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The construction and comparison of damage detection index based on the nonlinear output frequency response function and experimental analysis

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ABSTRACT

When the structures or parts are subjected to fatigue damage, its nonlinear characteristics will be characterized sensitively. The nonlinear characteristics of the system can be well described by the nonlinear output frequency response function deduced by the Volterra series. The nonlinear output frequency response function is the collection of frequency functions of various orders which contain different nonlinear information about the system. In other words, it is not intuitive when it is used directly for the detection of fatigue damage to structures or parts. Therefore, how to build an intuitive detection index will be the key to the application of the nonlinear output frequency response function in engineering practice. In this paper, based on the concept of information entropy, complexity and divergence, 4 detection indexes were proposed and the definition and estimation methods were given. Fatigue tests were carried out on the specimens by a fatigue test machine, and a series of specimens with different fatigue cycle times were obtained. The nonlinear output frequency response function was estimated by using the data of the hammer excitation measurement. The detection effect of 4 detection indexes and traditional detection index Fe was analyzed and compared. The results show that the proposed detection indexes are more sensitive and effective for detecting fatigue damage before microcracks formed.

1. Introduction

For mechanical equipment fatigue damage might be a huge security risk. So it is necessary to have an effective means to discover fatigue damage and the disaster will be eliminated in the embryonic stage. The damage range studied in this paper was limited as the fatigue state which the parts had been subjected to the varying load for some time but microcracks hadn't formed.

Researchers have made extensive research on the application of linear detection methods based on natural frequencies, modal shapes and so on. They have the advantages of easy to collect signal, easy to select detection position, convenient for

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calculation and so on. Nevertheless they are mainly aimed at the linear characteristics of the structure. Their effect on detecting fatigue damage before microcracks formed is not obvious. As a consensus, many studies have shown that nonlinear characteristics are manifested by fatigue damage. The detection of fatigue damage before microcracks formed is more effective by using nonlinear effects [1]. The appearance of damage is often accompanied by nonlinear characteristics. Therefore, the emergence of nonlinear characteristics can be served as an index of early damage. Many studies have tried to use nonlinear detection methods to detect damage. The study of Broda [2] shows that the nonlinearity of the cracked beam is particularly strong near the damage. Tsyfansky [3] developed a new effective method for detection of cracks by the utilization of these non-linear effects which can detect system damage in the presence of interference signals. Tsyfansky [4] found that super harmonic vibration regimes appear in the system response because of the influence of the elastic non-linearity of typical cracks, and then a new vibration method for the detection of cracks is developed by features of these regimes. Mozuras and Volkovas [5] developed a defective structure 'beam with fixed ends' model to quantitatively determine defect size and calculate the control conditions for maximum sensitivity. Volkovas [6] discussed the application of nonlinear detection in the fault diagnosis of mechanical system.

As an effective tool for the analysis of the nonlinear system, Volterra series [7] has been studied extensively since 1887 [8–10]. Volterra series kernel, generalized frequency response function, provides a method to describe the frequency characteristic of nonlinear system, but the increasing of the dimension will cause the dimension disaster. In such a situation, Lang and Billings [11] proposed nonlinear output frequency response functions (abbreviated as NOFRFs) defined by the Volterra series, a transformation style of generalized frequency response function. The problem of dimensionality disaster was avoided. The NOFRFs is the collection of frequency functions of various orders which contain different nonlinear information in the system. Peng's earlier studies [12] have shown that NOFRFs can describe the nonlinearity completely. Studies have shown that the NOFRFs can characterize the nonlinear characteristics of damage well. The results of numerical simulation studies verify the effectiveness of the NOFRFs [13]. In the study, NOFRFs was used to detect cracks in beams using frequency domain information and result show that the NOFRF is a sensitive indicator of the presence of cracks [14]. Cheng [15] detected the position of non-linear components in two dimensional periodic structures by using NOFRFs. Peng [16] combined the NARMAX model with NOFRFs and detected the damage of aluminum plate successfully. Huang [17] estimated the NOFRFs using the hammer excitation output response and the improved NARMAX model, and successfully detected cumulative fatigue damage on the engine connecting rod.

However, the NOFRFs will be different according to the type of input signal. That is, the NOFRFs measured on different occasions is not comparable, and cannot directly reflect the extent of damage. At the same time, the NOFRFs have multiple orders, and each order of the NOFRFs is expressed as a one-dimensional function of frequency. Which makes it neither easy to calculate, nor easy to intuitively observe in the engineering application. So, the NOFRF is not easy to directly used to determine the system damage in the practical application. Thus, how to build an intuitive detection index will be the key to the application of the NOFRFs in engineering practice.

NOFRFs can be easily estimated by test signals. Furthermore, the information about the damage of parts or structures, even very small damage, can be expressed sensitively by NOFRFs. Therefore, damage detection index can be constructed through NOFRF. Then, the detection of damage to parts or structures using NOFRF can be explored. Peng and Lang et al. [16] constructed an index named simple index Fe based on the NOFRFs typically. Fe is a function of order. Each order of Fe is constructed by the same order of NOFRFs. It can separately express the various orders of NOFRFs with visual numbers instead of non-intuitive functions, which can also indicate the degree of non-linearity of the system. So it can reflect the damage intuitively. At present, it has been widely recognized and used as a traditional index. It quantifies the degree of nonlinearity of each order into various values. However, it has several shortcomings. On the one hand, when fatigue damage occurs in the system, the degree of non-linearity of each order varies little. It will be difficult to determine whether the system is damaged and how much damage by the traditional index Fe. On the other hand, the nonlinear characteristics of the system are characterized by multiple Fe values. The damage information of each order is separated, which will be detrimental to the judgment of damage degree in engineering practice. Thus, it is necessary to propose a new index that can reflect fatigue damage more sensitively and more intuitively, so that it can be effectively applied in engineering practice.

In this paper, 4 detection indexes will be proposed based on the concepts of information entropy, complexity and divergence, namely NOFRFs entropy index Ne, NOFRFs frequency domain complexity entropy index IFEn, NOFRFs non-linear scale index NL, NOFRFs divergence index NDI. Fatigue test was carried out on the specimens by fatigue testing machine. A series of specimens with different fatigue cycles are obtained. Because the information from a wide frequency range can be triggered by hammering, including damage information, pulse hammer experiment was carried out. The NOFRFs were estimated by using the data obtained from the hammer experiment. The effect of detection of 4 detection indexes and traditional detection index Fe was analyzed and compared. The proposed detection indexes are more sensitive and effective for detecting fatigue damage.

2. Theoretical fundamentals

2.1. NOFRF theory

In Ref. [11], the definition of NOFRF is given: