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Journal of Sound and Vibration 285 (2005) 365–390
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Damage detection of mono-coupled periodic structures based on sensitivity analysis of modal parameters

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Received 6 October 2003; received in revised form 10 March 2004; accepted 26 August 2004
Available online 23 November 2004

Abstract

A sensitivity-based method for localization and assessment of damage in mono-coupled periodic structures is presented in this paper, in which slopes and curvatures of mode shapes are used to localize damage, and natural frequencies are then utilized to quantify the damage. The expressions of sensitivity coefficients of mode shapes, slopes, and curvatures of a mono-coupled periodic system are first derived in terms of receptances of periodic element. A mono-coupled periodic spring-mass system with 10 degrees of freedom is used to carry out a sensitivity study to compare the sensitivities of natural frequencies, mode shapes, slopes, and curvatures to damage. The results show that the sensitivities of these modal parameters in a mono-coupled periodic structure do not depend on the structural parameters, and therefore there is no need for a prior analytical model of the structure. The study also demonstrates that among these modal parameters, curvatures of modal shapes are most sensitive but slopes of mode shapes seem to be more indicative of damage location. A 20-element mono-coupled periodic spring-mass system is adopted to demonstrate the capacity of the proposed method to localize and quantify damages in the mono-coupled periodic system. Finally, a 3-storey near mono-coupled periodic experimental building is used to verify the actual application of the proposed method in consideration of the influence of measurement noise and non-perfect periodicity of actual engineering structures. Numerical and experimental results illustrate that only using a few lower modes with or without noise pollution can accurately detect damages in a mono-coupled periodic or a near mono-coupled periodic structure, either single or multiple damage locations and slight or severe damages.

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2004.08.012

1. Introduction

In civil engineering structures, it has already been accepted that damage, either local or global, can be observed through changes in dynamic characteristics: natural frequencies, modal damping ratios, mode shapes and their derivatives [1]. This makes vibration-based damage detection techniques attractive in civil engineering applications. Since modal shapes and their derivatives such as slopes and curvatures provide local information of structures, a variety of damage localization methods based on the changes in mode shapes and mode shape derivatives were developed [2]. Shi and Law used incomplete mode shapes to locate the damage of a 31 bar truss structure [3]. Abdo and Hori clarified the relationship between damage characteristics and changes in the rotation of mode shape and found that the rotation of mode shape is promising in detecting and locating damage in structures [4]. Wahab [5], among others [6], demonstrated the use of changes in the curvature mode shape to detect and locate damage in a real bridge and found that the curvature mode shapes are highly sensitive to damage. Wolf and Richardson [7] found that both the modal assurance criterion (MAC) and the coordinate modal assurance criterion (COMAC) were not sensitive enough to detect damage in its earlier stages. Ndambi et al. [8] conducted a comparative study between the use of natural frequencies and mode shape derivatives for damage assessment in reinforced concrete beams. They found that frequencies are affected by accumulation of cracks in the beams and are not influenced by the crack damage locations whereas the MAC and COMAC factors are less sensitive to crack damage compared to frequencies and the strain energy method appears to be more precise than the flexibility matrix method. All these studies showed that using mode shapes and mode shape derivatives could localize damages of structures under some circumstances. However, all methods discussed above require a baseline reference data to obtain the sensitivity coefficients, usually a prior finite element model of the structure in its undamaged condition, which poses a restriction on the applicability in some cases where the analytical model of the undamaged test structures is not available. Parloo et al. [9] presented a mode shape sensitivity-based method for the localization and assessment of damage in which the sensitivity coefficients make no use of the original analytical model. However, the exact sensitivities are calculated on the basis that all mode shapes of the intact structure should be available. In practice, only a limited number of modes can be measured, that is, an approximation of the sensitivities to some content has to be obtained instead.

Engineering structures including multi-storey buildings, elevated guideways for high-speed transportation vehicles (“Maglev” systems), multi-span bridges, chemical pipelines, stiffened plates and shells in aerospace and ship structures, space station structures and layered composite structures, can be considered as a periodic or a near periodic system. Zhu and Wu [10] discussed the sensitivity of natural frequencies to damages in a mono-coupled periodic structure. They found that the sensitivity of natural frequencies does not depend on the structural parameters, and therefore there is no need for the detailed structural parameters of the structures to obtain sensitivity coefficients of natural frequencies. To extend the work [10], the first objective of this paper is to derive the explicit expressions for mode shapes, slopes, and curvatures, consecutively, to obtain the sensitivities of these modal parameters to damages in mono-coupled periodic systems. A mono-coupled periodic spring-mass system with 10 degrees of freedom is then used to discuss and compare the sensitivities of different modal parameters, including natural frequencies, mode shapes, slopes, and curvatures, to damages and their capacity for damage localization. A