ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1165438

PROBLEMS REVIEW OF THE HEALTH MONITORING OF TALL TYPE BUILDINGS

Khikmat Saidov, Janusz Szpytko

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
A. Mickiewicza Avenue 30, 30-059 Krakow, Poland
e-mail: ksaidov@student.agh.edu.pl; szpytko@agh.edu.pl

Abstract

Structural monitoring systems are widely adopted to monitor the behaviour of structures during forced vibration testing or natural excitation. Structural monitoring systems can be found in a number of common structures including aircrafts, ships, bridges, mechanical and civil structures. For example, some building design codes mandate that structures located in regions of high seismic activity have structural monitoring systems installed. This paper is focused on selected problems review of the health monitoring of tall type buildings and automation. The actual problem in structural health monitoring (SHM) is to find the structural damage and its location by performing some statistical pattern recognition on the measured data termed as feature extraction. The damage caused by environmental loads should be repaired; otherwise, it will expand with time and might lead to complete system failure. Dynamic parameters such as velocity, acceleration, and displacement play a significant role in determining the structure dynamics. As well as this paper highlights comprehensive survey about monitoring system used in civil structures (buildings) involving the issues such as influence of different outer forces on buildings and other critical methods for proper analysis of monitoring system used in tall type buildings. Additionally, wide-scale review related to an automation aspect of structural health monitoring of buildings has been presented. A significant observation from this review is that although there are many more SHM studies being reported, the investigators, in general, have not yet fully embraced the well-developed tools from statistical pattern recognition. As such, the discrimination procedures employed are often lacking the appropriate rigor necessary for this technology to evolve beyond demonstration problems carried out in laboratory setting.

Keywords: *structural health monitoring (SHM), tall frame type buildings, automation*

1. Introduction

Tall buildings are frequently believed to be non-sustainable, generally due to the large amount of materials required for the structure. A high-rise tall building requires a wind-load resisting system, while low-rise buildings may resist the wind load with almost the gravity-load resisting system only. Furthermore, tall buildings require a gravity-load resisting system with heavier components (especially at the lower stories) than low-rise buildings. Nevertheless, the greater amount of material required by high-rise with respect to low-rise structures (premium for height) depends mainly on the wind-load resisting system.

The development of new materials and advanced construction techniques in recent years has resulted in the emergence of many super-tall buildings, which are mainly wind-sensitive structures. A statistical report from the Council on Tall Building and Urban Habitat [15] indicates that 37 tall buildings over 300 m have been built throughout the world since 2000. Due to rapid urban developments in some countries, more super-tall structures will be built. For these high-rise structures, wind loads usually control their structural design, resulting in a higher emphasis on understanding the structural behaviour of super-tall buildings under strong wind actions, in particular in typhoon or hurricane-prone regions.

Although important advances have been made for evaluation of the wind effects on tall buildings by wind tunnel testing and numerical simulation, many critical phenomena might only be investigated by full-scale experiments on prototype structures. Field measurement is still regarded as the most reliable way for investigation of the wind effects on buildings and structures as well. Multiple studies on wind effects on tall buildings have been carried out by field measurements over the past three decades [9]. In particular, several full-scale measurement studies on the wind effects on super-tall buildings are being conducted, including the programs on four Chicago super-tall buildings by Notre Dame University and the University of Western Ontario [33] and on ten super-tall buildings in Hong Kong, Taiwan and mainland China by City University of Hong Kong [39, 40]. However, opportunities to conduct full-scale measurements are still quite rare, and hence the data obtained are of significant value.

Moreover, it has been recognized the importance of full-scale testing as a benchmark for both wind tunnel and CFD modelling. Literature review reveals that comprehensive full-scale measurements of wind effects on super-tall buildings (buildings with a height > 400 m) have seldom been conducted under typhoon or hurricane conditions. Thus, such a database needs to be created and modified.

The earthquake and also wind load acting on the buildings are termed as lateral loads since their effect is felt generally in the horizontal direction. This is in contrast to the weights of the building, which act vertically down due to gravity. Forces due to earthquake, called seismic forces, are induced in a building because of the heavy masses present at different floor levels. Such forces are called inertial forces that are calculated by the products of the masses and their respective accelerations. If there is no mass, there is no inertial force. Accelerations generated by the seismic waves in the ground are transmitted via the vibrating structure to the masses at various levels, thereby generating the so-called horizontal seismic forces. The building behaves like a vertical cantilever, and swings horizontally almost like an inverted pendulum, with masses at higher levels swinging more (Fig. 1). Hereby, the generated seismic forces are higher at the higher floor levels. Because of the cantilever action of the building (fixed to the ground and free at the top), the forces accumulate from top to bottom. The complete horizontal force acting on the ground storey columns is a sum of the forces (seismic loads) acting at all the levels above. This is termed as the base shear and it leads to highest stresses in the lowermost columns [10].

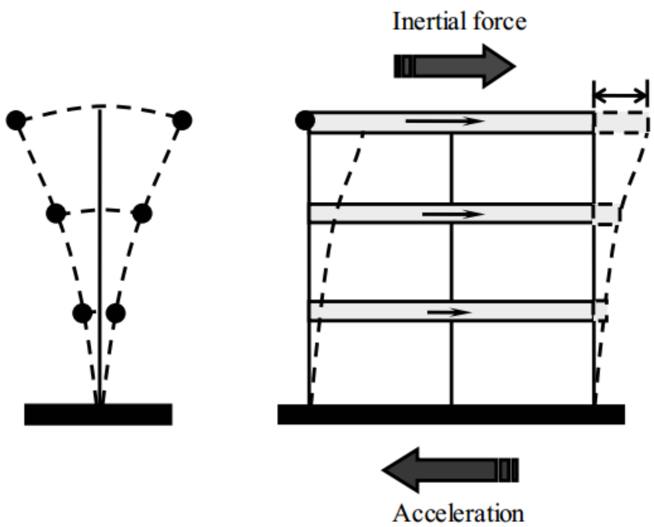

Fig. 1. Draft of seismic forces generated by masses vibrating [10]

The development of structural health monitoring technology for surveillance, evaluation and assessment of existing or newly built buildings has now attained some degree of maturity. On-structure long-term monitoring systems have been implemented on buildings in Europe [2, 7, 11, 43], the United States [47, 55], Canada [13, 42], Japan [24, 58], Korea [35, 60], China [46, 56, 59] and other countries [44, 45, 53].

Building and bridge structural health monitoring systems are generally envisaged to:

1. validate design assumptions and parameters with the potential benefit of imp roving design specifications and guidelines for future similar structures;
2. detect anomalies in loading and response, and possible damage/deterioration at an early stage to ensure structural and operational safety;
3. provide real-time information for safety assessment immediately after disasters and extreme events;
4. provide evidence and instruction for planning and prioritizing building inspection, rehabilitation, maintenance and repair;
5. monitor repairs and reconstruction with the view of evaluating the effectiveness of maintenance, retrofit and repair works;
6. obtain massive amounts of in situ data for leading edge research in building and bridge engineering, such as wind- and earthquake-resistant designs, new structural types and smart material applications.

The development and implementation of a structural health monitoring system capable of fully achieving the above objectives and benefits is still a challenge at present, and needs well-coordinated interdisciplinary research for full adaptation of innovative technologies developed in other disciplines to applications in the civil engineering community. Actually, structural health monitoring has been a subject of major international research in recent years [3, 12, 57]. The research in this subject covers sensing, communication, signal processing, data management, system identification, information technology, etc. It requires collaboration between civil, mechanical, electrical and computer engineering among others. The current challenges for building structural health monitoring are being identified as distributed and embedded sensing, data management and storage, data mining and knowledge discovery, diagnostic methods, and presentation of useful and reliable information to building owners/managers for decision making on maintenance and management.

The paper is focusing on selected problems review of the health monitoring of tall type buildings and automation. The actual problem in structural health monitoring (SHM) is to find the structural damage and its location by performing some statistical pattern recognition on the measured data termed as feature extraction. The damage caused by environmental loads should be repaired; otherwise, it will expand with time and might lead to complete system failure. Dynamic parameters such as velocity, acceleration, and displacement play a significant role in determining the structure dynamics.

2. Monitoring system used in tall type buildings

Most global structural health monitoring methods are cantered on either finding shifts in resonant frequencies or changes in structural mode shapes. The premise that changes in the dynamics characteristics of a structure indicate damage is compromised by the fact that temperature changes, moisture and other environmental/ecological factors also produce changes in dynamic characteristics. If the causes of changes in dynamic characteristics other than damage are considered to be noise in the measurement, then the changes due to damage must be significantly larger than the noise in order for the techniques to work.

When environmental forces influence on buildings, the structure of buildings will be under stress-strain state. Parameters of stress-strain state are transmitted to Control room (where computers have special software) via sensors, such as vibration, displacement, strain and temperature. If income data is positive there will be no Alarm, if data is negative the Alarm turns on and it will be shown in software those point in structure that was detected problem (Fig. 2).

Early works in structural health monitoring revealed that loss of a single member in a structure could result in changes in the fundamental natural frequency of one to as much as thirty percent [5, 54]. Indeed, if a member is not strained in the fundamental mode, then the loss of that member has no effect on the fundamental frequency or mode shape. By the same argument, if the structure was statically determinate then the loss of any member would result in an unstable structure. In concrete structures where most of the stiffness is contributed by the concrete, the deterioration of the reinforcing steel has been shown to have little influence on the natural frequency [22].

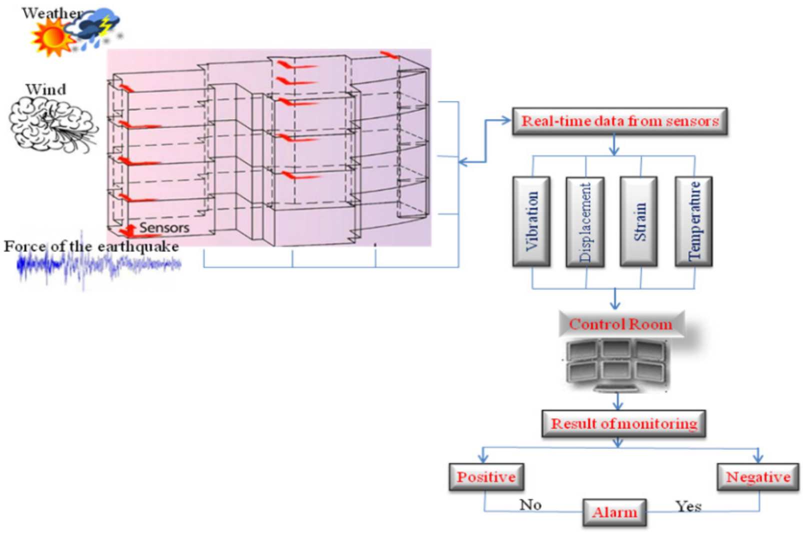

Fig. 2. The SHM process sketch in tall type buildings

In highly redundant structures such as shells, damage in the form of a notch produced changes in the dynamic characteristics that were not measurable [52]. It is easy to see that some forms of damage may not affect the frequency at low levels of vibration, for example: the loss of a bolt in a connection with several bolts may appear to be fixed because the friction provided by the remaining bolts may be sufficient to keep the members to the connection from rotating at low levels of forces. Although the loss of important members in a structure does result in measurable changes in natural frequencies, this approach cannot capture many forms of damages. Therefore, it provides only necessary, but insufficient conditions to fully assess or characterize damage in a structure.

The structural health monitoring of tall buildings generally uses vibration data on the base of vibrations forces will be displacement and strain. The damage reflects the changes of structural parameters, such as the damping coefficients and stiffness. Only few researches used a data-mining technique on SHM. In paper [23] classification methods were used to determinate the modal parameters, such as the vibration intensity, the structure is natural frequencies and the damping coefficients.

The new generation of high-rise buildings is higher and more slender than those buildings, which were built before. In addition, increased use is made of high-strength materials, although these do not have a higher stiffness than the conventional materials. Both aspects increase the sensitivity of tall buildings to dynamic behaviour. The design has to ensure correct reliability and comfort, as wind-induced vibrations may cause discomfort. Consequently, the dynamic analysis plays significant role in the design. Damping is the most essential but most uncertain parameter affecting the dynamic responses of buildings. The causes of dispersion of full-scale damping are differences in structural materials, foundations and soil, architectural finishing, vibration amplitude, and joint types. Damping data have been collected by several researchers, e. g.: [29, 31, 37] as there is no theoretical method for estimating damping in buildings, it should be evaluated from full-scale data received from measurements.

In order to establish the damping in buildings, measurements of accelerations are performed in most of the times the top floor of the building subjected to random wind loading. These accelerometers are placed in various directions in order to be able to identify the several vibration modes with corresponding damping values. The modal properties of tall buildings are derived from these measurements on existing buildings. Measured accelerometer signals are translated into values for the damping and natural frequency. In order to obtain reliable values for the modal properties, the distillation of these parameters from the measured signal is an immensely important step. Several damping estimation techniques and modal identification techniques exist. Significant are the quality of estimated damping, the user − friendness and the efficiency of the damping estimation techniques.

Support vector machines (SVMs), also known as support vector networks [16] are supervised learning models with associated learning algorithms that analyse data and recognize patterns, used for regression and classification analysis. Given a set of training examples, each marked as belonging to one of two categories, an SVM training algorithm builds a model that assigns new examples into one category or the other, making it a non-probabilistic binary linear classifier. An SVM model is a representation of the examples as points in space, mapped so that the examples of the separate categories are separated by a clear gap that is as wide as possible. New examples are then mapped into that same space and predicted to belong to a category based on which side of the gap they fall on. The SVMs provide a compromise between the pure nonparametric and parametric the approaches: As in linear classifiers, SVMs estimate a linear decision function, with the particularity that a previous mapping of the information into a higher-dimensional feature space might be needed. This mapping is characterized by the choice of a class of functions called as kernels. The support vector method was introduced by [8]. The SVMs operate within the framework of regularization theory by minimizing an empirical risk in a consistent and well-posed way. A clear advantage of the support vector approach is that sparse solutions to classification and regression problems are normally obtained.

Support vector machine (SVM) is a most highly desirable classification method, because it offers a hyper-plane that represents the largest separation (or margin) between the two classes. However, it needs to solve the quadratic programming (QP) in order to reveal a separation hyper-plane, which causes an intensive computational complexity. A method of reducing training data is to use the geometric properties of SVM. Convex hull has been applied in training SVM [6].

In computational geometry, a number of algorithms are known for computing the convex hull for a finite set of points. The Graham scan [25] finds all vertices of the convex hull ordered along its boundary by computing the direction of the cross product of the two vectors. The Jarvis march (gift-wrapping) [30] identifies the convex hull by angle comparisons and wrapping a string around the point set. The Divide and Conquer method [48] is applicable to the three-dimensional case.

Divide-and-conquer is a standard approach to solving complicated computational problems by splitting them into smaller, easier sub-problems which can be independently solved, and then integrated to give a global solution [17]. A number of well-known algorithms use a divide-and-conquer approach, such as merge sort and rapid sort and the fast Fourier transform. The efficiency of solving the sub-problems and the efficiency of this merging process will determine how effective a divide-and-conquer approach can be. While classical divide-and-conquer algorithms provide globally optimal solutions to problems, this is most probably an unrealistic aim for phylogenetic methods. Given that most optimization-based phylogenetic problems are likely to be NPcomplete [27], so there is very unlikely to be a polynomial-time algorithm to solve them: NPcompleteness has been shown for parsimony [28], compatibility [19], distance metrics [20] and likelihood problem [4]. Thus, we should expect phylogenetic divide-and conquer strategies to be heuristic rather than exact algorithms.

There is no guarantee that solutions to sub-problems will be adequate and thus no guarantee that they will all be compatible or readily combinable. Even obviously disjoint sub-problems can be incompatible (while quartets with less than three leaves in common have to be pairwise compatible, three such quartets can be incompatible). In the phylogenetic context, there may be choices to be made in the order sub-problems are combined and even between which sets of sub-problems to consider at all.

The incremental convex hull [32] and quick hull [21] algorithms consist of eliminating some points on the convex hull, so that problems are easily solved. By using a non-convex loss function, it forms a non-convex SVM type. However, some good properties of SVM, for instance, the maximum margin, cannot be guaranteed [14], because the intersection parts of data sets are not satisfied convex conditions.

The structural health monitoring of tall buildings generally uses vibration data. The damage reflects the changes of structural parameters, such as the damping coefficients and stiffness. Only a few research used a data-mining technique on SHM. In classification methods were used to determinate the modal parameters, like the vibration intensity, structure's natural frequencies and the damping coefficients.

One class of structure that is especially well suited to benefit from continuous monitoring is tall buildings. These structures affect the comfort and safety of a great number of people in both residential and office environments, and as state-of-the-art structural analysis software and wind tunnel testing used in the design of these structures are advancing quickly, the correctness and validity of their results need to be calibrated with respect to actual performance. This becomes particularly essential to insure the economy and efficiency of future designs with enhanced complexity and height generally governed by serviceability and habitability limit states under wind that are especially sensitive to the amount of inherent damping in these systems.

The Burj Khalifa project is the tallest structure ever built by man (Fig. 3), that rises 828 meters into Dubai skyline tall and it consists of 162 floors above grade and 3 basement levels. The development of the survey and Structural Health Monitoring (SHM) program for Burj Khalifa, at the time of the system installation, is probably one of the most comprehensive survey and real-time Structural Health Monitoring (SHM) programs in the history of super tall buildings that will track the structural behaviours and responses of the tower during construction.

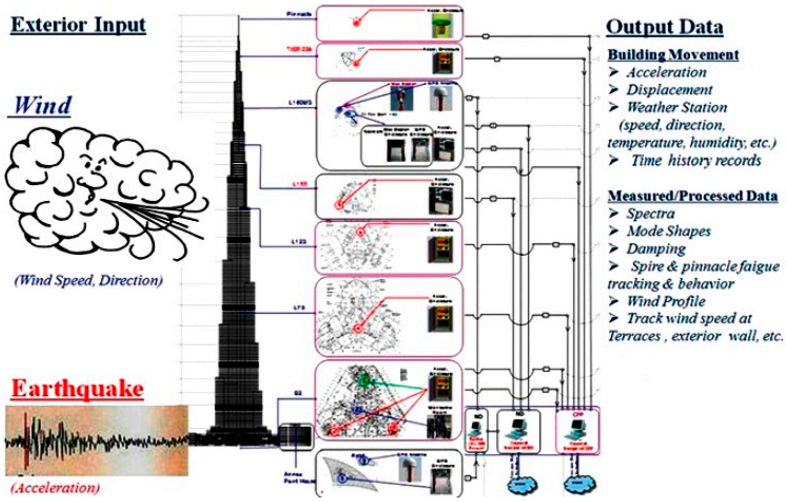

Fig. 3. Detailed summary of the permanent real-time Structural Health Monitoring (SHM) program [1]

The monitoring of system structural at Burj Khalifa consisting of:

1. three (3) pairs of accelerometers at the foundation level of the tower to capture base accelerations,
2. six (6) pairs of accelerometers at levels 73, 123, 155 (top of concrete), 160 M3, Tier23A, and top of the pinnacle to measure the tower acceleration simultaneously at all levels,
3. a GPS system to measure the building displacement at level 160 M3,
4. twenty three (23) sonimo-meters at all terrace and setback levels, including the top of the pinnacle at +828 m above ground, to measure wind speed and direction,
5. weather station at level 160 M3 to measure, wind speed and direction, relative humidity, and temperature.

Structural Health Monitoring (SHM) program Burj Khalifa was an extension to the already developed temporary Structural Health Monitoring (SHM) system developed to monitor the building behaviour during construction, and developed in cooperation between Samsung Construction &Trading, The University of Notre Dame, and the wind tunnel testing facility at Cermak Peterka, Petersen (CPP). See Fig. 3 for the detailed configuration of the Structural Health Monitoring (SHM) program concept developed by the author for Burj Khalifa. Since completion of the installation of the SHM program at Burj Khalifa, most of the structural system characteristics have been identified and included measuring the following:

1. building acceleration at all levels,
2. building displacements at level 160M3,
3. wind profile along the building height at most balcony areas, including wind speed and direction, which still needs calibration to relate to the basic wind speed,
4. building dynamic frequencies, including higher modes,
5. expected building damping at low amplitude due to both wind and seismic events,
6. time history records at the base of the tower [1].

Unfortunately, only limited studies have pursued full-scale investigations related to habitability performance of structures [18] and validation of their design practice [38], while most published full-scale damping observations under service conditions are derived from mid-rise buildings, associated largely with the Fampus Japanese database [50]. For this reason, the authors initiated the Chicago Full-Scale Monitoring Program 2002 to permit the response of three tall buildings in Chicago to be compared against design predictions, including their levels of inherent damping [34].

Basically, the structural health monitoring SHM system used in many buildings historically, including the Chicago Full-Scale Monitoring Program (CFMP), has been a wired system, frequently termed spoke and hub due to the fact that the sensors are located throughout the structure and then wired to a central data acquisition unit. This is a proven technology that has been applied to a wide range of structures, however suffers from two important issues connected with its cables:

1. instrument cables are very costly and complicate to deploy and maintain,
2. lengthy cables essentially serve as antennas, allowing noise to infiltrate the system.

In the aforementioned applications to tall buildings, where response at the highest floor is mainly the sole observed quantity, the wired hub-and-spoke systems have proven to be exceptionally reliable [34]. However, since this type of system originates from the small-scale laboratory setting, it becomes increasingly less practical in full-scale when sensors are distributed over large and complex structures. Probably more importantly, the use of cables inherently creates a rigid system that cannot be easily expanded or redeployed. Environmental effects such as moisture variation and temperature variation can introduce severe noise in the reading. Integrated with the facts that typical damage to the structure is small and the signal-to-noise ratio is frequently not large enough to determine the extent and locations of the damage based on the global dynamic characteristics of the damaged structure of buildings. Along with methods based on the use of stiffness, mass or damping matrices suffer from the fact that these matrices are computed based on idealized situations not likely to be found in real life.

3. Automation problem of the system health monitoring

While designing a Structural Health Monitoring (SHM) system, one should always focus on the certain requirements of the structure under test. The first step in the design process consists in identifying the probable degradation mechanism and the associated risks factors, in collaboration with the structure’s designer and owner. Consequently, the expected responses to these degradations are established and an appropriate Structural Health Monitoring Systems is designed to reveal such conditions. Only at this stage, the appropriate sensors should be selected.

Once the sensors are verified and installed, data collection can start. If these logical steps are followed and the monitoring data is adequately acquired and managed, data analysis and interpretation will be immensely simplified. In addition, if one designs an SHM system starting from a specific sensor system, it frequently ends up with a great quantity of data, but no plans on how to analyse it. When selecting the best suitable sensors for the specific risks associated with a given structure, it is often important to integrate different measurement technologies.

The use of relational database structures can immensely oversimplify the handling of this large and heterogeneous data-flow. With an adequate data structure, the measurement data and other related information on the monitoring network, the structure and its environment can be organized in a single repository that will follow the structure's life in the years and near future.

The aim of structural health monitoring for civil structural engineering is not only detection of sudden or progressive damages but also monitoring their performance under operational conditions or under some particular environmental issues such as earthquakes [41].

One of the essential aspects for the application of damage detection techniques as a part of monitoring practices is an automated identification and tracking procedure, because traditional modal identification requires extensive interaction from an experienced user [49].

Currently, there are few advancements in this field, with the development of methods based on control theory and methods based on conventional signal processing. As regards the first class of methods, during modal analysis the model order is usually over-specified to get all physical modes present in the frequency range of interest. Nevertheless, physical and mathematical modes have to be refined.

This practice requires large interaction with an expert user. In addition, most of the classical model order selection tools used in time domain and in frequency domain identification only allow to verify if the model order used is appropriate but do not separate physical from mathematical modes [51]. Thus, the stabilization diagram is yet significant tool in modal analysis to separate physical from mathematical modes. Selection of physical poles is not however a trivial task since it might be difficult and time-consuming depending on the quality of data obtained, the performance of the estimator and the experience of the user. Extensive interaction between tools and user is generally inappropriate for monitoring purposes [36] – Fig. 4.

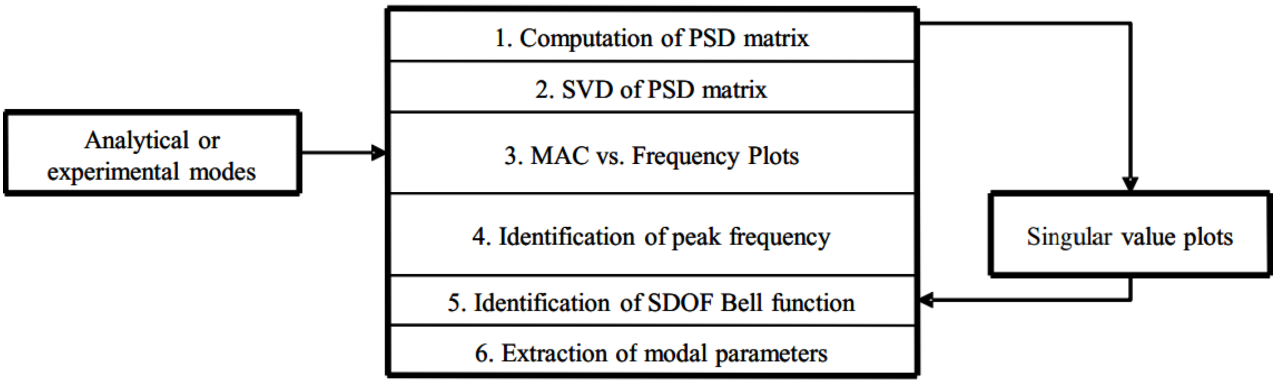

Fig. 4. The algorithm for automated modal identification [36, 49]

Short explanations the Fig. 4: an automated procedure is based on Enhanced Frequency Domain Decomposition (EFDD). An alternative approach to the automated identification of the modal parameters of the structure is herein proposed. It is based on the Enhanced Frequency Domain Decomposition procedure for the modal identification in operational conditions. Identification of the auto power spectral density function of the corresponding Single Degree Of Freedom (SDOF) system by comparing the mode shape estimate with the singular vectors at the frequency lines around the peak after defining a Modal Assurance Criterion (MAC) rejection level. The Inverse Fourier Transform (IFT) of the identified spectrum (SDOF Bell function) for the corresponding SDOF system allows the computation of the damping ratio by the logarithmic decrement technique. The described procedure can be automated if the mode shapes (experimental or numerical) of the monitored structure are known according to the procedure shown in Fig. 4. As in the time domain the output of a linear dynamic system can be expressed in terms of its mode shapes and generalized coordinates, performing the SVD of the PSD matrix it is decomposed into a set of auto-spectral density functions, each corresponding to a SDOF system. Since the peaks of the SV plot indicate a mode (when spurious harmonic modes do not exist) and the singular vector associated to the peak frequency approximates the true mode shape. In fact, the plot of MAC vs. frequency will illustrate an absolute maximum at the frequency of the mode itself, where the singular vector obtained from the SVD of the PSD matrix approximates the effective mode shape of the structure. After the identification of the peak frequency, the mode characterization is performed according to the standard EFDD procedure [36, 49].

System of SHM is the system that will automate process monitoring and collecting data from structure of buildings and facilities such as stress-strain state, temperature and displacement of constructions from acting loads in real-time as mentioned in Fig. 2.

According to paper [49], recently, an interesting proposal for automated modal identification based on Least Square Complex Frequency (LSCF) method has been published. This method moves from the identification of a model with sufficiently high order using a frequency-domain Maximum Likelihood estimator. A first validation of the poles is performed on the base of both stochastic and deterministic criteria, which allow the identification and removal of a first group of non-physical poles.

Consequently, as regards the methods based on conventional signal analysis in paper [26] authors have proposed the so-called Time Domain Filtering method, which is based on the application of a band-pass filter to the system response with the aim of isolating the single modes in the spectrum. However, the frequency limits of the filter are user-specified based on the Power Spectral Density (PSD) plots of the response signals and, if excitation is obscure, it is sometimes complicated to identify the regions where certain modes may be located according only to power spectrum plots.

A significant challenge in developing an SHM strategy for civil infrastructure is that except for certain types of public and private housing, every structure is unique. This means that there is no baseline derived from type testing or the expensive qualification procedures applicable for aerospace structures. Thus, a unique feature of SHM for civil infrastructure is that a major part of the system has to be geared towards a long-term evaluation of what is ‘normal’ structural performance or health, the two terms being synonymous.

Specification issues that require automation of the decision making process in the evaluation of the technical state of the tall type structure cover:

1. Damage detection on the basis of influence coefficients. This method uses a time-domain identification procedure to detect structural changes on the basis of noise-polluted measurements. Application of the identification procedure under discussion yields the optimum value of the elements of equivalent linear system matrices (influence coefficients). By performing the identification task before and after potential structural changes (damage) in the physical system have occurred, quantifiable changes in the identified mathematical model may be detected by analysing the probability density functions of the identified system matrices.
2. Damage detection using neural networks. Among the structure-unknown (model-free) identification approaches that have been receiving growing attention recently are neural networks. Not only do neural networks not require information concerning the phenomenological nature of the system being investigated, they also have fault tolerance, which makes them a robust means for representing model-unknown systems encountered in the real world.
3. Reliability and risk analysis. The model updating methodology based on a nonlinear physics-based model of the monitored structure will be used not only as a tool for tracking the health of the structure, but also as a basis to assess the reliability of the structure in performing as

expected under uncertain current and future loads. Reliability of the structure against various potential limit-states can be evaluated using a probabilistic mechanics-based model of the structure and a probabilistic representation of current and future load effects and deterioration effects. The combination of probabilistic non-destructive structural health monitoring techniques and computational methods of reliability analysis provides a powerful tool to continuously competency monitor of the structure under consideration.

4. Probabilistic modelling and computational decision theory. Probabilistic networks (or Bayesian probabilistic networks) provide a comprehensive framework for modelling and analysing uncertainties. Although there have been a number of developments in this field, there are still numerous challenges in extending the theory and tools to address a larger range of applications, including the incorporation of background knowledge into the model-building process, providing large-scale database support for probabilistic modelling and decision support, and relating probabilistic modelling to other mathematical and statistical methods.

4. Conclusions

The basic premise of SHM feature selection is that damage will significantly alter the stiffness, mass or energy dissipation properties of a system, which, in turn, alter the measured dynamic response of that system. Although the basis for feature selection appears intuitive, its actual application poses many essential technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly manipulate the lower-frequency global response of structures that is normally measured during system operation. Stated another way, this fundamental challenge is similar to that in many engineering fields where the ability to capture the system response on widely varying length- and time-scales, as is needed to model turbulence or to develop phenomenological models of energy dissipation, has proven difficult.

Another fundamental challenge is that in major situations feature selection and damage identification must be performed in an unsupervised learning mode. That is, data from damaged systems are not available. Damage can accumulate over widely varying time-scales, which poses significant challenges for the SHM sensing system. This challenge is supplemented by many practical issues associated with making accurate and repeatable measurements over long periods at a limited number of locations on complex structures often operating in adverse environments.

Finally, an important challenge for SHM is to develop the capability to define the required sensing system properties before field deployment and, if possible, to demonstrate that the sensor system itself will not be damaged when deployed in the field. If the possibility of sensor damage exists, it will be necessary to monitor the sensors themselves. This monitoring can be accomplished either by developing appropriate self-validating sensors or by using the sensors to report on each other's condition. Sensor networks should also be fail-safe. If a sensor fails, the damage identification algorithms must be able to adapt to the new network. This adaptive capability implies that a certain amount of redundancy must be built into the sensor network.

In addition to the challenges described above, other non-technical issues must be addressed before SHM technology can make the transition from a research topic to actual practice. These issues include convincing structural system owners that the SHM technology provides an economic benefit over their current maintenance approaches and convincing regulatory agencies that this technology provides a significant life-safety benefit. All these challenges lead to the current state of SHM technology, where outside of condition monitoring for rotating machinery applications SHM remains a research topic that is still making the transition to field demonstrations and subsequent field deployment. There are many ongoing and new structural monitoring activities, but these systems have been put in place without a pre-defined damage to be detected and without the corresponding data interrogation procedure. As such, these monitoring activities do not represent a fully integrated hardware/software SHM system with pre-defined damage identification goals.

Structural Health Monitoring (SHM) is not a trend or new technology. Since ancient times, architects, engineers and artisans have been keen on observing the behaviour of built structures to discover any sign of degradation and to expand their knowledge and improve the design of future structures. Taller buildings and larger domes were constructed, and sometimes failed during construction or after a short time. Those failures and their analysis have caused to new insight and improved design of future structures. As for any engineering problem, receiving reliable information is always the first and fundamental step towards finding a solution. Monitoring structures is our way to get quantitative and qualitative data about our buildings and assist us in taking informed decisions about their health and destiny. This paper has presented the challenges and advantages related to the implementation of Structural Health Monitoring system, guiding the reader in the process of analysing the risks connected with the construction and operation of a specific building and the design of a matching monitoring system and data analysis strategy.

As well as to the challenges described above, other non-technical issues have to be addressed before structural health monitoring technology can make the transition from a research topic to actual practice. These issues involve convincing structural system owners that the SHM technology provides an economic benefit over their current maintenance approaches and convincing regulatory agencies that this technology provides an important life-safety benefit. All these challenges lead to the current state of SHM technology, where outside of condition monitoring for rotating machinery applications SHM remains a research topic that is still making the transition to field demonstrations and subsequent field deployment. There are many ongoing and new updated structural monitoring activities, but these systems have been put in place without a pre-defined damage to be detected and without the corresponding data interrogation procedure. As such, these monitoring activities do not represent a completely integrated hardware/software SHM system with pre-defined damage identification goals.

Acknowledgment

The work has been supported by the Polish Ministry of Science and Higher Education from funds for year 2015.

References

[1] Abdelrazaq, S. E., *The program in place at the Burj Khalifa tower serves as a model for new monitoring programs*, http://cenews.com/article/9742/structural-vital-signs, 2014.

[2] Andersen, E. Y., Pedersen, L., *Structural monitoring of the Great Belt East Bridge*, In: Krokebogr, J. (editor), *Strait crossings*, 94, pp. 189-95, Balkema, Rotterdam 1994.

[3] Auweraer, H., Peeters, B., *International research projects on structural health monitoring: an overview*, Structural Health Monitoring, Vol. 2 (4), pp. 341-358, 2003.

[4] Addario-Berry, L., Chor B., Hallett, M., Lagergren, J., Panconesi, A., Wareham, T., *Ancestral maximum likelihood of evolutionary trees is hard*, Journal of Algorithms in Bioinformatics, Vol. 2812, pp. 202-215, 2003.

[5] Begg, R. D., Mackenezie, A. C., Dodds, C. J., Loland, O., *Structural integrity monitoring using digital processing of vibration signals*, Proceedings of the 8th Annual Offshore Technology Conference, pp. 305-311, Houston, TX 1976.

[6] Bennett, K. P., Bredensteiner, E. J., *Geometry in Learning*, Geometry at Work; Edited by C, Gorini, Mathematical Association of America, 2000.

[7] Brownjohn, J. M. W., Moyo, P., Omenzetter, P., Chakraborty, S., *Lessons from monitoring the performance of highway bridges*, Structures Control Health Monitoring, Vo. 12 (3-4), pp. 227-244, July 2005.

[8] Boser, B. E., Guyon, I., Vapnik, V., *A training algorithm for optimal margin classifiers*, Fifth ACM Workshop on Computational Learning Theory (COLT), pp. 144–152, ACM Press, New York 1992.

[9] Campbell, S., Kwok, K.C.S, Hitchcock, P.A, Tse, K.T., Leung, H.Y., *Field measurements of natural periods of vibration and structural damping of wind-excited tall residential buildings*. Wind and Structures, Vol. 10 (5), pp. 401-420, 2007.

[10] CPWD, *Handbook on seismic retrofit of buildings*, Central Public Works Department & Indian Building Congress, In association with Indian Institute of Technology, Madras 2007.

[11] Casciati, F., *An overview of structural health monitoring expertise within the European Union*, In: Wu, Z. S., Abe, M. (Editors), Structural Health Monitoring and Intelligent Infrastructure, pp. 31-37, Balkema 2003.

[12] Chang, P. C., Flatau, A., Liu, S. C., *Health monitoring of civil infrastructure*, Structural Health Monitoring, Vol. 2 (3), pp. 257-267, 2003.

[13] Cheung, M. S., Naumoski, N., *The first smart long-span building in Canada - health monitoring of the Confederation Bridge*, Proceedings of the 1st international workshop on structural health monitoring of innovative civil engineering structures, Mufti, A.A. (Editor), pp. 31-44, ISIS Canada Corporation, Winnipeg 2002.

[14] Collobert, R., Sinz, F., Weston, J., and Bottou, L., *Trading convexity for scalability*, Proceedings of the 23rd International Conference on Machine Learning (ICML '06), pp. 201-208, Pittsburgh, USA 2006.

[15] CTBUH, *Council on Tall Building and Urban Habitat*, The tallest 20 in 2020: entering the era of the megatall, Chicago 2011.

[16] Cortes, C., Vapnik, V., *Support-vector networks*, Machine Learning, Vol. 20 (3), pp. 273-297, 1995 (doi:10.1007/BF00994018).

[17] Cormen, T. H., Leiserson, C. E., Rivest, R. L., *Introduction to Algorithms*, MIT Press, Cambridge, MA 2001.

[18] Denoon, R. O., Letchford, C. W., Kwok, K. C. S., Morrison, D. L., *Field measurements of human reaction to wind-induced motion*, Proceedings of 10th International Conference on Wind Engineering, Wind Engineering into the 21st Century, Copenhagen 21-24 June 1999, Balkema, Rotterdam 1999.

[19] Day, W. H. E., Sankoff, D., *Computational complexity of inferring phylogenies from dissimilarity matrices,* Bulletin of Mathematical Biology, Vol. 35, pp. 224-231, 1986.

[20] Day, W. H. E., *Computational complexity of inferring phylogenies from dissimilarity matrices*, Bulletin of Mathematical Biology, Vol. 49 (4), pp. 461-467, 1987.

[21] Eddy, W., *A new convex hull algorithm for planar sets*, ACM Transactions on Mathematical Software, 3 (4), pp. 398–403, 1977.

[22] Friswell, M. I., Penny, J. E. T., *Is damage location using vibration measurements practical,* Euromech 365 International Workshop: DAMAS 97, Structural Damage Assessment using Advanced Signal Processing Procedures, Sheffield (UK) 1997.

[23] Forstner, E., Wenzel, H., *The application of data mining in bridge monitoring projects: exploiting time series data of structural health monitoring*, Proceedings of the 22nd International Workshop on Database and Expert Systems Applications, 2011.

[24] Fujino ,Y., Abe, M., *Structural health monitoring - current status and future*, Proceedings of the 2nd European workshop on structural health monitoring, Boller, C., Staszewski, W. J. (Editors), pp. 3-10, Lancaster (PA), DEStech, 2004.

[25] Graham, R. L., *An efficient algorithm for determining the convex hull of a finite planar set*, Information Processing Letters, Vol. 1 (4), pp. 132-133, 1972.

[26] Guan, H., Karbhari, V. M., Sikorski, C. S., *Time-domain output only modal parameter extraction and its application*, Proceedings of the 1st BIOMASS Conference, Denmark2005.

[27] Garvey, M. R., Johnson, D. S., *Computers and Intractability: A guide to the theory of NP-completeness*, A Series of Books in the Mathematical Sciences, Victor Klee (Editor), Freeman, New York 1979.

[28] Graham, R. L., Foulds, L. R., *Unlikelihood that minimal phyogenies for a realistic biological study can be constructed in reasonable computation time*, Journal of Mathematical Biosciences, Vol. 60, pp. 133-142, 1982.

[29] Haviland, R., *A study of the uncertainties in the fundamental translational periods and damping values for real buildings*, Massachusetts Institute of Technology, 275, PB-253, pp. 188, 1976.

[30] Jarvis, R. A., *On the identification of the convex hull of a finite set of points in the plane*, Information Processing Letters, Vol. 2 (1), pp. 18-21, 1973.

[31] Jeary, A.P., *Damping in buildings – a mechanism and a predictor*, Earthquake Engineering and Structural Dynamics, Vol. 14, pp. 733-750, 1986.

[32] Kallay, M., *The complexity of incremental convex hull algorithms in RD*, Information Processing Letters, Vol. 19 (4), pp. 197, 1984.

[33] Kijewski-Correa, T., Kochly, M., *Monitoring the wind-induced response of tall buildings: GPS performance and the issue of multipath effects*, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 95, pp. 1176-1198, 2007.

[34] Kijewski-Correa, T., Kilpatrick, J., Kareem, A., Kwon, D. K., Bashor, R., Kochly, M., Young, B. S., Abdelrazaq, A., Galsworthy, J., Isyumov, N., Morrish, D., Sinn, R. C., Baker, W. F., *Validating wind-induced response of tall buildings: Synopsis of the Chicago full-scale monitoring program,* Vol. 132 (10), pp. 1509-1523, 2007.

[35] Koh, H. M., Choo, J. F., Kim, S. K., Kim, C. Y., *Recent application and development of structural health monitoring systems and intelligent structures in Korea*. In: Structural health monitoring and intelligent infrastructure, Wu, Z. S., Abe, M., (Editors), pp. 99-111, Lisse, Balkema 2003.

[36] Lanslots, J., Rodiers, B., Peeters, B., *Automated pole-selection: proof-of-concept and validation*, Proceedings of the International Conference on Noise and Vibration Engineering (ISAM) Leuven, Belgium 2004.

[37] Lagomarsino, S., *Forecast models for damping and vibration periods of buildings*, Journal of Wind Engineering and Industrial Aerodynamics, Vol. 48, pp. 221-239, 1993.

[38] Li, Q. S., Xiao, Y. Q., Wong, C. K., and Jeary, A. P., *Field measurements of typhoon effects on a super tall building*, Engineering Structures, Vol. 26 (2), pp.233-244, 2004.

[39] Li, Q. S., Fu, J. Y, Xiao, Y. Q., Li, Z. N., Ni, Z. H., Xie, Z. N., Gu, M., *Wind tunnel and full-scale study of wind effects on China's tallest building*, Engineering Structures, Vol. 28, pp. 1745-1758, 2006.

[40] Li, Q. S., Zhi, L. H., Tuan, A. Y., Kao, C. S., Su, S. C., Wu, C. F., *Dynamic Behavior of Taipei 101 Tower: field measurement and numerical analysis*, Journal of Structural Engineering, ASCE, Vol. 137, pp. 143-155, 2011.

[41] Mufti, A., *Guidelines for structural health monitoring*, University of Manitoba, ISIS, Canada 2001.

[42] Mufti, A., *A structural health monitoring of innovative Canadian civil engineering structures*. Structural Health Monitoring, Vol. 1 (1), pp. 89-103, 2002.

[43] Myrvoll, F., Aarnes, K. A., Larssen, R. M., Gjerding-Smith, K., *Full scale measurements for design verification of bridges*, In: Proceedings of the 18th International Modal Analytical Conference, pp. 827-835, Society for Experimental Mechanics, Bethel (CT) 2000.

[44] NHAI, *National Highways Authority of India Instrumentation (structural monitoring system) for Yamuna building at Allahabad/ Naini, Tender document*, 2002 (http://www.nhai.org/nit.htm).

[45] Nigbor, R. L., Diehl, J. G., *Two years' experience using OASIS realtime remote condition monitoring system on two large buildings and bridges*, In: Structural health monitoring: current status and perspectives, Chang F. K. (Editor), pp. 410-417, Technomic, Lancaster (PA) 1997.

[46] Ou, J., *The state-of-the-art and application of intelligent health monitoring systems for civil infrastructures in mainland of China*, In: Progress in Structural Engineering, Mechanics and Computation, Zingoni, A., (ed.), pp. 599-608, Balkema/Taylor and Francis, London 2004.

[47] Pines, D. J., Aktan, A. E., *Status of structural health monitoring of longspan bridges in the United States*, Progress in Structural Engineering and Materials, Vol. 4 (4), pp. 372-380, 2002.

[48] Preparata, F. P., Hong, S. J., *Convex hulls of finite sets of points in two and three dimensions*, Communications of the ACM, Vol. 20 (2), pp. 87-93, 1977.

[49] Rainieri, C., Fabbrocino, G., Cosenza E., *Automated operational modal analysis as structural health monitoring tool: theoretical and applicative aspects*, Key Engineering Materials, Vol. 347, pp. 479-484, 2007.

[50] Satake, N., Suda, K., Arakawa, T., Sasaki, A., and Tamura, Y., *Damping evaluation using full-scale data of buildings in Japan*, Journal of Structural Engineering, Vol. 129 (4), pp. 470-477, 2003.

[51] Soderstrom, T., *Test of pole-zero cancellation in estimated models*, Automatica, Vol. 11 (5), pp. 537-541, 1975.

[52] Srinivasan, M. G., Kot, C. A., *Effects of damage on the modal parameters of a cylindrical shell*, Proceedings of the 10th International Modal Analysis Conference, pp. 529-535, 1992.

[53] Thomson, P., Marulanda, C. J., Marulanda, A. J., Caicedo, J., *Real time health monitoring of civil infrastructure systems in Colombia*, In: Health Monitoring and Management of Civil Infrastructure Systems, Chase, S. B., Aktan, A. E. (Editors), pp. 113-121, The International Society for Optical Engineering, Bellingham (WA) 2001.

[54] Valdiver, J. K., *Detection of structural failure on fixed platforms by measurement of dynamic response*, Publisher: Offshore Technology Conference, Document IDOTC-2267-MS. M.I.T. and Woods Hole Oceanographic Institution, 1975.

[55] Wang, M. L., *State-of-the-art applications in health monitoring*, In: Invited presentation to Workshop on Basics of Structural Health Monitoring and Optical Sensing Technologies in Civil Engineering, Taiwan National Central University, pp. 113-142, 2004.

[56] Wong, K. Y., *Instrumentation and health monitoring of cable-supported bridges*, In: Structural Control and Health Monitoring, Vol. 11 (2), pp. 91-124, 2004.

[57] Worden, K., Dulieu-Barton, J. M., *An overview of intelligent fault detection in systems and structures*, International Journal of Structural Health Monitoring, Vol. 3, pp. 85-98, 2004.

[58] Wu, Z.S., *Structural health monitoring and intelligent infrastructures in Japan*. In: Structural health monitoring and intelligent infrastructure, Wu, Z. S., Abe, M., (Editors), pp. 153-167, Lisse, Balkema, 2003.

[59] Xiang, H.f., *Health monitoring status of long-span bridges in China*, In: Proceedings of the workshop on research and monitoring of long span bridge, pp. 24-31, 2000.

[60] Yun, C. B., Lee, J. J., Kim, S. K., Kim, J. W., *Recent R&D activities on structural health monitoring for civil infra-structures in Korea*, KSCE Journal of Civil Engineering, Vol. 7 (6), pp. 637-651, 2003.