Mechanical Systems and Signal Processing 156 (2021) 107573

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Continuous Scanning Laser Vibrometry: A raison d'être and applications to vibration measurements

D. Di Maio [a,*], P. Castellini [b], M. Martarelli [b], S. Rothberg [c], M.S. Allen [d], W.D. Zhu [e], D.J. Ewins [f]

[a] University of Twente, the Netherlands
[b] Universitá Politecnica delle Marche, Italy
[c] Loughborough University, UK
[d] University of Wisconsin-Madison, United States
[e] University of Maryland Baltimore County, United States
[f] Imperial College London, UK

ARTICLE INFO

Article history:
Received 16 September 2020
Received in revised form 22 December 2020
Accepted 23 December 2020
Available online 12 February 2021

Keywords:
Continuous scanning
CSLDV
SLDV
Vibrations

ABSTRACT

Continuous Scanning Laser Doppler Vibrometry (CSLDV) methods first appeared in the literature in the early 1990s and over the past three decades they have undergone an evolution in terms of procedures and applications which constitute a new state-of-the-art now described in this review paper. The advances in vibration measurement performed by Scanning Laser Doppler Vibrometers augmented the capability of measuring vibration data from a grid of a few hundred measurement points to a single scan which traverses and measures at many thousands of points on the same structure. The deflection shapes of vibration modes can be created by assembling two pieces of information from a scanning measurement - temporal and spatial - and the more measurement 'points', the better the spatial density and resolution of the deflection shape(s). The introduction of Continuous Scanning techniques challenged the traditional principle that the number of measurement points defines the spatial definition of the deflection shape. Thereafter, high definition deflection shapes could be achieved by measuring a single time series from a continuously sweeping trajectory covering the same surface area that would traditionally be covered by a set of fixed-point measurements, each of which spans a range of frequencies. The CSLDV approach compresses both the temporal oscillation and the spatial distribution of the deflection shape into one LDV output-modulated signal, whereby the harmonic oscillation and the spatial distribution across a swept area were now defined by a central response harmonic and its sidebands. This change of perspective in vibration measurements from the conventional stepped-scan method to the continuous-scan approach allowed several researchers to exploit and expand the potential of the scanning vibrometer further than its initial design specifications. This paper starts with the raison d'être, with a brief historical account of how vibration measurements have developed over the past decades, and then moves to the theoretical background and applications of the CSLDV approach. Finally, the paper presents a philosophical and technical account of the research work carried out by several colleagues over the past thirty years and aims to provide a chronological order to the various advancements that CSLDV techniques offer in engineering structural dynamics.

* Corresponding author at: Faculty of Engineering Technology, Applied Mechanics group, Building The Horst - HR N148, P.O. Box 217, 7500 AE Enschede, the Netherlands.

E-mail address: d.dimaio@utwente.nl (D. Di Maio).

https://doi.org/10.1016/j.ymssp.2020.107573
0888-3270/

Contents

1. Introduction

To those who might be interested in vibration measurements by scanning laser Doppler vibrometer (SLDV), this is a review about Continuous Scanning LDV measurement method and applications. Before we shall proceed, the authors wish to point interested readers to Rothberg et al.'s most recent review paper on the SLDV measurement technology [1].

The following paragraph will recall the significant steps in the development and use of the SLDV system. Optical measurements based on laser light and the Doppler frequency shift principle were seen for the first time in the late 60ies [2] when it was developed as a single point laser measurement. It took several years before the Laser Doppler velocimeter was then built as scanning laser Doppler vibrometer known as SOVAS [3] for vibration testing. The major innovation was a set of two scanning mirrors introduced in front of the laser head to divert the laser beam in both X- and Y directions on the target measurement point. The integration of a video camera augmented the system's capacity to create a measurement grid on a target test structure. The measurement points of a generated grid are not measured at once, but one after another by stepping them in an order optimized for the X-Y scanning mirrors (one can notice this while the SLDV performs a test). The laser light of the LDVs is a Helium-Neon laser, with the modern versions using a new infrared laser light which improves the Signal-To-Noise Ratio; the lasers are eye-safe and, therefore, pose no health hazard. The SLDV can scan a nearly endless number of measurement points providing a high-definition spatial resolution of the deflection shape without creating mass loading, which the same number of accelerometers would have had on the structure system response. The SLDV is not the only non-contact optical-based method, and some references are also provided for alternative optical methods such as shearography [4], holography [5] and Electronic Speckle Pattern Interferometry (ESPI) [6–10] which were also used for vibration measurements.

Those methods are complementary to the SLDV technology and some times more advantageous than the SLDV technology when dealing with transient response analysis because the whole target surface can be measured at once.

The SLDV also presented some limitations as the noise caused by speckle interference, optical access and curvature of the geometry because of the LDV measures along the line of sight of the laser beam. Some of those limitations were eventually overcome using the infrared laser light and the adoption of two other scanning heads to achieve the three-dimension scanning LDV system. This short briefing shall not discuss the pros and cons of the SLDV, but the authors suggest the following references [11–13] which report details about developments, method and applications very extensively. Furthermore, some useful insights about how the SLDV performs against another optical technique known as Digital Image Correlation (DIC) can be found in [14,15].

The SLDV measurement system has definitively provided a tool for investigating vibration responses in the field of engineering and several other ones. The scanning mirrors can be considered the primary enabler of the LDV measurement system's success, which could be further developed when the laser beam was scanned continuously rather than in stepped mode.

- How is the continuous scanning achieved as opposed to the stepped method?

In both cases, the scanning mirrors are driven by voltages which can be either constant (DC) or alternating (AC) amplitudes. The DC input to the scanner moves the mirrors to a specific and fixed location. The AC input is a continuous sinewave which oscillates the mirrors between a maximum and minimum, the same sinewave to the X-Y mirrors creates a 45-degree angle straight-line [16].

- Why is continuous scanning a"more elegant" measurement technique than the stepped method?

We shall use this simple example. Assume that one performs the so-called Fast-scan ODS measurement, which is the acquisition of a deflection shape at the excitation force's tone. The deflection shape spatial resolution depends on the number of acquisition points, and so the more the points, the better the definition. However, by performing a crude FFT analysis of the deflection shape, one would immediately recognize that no matter the number of acquisition points, there is always a unique set of measurement points required to define a deflection shape. The number of FFT coefficients can be related to the minimum number of measurement points necessary to measure that shape. The challenge is that no one knows how many measurement points make a set of references and where those measurement points should be on the test structure, thus resulting in acquisition waste of time.

The basic principle explained in the paragraph above was an intuition researched in [17–19], where Hanagud, Sriram and Craig worked early experiments on the Continuous Scanning method applied to structural dynamics. In particular, Sriram explained very well the convenience and elegance of the method in the following statement "*When the LDV sensor is scanned over the line of interest, the spatial variation of velocity is transformed into a temporal variation of the velocity signal, depending on the form of the scan. It is convenient to analyse the velocity signal $v(t)$ in the frequency domain* [18]". Both spatial (as shape) and temporal (as oscillation) data conjugate in one single time series that can be processed at once.

Although the early reference attributes the novelty of the method to Hanagud et al., we shall also remember that the past Mr A.B Stanbridge, who worked at Rolls-Royce until late 80′s, attempted the measurement of the vibration modes of bladed discs by using contactless microphones. The microphone, set up on a gramophone, continuously scanned a circle over a vibrating disc (stationary) and measured an amplitude modulated time history. That response signal could be resolved in two frequency sidebands the spacing of which identified the nodal diameter mode of the disc. Stanbridge was not interested in any publication at the time he worked at Rolls-Royce, and private conversation revealed his early attempts on this matter. Stanbridge et al. also authored a review on CSLDV at ISMA conference [20].

To conclude, the continuous scanning LDV method allowed finding the polynomial coefficients describing a deflection shape in a matter of seconds because the laser beam continuously scans the target surface while the acquisition system records an amplitude-modulated LDV output signal. The change of perspective using the SLDV from stepped to continuous was initially considered very useful in the modal analysis research context. One could obtain resonances and shapes in a shorter time than ever done before with accelerometers, thus enabling, for instance, better model validation/updating processes. This manuscript is built in two parts: a "raison d'être" and a review exclusively focused on the developments carried out on the Continuous Scanning methods and its applications. The first part shall suit better young practitioners to understand how (i) the SLDV improved vibration measurements and (ii) the CSLDV created straightforward access to shape order from a single LDV time history. The second part shall provide a chronological account of the theory, methods and applications developed over the past two decades by many authors on the CSLDV research topic.

2. A brief history of vibration measurements (1960–2020) and the raison d'être of vibration measurements today

There has always been a need for measuring the vibration of engineering structures, primarily because of the deleterious effects of vibration on their integrity. In the early days, a measurement was the only option to understand how structures were vibrating in service. Simple analytical models began to be used in the 1960s, but detailed measurements were still required to complement these models where they were inadequate. This was the era of mechanical impedance (experimental) and receptance (analytical) methods which were the precursors to the FRFs (Frequency Response Function) and modal analysis techniques of today. These were the earliest applications of combining experimental and theoretical vibration data and the realisation that not only was the accuracy of measured data an important feature but so also was the correct choice of which quantities had to be measured: early signs of awareness of epistemic as well as aleatoric uncertainty in measurements.

In the early 1970s, the introduction and widespread availability of the FFT-based Fourier analysis capabilities transformed vibration measurement capabilities by providing easy access to relatively large amounts of data. This, in turn, led on to the current technologies of modal testing and analysis. Parallel to these experimental developments, finite element modelling was becoming much more accessible and powerful, but it was already realised that, as these models improved, so also did expectations rise and so recourse was routinely made to measurements for confirmation of the 'correct' values for the vibration characteristics of greatest interest. This approach evolved through the 1980s to the 1990s and led to the development of systematic procedures for model validation using a combination of analytical models and experimental measurements to validate models for design optimisation. These models could also be used for structural monitoring and diagnostics so that both Test and Analysis played equal roles in managing both design and in-service vibration conditions. Indeed, today we talk of a Fusion of Test and Analysis [21] as being the most powerful approach to assuring Structural Performance which matches the Functional Performance of most advanced structures, vehicle and machines. This means that there is an enduring future for the most accurate and cost-effective vibration measurement technologies. This paper explores the significant role which Continuous Scanning Laser Doppler Vibrometry can play in this arena.

2.1. What types of vibration measurement are required/possible?

2.1.1. Vibration parameters

In structural dynamics, the parameters which are used to describe the vibration characteristics in both spatial and temporal domains include:

a) spatial properties of mass, stiffness and damping distributions in space
b) modal properties of natural frequencies, mode shapes and damping factors
c) temporal response levels generated by external excitation forces.

The most important of these, from the perspective of the immediate consequences for the integrity of the vibrating structure, are the response levels (deflections, stresses….) as they are the most closely linked to structural performance. Next are the spatial properties because it is these that we need to be able to modify to change the design in order to achieve acceptable levels of response. The intermediate modal parameters are very useful to explain how and why the response levels are what they are, and to indicate what spatial parameter changes might be most effective to reduce vibration response levels. They provide a means for the two physical models to communicate with each other.

2.1.2. The alternative data sets

It is useful to consider the size of the data sets which are associated with each of these three categories of information. The **spatial data set** is usually very large because in most cases it is based on a finite element model which will typically have N DOFs (N, typically, being in the 1000s or millions) and will consist of 2 NxN matrices[1] containing the individual mass, stiffness and damping elements. The **response data set** will consist of a family of response plots, invariably measured as time histories but usually presented as frequency spectra, and often as frequency response functions (which are ratios of two spectra). A full set of these will be contained in an NxN matrix of FRFs. However, unlike the spatial property matrices, each element in the FRF response matrix will be defined at a (large) number of individual frequencies – typically, 2000 or 4000 different frequencies. Thus, the response property data set will contain many more individual items of data than the spatial data set. The reason for this is that the FRF data sets are heavily overdetermined. The **modal data set** is, in theory, the same size as the spatial information – i.e. contained in 2 NxN matrices - but there is an important characteristic which applies in most practical situations and which allows the modal data set to be drastically reduced in quantity while incurring negligible errors in the relevant information about the structures vibration behaviour in practice. This useful characteristic is the fact that many – if not most - of the modes of vibration will have natural frequencies that are higher than the working frequency range (i.e. the range in which there exist excitation forces). As a result, these high modes cannot be excited in practice and so can be eliminated from the data set. This means that the spatial data set is by far the most economical of the three alternatives.

However, in practice, we have little choice over which format we shall use in measurements because the only option is response. We cannot measure mass and stiffness distributions, and we cannot measure modes explicitly. All we can measure is response time histories and/or frequency spectra, and we must find ways to transform these data into the more

[1] It should be noted that this simple explanation does not mention the considerable complications of including damping, but suffice it to say that in the undamped cases all the data are real; when damping is included, the data become complex.

economical modal format. This is routinely undertaken through modal analysis – where we extract the properties of the individual modes, by determining their individual contributions to the total response.

2.1.3. Vibration measurement strategies

We are always looking for improved vibration measurement methods to provide us with the information we need, and that includes the modal properties in many situations. Here we explore the prospects of a relatively new measurement technique using the Continuous Scanning Laser Doppler Vibrometer device, and we shall seek to devise highly effective measurement procedures for determining the key vibration properties of practical structures. We shall, in particular, devise particularly efficient methods which means finding ways of measuring the minimum amount of data necessary to deliver the information that is required. This is a change from traditional practice where it is often the case that we measure many 1000s of times more data than are strictly necessary, taking into account the underlying order of other vibration behaviour characteristics.

2.1.4. Response data

We know that if we measure FRF data, we can readily derive the underlying modal properties by analysing the FRF data directly. In general, we can derive the eigenvalue properties from one single FRF using curve-fitting on measured FRF datasets. Typically, with modern instrumentation, we shall measure the FRF (frequency, modulus, phase) at – say – 4000 individual frequencies, involving 12,000 items of data. We can then extract the four modal parameters (modulus, phase, frequency, damping) for each of the – say – 50 visible modes in the frequency range, and this comprises 200 items of data. With these modal data, we can reconstruct or regenerate the FRF curve of interest using the set of 200 modal parameters – a reduction of 60x in the quantity of data compared to those which constitute the original FRF data set.

It is worth noting here that the methods of curve-fitting measured FRFs to extract modal properties date back to days when measured data had somewhat lower accuracy than is the case today and so averaging using 10 or 20 points in the FRF curve per resonance was desirable. However, it is theoretically possible to extract the essential modal properties (4 data items) from just 2 FRF points near each resonance (6 data items). In practice, today, it is realistic to use just 3–5 FRF data points per resonance, and a significant reduction in the measured data required is achieved by applying this philosophy (1000 data items instead of 12000).

2.1.5. Mode shape data

In order to determine the rest of the modal data set – the eigenvectors, or mode shapes - we normally make one additional FRF measurement for each of the DOFs to be included in the mode shape description: typically - say – 500 DOFs. With a target data set of our measured modal properties of 50 modes, each depicted at 500 Degrees of Freedom (DoFs), we seek to define these 25,000 modal properties from a set of 500 FRFs. The quantity of the actually-measured data items for this process is considerable: 500×12000 (6,000,000 items of data) for FRF data. Meanwhile, the Modal data set = 6,000,000:25,000 or a ratio of 240x. Clearly, the modal data set is dramatically more efficient than the response data set, which is the only set we can measure.

In practice, one way of reducing the volume of data used to describe the mode shape features is simply to reduce the density of points (DOFs) so that the coverage is sparse. For example, if every other point is dropped, then there would be $4\times$ fewer data to describe a 2-dimensional mode shape. However, it is important that this reduction is not so great that otherwise, distinctly-different modes can no longer be differentiated from each other. In order to determine an acceptable reduction in density of mode shape descriptions, it is possible to curve-fit the full mode shape data set and from that determine the underlying 'spatial order' of the mode shape. If a particular mode shape has the form of a parabola along a given section, such a curve-fit process will establish that only three parameters are necessary to describe the shape in full detail even when defined at 200 DOFs. Hence, it is important to be able to establish the 'order' of any given mode shape because that order indicates the maximum number of parameters (data items) that are essential to define the shape completely, and in sufficient detail to distinguish it from any other modes in the range of interest. In a practical context, it is well known that if there are - say – 30 modes of interest on a particular structure, then it is necessary to measure at a minimum of 30 DOFs to guarantee this mode–mode differentiation. However, in this case, it is critical that the 30 DOFs be very carefully selected. In practice, it may be wise to measure at 50 or 60 DOFs to be sure, but that is still a dramatic reduction from the notional 500 DOFs at the outset.

This feature of the order of individual mode shapes is a key characteristic in modern model validation exercises. It is a feature which the CSLDV vibration measurement method is ideally suited to address in a way that no other method can.

2.2. SLDV methodology for modal testing.

2.2.1. Step scanning

The SLDV instrument has long been used to measure FRF data in the conventional way, providing a non-contacting transducer to measure velocity response, rather than acceleration or strain, both of which require attached transducers. The basic approach is (i) to choose a reference DOF on the test structure and place an excitation source at that DOF; (ii) to excite the structure with a controlled and measured excitation signal; (iii) to direct the laser beam at a specific DOF of interest and to measure the excitation force and the velocimeter signals and perform whatever spectral analysis is necessary to measure an

FRF (narrow-band filtering for sinusoidal excitation; DFT analysis for periodic and transient excitation; PSD analysis for random excitation). Similar measurements can then be made at each of any number and choice of other DOFs of interest, thereby amassing the requisite set of FRFs for conventional modal analysis.

With an SLDV measuring the response, step (iii) above can be replaced as follows. From the first FRF measurement, identify the resonance regions and select a narrow frequency band around each. Accurate primary FRF data are then measured at only a few (3–5) frequency points in each of those bands. At each chosen frequency in the narrow band, excite the structure with a steady single frequency excitation and measure the amplitude at each DoF by stepping the laser from one measurement DOF to the next. This process measures an ODS at each frequency, acquiring the individual points sequentially in a step scan. This takes a certain length of time to acquire the full set of selected DOFs, but it still offers a distinct time advantage over conventional alternatives.

2.2.2. Continuous scanning

It is also possible to use an SLDV in a continuous scan mode, using the same physical test setup, but when acquiring the data required to extract the mode shapes, the measurement point (where the laser is targeted) is scanned continuously over the whole area of the test structure, rather than stepping over the area in a step-scan mode described above.

The resulting LDV signal is no longer a steady sinusoid, but a modulated sinusoid where the modulations are governed by the steady-state amplitude at every point on the structure as the LDV beam traverses the target area. The amplitude modulation of the LDV time history is transformed in the frequency domain as a set of sidebands which are regularly spaced, and the frequency separation between them is a multiple of the specific scanning rate. The actual deflection shape can then be reconstructed from a simple polynomial expression whose coefficients are determined by the sidebands themselves and, as a result, are relatively few in number. The resulting formula is a polynomial description of the deflection shape. The saving in data storing allowed by the CSLDV with respect to the step scanning LDV is illustrated in Fig. 1.

2.2.3. The importance of the deflection shape order

A distinct advantage of this approach is that the essential output from the analysed time history is the order of the mode shape section along the scanned line. If there are just n non-trivial sidebands, the mode shape is defined by an nth order polynomial, and that limits the number of individual DOFs at which it needs to be defined in order to capture its essential shape. This is a dramatic advantage over the alternative approach discussed in Section 6.1 of measuring perhaps 100s of DOFs and then reducing their number, step by step, until the order of the mode shape polynomial becomes clear. In the Continuous Scanning approach, the order of the mode shapes **is** the primary output.

2.2.4. The final advantage: Mode shapes from ODSs

In the previous paragraph, we have just talked of measuring an ODS. This is not a mode shape because the actual deflection shape, we have observed includes contributions not only from the mode whose natural frequency is just close to the excitation frequency, but also from neighbouring modes. The true mode shape can be obtained by performing a modal analysis on the set of measured ODS deflection shapes (or shapes, because these need to be measured at 3–5 frequencies near each resonance) at each of the measured DOFs. However, in the CSLDV case, we only need to perform the modal analysis on the 120 significant spectral coefficients and not all 10,000 individual measurement DOFs. Once again, the CSLDV method has a distinct advantage of efficiency as well as elegance in delivering the vibration information required by the user in a uniquely effective way.

3. CSLDV methods and applications

The first part of this paper explained the *raison d'être* of the Continuous Scanning philosophy. From here on, the manuscript will present the technical aspects of methods and applications that were developed by several authors during the past two decades.

The next sections are described as follows:

- Section 4 will provide theoretical background which will be focussed on the polynomial, the demodulation and the lifting methods.
- Sections 5 and 6 of the paper will go through the applications of the CSLDV methods both in stationary and rotating conditions for modal analysis, diagnostics and inverse methods.
- Section 7 will present some useful recommendations in terms of usability of the CSLDV methods before
- Section 8 will draw conclusions about this manuscript.

4. Theoretical background

Continuous Scanning measurements can be achieved at best by any non-contact sensors. However, the peculiarity of laser light is in its small laser spot, for Helium-Neon red laser approx. 1 mm^2, making it a point-sensor. Therefore, the use of scanning laser enables accurate scans which can be both short and long; see Tables 1 and 2. In both cases, the spectral informa-

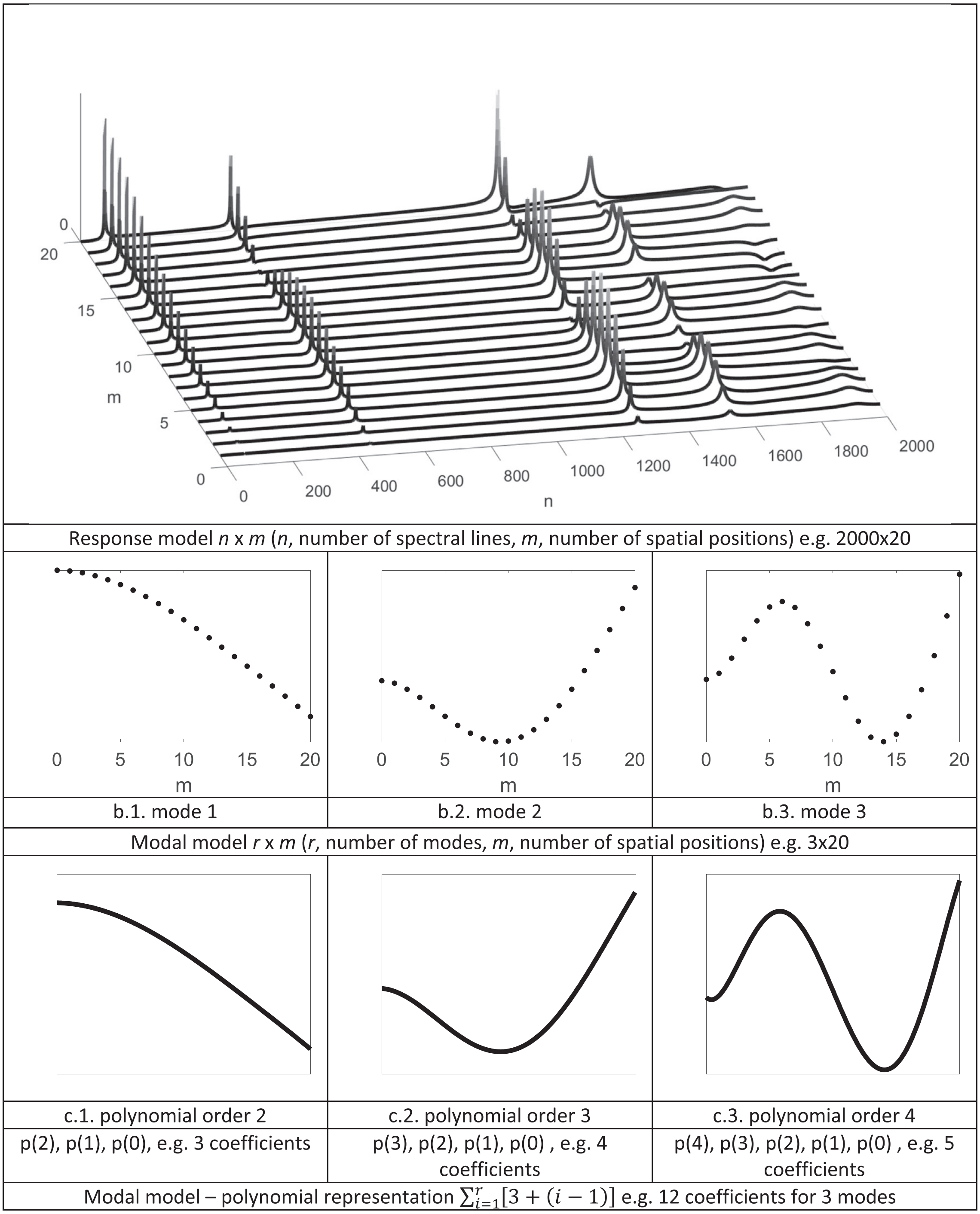


Fig. 1. Stepped and continuous scans.

tion is similar, spectral sidebands, but the short scan can measure rotational and translational rigid body motions, and the long scans can measure the deflection shapes of vibration modes. For the first time, both scan lengths were presented by Stanbridge et al. in [22], where both Cartesian and Polar scanning methods on two-dimensional structures are attempted and described. The research investigation and exploitation of the Continuous Scanning was carried out further than Sriram et al. did in their precursor paper. During the same years, the late nineties, Bucher in [23] reports a study on Continuous Scanning method for a two-dimensional plate structure.

An inherent issue of laser-based measurements, as most cited in the literature, is the speckle noise. Perhaps, it might be less problematic in the newly infrared laser light-based systems than in the older red light Helium-Neon. Nevertheless, the

Table 1
Short scans [16].

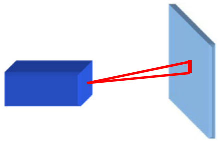
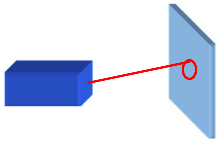
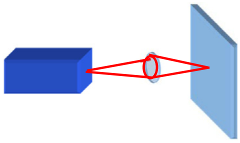
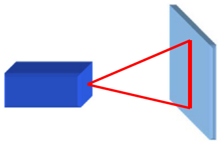
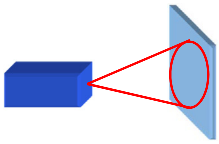
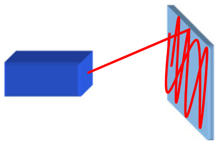
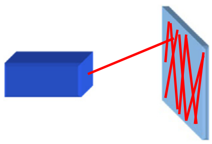
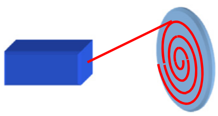
Mirror driver signals	Scan type		Application
One sinewave	Line scan		Translational and one angular vibration recovering
Two sinewaves at the same frequency	Circular scan		Translational and two angular vibrations
	Conical scan (by co-focal lens)		Three translational vibrations

Table 2
Long scans [16].

Mirror driver signals	Scan type		Application
One sinewave or triangular wave	Line scan		One-dimensional structures (beams) Raster scans across a plate
Two sinewaves at the same frequency	Circular scan		2-D structures: Circular scan on a plate or a disc
Two sinewaves at different frequencies not fractionally related	Area scan (LLLLissajous trajectory)		2-D structures (plates)
Two triangular waves at different frequencies not fractionally related	Area scan		2-D structures (plates)
A triangular wave and a sinewave at different frequencies not fractionally related in polar coordinates	Circular area scan		2-D structures (discs)

speckle noise is related to signal drops-out occurring at the LDV decoder and which turn into pseudo-vibration spectral lines. More clearly, when a coherent laser beam is incident on a surface that has roughness comparable with or larger than the laser wavelength (from 633 nm for the red HeNe laser to 1500 nm for an infra-red laser), the component wavelets of the scattered light become dephased. These dephased, but still coherent, wavelets interfere constructively and destructively, thus resulting in a chaotic distribution in backscatter of high and low intensities, referred to as a "speckle pattern". When speckle patterns are stationary, measurements are usually straightforward, though small adjustments in the position of the incident beam are sometimes necessary to avoid low signal amplitude from the collection of predominantly dark speckles on the photodetector. When the surface moves, however, the speckles change too, in a manner that combines translation with some more general change to the pattern itself known descriptively as boiling [24]. The photodetector now collects a continuously changing population of speckles, and this can cause two problems. The first is short duration loss of signal amplitude, known as signal drop-out, caused mainly by sampling darker regions of speckle pattern [25] while the second is a phase noise as speckles leave the photodetector active area to be replaced by new speckles [26,27]. Both noises are generally indistinguishable from the vibration measurements of interest. While signal dropouts can be mitigated to some extent by introduction of higher power (invisible) infrared lasers in more recent instrument designs, phase noise occurs even for healthy signal amplitude.

In CSLDV, the continuous and large amplitude of motion of the laser beam across the surface causes changes to the speckle pattern on the photodetector, and consequently, relatively high output noise is observed. This noise is seen at the scan frequency and its harmonics, and it is not directly related to the excitation frequency of the surface [28]. This common characteristic of speckle noise is the consequence of both signal drop-out (evident as spikes in the output) and phase noise (evident as random noise in the output) contributing broadband noise that repeats (as long as the scan path repeats) with every pass of the laser beam along or around the same path on the target surface. The output noise is therefore pseudo-random, with an associated spectrum comprising peaks at scan frequency and integer multiples as observed. While problematic in many LDV applications, CSLDV methods allow excitation and scan frequencies to be chosen such that spectral peaks associated with speckle noise can easily be distinguished from vibration response in the frequency domain. However, when the CSLDV is applied as done by Sracic et al. in [29], who developed the so-called "lifting method", the speckle noise biased sample data collected for generating an FRF, as will be discussed in Section 5.4.

4.1. Short scan method

The short scan method was developed to measure the translational and rotational rigid body motion of the scanned area, which implies a central frequency at the excitation frequency and two sidebands at ± the scanning frequency. The short scan method did not progress as much as the long scan ones, possibly because the applications to exploit this technique were not available for industrial applications. The underlying theory is available at these references [16,30,31] where the equations for deriving the three translations and the three rotations were presented. Experimental validations were successfully yielded on the three translations and two rotations, but one in-plane rotational degree of freedom was missed because of a co-focal lens used in the measurements.

The last degree of freedom that is the in-plane rotation could not be achieved by using such a lens because the laser beam was not addressed to the vibrating target with the correct angle of incidence (the lens creates a 90-degree angle with the rotational axis). The laser beam required an angle of incidence with respect to the rotation direction, which had to be achieved by a unique scanner design. The single point laser beam was directed through a hollow shaft to a mirror fixed on it (mirror 1) which deflected the beam to another mirror (mirror 2) which, in turn, reflected the laser beam on the rotating surface with the correct angle of incidence, as showed in Fig. 2.

The scanner was built, and the experimental validation of the in-plane rotation was carried out [32]. Eq. (1) represents the in-plane rotation Θ_{z0}, that can be recovered from the CSLDV output signal:

$$\Theta_{z0} = \frac{Amp_{\omega} + V_{z0}\cos(\varphi)}{R\sin(\varphi)} \tag{1}$$

where Amp_{ω} is the peak amplitude at the central frequency, R is the scan radius, φ is the beam angle with respect to the surface normal, see Fig. 2, and V_{z0} is the out-of-plane vibration which is required to be known a priori. This scanner design proved to be suitable for the measurement of the six degrees of freedom, but it was impractical for any application. The next generation of the six-DOF scanner was a more compact design, which was eventually used to measure vibrations in the three

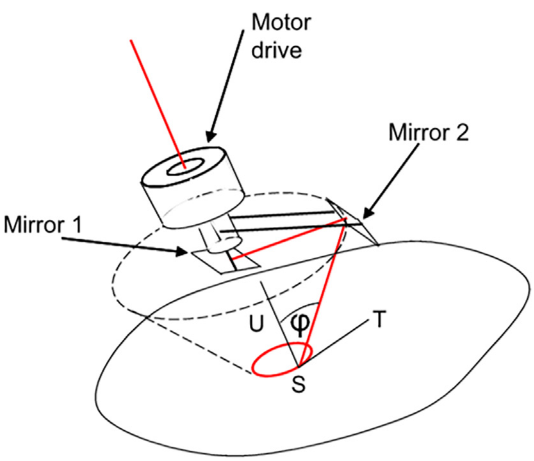


Fig. 2. Scanner sketch from AB Stanbridge.

directions in space at once for every measurement point on a beam of square section which was bended in X, Y and Z directions . The research focussed on the ability to exploit a single point LDV to 3D scanning measurements [33].

4.2. Long scan method

As opposed to the short scan method, the long one is aimed at measuring deflection shapes of vibration modes, and it has been widely applied since its first use. The principle of the modulated output signal and its spectral sidebands still holds, but the processing to yield a deflection shape may vary according to the technique employed.

This section will briefly recall the basic principles of Polynomial, Demodulation, Lifting methods, Mode/Pattern matching and Inverse method.

4.3. Polynomial method

Generally, most of the Continuous Scanning techniques employed in ODS recovering involves sinusoidal excitation of the structure: experimental structures are excited by sinusoidal input forcing so that the response at any point, measured at any direction, is also sinusoidal at the same frequency, assuming the vibration response to be linear.

Hereafter an important statement, as reported in [16], about the ODS "...by directly applying these techniques, ODSs can be determined, these being forced vibration patterns of the structure and not natural or "normal" mode shapes. In fact, ODSs have contributions from more than one natural mode, each with a different mode shape and phase-shift between the motions in all the measurement locations. A perfectly real ODS is normally produced on undamped structures, in the case of damped structures, it is possible to generate a real ODS if a multiple-input normal mode test is made. However, in practice, lightly-damped structures, vibrating at a frequency close to the natural frequency, assume nearly real ODSs which are normally the same as the undamped natural mode shapes. In other cases, particularly if there are close natural frequencies, or with heavily-damped structures, an ODS may be markedly complex. If frequency responses are available, modal analysis may be applied, a process which eliminates the contributions from extraneous modes, extracting the natural mode shapes".

What it is commonly referred to as the Polynomial method is a technique based on the extraction of the Chebyshev polynomial coefficients. These can describe the terms of the oscillatory LDV output signal, as first presented by Sriram et al. [19]. The equation representing the velocity distribution of a unitary length beam between $0 \leq x \leq 1$ is:

$$v(x,t) = g(x) + \varnothing(x)sin(\omega_b t) + \psi(x)cos(\omega_b t) \tag{2}$$

where

$$\begin{aligned} g(x) &= C_0 + \textstyle\sum_1^\infty C_i cos(icos^{-1}x) \\ \varnothing(x) &= A_0 + \textstyle\sum_1^\infty A_i \cos\left(icos^{-1}x\right) \\ \psi(x) &= B_0 + \textstyle\sum_1^\infty B_i cos(icos^{-1}x) \end{aligned} \tag{3}$$

and which are, by letting $T_i(x) = \cos\left(icos^{-1}x\right)$, Chebyshev series expansions for $g(x)$, $\varnothing(x)$ and $\psi(x)$. One can notice that such a definition describes the ODS in terms of Chebyshev coefficients. However, it missed developing a transformation matrix which enabled the amplitudes of the sidebands to be transformed into polynomial coefficients. The generalization of the polynomial method was achieved by Stanbridge in [34], where one will also appreciate the use of the polar coordinate system for scanning at a uniform rate a cantilever plate. Although a squared shape structure is better scanned in Cartesian coordinates, Stanbridge showed that the ODS reconstruction could be achieved by circular scanning. The equation describing the response velocity along the scanned circular path s is:

$$v_z(s,t) = V_R(s)cos(\omega t) + V_I(s)sin(\omega t) \tag{4}$$

which transforms to the following after the substitution of the sine and cosine function driving the mirrors

$$v_z(t) = V_{R0}cos(\omega t) + V_{I0}sin(\omega t) + \sum\nolimits_{n=1}^{p}\left\{\frac{V_{Rn}+V_{In}}{2}cos(\omega - n\Omega)t + \frac{V_{Rn}-V_{In}}{2}cos(\omega + n\Omega)t\right\} \tag{5}$$

Stanbridge expanded his case studies to several scanning paths, reporting here the general case represented by the two-dimension scan in the Cartesian coordinate system. The scanning mirrors, in X- and Y-direction, are driven by two sinewaves the rates of which are not multiples of each other to avoid tracing the same scan path after some number of scan cycles. The LDV output signal is a modulated waveform, the frequency content of which is made up of sidebands around the excitation frequency related to X- and Y-scan rates. Therefore, the vibration response of a structure scanned in Cartesian coordinates is the following one:

$$v_z(t) = \sum\nolimits_{n,m=0}^{p,q} A_{Rn,m} cos\left[(\omega \pm n\Omega_x \pm m\Omega_y)t\right] + \sum\nolimits_{n,m=0}^{p,q} A_{In,m} sin\left[(\omega \pm n\Omega_x \pm m\Omega_y)t\right] \tag{6}$$

where the amplitudes of the sidebands can be converted in the polynomial coefficients by the following relationships:

$$\begin{aligned} \{V_R\} &= [T]\{A_R\}[T]^T \\ \{V_I\} &= [T]\{A_I\}[T]^T \end{aligned} \tag{7}$$

where [T] is the transformation matrix from spectral to spatial coefficients. The same relationship holds for the case of a line scan, instead of area scan, where one scan rate is used for either the X- or Y-axis or both to achieve a diagonal line. The transformation matrix [T] allows the frequency spectral lines to become polynomial coefficients and the other way around. More details about the polynomial method are available in Martarelli PhD thesis [16].

4.4. Demodulation

The demodulation method differs from the polynomial one for two main reasons. One, it is a very slow scan as opposed to the polynomial method, which allows much faster rates in both directions, X and Y. The other one is the reconstruction of the deflection shape, which is no longer based on spectral sidebands. It is based on signal demodulation because the ODS is the envelope of the modulated signal. Therefore, very slow scan rates are required for measuring at least a few vibration cycles at a point before the laser moves to the next infinitesimal adjacent point. The demodulation process is highly dependent on the data quality as a deflection shape depends on the envelope of the LDV modulated vibration signal. The mathematical process is simple, by starting from Eq. (4) and multiplying by sine and cosine of the excitation frequency one will get the following two equations:

$$V_R(t)cos^2\omega t + V_I(t)sin\omega tcos\omega t = \frac{1}{2}V_R(t) + \frac{1}{2}V_R(t)cos2\omega t + \frac{1}{2}V_I(t)sin2\omega t \tag{8}$$

$$V_R(t)sin\omega tcos\omega t + V_I(t)sin^2\omega t = \frac{1}{2}V_I(t) + \frac{1}{2}V_R(t)sin2\omega t - \frac{1}{2}V_I(t)cos2\omega t \tag{9}$$

To obtain the envelope of the LDV modulated signal, it is just necessary to apply a low pass filter, definitely lower than the excitation frequency. Note that the vibration envelope has got an oscillatory rate smaller than the excitation frequency (the ODS frequency) which is the carrier.

The demodulation method is sensitive to the Signal to Noise Ratio (SNR) of the LDV signal, which means noisy data might result in noisy deflection shapes. However, when the SNR of the LDV is excellent, the ODS reconstruction can be used for damage detection as will be presented in the application methods.

4.5. Lifting method

In the limit of high scan frequencies, one can treat the system as a Linear Time Periodic (LTP) system, a system in which the natural frequencies are constant, but the mode vectors can be periodic functions of time. Allen et al. proposed a variety of CSLDV methods for this case for impact excitation [35], and because it is possible to estimate transfer functions between the input and response in this framework [36] many traditional concepts could be applied. For example, one can mass normalize the mode shapes obtained by CSLDV [37] or perform output-only CSLDV measurements using traditional power-spectra based approaches [38].

One advantageous feature of this method is that the measurements are transformed or "lifted" into a new space in which it is as if one has a measurement from a fixed sensor at many different points on the structure. For example, if the scan frequency is 100 Hz and the sample rate is 20 kHz, then one obtains 200 time histories sampled at 100 Hz that are identical to what would be obtained from 200 independent lasers except that there is a known phase delay between points. Hence, curve fitting can be done using traditional methods, and the mode shapes are readily found at each point on the structure. Such measurement requires that the sample rate is integer related to the scan frequency, and this is generally achieved by sampling at a high rate and resampling the measurements after measuring the scan frequency very precisely (i.e. to one part in a million typically), as was explored in detail in [39] and [40]. An example of this is shown in Figure 4 below for CSLDV applied to a free-free aluminium beam.

The approaches based on LTP system theory are only applicable if the scan pattern is a closed Lissajous figure, which is more restrictive than the conditions required for the polynomial approach. These approaches were compared in [41].

4.6. Mode/pattern matching method

Mode/pattern matching was developed with the ambition to apply CSLDV methods in all those applications where vibration shape patterns are expected, for instance, vibration tests of cantilever blades. The pattern matching approach is based on the idea that selected mode shapes, forming the CSLDV signal, can act as filters of the CSLDV data measured during the experiment. Therefore, such a modal filter verifies "if" and "at which frequency" that mode occurs. A new approach in processing of data from a Continuous Scanning test was presented in [42]. The idea is to use a priori knowledge, coming from theory or previous experiments, of a specific structure's mode shapes as a way of filtering data obtained by CSLDV. That technique is based on modal analysis principles which are the identification of the mode shapes on the basis of their nodal lines position, i.e. first, second bending and/or torsional. The expected mode shape is now used as a filter to associate to an LDV

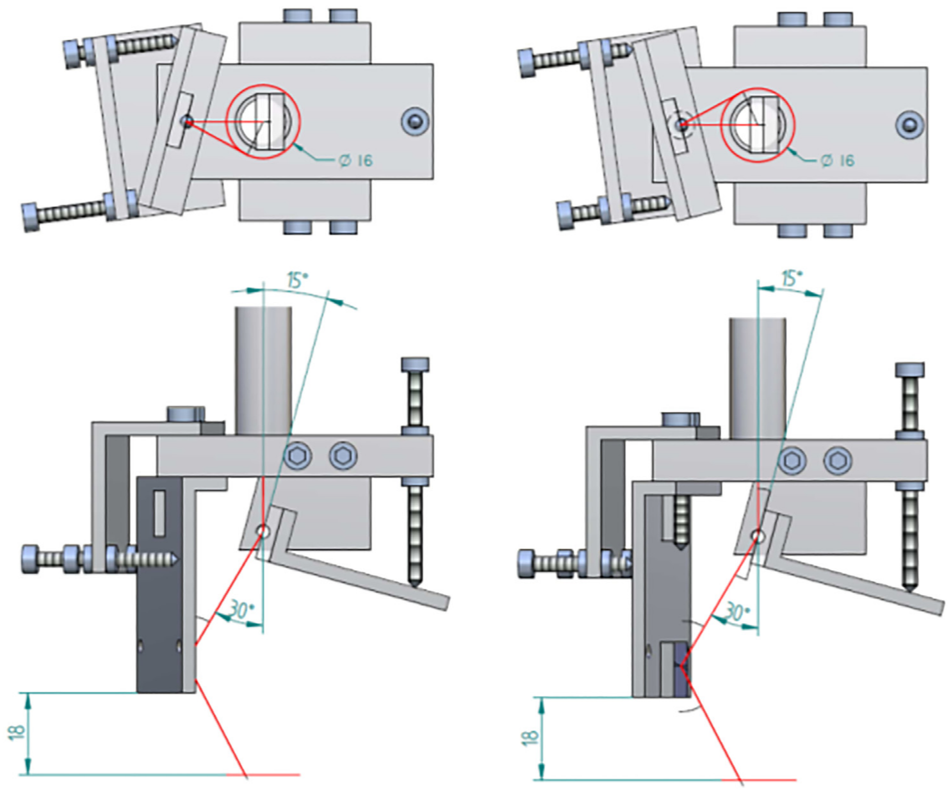


Fig. 3. Scanner developed for the in-plane rotation.

modulated output signal its characteristic deflection shapes. This process can be performed both in the time domain [43] and in the frequency domain [42]. In the time domain, the iterative procedure consists of synthesizing the vibration data from one or more known mode shapes followed by maximisation of the correlation between measured and simulated data in order to extract natural frequency, relative amplitude (called mode gain) and phase of each mode. In this approach, the set of unknowns are the identification of each mode shape presence and its natural frequency, mode gain and phase. The a priori knowledge makes it possible to reduce the number of unknowns, and then to be faster, or more robust to the noise level. The technique proposed overcomes both the requirement of polynomial hypothesis and the need for time resampling by exploiting the a priori knowledge of the ODS, no matter how many of them are excited.

The procedure follows a series of steps listed hereafter:

1. Data collection.
2. Selection of a set of candidate mode shapes.
3. Synthetic CSLDV signal calculation (in time domain or frequency domain).
4. ODS contribution separation (in time domain or frequency domain).
5. The data collection is performed as in the CSLDV standard approach.

The pattern of these sidebands (kernel) identifies a unique mode shape, and therefore it can be exploited as a template for a pattern-matching procedure (like that used, e.g., in image processing) that aims at identifying the presence of that mode in the spectrum of the CSLDV vibration signal. The method is based on the sliding window approach, that is a typical brute force method in Time-series Subsequence Matching. This approach makes the procedure less sensitive to noise. Fig. 5 shows the simulated ODS and their respective sidebands, whereas Fig. 6 shows the measured spectral sidebands and their error with the matching modes.

4.7. Inverse method

The inverse method technique is advantageous in all testing conditions involving high modal density in narrow frequency ranges. Closely spaced resonances can affect the sidebands which might coalesce and therefore becomed unhelpful for the deflection shape reconstruction. The change of scanning frequency to allow all sidebands to be distinguished from each other might not always be possible, and so the inverse method can be used for recovering data that otherwise would be of no use.

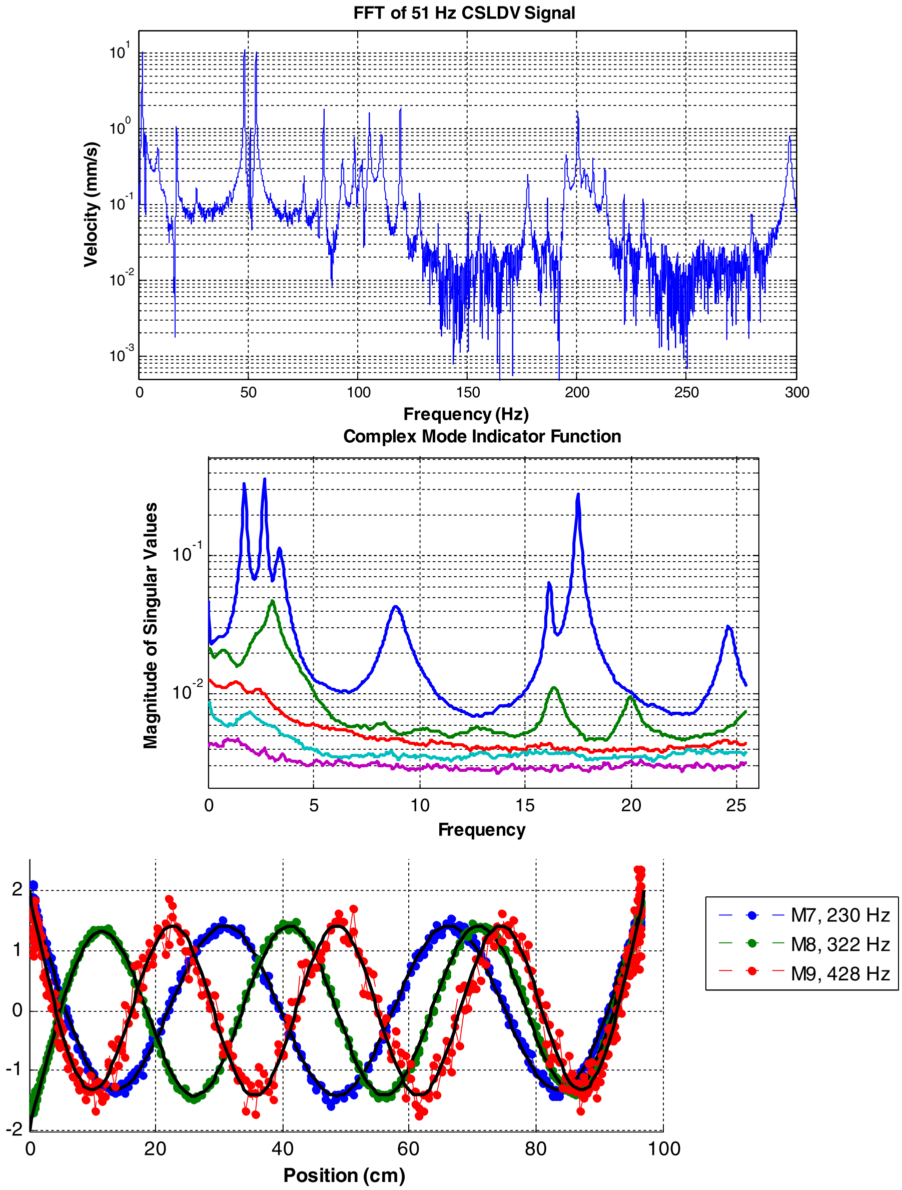


Fig. 4. (a) FFT of CSLDV Signal when scanning at 51 Hz, showing multiple harmonic components due to modulation between vibration modes and the scan frequency, (b) Spectrum after lifting the signal to create 402 pseudo-FRFs and then computing the complex mode indicator function from the 402 FRFs. (c) Sample mode shapes at 402 points for the noisiest (most weakly excited) modes, adapted from [35].

The inverse approach [44] is based on the solution, in the least squares sense, of a set of linear equations defining the relations between the contributions of each cluster of frequencies (central frequency and sidebands) thus defining the spectral pattern of a certain ODS in the complex spectrum measured. Fig. 6 shows a numerical example when the sidebands coalesce together forming a new one which cannot be directly taken for ODS analysis. The sideband (see red circle in Fig. 7) bears the vibration contributions from two nearby modes and, therefore, it needs to be decoupled in their individual components.

The problem, for a single scan frequency combination, can be formulated as a linear system in Eq. (10)

$$A_s X = B_s \tag{10}$$

where B_s is a vector representing the complex spectrum (estimated over $n$spectral lines) of the CSLDV vibration velocity signal (each row element $b_k$corresponds to a spectral line), X is the matrix of unknowns and A_s is a coefficient matrix. Matrices X and A_s are block matrices defined as in equations (11) and (12), where m represents the number of sidebands considered for the complete set of ODSs and, therefore, the polynomial order of the ODSs.

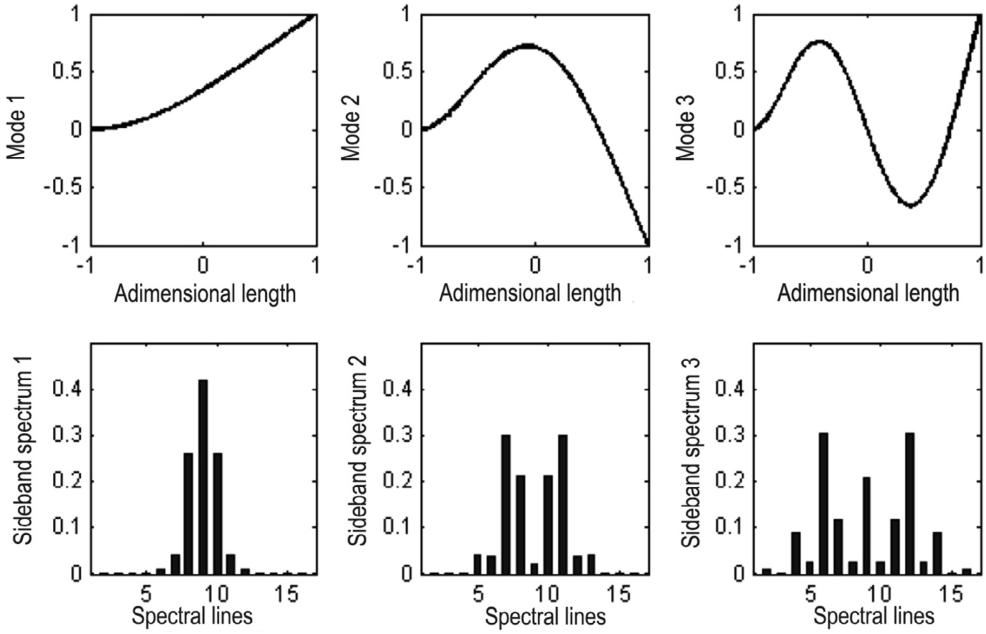


Fig. 5. Mode shapes and related sidebands spectra.

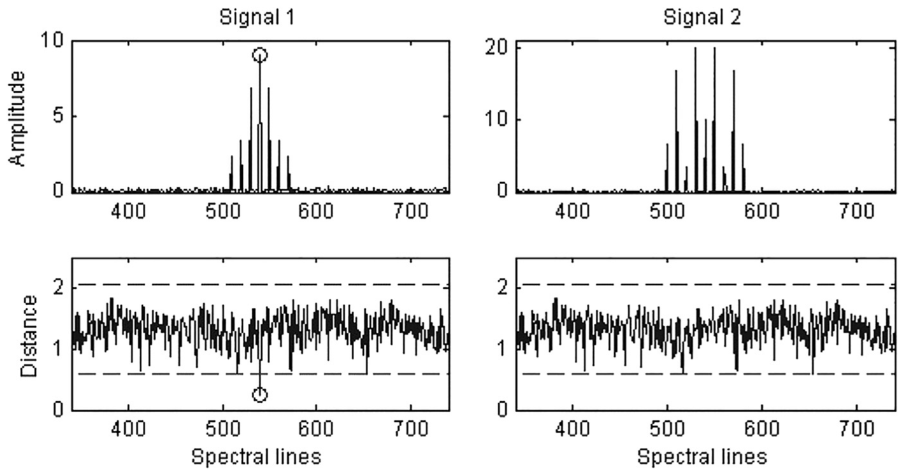


Fig. 6. Euclidean distance trend for Signal 1 (left) and Signal 2 (right).

$$\begin{cases} X = (X_h) h = 1, \cdots, n \\ x_{h+l} \in X_h l = -m, \cdots, m \end{cases} \tag{11}$$

$$\begin{cases} A_s = \left(A_{s,\alpha\beta}\right) \ \alpha = 1, \ldots, n \ , \ \ \beta = 1, \ldots, 2m+1 \\ \left(\alpha_{ij}\right)_{s,\alpha\beta} \in A_{s,\alpha\beta} \\ \left(\alpha_{ij}\right)_{s,\alpha\beta} = \begin{cases} 1 \ if \ \omega_k = \omega_{h+l} \\ 0 \ otherwise \end{cases} \end{cases} \tag{12}$$

In order to solve for $x_{s,h+l}$ it is important to consider multiple scan frequencies n_s, which implies to reformulate the problem in equation (10) as a block matrices system

$$\begin{cases} A = XB \\ A = (A_s) s = 1, .., n_s \\ B = (B_s) \end{cases} \tag{13}$$

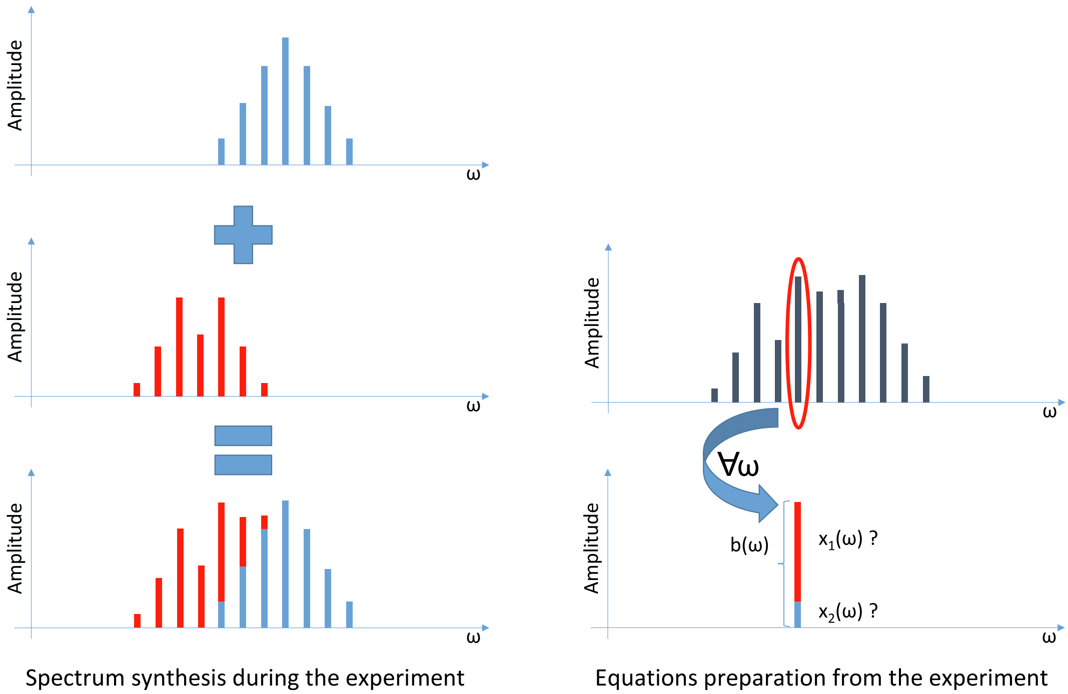


Fig. 7. Spectrum obtained during the experiment and equation system preparation.

Such a system can then be solved in a least-squares sense, thus obtaining the coefficients of each cluster of frequencies (central frequency and related sidebands) that are needed to identify the related ODS. Indeed, once such coefficients are estimated, the ODS can be recovered exploiting the classical polynomial approach proposed by Stanbridge et al. in [22].

As a matter of example, a cantilever beam was modelled by having closely spaced resonances, and a multi-sine excitation test has been simulated. The excitation frequencies considered, 10, 11 and 13 Hz, correspond to the virtual resonance frequencies of the first three modes of the beam. The CSLDV output spectrum obtained when the laser beam virtually scans over a straight line along the beam at the frequency of 1 Hz is shown in Fig. 8. The overlapping of the sidebands belonging to the three different clusters (one for each mode involved) is evident, and the characteristic sideband spectral patterns at the different central frequencies are unrecognizable. A classical peak peaking approach would not make it possible a correct estimation of the ODSs excited.

The inverse approach makes it possible to recover the three ODSs properly, as shown in Fig. 9, where the ODSs obtained from the virtual continuous scan test are compared with the ODSs extracted from a simulated step scan test, the latter constituting the reference test (See Fig. 9).

5. Applications of CSLDV methods

The Continuous Scanning enabled acquisition at an incredibly fast rate with high spatial coverage. Although most of the research was carried out with structures which were planar or low curvature, the Continuous Scanning can be extended to more complex geometries by using three scanning laser heads. The next sections will cover the applications across different subject areas in both stationary and rotating conditions. The authors hope to have collected all the papers so far produced in literature and faithfully reproduced hereafter.

5.1. Modal testing and analysis

Modal testing and analysis is the process that extracts four modal parameters. These are the natural frequency, damping, Real and Imaginary part of the modal constant from frequency response functions, which are acquired at several locations on the structure. The spatial representation of the mode shapes is reconstructed by the number of points measured and the more measurement points the better the shape resolution. As already pointed out in section 2.1.5 Mode Shape data, traditional modal testing based on contact sensors such as accelerometers acquired many spectral lines at fewer locations. The CSLDV approach allowed Stanbridge and Ewins to reverse this by augmenting the spatial resolution of the deflection shape without adding measurement points and, at the same time, by reducing the number of spectral lines required to extract the natural frequency and damping. Martarelli in [16] showed the simple process of stepping-through resonances by sine

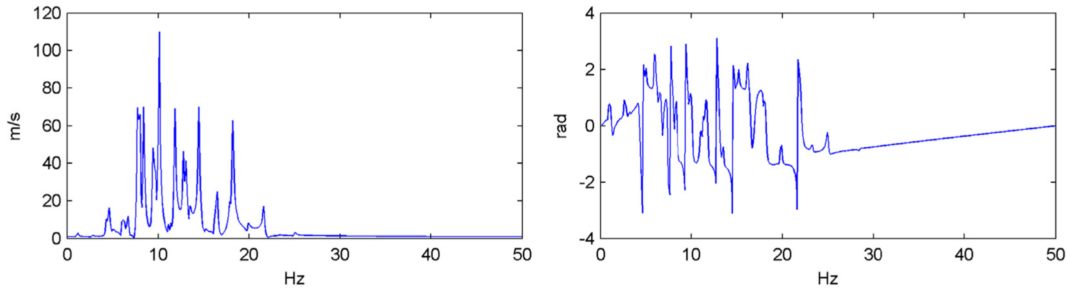


Fig. 8. Simulated CSLDV output spectrum: amplitude (left) and phase (right) data.

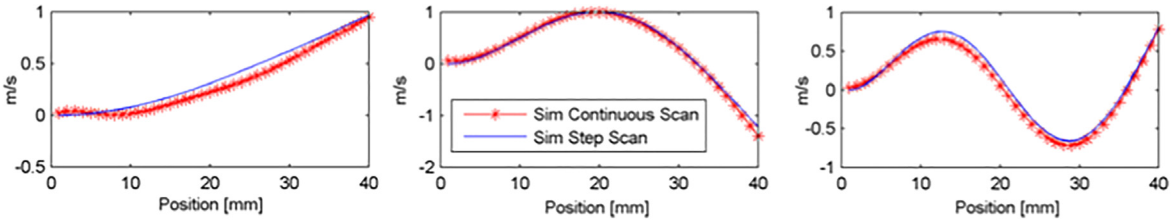


Fig. 9. ODSs extracted from the virtual multi-sine excitation test: comparison between simulated CSLDV and step scan (reference) results.

excitation and used the central spectral sidebands (response at the excitation frequency) for constructing a frequency response function to be processed by modal analysis. A similar approach was used in [45,46] where Di Maio et al. exploited the use of multi-harmonic excitation to measure at once the spectral sidebands which would be required for extracting the modal parameters. The benefit was to excite at once the system response in the region of resonance rather than stepping-through it. The use of random excitation was first attempted by Vanlanduit in [47] and later re-proposed in [48]. The significant difference is about the SNR between the sinusoidal excitation, which delivers the vibration energy to a single harmonic and the random excitation which spreads the vibration energy across a broader range of frequencies. Another limitation of the random excitation is the selection of the scanning rates. The random excitation excites sidebands (spaced by the scan rate) for every spectral line which makes the frequency spectrum very dense with sidebands coalescing on each other, as shown in Fig. 10. It is, therefore, necessary to use the right scan rate to reconstruct an FRF from the CSLDV measurements as well indicated by Vanlanduit in [47]. However, such a limitation could be lifted with the introduction of two new methods by Castellini et al. and explained in Sections 4.6 Mode/pattern matching method and 4.7 Inverse method.

Alternatively, the use of modal hammer allowed to exploit the CSLDV methods in the modal analysis, as shown in [49,50]. The transient response of a structure excited by an impulsive force, measured at a given point, is a summation of exponentially-decaying harmonic functions. If the transducer scans continuously over the test object during its transient free response, the signal acquired is further modulated by the mode shapes of the structure:

$$v(x,t) = \sum_{r=1}^{N} V_r(x) \cdot cos(\omega_{d_r} t) \cdot exp(-\xi_r \omega_r t) \tag{14}$$

where $V_r(x)$ is the mode shape, ω_{d_r} and ω_r, are the damped and undamped natural frequencies and ξ_r is the damping factor of the *rth* mode of an N degrees-of-freedom structure, while *x* is a harmonic function of frequency Ω. As a matter of example, we report the area scan carried out of a bladed disc where a single blade was scanned while the laser beam is scanning it, see Fig. 11. The most relevant aspect of this exercise was to demonstrate that a 50 seconds scan (in Fig. 11a) allowed to measure the dynamics of a single blade by identifying its modal parameters (Fig. 11b) and reproduce the mode shape of the single blade as modelled in the FE in Fig. 11c & d. This example shows the level of information compressed in a single time record measured by CSLDV area scan method.

As already proposed and discussed in the Section 4.5 Lifting method, Allen et al. exploited the Continuous Scanning capacity of measuring an "infinite" number of measurement points and performed modal analysis on recollected response frequency lines which could be organized in frequency response functions; the excitation was by a modal hammer. Even in this case, despite the different data processing, one can appreciate how much dynamics can be retrieved by a single LDV output time history.

An area that is yet relatively unexplored by the CSLDV methods is the nonlinear modal testing. There are a few publications presented by Ehrardt et al. in [51,52] where the Continuous Scanning is applied for high vibration response amplitudes and typically in the nonlinear range. Amongst the several technical aspects which readers can find in the cited papers, it is interesting to highlight how CSLDV can detect and measure the vibration super-harmonics leak into higher-order modes. This leakage is known as parasitic excitation in modal testing. However, as the CSLDV scans the whole surface, it can readily

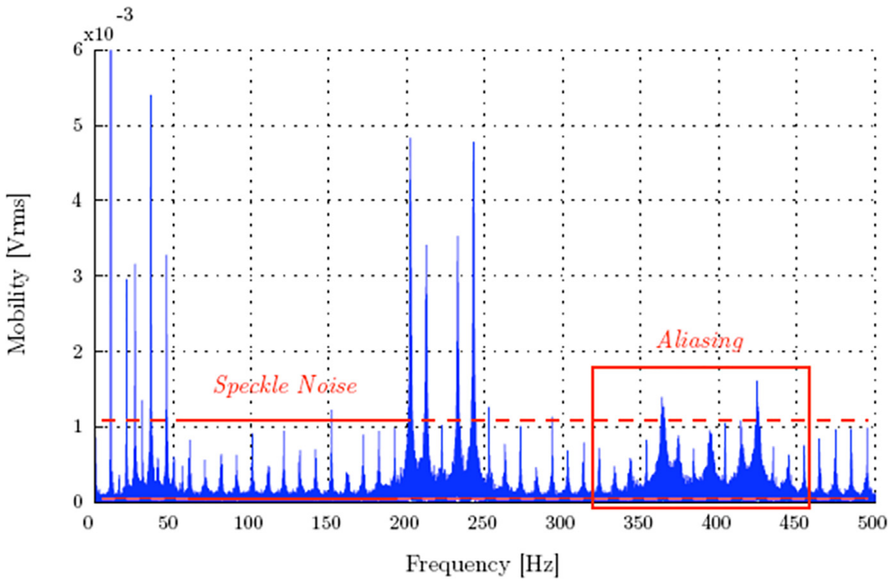


Fig. 10. CSLDV response to Pseudo-Random vibration for a cantilever beam [48]

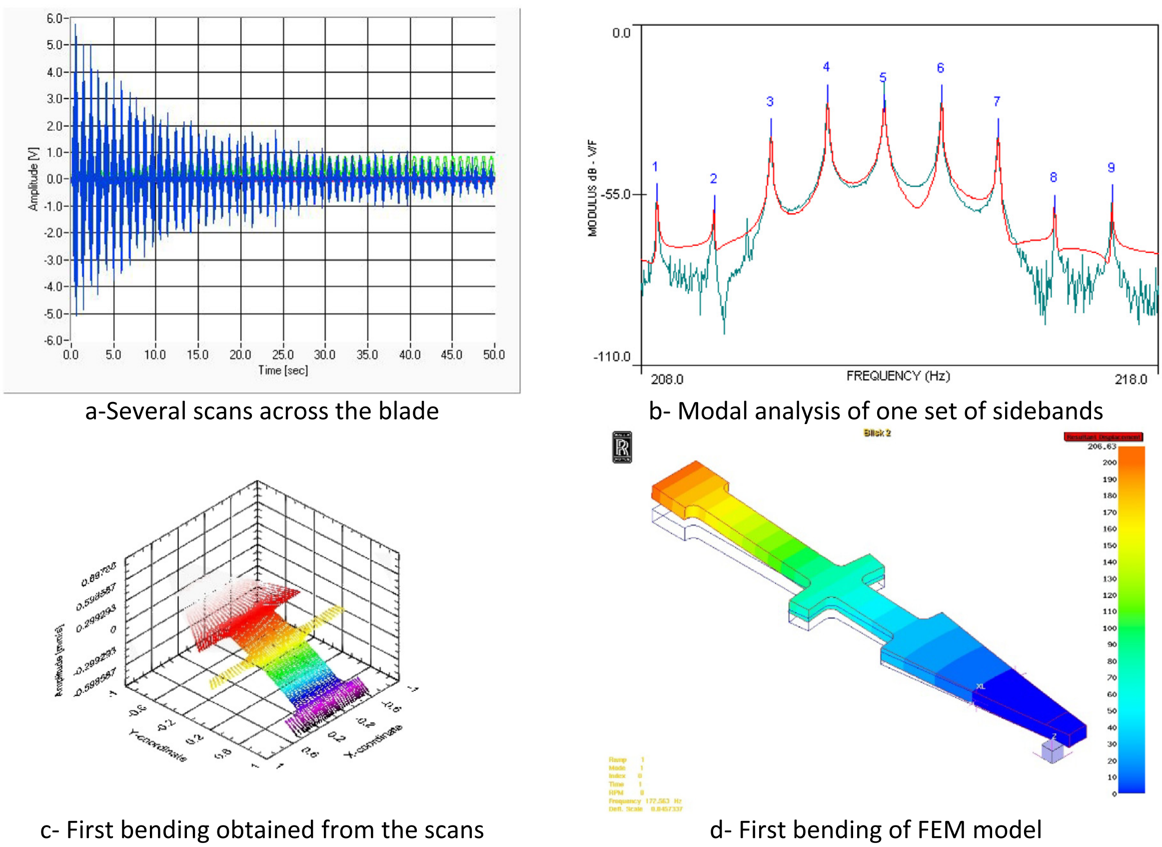


Fig. 11. A set of pictures showing the CSLDV applied to a bladed disc [49,50]

identify which vibration modes are actually excited from such leaked spectral energy caused by the nonlinearity. Finally, we shall conclude this section with a matter about large deflections and SLDV measurements. Castellini et al. [53] investigated the large vibrations using the laser beam set at fixed locations on a beam subjected to large deflections. The paper reports how the large deflections enable a small CSLDV scan around the target measurement point leading to the same modulate LDV time history achieved by an active scanning laser beam, rather than stationary.

5.2. Model updating

As we learnt, the Continuous Scanning enables measuring high spatial density deflection shapes which is an important parameter in model updating and which has seen some attempts by Zang and Schwingshackl in [54–56]. Schwingshackl reports in [55] the application of constant continuous scan to measure vibrations of an aero-engine combustion chamber. The technique, in this case, does not rely on the X-Y scanner of the SLDV system to scan but a single point laser that is shone against a 45-degree angle mirror which is attached to an electric motor driven by constant DC voltage. The laser beam scans the inner side of the chamber at a uniform constant low scan rate to measure the LDV signal amplitude modulation. The post-processing of the signal is carried out by demodulation. The results of the ODS are of high quality, and the paper innovates on new capability to measure cylindrical structures. Early attempts on axisymmetric structure were carried out by Stanbridge and Ind in [57,58] where ODS of cylindrical and conical structures were investigated. The novelty of those researches was on the setup created for performing the Continuous Scanning. Either cylinder or conical structures could be mounted on a rotary table which was actuated by a motor enabling an oscillatory rotation of a specific period. A continuous straight-line scan was then performed along the longitudinal axis of the axisymmetric structure which coupled with the oscillatory motion of the table yielded a continuous area scan.

5.3. Diagnostics and health monitoring

The subject areas where the CSLDV methods could thrive the most were in diagnostics and structural health monitoring, where, as one expects, the high spatial density of the ODS offered the best foundation for monitoring structural changes. The first paper reported was by Khan et al. [59] where damaged beams, presenting a crack, were studied by CSLDV methods. The paper shows that the higher spatial density of ODS from CSLDV can be used for detecting damage in both a metal plate and a concrete beam. A kink in the ODS profile identified the damage, and this local ODS change is associated with a higher number of sidebands caused by local increased curvature in the crack region. It became clear that derivation of the deflection shape would lead to deformation, and this derivation process could be directly carried out on the polynomial function. It was attempted by Stanbridge et al. in [60] where deflection shape derivation was carried out by performing a straight-line scan on a freely suspended beam. The results were encouraging but, unfortunately, the deformation was not as accurate as expected because the strain was unreliable at the extremes of the beam, which required higher-order sidebands typically in the noise floor and therefore unusable. As strain measurements are more suitable for damage identification, the strain method based on CSLDV approach had to mature for another decade before producing the expected results for damage monitoring.

The use of mode shapes was often attempted in diagnostics and health monitoring but with scarce success, if not for some specific case studies. A brief observation about shortfalls can be given by saying that a mode shape might be insensitive to small local damage, which would require shapes from very high frequencies but those tend to be biased by noise or low spatial density. Some attempts were made on a damaged plate by exploiting the ODS properties, where the damage was created by permanent magnets [61,62]. The results showed that by scanning a wide range of frequency and retrieving the ODS from all those spectral lines, one would observe that some ODSs presented a deviation from their pristine shape. Following that observation, the research carried on by focusing on the spectral sidebands as indicators of structural modification over an incremental damage accumulation because the ODS recovery was seen unnecessary. The work was carried out both on numerical and experimental cases as reported in [63–65].

In [66,67] CSLDV was used to detect delamination in composite structures, by applying capabilities of Multi-Level wavelet-based processing. The processing procedure, schematically presented in Fig. 12, consists in a multi-step approach, with the selection of the optimal mother-wavelet that maximizes the Energy to Shannon Entropy Ratio and a pruning operation aiming at identifying the best combination of nodes inside the full-binary tree given by Wavelet Packet Decomposition (WPD). 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 with the final damage map. The effectiveness of the whole approach is proven on both simulated and real test cases. A sensitivity analysis to noise on the CSLDV signal is also discussed.

The demodulation method, already introduced in section 4.4 Demodulation, was used for damage detection with success in spite of the noise affecting the demodulation process. Hence, CSLDV methods were used in [68–70] to rapidly obtain spatially dense operating deflection shapes (ODSs) of beams under sinusoidal excitation. A curvature damage index (CDI) was proposed to identify the damage region based on curvature differences of the ODSs between damaged (y_d) and undamaged (y_p) beams:

$$\delta_{beam}^{CDI}(x) = \left[y_d''(x) - y_p''(x)\right]^2 \tag{15}$$

Structural damage can be identified in neighbourhoods with consistently high values of CDIs. An auxiliary CDI obtained by averaging normalized CDIs at different excitation frequencies was given in [69] and [70] to reduce measurement noise and improve damage detection results.

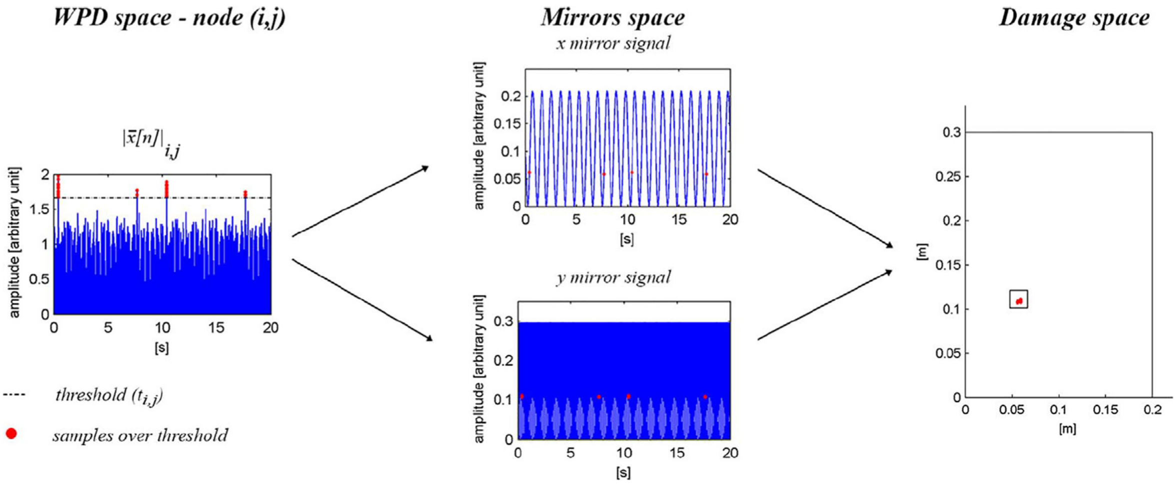


Fig. 12. Damage identification procedure.

The demodulation method presented above was used to obtain ODSs of the damaged beams. The polynomial method was used in [68] to obtain ODSs of a damaged beam from CSLDV measurement data, which can be considered as ODSs of the associated undamaged beam. A polynomial fitting method was proposed in [69] and [70] to fit the ODSs from the demodulation method, which can be considered as ODSs of the associated undamaged beam. No baseline information about the undamaged beams is needed. For damage detection purposes, Chen et al. [68] modified the demodulation method by introducing a phase variable θ. The steady-state velocity response of a structure under sinusoidal excitation, measured by a line scanning CSLDV, can be expressed as

$$\begin{aligned} v_d(x,t) &= V_d(x)\cos(\omega t - \alpha - \theta) \\ &= V_{I,d}(x)\cos(\omega t) + V_{Q,d}(x)\sin(\omega t) \end{aligned} \tag{16}$$

where x is the location of the laser spot along the scan line, ω is the excitation frequency, $V_d(x)$ is the ODS of the structure along the scan line, and α is the phase variable related to excitation and mirror feedback signals; θ adjusts amplitudes of the in-phase ODS component $V_{I,d}(x) = V_d(x)\cos(\alpha+\theta)$ and quadrature component $V_{Q,d}(x) = V_d(x)\sin(\alpha+\theta)$ to obtain their maximum and minimum values.

A convergence index was defined in [68] to determine a proper order to be used in the polynomial method; the convergence index can be expressed as

$$con(m) = \frac{RMS(\{\varnothing_m\})}{RMS(\{\varnothing_m\}) + RMS(\{\varnothing_m\} - \{\varnothing_{m+1}\})} \tag{17}$$

where $RMS(\cdot)$ denotes the Root Mean Square of a vector and $\{\varnothing_m\}$ denotes the ODS vector obtained from the m-th order polynomial. If $con(m) = 100\%$, $\{\varnothing_m\}$ is completely convergent. It was proposed that the proper value of m be two plus the least value of m with which $con(m)$ is above 90% since the curvature of an ODS (CODS) was used. A modal assurance criterion (MAC) was given in [69] to determine the proper order of the polynomial to be used in the polynomial fitting method.

Experiments on a beam with damage in the form of machined thickness reduction were conducted in [68]. The damage region can be successfully identified with consistently high CDI values, as shown in Fig. 13, and CDIs based on ODSs of the damaged beam from the demodulation method and polynomial method are good enough for damage detection, as compared with CDIs based on ODSs of the damaged and undamaged beams from the demodulation method.

Use of CODSs of high-order modes with high quality makes it easier to identify the damage than the use of the CODS of the first mode. Experiments on multi-damaged beams in [70] under sinusoidal excitation also showed the effectiveness of the use of the proposed CDI for damage detection, as shown in Fig. 14. Effects of different types of damage, such as different widths and depths, were also investigated in [70].

A new constant-speed scan algorithm was proposed in [71] for a CSLDV to create a two-dimensional (2D) scan trajectory. A new method was proposed in [72] to calculate the pose of an SLDV with respect to a specified measurement coordinate system, which is applicable to a 2D structure. The demodulation method and polynomial fitting method for obtaining ODSs and CODSs were extended from one-dimension beam structures in [68–70] to two-dimensional plate structures in [71]. The CDI introduced in Eq. (15) for beams was extended to that for plates (See Fig. 15):

$$\delta^{CDI}_{plate}(x,y) = \left[V''_d(x,y) - V''_p(x,y)\right]^2 \tag{18}$$

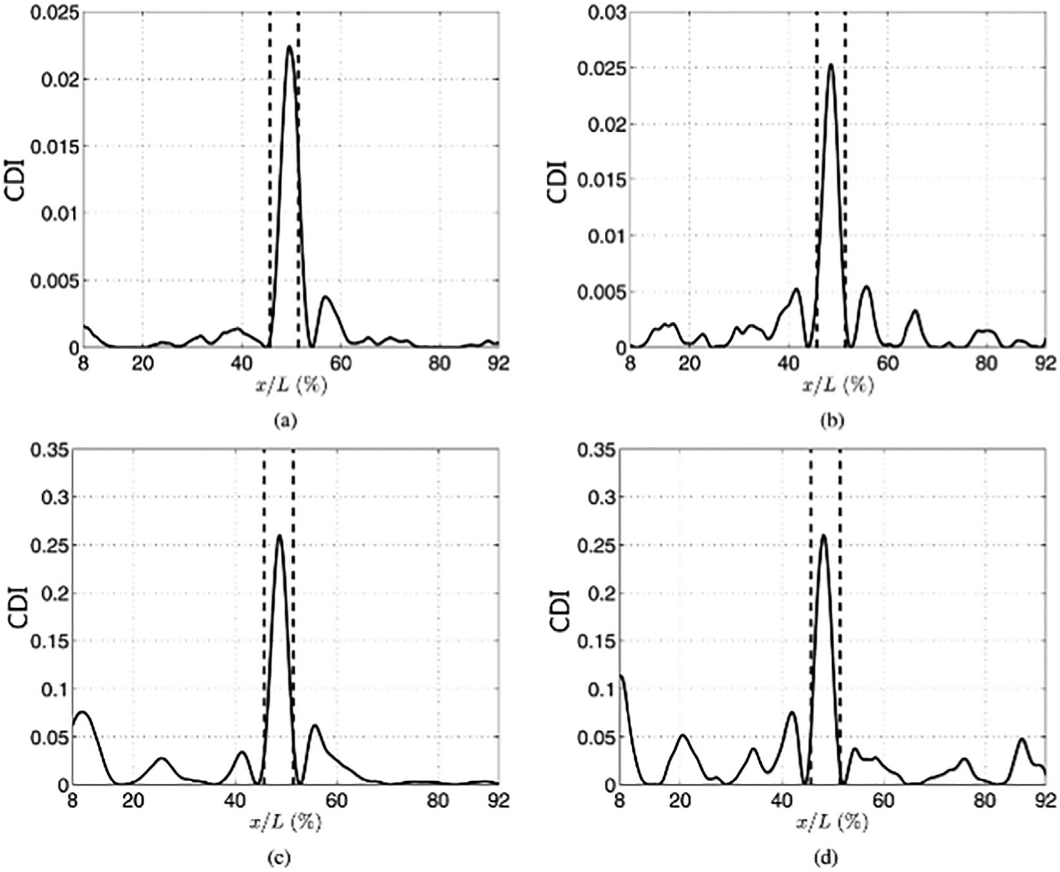


Fig. 13. (a) CODSs of the damaged beam, (b) CODSs associated with the ODSs in (a), (c) CDIs based on the CODSs of the damaged and undamaged beams, and (d) CDIs based on the CODSs of the damaged beam from the demodulation method and those from the polynomial method [1]. Locations of damage ends are indicated by two vertical dashed lines.

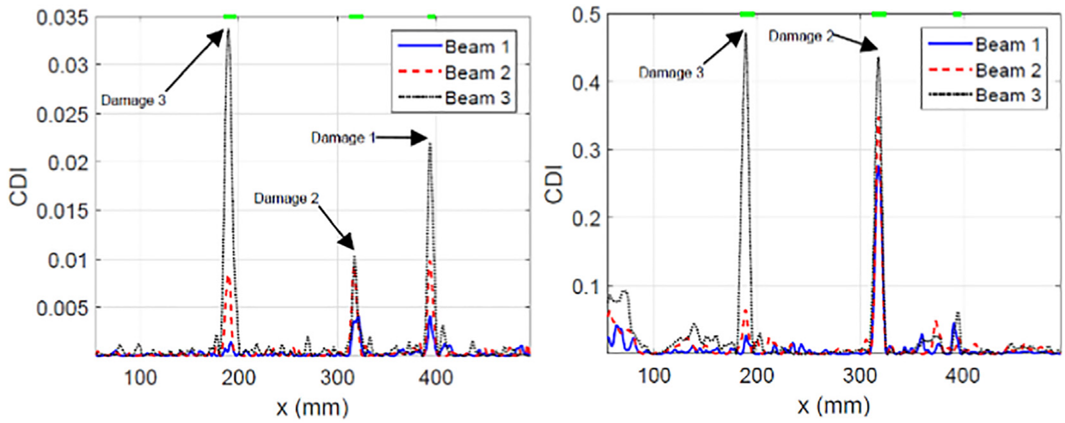


Fig. 14. CDIs of multi-damaged beams under sinusoidal excitation with excitation frequencies of (a) 72 Hz and (b) 453 Hz [70].

To reduce effects of spurious boundary anomalies of CODSs on damage identification due to signal processing, CODSs in the ranges [1%, 10%] and [90%, 100%] of each scan line in a scan area were disregarded. Experiments on a damaged plate under different sinusoidal excitation frequencies were conducted. As shown in Fig. 16, the damaged area of the plate can be successfully identified in neighbourhoods with consistently high values of CDIs at different excitation frequencies.

A CSLDV was used in [73] for identification of delamination in laminated composite plates. A novel wavelet-based method that uses continuous wavelet transforms of ODSs was proposed for damage detection. A wavelet transformation along a scan line was defined as

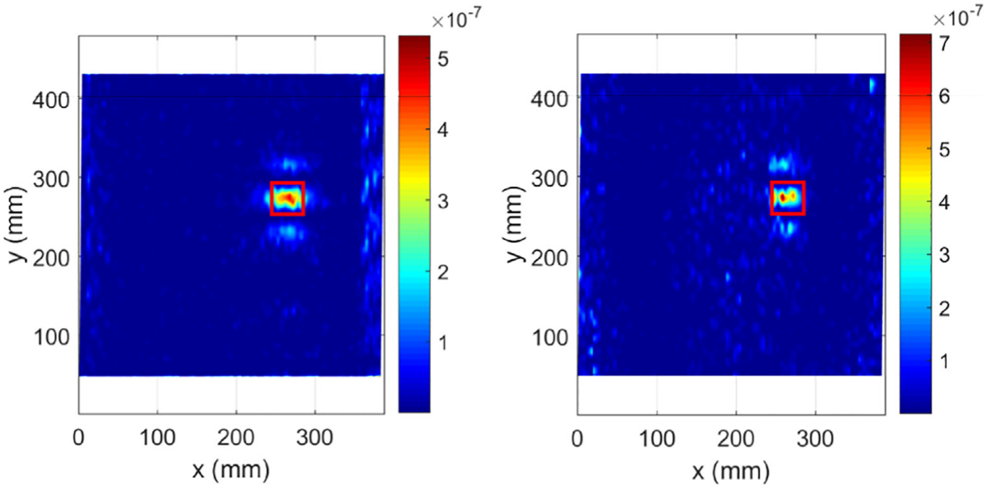


Fig. 15. CDIs for the damaged plate under sinusoidal excitation with excitation frequencies of (a) 98 Hz and (b) 163 Hz [71].

$$W_\psi z(u,s) = \int_{-\infty}^{+\infty} z(x)\frac{1}{\sqrt{s}}\psi\left(\frac{x-u}{s}\right)dx \tag{19}$$

where $\psi(x)$ is a wavelet function, and u and s are spatial and scale parameters. A wavelet damage index (WDI) δ was defined as

$$\delta_{plate}^{WDI}(u,s) = \left|W_{g_2}z_{xx}(u,s)\right|^2 = \left|\frac{1}{s^2}W_{g_4}z(u,s)\right|^2 \tag{20}$$

where $g_p(x) = (-1)^n \frac{d^p g_0(x)}{dx^p}$, in which $g_0(x) = \left(\frac{2}{\pi}\right)^{\frac{1}{4}}e^{-x^2}$, is the p-th order Gaussian wavelet function. An auxiliary WDI was proposed in [5] based on average values of normalized WDIs associated with different ODSs of a structure. An auxiliary CDI was also proposed based on average values of normalized CDIs from Eq. (18). Numerical and experimental investigations on a laminated composite plate were conducted in [73] with their results shown in Figs 15 and 16, respectively. Positions and lengths of delamination edges are accurately and completely identified based on local anomalies with high WDI and CDI values caused by delamination.

A comprehensive study by use of a CSLDV to detect hidden damage in a composite plate was conducted in [74]. The work was related to a round-robin study sponsored by the Society of Experimental Mechanics. No information about damaged locations of the composite plate was known since the plate was provided by the organizer, Dr Di Maio, of the round-robin study. Experimental results show that different CODSs have different sensitivities to local anomalies induced by the damage, and only two of the first seven CODSs from the corresponding ODSs of the plate can be used to detect locations of the hidden damage, as shown in Figs. 18 and 19. Finally, the estimated locations and sizes of the two damage are in good agreement with their prescribed locations and sizes.

A CSLDV was used in [75] to obtain a new type of vibration shape called Free Response Shape (FRS). An analytical response solution of a linear time-invariant Euler-Bernoulli beam with a uniform cross-section under a single impulse excitation was derived:

$$y(x,t) = \sum_{h=1}^{\infty} \varnothing_h(x,t)\cos\left(2\pi f_{h,d}t - \gamma_h\right) \tag{21}$$

where $\varnothing_h(x,t) = A_h Y_h(x)e^{-2\pi\zeta_h f_h t}$ is the h-th FRS of the beam along a scan line, in which A_h is determined by initial conditions of the impulse to the beam, ζ_h is the h-th modal damping ratio, and $Y_h(x)$ and f_h are the h-th mode shape and natural frequency of the corresponding undamped beam, respectively, and $f_{h,d}$ and γ_h are the h-th damped natural frequency and phase angle, respectively. The short time Fourier transform of the response was used to find decay times of FRSs and obtain nonzero FRSs. The demodulation method was extended for calculation of the FRSs based on equation (21). A new type of Free Response Damage Index (FRDI), based on curvature differences of the FRSs from the demodulation method and polynomial fitting method, can be defined as

$$\delta_{h,beam}^{FRDI}(x) = \left[\varnothing_{h,d}''(x) - \varnothing_{h,p}''(x)\right]^2 \tag{22}$$

The damage region of the beam is successfully identified near neighbourhoods with consistently high values of FRDIs associated with different modes. A new modal parameter estimation method using free response measured by a CSLDV system is proposed in [76] to estimate modal parameters of a structure, including natural frequencies, modal damping ratios, and mode shapes based on the concept of free response shapes.

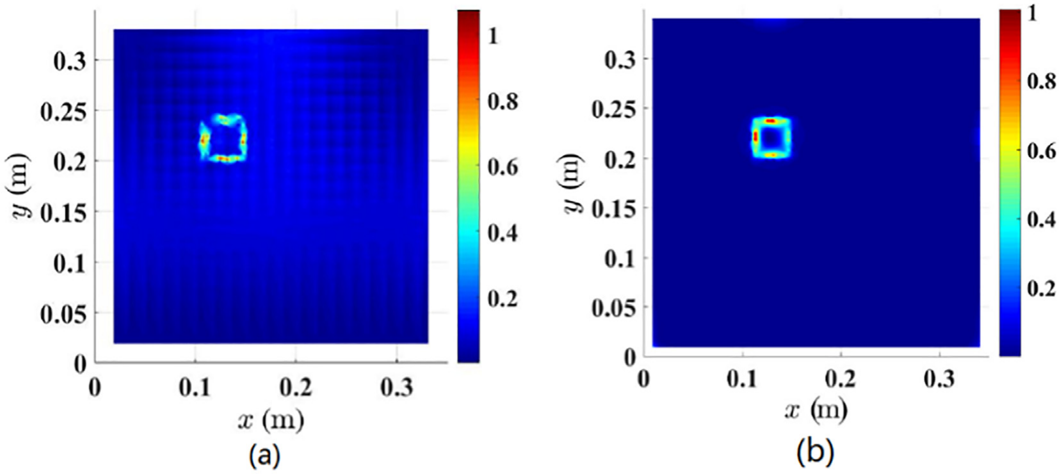


Fig. 16. (a) Auxiliary WDIs associated with the second and fourth modes of the composite plate from its finite element model, and (b) auxiliary CDIs associated with the second and fourth modes of the composite plate from its finite element model [73].

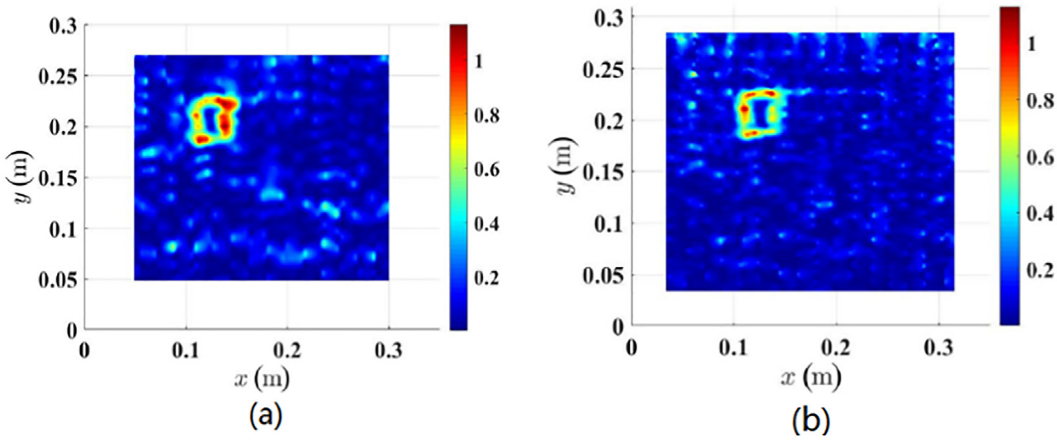


Fig. 17. (a) Auxiliary WDIs associated with mode shapes of the composite plate with excitation frequencies of 89 Hz and 150 Hz, and (b) auxiliary CDIs associated with mode shapes of the composite plate with excitation frequencies of 89 Hz and 150 Hz [73].

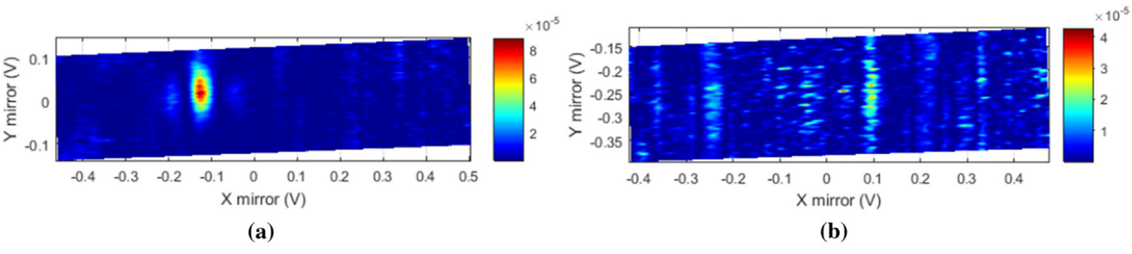


Fig. 18. Partial CDIs for scan areas (a) 1 and (b) 2 at the excitation frequency of 199.22 Hz [6].

A new Operational Modal Analysis (OMA) method based on the lifting method (see Section 4.5), which is a data processing method for CSLDV measurements of a structure under white-noise excitation, was proposed in [77]. A CDI associated with curvature differences of estimated mode shapes from the OMA method and polynomial fitting method was given. The lifting method transforms raw CSLDV measurements into measurements at individual virtual measurement points, as if the latter measurements were made by use of an ordinary SLDV in a step-wise manner. The m-th measurement on a virtual point k along a scan line can be expressed as $z_k^L(mT_{sc}) = z[(k-1)\Delta t + (m-1)T_{sc}]$, where $\Delta t = \frac{1}{F_{sa}}$, in which F_{sa} is the sampling

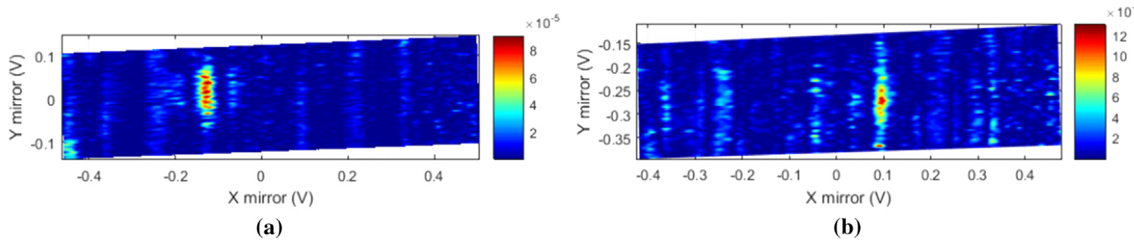


Fig. 19. Partial CDIs for scan areas (a) 1 and (b) 2 at the excitation frequency of 563.67 Hz [6].

frequency, and T_{sc} is the scan period. A correlation function with non-negative time delays between any two virtual points k_1 and k_2 on a beam, chosen as reference and measurement points, respectively, with white-noise excitation at an excitation point was derived:

$$\tilde{R}_{k_1k_2q}(T) = Re\left[\sum_{j=1}^{n}\tilde{A}_j\varnothing_{j,k_2}e^{\left(-\zeta_j\omega_j+i\omega_{j,d}\right)(k_2-k_1)\Delta t}e^{\left(-\zeta_j\omega_j+i\omega_{j,d}\right)T}\right] \quad (23)$$

where $T=(m_{k_2}-m_{k_1})T_{sc}$ is the time delay variable, in which m_{k_1} and m_{k_2} are measurement numbers of points k_1 and k_2, respectively, $\tilde{A}_j$ is a complex scale factor that depends on the reference and excitation points, ω_j is the j-th undamped natural frequency of the beam, $\varnothing_{j,k_2}$ is the value of the j-th undamped mode shape function of the beam at point k_2, and $\omega_{j,d}$ and ζ_j are the j-th damped natural frequency and damping ratio, respectively. Note that $\omega_{j,d}$, ζ_j, and $\tilde{A}_j\varnothing_{j,k_2}e^{\left(-\zeta_j\omega_j+i\omega_{j,d}\right)(k_2-k_1)\Delta t}$ can be estimated as the j-th damped natural frequency, damping ratio, and mode shape by applying a standard OMA algorithm to power spectra associated with correlation functions, respectively. Experiments on a damaged beam were conducted in [77] using the above OMA method, noting that if the scanning frequency of a CSLDV was lower than twice the largest natural frequency of modes of interest, an unaliasing procedure was used to calculate the true natural frequency of the beam. As shown in Fig. 20, experimental results were in good agreement with results from the numerical investigation.

Recently, two publications from Huang [78,79] exploit the rotational degree of freedom as a means for damage detection. Both numerical and experimental verification of a damaged cantilever plate showed a successful approach. Besides using a single SLDV to measure vibration along the laser line-of-sight direction, an investigation using a single SLDV to obtain 3D vibration measurement of a structure at a specified measurement coordinate system was conducted in [72]. The authors in [72] proposed an improved method to calculate the pose of the SLDV with respect to the coordinate measurement system.

5.4. Rotating machinery dynamic characterization

In the late nineties, the SLDV was used to measure under rotating conditions by synchronizing the scanning mirrors to a rotating object. The waveforms designed to drive the mirrors and allow the laser beam to track a single point were the same as the ones for achieving a circle by continuous scanning. The laser spot is fixed at a point on a rotating target in a non-stationary frame of reference. Strictly speaking, point tracking should not be classified as Continuous Scanning, but this section encompasses a series of techniques related to tracking methods because it acted as a precursor for extending the Continuous Scanning to moving objects. The point tracking is simply achieved by performing a circular scan, the rate of which is synchronized with the rotational speed of the target point. Most of the tracking techniques were applied to either rotating solid discs and bladed discs. In point tracking, one can make a further distinction between synchronous, that is when the laser was fixed at a point, and asynchronous methods, that is when the laser point had a relative speed with the moving object. In the asynchronous point tracking method in [16,80] the laser beam scans a circular path on a rotating solid disc and measures two sidebands which indicate that the nodal diameter mode excited while the disc was rotating. The relative amplitude difference of those two sidebands also identifies if the vibration wave travelled in- or out-of-phase with respect to the rotating direction. The synchronous tracking techniques exploiting the circular scan method are available in [81–84].

The tracking measurements showed great sensitivity to misalignment between the scanning mirrors and the rotational axis of the rotating target, and therefore, the alignment procedure had to be carried out very carefully. Sever et al. presented in [85] a method which was very useful and it is shown in Fig. 21. The alignment could be verified by point tracking performed at very slow rotation on a reflective patch of dimensions 5 × 5 mm where the laser beam was addressed, and the area outside the patch was coloured black to create drop-outs in the decoder signal level. An adequate alignment was assured if the laser spot did not go out the reflective patch during one revolution and, for high rotational speed, the signal level from the decoder had to show the maximum signal at all time.

Residual misalignments contribute measured velocity components primarily at the target rotation frequency while the geometry of the dual mirror configuration contributes to a measured velocity component primarily at twice the rotation frequency [86,87]. These have to be distinguished from genuine vibration in the frequency domain. In the case of the components associated with misalignment, best practice is first to minimise the misalignment using an experimental approach

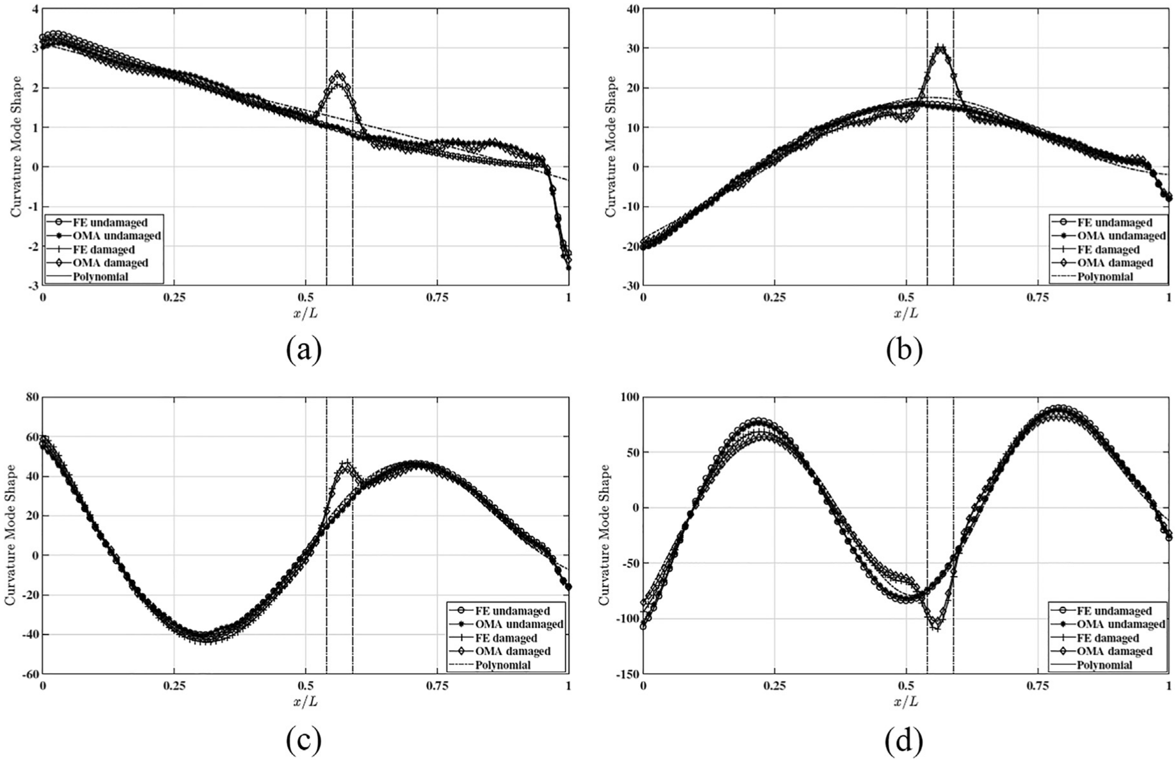


Fig. 20. (a) First, (b) second, (c) third, and (d) fourth curvature mode shapes of the damaged and undamaged beams from the OMA method and their finite element models [8]. Locations of damage ends are indicated by two dotted lines.

developed for the specific purpose [86,88]. For the component associated with the dual mirror geometry, exact prediction can be made to aid data interpretation. Sensitivity to misalignments and the appearance of other artefacts in measurements has been explored comprehensively [89] for a variety of tracking systems including the standard dual mirror head, a Dove Prism derotator and the self-tracking system of [85]. This brief introduction to point tracking highlights set-up and measurement challenges to be addressed before progressing to the continuous scan over a moving target. A simple trial and error adjustment of the X- and Y- waveform magnitudes is enough to minimize that distortion by verifying the circle symmetry against the edge of a disc which needs to be tracked. The primary issue of misalignment is to create a pseudo-vibration caused by the apparent oscillation the laser detects in one revolution because of the non constant distance of the target from the laser head. The pseudo-vibrations can be detected from the frequency spectrum and neglected, but the most challenging issue was the over-ranging of the decoder. The true vibration response would build on top of the pseudo-vibration which might be truncated by the decoder over-range, hence misalignment had to be minimized at the outset of the tracking measurements. This brief introduction about point track helps to understand which set-up and measurement challenges have to be addressed before attempting the laser beam to continuously scanning over a moving target.

The natural extension from point tracking is to scan continuously along a line or across an area under rotating conditions, and this was first shown by Halkon et al. [86] who attempted a continuous linear scan on a simple 4-bladed rotor. The waveform for a linear scan under rotating conditions requires that two trajectories, here rotation and translation, have to be superimposed. As one would expect, misalignment between optical and rotor axes is a critical factor affecting the vibration measured because the desired scan path, such as from top to bottom of the blade, will not be correctly followed. This initial attempt was then developed and extended [90–92]. Di Maio et al. applied the Continuous Scanning to bladed discs to investigate a problem about frequency veering in a mistuned bladed disc. The frequency veering happens when two families of modes, for instance, the second flap-wise and first torsional modes, come very close because of the stiffening effect caused on flap-wise modes by the centrifugal load and then veer apart. A few measurement points per blade cannot capture the mode shape accurately and therefore, one cannot calculate the mode shape coupling in the veering region, and more points would mean longer measurement time. The use of Continuous Scanning shortened the measurement process because any ODS could be measured at once at any excitation frequency and any rotational speed. After all, the research in [90] developed a rotating exciter which enabled asynchronous excitation instead of the engine order type achieved by DC magnets.

Furthermore, all blades were measured in a single time record because there was no interruption between one blade to the next one, as is visible in Fig. 22a & b. The laser beam scan rate was also designed to be independent of the encoder sampling rate, that means a constant laser scan rate was possible at any set rotational speed. Finally, Fig. 22c & d show the

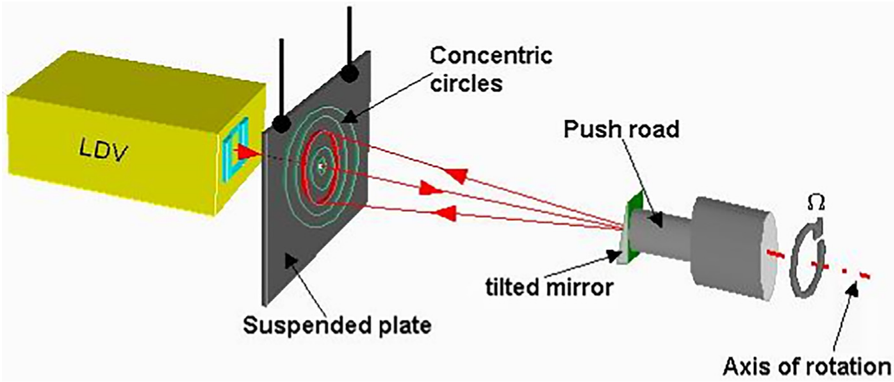


Fig. 21. Alignment method for performing Continuous Scanning and tracking [85].

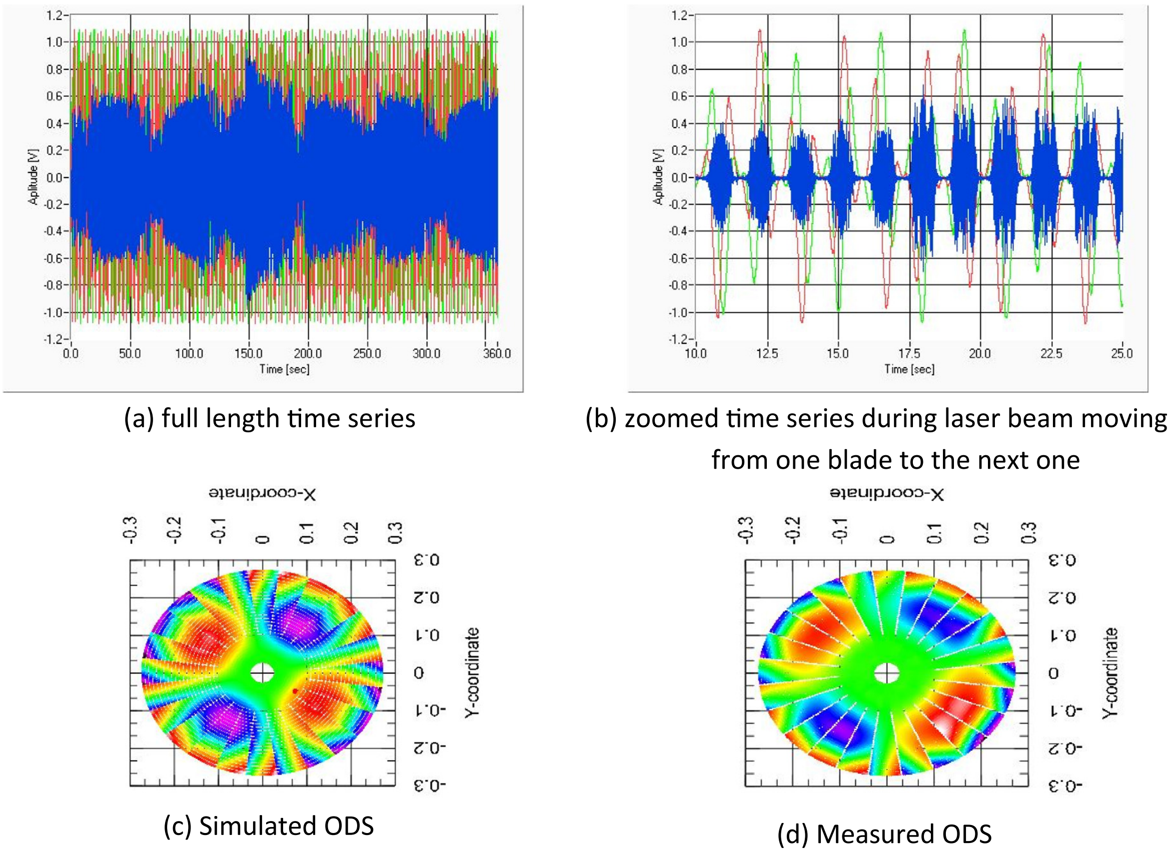


Fig. 22. Time series of the 24-bladed disc in (a), the zoom in (b), the simulated and measured ODS in (c) and (d) [90].

simulated and measured ODS of the 24-bladed disc. As one can gather, 360 s of acquisition enabled the recovery of a complex deflection shape.

Recently, a new publication from Martarelli et al. in [92] presented an innovative approach to tracking methods based on velocity coast-down or ramp-up of the bladed disc. That approach is conceptually very simple: it can be considered as the repetition of consecutive tracking CSLDV acquisitions at different rotational speeds, taking advantage of the very short acquisition time possible by CSLDV. At each acquisition, the actual rotational speed must be measured, and so the scanning laser beam synchronized with the structure rotation. In order to follow the coast-down with adequate accuracy, an acquisition must be recorded in the shortest duration possible so that it can be assumed the rotation speed is constant during the scanning. The main issue of the tracking CSLDV is that the continuous trajectory (the Lissajous path) is built in time-basis while

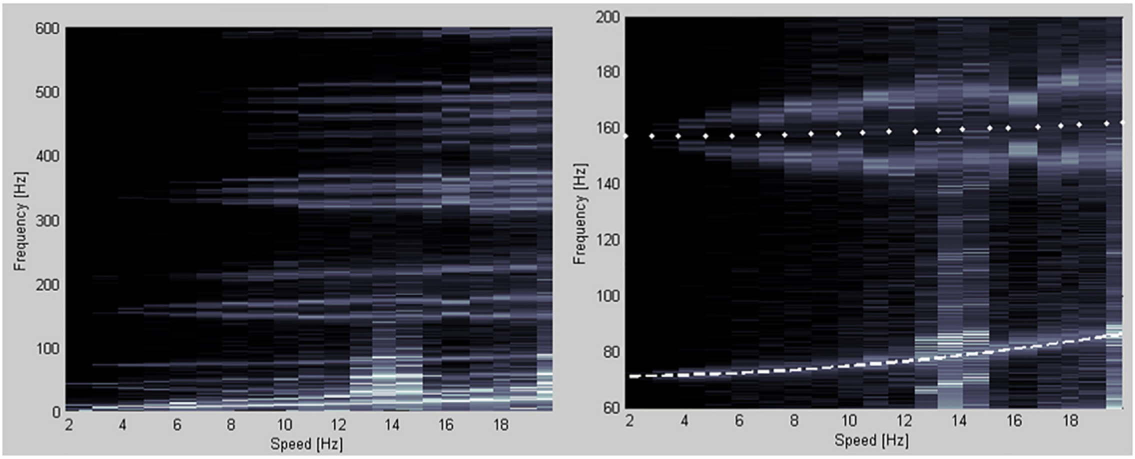


Fig. 23. Stepped CSLDV run-up spectrogram (left) and its zoom around the III and IV blade resonances [92].

the tracking is driven by the encoder and therefore is given in angular-basis. In order to match the two processes, the Lissajous trajectory must be resampled in the angular base for the given speed by using the encoder data. At each acquisition, then, the Lissajous path is calculated with the rotational speed measured at the beginning of the acquisition itself while the signal driving the mirrors is generated with the clock given by the encoder following the rotational speed variation. The tracking CSLDV signal can be processed off-line, i.e. after having collected the complete set of LDV outputs at each speed considered. The data post-processing allows calculating the ODSs at the different resonances for each speed recorded. Although it is simple in principle, its practical implementation is far from it. Considering the coast-down is about 40 s long, in order to take as much as possible measurements in that time, each cycle of that process, including the speed, trajectory calculation and surface scanning, has to be as fast as possible (about 2 s). Fig. 23 shows an example of measurement in ramp-up conditions.

Fig. 24 shows the ODSs recovered from the measurements in coast-down.

6. Transversal applications

Outside the mainstream research areas presented in the previous sections, the final part of the paper focuses on literature developed for applications in Dynamics characterisation of arbitrarily moving structures, Bio Engineering and Land Mines.

6.1. Dynamic characterization of arbitrarily moving structures

CSLDV was not only applied to rotating structures but also to arbitrarily moving structures such as, for example, linear motion.

In [93] authors describe the use of CSLDV as a tool for the dynamic characterisation of timing belts in IC (Internal Combustion) engines (cylinder head). In this application, the experimental approach still represents an issue, because it requires a measurement in operating conditions, since the belt mounting conditions might severely affect its dynamic behaviour, and the belt is continuously moving during running conditions. The paper discusses how the belt in-plane speed influences CSLDV signal and how an order-based multi-harmonic excitation might affect the recovery of ODS in a CSLDV test. A comparison with a standard SLDV measurement in stepwise operation is also given in order to show that a CSLDV test, if well designed, can indeed provide the same amount of information in a drastically reduced amount of time.

6.2. Bio-engineering

There are three interesting papers of Continuous Scanning applied to the human body and reported in [94–96]. Salman et al. in [95] applied CSLDV for active and passive elastography measurements on the human body. This fast CSLDV can replace several fixed LDVs and is especially advantageous for sensing human body natural vibrations (typically below 100 Hz) at multiple locations (e.g., along with small muscles). In this application, it is crucial to apply contactless systems, also to avoid to patient's disturbance, mass artefacts and set-up time due to traditional skin-mounted sensors (e.g., accelerometers array). Experimental measurements were conducted using a CSLDV with a 200 Hz linear scan rate, along scan lengths up to 5 cm, to measure low-frequency vibrations ($f < 100$ Hz) on gel samples which mimic human soft tissues. Validations of the CSLDV measurements were done using an array of several fixed LDVs distributed along the same scan line. Salman et al. in [96] demonstrated the use of a CSLDV for measuring in a non-contact fashion the velocity of

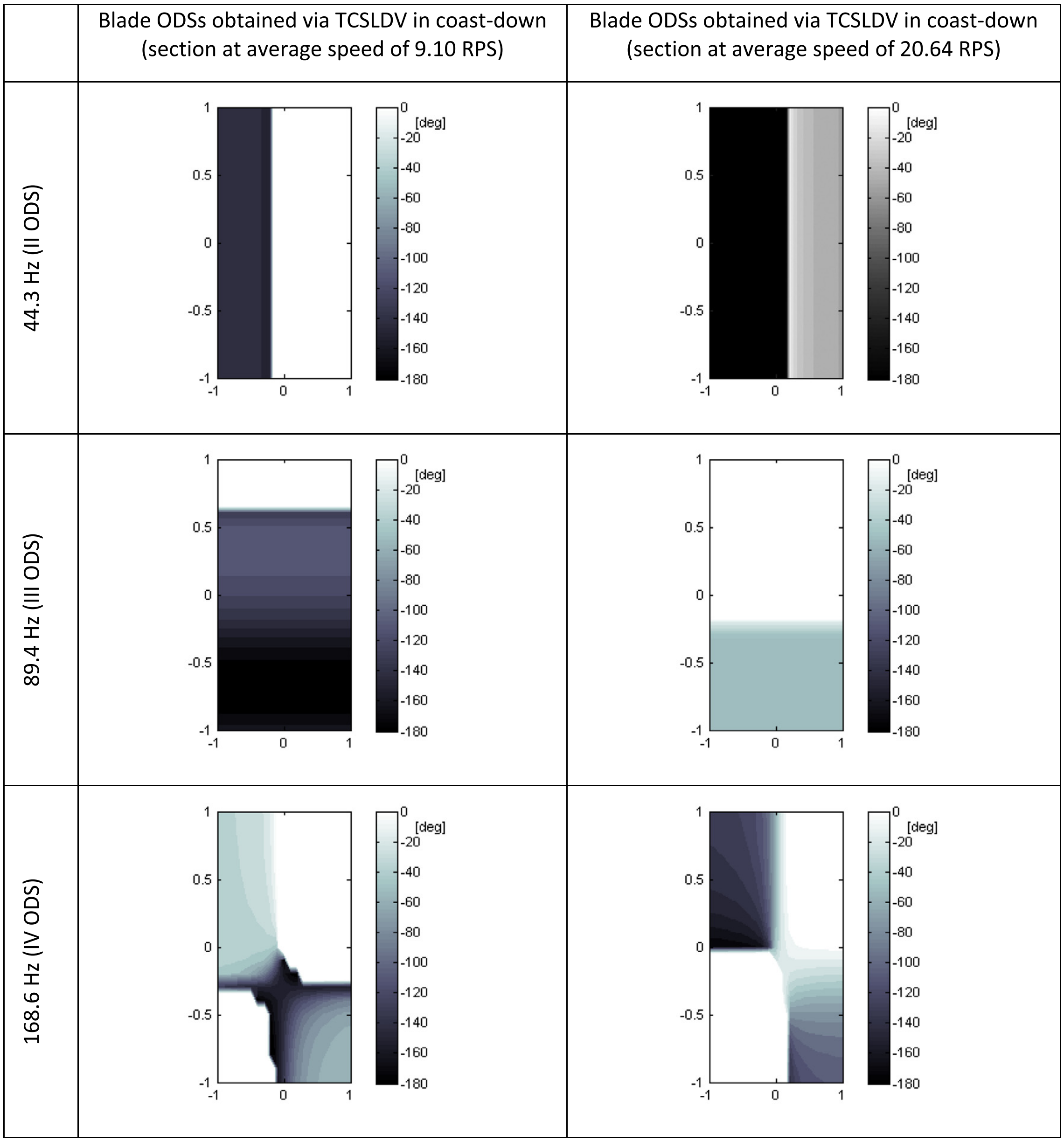


Fig. 24. Blade ODSs obtained via TCSLDV in coast-down (section at average speed of 20.64 RPS) [92].

low-frequency surface waves (f < 100 Hz) propagating over soft materials, namely here gel surfaces-mimicking human body soft tissues-and skeletal muscles, to develop an affordable and non-invasive elastography modality. This setup was used to measure the increase in surface wave velocity (related to the actual stiffening) over the biceps brachii muscle while voluntary contractions at an increasing level occur.

6.3. Land mines detection

Continuous Scanning was also applied to minesweeping because of the ability to scan a large surface rapidly. Several authors investigated in such a matter and literature is reported in [97–102]. The SLDV together with other types of sensors were mounted on a truck which slowly travelled across a land filled with several mock-up mines where the excitation was produced by loudspeakers, or micro-seismic shocks, while the Continuous Scanning was performed. In such specific application, the objective was not to recover the ODS of the land surface as the incredibly high level of speckle-noise would not

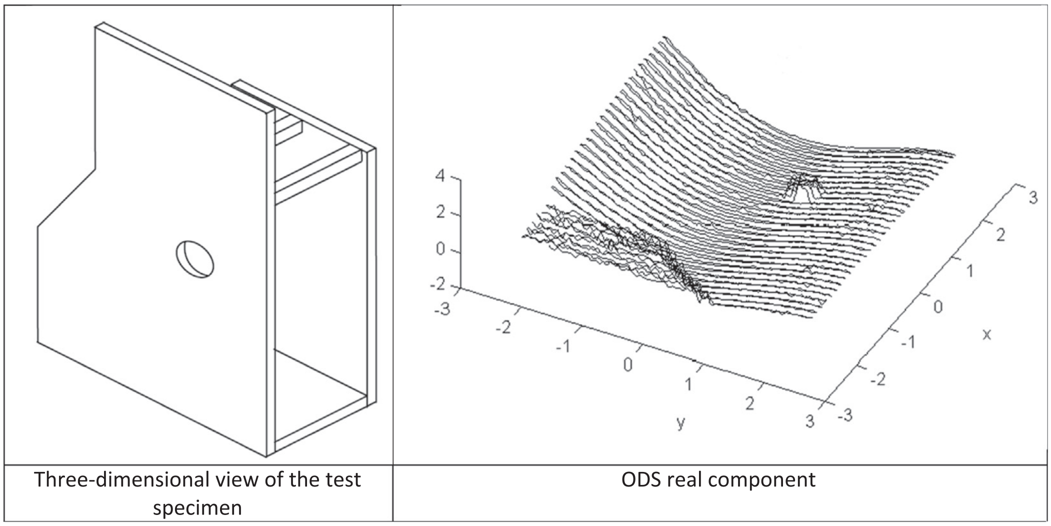


Fig. 25. Example of geometry with hole and nonuniform shape.

allow it. The goal was to investigate and search signatures created by the land mines in the LDV modulated time signal and which had some degree of success but at the cost of expensive signal processing.

7. Practical guidelines and limitations of CSLDV methods

CSLDV technology has been shown to be reliable when applied to multiple DOF vibration response measurements. However, any laser-based measurement technology presents limitations. The most notorious one is noise acquired by the photodetectors and such drawback is already discussed throughout the paper. This section focuses on other types of drawbacks that might help new practitioner to avoid.

The area scan method is a valid alternative to stepped scanning LDV with the advantage of having high-spatial, mostly unlimited resolution and of drastically reducing the testing time. The main drawback of the technique is the need to plan accurately the scanning frequencies for different reasons: (i) in the area scan the scanning frequencies in the two directions must not be integer multiples of each other, (ii) sidebands of one mode have not to coincide with sidebands of a consecutive mode, and this can happen with highly damped structures. However the settings of scanning frequency can be automated by using one of the blind methods presented in Sections 4.6 and 4.7.

Another limitation of the CSLDV is related to the intrinsic property of the laser Doppler vibrometer that measures the velocity of the tested object in the line of sight of the laser light. If the laser and the object surface normal are not aligned a cosine correction must be performed. This correction can be automated, as it is in commercial SLDV, only if the distance between laser head and measurement surface is known. A correction method for CSLDV application on 3D curved surfaces has been presented in [103].

Concerning the scanning area that a CSLDV can measure, although most applications concern plate-like structures, it has been demonstrated that the technique works also with 2D structures with arbitrary shapes. In [103] the SLDV has been used to measure the ODSs of an irregular plate presenting an hole as presented in Fig. 25. Similar challenges presented by cylindrical shape and holes were was also attempted in [55] where an aerospace structure, combustion chamber casing, was continuously scanned by a mirror set at fixed rotation speed while traversing the chamber along its longitudinal axis. The holes could be identified by corrupted data from the reconstructed deformed shape. Already mentioned earlier in the manuscript [58], a cylindrical structure was tested while mounted on turning table. The turning table oscillated at a frequency providing the radial scan rate while the laser beam scanned longitudinally so as to implement an area scan on the cylinder. Another interesting paper [104] shows how the CSLDV can be exploited for generating measuring grids, where geometrical discontinuities, such as holes and edges, generate noisy LDV modulated signals which are very distinguishable from the one measured on the continuous surfaces. Therefore, the data analysis enable to carve out the area which a laser can effectively measure.

As far as it concerns the scanning area, it is worth mentioning that optimization methods to create arbitrary scanning pattern has been presented in [105–107].

8. Conclusions

This review paper draws on the contents of around eighty of the most relevant publications in the subject, but there might still be others scattered in the scientific literature which could not be identified. The review focussed on the three fundamental pillars which are: (i) the Raison d'être, (ii) the Theoretical Background and (iii) the Applications of CSLDV. The main objective of the review is to provide future researchers with a document capable of reconstructing the evolution of Continuous Scanning methods across various research fields. In this review, Continuous Scanning was explained through the use of a scanning LDV system which best exploits the Continuous Scan mode. However, it should be borne in mind that any type of non-contact sensor could possibly be used in Continuous Scanning mode for retrieving responses which are not limited to vibration analyses but can be extended to thermal, acoustic and fluid response analyses. Within the field of vibration response analysis, the authors believe that there is a still room for extending the potential of the Continuous Scanning philosophy far beyond the actual state-of-the-art, and is not necessarily limited to deflection shape analysis. It is noted that the spectral sidebands are the most important features of the amplitude-modulated time series from CSLDV measurements and these sidebands encompass the most useful information from the response that can be evaluated by several means of data analysis, including the latest one of Artificial Intelligence. The significant advantage of using a laser vibrometer instead of alternatives such as video-based non-contact devices lies mainly in the wide frequency range and the sensitivity to low vibration amplitudes. These two characteristics enable CSLDV techniques to interrogate the vibration energy across higher-order harmonics, which are typically high frequencies and low amplitudes.

Funding

No funding were received for this piece of work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to dedicate this paper to the late A.B. Stanbridge who often reminded young and enthusiastic researchers that research is "99% perspiration and 1% inspiration!".

References

[1] S.J. Rothberg et al, An international review of laser doppler vibrometry: making light work of vibration measurement, Opt. Lasers Eng. 99 (2017), https://doi.org/10.1016/j.optlaseng.2016.10.023.
[2] W.L. Kuriger, A laser doppler velocimeter employing a scanning interferometer, Proc. IEEE 57 (12) (1969) 2161.
[3] B. Stoffregen, A. Felske, Scanning laser Doppler vibration analysis system, SAE Trans. (1985) 934–940.
[4] D. Francis, R.P. Tatam, R.M. Groves, Shearography technology and applications: a review, Meas. Sci. Technol. 21 (10) (2010) 102001.
[5] M. Georges, "Holographic Interferometry: From History to Modern Applications," in Optical Holography-Materials, Theory and Applications, Elsevier, 2020, pp. 121–163.
[6] X. Xie, L. Yang, X. Chen, N. Xu, and Y. Wang, "Review and comparison of temporal-and spatial-phase shift speckle pattern interferometry for 3D deformation measurement," in Sixth International Symposium on Precision Mechanical Measurements, 2013, vol. 8916, p. 89160D.
[7] A. Mujeeb, V.U. Nayar, V.R. Ravindran, Electronic Speckle Pattern Interferometry techniques for non-destructive evaluation: a review, Insight-Non-Destructive Test. Cond. Monit. 48 (5) (2006) 275–281.
[8] J.R. Tyrer, Critical review of recent developments in electronic speckle pattern interferometry, Holographic Nondestruct. Test. 604 (1986) 95–111.
[9] J.N. Petzing, J.R. Tyrer, Recent developments and applications in electronic speckle pattern interferometry, J. Strain Anal. Eng. Des. 33 (2) (1998) 153–169.
[10] L. Yang, X. Xie, L. Zhu, S. Wu, Y. Wang, Review of electronic speckle pattern interferometry (ESPI) for three dimensional displacement measurement, Chinese J. Mech. Eng. 27 (1) (2014) 1–13.
[11] P. Chiariotti, C. Rembe, P. Castellini, M. Allen, Laser doppler vibrometry measurements in structural dynamics, Handb. Exp. Struct. Dyn. (2020) 1–45.
[12] E.P. Tomasini, P. Castellini, *Laser Doppler Vibrometry: A Multimedia Guide to its Features and Usage*. Springer, Nature (2020).
[13] P. Castellini, M. Martarelli, E.P. Tomasini, Laser doppler vibrometry: development of advanced solutions answering to technology's needs, Mech. Syst. Signal Process. 20 (6) (Aug. 2006) 1265–1285, https://doi.org/10.1016/j.ymssp.2005.11.015.
[14] T.J. Beberniss, D.A. Ehrhardt, High-speed 3D digital image correlation vibration measurement: Recent advancements and noted limitations, Mech. Syst. Signal Process. 86 (2017) 35–48.
[15] M.N. Helfrick, C. Niezrecki, P. Avitabile, T. Schmidt, 3D digital image correlation methods for full-field vibration measurement, Mech. Syst. Signal Process. 25 (3) (2011) 917–927.
[16] M. Martarelli, Exploiting the laser scanning facility for vibration measurements, Technology & Medicine University of London Expl, Imperial College of Science, 2001.
[17] S. Hanagud and J. CRAIG, "A scanning laser technique for modal testing of distributed parameter systems," in 30th Structures, Structural Dynamics and Materials Conference, 1989, p. 1292.
[18] P. Sriram, S. Hanagud, J. Craig, N.M. Komerath, Scanning laser Doppler technique for velocity profile sensing on a moving surface, Appl. Opt. 29 (16) (1990) 2409–2417.
[19] P. Sriram, S.V. Hanagud, J.I. Craig, Scanning laser doppler technique for model testing of distributed-parameter systems, AIAA J. 30 (3) (1992) 765–766.
[20] A. B. Stanbridge and D. J. Ewins, "A review of 10 years of continuous-scan LDV developments," in Proceedings of international conference on noise and vibration engineering ISMA2006, 2006, vol. 1, p. 8.
[21] D.J. Ewins, Exciting vibrations: the role of testing in an era of supercomputers and uncertainties, Meccanica 51 (12) (2016) 3241–3258.
[22] A. B. Stanbridge and D. J. Ewins, "MODAL TESTING USING A SCANNING LASER DOPPLER VIBROMETER AB Stanbridge & DJ Ewins Imperial College of Science Technology and Medicine, Exhibition Road, London, SW7 2BX, U.K.," Mech. Syst. Signal Process., 1999.
[23] I. Bucher, "Measuring vibration spatial information using continuous laser scanning," in Third International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 1998, vol. 3411, pp. 409–417.

[24] P. Martin and S. Rothberg, "Laser vibrometry and the secret life of speckle patterns," in Eighth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 2008, vol. 7098, p. 709812.
[25] S. J. Rothberg and B. J. Halkon, "Laser vibrometry meets laser speckle," in Sixth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 2004, vol. 5503, pp. 280–291.
[26] S. Rothberg, Numerical simulation of speckle noise in laser vibrometry, Appl. Opt. 45 (19) (2006) 4523–4533.
[27] S.J. Rothberg, J.R. Baker, N.A. Halliwell, Laser vibrometry: pseudo-vibrations, J. Sound Vib. 135 (3) (1989) 516–522.
[28] M. Martarelli, D.J. Ewins, Continuous scanning laser Doppler vibrometry and speckle noise occurrence, Mech. Syst. Signal Process. 20 (8) (2006) 2277–2289.
[29] M. W. Sracic and M. S. Allen, "Experimental investigation of the effect of speckle noise on continuous scan laser Doppler vibrometer measurements," in 27th International Modal Analysis Conference (IMAC XXVII), 2009.
[30] A. B. Stanbridge and D. J. Ewins, "Measurement of total vibration at a point using a conical-scanning LDV," in Second International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 1996, vol. 2868, pp. 126–136.
[31] A.B. Stanbridge, D.J. Ewins, Measurement of translational and angular vibration using a scanning laser Doppler vibrometer, Shock Vib. 3 (2) (1996) 141–152.
[32] P. Giuliani, D. Di Maio, C. W. Schwingshackl, M. Martarelli, and D. J. Ewins, "Six degrees of freedom measurement with continuous scanning laser doppler vibrometer," Mech. Syst. Signal Process., vol. 38, no. 2, 2013, doi: 10.1016/j.ymssp.2013.01.004.
[33] D. Di Maio, E. Copertaro, Experimental validation of a newly designed 6 degrees of freedom scanning laser head: application to three-dimensional beam structure, Rev. Sci. Instrum. 84 (12) (2013), https://doi.org/10.1063/1.4845535.
[34] A.B. Stanbridge, D.J. Ewins, Modal testing using a scanning laser doppler vibrometer, Mech. Syst. Signal Process. 13 (2) (1999) 255–270, https://doi.org/10.1006/mssp.1998.1209.
[35] M.S. Allen, M.W. Sracic, A new method for processing impact excited continuous-scan laser Doppler vibrometer measurements, Mech. Syst. Signal Process. 24 (3) (2010) 721–735.
[36] S. Yang and M. S. Allen, "Harmonic transfer function to measure translational and rotational velocities with continuous-scan laser Doppler vibrometry," J. Vib. Acoust., vol. 136, no. 2, 2014.
[37] S. Yang, M. W. Sracic, and M. S. Allen, "Two algorithms for mass normalizing mode shapes from impact excited continuous-scan laser Doppler vibrometry," J. Vib. Acoust., vol. 134, no. 2, 2012.
[38] S. Yang, M.S. Allen, Output-only modal analysis using continuous-scan laser Doppler vibrometry and application to a 20 kW wind turbine, Mech. Syst. Signal Process. 31 (2012) 228–245.
[39] P. Castellini, F. Sopranzetti, M. Martarelli, Re-sampling of continuous scanning LDV data for ODS extraction, Mech. Syst. Signal Process. 72 (2016) 667–677.
[40] P. Castellini, F. Sopranzetti, M. Martarelli, and E. P. Tomasini, "Continuous scanning LDV by signal re-sampling method: A new signal processing approach," in Topics in Modal Analysis II, Volume 6, Springer, 2012, pp. 443–452.
[41] P. Castellini et al., "Recovery of operational deflection shapes from noise-corrupted measurement data from CSLDV: Comparison between polynomial and mode filtering approaches," in Conference Proceedings of the Society for Experimental Mechanics Series, 2014, vol. 8, pp. 83–91, doi: 10.1007/978-3-319-04774-4_8.
[42] P. Chiariotti, M. Martarelli, P. Castellini, Mode matching of continuous scanning laser doppler vibration data in the frequency domain, Opt. Lasers Eng. 107 (2018) 231–240.
[43] P. Castellini, P. Chiariotti, and M. Martarelli, "Mode filtering of continuous scanning laser doppler vibration data," in Topics in Modal Analysis, Volume 7, Springer, 2014, pp. 655–660.
[44] L. Mignanelli, P. Chiariotti, P. Castellini, and M. Martarelli, "Blind Identification of Operational Deflection Shapes from Continuous Scanning Laser Doppler Vibrometry Data," in Sensors and Instrumentation, Volume 5, Springer, 2016, pp. 105–111.
[45] D. Di Maio and D. J. Ewins, "Continuous Scan, a method for performing modal testing using meaningful measurement parameters; Part i," Mech. Syst. Signal Process., vol. 25, no. 8, 2011, doi: 10.1016/j.ymssp.2011.05.018.
[46] D. Di Maio and D. J. Ewins, "Advanced modal testing using continous scanning LDV methods," in Proceedings of the 8th International Conference on Structural Dynamics, EURODYN 2011, 2011.
[47] S. Vanlanduit, P. Guillaume, J. Schoukens, Broadband vibration measurements using a continuously scanning laser vibrometer, Meas. Sci. Technol. 13 (10) (2002) 1574.
[48] D. Di Maio, G. Carloni, and D. J. Ewins, "Simulation and validation of ODS measurements made using a Continuous SLDV method on a beam excited by a pseudo random signal," in Conference Proceedings of the Society for Experimental Mechanics Series, 2011, vol. 3, no. PART 1.
[49] R. Ribichini, D. Di Maio, A. B. Stanbridge, and D. J. Ewins, "Investigations on a novel technique for experimental structural dynamics: theoretical analysis of impact testing using CSLDV," in Eighth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 2008, vol. 7098, p. 709807, doi: 10.1117/12.802918.
[50] R. Ribichini, D. Di Maio, A. B. Stanbridge, and D. J. Ewins, "Impact testing with a continuously-scanning LDV," in Conference Proceedings of the Society for Experimental Mechanics Series, 2008.
[51] D.A. Ehrhardt, M.S. Allen, S. Yang, T.J. Beberniss, Full-field linear and nonlinear measurements using continuous-scan laser doppler vibrometry and high speed three-dimensional digital image correlation, Mech. Syst. Signal Process. 86 (2017) 82–97.
[52] D.A. Ehrhardt, M.S. Allen, Measurement of nonlinear normal modes using multi-harmonic stepped force appropriation and free decay, Mech. Syst. Signal Process. 76 (2016) 612–633.
[53] E. Copertaro, P. Chiariotti, M. Martarelli, and P. Castellini, "Exploiting Laser Doppler Vibrometry in Large Displacement Tests," in Rotating Machinery, Vibro-Acoustics & Laser Vibrometry, Volume 7, Springer, 2019, pp. 199–205.
[54] M. Allen and D. Aguilar, "Model validation of a bolted beam using spatially detailed mode shapes measured by continuous-scan laser doppler vibrometry," in 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 17th AIAA/ASME/AHS Adaptive Structures Conference 11th AIAA No, 2009, p. 2653.
[55] C.W. Schwingshackl, L. Massei, C. Zang, D.J. Ewins, A constant scanning LDV technique for cylindrical structures: Simulation and measurement, Mech. Syst. Signal Process. 24 (2) (2010) 394–405.
[56] C. Zang, D. Di Maio, N. Zampognaro, and D. J. Ewins, "FE model updating with the measured data obtained from the CSLDV technique," in Proceedings of SPIE - The International Society for Optical Engineering, 2006, vol. 6345, doi: 10.1117/12.693079.
[57] A. B. Stanbridge, P. R. Ind, and D. J. Ewins, "Line Coupling of Axisymmetric Substructures Using a Continuous–Scan LDV," in Proceedings of Conference and Exposition on Structural Dynamics. IMAC, Kissimmee, Florida, 2003.
[58] A. B. Stanbridge, P. R. Ind, and D. J. Ewins, "Measuring vibration of cylindrical surfaces using a continuous-scan LDV," in Sixth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 2004, vol. 5503, pp. 249–259.
[59] A.Z. Khan, A.B. Stanbridge, D.J. Ewins, Detecting damage in vibrating structures with a scanning LDV, Opt. Lasers Eng. 32 (6) (1999) 583–592.
[60] A.B. Stanbridge, M. Martarelli, D.J. Ewins, Measuring strain response mode shapes with a continuous-scan LDV, Shock Vib. 9 (1–2) (2002) 19–27, https://doi.org/10.1155/2002/543754.
[61] D. Di Maio, N. Zampognaro, C. Zang, and D. J. Ewins, "Effect of vibration excitation locations on structural damage detection using the CSLDV technique: simulation and testing," 2006, vol. 6345, pp. 63450O-63450O–10.
[62] D. Di Maio, C. Zang, and D. J. Ewins, "Identification of damage location using operational deflection shape (ODS)," in Conference Proceedings of the Society for Experimental Mechanics Series, 2007.
[63] D. Di Maio, "Use Of Continuous Scanning LDV For Diagnostics," in International Modal Analysis Conference (IMAC), 2016.

[64] S. Bruinsma, D. Di Maio, T. Tinga, Diagnostics based on continuous scanning LDV methods: numerical study, J. Phys. Conf. Ser. 1149 (1) (2018) 12012.
[65] D. Di Maio, "Damage monitoring using Continuous Scanning LDV methods: numerical approach.," in OPTIMESS2015, 2015.
[66] P. Chiariotti, G. M. Revel, and M. Martarelli, "Exploiting Continuous Scanning Laser Doppler Vibrometry and Wavelet Processing for Damage Detection," in Experimental Techniques, Rotating Machinery, and Acoustics, Volume 8, Springer, 2015, pp. 189–196.
[67] P. Chiariotti, M. Martarelli, G.M. Revel, Delamination detection by multi-level wavelet processing of continuous scanning laser doppler vibrometry data, Opt. Lasers Eng. 99 (2017) 66–79.
[68] D.-M. Chen, Y. F. Xu, and W. D. Zhu, "Damage identification of beams using a continuously scanning laser doppler vibrometer system," J. Vib. Acoust., vol. 138, no. 5, 2016.
[69] D.-M. Chen, Y.F. Xu, W.D. Zhu, Experimental investigation of notch-type damage identification with a curvature-based method by using a continuously scanning laser doppler vibrometer system, J. Nondestruct. Eval. 36 (2) (2017) 38.
[70] D.-M. Chen, Y.F. Xu, W.D. Zhu, Non-model-based multiple damage identification of beams by a continuously scanning laser Doppler vibrometer system, Measurement 115 (2018) 185–196.
[71] D.-M. Chen, Y.F. Xu, W.D. Zhu, Identification of damage in plates using full-field measurement with a continuously scanning laser Doppler vibrometer system, J. Sound Vib. 422 (2018) 542–567.
[72] D.-M. Chen, W.D. Zhu, Investigation of three-dimensional vibration measurement by a single scanning laser Doppler vibrometer, J. Sound Vib. 387 (2017) 36–52.
[73] D.-M. Chen, Y. F. Xu, and W. D. Zhu, "Non-model-based identification of delamination in laminated composite plates using a continuously scanning laser Doppler vibrometer system," J. Vib. Acoust., vol. 140, no. 4, 2018.
[74] D.-M. Chen, Y.F. Xu, W.D. Zhu, A comprehensive study on detection of hidden delamination damage in a composite plate using curvatures of operating deflection shapes, J. Nondestruct. Eval. 38 (2) (2019) 54.
[75] Y.F. Xu, D.-M. Chen, W.D. Zhu, Damage identification of beam structures using free response shapes obtained by use of a continuously scanning laser Doppler vibrometer system, Mech. Syst. Signal Process. 92 (2017) 226–247.
[76] Y.F. Xu, D.-M. Chen, W.D. Zhu, Modal parameter estimation using free response measured by a continuously scanning laser Doppler vibrometer system with application to structural damage identification, J. Sound Vib. 485 (2020) 115536.
[77] Y.F. Xu, D.-M. Chen, W.D. Zhu, Operational modal analysis using lifted continuously scanning laser Doppler vibrometer measurements and its application to baseline-free structural damage identification, J. Vib. Control 25 (7) (2019) 1341–1364.
[78] Z. Huang, C. Zang, Damage detection using modal rotational mode shapes obtained with a uniform rate CSLDV measurement, Appl. Sci. 9 (23) (2019) 4982.
[79] Z. Huang, C. Zang, A fast modal rotation measurement using a dual sinusoidal-scan continuously scanning laser doppler vibrometer, Meas. Sci. Technol. (2020).
[80] A. B. Stanbridge, M. Martarelli, and D. J. Ewins, "Rotating disc vibration analysis with a circular-scanning LDV," in Proceedings of SPIE, the International Society for Optical Engineering, 2001, vol. 4359, pp. 464–469.
[81] I. Bucher, P. Schmiechen, D. A. Robb, and D. J. Ewins, "Laser-based measurement system for measuring the vibration on rotating discs," in First International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 1994, vol. 2358, pp. 398–408.
[82] P. Castellini and C. Santolini, "Vibration measurements on blades of naval propeller rotating in water," in Second International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 1996, vol. 2868, pp. 186–194.
[83] P. Castellini, F. Giovanucci, G. Nava-Mambretti, L. Scalise, and E. P. Tomasini, "Vibration analysis of tyre treads: a in-plane laser vibrometry approach," in Society for Experimental Mechanics, Inc, 16 th International Modal Analysis Conference., 1998, vol. 2, pp. 1732–1738.
[84] A. Fioretti, D. Di Maio, D.J. Ewins, P. Castellini, E.P. Tomasini, Deflection shape reconstructions of a rotating five-blade helicopter rotor from TLDV measurements, AIP Conf. Proc. 1253 (2010), https://doi.org/10.1063/1.3455457.
[85] I. A. Sever, A. B. Stanbridge, and D. J. Ewins, "Turbomachinery blade vibration measurements with tracking LDV under rotation," in Seventh International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, 2006, vol. 6345, p. 63450L.
[86] B.J. Halkon, S.R. Frizzel, S.J. Rothberg, Vibration measurements using continuous scanning laser vibrometry: velocity sensitivity model experimental validation, Meas. Sci. Technol. 14 (6) (2003) 773.
[87] B.J. Halkon, S.J. Rothberg, Vibration measurements using continuous scanning laser Doppler vibrometry: theoretical velocity sensitivity analysis with applications, Meas. Sci. Technol. (2003).
[88] B.J. Halkon, S.J. Rothberg, Vibration measurements using continuous scanning laser vibrometry: advanced aspects in rotor applications, Mech. Syst. Signal Process. 20 (6) (2006) 1286–1299.
[89] S.J. Rothberg, M. Tirabassi, A universal framework for modelling measured velocity in laser vibrometry with applications, Mech. Syst. Signal Process. 26 (2012) 141–166.
[90] D. Di Maio, D.J. Ewins, Applications of continuous tracking SLDV measurement methods to axially symmetric rotating structures using different excitation methods, Mech. Syst. Signal Process. 24 (8) (2010) 3013–3036.
[91] A. Gasparoni, M.S. Allen, S. Yang, M.W. Sracic, P. Castellini, E.P. Tomasini, Experimental modal analysis on a rotating fan using tracking-CSLDV, AIP Conf. Proc. 1253 (1) (2010) 3–16.
[92] M. Martarelli, P. Castellini, C. Santolini, E.P. Tomasini, Laser Doppler vibrometry on rotating structures in coast-down: resonance frequencies and operational deflection shape characterization, Meas. Sci. Technol. 22 (11) (2011) 115106.
[93] P. Chiariotti, M. Martarelli, G.M. Revel, Exploiting continuous scanning laser Doppler vibrometry (CSLDV) in time domain correlation methods for noise source identification, Meas. Sci. Technol. 25 (7) (2014) 75204.
[94] M. Salman, K.G. Sabra, Broadband measurement of translational and angular vibrations using a single continuously scanning laser Doppler vibrometer, J. Acoust. Soc. Am. 132 (3) (2012) 1384–1391.
[95] M. Salman, K.G. Sabra, Synchronized vibrations measurements at multiple locations using a single continuously scanning laser Doppler vibrometer. Applications to non-contact sensing of human body vibrations, J. Acoust. Soc. Am. 130 (4) (2011) 2394.
[96] M. Salman, K.G. Sabra, Surface wave measurements using a single continuously scanning laser doppler vibrometer: application to elastography, J. Acoust. Soc. Am. 133 (3) (2013) 1245–1254.
[97] V. Aranchuk, A.K. Lal, C.F. Hess, J.M. Sabatier, Multi-beam laser Doppler vibrometer for landmine detection, Opt. Eng. 45 (10) (2006) 104302.
[98] R. Burgett, V. Aranchuk, J. Sabatier, and S. S. Bishop, "Demultiplexing multiple-beam laser Doppler vibrometry for continuous scanning," in Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XIV, 2009, vol. 7303, p. 73030I.
[99] V. Aranchuk, A. K. Lal, H. Zhang, C. F. Hess, and J. M. Sabatier, "Acoustic sensor for landmine detection using a continuously scanning multibeam LDV," in Detection and Remediation Technologies for Mines and Minelike Targets IX, 2004, vol. 5415, pp. 61–69.
[100] V. Aranchuk et al., "Speckle noise in a continuously scanning multibeam laser Doppler vibrometer for acoustic landmine detection," in Detection and Remediation Technologies for Mines and Minelike Targets XI, 2006, vol. 6217, p. 621716.
[101] N. Xiang and J. M. Sabatier, "Acoustic-to-seismic landmine detection using a continuously scanning laser Doppler vibrometer," in Detection and Remediation Technologies for Mines and Minelike Targets VIII, 2003, vol. 5089, pp. 591–595.
[102] R. D. Costley, V. Valeau, and N. Xiang, "Continuous scanning laser Doppler vibrometer for mine detection," in Detection and Remediation Technologies for Mines and Minelike Targets V, 2000, vol. 4038, pp. 711–718.
[103] A. B. Stanbridge, M. Martarelli, and D. J. Ewins, "Measuring area mode shapes with a scanning laser Doppler vibrometer," Proc. IMAC XVII, 1999.
[104] L. Pesaresi and C. W. Schwingshackl, "Automated measurement grid generation for scanning laser doppler vibrometers," in Topics in Modal Analysis, Volume 7, Springer, 2014, pp. 645–653.

[105] B. Weekes, D. Ewins, Multi-frequency, 3D ODS measurement by continuous scan laser Doppler vibrometry, Mech. Syst. Signal Process. 58 (2015) 325–339.
[106] B. Weekes, D. Ewins, F. Acciavatti, Continuous-scanning laser Doppler vibrometry: Extensions to arbitrary areas, multi-frequency and 3D capture, AIP Conf. Proc. 1600 (1) (2014) 361–376.
[107] L.I.U. Cuihong, Z. Chaoping, Z. Biao, Extension of continuous scanning laser Doppler vibrometry measurement for complex structures with curved surfaces, Chin. J. Aeronaut. (2020).