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The use of a non-probabilistic artificial neural network to consider uncertainties in vibration-based-damage detection

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ABSTRACT

The effectiveness of artificial neural networks (ANNs) when applied to pattern recognition in vibration-based damage detection has been demonstrated in many studies because they are capable of providing accurate results and the reliable identification of structural damage based on modal data. However, the use of ANNs has been questioned in terms of its reliability in the face of uncertainties in measurement and modeling data. Attempts to incorporate a probabilistic method into an ANN by treating the uncertainties as normally distributed random variables has delivered promising solutions to this problem, but the probabilistic method is less straightforward in practice because it is often not possible to obtain unbiased probabilistic distributions of the uncertainties. Moreover, the probabilistic ANN method is computationally complex, especially when generating output data. In this study, a non-probabilistic ANN is proposed to address the problem of uncertainty in vibration damage detection using ANNs. The input data for the network consist of natural frequencies and mode shapes, and the output is the Young's modulus (E values), which acts as an elemental stiffness parameter (ESP). Through the interval analysis method, the noise in measured frequencies and mode shapes are considered to be coupled rather than statistically distributed. This method calculates the interval bound (lower and upper bounds) of the ESP changes based on an interval analysis method. The ANN is used to predict the output of this interval bound by considering the uncertainties in the input parameters. To establish the relationship between the input parameters and output parameters, a possibility of damage existence (PoDE) parameter is defined for the undamaged and damaged states. A stiffness reduction factor (SRF) is also used to represent changes in the stiffness parameter. A numerical model and a laboratory-tested steel portal frame demonstrate the efficacy of the method in improving the accuracy of the ANN in the presence of uncertainties. The effect of different severity levels and the influence of different noise levels on the identification results are discussed.

1. Introduction

The vibration-based damage detection method has been widely used to increase the safety of civil engineering

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structures. Many approaches based on this method have been proven to be effective in addressing problems in both basic and complex structures. This approach explains that damage can affect both the physical and dynamic characteristics of the structural properties. Physical characteristics include the mass, stiffness and damping, while dynamic characteristics include the frequency response functions (FRFs), natural frequencies, damping ratio and mode shapes. For example, changes in both the mode shape and natural frequencies result when the stiffness of a beam structure is reduced. Vibration-based damage detection methods range from conventional direct methods, such as measurements of changes in frequencies [1,2], mode shapes [3–5] and FRFs [6,7], to the application of advanced computational methods such as fuzzy logic [8], genetic algorithms [9] and artificial neural networks (ANNs) [10,11].

One of the best explored computational approaches to vibration-based damage detection is ANNs. The ANN technique has proven effective in damage detection due to its capability to model the nonlinear relationship between the vibration parameters and the damage location and severity [12–17]. ANNs represent a type of computing that is inspired by the structure and the information processing capability of the human brain. This model mimics the real life behavior of neurons and the electrical messages they produce between the input processing of the brain and the final output from the brain. Once trained, an ANN is capable of pattern recognition and classification.

The issues of uncertainty become more significant as civil engineering structures become more complex. There are two types of unavoidable uncertainties in the application of ANNs in damage detection: modeling error and measurement noise. Modeling error refers to the existence of uncertainties in the finite element model (FE model) due to the inaccuracy of physical parameters, non-ideal boundary conditions, finite element discretization and nonlinear structural properties. This may result in the FE model not representing the exact behavior of the modeled structures, leading to the trained ANN model using data generated from the FE model being unable to represent the exact relationship between the input parameters (vibration data) and the damage information. On the other hand, noise in measurement data that are normally used in the testing phase may also lead to inaccurate damage identification. Bakhary et al. [10,18] demonstrated the effects of uncertainties in training and testing data on the performance of ANNs in structural damage detection, and they suggested the use of a probabilistic ANN method to consider the existence of uncertainties in the FE model and measurement data. The study demonstrated that the probabilistic method is capable of facilitating accurate damage detection based on noisy data. The probabilistic method was also proven efficient in handling noisy data in several other studies [10,17,19]. Despite its efficiency in handling noisy data, the probabilistic method suffers from several disadvantages such as its assumption of uncertain parameters as normally distributed random variables with a given variance. In practice, it is not possible to obtain the probability density function due to the complexity of the sources of uncertainty [20,21]. Furthermore, insufficient data in experimental studies also reduce the capability of obtaining an unbiased probability density function. Moreover, the probabilistic method requires multiple sets of data for the probabilistic analysis. These data sets are normally generated through an established FE model or ANN model based on a specific standard deviation. This process involves an iterative process of simulation that is very time consuming.

There have been several attempts to apply non-probabilistic methods to overcome the drawbacks of statistical methods. Most studies have used interval analysis to replace the uncertain parameters with intervals to produce an output that is also an interval. For example, Gabriele et al. [22] demonstrated the applicability of interval analysis in considering uncertainties in the context of model updating. The authors considered the uncertainties in frequencies to obtain intervals for the stiffness values. Damage detection was performed by calculating the stiffness central values. Garcia et al. [23] further demonstrated the efficacy of the interval analysis method by applying it to uncertainties in material properties. The existence of damage was determined by observing the load at which the structure changes from exhibiting elastic behavior to nonlinear behavior. Recently Wang et al. [24] improved the method by providing a new damage measure index (DMI) that combines the stiffness reduction factors (SRFs) and the possibility of damage existence (PoDE) using a non-probabilistic interval analysis framework. In their study, both the physical and dynamic characteristics are measured using interval analysis. Using a Taylor series expansion, the uncertainties of the interval bounds of the physical and dynamic characteristics of the damaged and undamaged states are derived based on the results of the FE model. Compared to the conventional probabilistic analysis, non-probabilistic interval analysis does not require any assumption about the uncertainties' distribution in the calculation of the PoDE. It requires only the upper and lower bounds of the uncertain parameters, which can generally be obtained in real engineering problems. Thus, damage detection with noisy data becomes simpler and computationally less complex compared to the approaches based on the conventional probabilistic method.

This study extends the applicability of the non-probabilistic method using ANNs to consider uncertainties in damage detection. For this purpose, an ANN is trained using frequencies and mode shapes as inputs and elemental stiffness parameters (ESPs) as the output variables. The uncertainties are considered by calculating the lower and upper bounds of the input parameters based on interval mathematics to produce the lower and upper bounds of the output parameters (ESP). Therefore, two identical ANNs are used to determine the upper and lower bounds of the noisy input data. SRFs and PoDE are later used to define the reduction in the ESP values and the existence of damage. To provide a better indicator of damage existence, the DMI is adopted. The applicability of the proposed method is demonstrated through a numerical model and a lab experiment on a steel portal frame. A sensitivity study on the effects of different levels of uncertainties on the input and output parameters is also conducted. The results show that the proposed method is able to efficiently provide the location and severity of damage.

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