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Damage Assessment of a Cable-Stayed Bridge Based on Effective Empirical Mode Features using Empirical Wavelet Transform

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ABSTRACT: Intelligent damage detection of civil infrastructures is vital to improve damage prediction performance and reduce maintenance costs. Therefore, the development of efficient techniques for detecting structural damages in an early stage is extremely important to support making decisions on structure repair. In this paper, a new damage detection method based on effective frequency band with empirical wavelet transform for a cable-stayed bridge was proposed which consists of two stages: (1) signal processing and feature extraction, (2) damage identification by combining effective features. In the first stage, structural response data was decomposed into empirical modes using empirical wavelet transform to obtain the component related to structural damage, and a set of features as damage-sensitive features were extracted from the frequency spectrum of modes. A support vector machine was applied to evaluate the results. In the second stage, by applying feature selection methods, an optimal subset of features that carries the most significant information about the structural damage was obtained as a damage index. Next, it was used in the feature extraction process. To verify the proposed damage detection method, response data obtained from a cable-stayed bridge, the Yonghe Bridge, was employed. Results showed that the second and third empirical modes obtained from the empirical wavelet analysis contain fault information and using its corresponding frequency spectrum in the feature extraction process improves detection performance by about 5% compared to conventional methods. It also increases the detection accuracy to about 94% by employing effective feature combinations rather than a single feature.

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1- Introduction

Intelligent damage identification of civil infrastructure systems in an early stage is essential for Structural Health Monitoring (SHM) to prevent catastrophic failures and reduce maintenance costs. Thus, research and development of damage identification techniques are needed to achieve accurate detection automatically [1-2]. Vibration-based methods that utilize changes in measured vibration response of the structures for damage detection have received considerable attention in the last two decades. The basic idea of these methods is that modal parameters are functions of physical properties of the structure, and damage changes dynamic characteristics affecting the measured vibration response [3]. Vibration-based damage detection methods include three steps: signal monitoring, signal processing, and data interpretation [4]. Signal processing extracting useful features from structural signals is the key component and the most challenging issue [5]. The main processing techniques are based on time, frequency, and time-frequency analysis. Each signal processing method has its advantages and disadvantages, which may influence the performance of the damage detection procedure. Thus, choosing a signal processing technique for detecting damage is essential to avoid erroneous results or false alarms. In this paper, the proposed approach is an extension of a method proposed by Ghodrati *et al.* [6]. The first stage of this study is aimed at increasing the accuracy of damage detection by applying Empirical Wavelet Transform (EWT) and extracting features from the frequency spectrum of modes. In the second stage, an effective empirical mode is obtained, and the combination of mode features is proposed as a damage index to improve the performance of the damage detection process by using feature selection methods. A Support Vector Machine (SVM) is used as a classifier to investigate the ability of each feature set. The proposed approach is verified using a numerical dataset and a real dataset recorded from a cable-stayed bridge, the Yonghe Bridge, as a benchmark problem.

2- Methodology

2- 1- Feature Extraction

Feature extraction is a crucial step for signal processing to extract the suitable features in the time-frequency domain. The extracted features can reflect the relevant and useful information of damage from vibration signals. The features

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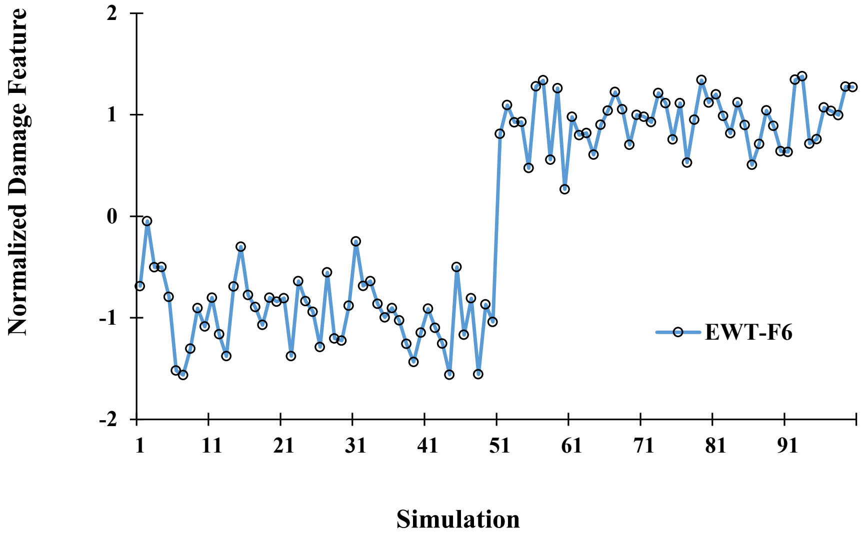

Fig. 1. Normalized damage feature extracted from 3rd empirical mode.

Table 1. Selected features by feature selection methods and classification accuracy.

Feature Selection Method	Optimal Feature Set	Accuracy (%)
FS	F10, F8	93
GA	F2, F4, F6, F10	94
RF	F2, F3, F1, F6, F8	93

correspond to spectral shape properties and statistical properties of the spectrum are used in this paper. These descriptors consist of mean, variance, root mean square, spectral crest factor, spectral flatness, spectral slope, spectral skewness, spectral spread, spectral kurtosis, and spectral flux [6].

2- 2- Empirical Wavelet Transform

The Empirical Wavelet Transform (EWT) is an adaptive data analysis technique to extract various modes of a time-domain signal by defining a series of wavelet filters. The EWT decomposes the input signal to narrow sub-bands in the time-frequency domain [7].

2- 3- Feature Selection And Svm Classifier

Feature selection is the procedure of selecting a subset of important and relevant features and includes four key steps, namely, subset generation, subset evaluation, stopping criteria, and result validation [8]. In this paper, the Forward Selection (FS), Genetic Algorithm (GA), and Random Forest (RF) methods are employed for feature selection.

The support vector machine (SVM) is a linear machine learning algorithm that can be applied to classify one or more classes successfully by locating the optimal separation plane (boundaries) between various classes [9]. The SVM separates input data by a linear hyperplane:

$$f(x) = w\,x + b = \sum_{k=1}^{m} w_k\,x_k + b = 0 \qquad (1)$$

Where b is a scalar, and w is the weight vector.

3- Results and Discussion

This paper aims to obtain a damage index for detecting damage in a cable-stayed bridge. The data decomposes into empirical modes using EWT, and spectral features are then extracted from the frequency spectrum of the modes. Normalization is performed before the feature selection process to avoid slow training speed and data singularity. For each empirical mode, the important features are selected and combined using feature selection methods to improve the detection performance. Finally, the SVM classifier is an automated decision-making tool for classification tasks is used to find the effective empirical model and damage index. In the classification part, 70% of data is selected randomly as the train set and the other 30% as the test set. Cross-validation is performed to investigate how the results of a classification scheme will generalize to an independent data set. The repeated random sub-sampling validation method is employed here for cross-validation. Notably, all calculations were carried out using MATLAB software.

The proposed approach is validated using a suite of numerical and full-scale studies (a cable-stayed bridge in China and a Bridge Health Monitoring Benchmark Problem). For the numerical study, an accelerometer located on the model is considered to record the vertical accelerations. The gusset plates at node N1 are eliminated, and the moment of the transverse beam connecting at this node is released. Also, 10% white noise is added artificially. Fig. 1 depicts the effectiveness of the proposed method, which gives an average accuracy of 100%.

For the full-scale study, the available data consists of 24h records (24 parts of 1h length). Data in the healthy and damaged conditions are recorded on 17 January and 31 July 2008, respectively. The sampling frequency of data is 100 Hz.

The results in Table 1 show the subset of important features extracted from an effective empirical mode and classification accuracy obtained by SVM. The results showed that the 2^{nd} and 3^{rd} empirical modes are efficient for the feature extraction process. Using the proposed approach improved the identification performance to about 94% accuracy.

4- Conclusions

In this study, a novel detection approach based on features extracted from an effective empirical mode in EWT is proposed to perform automatic damage identification of the bridges. Efficient extracted features are chosen and combined as an optimal feature set through feature selection methods to improve final results and reduce false alarms or misclassification. The feature selection methods consist of the forward selection, genetic algorithm, and random forest methods. This approach is verified using a suite of numerical and full-scale studies. The numerical study has shown that the performance of empirical mode features is highly promising for the task of damage identification. The results confirm that the proposed algorithm yields an average classification accuracy of 100% for a numerical benchmark problem. Besides, for the case of a full-scale study (Yonghe bridge), the damage is detected with an average accuracy of about 94%. The feature subset consists of *F2*, *F4*, *F6*, and *F10* obtained by the genetic algorithm. Also, the peak accuracy is about 93% achieved by the forward selection and random forest methods.

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