Research on Intelligent Structural Health Monitoring System

Juanni Li and Wei Wang
School of Science, Xi’an Shiyou University, Xi’an, China

*Corresponding author e-mail: kikilee@xsyu.edu.cn

Abstract. The basic concepts of structural health monitoring are explained, the research status and its application in engineering are outlined, and the key activities of the health monitoring system are introduced. Finally, the application of statistical methods and machine learning methods in the process of damage identification is summarized.

Keywords: Structural Health Monitoring (SHM), Damage Detection, Evaluation

1. Introduction
In modern society, the development of countries heavily dependent upon the projects related to the national economy and the potential life-safety, such as buildings, roads, railways, bridges, aircraft, giant ships, power generation systems, large dams, offshore oil platforms, etc [1, 2]. However, engineering structures today are continuously ageing and during long-term use they will inevitably be damaged due to various mechanical failure, environmental factors, human errors [3]. Malfunctioning of their structures often has serious consequences. If judgments and alarms can be made timely, we can prevent the further damage and cause other accidents.

Therefore, monitoring the health of large and complex structures has aroused widespread attention. As Branko Glisic and Daniele Inaudi elucidates The safest and most durable structures are those that are well managed. Measurement and monitoring often have essential roles in management activities [4]. On the one hand, the monitoring of these complex structures can find potential problems and minimize the harm caused by the problems. On the other hand, the data obtained during the monitoring process are used to optimize the operation, maintenance, repair.

However, the increasing complexity of the structure and the diverse context of use have brought new challenges to the monitoring process. The manual timing, fixed-point detection and periodic screening used in the past are difficult to detect abnormal phenomena of structure. To prevent problems before they happen, an intelligent structural health monitoring (Structural Health Monitoring, SHM) system came into being.

By monitoring the structure health, structure system can be maintained in a good state for a long time, to reduce maintenance costs, and improve the reliability and safety of the system.

2. Basic Notions
Structural Health Monitoring is an expression being around for more than third decades now. However, the definition of SHM is still an open question so far [5-7]. Some researchers believe that SHM is a process, while others believe that SHM is a technology.
The process theory view that SHM is a monitoring process. The purpose of monitoring is to identify unusual structural behavior, determine where the unusual behavior occurs, and finally repair it. Such as: Branko Glisic and Daniele Inaudi described SHM as a process aimed at providing accurate and in-time information concerning structural condition and performance [4]. Farrar C R, Worden K. illustrate that the term SHM usually refers to the process of implementing a damage detection strategy for aerospace, civil or mechanical engineering infrastructure. The process refers to the use of periodic, dynamic response measurement methods to measure changes in structure and mechanical systems over time. The measurement information can reflect damage-sensitive features and statistical analysis of these features can determine the health of the system [8].

The technical viewpoint emphasizes various technologies in the process of structural monitoring, including sensor perception technology, monitoring system response technology, identification technology, diagnosis technology, etc. Such as: SHM is the technology that will allow the current time-based maintenance philosophies to evolve into potentially more cost effective condition-based maintenance philosophies. Condition-based maintenance means that the sensor system installed on the structure continuously monitors the response of the system. If there is an abnormality, the operator will be notified of the detection of damage or degradation, so that corrective measures can be taken before the damage or degradation reaches a certain critical level to reduce Loss of life safety and economic benefits [9]. Xiaoli Zhang describes intelligent structural health monitoring (ISHM) refers to various information sensed by the sensor network integrated in the structure through real-time collection and analysis, and monitor the parameters that best reflect the health of the structure [10].

As can be seen, various definitions indicate different understandings in the SHM field. However, the goals of SHM research are unified. Structural Health Monitoring (SHM) aims to detect and diagnose the state of the components of the structure during the life cycle. If it does not match the target state, corrective actions are taken to make the structure consistent in a healthy state [11].

In terms of monitoring time domain, the SHM monitoring process can be permanent monitoring, continuous monitoring for a period of time, and periodic discontinuous monitoring. Which monitoring method is used depends on the specific needs of the monitoring project. In terms of the selection of representative parameters for SHM, in general they include three types[4]: Mechanical level (average strain, average curvature, average shear strain, inclination (rotation), deformation, displacement, cracks opening, stress, load); Physical level (displacement , velocity, acceleration, wave propagation characteristics, vibration mode, temperature, temperature gradients, humidity, pore pressure); Chemical level: chloride penetration, sulfate penetration, pH, penetration, rebar oxidation, steel oxidation, timber decay.

3. Core Activities of SHM

With the advent of the era of big data, various traditional statistical methods and machine learning methods have been applied to SHM to make it more intelligent. The core activities of the structural monitoring process are: establishing the monitoring aim, design and installation of sensor network, data collection and transmission, data analysis, health diagnosis, evaluation of the structures safety and repair of damaged structures. The monitoring core activities are represented schematically in Figure 1.

3.1. Establishing the Monitoring Aim

It is very important to establish the monitoring aim in the early stages of project. Each structure has its own particularities and, consequently, the representative parameters should be selected according the context of the monitoring use. TANG Xu, ZHU Ya-zhou, et al., described the application of optical fiber material in ship structure. When the external hull structure is affected by the external environment, the temperature changes and the structure is strained, the internal FBG sensor is also affected by the stress and temperature, so as to achieve the effect of sensing the changes in the external environment [12]. Goutham R. Kirikera, Vishal Shinde, et al., modeled the propagation of asymmetric Lamb waves representing acoustic emission (AE) by superimposing the bending vibration modes of
the board. The SNS based on the data acquisition channel can locate the damage in the sensor grid [13].

![Figure 1. The monitoring core activities](image)

### 3.2. Design and Installation of Sensor Network

Obtaining reliable data is an important step in the process of solving any engineering problem. Therefore, sensors are the basis of structure monitoring. Sensors can comprehensively obtain the environmental load, local and overall characteristics of the structure. With the increasing complexity of the structure and increasing requirements for monitoring accuracy, sensors have expanded from a single-dimensional distribution to a multi-dimensional sensor network [14, 15]. We can take decision whether the structure is healthy based on the quantitative data obtained by sensor network.

In order to be better used in the monitoring process, the sensor is required to have the characteristics of miniaturization, reliability and durability, high sensitivity, and easy installation. There are many kinds of sensors for intelligent structural health monitoring, such as resistance strain wires, optical fibers, piezoelectric ceramics, electro-sensitive materials, shape memory alloys, piezoelectric polymers, etc. The data acquisition process involves selecting sensor types according to project requirements, definition of reading frequency, setting the compatibility with the environment number and locations, making an appropriate schedule of measurements and creating installation procedures.

### 3.3. Data Collection and Management

Acquire and collect data through sensors, and then quantify and analyze these measurement data, unify the data format and perform data management. Finally, the processed data is stored in the data memory through the data transmission line. When the monitoring data exceeds the predefined threshold, a warning message will be prompted. As the running time of the SHM system accumulates, the amount of data collected by the sensor will increase. Management, analysis and storage algorithms are a very important part of the SHM system. Advanced data management includes: providing for
access to data, visualization, data analysis, interpretation, data processing early alarm and export of data.

3.4. Health Diagnosis
In the actual structural health monitoring process, there is no one-to-one correspondence between damage and representative parameters. The same type of damage may correspond to changes in multiple representative parameters. While, the change of a certain parameter is caused by multiple types of damage. There is a multi-dimensional information mapping relationship between them. For example, in the process of bridge structure monitoring, several parameters are often required to be monitored, such as average strains, slabs and shells, crack occurrence and quantification, and curvatures in beams [4].

Therefore, in order to accurately diagnose the health of the structure based on data, the following core content is necessary:
(1) Raw data acquisition
(2) Data analysis and processing
(3) Algorithm reliability
(4) Field experience accumulation and application.

3.5. Evaluation of the Safety of Structure
Structures have different life periods: construction, testing, service, repair and refurbishment, and so on [4]. Each of these periods have the same or different monitoring parameters. The measured values obtained through online real-time can reflect the health status of the structural system in different periods. At each period, the measured value is compared with the pre-defined reference value, and the appropriate decision is selected based on the comparison result.

3.6. Repair of Damaged Structures
A high-quality health monitoring system, in addition to monitoring the real-time data of the sensors and identifying damage, it is needed to determine the residual life and organization of maintenance, repair operations. With the advent of the intelligent age, the next step towards smarter structures would be to make self-repairing materials/structures, or at least materials/structures with embedded damage-mitigation properties [16].

4. Damage Identification Method
Normally, small cracks and damage are difficult to detect. Once the structural deficiency is recognized, the economic losses are already generated. In order to monitor structural health more accurately and sensitively, many advanced information technologies are used in the damage monitoring process [17-19]. According to previous research, the methods for damage identification can be summarized as methods based on statistics and methods based on machine learning.

In statistics-based methods’ views: "probability theory" based on the frequency of events is a more objective basis for the formulation of a prediction. While, methods based on machine learning generally have non-parametric and data-driven characteristics.

4.1. Statistics-based Methods
The goal in SHM is to convert time stamped input signals into diagnostic and prognostic information about the structure of interest. In order to reflect the real-time status of structure, the use of statistical methods not only needs to extract features from the monitored signal, but also requires a predetermined fixed model to fit the data. Linear simulation features are the most common features in the damage detection process, such as: resonant frequencies, mode shapes, or properties derived from mode shapes [20].

According to the requirements and content of damage identification, it can be divided into three level: firstly, the basic level is only used to determine whether there is damage to the structure;
secondly, the factorial level adds the cause of damage to the structure on the basis level; thirdly, the predictive level requires statistical analysis of a large amount of test data to be formed.

4.2. Machine Learning Methods
This approach is based on the discipline of the pattern recognition aspects of machine learning. In computer systems, "experience" usually exists in the form of "data". Provide the empirical data in the SHM to the computer, and use the "learning algorithm" to generate a "model" based on these data. In the face of new situations, the model will provide response judgments.

A variety of machine learning methods have been applied to damage detection fields, and some representative works are:

Support Vector Machine (SVM) has become the mainstream technology of machine learning due to its excellent performance in text classification tasks. In damage identification, first select the kernel function parameters and penalty parameters of the SVM to obtain the optimal parameters. After that, the SVM is trained according to the optimal parameters and the data obtained by the sensor, and the damage recognition model is obtained. Finally, the trained SVM model is used to identify and judge the damage.

A neural network is a widely parallel interconnected network composed of adaptable simple units. During damage detection period, neural networks map structural damage sensitive feature vectors to pattern damage categories. The mapping is achieved through a set of hierarchical connected neurons. Each neuron performs local nonlinear calculations, and data information is passed to the neurons in the next layer through the network input layer. Various parameters are estimated through iteration, and the stage of parameter estimation is also the learning or training stage of the neural network.

5. Conclusion
SHM is an indispensable part in the process of social industrialization progress, and has a very wide range of applications in bridges, construction, aviation and other fields. This article introduces the basic concepts and research status of SHM, and then explains the core activities of the SHM system. With the advent of the era of big data, new information technology has been introduced into SHM to enable it to better detect damage. Finally, the application of different methods in the damage detection process is described.

Acknowledgments
This work was financially supported by Major Innovation Project of the Ministry of Industry and Information Technology, Ministry of Industry and Information Technology (2016) No. 24, Z17002. and Shaanxi Provincial Association for Science and Technology Young Talents Support Program Project, 20200509.

References
[1] Zhi Zhou, Thomas W. Graver, Luke Hsu et al., Techniques of Advanced FBG sensors: fabrication, demodulation, encapsulation and their application in the structural health monitoring of bridges. Pacific Science Review, 2003, 5(2):116–121
[2] Tan Si-yun, Zhou Sheng-fei, Chun Wan et al., Research on remote health monitoring system for Wuhan Chang Jiang Bridge at Tianxingzhou, Proceedings-International Conference on Electrical and Control Engineering (ICECE 2010), 2010, 1746–1749
[3] Mickens T, Schulz M, Sundaresan M. Structural Health Monitoring of an Aircraft Joint. Mechanical Systems and Signal Processing, 2003, 17(2):285–303.
[4] Fabio, Casciati. Fibre Optic Methods for Structural Health Monitoring. Branko Glisic and Daniele Inaudi, John Wiley & Sons, Chichester, 2007. No. of pages: 262. ISBN 978-0470-06142-8. Structural Control & Health Monitoring, 2010.
[5] Lifeng Du, Zhigang Yan. The Application of Fiber-optical Sensory in Structure Monitor System. Journal of Xuzhou Institute of Technology, 2007, 22(4):37–40.
[6] G. W. Housner, L. A. Bergman, T. K. Caughey et al.. Structural Control: Past, Present, and Future.Journal of Engineering Mechanics, 1997, 123(9): 890-897.

[7] N. Hoschke, C. J. Lewis, D. C. Price et al.. A Self-organizing Sensing System for Structural Health Monitoring of Aerospace Vehicles. Advances in Applied Self-organizing Systems/Advanced Information and Knowledge Processing, 2008, Part II, 51–76.

[8] Charles, R., Farrar, et al. An introduction to structural health monitoring. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2007.

[9] Farrar C R, Worden K. Structural Health Monitoring: A Machine Learning Perspective. 2012.

[10] Xiaoli Zhang, “Study on the Optical Fiber Structural Health Monitoring System and Its Sensor Network Reliability”. Nanjing University of Aeronautics and Astronautics, 2012.

[11] Balageas D, Fritzen C P , Gemes A . Structural Health Monitoring || Index. 2006, 10.1002/9780470612071: 493-495.

[12] TANG Xu, ZHU Ya-zhou, SHEN Zhong-xiang et al. Research on application of optical fiber sensing material in ship structural health monitoring. SHIP SCIENCE AND TECHNOLOGY, 2020, 42(12): 182-185.

[13] Kirikera Goutham R., Vishal Shinde, Mark J. Schulz et al.. Damage localisation in composite and metallic structures using a structural neural system and simulated acoustic emissions. Mechanical Systems and Signal Processing, 2007, 21(1): 280–297.

[14] Takeda S, Aoki Y, Ishikawa T et al.. Structural health monitoring of composite wing structure during durability test. Composite Structures, 2007, 79(1): 133–139.

[15] N. Hoschke, C. J. Lewis, D. C. Price et al.. A Self-organizing Sensing System for Structural Health Monitoring of Aerospace Vehicles. Advances in Applied Self-organizing Systems/Advanced Information and Knowledge Processing, 2008, Part II, 51–76.

[16] Balageas D, Fritzen C P , Gemes A . Structural Health Monitoring || Vibration-Based Techniques for Structural Health Monitoring. 2006, 10.1002/9780470612071: 45-224.

[17] Tschoppe C, Wolff M.. Statistical classifiers for structural health monitoring. IEEE sensors Journal, 2009, 11(9): 1567–1576.

[18] Dong Lixin, Xiao Dengming, Liu Yilu. Insulation fault diagnosis based on group grey relational grade analysis method for power transformers. Journal of Southeast University, 2005, 21(2): 175–179.

[19] Ch. Efstatiiades, C.C. Baniotopoulos, P. Nazarko et al.. Application of neural networks for the structural health monitoring in curtain-wall systems. Engineering Structures, 2007, 19(12): 3475–3484.

[20] Farrar C R, Czarnecki J J, Sohn H , et al. A review of structural health monitoring literature 1996-2001. Data Acquisition, 2002.