

CONTINUOUS MONITORING SYSTEM ON BRIDGES TO PREVENT EMERGENCIES

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Annotation. In the first stage of the proposed method, artificial neural networks are trained with an unsupervised learning approach with input data composed of accelerations gathered on the healthy bridge. Based on the acceleration 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. Subsequent to this, by comparing damage indices with said threshold, it is possible to discriminate between different structural conditions, namely between healthy and damaged. From here and for each damage case scenario, receiver operating characteristic curves that illustrate the trade-off between true and false positives can be obtained. Lastly, 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.

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

1.Introduction. Visual inspections are regarded as the basic technique for the assessment of condition of in-service bridges, as this technique is intuitive and provides information in a direct way exclusively based on observation. However, this technique used alone has many shortcomings due to the growing complexity in the design of modern structures. One can mention as disadvantages the fact that the technique may not be practicable if the structure has restricted accessibility or if the traffic is excessively disturbed, its application is time-discrete and the conclusion of the visual inspection is inevitably subjective. In this sense, effort was placed in developing damage detection techniques that handle measurement data to find structural changes [1].

Structural health monitoring techniques comprise non-physically and physically based methods. The former uses a system model to study a physical structure and predict the responses; examples of methods that fall into this category are the probabilistic, non-parametric and autoregressive models (AR) methods [2]. The physically based methods perform damage identification by comparing natural frequencies and mode shapes data between the healthy and damaged structural model [3]; examples of methods that fall into this category are the vibration-based damage identification methods (VBDIM), such as frequency response [4], mode shape and strain energy methods [5], modal flexibility and modal stiffness methods. Many

broad classes of damage detection algorithms have emerged, most dealing with vibration measurements and modal analysis of the structural system. Although structural properties like damping, modal shapes and frequencies are not directly measurable, they can be inferred from other measured data. These properties have somewhat clear definitions and allow the relatively easy design of algorithms that define them, therefore being good candidates for parameters of a damage detection technique.

Damage identification is far from being a forthright process, from the basic step of defining what damage is up to decoding it in mathematical terms. Due to the random variability in experimentally measured dynamic response data, statistical approaches are desired to make sure that the perceived changes in the structure's response are coming from existing damage and not from variations in the operational and environmental conditions. The careful integration of recent sensing technology with traditional inspection and avant-garde diagnostic techniques will provide essential information that engineers and policy-makers need to manage the structures that serve our society.

2. Artificial neural networks. The first stage of damage identification uses methods which provide a qualitative indication of the presence of damage in the structure, which can be accomplished without prior knowledge of how the system behaves when damaged. These algorithms are referred to as outlier or novelty detection methods. To solve the task of novelty detection, one can use learning algorithms, such as artificial neural networks (ANNs).

Artificial neural networks are a family of mathematical models inspired by the structure of biological neural networks (Fig. 1) in which the basic processing unit of the brain is the neuron. Neurons interact with each other by summing stimuli from connected neurons. Once the total stimuli exceed a certain threshold, the neuron fires a phenomenon called activation and it generates a new stimulus that is passed onto the network. Knowledge is encoded in the connection strengths between the neurons in the brain approaches depending on the nature of the problem being solved and the type of training data available. In unsupervised learning, the aim is to discover groups of similar instances within the data while having no information concerning the class label of the instance or how many classes exist. In supervised learning, the instances are given with known labels, the corresponding correct outputs. In every training step, a set of inputs is passed forward in the network giving trial outputs that can be compared to the desired outputs. If it happens that the error is small, the weights are not adjusted; otherwise, the error is passed backwards and the training algorithm uses it to adjust the weights trying to decrease the error this algorithm is known as the back propagation algorithm.

ANNs are a powerful tool for SHM in the aid of problems in sensor data processing that require parallelism and optimization due to the high complexity of the variables' interactions. Generally, the ANNs offer solutions to four different problems: auto association, regression, classification and novelty detection.

Prosaic examples of potential applications of ANNs are speech recognition and generation, optimization of chemical processes, manufacturing process control, cancer cell analysis, transplant time optimizer, recognition of chromosomal abnormalities, solution of optimal routing problems, such as the Traveling Salesman Problem, et cetera.

3. **Performance of a classifier.** The damage detection process concerning civil engineering structures involves a significant amount of uncertainty, during the training phase of the network, the connection weights w_{ij} are continuously adjusted. The type of training can involve unsupervised and supervised learning generally due to [6]: inaccuracy in the FEM discretization; uncertainties in geometry and boundary conditions; non-linearity in material properties, environmental settings (e.g. variations in temperature and traffic); errors associated with measurements (e.g. noise) and signal post-processing techniques.

The consequences of false detection can be more or less stern and it is, thus, imperative to carefully investigate the sources of uncertainties, quantify and control their influence. The analysis of Type I (false positive) and Type II (false negative) errors is a frequent practice of reporting the performance of a binary classification, where there are four possible outcomes from an inspection event in a structure. Two statistical tools that enable the evaluation of these errors, in terms of unwanted results (false positives and negatives) and desired results (true positives and negatives), are the probability of detection (POD) curve and the receiver operating characteristic (ROC) curve [7], the latter used in this paper.

A ROC curve is a two-dimensional graphic in which the true positive rate (TPr) is plotted against the false positive rate (FPr) for a given threshold. The graphic demonstrates thus relative trade-offs between benefits and costs, respectively, TPr and FPr, depending on a threshold that is selected (Fig.1). A very high (strict) threshold will never indicate damage since the classifier finds no positives, resulting in 0% of false and true positives, whereas a very low (lenient) threshold will always indicate damage since everything is classified positive, resulting in 100% of false and true positives. One common way to define the best threshold is by fixing an acceptable FPr and then trying to maximize the TPr.

The ROC curve provides a tool for cost-benefit analysis assisting the practitioner in the selection among different available classifiers and their detection threshold. The optimal detection threshold will commonly be the one that minimizes the total expected cost, which will be connected with the odds of false detection. The accepted idea is that one point in the ROC space is considered better than another if it is associated with a higher *TPr* for the same *FPr*. The closer the curve is to the left the ROC space, resembling an inverted L shape, the superior the performance of the classifier; the closer the curve is to a 45° diagonal in the ROC space, the less accurate is the classifier.

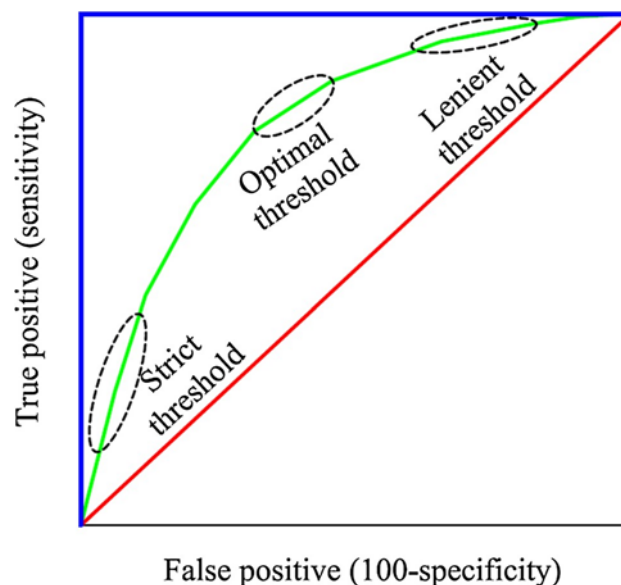


Fig. 1 ROC curves: blue line, exceptional; green line, good; red line, worthless

4. Bridge and FE model. The method here proposed has the potential to be readily used once plenty of data are collected on the real structure of interest, meaning that there is no need to develop a complex structural model. While the damage detection method is a model-free method, in the lack of measurements from an existing bridge that could be used as a case study, the authors decided to obtain the data from a Finite Element model of a fictitious, yet realistic, bridge.

A numerical 3D finite element (FE) model of a single-track railway bridge was developed using FEM software ABAQUS [8]. The structure consists of the following parts: the concrete deck of constant thickness, the two steel girder beams that support the deck and the steel cross bracings that connect the girders. The deck and the girderbeams were modelled as shell elements and the cross bracings were modelled as truss elements. All the elements of the bridge are assumed to be rigidly connected to each other.

The methodology proposed in this paper provides a rational fashion for enhancing the damage diagnosis strategy for damaged structures, allowing for both improvements in safety and reduction of bridge management cost. The method proposes the use of past recorded deck accelerations in the bridge as input to an Artificial Neural Network that, after being properly trained, is able to predict forthcoming accelerations. The difference between the measured value and the value predicted by the network will work as a primary indicator that damage may exist. This study comprises the statistical evaluation of the prediction errors of the network by means of a Gaussian Process, after which one can select the detection threshold in regard to a Damage Index. Based on the selected threshold, the expected total cost associated with the damage detection strategy can be calculated. Within the interval of viable thresholds, the optimal will be the one that yields the lowest cost. From the attained results, it is possible to derive some general conclusions:

- lower vehicle speed seems to overall provide measurements that enable

better predictions by the trained network, in the sense that the prediction errors in both healthy and damaged structural condition are inferior than for higher speeds;

- the two sensors placed in the middle of the bridge seem to be the most efficient in the discrimination between healthy and damaged data, apparently disregarding where in the bridge damage takes place. This may be explained by the fact that the response of the simply supported bridge is emphasized at half-span;

- the ROC curves associated with scenarios where damage is more severe generally present a superior

trade-off TP/FP, since to conserve the same probability of TP one needs to accept an inferior probability of FP, when compared to less severe damage;

- the ideal threshold for the damage detection system will be the one that yields the lowest expected total cost regarding the detection process, where the costs related with false detection have particular impact.

The proposed method has although some weaknesses that can be tackled with additional research. This could concern the study of environmental and operational effects on the damage detection process-other relevant parameters than accelerations may be given as input to the neural networks, such as temperature measurements. The consideration of these will almost certainly produce networks with higher prediction accuracy, making the algorithm more shielded against the influence of damage unrelated factors that can induce significant changes in the behavior of the structure. This study presents a limited number of damage scenarios. A wider range of possible locations for damage in the bridge could be considered, including multiple damage scenarios. It would also be interesting to understand the limitations of the proposed method in terms of the smallest damage that can be detected.

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