# Model based structural health monitoring systems for civil engineering structures

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Abstract

The structural health monitoring (SHM) technology and non-destructive testing (NDT) started to play a very important role in assuring the safety and operational conditions of engineering structures. The NDE methods are rather mature and able to detect damage with considerable reliability during periodic inspections. The SHM systems are able to offer online reports on object's structural health since the sensors, signal processing units and decision modules are integrated with the monitored object. This paper describes the role of structural health monitoring (SHM) systems in civil engineering structures, discusses the structure of SHM systems and highlights the benefits of theoretical and numerical models for improvement of SHM systems' performance. The paper presents the experimental tests on SHM expert modules using baseline free methods and methods based on reference models.

*Keywords: structural health monitoring systems, civil engineering structures, model based methods*

## 1. Introduction

Surveillance may be understood as a set of processes of identification, tracking, analysis and response which organize the considered problem. The most common civil engineering applications of surveillance technologies are systems for air transportation, where the principal goal is to ensure the safe, expeditious and economic performance of air traffic.

While surveillance aims at broad activities ranging from social behaviors to physical or financial processes the term Structural Health Monitoring (SHM) refers to collection and analysis of selected structural parameters of an engineering object. Recently, the SHM systems are dynamically developed in Asia, particularly in China, Japan, Singapore and recently also in Europe (Belgium, UK, Germany, etc.) as well as in United States and Canada. Initially, the SHM systems in civil engineering structures were used in long span bridges (e.g. [1]) and very tall buildings. At present the automated damage detection systems are installed in dams, harbor protection structures, cooling towers, mountain and sub-sea tunnels, and power stations.

The SHM system is a kind of nondestructive testing (NDT) system. NDT is widely used in mechanical objects and it is understood as field of knowledge with the aim of defining the widely understood technical state of an engineering object by means of objective methods with the aim of increasing their durability, reliability and effectiveness. Information on object's technical state is a base for the maintenance decisions in each phase of the object's life [2]. NDT is conducted in a form of a periodical inspection. Therefore, measurement sensors and actuators are mounted to the object only when given tests are performed. It is difficult to ensure the identical measurement condition, like sensor location or contact condition, in the successive evaluation tests. NDT technologies are implemented locally and offline.

The aim of SHM system is, like in NDT, the evaluation of the object's structural health. However, the SHM system is designed for continuous monitoring of selected structural parameters. The sensors and actuators of the SHM system are permanently mounted on the object or even built into the object. The SHM system have high level of automation combined with ability to send reports concerning unexpected events. The SHM system can provide better information on the size and location of damage than NDT. SHM technologies are usually implemented globally and online.

The tasks of an SHM system are defined as the following [3]:

I. Detection of the existence of damage,
II. Detection of damage location,
III. Identification of damage type,
IV. Prediction of damage development

With rapid development of nanotechnologies, new tasks have been recently considered (e.g., [5]):

V. Ability of self-diagnostics,
VI. Ability of self-repair,
VII. Ability of active control.

The most advanced SHM systems are design for aerospace structures and military applications. SHM systems for civil engineering structures may also [3]:

1. Provide data for improvement of design specifications and guidelines,
2. Provide real time information and warnings on extreme events,
3. Support safety assessment immediately after disasters,
4. Provide data for planning the inspections,
5. Provide data for maintenance, repair or modernization.

## 2. Structure of SHM systems

An example of block diagram of SHM system is given in Fig. 1. The SHM system usually has a hierarchical structure. The lowest level of SHM system is focused on the selected sub-system, e.g., main girder of the bridge. The data analysis and damage detection is limited to the sub-system. The higher level of the SHM is devoted to management of the entire object like whole bridge. At this level the global decisions are performed, concerning the division and coordination of tasks performed by lower level SHM systems. The hart of the SHM system is an expert system. The execution part of the expert system consists of three basic modules:

1. Diagnostic module,
2. Module for monitoring operating conditions,

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3. Damage accumulation models, data base

The first module tests the integrity of the particular sub-system elements while the second module monitors the exploitation conditions including loads, temperature, humidity etc. The third module is designed for data storage and evaluation of damage accumulation. The execution modules are based on theoretical or numerical models of an engineering object.

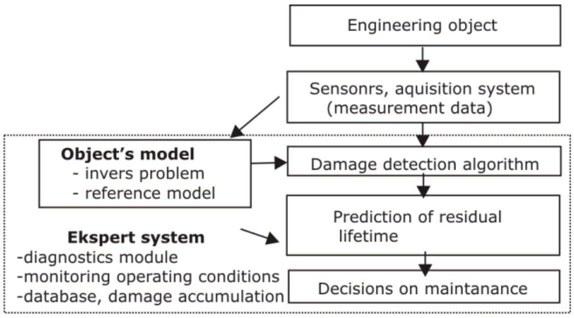


Figure 1: Block diagram of SHM system

## 3. Classification of SHM systems

There are several classifications of SHM system with respect to different criteria. Due to range of application, SHM systems are divided into: global systems and local systems. Global SHM covers the whole plant while local SHM is devoted to single structural element. The SHM systems can be passive or active. Active systems introduce additional excitation into monitored object. Systems based on Lamb waves, ultra-sonic testing, electro-mechanical impedance or experimental modal analysis are examples of active SHM systems. Systems based, e.g., on acoustic emission, where the elastic waves are generated by development of micro damage, are passive SHM systems.

SHM systems can be classified with respect to the physical phenomena used for object diagnostics:

- electrical diagnostic modules,
- electro-mechanical,
- electro-magnetic,
- optoelectronic,
- geodetic appliances
- visual/high resolution cameras
- infrared testing (thermal diagnostics)
- methods utilizing other physical phenomena (radiographic, comparative vacuum, etc.)

SHM systems installed in civil engineering objects are usually based on geodetic devices used for displacement measurements, strain measurements by vibrating wire extensometers and dynamic response measurements obtained by accelerometers (electro-mechanic devices).

## 4. Model based diagnostics

SHM systems use theoretical and numerical models for precise definition of object's technical state. Due to selection of input data, the system can be divided into the following [4]:

- base line free methods
- methods based on numerical model,
- methods based on statistical global diagnostics models.

The first group of methods does not require knowledge of the object characteristics in the reference state. Such methods are the most attractive since they do not require any knowledge nor experimental testing of the undamaged structure. However, the applicability of such systems and their effectiveness in detecting damage is limited [6]. More reliable information on current structural state can be obtained by model based methods. This group of methods uses reference models of the structure in undamaged state (Fig. 2). The diagnosis is obtained through the analysis of changes between the numerical models in reference state, current state and damaged state. The numerical models are updated on experimental data collected during object's life. This approach helps to identify the type and size of the damage. The third group of methods, statistical diagnostics models, assumes that extensive set of measurements is conducted on structures in references state, and on the basis of a series of measurements a statistical model is built.

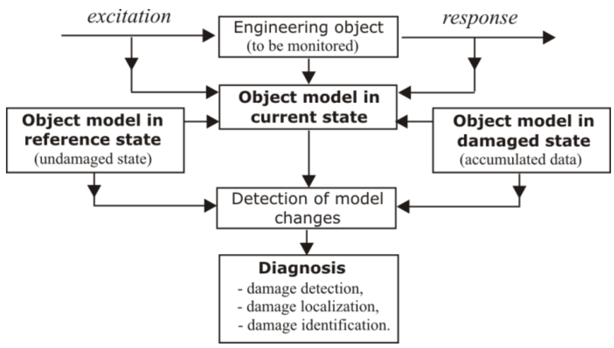


Figure 2: Block diagram of model based diagnostics

The paper presents the examples of SHM systems based on baseline free methods (SHM system monitoring low frequency vibrations of cantilever beam and simply supported plate, [6]) and model based methods (SHM system for Sports Arena "Olivia" [7].

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