OPTICAL METHODS FOR VIBRATION MEASUREMENTS IN NUCLEAR APPLICATIONS

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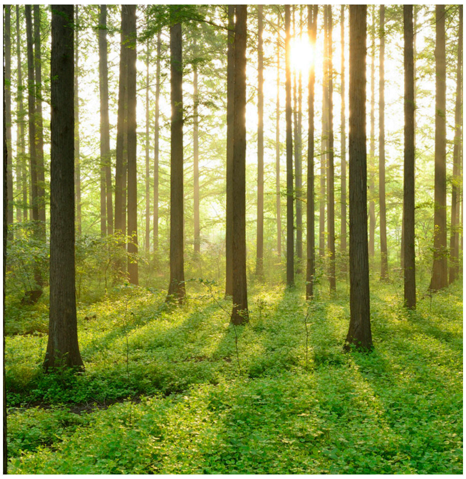

NUCLEAR

VIBRATIONS IN
NUCLEAR APPLICATIONS

Energiforsk

Optical methods for vibration measurements in nuclear applications

Survey

KALLE RAUNIO, VESA NIEMINEN AND JUHA VIRTANEN

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Foreword

Vibration problems in nuclear power plants can lead to extensive loss of income due to operating at reduced power, or even to down time. Having up to date vibration monitoring systems is an important tool to discover problems early and analyse to find the root cause.

The objective of this project was to map different kinds of commercially available optical vibration measurement methods and tools that can be used in a nuclear power plant. The different methods and tools have been compared according to different features. Opportunities and drawbacks with these novel systems are compared to traditional techniques.

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These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Sammanfattning

Syftet med denna undersökning var att identifiera och samla in information om tillgängliga metoder för optisk vibrationsmätning, som skulle kunna användas för att mäta på olika komponenter i kärnkraftsanläggningar.

Den tekniska utvecklingen av utrustning och metoder för att mäta vibrationer har avancerat snabbt under de senaste åren. Det finns numera ett brett utbud av olika metoder för att mäta och analysera komponenters vibrationsbeteende och -egenskaper. Vilken metod som bör väljas beror på vilken komponent som ska analyseras, de förutsättningar som råder på mätstället och vilken information man har behov av. Kunskap om olika metoders förutsättningar, egenskaper och lämplighet, och naturligtvis också kostnader, är därför värdefull.

Vibrationsmätning i kärnkraftsapplikationer kräver mätmetoder och utrustning som är enkel att använda och som effektivt skapar användbara resultat. Genom att studera det en komponents vibrationsbeteende kan man hitta problem, och få ledtrådar vad gäller fortsatt analys eller för nödvändiga serviceåtgärder. Moderna optiska mätmetoderna väl lämpade att användas för att fånga en helhetsbild av vibrationsbeteendet hos en konstruktion eller komponent. De kan användas som ett komplement till permanenta sensorbaserade mätsystem eller som enda mätteknik. Optiska mätmetoder som är baserade på en kontaktlös mätprincip är effektiva för sådana vibrationsmätningar, där information behövs snabbt för att kunna bestämma hur man ska gå vidare med vibrationsproblemet. Olika metoder kräver olika lång förberedelsetid.

I projektet har relevanta optiska mätmetoder som kan fånga helhetsvibrationsbeteenden hos komponenter som är relevanta i kärnkraftsapplikationer kartlagts. I denna studie beaktas endast stationära strukturer eller komponenter som turbiner, generatorer, dieselgeneratoraggregat, rörledningar och tryckkärl. Endast helhetsbeteende studeras, inte exempelvis lokala deformationer. Vanligtvis räcker totala vibrationsnivåer och möjligen några viktiga naturliga frekvenser och moder för att identifiera potentiella problem i strukturer eller komponenter.

Endast metoder som redan finns tillgängliga som kommersiella produkter och som också har testats i liknande tillämpningar har utvärderats. För varje metod presenteras relevanta för- och nackdelar. Resultaten är sammanfattade i en tabell som jämför olika funktioner och egenskaper hos de studerade optiska mätmetoderna.

Denna studie är baserad på en omfattande litteraturöversikt, tillgänglig kommersiell produktinformation och diskussioner med företrädare för deltagande kärnkraftverk (NPP). Dessutom har författarnas bakgrund och kunnande om vibrationsmätmetoder och mätteknik använts i denna studie.

Summary

The aim of this survey was to identify and gather information relating to available optical methods for vibration measurements, which could be applicable to the nuclear industry machinery.

Technological development of equipment and methods for measuring vibrational stage of machinery have been quite fast during past years. There exists nowadays a wide range of different methods for capturing vibration behavior and target characteristics. However, depending on the need, usually only certain methods are preferable, requiring an understanding of measurement method principles, features and suitability, and of course, also measurement costs.

Especially in nuclear applications, a measurement method and equipment capable of straightforward vibration trouble-shooting tasks is needed. Usually, it is necessary to capture quite effectively the vibrational status of potential targets, in order to be able to identify problematic targets or to allocate more sophisticated measurement methods or necessary service actions. If permanent and traditional sensor-based measurements are omitted, modern optical measurement methods are quite attractive for capturing overall vibrational behavior of a target structure or machine. Further, based on a non-touch measuring principle, optical measuring methods are effective for this kind of vibration measurement purposes. However, the measurement setup preparation time depends on the method used.

This survey gathers all relevant optical measurement methods for capturing overall vibrational behavior of target structures, which are relevant in nuclear applications. In this case, only stationary structures or machinery are considered, like turbines, generators, emergency power units, piping and pressure vessels. In addition, only macro-scale behavior is relevant, for example, capturing of strain information is not included. Usually, overall vibration levels and possible captured eigenfrequencies and -modes of the target are enough for pointing out potentially problematic structures or machines.

This survey gathers potential optical measurement methods suitable in nuclear applications. Only methods, which are already available as a commercial product and also tested in full scale applications have been evaluated. From each method, relevant pros and cons, when considered for above-mentioned purposes, are presented. In addition, a table for compiling features and properties the optical measurement methods was constructed in order to be easily compared with each other.

This study was based on extensive literature review, available commercial product information and discussions with representatives of few nuclear power plant (NPP) representatives. In addition, writers' background on general vibration measurement methods and technologies has been utilized.

Abbreviations

3DPT	3D point-tracking
3D DIC	3D Digital image correlation
CCD	Charge-Coupled Device
CSLDV	Continuous scanning laser Doppler vibrometry
DIC	Digital image correlation
EMA	Experimental modal analysis
ESPI	Electronic speckle pattern interferometry
FOV	Field of view
FPS	Frames per second
LDV	Laser Doppler vibrometry
MB-LDV	Multi-beam laser vibrometry
NPP	Nuclear power plant
ODS	Operational deflection shape
OMA	Operational modal analysis
PM	Preventive maintenance
PME	Phase-based motion estimation
PmD	Predictive maintenance
PRM	Proactive reliability Maintenace
RM	Reactive maintenance
ROI	Region of interest
SLDV	Scanning laser Doppler vibrometry
SNR	Signal-to-noise ratio
SWIR	Short-Wavelength-Infrared
WF-LDV	Whole field laser Doppler vibrometry

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1 Introduction

The aim of this survey was to identify and gather information relating to available optical methods for vibration measurements, which could be applicable to the nuclear industry machinery.

Technological development of equipment and methods for measuring vibrational stage of machinery have been quite fast during past years. There exists nowadays a wide range of different methods for capturing vibration behavior and target characteristics. However, depending on the need, usually only certain methods are preferable, requiring an understanding of measurement method principles, features and suitability, and of course, also measurement costs.

Especially in nuclear applications, a measurement method and equipment capable of straightforward vibration trouble-shooting tasks is needed. Usually, it is necessary to capture quite effectively the vibrational stage of potential targets, in order to be able to identify problematic targets or to allocate more sophisticated measurement methods or necessary service actions. If permanent and traditional sensor-based measurements are omitted, modern optical measurement methods are quite attractive for capturing overall vibrational behavior of a target structure or machine. Further, based on a non-touch measuring principle, optical measuring methods are effective for this kind of vibration measurement purposes. However, the measurement setup preparation time depends on the method used.

This survey presents identified measurement methods for optical vibration measurement for nuclear applications. As this document will be publicly available, all material used in this survey, in addition to writers' background knowledge, has been collected from the publicly available sources, literature and commercial equipment providers.

1.1 MOTIVATION

Motivation for the survey was based on a fact, that a wide range of new optical measuring methods and equipment for vibration measurements has been introduced during recent years. However, suitability of these methods especially for nuclear power plant environment have not been investigated. In order to find out the potential methods for nuclear applications, principles, properties, features and limitations of available methods have been evaluated in this report.

The following scope and requirements for the measurement system were set:

- Main scope: optical vibration measurement methods for trouble-shooting purposes in nuclear power plant environment
- Commercially available measurement systems and equipment
- Responses considered: vibrations, eigenfrequencies/modes
- Macro-scale vibration behavior (ie. no strains)
- Only stationary structures considered as targets: turbines, generators, emergency power units, pipings, pressure vessels
- Extensive enough inspection area

- Limited pretreatment needs for measured targets or surfaces
- Radiation resistance of measurement equipment not considered in this survey

1.2 STRUCTURE OF THE REPORT

Report consist of six main sections. The first section is the introduction where motivation and structure of the report is defined.

In the second section, optical measurement principles and all identified technologies are presented.

Identified technologies suitability to nuclear power plant environment is being discussed in the third section and compared with each other.

The fourth section discovers different parties working on identified optical vibration measurement techniques. In addition, a set of identified commercial solutions are listed.

The fifth section presents examples of the potential future prospects and current research topics of optical vibration measurement.

The final section summarizes findings of the survey and proposes the most suitable technologies for NPP vibration monitoring.

2 Optical Vibration Measurement Technologies

Vibration monitoring and modal testing is still nowadays typically made with conventional sensors. Optical measurement methods have been developed during recent years from laboratory equipment to industry grade equipment suitable for field measurements. Optical methods have some limitations but so do also conventional ones: what needs to be understood before proper measurement method will be chosen for each application.

Optical vibration measurement methods have multiple advantages compared to the conventional methods. Conventional methods usually require cabling and physical contact to the measured object. This could be especially a challenge if a target of measurement is lightweight and the sensor mass affects the objects natural frequencies. In addition, in extremely hot conditions, conventional sensors are quite often practically impossible. In some cases, increasing number of sensors is also quite often limited due to practical reasons.

In this survey, the aim is to point out possibilities and limitations of optical methods considering nuclear power plant applications. In this chapter, the identified methods are introduced, and principles of each method are described.

2.1 DIGITAL IMAGE CORRELATION

The DIC method is an optical measurement technique that includes image processing and numerical computation to measure full-field displacement, deformation, and strain distributions at the surface of an object as it deforms. The technique requires a stochastic pattern with a good contrast (typically black and white) to be applied on the surface of the test object. Each pixel in the recorded images carries a value of intensity (e.g. with a value of 0 representing black and 100 representing white). The value is then used to help correlating a point in one image of the structure with the same point in another image by using a set of facets (or subsets) and a correlation algorithm, ultimately allowing for the computation of the displacement of the test object subjected to a quasi-static or dynamic loading. [1]

2.1.1 3D DIC

To measure deformation in three dimensions, the general setup requires a stereoscopic system that is based on the use of two cameras. 3D-DIC is a subset-based image matching method that can determine the full-field deformation by matching two images obtained from different views and that correspond to ‘‘before’’ and ‘‘after’’ deformation. The method uses the grayscale arrays of the subset to establish the relationship between the two images by a certain search method. The ‘‘relationship’’ between the subsets is the so-called correlation function. After the correlation matching, the true 3D coordinates of the point (before and after deformation) can be reconstructed using the image coordinates and the calibration parameters of the camera system. The schematic principle of 3D-DIC is presented in Figure 1. [2]

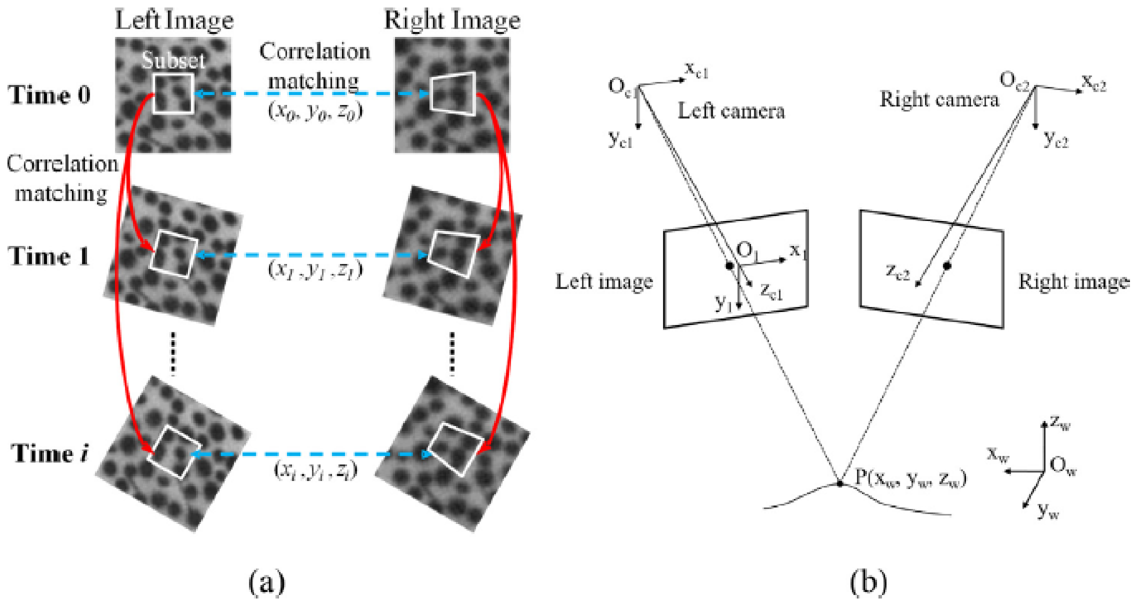

Figure 1. A schematic diagram of the principle of 3D-DIC. (a) Correlation matching procedure, (b) 3D reconstruction procedure involving two cameras [2].

2.1.2 3D point tracking

As opposed to tracking facets of pixels from image to image, 3D point tracking tracks the 3D motion of circular targets. Because discrete targets are being tracked, local strain cannot be calculated, as with DIC, unless numerous targets are used. Three-dimensional (3D) digital image correlation (DIC) and 3D point tracking (3DPT) are both displacement-based approaches that analyse stereo image pairs to measure the 3D motion of surface patterns or specific points, respectively. [3]

Although 3D DIC and 3D point tracking (3DPT) provide smooth mode shapes with high accuracy, these methods generally require a speckle pattern or high contrast markers mounted or painted on the surface of the structure.

2.1.3 Conclusions

The 3D DIC method is suitable for measuring the strain field, vibration as well as operational deflection shapes (ODS) and mode shapes (OMA) with reasonable accuracy. Full-field measurement acquisition time after installation and system calibration is rather fast and therefore the method is suitable for transient phenomena capturing.

Regarding all camera-based methods, the cameras have always a limited field of view and hence it may not be possible to see the entire structure at once, especially considering large structures. Spatial resolution depends how far the measured target is and what FOV(lens) is used for the acquisition.

Illumination needs have to be considered especially when high-speed cameras are used to acquire data from large areas. The pros & cons of 3D-DIC have been collected to Table 1.

Table 1. 3D-DIC pros & cons.

+	High spatial resolution
+	Instantaneous measurement; can reduce the testing time dramatically
+	Non-contact measurement; no mass loading
+	Noise floor of DIC can be in the nanometer range
+	Also strain measurement possible
–	Displacement based measurement; resolution limitations at high frequencies
–	Generally require a speckle pattern or high contrast markers mounted or painted on the surface of the structure
–	Requires calibration using e.g. a small calibration panel to identify the lens distortions and relative locations of the cameras with respect to each other
–	Temporal aliasing possible
–	High computational costs

2.2 VIDEO MOTION MAGNIFICATION

Motion magnification algorithm amplifies small motions in video that are not visible for human eye. Method can detect deflection, movement and vibration from the video of the object being inspected.

Motion magnification approaches can be divided in four different classes: Lagrangian, linear-Eulerian, phase-based Eulerian and Learning-based Eulerian approaches. The principles of these different methods are discussed in the following chapters.

2.2.1 Lagrangian (Layer) Based Motion Magnification

Layer-based motion magnification pipeline is presented in Figure 2.

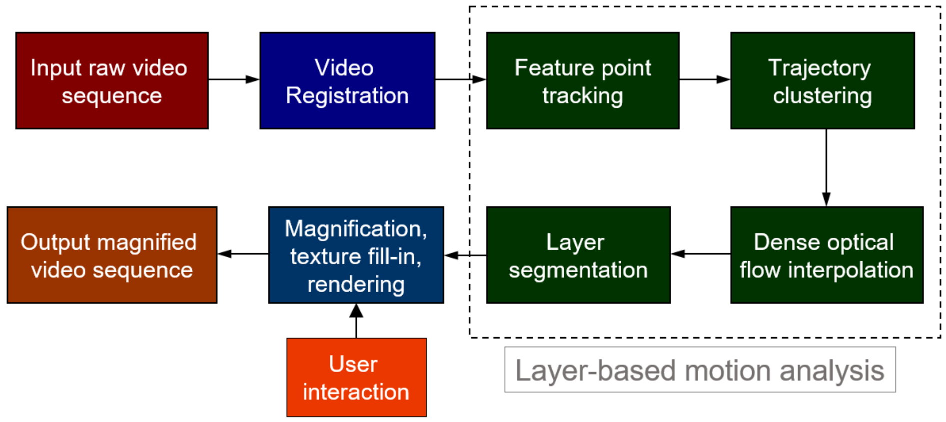

Figure 2. Layer-based motion magnification pipeline.

In Layer-based motion estimation method, algorithm finds reliable feature points from input sequence from where the affine motion is estimated. Clustered feature point trajectories are then derived to motions trajectories. Clustered feature points are segmented into layers using pixel colour, position and motion. User specifies magnification factor for selected motion layers. [4]

The Layer-based method is considered as a Lagrangian approach where the observer is considered to follow the measurement points along the target. In this approach, frame pixels are magnified by using extracted motion field. Lagrangian approach is computation intensive and method has drawback in sense that errors in the estimated motion field are visible in the reconstructed video. [1]

Output examples of Layer-Based motion magnification process phase can be seen in Figure 3.

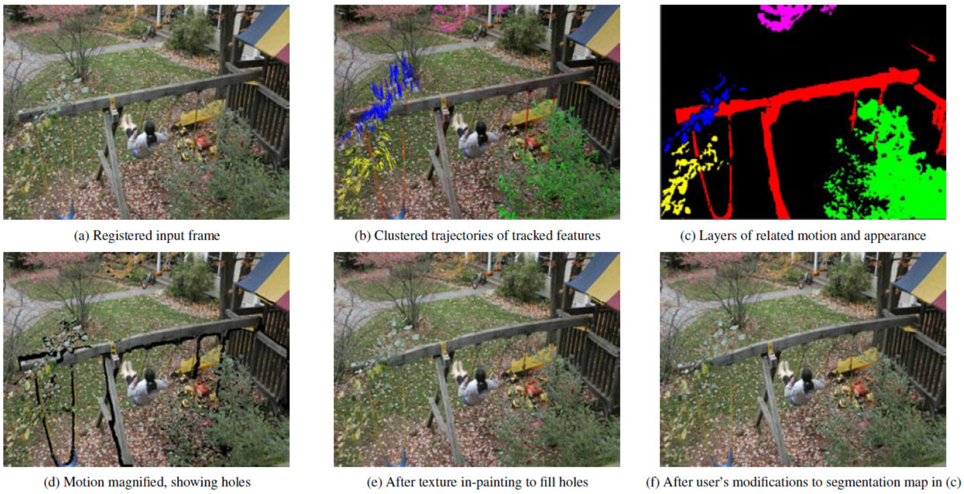

Figure 3. Layer-Based motion magnification process phase outputs (see pipeline phases Figure 2). [4]

2.2.2 Linear Eulerian Video Magnification

Eulerian approach differs from Lagrangian method by its observation angle. In the Eulerian approach, the moving points are observed from a fixed position, while in the Lagrangian approach the observer moves along the points.

In the Eulerian motion magnification algorithm, feature-tracking method is not needed. In the Eulerian method, sub-pixel intensity variation of image sequence is magnified to objects motion.

The main steps of the Eulerian video magnification algorithm are depicted in Figure 4. This Eulerian approach uses Laplacian pyramid smoothing kernels where difference of each level blurred image is saved. Each pyramid level is band pass filtered in time and frequency domain and amplitude of filtered intensity signal is amplified. Amplified images are reconstructed back to video, where motion is magnified at the selected frequency band. This liner Eulerian algorithm is effective but produces some noise and ringing artefacts around magnified areas. [5]

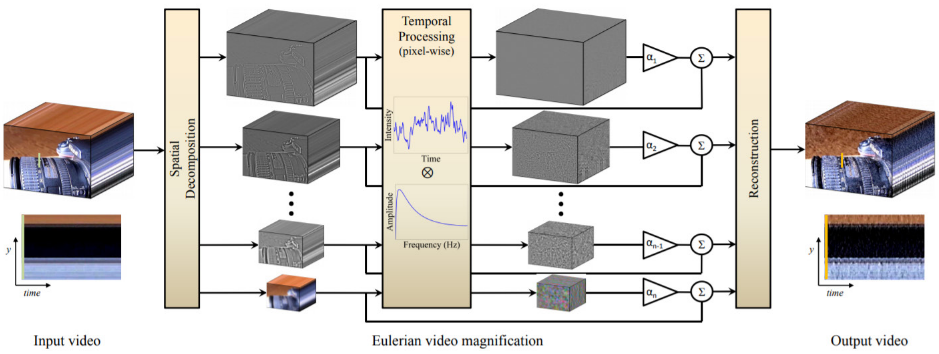

Figure 4. Overview of the Eulerian video magnification framework: Laplacian pyramid, Intensity band pass filtering, Amplifications of filtered intensity signal and video reconstruction. [6]

2.2.3 Phase-Based Video Magnification

The phase-based motion magnification algorithm decomposes the signal of a video into the local spatial amplitude and phase using a complex-valued steerable pyramid filter bank. The local spatial phase signals are temporally Fourier decomposed into a series of sinusoids representing harmonic motion. The phase signals are then temporally band pass filtered, amplified, and recombined back to form a motion magnified video. The result is that the video then has magnification of the motion in a specified band of temporal frequencies. [5]

Phase-based motion magnification technique is improved from Eulerian technique compared to the other methods that picks up the small motion in a series of recorded images based on the Fourier transform shift [1]. The Phase-based motion estimation (PME) mainly originates from the Fourier transform shift theorem, which indicates that the any motion in the spatial domain results in variations to the phase in the frequency domain. [7]

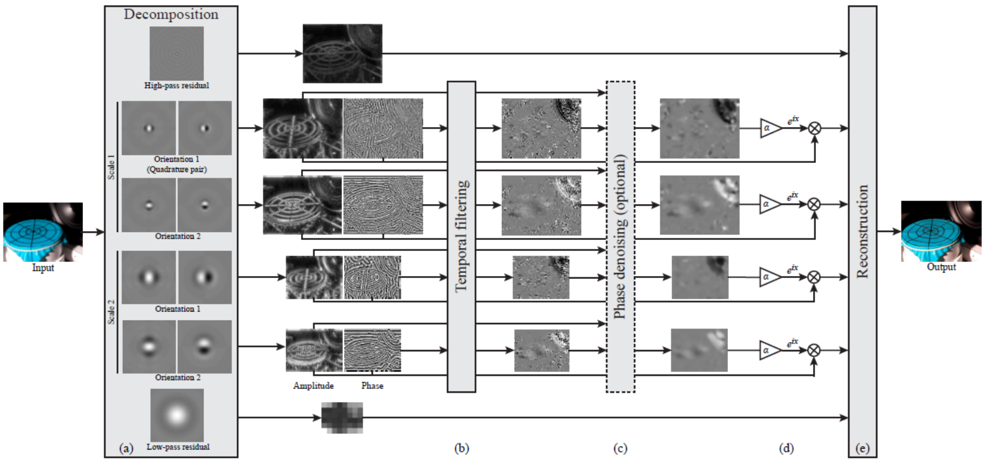

Figure 5. Phase-Based improved Motion magnification workflow: (a) 2D complex steerable pyramid filters decompose the video into amplitude and phase at different scales, (b) the decomposed phases are band pass filtered in frequency, (c) amplitude-weighted smoothing is applied, (d) the band passed phases are amplified or attenuated, and (e) the video is reconstructed [8]

2.2.4 Learning-based Video Motion Magnification

Learning-based video motion magnification method uses deep convolutional neural networks to learn filters automatically from the examples. Learning-based method is also Eulerian approach where decomposition is learned from examples.

In Learning-based method, networks encoder does the spatial decomposition filtering and extracts the shape representation from the frame. Manipulator gets the shape representation as an input and multiplies the difference that magnifies the motion. Convolutional encoder and decoder of the method enables their function at wide resolution range. The method architecture is illustrated in Figure 6.

It is addressed that this approach produces less artefacts and noise than previous methods. [9]

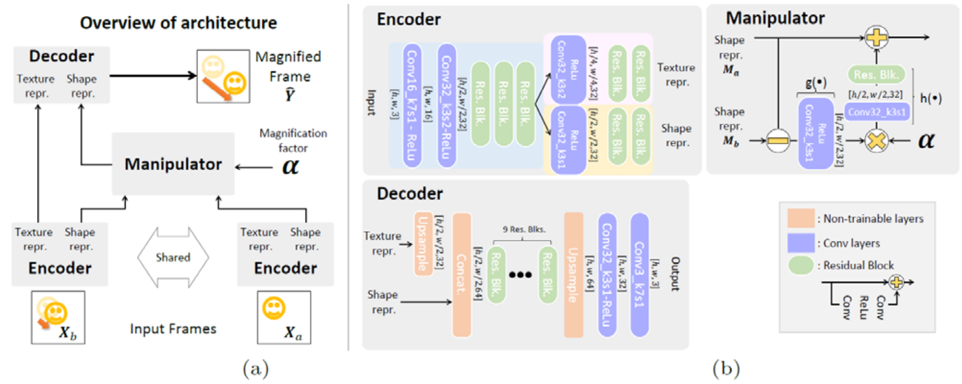

Figure 6. Deep Convolutional Neural Network Architecture consist of three parts: Encoder, Manipulator and Decoder. [9]

2.2.5 Conclusions

All algorithms introduce some artefacts to the result video that needs to be considered when conclusions are made from the motion-magnified video. Additional masking could be used on top of the ROI to mitigate some of the artefacts and speed up the algorithm performance.

Motion magnification is suitable for preliminary troubleshooting at field conditions for large objects. Results should be ensured with standardized methods before deciding on any further (maintenance) actions. If only single camera is used in measurements, motion and vibration detection can be made only in-plane perpendicular to the line-of-sight. Commercial solutions for 3D-measurement using motion magnification is not currently available. Surface preparation is not necessary in motion magnification setup that speeds up the measurement settings. It is possible to run motion magnification algorithms in real-time that makes their usage even more suitable for trouble shooting purposes.

Motion magnification pros & cons are collected to Table 2.

Table 2. Motion magnification pros & cons.

+	No additional surface preparation needed
+	Non-contact measurement; no mass loading
+	Quick measurement setup
+	Fast measurement and analysis; might lead to quick root cause analysis
+	Visual indication; ease of interpret
−	Amplitude resolution limitations
−	Frequency resolution
−	Temporal aliasing possible
−	Illumination conditions; at higher frequencies at indoor
−	Measures only in plane vibrations
−	Poor absolute amplitude measurement accuracy: depends on actual distance to object etc., no on-site calibration

2.3 LASER DOPPLER VIBROMETRY

Laser Doppler Velocimeter (LDV) is a technique used to measure the instantaneous velocity of the target. The laser Doppler velocimeter sends a monochromatic laser beam towards the target and collects the reflected radiation. According to the Doppler effect, the change in wavelength of the reflected radiation is a function of the targeted object's relative velocity. Detection of the Doppler frequency shift, that occurs when light is scattered by a moving surface, is the basis of LDV. This frequency shift is directly proportional to the surface velocity and so its detection enables convenient and non-contact measurement of vibration velocity. Detection is not entirely straightforward as the laser has a frequency typically 6 or 7 orders of magnitude higher than the Doppler shifts, which are typically in the low MHz range. Scattered light from the target has to be mixed interferometrically with a mutually coherent reference beam to produce a beat in the collected light intensity at the difference in frequency between the target and reference beams, i.e. down in the MHz range where demodulation is possible electronically. Such a configuration still leaves a directional ambiguity in the measurement because demodulation only identifies the modulus of the frequency shift. [10]

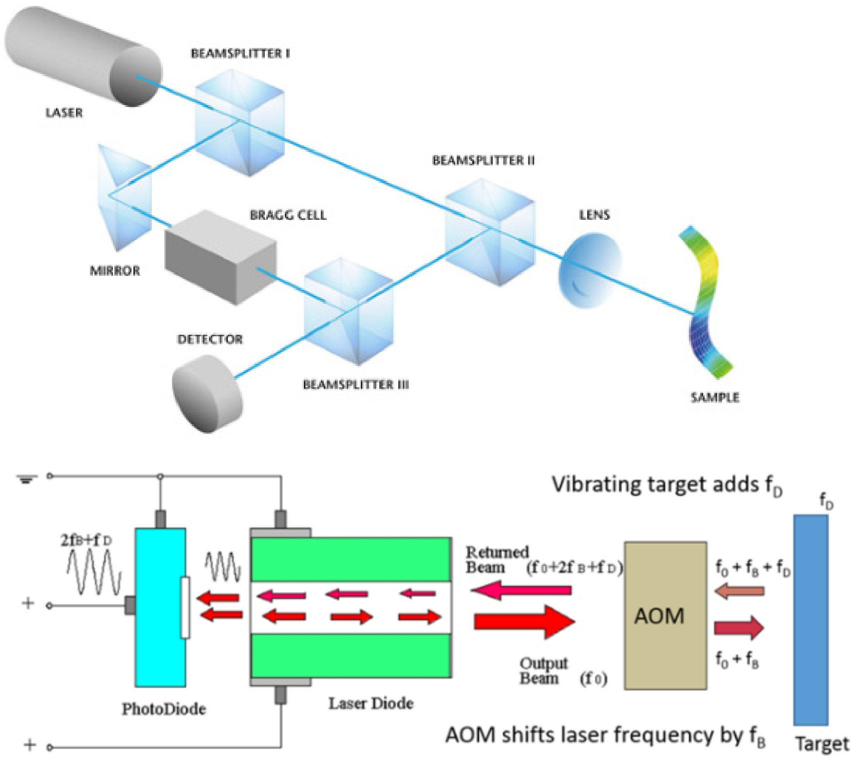

Figure 7. Heterodyne self-mixing interference system schematic (by Polytech and OMS).

Like all optical methods, laser vibrometers are capable to record the response of structures without any mass-loading effects and do not alter structural stiffness. In addition, high spatial resolution may also be achieved, if the laser vibrometers are empowered with precise scanning capabilities. However, laser scanning vibrometers are relatively expensive and the response of the structure is measured sequentially, which increases the measurement time considerably if a high spatial distribution is required.

Laser doppler vibrometry device typically uses either Helium-Neon (HeNe) laser, Short-Wavelength-Infrared (SWIR) laser, or laser diodes. The invisible SWIR laser wavelength is 1550nm and it can use ten times higher power than HeNe laser, and still maintaining eye safety. [11]

Several types of Laser Doppler vibrometers applying the same basic principle exist, which are listed below:

- Single-point Vibrometer
  - × 1D Translational vibration
  - × 1D Torsional vibration by two parallel LDV beams
- Multi-point Vibrometer
- Scanning Vibrometer (SLDV)
- 3D Scanning Vibrometer (3D SLDV)
- Multi-Beam Laser Vibrometer (MB-LDV)
- Tracking laser Doppler vibrometry (TLDV)
- Continuous-scan LDV (CSLDV)

Some of these types are presented briefly in following chapters.

2.3.1 3D SCANNING LASER DOPPLER VIBROMETRY

Scanning LDV (SLDV) measures each point in series making the measurements sequentially. SLDV is automating the relocation of a single laser beam using optical devices (typically a pair of orthogonally mounted galvanometer mirrors) to scan point-by-point across a structure. With SLDV, it is possible to measure rapidly the response with a spatial resolution limited only by the laser beam diameter, typically a few tenths of a millimetre, and the time required to capture each time record. The SLDV has been widely used e.g. in Experimental Modal Analysis (EMA) applications. [10]

Using single SLDV measures naturally only out of plane vibrations in direction of line of sight. Using three SLDVs directed to same measurement point simultaneously, it is possible to measure tri-axial vibration velocity. These three SLDV heads ideally have different Bragg cell frequencies such that any crosstalk is negligible. Today's 3D scanning laser Doppler vibrometry (3D SLDV) state-of-the-art offers automated, tri-axial vibration surveys on large, three-dimensional structures (such as a vehicle) using three SLDVs each mounted on a robot arm, Figure 8. [10] Another example of 3D SLDV setup is shown in Figure 9.

Figure 8. 3D SLDV on a whole vehicle body: instruments mounted on a robot arm [10].

Figure 9. Setup of the 3D SLDV system (Polytech)

2.3.2 Multi-Beam Laser Vibrometer

The multi-beam laser vibrometer (MB-LDV) can measure from several points simultaneously, presented in Figure 10. This technology has many advantages over the single beam scanning method. The modal vibration patterns can be calculated from the relative phase between the measurement positions with one measurement. Multi-beam LDV system has also shorter measurement time than single beam systems for the same inspection area. MB-LVD system is usually customized to customer needs and currently available MB-LDV systems have 8 to

16 beams in the pattern. However, this method is limited with flexibility on beam orientations. [12]

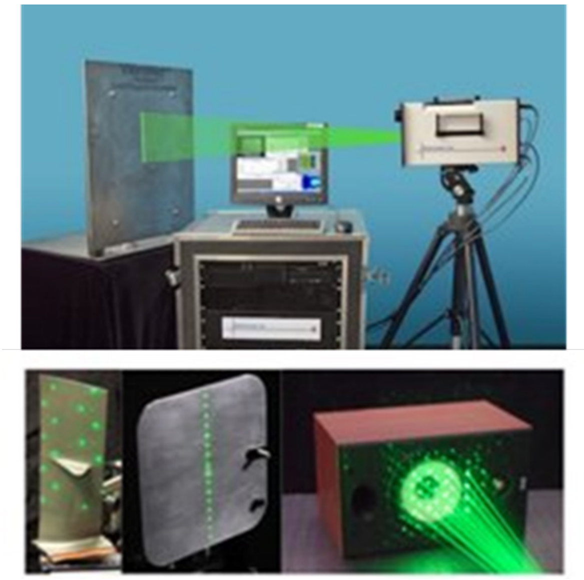

Figure 10. MB-LDV equipment [12].

Another similar LDV system is shown in Figure 11. This multi-channel 256-beam, whole-field laser Doppler vibrometry (WF-LDV) system has been demonstrated at laboratory conditions. The multi-channel whole field LDV measures simultaneously from multiple points. Advantages of this concept is the much faster interrogation process and capability to scan larges area within seconds compared to SLDV. It has been used as part of Remote Acoustic Impact Doppler (RAID) system to measure corrosion from DC 10 UK Royal Air Force aircraft. It has been addressed that currently it could be possible to manufacture this type of LDV with 625 channels. [13]

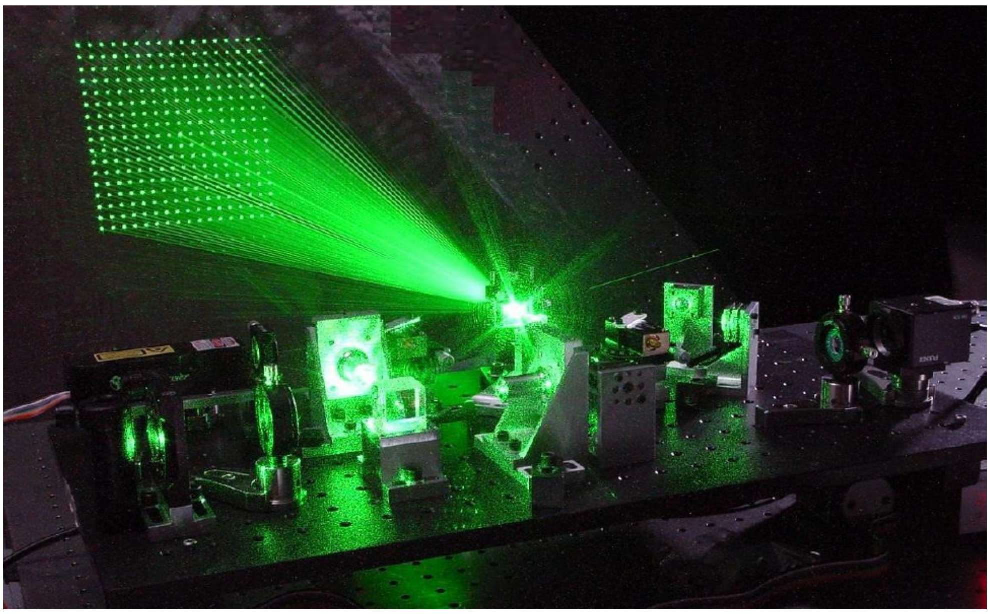

Figure 11. 256-beam WF-LDV at laboratory [13].

2.3.3 Multi-point LDV

In addition to MB-LDV, multi-point solutions have been introduced, where user-configurable LDV sensor heads are connected to a central unit containing a single laser system and a multi-channel interferometric detection system. As an example, in the multi-point head shown in Figure 12, eight sensor heads are connected to a one optical unit. Inside the optical unit, the output of the laser is split into eight measurement and eight reference channels. For each measurement channel, light is coupled into an optical fibre of the measurement head and focused to the measurement point on the structure of interest. Backscattered light is collected through the same lens and guided back to the optical unit for interferometric detection, using a second fibre. The interferometric signals from each channel are mixed down for demodulation. The flexibility afforded includes 3D measurement at a point by appropriate combination of a minimum of three sensor heads. [10]

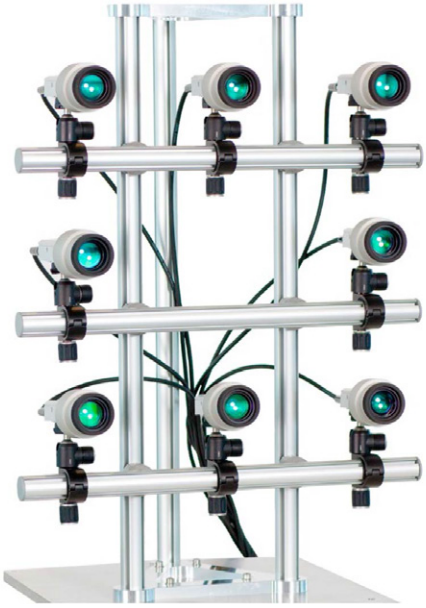

Figure 12. 8-channel optical setup of Polytec Multipoint Vibrometer.

2.3.4 Continuous-scan LDVs

Where SLDV scans measurement area point by point, the continuous scanning laser Doppler vibrometry (CSLDV) measures along programmed path continuously at specifically selected scan frequencies. This can greatly accelerate measurement acquisition time compared with SLDV but requires specialised processing algorithms, because the measurement point is constantly moving. CSLDV suffer from phenomena called "speckle noise". When rough surface is illuminated with monochromatic light, the backscattered light detected with sensor, retain the random noise mostly derived from the surface characteristics. This noise is more present in continuous scan method since surface under the point changes continuously. Scanning frequency should be selected so that it is not close to the object's vibration frequency or its harmonics frequencies. Measurement results from a vehicle using CSLDV is presented in Figure 13. [10] [14]

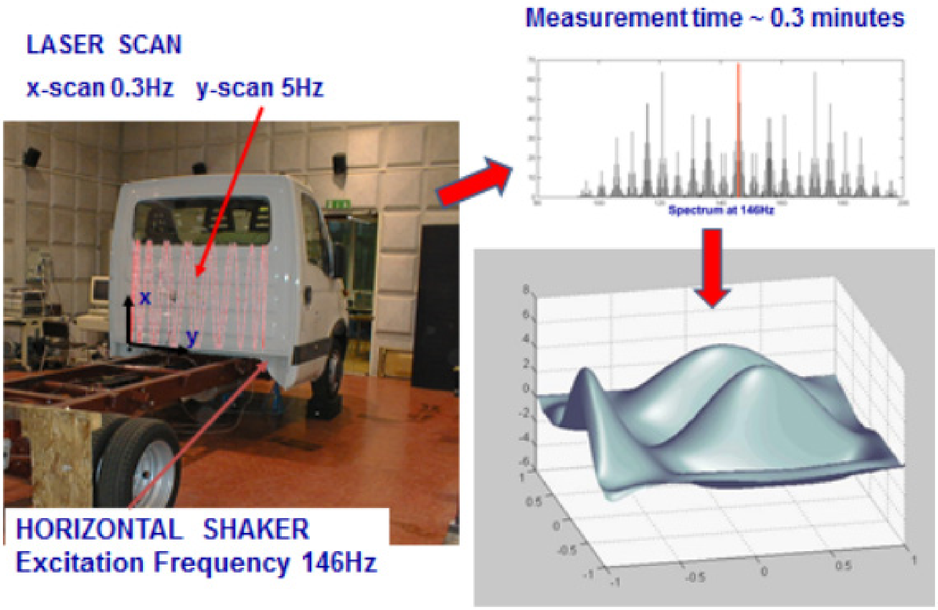

Figure 13. Continuous-scan laser Doppler vibrometry. Vehicle cab scan pattern (left), velocity spectrum (top right) and reconstructed ODS (bottom right) [10].

Da-Ming Chen and W. D. Zhu have conducted an experiment where they attached tree continuous scanning laser Doppler vibrometers (3D CSLDV) to scan synchronously the same path (Figure 14). In this approach, each CSLDV position needs to be determined accurately so they can scan synchronously the same point. The scan trajectory is defined from the shape of the target and rotation angles are obtained from one of the CSLDV. This method is capable to measure 3D operational deflection shape (ODS) of the target. Currently, the method has been proven to work in a laboratory environment. [15]

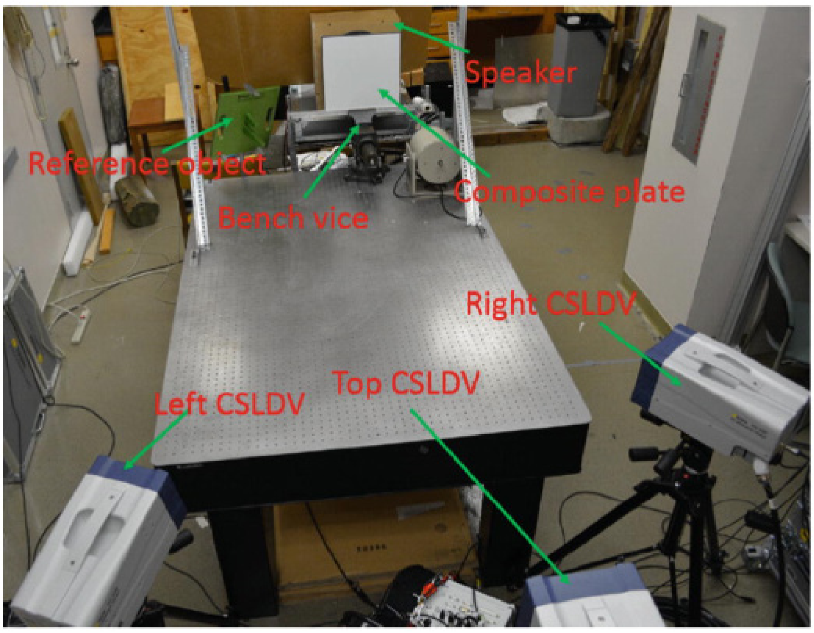

Figure 14. Setup of the 3D-CSLDV system [15] .

2.3.5 Conclusions

LDV method offers at the moment best displacement and velocity resolution. The displacement noise floor for the LDV is significantly better than most of the other optical methods. LDV method is suitable for both microscopic measurements and for measurements done over long distance. The LDV has been used long time in industrial applications and both 1D as well as 3D LDV systems are commercially available. The LDV has also very wide frequency band, up to 1 MHz. Temporal anti-aliasing is not either a problem with this method, because aliasing can be avoided by anti-alias filtering.

The 3D SLDV laser alignment is sensitive and if alignment changes during the tests, calibration has to be carried out again. The SLDV methods scanning speed is rather slow since it measures the selected area point by point. The 3D SLDV equipment are also quite expensive.

Laser Doppler vibrometer with Short-Wavelength-Infrared (SWIR) laser technology gives good signal quality in the most challenging measurement tasks. It can measure dark surfaces, rough surfaces and surfaces with poor reflectivity. Due to HeNe laser lower wavelength (λ=630nm), it is possible to measure object through the water. HeNe LDV is also more suitable for measuring microstructures, since it has smaller laser-spot size that higher wavelength SWIR laser. [11]

Currently available MB-LDV devices can measure simultaneously up to 16 points. This device has been demonstrated in outdoor field conditions and measurements were made when the equipment was attached to a moving forklift. However, this method is limited with flexibility on beam orientations.

Pros and cons of different methods based on Laser Doppler vibrometer have been collected to Table 3.

Table 3. Different LDV method pros & cons.

LVD Pros & Cons	
+	Widest dynamic range, typically up to 100 kHz
+	Measures velocity; better amplitude resolution at higher frequencies compared with image based methods
+	Non-contact measurement; no mass loading
+	Also torsional vibration measurement capability by two LDV beams
+	Relatively quick measurement setup
+	Temporal aliasing is not a problem
SLDV, 3D-SLVD	
+	3D measurement possible, automated acquisition of spatial information as dense as needed
−	Measures each point in series; only able to make measurements sequentially
CSLDV (Mostly 1D, also 3D possible)	
−	Typically CSLDV time history have to be resampled at desired spatial resolution in order to recover the vibration data on the trajectory swept by the laser
−	Scan area and measurement direction limited with flexibility on beam orientations (1D CSLDV)

2.4 INTERFEROMETRIC METHODS

2.4.1 Holographic Interferometry

Holographic interferometry is increasingly used for non-destructive testing at industry and can also be used for vibration testing.

In holographic interferometry the light beam is split to a reference beam and an object beam. Object beam illuminates the measured object. The scattered object wave and reference waves are captured with a CCD camera. Hologram is formed from phase and amplitude information of the light. System set up is illustrated in Figure 15.

Technology is still under development and does not yet full fill the industry requirements as: ease of use, real-time, reasonable price, robustness for industry environment etc. [16]

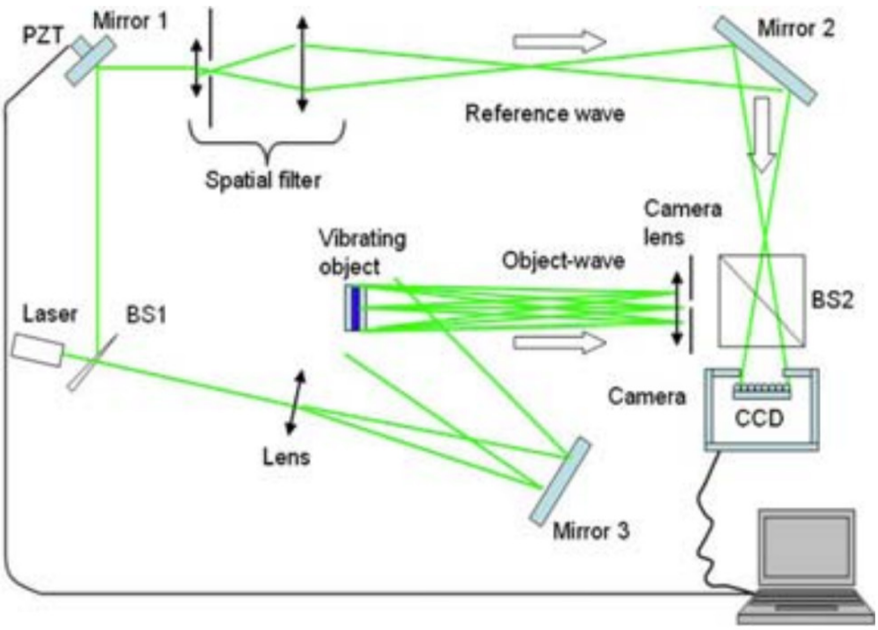

Figure 15. Diagram of holographic interferometry measurement system setup [16].

2.4.2 Electronic Speckle Pattern Interferometry

In electronic speckle pattern (ESPI) measurement object is illuminated with coherent laser light and reflected interference speckle pattern of the surface is recorded with a CCD camera (Figure 16). When test object is loaded and surface deforms, the captured speckle interferogram also changes. Superimposed interferogram images shows the fringe pattern, which contour lines, corresponds deformation amplitude. [17]

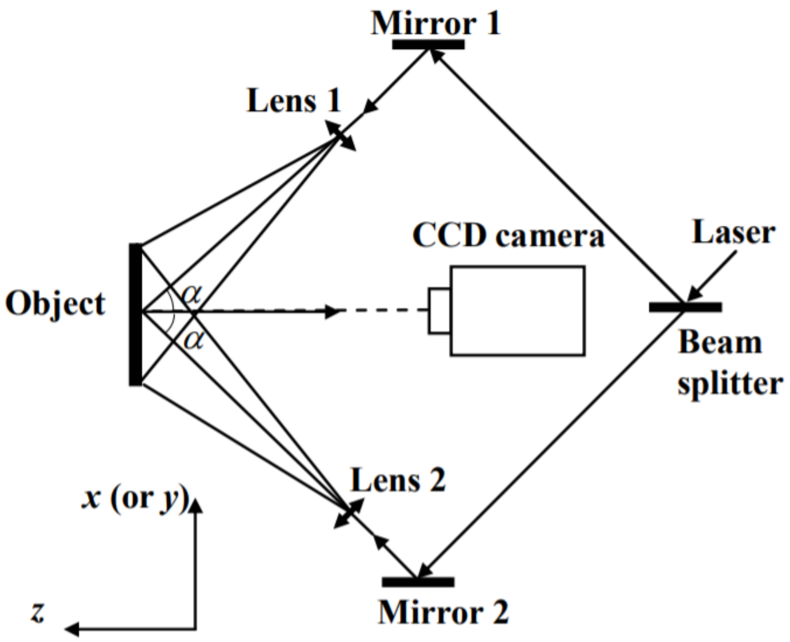

Figure 16. Schematic of in-plane ESPI setup [18].

2.4.3 Conclusions

ESPI can measure displacements at sub-micron level either in-plane or out of plane. However, ESPI method is quite sensitive to vibrational noise. Based on short literature survey, this method has not been used for vibration measurement applications as widely as other most common methods presented in this survey.

3 Suitability for Large Objects Vibration Monitoring at Nuclear Power Plants

3.1 DIC

It is addressed that 3D Digital Image Correlation is suitable for vibrations as well as strain and stress monitoring for large objects. One example of the large scale object monitoring is depicted in Figure 17, where wind turbine blade deflections are measured with 3D DIC [2]. 3D DIC is also proved to be suitable for measuring rotating objects, for example, vibration measurement on rolling tire [19]. Several papers demonstrate suitability of this method for full-scale operational deflection shape (ODS) and modal testing applications. [1], [2], [20], [21], [22]

Some limitations also exist from industrial application point of view. Measurements at especially high frequencies is limited by the noise floor of the DIC system. The technique requires a stochastic pattern preparation (typically black and white) to be applied on the surface of the test object. Anti-Aliasing is hard to accomplish, but this applies to any of camera-based methods. One suggested method is to avoid this, is to measure the object with single conventional accelerometer ensuring that any frequencies above the Nyquist frequency of the camera are not present. [21]

The highest measurable frequency is largely dictated by the frame rate of the used camera. The camera's resolution usually decreases when frame rate is increased and if FOV increases, the measured spatial resolution degreases. [20]

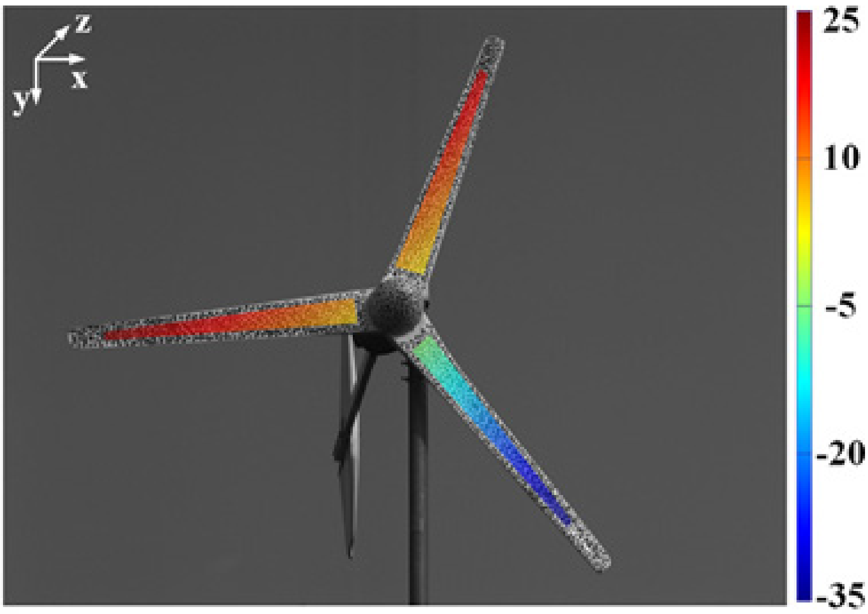

Figure 17. Full-field displacement distribution of the wind turbine blades (z direction, units in cm). [2]

3.2 MOTION MAGNIFIGATION

Currently, commercial providers of motion magnification technology enable only measuring in-plane vibrations and displacements, so 3D vibration measurement is not possible. They use only one 2D camera data individually for image processing, measuring in-plane vibrations perpendicular to line-of-sight. Therefore, traditional full 3D ODS or experimental modal testing cannot be directly replaced by these methods using currently available systems. However, these motion amplification systems can be used for other industrial condition monitoring related measurements. It is suitable for preliminary troubleshooting at field conditions e.g. indicating vibration and displacement from process industry pipelines and pressure vessels, misalignment of gensets and electric motors. Examples of commercial providers for motion magnification measurements are RDI Technology and Erbessd-Instruments.

The technology has some advantages and is currently used and tested in many fields of industry. Motion magnification technology does not need any additional surface preparation, but it would benefit from additional markers and from high contrast speckle pattern, which helps the motion/vibration to come more accurately visible.

However, the technology still has some limitations that need to be carefully taken into consideration. Lightning conditions can be in some cases hard to arrange for large-scale indoor measurements. Usually the existing lighting interfere measurements at 50 or 60Hz frequency. For this reason, DC light source is recommended for measurements, but usually it is hard to arrange enough light for the large measurement targets. Surrounding lighting usually needs to be switched off to be sure, that it will not interfere the measurements. This can be sometime safety issue if the measurement area cannot be isolated during settings and measurements.

Measurements at especially high frequencies is limited by the noise floor of the technology. Absolute amplitude measurement accuracy is also quite poor using current commercial systems, because there does not exist any on-site calibration procedure for each measurement setup. The absolute accuracy depends on e.g. actual distance to the object etc. However, relative displacements can be measured adequately.

As an example, RDI's Iris M and Iris MX motion magnification technology can only measure in-plane vibrations and displacements, since they use only one 2D camera. The new Iris CM is continuous monitoring system that controls three cameras simultaneously. However, Iris CM software does not support real 3D vibration measurement. The Iris CM can process the motion amplification in real-time.

3.3 LASER DOPPLER VIBROMETRY

3D SLDV

The 3D Scanning laser Doppler vibrometry (SLDV) is suitable for vibration and modal testing of large objects. 3D SLDV has good out-of-plane and in-plane displacement resolution. The displacement noise floor for the LDV is better than most of the other optical methods. The LDV has also very wide frequency band, up to 1 MHz. The SLDV has been used for a long time in industrial applications e.g. in Experimental Modal Analysis (EMA). Software capabilities of SLDV are typically sophisticated in the modal testing and includes capabilities for anti-aliasing and operating shape visualization.

The 3D SLDV measures sequentially points, which requires certain acquisition time, which naturally depends on e.g. number of measurements points. As an example, in the study presented in reference [21], scan time for approximately 500 3D SLDV points required 45 min. Although the alignment and calibration of the lasers is quite demanding, the setup time is approximately equal between the SLDV and the 3D DIC for experienced users [21].

CSLDV

Continuous-Scan Laser Doppler Vibrometry can be used to measure vibration and modal shapes of large object as Shifei Yang and Matthew S. Allen pointed out in their publication [23]. The CSLDV as well as SLDV can be used remotely, even hundreds of meters away. One benefit is also ability to obtain measurements with greatly increased spatial detail. Capability of CSLDV also for 3D measurements have been demonstrated in several papers, but it seems that readily available commercial solutions for 3D CSLDV does not actually yet exist. [15], [24]

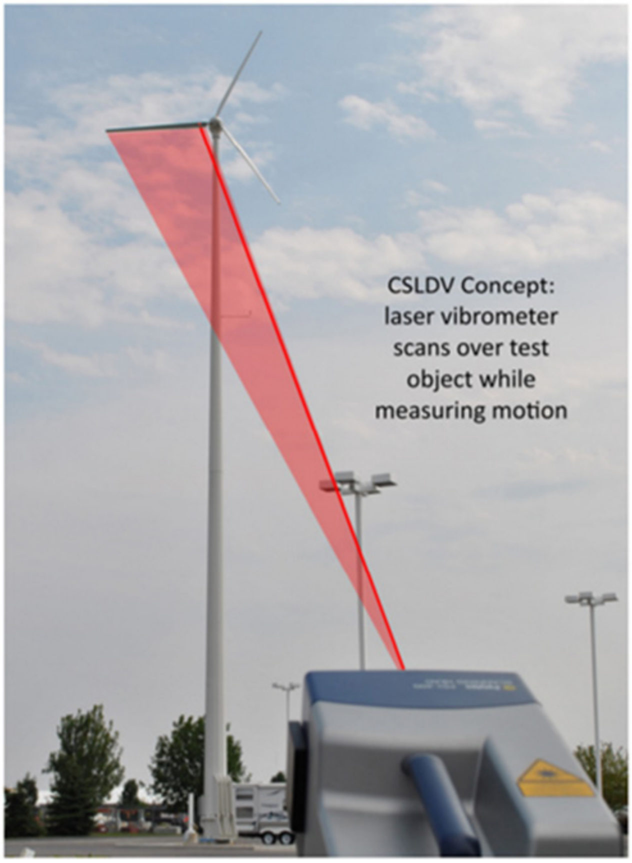

Figure 18. Wind turbine blade deflection measurement with CSLDV [23].

3.4 ELECTRONIC SPECKLE PATTERN INTERFEROMETRIC METHODS

It is possible to measure vibration from large objects with the ESPI system as shown in Figure 19. As mentioned earlier this measurement methods needs "rough" optical surface and smooth glossy surfaces so the windscreen requires treatment before target can be measured.

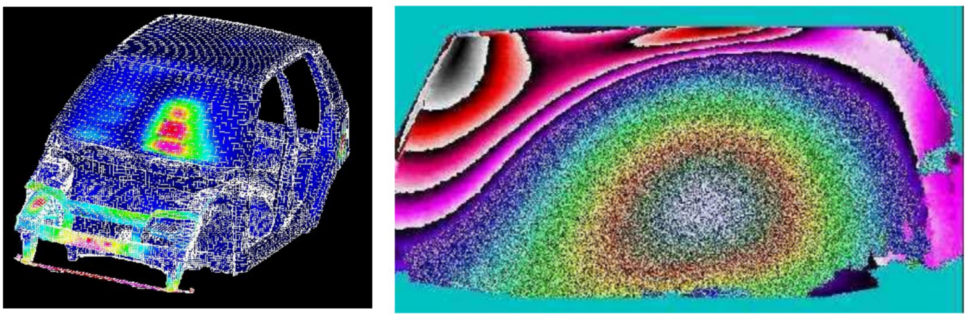

Figure 19. Operational deflection shapes of wind screen at 100Hz frequency: FE-calculated (left), ESPI (right) [25].

3.5 COMPARISON OF TECHNOLOGIES

This chapter compares the more mature technologies that could be applied in industrial applications. Table 4 shows comparison of four commercially available technologies that could be considered in the vibration measurements of a nuclear power plant. The 3D SLDV technology has the best performance in a few areas, which are bandwidth, the displacement resolution and capability to measure vibration in 3D. Software of the 3D SLDV is also designed for structural dynamics testing. 3D DIC method can also measure 3D vibrations and need only short measurement time. A drawback is a need of surface preparation (stochastic pattern) on the surface of the test object. Motion magnification benefits are its quick deployment and the fact that the surface of the object does not have to be treated. However, it enables only measuring in-plane vibrations and displacements, so 3D vibration measurement is not possible. ESPI method has short measurement time and short analysis time but needs optically rough surface.

If the different technologies are compared trough their references from industry applications, it can be found that ESPI technology does not have that many large-scale industry references than SLDV, DIC and Motion Magnification.

Table 4. Comparison chart between technologies suitable for nuclear environment.

	3D SLDV	Motion Magnification	3D DIC	ESPI
3D/2D method	3D	2D	3D	3D
Displacement resolution	picometers	1.25µm at 1m 56.25nm at 45mm (with 100m lens) *)	nanometers *)	>1.55µm (SWIR) >0.3µm (He-Ne)
Typical measurement time	1.5hours(~1000points)	seconds	seconds	seconds
Analysis Time	seconds	minutes	hours	seconds
Anti-aliasing	included	not available	not available	-
Setup Time	2 hours	1-2 hours	2 hours	-
Surface Preparation	no preparation needed (ideal for reflective surfaces)	no preparation needed (markers and high contrast pattern helps)	high contrast speckle pattern uslly needed	optically rough surface needed
No. Cameras/ Sensors	3	1	2	1
Typical Band Width **)	0-100kHz	up to some kHz range	up to some kHz range	up to some kHz range
Software for structural dynamics	Designed for structural dynamics testing	In its infancy, (simple FFT possible)	ODS and simple FFT possible	In its infancy
Scan area	mm^2 to several m^2	mm^2 to several m^2	mm^2 to several m^2	mm^2 to several m^2
Strain calculation	Researchy	-	Integrated	-

*) Depends on optics, ROI, system setup, surface of the target etc. These are extreme values

**) Typical range. Depends on application, instruments used and displacements to be measured. Theoretically can be higher

Typical measurement and analysis needs in a nuclear power plant environment is traditional 3D operational Deflection Shape (ODS) analysis and experimental modal testing using e.g. impact hammer. Because motion magnification technique currently is not able to measure 3D vibrations, most potential optical methods for these typical measurements are 3D DIC and SLDV. Table 5 shows comparison of three different methods for modal analysis: 3D digital image correlation, scanning laser Doppler vibrometry and conventional impact hammer test. This comparison table shows that 3D DIC method would be the good option for modal testing due to its high spatial resolution. Some properties of SLDV are also good compared to the others, but it can only measure predefined points and it is highly sensitive to changes in the measurement setup. The main difference is that the SLDV requires longer time to scan the sample, while the DIC requires only seconds to acquire the needed images. However, in order to get to the displacement results used for the modal analysis, DIC requires much longer time for the analysing phase. The displacement noise floor for the SLDV is significantly better than with the DIC for the out-of-plane results, but approximately equal for the in-plane results. As a conclusion, both optical methods are viable options for full-field measurements in vibration and modal testing. [20], [21]

Table 5. Comparison of modal analysis methods: Impact hammer, DIC, SLDV [20].

Impact Hammer Test	Digital Image Correlation Test	Scanning Laser Doppler Vibrometry
Easy to obtain trasfer functions	Obtaining tarsfer fuctions requires postprocessing beyond typical software capabilities	Easy to obtain trasfer functions
Test each point separately	Test each shape separately	Test each point in series
Data only at locations of response transducers	Data on entire visible surface of an object	Data at predefined points on visible surface of an object
Sensitivity depends on accelerometer	Sensitivity goes down as the field-of-view gets larger	Sensitivity related to laser light wavelength
Broadband excitation of all modes	Better suited for single frequency excitation	Broadband excitation of all modes
No stability requirements	Less sensitive to camera rigid body motion	Calibration is highly sensitive to changes in setup conditions
Inexpensive	Expensive	Very expensive
Requires contact and possible mass loading	Non-contacting and nonmass loading	Non-contacting and nonmass loading
Low spatial resolution	Very high spatial resolution	High spatial resolution

Regarding almost all 3D optical methods and both of above techniques, it must be noted, that a measurement system has to be stable after the calibration process. If some misalignment occurs during the test, measurement errors occurs and the system needs to be calibrated again. This might be problem, if the foundation upon which the measurement system has been set up, vibrates.

4 Technology Providers

In this chapter are listed identified companies, research centres and universities working in the area of surveyed technologies.

4.1 UNIVERSITIES

Motion magnification

- Massachusetts Institute of Technology, USA
- University of Warwick, USA
- University of Illinois, USA
- Hamad Bin Kalifa University, Quatar
- University of Technology, Iraq
- Papua New Guinea University of Technology, Papua New Guinea
- Hefei University of Technology, China
- University of Tromsø, Norway
- Tallinn University of Technology, Estonia
- Aalto University, Finland
- University of Oulu, Finland

Digital Image Correlation

- Aalto University, Helsinki, Finland [26]
- Tampere University, Tampere, Finland [27]
- KTH Royal Institute of Technology, Stockholm, Sweden
- Chalmers University of Technology, Göteborg, Sweden
- Massachusetts Institute of Technology, USA (MultiDIC Matlab ToolBox)
- Georgia Institute of Technology, Atlanta, Georgia
- Sandia National Laboratories, Albuquerque, New Mexico
- Laboratoire de Mécanique de Lille, Lille, France
- Institut National des Sciences Appliquées de Toulouse, Toulouse, France
- University of Limoges, Limoges, France
- École Polytechnique, Palaiseau, France
- University of Rome La Sapienza, Rome, Italy

4.2 RESEARCH CENTRES

- Fraunhofer Society for the Advancement of Applied Research, Germany,
  - × DIC, Video Motion Magnification, LDV (VibroTrack)
- VTT Technical Research Centre of Finland
  - × DIC, LDV
- Research Institutes of Sweden
  - × DIC
- University of Tokyo
  - × LDV (VibroTracker)

4.3 COMMERCIAL SOLUTIONS

In this chapter, available commercial solutions relating to optical vibration measurement equipment and software are listed. This is not a comprehensive list but represents a selection of identified solutions during the survey process.

4.3.1 Motion Magnification

Hardware:

- Company: RDI Technologies (www.rditechnologies.com)

  Products: IRIS M, IRIS MX, IRIS CM

Software:

- Company: RDI Technologies (Table 6, Figure 20)
  - × Software: Motion Amplification, Live Motion Amplification (real-time)
- Company: Erbessd Instruments (www.erbessd-instruments.com)
  - × Software: Dragon Vision

Table 6. Iris MX motion magnification specifications.

	Iris M		Iris MX		Iris CM	
Sampling Rate	(default) **120 fps**	(redused resolution) **1300fps**	(default) **1400fps**	(redused resolution) **29000 fps**	(default) **180 fps**	(redused resolution) **1300fps**
Frecuency Range	**3600cpm (0-60Hz)**	**39000cpm (0-650Hz)**	**42000cpm (0-700Hz)**	**870000cpm (0-14500Hz)**	**5400cpm (0-90Hz)**	**39000cpm (0-650Hz)**
Displacement	**2.5µm** at 1m distance with 50mm lense, **125 nm** at close focus					
Resolution	**HD**		**HD**		**HD**	
Sensor	**2,3 Mpixel Sony IMX174** (pixel sixe 5,86µm, 163fps)					
Multiple cameras	No (1 camera)		No (1 camera)		Yes (3 cameras)	
Motion amplification	post prosessing		post prosessing		real-time motion amplification	
Triggering	No		No		Time-Based, ROI displacement, Accelerometer	

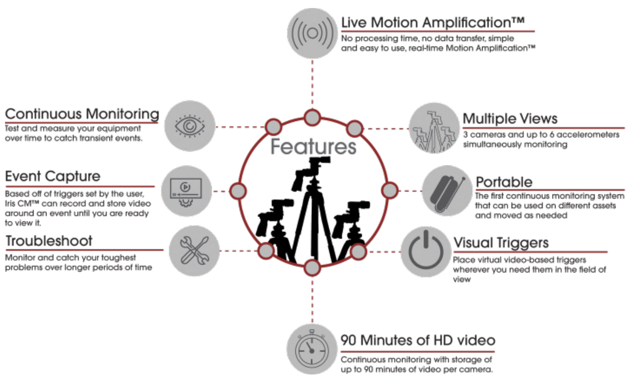

Figure 20. Iris M camera at left and Iris CM features depicted at right [www.rditechnologies.com].

4.3.2 DIC

Hardware:

- Correlated solutions (www.correlatedsolutions.com/vic-3d)
- GOM: ARAMIS (www.gom.com/metrology-systems/aramis)
- Dantec Dynamics A/S (www.dantecdynamics.com)

- LaVision (www.lavision.de/en/products/strainmaster)

Software:

- Correlated Solutions: Vic-2D, Vic-3D (www.correlatedsolutions.com/vic-3d)
- HOLO3: CorreliSTC (www.holo3.com/en/experiment-simulation/correlistc)
- Dantec Dynamics: Istra4D (www.dantecdynamics.com)
- GOM Correlate (www.gom.com/3d-software/gom-correlate.html)
- Image Systems: TEMA (www.imagesystems.se/tema/motion)
- Imetrum: Video Gauge (www.imetrum.com/products/digital-image-correlation)
- LaVision (www.lavision.de/en/products/strainmaster)
- Match ID (www.matchid.eu/en/software)

4.3.3 LDV

Hardware:

- ONO SOKKI (www.onosokki.co.jp)
- OMS Corporation (www.omscorporation.com/products)
- Ometron (www.ometron.com)
- Sunny Optical Technology (www.sunnyoptical.com/en)
- Polytec (www.polytec.com/eu/optical-systems)
- OptoMet GmbH (www.optomet.com/products)
- Holobright (www.holobright.com)

4.3.4 ESPI

Hardware:

- Dantec Dynamics (www.dantecdynamics.com)
- Laser Technology Inc (http://www.laserndt.com)
- isi-sys GmbH (www.isi-sys.com/isi-sys-homepage)

4.4 OPEN SOURCE SOLUTION

4.4.1 DIC

- multiDIC (www.github.com/MultiDIC/MultiDIC)
- DICe (www.github.com/dicengine/dice)
- dolphin_dic (www.bitbucket.org/mgenet/dolfin_dic/src/master)
- Ncor (www.github.com/justinblaber/ncorr_2D_matlab)
- pydic (www.gitlab.com/damien.andre/pydic)
- pyxel (www.github.com/jcpassieux/pyxel)
- py2DIC (www.github.com/Geod-Geom/py2DIC)
- YaDICs (www.yadics.univ-lille1.fr/wordpress)

4.4.2 Motion Magnification

- Live Motion Magnification (www.github.com/tschnz/Live-Video-Magnification)
- Video Magnification (www.people.csail.mit.edu/mrub/vidmag)
  - × Eulerian Video Magnification
  - × Phase Based Video Motion Processing
  - × Learning-based Video Motion Magnification
  - × Videoscope

5 Potential Future Optical Vibration Measurement Developments

5.1 MOTION MAGNIFICATION COMBINED WITH STEREOSCOPIC DIC

In order to use optical sensing techniques to identify dynamic characteristics of a structure at high frequencies, the signal-to-noise ratio (SNR) has to be improved. One possibility to achieve this, is an analysis combining phased-based motion magnification and 3D-DIC, using motion magnification at the image data pre-processing stage, see Figure 21. The magnified sequence of images using the motion magnification technique are post-processed using 3D-DIC or 3DPT to quantify infinitesimal deformations that are not recognizable using only the traditional stereo-photogrammetry methods. It has been proven, that this methodology enables extraction of lower amplitude information about the dynamic characteristics of structures at high frequencies compared with conventional 3D-DIC only. [1], [28]

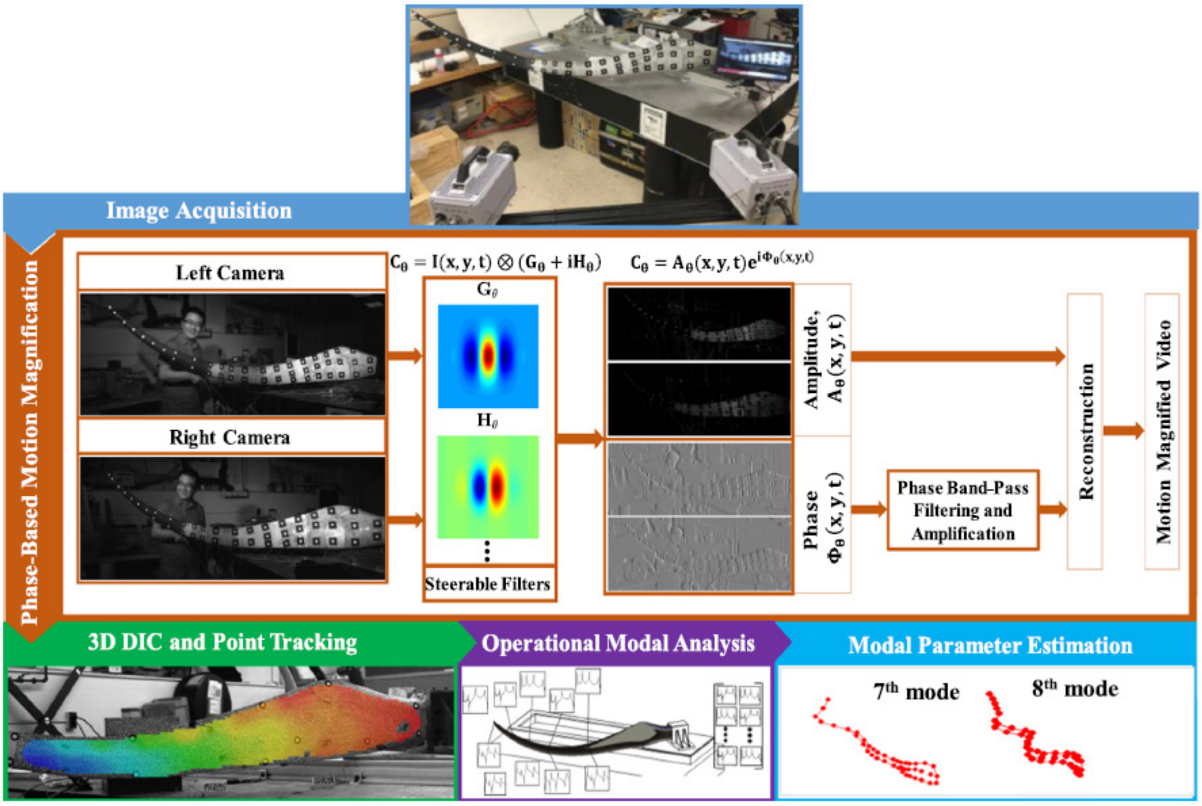

Figure 21. Workflow diagram showing methods sequential steps [1].

5.2 HANDHELD SINGLE-POINT LDV SCANNER

Recently, research effort has been addressed towards performing full-field scanning and 3D velocity measurements with a low-cost single point LDV sensor.

An important step in the LDV measurement procedure is the estimation of the pose of the instrument relative to a test object. Existing LDV pose estimation methods rely on the use of 3D range sensors to perform this task. An approach presented, for example in [29], is based on matching of a 2D camera image and a CAD model of the test object for real-time LDV pose estimation. It is possible to reconstruct the actual 3D vibration velocity vector when vibrometer measurements from at least three LDV angles of incidence at the point of interest are measured. It enables full field scanning and 3D velocity measurement using low cost single-point LDV, which would be much cheaper than 3D SLDV's. This method allows estimation of LVD position when either the target is moving or the LDV itself is moving.

This approach still has some limitations that needs to be solved before it could be taken in industrial use. The measurer's body and arm vibrations increase the noise level with 10dB. Further, it is assumed with this method, that a CAD model of the structure is available. As a drawback, it is not possible to measure any axisymmetric targets. [29]

Figure 22. Handheld LDV experiment: Polytec IVS200 attached with IDC µEye camera (Left). Handheld LDV measurement of bike frame exited with shaker (Right). [29]

6 Summary and Final Conclusions

6.1 SUMMARY

3D Digital image correlation is full-field image analysis method that calculates the displacement using the grey scale image values correlations. Suitability of this method for full-scale operational deflection shape (ODS) and modal testing applications has been presented in several papers in the literature. 3D DIC measurements have high spatial resolution and short measurement time over the whole field-of-view. Some limitations also exist from an industrial application point of view. Measurements at especially high frequencies is limited by the noise floor of the camera and DIC system used. Drawback is also a need of surface preparation (stochastic pattern) on the surface of the test object.

LDV method offers at the moment best displacement and velocity resolution. The displacement noise floor for the LDV is better than most of the other optical methods. LDV method is suitable for both microscopic measurements and for measurements done over long distance. The LDV has been used for a long time in industrial applications and both 1D as well as 3D LDV systems are commercially available. The LDV has also very wide frequency band, even up to 1 MHz. However, a drawback is that it requires longer time to scan the measurement object compared to, for example, DIC methods. In addition, if spatial resolution is increased, the measurement time also increases. Setup of the 3D SLDV system may be quite time consuming and if any misalignment occurs during the measurement, the setup and calibration needs to be done again. In addition, 3D SDLV equipment are still quite expensive.

Currently, motion magnification method can measure only vibrations in-plane perpendicular to the line-of sight. It could be a good method for trouble shooting purposes, since the setup procedure is rather easy and quick. Method have some limitations, that should be considered before making any further conclusions and actions based on measurements.

Electronic Speckle Pattern Interferometry method can measure the deformation in fractions of the used laser wavelength. Object surface needs to be optically rough to retrieve proper diffraction and usually surface needs to be treated. The method has been shown be to be capable of measuring vibrations from large objects.

6.2 FINAL CONCUSIONS

Optical vibration measurement systems have proven to be capable to measure large objects vibrations at industrial environment. These are developed continuously to be robust and suitable for harsh environment monitoring.

Optical vibration methods have multiple advantages compared to the conventional vibration measurement sensors. All surveyed methods have denser spatial resolution than conventional measurement methods can practically reach. As a non-contact measurement, they do not apply any additional mass loading to the measured object. However, some limitations exist for each optical method from industrial application point of view, which should be carefully considered in each case.

Three methods were distinguished in this survey, which could be applicable for vibration monitoring of large targets in nuclear power plant environment. Both the **3D SLDV** and **3D DIC** are viable options for full-field 3D measurements in vibration and modal testing. The **Motion Magnification** method is suitable for preliminary troubleshooting purposes, where it is not possible to make any additional pattern treatment.

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OPTICAL METHODS FOR VIBRATION MEASUREMENTS IN NUCLEAR APPLICATIONS

Optical vibration measurement systems have proven to be capable to measure vibrations in large objects in an industrial environment, and they are developed continuously to be more robust for harsh environment monitoring.

This survey presents a wide range of different methods for capturing vibration behavior and target characteristics, assessed from the preconditions of measuring vibrations in a nuclear power plant.

Depending on what needs to be measured and the preconditions at the site of the vibrating component, usually only certain methods are applicable. Thereby an understanding of measurement method principles, of features and suitability, and of course also of measurement costs is required.

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