paradigm is employed for the implementation of monitoring and management functions.

The software programs and the database system are installed on different computers at the Institute for Computational Engineering (ICE) in Bochum (Germany). The overall system consists of (i) server systems for on-line data synchronization, conversion and transmission, (ii) a RAID-based storage systems for periodic backups, (iii) a MySQL database system for persistent data storage and (iv) a web interface for remote access to the data.

The measurement data can be accessed remotely through the web-based interface or a direct database connection. Fig. 2a illustrates the use of the web-based interface to visualize the measurement data taken from the wind energy converter. Specifically, the figure shows the data recorded on April 24, 2011 and depicts the wind speed as well as the radial and tangential horizontal accelerations of the shaft at 63 m height. The same data sets can be queried directly from the database as displayed in a tabulated format as shown in Fig. 2b. The direct database connection not only allows authorized users to download the data from the SHM system but also provides remote access to the data from external software programs, for example, to automatically execute damage detection algorithms.

Horizontal Acceleration (g)					Wind Speed (m/s)			
time	B1_x	B1_y	B1_z		time	v	d	z	t

time	B1_x	B1_y	B1_z
1303676945350	0.712	-0.0024	0.0148
1303676945360	0.7104	-0.002	0.014
1303676945370	0.7116	-0.0016	0.0152
1303676945380	0.712	-0.0028	0.0124
1303676945390	0.7128	-0.0032	0.0116
1303676945400	0.712	-0.004	0.0116
1303676945410	0.712	-0.0048	0.012
1303676945420	0.7124	-0.006	0.0088
1303676945430	0.7104	-0.0068	0.0092

time	v	d	z	t
1303676945360	220	84	22	1672
1303676945380	223	83	33	1675
1303676945400	220	83	24	1673
1303676945420	233	84	18	1673
1303676945440	236	84	15	1673
1303676945460	233	82	26	1672
1303676945480	229	79	37	1667
1303676945500	221	82	23	1672
1303676945520	230	81	28	1664
1303676945540	227	80	37	1668
1303676945560	226	79	52	1664
1303676945580	240	79	52	1668
1303676945600	226	80	41	1672
1303676945620	229	77	32	1664
1303676945640	235	77	29	1660

(a) Web interface connection.   (b) Direct database connection.
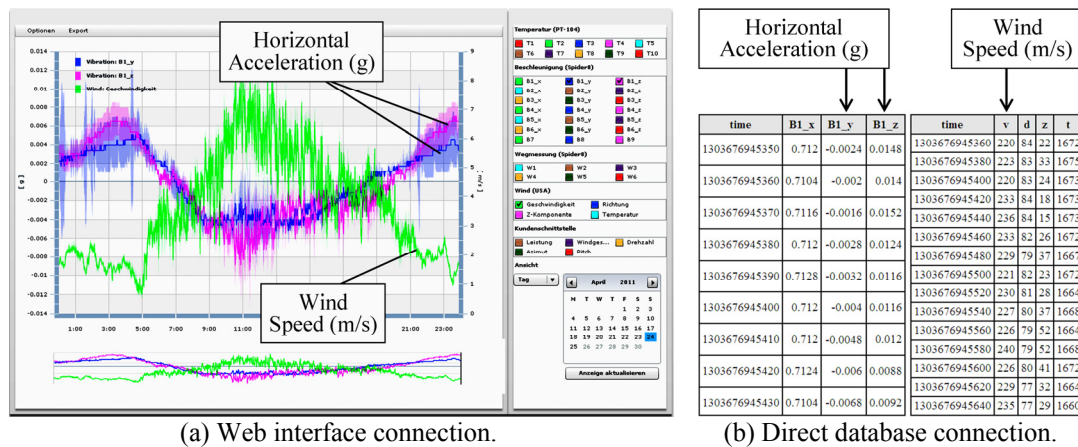Fig. 2. Remotely visualized acceleration and wind speed data measured on April 24, 2011.

A multi-agent software paradigm is adopted for the implementation of management and monitoring tasks [1]. Each software agent is self-contained software entity that is capable of carrying out monitoring tasks and – if necessary – proactively cooperating with other software entities autonomously without any direct intervention from the users [2]. Customary failures or malfunctions are manifold, e.g. communication problems when using long-distance lines, temporary power blackouts that affect the computer systems or simply hardware blackouts. If such functional failures should not be detected and eliminated timely, loss of valuable sensor data needed for accurate lifetime estimations occurs. The software agents are geographically and distributedly located, in this case, at the ICE in Bochum and Stanford University. The monitoring agent is implemented to autonomously detect malfunctions of the DAUs installed in the structure, and to react to them by notifying the responsible engineer via email alerts.

FE MODEL UPDATING USING SYSTEM IDENTIFICATION

One of the key features of the integrated monitoring framework is the linkage between the computational models representing the wind energy converter structure and the sensor measurement data. The purpose is to support model updating using real-time measurement data and to assess the conditions of the structure.

Finite Element Modeling of the Structural Wind Energy Converter System

The computation of the structural and dynamic behavior of the wind energy converter is carried out using the finite element software ANSYS [3]. Two individual finite element models of the wind energy converter are created. The first model is a complex 3D finite element model; the second model is a simplified approximation of the first model that is explicitly implemented for computationally efficient system identification.

The first finite element model is intended to provide a highly accurate and realistic detailed model of the structure. The 3-D finite element model comprises of the shaft of the wind energy converter, including the connection flanges between the shaft segments, the shaft access door (Fig. 3a), and the rotor blades (Fig. 3b). The discretization of the 3-D model yields large number of elements and requires enormous computational efforts, in particular, to compute the eigenfrequencies of interests. The second (simplified) finite element model is constructed for system identification purposes. The model encompasses the shaft and the rotor blades; it is composed of only 23 beam elements for the shaft and 20 beam elements for the blades. The nacelle at top of the shaft is modeled as an additional mass. The behavior of the foundation and the subsoil is captured by separate finite element models where continuous elastic support for the ground is assumed (Fig. 3c). The eigenvibration characteristic of the second model matches nearly perfectly with that of the first model (albeit the local effect of the cross section can, of course, not be mapped).
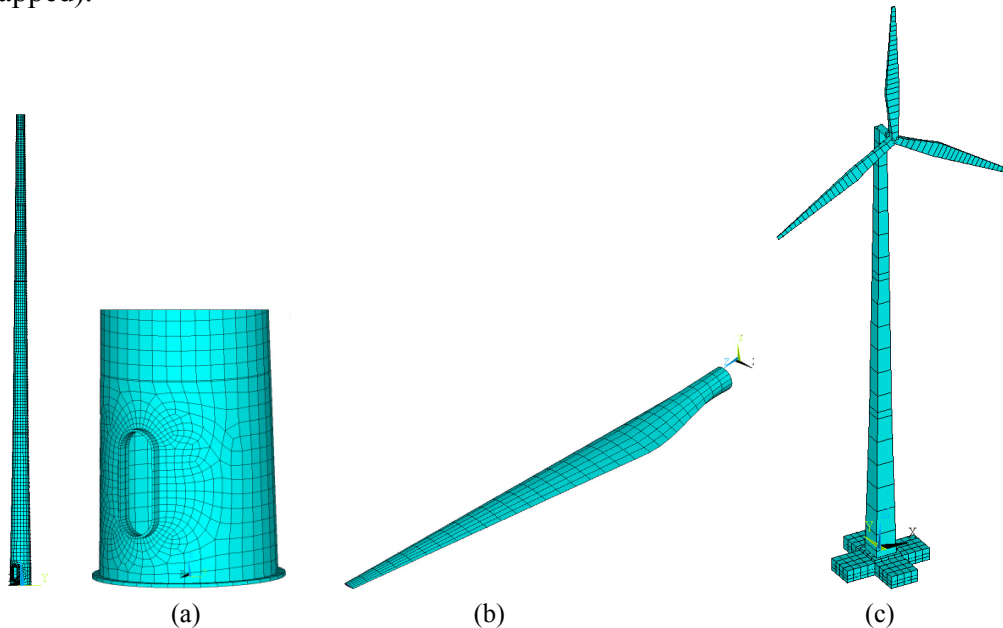

(a) (b) (c)
Fig. 3. 3D finite element models of the wind energy converter.

Determination of Modal Parameters and System Identification

To obtain highly qualified finite element models of an observed structure for SHM purposes, engineers increasingly employ sensor-based measurement data to validate and to update the structural model. The model updating process is accomplished by modifying the properties of the finite element models. These modifications are repeated until the computed structural responses (accelerations, velocities and displacements) approximate closely the measured responses. If the approximation problem is posed as an optimization problem minimizing the difference between the computed quantities and their measured counterparts, the problem becomes an inverse or a system identification problem. Modal properties are among the most commonly used parameters for the model updating process.

The extraction of the modal parameters from the actual measured data is based on Operational Modal Analysis (OMA); it is carried out by using the commercial software "ARTeMIS Extractor" [4]. Specifically, two OMA methods are utilized: (i) the Enhanced Frequency Domain Decomposition Method (EFDD) in the frequency domain and (ii) the Stochastic Subspace Identification Method (SSI) in the time domain. Fig. 4 shows the bending modes in the X-Z- and Y-Z-plane. Fig. 5 shows the close matches between the measurement-driven EFDD and SSI calculations and the model-predicted results from the finite element analysis (EFA), as indicated using the Modal Assurance Criterion (MAC) in terms of a MAC-matrix. In Fig. 5, it can be seen that the diagonals of the MAC-matrix tend towards the value of 1, which indicates high conformity between measurement-driven and model-predicted modal parameters.
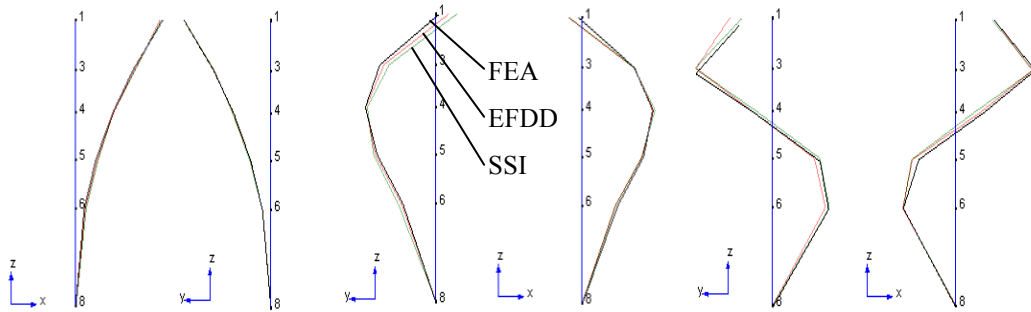

Fig. 4. First three bending modes of the wind energy converter in X-Z- and Y-Z-plane computed by FEA (black) and identified by EFDD (red) and SSI (green).
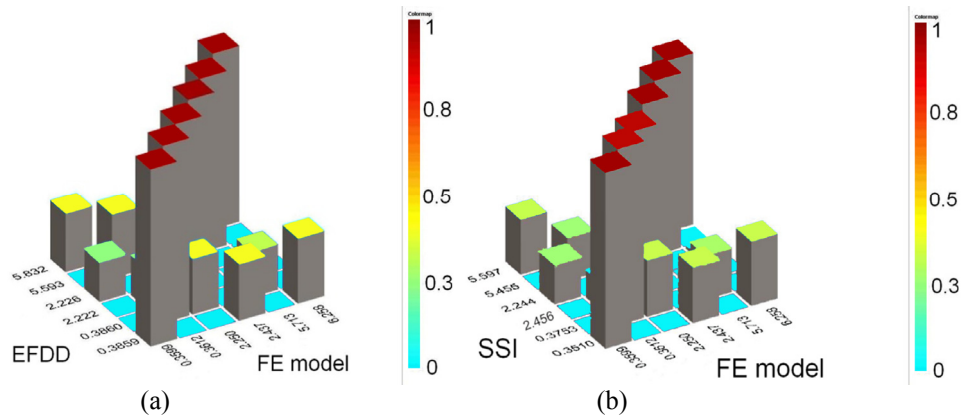

(a)   (b)

Fig. 5. MAC-matrix: comparison of eigenshapes from EFDD (a) and from SSI (b) with FE model.

Model Updating and Damage Detection

Clearly, most interesting is the non-destructive (system) identification of events that represent deteriorations or damages. It can neither be anticipated nor expected that serious damage events occur to the 12-year old wind energy converter observed within the time window of the current (36-month) research project. Therefore, synthetic damages are imposed on the structure to predict the structural response by means of a forward finite element computation. Several damage patterns can be created and archived in a "damage catalog" by this forward computational approach. If deteriorations or damages occur to the real structure, the a-priori created damage patterns would allow a rapid assessment of damages.

To demonstrate the performance of the proposed approach, characteristic damage scenarios are examined and benchmarked. As an example, the loosening of a high strength bolt at a specified location of a shaft connection flange is considered. This damage scenario is captured by introducing four stiffness reducing parameters (optimization or design variables). As noted by Zhang et al. [5], fundamental to model updating is the selection of the objective function, the updating parameters and the optimization procedure. This work employs the objective function which involves the weighting the MACs with the relative deviation of the modal frequencies as suggested by Bittner [6]. These criteria are computed from the aforementioned OMA methods. In the optimization loop according to the optimization strategy chosen, finite element analyses using ANSYS are carried out repeatedly, whereby each analysis takes about a few seconds. The optimization strategies adopted are the Differential Evolution (DE) and Evolution Strategies (ES) because both of them are best candidates for the solution of the non-linear, multi-modal non-standard optimization problems [7]. The optimization variables defined in the application example, along with the optimization history using ES for the damage due to the loosening of a bolt, are depicted in Fig. 6.
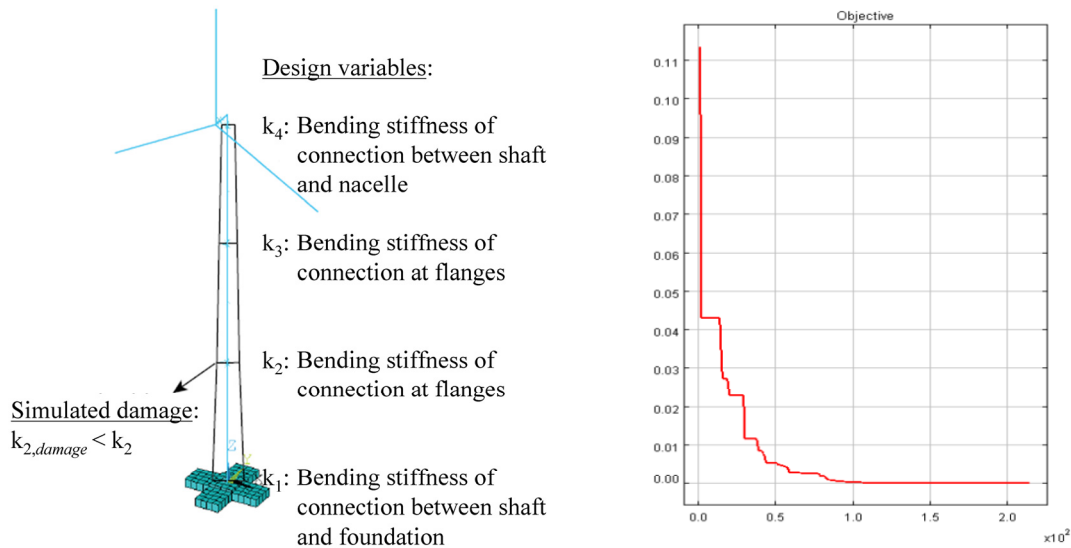

Design variables:

k_4: Bending stiffness of connection between shaft and nacelle

k_3: Bending stiffness of connection at flanges

k_2: Bending stiffness of connection at flanges

Simulated damage:
$k_{2,damage} < k_2$

k_1: Bending stiffness of connection between shaft and foundation

Fig. 6. Left: FE model for defect minimization. Right: Optimization history using ES applying the optimization criterion according to Bittner [6].

STOCHASTIC PROBABILISTIC-BASED LIFETIME ESTIMATION

Our recent research in lifetime oriented design of structures has indicated that the appropriate lifetime estimation has to take into account the realistic stochastic time variant actions (loading) as well as the induced stochastic lapse of strains on the structure's resistance level [8]. Both processes are observed through the SHM system and utilized for probabilistic computations leading to applicable lifetime estimation. In the following, the procedure for developing the lifetime estimation according to Hartmann, *et al.* [8] is briefly summarized.

The key of the lifetime estimation is the determination of failure probabilities for specific damage categories, which is usually based upon a weak point analysis for the total structural system. The problem is to guaranteed that the time variant probability $D(t)$ exceeding a given stochastic damage limit D_{limit} is less or equal than a given admissible failure probability P_{adm}:

$$P(D(t=T_{limit}) > D_{limit}) \leq P_{adm}. \tag{1}$$

Assuming linear dynamic behavior, the damage-dominating amplitudes of the induced vibrations can easily be computed. Furthermore, assuming the vibration behave as stationary Gaussian processes, the computational efforts required to obtain the responses can be reduced drastically,. For reliability analysis, mainly the mean values are of interest and the variances of the stress response can be readily computed using linear system theory (i.e. the spectral and covariance analysis). Subsequently, the spectral moments λ_0, λ_1, λ_2 and λ_4 of the dynamic response quantities can be determined using the analytical equations as suggested by Dirlic [9] and based on a semi-empirical peak counting method. Developing an appropriate Wöhler-curve (S/N-curve) for the damage category considered, a fatigue-loading function is constructed that mimics the damage evolution process. Using this function, damage jumps ΔD are assessed on the micro-time level of a wind load event. Hereby, the fatigue endurance strength, the load cycle number and the inclination of the S/N-curve are defined as random parameters. Accumulating the jumps ΔD over the long-term time window, up to $D(t=T_{limit})$, yields the desired assessment of the damage from which the remaining lifetime can be deduced. Since the random parameters are governed by their distribution functions, a variety of fatigue paths are created and checked to determine which one exceeds the stochastically defined limit damage D_{limit} first (as illustrated in Fig. 7).
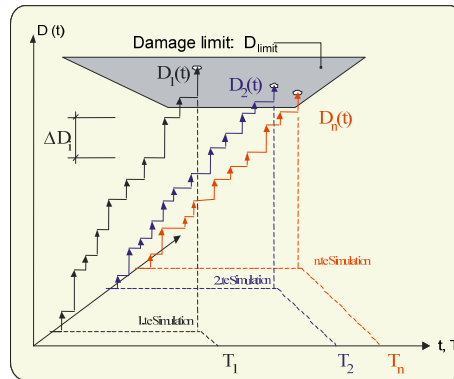

Fig. 7. Stochastic simulations using various fatigue paths.

CONCLUSIONS

This paper has presented an integrated framework for the probabilistic lifetime estimation of wind energy converter structures. Representative results have been shown for a 500 kW wind energy converter, which serves as a reference structure. The main innovation of the proposed framework is the coupling of sensor-based structural health monitoring with finite element model updating for probabilistic-based lifetime estimation. Coupling measured data and finite element models – i.e. measurement-driven and model-predicted modal parameters – potential probabilities of certain failures have been calculated and, based upon that, lifetime estimations can be computed. As the field of lifetime estimation matures, plenty of opportunities exist for extending the proposed framework. For example, system identification and damage localization, representing non-linear multi-modal non-standard optimization problems, can further be improved by expanding the network of sensors installed in the wind energy converter and by introducing more sophisticated finite element models.

ACKNOWLEDGMENTS

REFERENCES

1. Smarsly, K., Law, K. H., and Hartmann, D., 2011. A Multi-Agent-Based Collaborative Framework for a Self-Managing Structural Health Monitoring System. *ASCE Journal of Computing in Civil Engineering* (in press).
2. Wooldridge, M., and Jennings, N. R., 1995. Intelligent Agents: Theory and Practice. *The Knowledge Engineering Review*, 10(2), pp. 115-152.
3. ANSYS Inc. and ANSYS Europe, 2007. Theory Reference for ANSYS and ANSYS Workbench Chapter 14: Element Library.
4. ARTeMIS Software - Version 5.3. Structural Vibration Solutions (SVS), ApS, 2010, Novi Science Park, Niels Jernes Vej 10, DK 9220 Aalborg East, Denmark.
5. Zhang, X. Y., Sim, S. H., and Spencer Jr., B. F., 2008. Finite Element Model Updating of a Truss Model using incomplete Modal Data. In: *Proc. World Forum on Smart Materials and Smart Structures Technology*, Chongqing & Nanjing, China.
6. Bittner, U., 2008. Successive Model-Updating of the Dynamic Behavior of Casing Bodies on a Practical Example of an Axial Piston Pump. *NAFEMS Seminar "Interaction of Simulation and Testing: New Requirements and New Opportunities in Structural Dynamics"*. Wiesbaden, Germany.
7. Stangenberg, F., Breitenbücher, R., Bruhns, O. T., Hartmann, D., Höffer, R., Kuhl, D., and Meschke, G. eds., 2009. *Lifetime-Oriented Structural Design Concepts*. Berlin, Germany: Springer.
8. Hartmann, D., Weber, H, and Pflanz, G., 2009. Lifetime Analysis for Dynamically Loaded Structures at BMW. In: Stangenberg, F., Bruhns, O.T., Hartmann, D. et al. (eds.): *Lifetime-Oriented Structural Design Concepts*. Berlin, Germany: Springer, pp. 573-583.
9. Dirlik, T., 1985. Applications of computers in fatigue analysis. *PhD Thesis*, University of Warwick, England.