REVIEW THE BRIDGE MONITORING SYSTEM ON A REGULAR BASIS TO PREVENT EMERGENCY SITUATIONS

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Annotation. Abstract As civil engineering structures are growing in dimension and longevity, there is an associated increase in concern regarding the maintenance of such structures. Bridges, in particular, are critical links in today's trans- portation networks and hence fundamental for the devel- opment of society. In this context, the demand for novel damage detection techniques and reliable structural health monitoring systems is currently high. This paper presents a model-free damage detection approach based on machine learning techniques. The method is applied to data on the structural condition of a fictitious railway bridge gathered in a numerical experiment using a three-dimensional finite element model. Data are collected from the dynamic response of the structure, which is simulated in the course of the passage of a train, considering the bridge in healthy and two different damaged scenarios.

Keywords: Structural health monitoring Damage detection Model-free-based method Artificial neural networks Statistical model development Receiver operating characteristic curve · Bayes' theorem Probability-based expected cost

Introduction. The present time is without doubt the most appropriate for the development of robust and reliable structural damage detection systems as ageing civil engineering structures, such as bridges, are being used past their life expectancy and well beyond their original design loads. Often, when a significant damage to the structure is discovered, the deterioration has already progressed far, and required repair work is substantial and costly. Seldom will the structure be demolished and a new one constructed in its place. This entails substantial expenditures and has nega- tive impact on the environment and traffic during replacement. The ability to monitor a structure in real-time and detect damage at the earliest possible stage supports clever maintenance strategies and provides accurate remaining life predictions. For the exposed reasons, the demand for such smart structural health monitoring (SHM) systems is currently high.

The existing methods implemented in damage detection can be essentially divided into model-based and model- free. The first approach presupposes an accurate finite element model of the target structure, following that one obvious advantage of this approach is that the damage detected has a direct physical interpretation. Yet, it may be difficult to develop an accurate model of a complex structure and it can be intricate as well to obtain and update the parameters defining the structure. On the contrary, the model-free approach allows circumventing the problem of having to develop a precise structural model, mostly by means of artificial intelligence, but it is more difficult to assign a physical meaning to the detected damage. The model-free approach consists in training an algorithm on some acquired data, usually in an unsupervised manner, so that at the end it is able to tell apart different condition states of the structure. These algorithms are referred to as outlier or novelty detection methods: if there are significant deviations between measured and expected values, the algorithm is said to indicate novelty, meaning that the structure has departed from its normal condition and is probably damaged.

This paper presents a model-free damage detection approach based on artificial neural networks. The method is applied to data gathered from simulations of train passages on the finite element model of a fictitious railway bridge. The data sets are obtained from one healthy and two damage case scenarios of the bridge. This data would in reality be obtained directly from measurements performed on the real structure of interest, without the need to develop a complex numerical model. In the first stage of the pro- posed method, artificial neural networks are trained in an unsupervised manner with input data composed of gathered accelerations on the healthy bridge. Based on the acceler- ation values at previous instants in time, the networks are able to predict future accelerations. In the second stage, the prediction errors of each network are statistically characterized by a Gaussian process that supports the choice of a damage detection threshold. Then, by comparing damage indices with the threshold, the system is able to point out damage on the bridge. To evaluate the performance of the system, receiver operating characteristic curves that illus- trate the trade-off between true and false positives are generated. Finally, based on the Bayes' theorem, a simplified method for the calculation of the expected total cost of the proposed strategy, as a function of the chosen threshold, is suggested.

Literature review. A review of some of the most recent developments within SHM and damage detection that resulted in published articles in scientific peer-reviewed journals is here pre- sented. Regarding optimal sensor placement (OSP), a crucial part of any damage detection system, mention can be made to the work of Huang et al. [1] using genetic algorithms, where the proposed algorithm uses the sensor types as input and criteria about the desired measurement accuracy to deliver the optimal number of sensors and their location. The method was validated with experimental analysis on a single-bay steel frame structure case study. Li et al. [2] proposed a novel approach termed dual-structure coding and mutation particle swarm optimization (DSC- MPSO) algorithm. Using a numerical example of a three- span pre-stressed concrete cable-stayed bridge, this approach was demonstrated to have increased convergence speed and precision when compared to the other state-of- the-art methods (e.g. genetic algorithm). Still within the OSP topic, Yi et al. [3] proposed a new optimal sensor placement technique in multi-dimensional space since most available procedures for sensor placement only guarantee optimization in an individual structural direction, which results in an ineffective optimization of the sensing net- work when employing multi-axial sensors. A numerical study was conducted on a benchmark structure model.

Another common topic of research is the separation of the changes in structural response caused by operational and environmental variability from the changes triggered by damage. This is indeed one of the principal challenges to transit SHM technology from research to practice. Jin et al. [4] proposed an extended Kalmar filter-based artificial neural network for damage detection in a highway bridge under severe temperature changes. The time-lagged natural frequencies, time-lagged temperature and season index are selected as the inputs for the neural network, which pre- dicts the natural frequency at the next time step. The Kalmar filter is used to estimate the weights of the neural network and the confidence intervals of the natural fre- quencies that allow for damage detection. The method was tested with a numerical case study of an existing bridge. The published work regarding machine learning methods applied in SHM is continuously expanding.

Machine learning algorithms have been implemented to expose structural abnormalities from monitoring data. These algorithms normally belong to the outlier detection category, which considers training data coming exclusively from the normal condition of the structure (unsupervised learning). Worden and Farrar [5] have contributed with reputable work on monitoring of structures using machine learning tech- niques, such as neural networks, genetic algorithms, and support vector machines. Rao and Lakshmi [6] proposed a novel damage identification technique combining proper orthogonal decomposition (POD) with time-frequency analysis using Hilbert Huang transform (HHT) and dynamic quantum particle swarm optimization (DQPSO). The algo- rithm was tested with two numerical examples with single and multiple damages. Diez et al. [7] proposed a Clustering-based data-driven machine learning approach, using the *k*- mean clustering algorithm, to group joints with similar behavior on the bridge to separate the ones working in nor- mal condition from the ones working in abnormal condition. The feasibility of the approach was demonstrated using data collected during field test measurements of the Sydney Harbour Bridge. Zhou et al. [8] proposed a structural damage detection method based on posteriori probability support vector machine (PPSVM) and Dempster-Shafer (DS) evi- dence theory adopted to combine the decision level fusion information. The proposed damage detection method was verified by means of experimental analysis of a benchmark structure model. All the mentioned latter combined methods revealed to improve the accuracy and stability of the damage detection system when compared to other popular data mining methods.

There are several published works regarding the detec- tion of structural damage with the aid of Machine Learning techniques. Still, most of the proposed methods are based on a supervised learning approach, which requires data of the damage condition of the structure to be available. This poses a difficulty to the practical implementation of these methods because, as it is known, the data in damaged condition does not normally exist. The method presented in this paper consists in an updated mode-free damage detection algorithm using Machine Learning techniques based on the work of González [9]. The primary step in this study involves the development of a three-dimensional finite element model of a railway bridge. The vertical deck accelerations at different positions of the bridge are gath- ered using simulations of train passages and assuming that the bridge behaves in both normal and abnormal condi- tions, considering one baseline model and two damaged models, respectively. The first stage of the proposed method consists in the design and training of artificial neural networks (ANNs) which, given any input features, are trained to predict future values of the features. Following the validation of the best trained network, the second stage of the proposed algorithm consists in using the predicted acceleration errors to fit a Gaussian process (GP) that enables to perform a statistical analysis of the errors' distributions. After this process, damage indices (DIs) can be obtained and compared to a defined detection threshold for the system, allowing for one to study the probability of true and false detection events. From these results, a receiver operating characteristic (ROC) curve is generated and used to obtain information about the performance of the algorithm. Finally, a simplified method for the calculation of the expected total cost of the strategy based on the Bayes' Theorem is proposed.

Expected cost of the damage detection strategy. Even though the ROC curve constitutes a helpful tool for the determination of the best classifier, it is difficult to decide among thresholds solely based on their correspon- dent pair TPr/FPr. To assign a worth to each trade-off, the criterion was decided as that the best threshold will yield the minimum expected cost of the damage detection strategy. This cost will be given as the sum of several expenses, such as the ones associated with the flawed performance of the damage detection system, i.e. associ- ated with false positives and negatives. The first type of error is often associated with extraneous inspections and repairs while the second is associated with accumulation of damage by the lack of action, which can eventually lead to life-safety implications in the long run certain time, are analyzed. It all boils down to whether evidence suggests that the structure is healthy or damaged. The costs *C* that appear in are multiplied by the respective associated probabilities *p*. In this way, one can establish an equilibrium concerning the consequences of damage accumulation or potential structural failure and the expenses with safety measures to mitigate those conse- quences. It is however thought that the calculation process of the total expected cost can be simplified given the following assumptions:

- there are no costs associated with true negatives, as this corresponds to an ideal situation where damage does not exist and is not detected;
- the costs related to true positives are disregarded as that is what is sought from the system (to detect existing damage), meaning that these are ‘‘desired’’ costs;

• the costs related to false positives rely in inspections only. It is assumed that after detection and consequent inspection, no damage is found and therefore there is no need to proceed with repair. The costs of inspection will vary depending on several factors: the inspection technique, the frequency of inspections, the implications of performing inspection in the normal use of the structure (e.g. causing disturbances in the traffic flow), the restoration cost saved by earlier inspection, the difficulty in the access to the element to be inspected, et cetera;

• the costs related to false negatives are the most penalizing taking into account the potential tragic consequences that can result from missing damage. These costs are established based on risk assessment and valuation of material costs given the occurrence of a traffic accident. The values of human life loss, degree of injury resulting in inpatient and outpatient care, and of property damage are estimated reflecting their cost to society.

Regarding future research, once damage is detected, a subsequent step could be to study the correlation between measurements acquired from the different devices of the sensing system, in an attempt to pinpoint the location of damage. At the same time, optimal sensor placement could be carried out for the system to identify damage in a suf- ficiently accurate manner while avoiding redundancy in information. Finally, the suggested calculation of the expected total cost of the damage detection strategy is rather basic. Hence, the formulation of a more refined expression for the cost is desirable. Besides the economic considerations, some constraints may be considered, such as the minimum reliability level of the structure usually defined by the authorities or the limited time the system has to perform between each gathering of new data. In the end, it could even be possible to establish a schedule of inspection/repair based on the cost-benefit trade-off of each decision in the present and future moments.

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