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Delamination detection by Multi-Level Wavelet Processing of Continuous Scanning Laser Doppler Vibrometry data

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ABSTRACT

A novel non-destructive testing procedure for delamination detection based on the exploitation of the simultaneous time and spatial sampling provided by Continuous Scanning Laser Doppler Vibrometry (CSLDV) and the feature extraction capability of Multi-Level wavelet-based processing is presented in this paper. The processing procedure consists in a multi-step approach. Once the optimal mother-wavelet is selected as the one maximizing the Energy to Shannon Entropy Ratio criterion among the mother-wavelet space, a pruning operation aiming at identifying the best combination of nodes inside the full-binary tree given by Wavelet Packet Decomposition (WPD) is performed. The pruning algorithm exploits, in double step way, a measure of the randomness of the point pattern distribution on the damage map space with an analysis of the energy concentration of the wavelet coefficients on those nodes provided by the first pruning operation. A combination of the point pattern distributions provided by each node of the ensemble node set from the pruning algorithm allows for setting a Damage Reliability Index associated to the final damage map. The effectiveness of the whole approach is proven on both simulated and real test cases. A sensitivity analysis related to the influence of noise on the CSLDV signal provided to the algorithm is also discussed, showing that the processing developed is robust enough to measurement noise. The method is promising: damages are well identified on different materials and for different damage-structure varieties.

1. Introduction

The assessment of the health condition of structures necessarily involves damage detection and localization approaches. When dealing with vibration-based techniques, Laser Doppler Vibrometry (LDV) has to be cited as one of the most used, mainly because its non-intrusiveness. Indeed, this has led to utilize LDV in several application fields [1], ranging from vibroacoustics [2,3,4], to non-contact modal analysis chains [5] and even to biomedical applications [6]. During the years, several attempts have been made for developing fast and reliable methods for guaranteeing a correct use of LDV in Non-Destructive Testing (NDT) and Structural Health Assessment applications. The work of Castellini et al. [7] represents an example of such. Lately, the frequency approach has been extended to time-domain methods based on high-frequency guided wave investigations, as reported by Staszewski [8]. Indeed, the low-to-medium frequency (modal range) approach and the high-frequency one (ultrasonic range) can be sequentially combined in a double-step NDT technique, as proposed by Sharma [9], in order to provide an indication of potential regions of damage at first and an accurate identification of the orientation and length of the damage later. The goal is achieved by exploiting modal parameter changes as damages indicators and the full wavefield image of propagating waves, which is obtained by Scanning Laser Doppler Vibrometry (SLDV) in discrete configuration, to detect and analyze transient waveforms propagating in the ultrasonic range, which are locally sensitive to damages. An interesting approach was also proposed by Rezaei in [10]. Rezaei proposed to use the Empirical Mode Decomposition (EMD) method to process vibration signal acquired by LDV on a pipe. Damaged pipes are identified on the basis of an energy comparison of the EMD generated signals for the damaged and healthy pipes.

It is now well recognized by the scientific community dealing with vibration measurements that the presence of damages, which modify the modal behavior of the structure under analysis, can be assessed by LDV also in Continuous Scanning (CSLDV) [11] mode. When exploiting CSLDV the Operational Deflection Shapes (ODSs) of a structure can be recovered from a single time history acquired by the laser Doppler vibrometer while the laser beam scans, in a continuous way, all over the

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target vibrating surface. With respect to Discrete Scanning LDV, CSLDV presents the following advantages:

- an extremely high spatial resolution is guaranteed,
- the data structure is compact (e.g. a single time history contains both time and spatial information),
- the experiment is limited in terms of duration (e.g. acquisition time only depends on the required frequency resolution).

These characteristics have allowed for the use of CSLDV in different applications with respect to Experimental Modal Analysis (EMA) and vibration analysis. An example for machinery noise control problems is reported in [12]. Since the ODSs excited during the experiment cause an amplitude modulation on the velocity signal when CSLDV is used to perform a vibration measurement, this particular aspect can be exploited for damage detection in structural health assessment tests. Indeed, Stanbridge et al. [13,14] demonstrated the effectiveness of using CSLDV for detecting cracks when the crack produces a localized mode shape discontinuity. They proposed the use of a standard demodulation technique, i.e. multiplying in Hadamard sense the digitized CSLDV signal by a sine wave at the excitation frequency, and passing the result through a low-pass filter to extract the mode shape discontinuity. A similar approach was proposed by Di Maio in [15]. This approach, however, has two main drawbacks:

- the choice of the low pass-filter cut-off frequency might seriously affect the possibility of locating a discontinuity in the mode shape;
- several trials should be performed in order to identify the best-case scenario that is able to highlight the defect. This happens, for instance, when the defect is located on a nodal line for certain mode shapes: demodulation cannot recover the presence of the defect.

The idea of using wavelet processing of a CSLDV vibration signal for damage detection has come up because wavelets have been intensively investigated in the last decade for structural health assessment [16,17,18]. Cao et al. [19] also proposed to use wavelet processing on mode shapes extracted by SLDV. However, the efficiency of wavelet processing in extracting the damage information (either from the modal curvature or from a discontinuity in the mode shape) is strongly dependent on the dimension of the damage with respect to the spatial sampling used in the experiment. CSLDV overcomes these limits, since it provides a single time history that inherently contains the ODSs information with an almost infinite spatial resolution.

For these reasons Chiariotti et al. proposed a novel approach that exploits Wavelet-domain processing to extract features related to the damage in the CSLDV signal [20,21]. They suggested exploiting the Wavelet Packet Decomposition method and a dedicated thresholding procedure on the decomposed CSLDV signal to extract spatial information on the location of the damage. The link between temporal and spatial data is provided by the mirror signals driving the laser spot over the target surface during the scan. The approach proposed by Chiariotti et al. grounds on two main assumptions:

- A vibration signal acquired by CSLDV is amplitude-modulated by the ODSs excited during the vibration test.
- Since the laser spot continuously scans the surface of the test specimen, the possibility of passing on a damaged area is highly realistic. For instance, the presence of a crack on the structure can introduce discontinuities on certain mode shapes, as well as other complex phenomena linked to the interaction of the laser light with the damage edges. Diffraction, speckle noise in the optical signal coming back to the detector active area and eventually signal drop-outs (depending on the extension of the crack in the scan direction) are just few examples of these phenomena. The modulating signal will therefore reflect the discontinuity the more, the more relevant is the damage. Speckle noise, which naturally affects CSLDV [22], has also to be taken into account. However, while the latter is periodic in nature and strongly related to the scan frequency, the phenomena related to light-damage interaction, e.g. for superficial damages, are still periodic but dependent on the transits of the laser spot over the damage. Similar phenomena take place for sub-surface damages: either local distortions of mode shapes or local modes of the damaged area can be introduced. In both cases, the amplitude modulation phenomenon produced by the vibrating structure on the CSLDV signal will carry these distortions.

These holding, a proper processing can reveal the damage-related information and thus can help in identifying the damage location. Wavelet-processing is the best candidate for enhancing these discontinuities, which are introduced by the presence of a damage, in the signal and for localizing them in time and spatial domains. The wavelet-based processing is also less sensitive to measurement noise with respect to standard demodulation, since this noise, which is generally Gaussian in nature, is uniformly spread throughout the wavelet space.

This paper aims at presenting a substantial evolution of the approach described in [20,21] by introducing a Multi-Level Basis Selection (MLBS) procedure that makes the whole technique fully automated. Moreover, the combination of information collected on different nodes of the Wavelet Packet Decomposition (WPD) tree gives the method higher robustness than the single-node one previously proposed to the scientific community. The algorithm for MLBS exploits a double step node-selection approach: the first is based on an entropy analysis on the maps of potential damage, which are given as output at each node of the WPD tree, while the latter performs an energy analysis on the wavelet coefficients of the residual nodes to identify those nodes that carry the damage information. By properly combining maps belonging to the final nodes distribution a more robust localization of the damage is obtained and a Damage Reliability Index (DRI) can be introduced.

The paper is thus organized as follows: Section 2 presents the Damage Detection procedure proposed; Section 3 reports results both from virtual and real test cases characterized by sub-surface damages. The main conclusions are summarized in Section 4.

2. Methods

A sub-surface damage in a structure can be recognized by a vibration-based technique in frequency domain if either a global mode is deformed by the damage or a local mode of the damaged area is excited. This approach therefore requires a detailed analysis of different frequency ranges either in terms of the modal content or in a *rms* (root mean square) based fashion (see [7,23]). When working with CSLDV, the damage information content is implicitly carried by the amplitude modulation effect that characterizes the CSLDV signal, and since the damage can influence global and local modes there can be discontinuities in the modulating signal. This has a fundamental implication: indeed the damage information, which is hidden in such discontinuities, can be spread in frequency ranges that differ from those where the modes take place. Wavelet-based processing, and in particular Wavelet Packet Decomposition (WPD) [24], since it produces a full binary-tree, thus results in a well suited method to identify these discontinuities and therefore to spatially locate the damage.

The algorithm proposed by the authors in this paper consists in four main steps:

i. Pre-processing step, where a normalization of the CSLDV signal is performed;
ii. WPD processing step, where the signal is decomposed using WPD and properly thresholded to extract the damage information on each node of the wavelet packet tree;
iii. MLBS step, where selection of those nodes of the decomposition tree that actually carry the damage information are selected from the