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Structural damage diagnosis under varying environmental conditions—Part I: A linear analysis

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Abstract

A damage detection method is proposed for structural health monitoring under varying environmental and operational conditions. The method is based on principal component analysis (PCA) applied to vibration features identified during the monitoring of the structure. The advantage of the method is that it does not require to measure environmental parameters because they are taken into account as embedded variables. The number of principal components of the vibration features is implicitly assumed to correspond to the number of independent environmental factors. Since the environmental effects may be effectively eliminated by the proposed procedure, the residual error of the PCA prediction model remains small if the structure is healthy, and it increases significantly when structural damage occurs. Novelty analysis on the residual errors provides a statistical indication of damage. In the present paper, the environmental conditions are assumed to have a linear (or weakly non-linear) effect on the vibration features, and the PCA-based damage detection method is illustrated using computer-simulated and laboratory testing data. The extension of the proposed method to non-linear cases is addressed in a companion paper where the efficiency of the method is verified using data obtained from a 1-year in situ monitoring of a bridge.

Keywords: Structural health monitoring; Environmental variation; Temperature effect; Principal component analysis; Novelty detection; Bridge diagnosis

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1. Introduction

Vibration-based structural health monitoring consists in detecting damages in structures from changes in vibration features extracted from periodically spaced measurements. For example, damages may be characterised by changes in the modal parameters, i.e., natural frequencies, modal damping ratios and mode shapes. A detailed review of this research topic is available in Ref. [1]. Structural parameters such as measured flexibility and/or stiffness matrix constructed from identified modal parameters may also be used for damage detection and localisation [2,3]. There is also a large amount of research using other damage-sensitive features without the need to identify the modal parameters, such as novelty analysis with auto-regressive models [4,5], principal component analysis [6,7], χ^2-test based on realisation analysis [8], independent component analysis [9], and more recently a novelty analysis based on a Kalman model [10], etc.

In most of the previous analyses, vibration characteristics of structures were estimated with the assumption of a constant environmental condition. However, in practical situations, structures are often subject to changes in environmental and operational conditions (e.g., temperature, temperature gradients, humidity, wind, traffic, etc.), which may mask the changes caused by structural damages. If the effect of these environmental variations is not taken into account in the damage detection process, false-positive or negative damage diagnosis may occur so that vibration-based health monitoring becomes unreliable. Accordingly, during the last years, structural dynamicists have become increasingly concerned with modal parameter variability due to environmental conditions [11–24].

One of the methods used to solve this problem is to perform correlation between the measured vibration characteristics (e.g., the natural frequencies) and the corresponding environmental conditions (e.g., ambient temperature) [16–21]. Thus, the reference state of the structure may be parameterised to reflect the different environmental and operational conditions, and the structural damages are only responsible for the additional changes in features. However, this approach is subject to several practical drawbacks. As pointed out by Kullaa [23], although temperature measurements are relatively easy to perform, the optimal locations of temperature sensors may be difficult to determine or to reach. In practice, a large number of sensors are often installed at different locations, and only a few of them are retained according to their sensitivity to the change in features. For example, in a recent work by Ko et al. [20], 20 temperature measurements were selected among a set of 83 temperature sensors installed permanently on a cable-stayed bridge. Another difficulty also lies in the fact that the environmental variables that affect the features are sometimes not easy to determine. Moreover, once the correlation between the measured features and the environmental variables has been established, the sensors that measure the environmental variables must remain located at the same place on the structure. Failure of any of them may cause problems for the health monitoring afterwards.

Another method has been proposed by Sohn et al. [22], Kullaa [23], etc. in which the environmental variables are not measured, and only the identified vibration features are analysed. Sohn et al. used an auto-associative neural network to train the data measured in varying environmental conditions. In this method, target outputs correspond to the inputs of the network, and the bottleneck layer captures the embedded environmental factors. The method has been used to analyse a simulated computer hard disk drive, and the coefficients of the transfer function were chosen as vibration features. Kullaa applied a linear factor analysis, consisting of an iterative