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Non-model-based damage identification of plates using principal, mean and Gaussian curvature mode shapes

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A B S T R A C T

Mode shapes have been extensively used to identify structural damage. This paper presents a new non-model-based method that uses principal, mean and Gaussian curvature mode shapes (CMSs) to identify damage in plates; the method is applicable to mode shapes associated with low and high elastic modes on dense and coarse measurement grids and robust against measurement noise. A multi-scale discrete differential-geometry scheme is proposed to calculate principal, mean and Gaussian CMSs associated with a mode shape of a plate, which can alleviate adverse effects of measurement noise on calculating the CMSs. Principal, mean and Gaussian CMSs of a damaged plate and those of an undamaged one are used to yield four curvature damage indices (CDIs), including Maximum-CDIs, Minimum-CDIs, Mean-CDIs and Gaussian-CDIs. Damage can be identified near regions with consistently higher values of the CDIs. It is shown that a mode shape of an undamaged plate can be well approximated using a polynomial of a properly determined order that fits a mode shape of a damaged one, provided that the undamaged plate has a smooth geometry and is made of material that has no stiffness and mass discontinuities. Fitting and convergence indices are introduced to quantify the level of approximation of a mode shape from a polynomial fit to that of a damaged plate and to determine the proper order of the polynomial fit, respectively. A weight function is applied to the proposed CDIs to alleviate adverse effects of measurement noise on the CDIs and manifest existence of damage in the CDIs. A mode shape of an aluminum plate with damage in the form of a machined thickness reduction area was measured to experimentally investigate effectiveness of the proposed CDIs in damage identification; the damage on the plate was successfully identified. The experimental damage identification results were numerically verified by applying the proposed method to the mode shape associated with the same mode as that of the measured one from a finite element model of the damaged plate.

1. Introduction

Vibration-based damage detection has been a major research topic of structural dynamics in the past few decades. Measured modal characteristics, such as natural frequencies and mode shapes, are processed in various methods for detecting, locating and characterizing damage in structures, since modal characteristics are related to physical properties of structures, such as mass,

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stiffness and damping, which can change due to damage. A method can be categorized as a model-based or non-model-based method; the difference between them is that the former requires use of an accurate model of a structure and the latter does not. A method that only requires a minimum amount of measured natural frequencies was developed to accurately detect locations and extent of damage in such structures as lightening masts [1,2], space frames [3] and pipelines [4]. It is model-based and requires an accurate physics-based model of a structure, and effectiveness of the method highly depends on accuracy of the model of the structure. However, it can be difficult to construct models of most structures that can accurately predict their natural frequencies before and after occurrence of damage.

Methods that use measured mode shapes to identify damage in a structure can be good alternatives. While effects of damage on natural frequencies are global, those on mode shapes are local; abrupt changes in mode shapes in the neighborhood of damage can be observed. A two-dimensional gapped smoothing method was developed based on a one-dimensional gapped smoothing method [5]. Curvature mode shapes (CMSs) and curvatures of operating deflection shapes were used in the two-dimensional method to identify damage in plates [6], where mode shapes of an undamaged plate were not needed. A gapped polynomial fitting the curvatures was used to eliminate global trends of CMSs and curvatures of operating deflection shapes at each measurement point. A method that used curvatures of frequency-shift surfaces of plates to identify damage was proposed in Ref. [7]; curvatures of frequency-shift surfaces of associated undamaged plates could be obtained using a technique of locally weighted regression. It was shown to be better than the two-dimensional gapped smoothing method, since a frequency-shift surface contained information of a squared mode shape. A CMS-based method

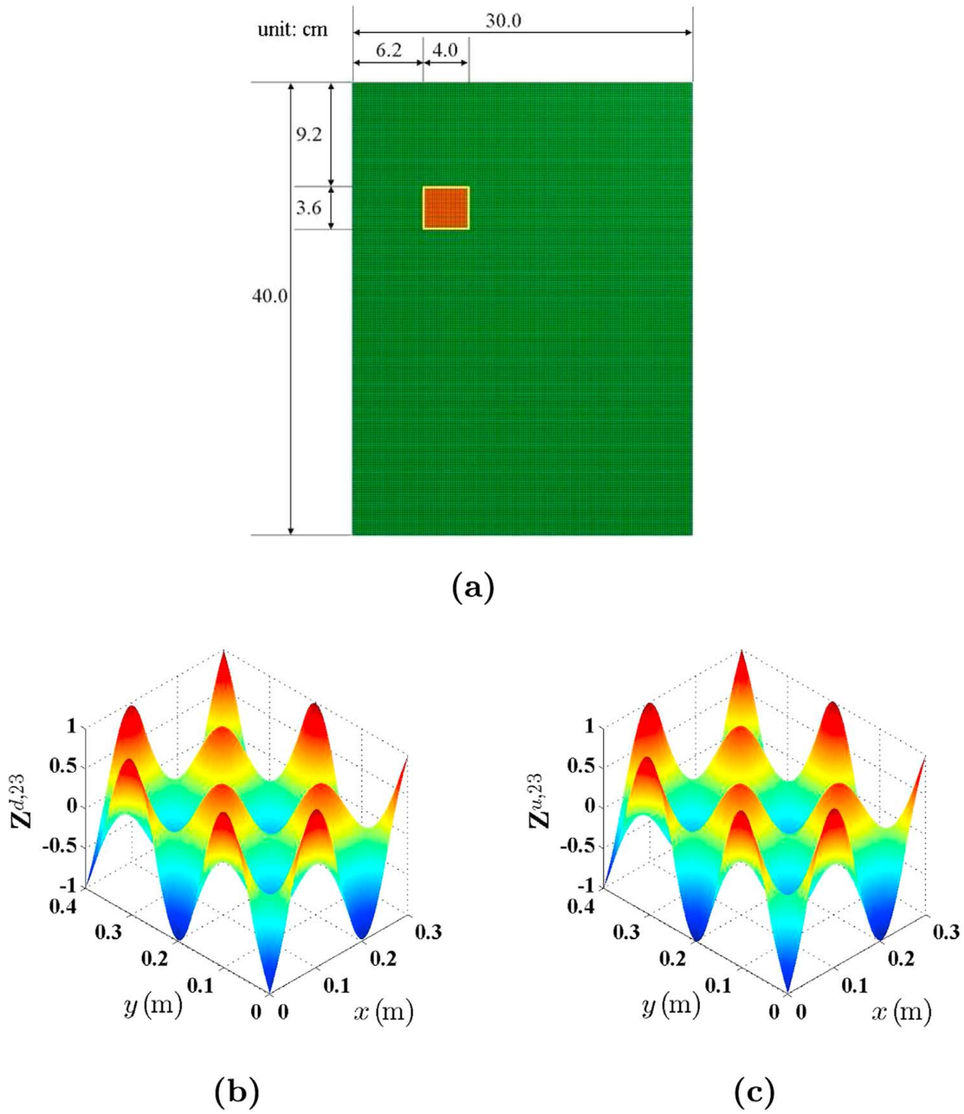

Fig. 1. (a) Finite element model of a plate with damage in the form of a thickness reduction area, (b) the 23-rd mode shape of the damaged plate and (c) the 23-rd mode shape of an undamaged plate of the same dimensions and material properties as the damaged one.