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A new surface fractal dimension for displacement mode shape-based damage identification of plate-type structures

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ABSTRACT

Vibration-based nondestructive testing is an area of growing interest and worthy of exploring new and innovative approaches. The displacement mode shape is often chosen to identify damage due to its local detailed characteristic and less sensitivity to surrounding noise. Requirement for baseline mode shape in most vibration-based damage identification limits application of such a strategy. In this study, a new surface fractal dimension called edge perimeter dimension (EPD) is formulated, from which an EPD-based window dimension locus (EPD-WDL) algorithm for irregularity or damage identification of plate-type structures is established. An analytical notch-type damage model of simply-supported plates is proposed to evaluate notch effect on plate vibration performance; while a sub-domain of notch cases with less effect is selected to investigate robustness of the proposed damage identification algorithm. Then, fundamental aspects of EPD-WDL algorithm in term of notch localization, notch quantification, and noise immunity are assessed. A mathematical solution called isomorphism is implemented to remove false peaks caused by inflexions of mode shapes when applying the EPD-WDL algorithm to higher mode shapes. The effectiveness and practicability of the EPD-WDL algorithm are demonstrated by an experimental procedure on damage identification of an artificially-induced notched aluminum cantilever plate using a measurement system of piezoelectric lead-zirconate (PZT) actuator and scanning laser Doppler vibrometer (SLDV). As demonstrated in both the analytical and experimental evaluations, the new surface fractal dimension technique developed is capable of effectively identifying damage in plate-type structures.

1. Introduction

In-service engineering structural systems, including airplanes, bridges, buildings, etc., suffer from material degradation and structural damage with increasing age. Sudden failure of structures may happen due to invisible internal deficiency or damage accumulation. A dependable and effective damage identification technique is critical to provide warning for repair and maintenance of structures in use. Nondestructive testing (NDT) can detect and evaluate flaws (irregularities and discontinuities) without disrupting service of structural systems [1]. NDT can be categorized as either local or global one. The local NDT, such as thermography, X-ray imaging, acoustic emission, ultrasound, etc., requires that vicinity of damage is known a

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priori and damage area is readily accessible, which cannot be guaranteed for most cases. To overcome these limitations, the global NDT based on vibration analysis has been increasingly investigated in recent years. The basic principle for vibration-based damage identification techniques is that the structural modal parameters (e.g., frequency, modal damping, mode shape, etc.) would change with respect to physical property change of structures (e.g., mass, damping, and stiffness) [2]. Therefore, it is feasible that damage can be identified through inspection of structural modal parameters.

Based on structural modal parameters, numerous algorithms for damage identification of beam- and plate-type structures were developed, and they were primarily categorized as natural frequency-based method, damping-based method, and mode shape-based method [2,3]. Because of model dependency, low sensitivity to damage, and either false-positive or false-negative multiple damage identification, the natural frequency-based method is rarely used in complex structures or multiple/severe damage cases [3]. Modena et al. [4] showed that crack could cause larger changes in damping when compared to natural frequency and lower mode shape. But Leonard et al. [5] indicated that damping is function of the open-close degree of crack controlled by excitation amplitude, which reduces repeatability of measurements. Furthermore, various environmental factors, such as temperature, humidity, etc., increase uncertainty in modal damping testing [6,7]. Better than the frequency-based method, the mode shape-based method processes spatial description of vibration amplitude which is prone to locate and quantify spatial variability caused by damage [8]. Also, mode shape testing is relatively more stable under environmental impact. Thus, the mode shape-based method is the most popular technique for dynamics- or vibration-based damage identification [3]. The easiest way for damage identification using mode shape is based on the fact that the biggest difference region is the most possible damage area when comparing intact structure with damage one [9–11]. But for existing structures, experimental mode shape data of intact structure cannot be always found or available. Moreover, it is impossible to develop an accurate numerical finite element model due to impartial or incomplete design information, error between construction and design, complexity of boundary, etc. Thus, non-baseline methods for real-time structural damage identification [12–15] becomes more viable. In the stage of identifying existence and location of damage, baseline data from healthy structures is not essential any more. To put it simply, distinct roughness (or irregularity) in displacement mode shapes, local peaks in strain mode shapes, and zero-crossing in curvature mode shapes can be employed to indicate location of damage. But in the stage of quantifying damage severity, non-baseline data alone cannot cope with damage quantification. In order to overcome the above-mentioned difficulty, many attempts were made to both locate and quantify damage. Among them, fractal dimension (FD) is a novel indicator for each damage identification stage. The FD is a measure of space-filling capacity, and therefore, it has been used to describe irregularity of complex shapes [16]. The Katz's waveform dimension (KWD) was noted for its capability of quantitatively measuring complexity of a waveform [17]. Hadjileontiadis et al. [18] first developed fractal dimension crack detector (FDCD) based on the KWD for a cracked cantilever. But Wang and Qiao [19] found that FD variation induced by damage was covered with inflexion area of higher mode shapes, and they subsequently developed a generalized fractal dimension method by introducing a scale parameter. Qiao and Cao [20] proposed a mathematical solution called isomorphism to solve the inflexion of higher mode shapes and developed a new fractal dimension called approximate waveform capacity dimension (AWCD) to detect crack in the beam. Bai et al. [21] eliminated natural inflexions of higher mode shapes by means of affine transformation. In order to avoid no conventional physical meaning of FD in damage identification, Li et al. [22] established the relationship between difference of angles of sliding windows and stiffness of beam. It should be noted that the KWD-based method is not suitable for two-dimensional (2D) structural damage identification. But Hadjileontiadis et al. [23] extended the FDCD [18] to 2D damage identification by partitioning thin plates into successive horizontal, vertical, and diagonal slices and then treating each slice as a beam for analysis. Obviously, the extended 2D FDCD method is still essentially a one-dimensional (1D) version algorithm for damage identification of plate-type structures. As a result, there is a need to develop non-baseline, mode shape-based two-dimensional fractal dimension (2D-FD) damage identification methods for plate-type structures.

To achieve such a goal, a new surface fractal dimension, termed edge perimeter dimension (EPD), is formulated, from which an EPD-based window dimension locus (EPD-WDL) modal irregularity identification algorithm is established for damage localization and quantification in plates, particularly with notch-type damage. The rest of the paper is organized as follows. An analytical notched plate model for simply-supported plates with a single notch derived from Heaviside step function is presented in Section 2, in which a panorama containing possible notch is provided. A new surface fractal dimension called the edge perimeter dimension (EPD) and an EPD-based window dimension locus (EPD-WDL) modal irregularity recognition algorithm for damage identification of plate-type structures are proposed in Section 3. In Section 4, the proposed EPD-WDL algorithm for damage identification is thoroughly examined using the analytical model given in Section 2. Effectiveness and applicability of damage identification algorithm are illustrated by an experimental testing of a notched aluminum alloy plate using a measurement system of piezoelectric lead-zirconate (PZT) actuator and scanning laser Doppler vibrometer (SLDV) in Section 5. Finally, the concluding remarks are given in Section 6.

2. Analytical notched plate model

2.1. Free vibration of notched plates simply supported at all edges

Free vibration of a plate with simply-supported boundary of length $L_x \times$ width $L_y \times$ thickness h_0 with a notch defect at (x_D, y_D) as shown in Fig. 1 is considered. Dynamic behavior of locally-notched plates can be formulated from the general equation of motion for plates of variable thickness by Leissa [24]: