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Application of Artificial Intelligence and Meta-heuristic Algorithms in Civil Health Monitoring Systems

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Abstract

After the discovery and manufacturing of every accomplishment, the mankind tends to make it sustainable in terms of different aspects that one of them can be its durability. Nowadays, a science titled "health monitoring" has provided such a consideration in different fields. For example, civil engineering sciences, in various branches, aim to construct various civil engineering accomplishments, followed by the higher goals of making them durable and healthy. The present study tries to give an account about the various study fields like structural engineering, bridge construction, dam construction, hydraulic and on-beach constructions, road engineering and building, water resources management and so on along with the mentioning of the various methods extant for the implementation of such study fields. But, in between, there is an appropriate method that provides such objectives as cost-effectiveness, access to the entire required details, awareness of the civil infrastructures in order to estimate the remained lifetime of the structure in line with the continuation and/or change of the uses. Also, it has high precision and minimally influenced by the environment, so, it can be said that it has very little error in its collection of information. For instance, this method can be used to evaluate the ruination of the structures based on modal properties, which can have static or dynamic foundations such that the current state of the structure is compared to its ideal state to monitor the degree of the structure's ruination or its soundness. In present study, it was tried to investigate the artificial intelligence science as one of the richest methods possessing all the prerequisites as well as having more traits in common with the various sub-disciplines of civil engineering so that it can be utilized more comprehensively and in a more centralized manner.

Keywords: Health Monitoring; Modal Features; Dynamic Methods; Static Methods; Breakdown.

1. Introduction

The science of health monitoring has been specifically examined in various areas of civil engineering and also, more precise methods have been developed for monitoring the structures' soundness due to ever-increasing progresses made in sciences; but, these methods have their own weaknesses and strengths. As an example, the structural conditions of a bridge are visually inspected on a regular basis. Besides the time-consuming and costly nature of these inspections, the monitoring of the entire bridge structure is impossible due to lack of access to certain cross-sections. Therefore, applying a non-destructive damage identification method is necessary to simultaneously increase the safety and ensure the status quo of the structure. During the recent years, vibration-based damage identification has been used to evaluate the damage of entire structure. In such a state, the recognition of the structural failures is based on the idea that dynamic response of the structure will be changed as a result of damage. In this way, it is possible to determine the location and the intensity of the damage by examining dynamic response of the structure before and after advent of the damage. The present study

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examines the structural health monitoring science in various sub-disciplines of civil engineering such as the steel and concrete bridges, concrete dams, space frames, coastal constructions, etc. with the methods used for this purpose. In the end, the most optimal method characterized by high precision, lowest error in recording the responses and some other features will be investigated.

Using a structural health monitoring system, the reliable information on the structure is gathered and the structural defects are recognized in the preliminary stages of the damage development. Early recognition of the flaws via the health monitoring system results in a reduction in the maintenance costs and prevents such catastrophes as the failure of bridges, dams, structures and so on. A vast range of the techniques, algorithms and methods have been utilized for the structural health monitoring of various fundamental elements of structures, from beams and plates to more complex structures like bridges and buildings.

In present study, fuzzy genetic system has been proved as an optimum method for the health monitoring of the civil structures. This confirmation is shown herein by the results of various previous studies along with their references.

2. A Review of General and Basic Concepts

In this part, some of the researches conducted in the area of structural damage identification are reviewed. The majority of these studies conducted during the past three decades have been focused on measuring the dynamic responses of the structures. Generally, if the structures are likened to human body, the health monitoring system can be likened to a doctor who measures certain parameters and characteristics so as to obtain information on the patients' healthiness. In structures, these features are measured as essential principles titled "modal features of a structure" (frequency, modal shape and modal damping) in all of the methods. These features are a function of physical characteristics of that structure. Therefore, the change in the physical characteristics of a structure can be recognized from the change in its static and/or dynamic response. These methods are vibration-based.

2.1. The Importance and Necessity of the Structural Health Monitoring of Bridges

About 2.5 million bridges are currently being exploited in the global transportation network. Based on a report issued by American Federal Highway Administration (FHWA), 28% of the total 595000 bridges in service have been assessed inefficient in 2005 and only a fraction of these bridges (about 15%) have been found with structural defects. In Europe, 10% of the bridges are structurally flawed and no statistics is available about the bridge structures in Asia. However, it is assumed that averagely, 10% of the bridges are structurally flawed. In other words, there are 250000 bridges that are in definite need of structural health monitoring, rehabilitation and inspection [1]. The increase in the ages of bridges, the unpredictable nature of the loads and the poor design of the components result in the inefficiency of bridges. So, the structural health monitoring methods (SHM) are applied to prevent development of the damages and optimization of the repair and maintenance activities so as to prevent the accidents similar to the failure of Mississippi (I-35W) bridge. Figure 1 shows the Mississippi (I-35W) bridge after failure.

Figure 1. The failure of Mississippi (I-35W) bridge

The conditions of a bridge are usually assessed through periodic visual inspection. Although crucial information is obtained through the inspections, they are envisaged time-consuming and costly. The inspection of the whole parts of bridge is not possible due to its inaccessible cross sections and the damages in such points are usually left unrealized. Furthermore, identifying internal damages and their sources is very difficult. So, it seems necessary to implement a bridge health monitoring system and then make a report indicating when and where the repair and maintenance operations are needed. A successful health monitoring system reduces the maintenance costs and prevents total failures through early identification of damages [2, 3].

In structural health monitoring of bridges, visual inspection is a confirmed principal method. Its reliability largely depends on the experience and skill of the inspector. The objective of structural health monitoring methods is to be used along with the bridge inspection and examination. To do so, the well-known vibration-based health monitoring method is applied [4-6].

The American transportation organization annually publishes the reports on the bridges in the US. Based on the report issued by the organization in 2013, more than 66405 bridges are structurally defected. To put it differently, one out of every nine bridges (11%) have deficits in their structural members. The bridges with structural flaws are in severe need of maintenance, fortification or replacement. While a great many of the bridges have been planned for a lifetime of 50 years with no need for essential repairs, the average age of the bridges in the US is 43 years and the average age of the bridges found with structural defects is 65 years old. With a futuristic perspective, it can be concluded that one out of every four bridges (in sum 170000 bridges) will be 65 years old within the next ten years and they are highly likely to become defective in this age [4].

Visual inspection cannot identify all damages of bridges alone, so a solution should be sought to supplement the visual inspection so as to more accurately accomplish the structural health monitoring of the bridges. The following section gives the basic principles of these methods.

2.2. The Necessity and Importance of Damage Identification

Occurrence of failure in buildings, bridges, oil platforms and, in general, in the entire structural systems during their lifetime is an inevitable issue. So far, there are numerous recorded examples of various types of failures in different engineered structures which have caused abundant life and financial losses. The majority of these failures can be modified through preliminary examination of the structures' current statuses and, in such way, development of structural failures and collapses of buildings can be prevented. This makes the structural health monitoring more importance in earthquake-prone regions where the topical damages of the structural elements can be the origin of the total devastation. Thus, identification of damages in the structural systems and their members is deemed necessary and important for increasing the soundness and ascertaining the status quo of the structures. If the damages in the structural systems are somehow identified, the total failure of the structure can be prevented by repairing or replacing the impaired elements. Consequently, the damage identification systems can play a very important role in making the structures safe and improving them as well as preventing the financial and life losses resulting from the collapse of the structures.

Generally speaking, the damage refers to the changes in a system that have adverse effects on the system either at present or in future [5]. In a simple definition, damage is described as any change in or deviation from the primary geometry or masonry characteristics as well as the change in the boundary conditions and integration of a system that have adverse effects on system performance. Damage is accompanied by changes in the physical attributes of the materials (mass, stiffness and damping). The catastrophic damages followed by huge life and financial losses have led to an increase in the interests in fault detection. The ever-increasing development of computers and the computational and artificial intelligence methods, the development and progress of sensor building technology and their relationships with different sciences, especially in the area of fault detection, have all drawn the attentions of many researchers from this study field to fault detection based on computational solutions.

2.3. System Identification

System identification issue refers to the obtaining of a mathematical model of a phenomenon (like dynamic system) using laboratory information. This technique is applicable to many of the engineering areas like airplane and automobile industries, as well. Figure 2 displays system identification and its uses in various sciences.

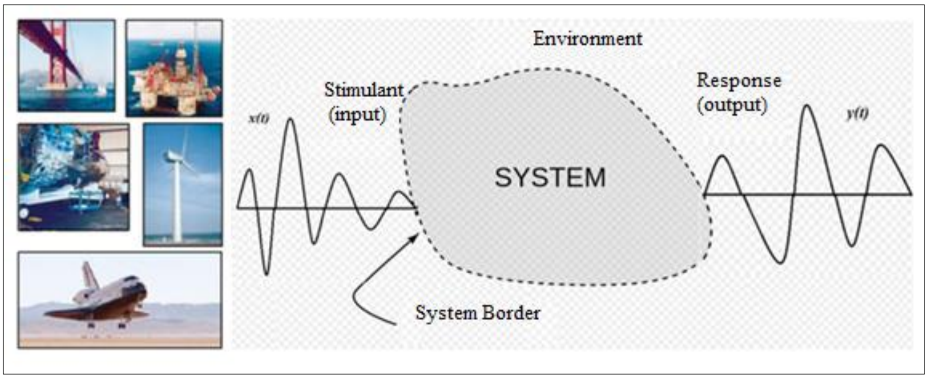

Figure 2. System identification and its uses [3]

2.4. Classification of Damage Identification Science

In regard of the structural health monitoring, damage is defined as the changes in the structural system that negatively influence its performance at the present time and in future. In general, damage identification methods are categorized to two local and general categories. The local methods can only detect the damage on the structure or in its vicinity. Such a limitation has paved the way for the invention of completely different approaches to the complex systems analyses. Generally, these methods are classified to four levels [6]:

Level One: Determination of the Damage Existence

Level Two: Determination of the Geometrical Location of the Damage

Level Three: Determination of the Damage Intensity

Level Four: Determination of Residual lifetime of the structure upon the Emergence of Damage

In frequency-based damage detection methods in which a preliminary structure model is not used for the comparisons, only the Level One and Two damages are detectable. Having a preliminary structural model, Level Three damages can be detected, as well. To determine the Level Four damages, besides the damage detection methods, there is usually a need for such sciences as fracture mechanics, fatigue-life analysis and structural design assessment [3].

2.5. Types of Damage detection Methods

Ordinarily, the structural damage detection methods include two general steps [7]:

1. Selection and Extraction of the Structure Specifications.
2. Selection of an Appropriate Identification Pattern.

The first step includes the selection and extraction of damage-sensitive specifications of the structure. These specifications are extracted from the data measured based on the structure dynamic response. This stage is composed of combining a large volume of the data obtained from numerous sensors and converting them to the data which can be analyzed by means of optimization and/or statistical algorithms. Also, numerous data normalization methods are applied to remove the changes in executional and environmental conditions from the data. In the next stage, a proper pattern is utilized for a collection of data (discrete or continuous) to detect the damage. These patterns are more based on the measurements of structure strain and displacement in static methods and based on the measurements of structure strain, displacement and acceleration in dynamic methods. The following part presents a review of the modal analyses and some important structural damage detection methods.

2.6. The Necessity and Importance of the Fault Detection Methods Based on Vibration Specifications

The current damage detection methods are either visual inspection or local testing methods, including magnetic field methods, thermal field methods and ultrasonic methods. The application of local damage identification method entails having access to the pre-identified damage location. These methods have weaknesses. As an example of the weaknesses common in these tests, the failure occurrence, despite the periodical inspections and local tests, in a bridge in South Korea in 1994 can be pointed out that as a result of which 32 individuals were killed and 20 others were injured. Figure 3 exhibits a view of the bridge after failure. The bridge collapsed when it was only 15 years and the periodical inspection tests were periodically performed thereon. The specialized investigations signified that the bridge collapse happened for such a reason as the fatigue of some of its members not been inspected and tested. The occurrence of such incidents reveals the shortcomings of the local tests and the necessity for making use of methods capable of performing general and comprehensive evaluation of the structures.

Figure 3. The failure of the bridge in Seoul despite of the local inspections [8]

Vibration-based damage identification is of the methods used to assess the damage in the all parts of the structure. The theoretical foundations of the modal analysis propose fault detection via tracking the changes in the dynamic specifications or structural response induced by damages as a solution that provides the possibility of structural health monitoring of bridges in a precise manner, in addition to completing visual inspection. Thus, the present study posits the fault detection problem based on modal parameters in a form of optimization problem and then evaluates the efficiency of this method in locating and identifying intensity of the damage.

2.7. A Review of the Structural Health Monitoring Methods

A wide range of techniques, algorithms and methods have been utilized for the structural health monitoring of various structures, from structural members such as beams and plates to the more complex structures like bridges and buildings. Doebling et al [3] presented a comprehensive review of various vibration-based damage detection methods used up to 1996. Sohn et al [7] presented an updated version of this literature up to 2001 followed by a review of the vibration-based damage identification methods by Carden and Fanning [9] who made special emphasis on the articles published from 1996 to 2003. Modares and Waksmanski [2] have reviewed the health monitoring methods of steel bridges and concluded that the useful lives of bridges gradually decreases due to the unpredictable nature of the peripheral loads unless the damage is detected and effectively fixed.

The majority of the structural health monitoring systems, reported in the reference part, were based on modal analysis methods and used the response of structure to vibration to measure the various specifications. Analyzing any change in these specifications, it is expected that the damage location can be determined [13-15]. Damage identification is the first and most important stage of structural health monitoring method that is discussed, before the higher levels, in all stages of damage identification (comprised of damage detection, its location, its intensity and determination of residual useful life) [6]. Many of the vibration-based methods employ modal system identification and comparison modal parameters of the defective structure with the healthy one to detect the preliminary damages [16-20].

2.7.1. Natural Frequency-based Methods

During late 1970s, the relationship between the physical parameters and the modal parameters was taken into account to present a method based on natural frequency in the structural damage identification. The investigations indicate that damage causes changes in the natural frequencies of the structure. The natural frequencies can be determined simply and with an appropriate accuracy. Moreover, in comparison to the other modal parameters, the natural frequency has a lower sensitivity to the random error. That is why the methods based on vibration frequency have been more frequently applied compared to other methods. However, the natural frequency are intensively sensitive to environmental conditions like temperature and humidity. In addition, although the natural frequency is the general feature of the structure, it cannot provide information on the location of the possible errors and only the higher modes can be used to determine the damage location due to their corresponding mode shape. However, determining the frequencies of higher modes is difficult in the majority of the real structures [10].

Due to the low sensitivity of the natural frequencies to damage, the use of this method necessitates very accurate measurements. Although the use of natural frequency in damage identification is difficult, there are many researches performed in this regard. Nowadays, the natural frequencies are applied in combination with other modal parameters in the damage identification.

Vandiver [22 and 23] has investigated the changes in the corresponding frequencies of the first two buckling modes and the first torsional mode of a lighthouse to determine its damage. He concluded that the change in the effective mass only causes a 1-percent change in the frequencies. Also, in a damage corresponding to disintegration of the majority of the members, the changes in frequency will be more than a percent.

Cawley and Adams [11] presented a method in which the location and intensity of damage to the structure is determined using natural frequencies obtained from the laboratory results and forming sensitivity matrix. Although this method estimates the damage rate with an appropriate accuracy, it is in need of a considerable number of modal frequencies and this is a difficult task in the existing structures.

2.7.2. Mode Shape-based Methods

Mode shape is a structure-specific parameter. Many of the researchers believe that the mode shape can be used as a reliable index in the structural health monitoring.

2.7.2.1. Direct Methods

Mode shape is the displacement pattern corresponding to a certain natural frequency of a structure. This parameter reflects the relative displacement of the various members of a structure in a given mode. Therefore, it encompasses spatial information of a structure. Structure damage causes changes in the mode shape in vicinity of the damaged area. In this way, the comparison between the mode shapes can be used as a structural health monitoring method. Modal assurance criteria (MAC) and coordinate modal assurance criteria can be mentioned as the common methods used to compare the mode shapes.

To identify the damage in a laboratory model, Ching and Bech [12] have use the mode shapes before and after damage. In their study, the laboratory structure was studied under two controlled and uncontrolled states. The bracings were eliminated in the controlled state to impose the damage. In the controlled state, the torsional strength of the beam-to-column connection was reduced to model the damage. The obtained results indicated that the damage can be well detected in the controlled state but the modes extracted for the uncontrolled state were found having less sensitivities to the damage.

2.7.2.2. Mode Shape Curvature-based Methods

The mode shape curvature-based method is one of method most frequently used in detection of structural damage. The method is based on the assumption that that the changes in the mode shape curvature are concentrated in the place where there are more damages. The curvature is defined as the second derivative of mode shape. The mode shape curvature-based method is more sensitive to damage compared to mode shape-based method.

The concept "mode shape curvature" was introduced by Pandey et al [13]. Using finite element model, they obtained the mode shape curvatures corresponding to the healthy and damaged states of a cantilever beam and a simple beam. They considered the failure in the form of elasticity module reduction in their model. The results pertinent to the simple beam indicated that the mode shape curvature is increasingly sensitive to failure compared to MAC.

2.7.3. Modal Strain Energy-based Methods

Modal strain energy can be used as an index for the structural health monitoring. A mode shape subjected to a given loading possesses a considerable amount of strain energy. Due to the structural damage, the amount of this energy changes because of the sensitivity of the frequency and mode shape to the damage. The failure detection using the changes in the modal strain energy, besides determining the damage location, is an appropriate index in the determination of its intensity. This method has been applied in many researches.

Dixit and Hanagud [14] have investigated the results of various mode shape-based methods used on the beam subject to different boundary conditions and concluded that the modal strain energy offers a more acceptable estimation compared to the other methods. However, its accuracy depends on the number of the modes.

2.7.4. Flexibility-Based Methods

Another group of the damage identification methods deals with the static behavior of the structures using the flexibility matrix. The flexibility matrix of a structure is the inverse of its stiffness matrix. Hence, it is indicative of the relationship between energy and structural displacements. Precise determination of the flexibility matrix necessitates the measurements of all modes and frequencies. Due to the inverse relationship between the flexibility matrix and the natural frequency, the matrix becomes rapidly convergent as the number of modes increases. Thus, a proper approximation of the flexibility matrix can only be obtained using low frequencies. So, flexibility matrix is more sensitive to the changes in the lower modes.

The researches wherein flexibility matrix has been used as the failure indicator, have presented acceptable results. Pandey and Biswas [15] used flexibility matrix changes for the health monitoring of several numerical models and a laboratory model. Their acceptable results obtained for the numerical and laboratory models are reflective of the reliability of the method in health monitoring of the macro-scale structures. The results of the numerical models showed that the method offers the best results when failure is in the position corresponding to the maximum flexural moment. Also, they expressed that the flexibility matrix is slightly influenced by the higher modes.

Patjawit and Kanok [16] proposed a method based on the modal flexibility for health monitoring of the highway bridges. The method is laid upon the principle that flexibility matrix is indicative of the general status of the structure and changes in it can be an appropriate index for the structural damage estimation. They examined the method using a steel beam, a concrete beam and a bridge. Their results indicated that the flexibility index is considerably more sensitive to the failure. They considered the flexibility index of the bridge measured in the current situation as a baseline for the future evaluations.

2.7.5. Damping-Based Methods

As a modal parameter of the structures, damping can be considered as an index for the structural damage detection. Damping is less frequently used for the structural damage identification compared to frequency- and mode shape-based methods due to the fact that no appropriate method has been so far introduced for the accurate determination of the structure damping ratio. However, the structural damage identification using damping has advantage compared to frequency- and mode shape-based methods. Its advantage is that this method can determine the nonlinear effects of the damage.

Salane and Baldwin [17] performed a dynamic test on a steel bridge with a concrete deck to measure the steady state response and natural frequency. Their investigations indicated that damping does not change with a certain trend due to the created damage. That is why, although damping is influenced by the damage, it cannot be applied as an indicator for it.

Using wavelets, Curdelli et al [18] proposed a method for the simultaneous determination of damping and structure frequencies from its free vibration responses. In addition, they have investigated the frequency and damping variations to detect the damage in two numerical models and two laboratory models. Their results demonstrated that the damping is much more sensitive to the damage than the natural frequency.

Kiral et al [19] examined the vibration response and modal specifications of a composite beam. Then, they created damages with various intensities to investigate the natural frequency and damping variations and found that the damping is more sensitive to damage.

2.7.6. Methods Based on Frequency Response Functions

Generally, frequency response functions (FRF) are complex functions defined in the frequency region. FRFs can be defined as the structure input-to-output ratio. Some researchers have directly used FRFs for the structural health monitoring instead of modal parameters. Direct use of the measured FRFs results in the elimination of the errors originating from the data modal analyses. Moreover, FRFs encompass a large volume of information on the structure dynamic behaviors. In modal analysis, a large part of information is destroyed in the extraction process of modal parameters.

So far, numerous FRF-based methods have been presented for the structural damage detection. Wang and Lin [20] proposed an FRF-based method for the structural damage identification. The method was tested using the numerical and laboratory results of a three-span steel frame. The numerical results indicated that the proposed method can determine the location and intensity of the failure with an acceptable accuracy. However, the laboratory results were not acceptable. In their ideas, the offered methods are unreliable in the estimation of trivial damages because the changes made in the vibration data might be due to the existence of error, thereby be undetectable.

2.7.7. Methods Based on Model Updating

Another method of damage identification is the numerical model updating. These methods are in need of forming a numerical model such the finite element model. In general, the numerical model updating is a constrained optimization problem in which the differences between the measured results and the analytical results are minimized based on the correction of numerical model characteristics such as stiffness, mass and damping. The objective function definition and determination of updated parameters are amongst the most important factors influencing the success of these methods.

Choi and Kwon [21] employed finite element model updating for the failure detection of a steel bridge. The numerical model of the bridge was constructed based on its design maps and updated using the static and dynamic experiments. To do so, first, the stiffness of members was set for the regeneration of the measured deformations. Then, the structure mass was redefined based on the measured natural frequencies. The obtained finite element model was subjected to the static loading to determine the members with maximum stress. Based on their observations, eight members were found more vulnerable than the others.

Some of the model updating methods do not need the data on healthy structure and, on the other hand, the failure intensity is clearly identified by these methods. Due to the same reasons, these methods are widely paid attention today [22].

2.7.8. Signal Processing-Based Method

Time series analysis is one of the widely used signal processing methods. In the majority of these methods, a time series model is at first assigned to the vibration data. Then, the structural health monitoring is performed by extracting the model parameters. A time series is a set of data observed at sequential times. Time series model is a statistical model assigning a set of information to a series.

Signal processing methods study the time history variations or their corresponding spectra and identify the failure through appropriate signal processing algorithms and methods. Various signal processing techniques are classified as follows in terms of the parameter extraction: time domain method, frequency domain method, time-frequency domain method (or time-scale domain). The time domain methods use linear and nonlinear history time functions to obtain the signal attributes.

The other well-known methods in regard of signal processing are the frequency domain and/or time-frequency domain. Fourier transform is one of these most frequently used methods. The method has some weaknesses. Fourier transform with the omission of time or space parameter from the signal causes the time or the place of an incident not to be clear. To eliminate this effect, the short-term Fourier transform methods were invented in which a small domain of the signal is processed. However, how to select the domain influences its accuracy. The wavelet transform is an almost new method in signal processing, meeting the disadvantages of the prior methods. Wavelets are combinations of functions having the ability to describe signal in a given time period. Wavelets are functions of two values, named time and scale, the latter of which can be corresponding to the frequency. The major advantage of using wavelet transform is the local analysis of a signal.

Ovanesova and Suarez [23] employed various methods of continuous and discrete wavelet transforms (CWT&DWT) to monitor the structural health of a beam and a one-storey frame subject to static and dynamic loads. The proposed method is based on the assumption that the structural damage causes confusion in the structure response. The confusion might be undetectable in the direct investigation of the structure response; but the lack of signal uniformity can be determined using the continuous wavelet transform coefficients or partial signal obtained from discrete wavelet transform. Their results indicated that the damage location can be determined with a high degree of accuracy.

Zho and Law [24] proposed a method based on wavelet transform of displacement time history under moving loads to perform structural health monitoring of a beam. The numerical and laboratory models of the beam were investigated to explain the method. The structure response was measured at a point and the continuous wavelet transform was applied to determine the damage location. Moreover, an index was presented for the estimation of the cracking depth. The suggested method provided acceptable results for the estimation of various damage scenarios in the numerical model.

2.7.9. Artificial Intelligence-Based Method and Evaluation of Uncertainty

Neural Networks provide some powerful methods in solving the problems such as pattern recognition, data analysis and control. These methods are inspired by the biologic systems such as the human brain and consisted of a computational structure including a combination of the processing units (neurons). The neural networks can be used in solving the inverse problems like structural health monitoring and damage estimation.

In confrontation with computational problems in the real world, using a combination of computational methods predominantly outperforms the exclusive use of them in separate. This reality leads to the creation of systems such as neuro-fuzzy computing methods. The neural networks are used in these systems for the pattern recognition and adaptation to environmental variations. The fuzzy inference systems are used along with these neural systems to systematically describe the human knowledge and make deductions and a proper decision. Combining the two aforesaid methods with optimization techniques with no differentiation results in a new method called neuro-fuzzy computing and soft calculation.

Shu et al [25] used the dynamic response of the structure to offer a failure detection algorithm based on an artificial neural network. The finite element model of a railway steel bridge constructed in Abacus was used. In one state, the failures have been taken into consideration separately and in another one, several failures have been considered together in another state. In their study, numerical tests were conducted on the finite element model considering the specifications of different trains to validate the approach. They concluded that the proposed method can accurately determine the location and intensity of the failure and that determining the failure location is much more difficult than the failure intensity determination.

2.8. Dynamic System Identification and its Use in Structural Fault Detection

The process of moving through the path from observing the data to achieving a mathematical model is the essential topic discussed in engineering sciences and applications. The process is called system identification method in the control areas and its objective is to obtain dynamic models (differential equations) from the observed input and output signals. Its fundamental concepts are in common with the general processes of model construction in statistical works and other sciences.

System identification is an area in which the dynamic systems are modeled using empirical data. Generally, an identification experiment is undertaken by stimulating the system and its inputs and outputs are observed within a time interval. The signals are normally stored in a computer to be used for next analyses. The structural health monitoring process embraces the observations carried out on a system during a period using the measured dynamic responses recorded by a series of sensors to extract the fault-sensitive indicators, followed by a statistical analysis of them to determine the system health.

2.8.1. Fuzzy Genetic System

Failure detection problems are those inherently accompanied by uncertainty and error or the loss of part of the input information. The input information are usually obtained from the sensors installed on the structures. The information measured by these sensors are often processed before being used as a failure index. Based on the information obtained from sensors, the structural health monitoring system should be able to provide the maintenance engineer with certain outputs. The defective state of a system can be investigated through a five-step process as expressed by Rytter in 1993 [6].

a. Existence: is there any fault in the system?

b. Location: where is the fault in the system?

c. Type: what is the failure type?

d. Size: how intense is the fault?

e. Prediction: how much is residual useful life of the structure?

The more the number of above questions that the health monitoring method responses, the more complete and more valuable the structural health monitoring system is. The answers to these questions should be as accurate as possible. The answers that are explained in phrases and words are more useful to the maintenance engineers than those explained by numbers. Amongst several soft calculation methods, fuzzy logic is the method that receives numerical inputs and provides verbal outputs. However, the fuzzy logic lacks the ability to learn from the input data and the rules governing the fuzzy system should be specified by an expert. The fuzzy rule base development is a difficult task and it gets more complicated when the number of the inputs and outputs increase.

Combining the fuzzy logic method with the genetic algorithm gives a soft calculation algorithm called genetic fuzzy system (GFS) that can automatically generate fuzzy rules from the input data.

In a dissertation by Jahan, the fuzzy genetic system was applied to health monitoring system of bridge structures. The key objective of using genetic algorithm was to propose an automatic fuzzy system design and to attain maximum precision in failure detection. This method was used for failure detection of a single-span railway bridge characterized by steel beams as well as a concrete bridge [26]. To study the failure detection, the numerical models of these two bridges were constructed using their measured dynamic specifications. To evaluate the efficiency of fuzzy genetic system in detecting the failure and the effect of modeling method, two 3D finite element model and a simplified 2D model of beams were used. After completing the analyses in order to control the uncertainties, noise values were added to the measured frequencies and its effect was investigated on the success of the identification method. The examinations of the dissertation indicates that the natural frequency possesses an appropriate sensitivity to the imposition of various failure scenarios to the structure. Moreover, the natural frequency, compared to other modal parameters, has a lower sensitivity to the random error. The increase in the number of the measured modes and application of the torsional modes cause the precise detection of the failure even in the symmetrical structures. Using the first eight frequencies provides for the estimation of the failure location and intensity with an acceptable accuracy. Also, the results showed that an acceptable precision in the failure identification can be attained using the simplified 2D model characterized by less complicacy and calculation volume [26].

3. Application of Health Monitoring Methods in Various Areas

3.1. Structural Health Monitoring of Dams

Dams are constructed with the aims of storing water, supplying the water-driven power plants, preventing floods development and so forth. They are considered as the structures of a high significance, so their health monitoring should be inevitably taken into consideration.

Since the dams are subject to repeated loading and un-loading resulting from the water accumulation and discharge and/or such other factors as the regional climatic changes, flood and earthquake, they are prone to failure under the force of various stresses and deformities.

In order to investigate how to monitor and inspect the Karkheh Dam, which is a reservoir dam, some precise tools were installed at different points on the dam and the modal information and physical changes were investigated using them. But, since the primary objective is to prevent the dam from failure, the visual inspections were carried out simultaneously at different points of the dam by the experts who looked for the harmful factors influencing the dam's vulnerability.

The visual inspections included:

1. Upstream part of the dam body: this part is investigated and controlled once every ten days in terms of slides, holes, cavities, cracks, fracture, erosion, etc.

2. Dam Crown: one of the most important accesses used for the possible repairs is the dam crown and on the other hand, it is possible that rain and snow accumulate on it. Thus, the slope and the atmospheric conditions are continuously evaluated at this point.

3. Weir: one of the essential issues that have to be taken into account is to prevent the concrete surface from failure due to the emergence of cavitation and erosion as a result of passage of water flow through the structure.

4. There are many cases in this regard and the interested readers can find more information about them by referring to an article by Qafury and Malek Mohammadi [34].

Reza Qanbary et al [33] in their studies diagnosed the failure in the dam body with a high precision using the data obtained from the modal analysis of an arch dam based on static wavelet transform and without any need to the healthy structure model. They modeled Amirkabir concrete arch dam in ANSYS software to detect the structure failure in the form of modeled elements considering several scenarios. The method was essentially based on the insertion of data pertinent to the ability of the elements to be generated and their death into the software. Thus, the intended elements are, so-called, killed by multiplying the stiffness by a very small number. Upon the completion of the analyses, dam frequency responses were subjected to the wavelet transform analysis. In this study, they obtained the results such as damage identification with no need for the data of the healthy structure and the high sensitivity of the static wavelet transform to any discontinuity, the determination of the failure location with a higher precision and so forth.

3.2. Hydraulic Monitoring of the Hydraulic Drains

Given the important role of the hydraulic structures in the stability and safety of the dams, the monitoring and measurement of the hydraulic parameters for the problems such as cavitation, erosion, valve vibrations and hammering flows are of great importance. The aforementioned problems are influenced by the parameters such as the discharge rate, flow velocity, hydrodynamic pressure, air speed, effective depth of water and the concentration of the flow air. Measurement of some of these parameters can help preventing failure from happening.

It can be understood that the damages created in the hydraulic structures originate from different sources. For instance, when the cavitation occurs as a result of the extant ruggedness of the surface, further damages start in the downstream of the dam. Over time, cavities are created in the concrete surface and they become larger as the flows collides the surfaces of the cavities and the gravels and the concrete surface are removed and carried due to the pressure difference between them and the other regions. It is evident that the damage followed by this incident is erosion that results in the vibration of bars subject to the flows and also mechanical damages.

According to the fact that all parameters affecting the failure are hydraulic and measurable, the monitoring method is based on certain sensors as summarized below:

1. The water dynamic pressure: to measure pressure, a pressure sensor can be used in the distance between the service valve and emergency valve as well as in the downside of the service valve on the floor.
2. Air speed: using vane anemometer is recommended for the measurement of the air speed in the air supply ducts for aeration as well as in the distance between the free water level and the tunnel roof.
3. Air pressure: an air pressure sensor can be installed between the valve housing and the lower discharge tunnel as well as in the ending section of the air supply duct and in the beginning, middle and ending parts of the lower discharging tunnel roof.

The use of novel methods for the direct evaluation of the hydraulic parameters:

1. The use of DECAVER device for the evaluation of friction rate and its total value in various parts of the path. Amongst the advantages of the device are its spatial adjustability and accurate measurements.
2. Chinese experts, as well, have invented a method by means of which they successfully monitored the tunnel weirs of Xialangdi dam by evaluating the sound differences between cavitation and cavitation occurrence [32].

3.3. Coastal Constructions

The coastal constructions should also be subjected to health monitoring because about two third of the world population live on the beaches and/or in the vicinity of them. Additionally, developments in the recreational and building fields make the protection of these structures against the dangers such as storms, more important. Also, it should be noted that a considerable part of the global business takes place through the entrance and exit of vessels to and from the ports.

The method that is proposed in a research by Eqbal Shakery et al. [30] for the health monitoring is visual inspection performed by the signs such as broken armor and displaced stones as vivid indicators of damage or failure. To perform health monitoring via visual inspection of the structures, the personnel who are aware of the wave conditions, ebb and flow and the flow harvested during the recording period should be hired. Access to the armor section is a common problem because it is in the ebb and flow area covered with grass and algae [30].

The crucial information that have to be considered in visual inspections are:

- Counting the broken armor units including all of the cases in which crushed stones are found.
- Marking the cracks or the possible displacements.

- Estimating the elevation of the selected locations using a reference point.

3.4. Offshore Platforms

Due to exploitation of the oil and gas fields and high cost of erection and installation, the marine platforms are considered as the national capitals so their health monitoring is inevitably necessary.

As explained in details in previous sections about the basics, principles and methods of structural health monitoring, for example, the natural frequency evaluation can be used to figure out the structure health status and other methods like time domain and so forth are also applicable. But, the important point that should be considered in selecting the methods is the cost. For example, 529 sensors were installed on CB32A, a fixed pier platform, to monitor the structure health in order to determine the exact location of the damage and its intensity and this can be economically unjustifiable [27].

According to the studies conducted on frequency area, FDD is deemed a precise and appropriate method for the fixed pier marine platforms.

To record the frequency responses of the structure using the sensors, environmental stimulants like wind, wave and so forth and changes in the physical responses (speed, displacement and strain) as well as the dynamic response variations like wind, humidity, temperature and so on are taken into consideration. The minimum number of the required accelerometers is determined according to the number of the target mode shapes depending on the sensor specifications, i.e. measured frequencies.

3.5. Monitoring and Quality Management of Water Resources

According to the population growth and considering their needs for water resources and also based on the fact that over 70% of the ground surface is covered with water, monitoring and management of these resources is of a great importance.

Generally, the water resources quality monitoring is a programmed process of collecting specimens, measuring and recording or marking the various characteristics of water. It often aims to evaluate the proportion and match with the specified applied goals.

Monitoring Based on Field Inspections: in this method, the physical and chemical specifications of water like PH, TDS, total hardness and temporary hardness, etc. are investigated in the laboratories. Then, the averages of them are assessed and compared with the standard levels of drinking water in Iran and the world.

As the previously mentioned materials about the disadvantages of health monitoring by visual inspections and field inspections, here, again, some examples of their shortcomings can also be pointed out, for example the lack of information about the water resources quality variations trend in the short run, the impossibility of permanently assessing the features of water resources quality in various regions.

With the advancement of sciences, a software was designed by combining GPS, ArcGIS and databases. Using this software, resource inspection and resource location identification and readings are performed automatically. The mechanism of this software is as follows: when the inspector approaches the required source within a range with a radius of 25 meters, the system itself automatically displays the resource specifications and opens its corresponding forms so as to record the other readings in the system. In this method, as well, no certainty was observed for various pollution evaluation phases in different indices [31].

3.6. Quality Monitoring of the Surface Waters in Road-Paving Projects

With the development of cities and increase in the pollution and the entry of the pollutants into the rivers, the monitoring and control of the water resources become inevitable issue. As explained in the section on the monitoring and quality management of the water resources, there is a need for an evaluation system upon the completion of the required information collection. Beside decision-making and analyzing the required cases and also responding to the questions such as “is the resource polluted? which of the parameters determine higher pollution” and so on, the evaluation system has to also offer the existent solutions.

Maryam Zargarnejad Soltani et al., in their study on the artificial intelligence science, have used Visual C# software to take advantage of DSS expert system, which is in fact the interface between the user and specialist’s knowledge perception. It is evident that before encoding the program, the users should be interviewed so that their needs and the type of decision-making support tools are determined in a manner where useful results will be obtained. In their study, the water physical and chemical specifications were determined using NSF-WQI method that is the water quality index used by the American national institute [29].

3.7. Road Surface Monitoring and Traffic Control

With the population growth and the ever-increase in the traffic and expansion of the machine life, the road accidents have also increased in number. As the development of technology and wireless communication systems, an instrument has been designed under the title of wireless sensor network. These instruments can be installed on the vehicles to monitor the damage development such as holes created on the road surface over time. The on-time monitoring of these damages can prevent irreparable incidents like accidents; moreover, the expansion of the damages and failures as well as repair costs can also be prevented. In this system, the wireless sensor network, installed on mobile vehicles, send the information to fixed nodes along the path and then, to the central control unit. Given the fact that information such as angular slope in three directions, instantaneous acceleration, temperature, air pressure and magnetic north are sent to the control unit at the time unit, the information received from every vehicle is recorded separately and the speed of vehicle and its displacement are calculated [28].

Putting all the recorded spatial position at the side of one another in the database, the displacement points of the vehicles can be calculated to the three coordinate system direction and geometrical shape of the road surface can be obtained in 3D.

Figure 4. Holes on the road surface and the 3D view produced by the system

4. Conclusion

Given that the health monitoring science was introduced herein for various sub-disciplines of civil engineering, it can be found out that:

- Regardless of the fact that some required sections and details are not available to human resources, the costs spend for monitoring and inspection by the human resources are much higher than using sensors for reading.
- The various methods utilized for the evaluations in any study field, including static or dynamic examinations, should provide the maximum use of these data for full-length evaluation of the structures so that the most useful response could be extracted from them in addition to the assessment of the outputs indicating the damages and failures. Among the methods studied up to now, fuzzy genetic method is the richest one because it is carried out based on a simple comparison featuring higher precision and more accurate responses and provides an analysis very much close to the investigations by specialist experts according to the information gathered for both the structure and quality monitoring of the surface waters, as conducted in a research by Sa'eid Jahan and Maryam Zargarnejad Soltani. So, the method is more cost-effective compared to the other methods in terms of the responses provided as outputs of the analyses; in addition, the method does not need reevaluation by the human workforce and experts.
- According to the fact that the health monitoring is mostly carried out for the projects of a high importance and these projects are predominantly enumerated amongst the national capitals, the investments made on the sensors and readings of the information should be evaluated by the evaluation system so as to make it clear that whether they are useful or not. The relative information gathered by these sensors has to be accompanied by a decisive response resembling the response of human brain various analysis conditions.

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