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Mode matching of Continuous Scanning Laser Doppler Vibration data in the frequency domain

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ABSTRACT

Applications as structural diagnostics, condition monitoring and fatigue testing are requiring the development of vibration tests characterized by reduced testing time, fine spatial resolution and high Signal to Noise Ratio (SNR). In this context, Continuous Scanning Laser Doppler Vibrometry (CSLDV) can have a great impact as a substitute of classic Discrete Scanning Laser Doppler Vibrometry (SLDV). In fact, CSLDV makes it possible to measure the target structural vibration much faster and with finer spatial resolution than SLDV, as well keeping an acceptable level of SNR. CSLDV joins together the spatial and time information, because the vibration datum obtained from the laser, which continuously scans (over time and space) the structure under test, is modulated by the Operational Deflection Shape (ODS) excited during the experiment. This results in a spectrum characterized by sideband patterns uniquely associated to the ODS excited. However, the current drawback in fully exploiting CSLDV in everyday testing is related to the necessity of being managed by an expert operator who knows how to extract meaningful information from data measured. This paper proposes a procedure which aims to automatize the information extraction process from CSLDV signals, in order to ease the utilization of CSLDV in vibration laboratories. The idea starts from a simple observation: if the mode shapes of the structure under test are known a priori, e.g. from a numerical model, an analytical formulation or previous measurements, as is the case for fatigue tests, it is possible to settle a procedure that searches for similarities between those known mode shapes (the candidate mode shapes) and ODSs that actually modulate the signal measured. This procedure can therefore be considered a pattern matching technique that is able to identify the resonance frequency related to each ODS and the mode shapes that better match with the ODSs excited. A detailed description of the algorithm is given in this paper. Moreover, the procedure is analyzed in order to discuss its sensitivity to noise, overlapping of resonance frequencies (close modes situation) and ODS complexity. The application of the approach to experimental data is also discussed.

1. Introduction

Speeding up the testing time and keeping a fine spatial resolution are becoming key requirements in vibration-based tests for applications like structural diagnostics, condition monitoring and fatigue testing. Moreover, very often, in these applications, the processing method relies on the comparison between an a-priori status of the target structure (e.g. the undamaged status) and the current one, so to associate any deviation to a structural modification (e.g. thus indicating the presence of a damage). Discrete Scanning Laser Doppler Vibrometry (SLDV) has been used a lot for this purpose during the last ten years, since it gives the possibility to analyze a structure contact-less, with a very fine spatial resolution and keeping a high Signal to Noise Ratio (SNR). In Discrete SLDV the laser spot is steered on a point of the target surface by exploiting automated mirrors; the measurement is performed on that point and then the laser is moved to another point. This process repeats until a scan over the target area is completed. Testing time is therefore related to the spatial resolution (spatial distance between two consecutive points) with respect to the area to be scanned. This is the main drawback of the approach. Indeed, if an extremely fine spatial resolution is sought, testing time can increase exponentially, and the structure itself can modify its behavior during the test duration.

The Continuous Scanning Laser Doppler Vibrometry (CSLDV) method entered in the vibration testing measurement community as an alternative to conventional Discrete Scanning Laser Doppler Vibrometry (SLDV). Its main appeal is related to the reduced testing time, since the laser spot is continuously moved over the target surface while acquiring vibration data. This makes it possible to collect time and spatial data simultaneously, utilizing a spatial resolution that depends on the sampling frequency adopted during the measurement. Original efforts in

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CSLDV relate to experiments by Sriram et al. [1] in extracting Frequency Response Functions using broadband excitation and synchronous sampling at the laser scan speed. However, the major contributions to the development of this measurement technique are due to Stanbridge et al. [2,3], who proposed to extract mode shapes exploiting the amplitude modulation effect induced by the ODS of the structure on the time vibration signal collected when the laser scans continuously (at scan rates independent to the sampling frequency) the target surface. Initially, this method was proposed for near-resonance excitation conditions, e.g. step sine testing, with the drawback of being quite time demanding. Over the years several researchers have kept working on CSLDV for extracting ODS, highlighting its good performances even in case of broadband excitation, e.g. impact testing [4], broadband [5] and operational excitation [6,7]. Different approaches have been developed, as the lifting approach proposed by Allen [8–10], which exploits high scanning rates to rearrange data collected at each point along the scan path as they were measured in Discrete Scanning mode. Alternative use of CSLDV can be cited for vibro-acoustic applications [11], damage detection [12], moving targets [13] and biomedical applications [14]. A multi-beam CSLDV approach was also proposed by Aranchuk et al. [15] for land-mine detection.

The key feature of a CSLDV measurement is that the time history acquired appears as an amplitude modulated signal, whose modulation is due to the Operational Deflection Shapes excited. As suggested by Ewins et al., an ODS can be modeled by a polynomial, whose coefficients are directly related to the sidebands that characterize the vibration spectrum of the CSLDV signal. The sidebands around the resonance frequency of a specific ODS are spaced by the laser beam scanning frequency, while the number of sidebands are directly related to the ODS spatial complexity. Conventionally, the recognition of resonance frequencies and the recovery of ODSs in the processing of CSLDV data are performed starting from the observation of the CSLDV output spectrum. This process has obviously to be performed by an expert experimenter used to treat with CSLDV data. Some years ago Chiariotti et al. [16] presented a new philosophy for CSLDV data processing that reverses this approach. Indeed, their *mode-matching processing* starts form this observation: if a specific ODS produces a unique sideband pattern, then the identification of that pattern within the CSLDV spectrum, in a pattern matching-like approach, proves that the same ODS was excited during the test. It is then possible to create a set of sideband patterns starting from a set of ODSs (e.g. obtained theoretically, numerically, experimentally, etc.) and look for those patterns within the CSLDV spectrum. Those patterns that are recovered in the spectrum correspond to the candidate shapes that better match with the ODSs that effectively modulate the CSLDV signal. The procedure, therefore, does not extract neither ODSs nor mode shapes, but indicates which ODSs, among those excited, best resemble those constituting the set of candidate shapes. In this sense, it is not inappropriate to state that the candidate shapes can be both mode shapes (e.g. obtained analytically or numerically) and ODSs (e.g. obtained experimentally from previous measurements, as it can happen in fatigue testing).

The implication of this approach on applications such as condition monitoring/diagnostics, fatigue testing, etc. is straightforward. Indeed, if a structure undergoes to structural modification because of the presence of a damage/defect, the approach can be exploited to check whether the sideband patterns of the undamaged target are still present in the CSLDV vibration spectrum. Any fail in identifying the patterns associated to the undamaged structure might suggest a structural modification. The advantage with respect to a classic Discrete SLDV approach, where modal variations are looked for, is in the possibility to carry on the test in a much shorter time improving the spatial resolution, as well keeping an acceptable level of SNR. The spatial resolution aspect is particularly important, since a finer spatial resolution increases the probability to get vibration data over the damaged area.

The paper is organized as follows: Section 2 describes the proposed method. Section 3 aims to discuss the sensitivity of the approach to the three phenomena that mainly interfere with a correct identification of the patterns, i.e. Signal to Noise Ratio (SNR), sideband spectra overlapping and ODS complexity. Section 4 describes the results obtained when utilizing the approach on real test cases, while Section 5 draws the main conclusions of the work.

2. Mode matching procedure in frequency domain

The aim of the method proposed in this paper is to exploit an a-priori knowledge of mode shapes or ODSs, which can be known from any other approach such as numerical, analytical models, previous experimental testing, etc., to create a set of virtual sideband patterns to be looked for in the CSLDV spectrum. Those virtual patterns that best match with those effectively present in the CSLDV spectrum make the labeling of modes and ODSs possible. In practice, this technique emulates and reverses what an expert experimenter usually does when analyzing CSLDV data. Indeed, the experimenter looks for a sideband pattern in the CSLDV spectrum and recovers the ODS from this pattern. The proposed approach starts with the creation of a database in which each mode shape/ODS is identified as a sideband pattern. Once this data base is created, a pattern matching procedure in the CSLDV spectrum is started. In such a way, the pattern that best matches within the CSLDV spectrum indicates that an ODS, similar to the corresponding mode shape/ODS that produced that pattern, was excited during the test. The output of the procedure consists of:

- the resonance frequencies corresponding to the central frequencies of the sideband pattern better matching with the candidate ones,
- a set of mode shapes that best matches with the ODSs that effectively modulate the CSLDV signal measured.

A clarification is needed. This mode matching procedure makes it possible to identify the candidate shapes that better match with those ODSs that effectively modulate the CSLDV signal. This procedure does not extract neither ODSs nor mode shapes, it identifies and labels which ODSs, among those excited, best resemble those constituting the initial data base. In this sense, it is not inappropriate to state that the shapes populating the initial database can be both mode shapes (e.g. obtained analytically or numerically) and ODSs (e.g. experimentally obtained).

A detailed description of the mode matching procedure is reported hereafter.

2.1. Step1: CSLDV data collection

The first step of the approach consists in collecting vibration data utilizing CSLDV. The laser spot is moved continuously along the whole length of the target (any kind of scan path can be exploited) and the vibration velocity of the target is measured. As a result of this continuous movement of the laser spot, the vibration time history ($v_z(t)$) is amplitude modulated by the ODSs excited.

2.2. Step 2: creation of shapes database

A database containing mode shapes/ODSs is created. These shapes can be calculated analytically or via numerical models (e.g. FE models), can be the result of a model updating procedure, or can be arbitrarily picked from previous experiments on the same structure (e.g. as it can happen in fatigue testing or in structural diagnostics). Just to make an example, if we are experimentally dealing with a clamped-free beam, the mode shapes filling the shapes database can be defined analytically using the formulation proposed in [19]:

$$X_i = \left[cosh\left(\lambda_i \frac{x}{L}\right) - cos\left(\lambda_i \frac{x}{L}\right)\right] - \sigma_i\left[sinh\left(\lambda_i \frac{x}{L}\right) - sin\left(\lambda_i \frac{x}{L}\right)\right] \quad (1)$$

where x is the coordinate position along the beam length L, while λ_i and σ_i are the non-dimensional frequency amplitude parameters. Moreover, since the actual constraint of a structure can be partially known or even unknown, it is plausible to insert, in the shapes database, modes that are obtained with different types of constraints (e.g. pinned-free, etc.).