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Identification of multiple damage in beams based on robust curvature mode shapes

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ABSTRACT

Multiple damage identification in beams using curvature mode shape has become a research focus of increasing interest during the last few years. On this topic, most existing studies address the sensitivity of curvature mode shape to multiple damage. A noticeable deficiency of curvature mode shape, however, is its susceptibility to measurement noise, easily impairing its advantage of sensitivity to multiple damage. To overcome this drawback, the synergy between a wavelet transform (WT) and a Teager energy operator (TEO) is explored, with the aim of ameliorating the curvature mode shape. The improved curvature mode shape, termed the TEO-WT curvature mode shape, has inherent capabilities of immunity to noise and sensitivity to multiple damage. The efficacy of the TEO-WT curvature mode shape is analytically verified by identifying multiple cracks in cantilever beams, with particular emphasis on its ability to locate multiple damage in noisy conditions; the applicability of the proposed curvature mode shape is experimentally validated by detecting multiple fairly thin slots in steel beams with mode shapes acquired by a scanning laser vibrometer. The proposed curvature mode shape appears sensitive to multiple damage and robust against noise, and therefore is well suited to identification of multiple damage in beams in noisy environments.

1. Introduction

Structural damage detection has been widely discussed in mechanical, aerospace, civil and infrastructure fields in the literature [1–6]. Especially, vibration-based damage detection has become an active research topic in relatively recent years [7–12]. Furthermore, identification of multiple damage in beams relying on vibration characteristics has attracted much more attention from researchers due to the higher challenge and greater significance compared to single crack identification [13].

Representative investigations for identifying multiple damage in beams using vibration characteristics are as follows. Morassi and Rollo [14] presented a technique for detecting two cracks in beams relying on the changes of the first three natural frequencies. Patil and Maiti [15,16] developed a method for identifying multiple cracks in a beam using a transfer matrix method to simulate transverse vibration of the beam, with each crack modeled by a rotational spring. This method was further extended by Murigendrappa et al. [17] to multiple crack detection in long pipes containing fluid. Lee [18] and

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Kbiem and Lien [19] treated diagnosis of multiple cracks in a beam as a nonlinear optimization problem with the objective function involving variables of crack depths and locations. Singh and Tiwari [20] derived a damage indicator from a probability density function to characterize multiple cracks in shafts. Lin and Cheng [21] developed a frequency change index and used it to determine the depths of two cracks in beams. On the whole, these methods feature identification of multiple cracks by relating the crack locations and/or depths to the frequency characteristics of the beam under inspection.

In contrast with frequency characteristics, curvature mode shape, arising from the second order differentiation of the measured displacement mode shape, is a prevalent dynamic quantity for use in depicting cracks in beams [22–27]. Lin and Cheng [21] effectively utilized curvature mode shapes to detect double cracks in beams. Dawari and Vesmawala [28] employed the difference between a pair of curvature mode shapes (modal-curvature difference) for damaged and intact mode shapes to identify double cracks in beams. Abdel Wahab and De Roeck [29] identified multiple faults in a continuous beam by averaged modal-curvature difference arising from pairs of damaged and intact mode shapes. Sung et al. [30] explored the normalized curvature of a uniform load surface to reveal multiple damage in beam-like structures. In common, these methods favorably use the capability of curvature mode shape to locate multiple cracks in beams.

Despite the prevalence of their use, curvature mode shapes have a noticeable drawback of susceptibility to noise, caused by the second order differentiation of mode shapes. This differentiation can amplify slight noise present in a mode shape, usually producing a noise-dominated curvature mode shape [31] with obscured damage signature. Several researchers have attempted to tackle this problem from the perspective of optimal sampling interval [32] or signal processing [33–35], but no satisfactory solutions have been obtained. It will be important and advantageous to develop a regime that can overcome the drawback of curvature mode shape to provide a reliable multiple damage identification method. To that end, this study explores a regime to improve the curvature mode shape with the aim of overcoming the drawback of susceptibility to noise. The regime is based on the synergy of a Teager energy operator (TEO) and a wavelet transform (WT) in characterizing damage.

The rest of the paper is organized as follows. Section 2 addresses the complementary merits of the TEO and WT for damage characterization. Section 3 formulates the synergic mechanism of TEO and WT that gives rise to a TEO-WT curvature mode shape. Section 4 verifies the TEO-WT curvature mode shape in analytical cases of cantilever beam with multiple cracks. Section 5 experimentally validates the TEO-WT curvature mode shape using a steel beam with its mode shapes acquired by a scanning laser vibrometer (SLV). Finally, the study is summarized with conclusions in Section 6.

2. TEO and WT for damage detection

2.1. Basic definitions

2.1.1. TEO

The discrete version of the TEO was proposed by Kaiser [36,37] with the aim of calculating the instantaneous energy of a temporal signal. Let x_n be samples of a cosine signal, given by the following:

$$x_n = A\cos(\Omega n + \phi), \tag{1}$$

where A is the amplitude, Ω the digital frequency, ϕ the arbitrary initial phase, and n the temporal sampling point. The signal values at three successive points are

$$x_{n-1} = A\cos(\Omega(n-1)+\phi), \quad x_n = A\cos(\Omega n+\phi), \quad x_{n+1} = A\cos(\Omega(n+1)+\phi). \tag{2}$$

From the trigonometric identities, one can obtain

$$x_n^2 - x_{n-1}x_{n+1} = A^2\sin^2(\Omega). \tag{3}$$

As stated in [37], $E_n = x_n^2 - x_{n-1}x_{n+1}$ is defined as the Teager energy, a measure of the instantaneous energy of a temporal signal. From Eq. (3), it can be seen that the Teager energy of a harmonic is a particular constant $A^2\sin^2(\Omega)$ over its duration. Furthermore, when Ω is restricted to a small value that satisfies $\Omega \approx \sin(\Omega)$, the Teager energy can be approximated by $A^2\Omega^2$:

$$E_n = x_n^2 - x_{n-1}x_{n+1} = A^2\sin^2(\Omega) \approx A^2\Omega^2 \tag{4}$$

For a generalized discrete signal $f[n]$, not limited to a harmonic, the Teager energy can be calculated using the TEO defined by the following:

$$\Psi[f[n]] = f^2[n] - f[n-1]f[n+1]. \tag{5}$$

Unlike the usual usage of treating temporal signals, this study utilizes the TEO to process spatial signals with n referring to the spatial sampling point. For a spatial signal, the TEO gives rise to point-wise spatial energy instead of temporal instantaneous energy. Ideally, damage can cause a change in the point-wise spatial energy of structural spatial responses, in turn manifesting the location of the damage.