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A Literature Review of Non-Contact Tools and Methods in Structural Health Monitoring

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Introduction

Large-scale structures and infrastructures including buildings, bridges, dams, aircraft, rails are subject to damage and deterioration throughout their lifecycle [1,2]. Structural Health Monitoring (SHM) is a multi-discipline field for damage identification and disaster mitigation of structures at an early stage in aerospace, civil and mechanical engineering [2-5]. Generally, SHM systems involve the implementation of sensors, smart materials, data transmission, computational power, and post-processing techniques [6]. SHM systems differentiate from traditional damage detection systems because it integrates automated health assessment analytics with data sensing, from which a more efficient structural condition valuation can be formulated [7]. The complexity of the systems can be classified into four levels: detection, localization, the extent of damage, and prognosis of a remaining lifetime. In simple terms, they begin from only detecting the presence of damage, to characterize the severity and predict the remaining lifetime [7,8].

SHM can be categorized in many categories, for instance, sensor parameters, sensor types, active or passive, etc. Nevertheless, most relevantly they can be differentiated in local and global methods [6]. Local methods usually implement Nondestructive evaluation (NDE) methods (i.e., ultrasound, magnetic inspection, acoustic emission eddy current, etc.) to extract imperfections features in the vicinity of the potential damage area. They are highly sensitive and are able to find small defects. On the other hand, global methods, which are vibration-based, operate under the statement that damages influence the behaviour of the whole structure in terms of time and space. Thus, it extracts potential damage through changes in stiffness, mass or energy [6,9]. In both approaches, sensors are imperative elements for data extraction. Usually, contact sensors such as strain gauges, accelerometers, fibre optics, and linear variable differential transformers to name a few, are widely deploy for structural health monitoring. However, they require installation, which is often time-consuming, costly and in many cases not achievable as the structures are hard to access. Besides, as the time pass, this sensor also requires periodical maintenance and potential replacement producing extra costs. Moreover, contact methods can generate extra mass loading which is counterproductive in lightweight structures.

Alternatively, non-contact methods have the potential to eliminate the challenges of contact-based sensors. Besides, remote data collection can be achieved in both local and global methods [10,11]. With the advent of technology, more tools are being applied for contactless sensing which is overtaking traditional contact sensing. This paper reviews the emergent approaches on non-contact methods and tools i.e., vision-based, wireless, embedded sensors, guided waves, etc. A literature review of non-contact methods and tools is the aim of this paper. A detailed description of the work principles of tools and sensors is not attempted rather the purpose of this work is to summarize the state of the art of non-contact methods and how new technologies are been employed in Structural Health Monitoring.

This document is presented as follows; the methodology undertaken to select the papers reviewed is presented in section 2. The specific classification and descriptive usage of the contactless methods are discussed in section 3. Finally, conclusions are presented.

Methodology

In this review paper, the methodology employed was undertaken according to the following steps. First, the literature was collected from the SCOPUS database due to it indexes the largest number of journals and is commonly used in engineering fields [12,13]. The initial search was performed on the 21st of January 2021 with the keywords “structural health monitoring” and with the aim of obtaining exclusively the non-contact literature, the specific query was: TITLE-ABS-KEY (“structural health monitoring” AND non-contact* OR noncontact* OR contactless). The boolean operators (AND, OR, *) are used to include entirely the non-contact literature and to incorporate potential literature with different spellings of non-contact. An initial 623 results were obtained, a further limit was imposed on only English language documents. The search was not limited to a time frame, resulting in 608 documents from 1994 to 2021 plotted in Figure 1. Then, the 608 articles were browsed and 92 irrelevant documents (e.g., medical fields) were excluded and subsequently were classified according to the main method/tool, Table 1 summarizes it.

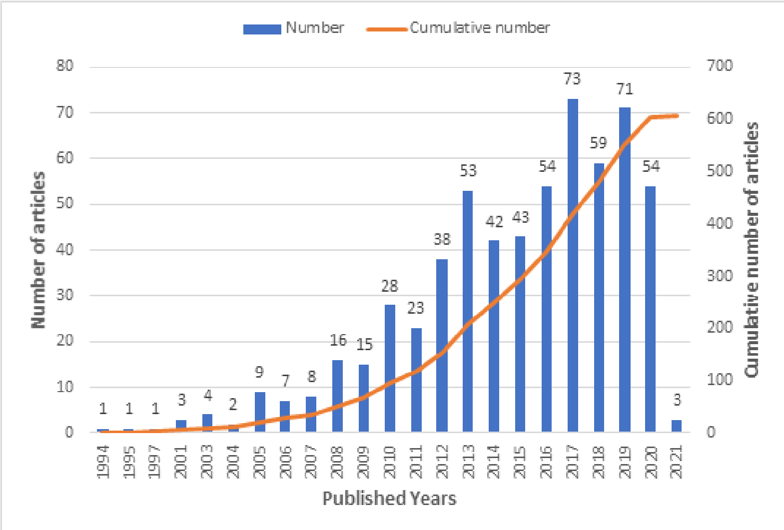

Figure 1: Research publications on the use of non-contact methods and tools in structural health monitoring.

Table 1: Non-contact methods/tools in SHM.

Methods	Number of Articles	Percentage
Vision-based	146	28.29%
Guided Waves	91	17.64%
Ultrasound	49	9.50%
Vibration	47	9.11%
Magnetic Methods	33	6.40%
Acoustic based	31	6.01%
Displacement based	28	5.43%
Thermal Inspection	18	3.49%
Wireless	17	3.29%
Optical Methods	13	2.52%
Hybrid Testing	11	2.13%
Microwaves	10	1.94%
Strain based	8	1.55%
Spectroscopy	8	1.55%
Tomography	6	1.16%
Grand Total	516	100.00%

Non-Contact Techniques

The classification previously exposed in Table 1 is now depicted in Figure 2 for illustration proposes. The 516 papers were classified based on their main method or tool. Nevertheless, in many methods exits and overlapping effect. For instance, in vision-based, SHM approaches are vibration-based which are also shown in the classification. Additionally, for example in wireless tools, displacement-based methods are utilized. Thus, this classification was done with the aim of collecting the majority and most relevant methods and tools according to the author.

Vision-based

In the last decades with the rise of powerful computers and digital cameras, vision-based and image base as a means of structural health monitoring has gained attention [1]. Vision-based methods have the advantage of remote sensing, and more data is acquired as opposed to the contact methods which data is obtained in point-wise measurements. As depicted in Table 1 the vast majority of the studies for non-contact methods is based on vision-based i.e., camera, video etc. A complete literature review is not attained as it should be done solely. However, many promising approaches are presented below.

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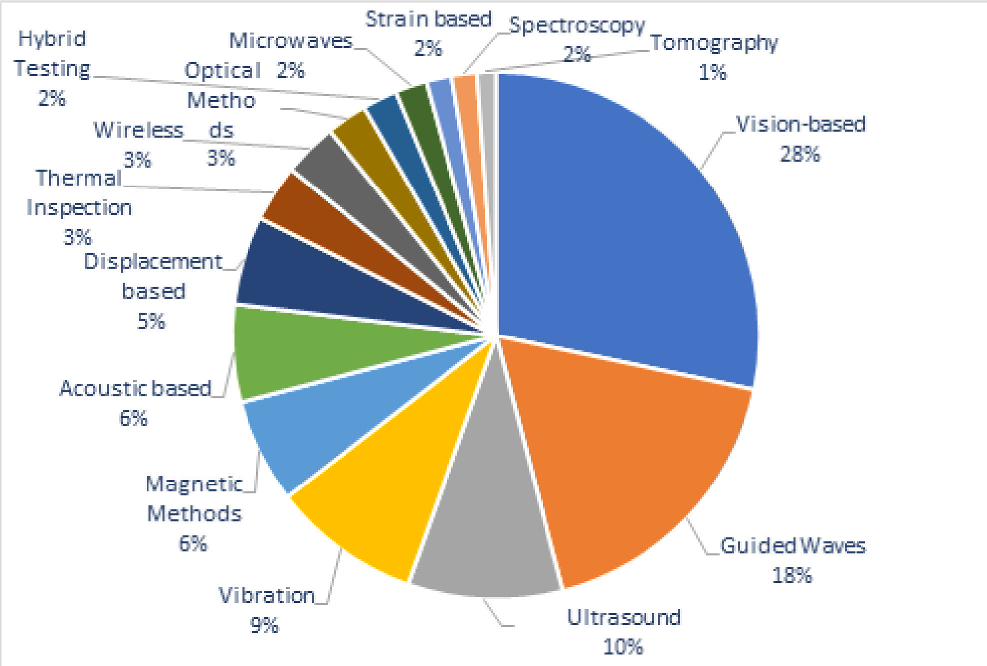

Figure 2: Classification in term of percentage of Non-contact methods.

For instance, a video-based approach was reported in Yang et al. [14]. A vibration-based approach to acquired modal data (i.e., natural frequencies, damping radio, mode shapes) through a digital camera was investigated. Additionally, the blind source separation (BBS) method was applied as a post-processing technique for unsupervised data extraction. The method was experimentally tested with a small-scale building and a cantilever; both were stimulated through a hummer and the data was read. Moreover, a high concordance was found from cross-validating the data from traditional accelerometers attached to the structure.

Ribeiro et al. [15] studied the applicability of the video-based system for dynamic measurements. High-speed cameras were in-field deployed for acquiring displacement data of railway bridges. The data was positively compared with traditional LVDT measurements. Winkler & Hendy [16] achieved displacement measurements of London's Docklands railway bridges using digital cameras and digital image correlation technique.

The usage of high-speed cameras was also reported in Baqersad, Niezrecki & Avitabile [17]. Displacement measurements of wind turbines are obtained from a video-based approach. Three-dimensional point tracking along with digital image correlation (DIC) was employed for extracting the data. It was further analyzed in a finite element model for obtaining strain measurements and contrasting them to data acquired from traditional strain-gauges. The results showed a high agreement between the contact and the no-contact method.

Digital image correlation (DIC) is used as a means of health monitoring of bridges in Nonis et al. [18]. The system used a digital camera for periodically image acquisition. The images are processed and strain measurements are derived. It was reported that cracks, spall, and bridge deformation were successfully identified. Similarly, Peddle et al. [19] reported DIC technology deployment to measure in-field displacement data of two bridges. A great correlation was found when compared with traditional linear variable differential transformers (LVDT). DIC implementation has been also used for structural health monitoring of rotating structures. For instance, Baqersad et al. [20] reported modal analysis throughout digital image correlation (DIC) using digital cameras. Moreover, finite element analysis and a conventional modal analysis with attached accelerometer were performed. The three data were cross-validated and high accuracy were determined. Recently, Khadka et al. [10] evaluated the implementation of digital image correlation cameras on Unmanned Aerial vehicles for vibration monitoring of rotating wind turbines. A small-scale wind turbine was experimentally tested. The system was capable to remotely obtain the dynamic characteristics and measure the deformation.

Unmanned Aerial Vehicles (UAVs) are a promising technology that allows remote sensing. They can overcome the limitations of stationary cameras. The implementation of UVAs in structural health monitoring has gained attention in the last decade. For instance, Reagan, Sabato & Niezrecki [21] presented a feasibility study of the usage of digital image correlation with UVA of bridges. The system was capable to detect changes with an uncertainty of 10^{-5}m. In the same manner, Ellenberg et al. [22] reported a study of UVAs implementation to obtain deformation measurements of bridges. Optical metrology and an X-Box Kinect system were

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studied. The systems were tested on a bridge component to attempt deformation measurements. The findings suggest that the RGB camera could detect cracks from different distances. Previously Abdelbarr et al. [23] had proved the accuracy of RGB cameras for structural health monitoring. Yoon, Shin & Spencer [24] reported structural displacement measurement using a UAV system.

The above techniques employ the usage of digital cameras as a means of acquiring structural data to be processed. However, this data alone does not mean anything without being processed. Thus, computer algorithms are widely employed for identifying potential damage [25]. Often the vibrations modes are too small to be identified in non-contact image-based approach. For instance, Civera, Zanotti Fragonara & Surace [26] investigated the applicability of video magnification for damage characterization in deflection shapes. The named, phase-based motion magnification (PBMM) algorithm, restores the post-processed source obtaining a good signal-to-noise ratio. The method was tested on a damaged beam finding that the modal data was successfully obtained. Artificial intelligence was reported in work by Rivera-Castillo et al. [27]. Displacement measurements from 2D photogrammetry were post-processed using AI. Yuan et al. [28] reported the implementation of machine learning as a tool for data analysis and augmented reality for improving visual inspections.

Guided waves

Guided waves are a specific type of elastic waves with high sensitivity to damage due to fast and strong propagation on paths defined by the material boundaries of the structure [29,30], This technique is discussed below, moreover, Lamb waves, which are a type of guided waves, are also presented.

In Masserey & Fromme [31] high-frequency guided waves technique was reported as a means of fatigue crack growth monitoring. Guided ultrasonic wave, unlike bulk ultrasonic technique, have a high sensitivity to detect small damages. An aluminium specimen including a fastener hole with an induced fatigue crack was experimentally tested. A wedge transducer attached to the structure were used for guided wave generation and the response was measured throughout noncontact laser interferometry. The presence of damage is detected due to the changes in the guided wave signal response. Additionally, the wave propagation and response were numerically simulated using a three-dimensional finite difference code to validate the experimental data. Similarly, Chan, Masserey & Fromme [32] reported the usage of high-frequency guided waves to detect hidden damage in aircraft structure. The exact approach previously explained was capable to detect fatigue crack growth in the 2nd layer of a multilayer structure.

In the same manner, Rizzo, Han & Ni [33] reported a guided ultrasonic wave approach for health monitoring of immersed structures. This method aimed to present a non-contact *in-situ* technique for underwater structures i.e., ships, submarines, and underwater pipes. The proposed system includes the usage of a Q-switched Nd:YAG pulsed laser for guided wave generation and two transducers for data acquisition. An aluminium plate with two induced damage i.e., notch and a drilled circle was used for the experiments. The plate was submerged into a water pool along with the two non-contact transducers and through the usage of optical lenses (mirror and focusing), guided wave generation was achieved in a non-contact manner. Although a high sensitivity and changes in the response of GW, due to the damage, controversial results were reported. However, in a subsequent work presented by Pistone, Li & Rizzo [34] the guided wave propagation in immersed media was numerically simulated with Finite Element Analysis and the same experiment previously explained was carried out. The findings suggest that this technique can detect cracks and holes in a non-contact approach in immersed media.

Guided wave propagations offer a good alternative to characterize damage in structures. Many applications as those mentioned above have been reported for metallic materials. However, in composite materials, there are not many studies reported, mainly because the behaviour of the guided waves in composite structures is a complex problem [35]. A deeper understanding led to work by Aizawa et al. [36] where the scattering behaviour of guided waves in composite materials was studied. First, a three-dimensional (3D) finite element analysis was generated to understand the interaction of the guided wave in composite plates with delamination damage. The influence of the delamination size was a systematic study in the FE simulations. Then two CRFP specimens, with induced impact damage, were experimentally tested. An attached piezoelectric transducer and a non-contact laser interferometer for generation and measurement of the waves was employed. High accordance was found in both data, moreover, it was concluded that the delamination geometry (i.e., size and depth) has a strong influence on guided wave response.

Similarly, implementation of guided waves for health monitoring in composite materials was reported by Sherafat et al. [37]. A composite skin-stringer joint structure composed of three CFRP plates bonded together was tested. The system, in this case, utilizes two piezoceramic transducer and a non-contact 3-D laser Doppler vibrometer (LDV) for plane guided waves generation and measurement respectively. Two bonding conditions, bond and unboned (damage and undamaged) were investigated with the A0 and S0 mode signals. The damage characterization included changes in reflection, transmission in the guided waves as a function of frequency. In the A0 mode not clear changes in the parameters were founded, however, clear changes in S0 parameters were confirmed in the experimental tests.

Lamb waves

Lamb waves can predictably propagate in plate-like structures, thus they are widely employed for such structures [38]. In the study presented by Mallet et al. [39] lamb waves propagation for

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means of damage detection in structures is investigated. A non-contact approach is attained by laser vibrometer measurements of the guided waves. This system is tested for damage detection in aluminium plates with two different severities of damage. The first plate had a rectangular slot in the centre and the second had a hole in the centre to simulate artificial damages in metallic structures. The results were further validated with numerical simulations and experimental tests with a piezoceramic transducer. Similarly, Leong et al. [40], presented the same approach to characterize cracks in metallic structures with the use of lamb guided waves and a commercial laser vibrometer. An aluminium plate previously drilled in the centre, simulating fatigue crack, was tested. Overall, both methods showed rapid damage detection and characterization.

The usage of lamb waves was also reported in Lee, Kang & Park [41] which guided waves to localize and quantified damage was investigated. A non-contact scanning laser source system was implemented to achieve lamb wave propagation on plates structures. The structural response was measured throughout an embedded piezoelectric sensor. 3-D flaw images were constructed to visualize the wave propagation. Fatigue Cracks were successfully identified due to the scattering of lamb waves affected by the damage.

The usage of Lamb waves has not been only used in metallic structures. They have been exploited for composite materials as the lamb wave generation can propagate long distance and their velocities are sensitive to the in-plane stiffness of the laminates, however, the implementation of the methods is difficult [42].

A need to understand the propagation of Lamb Waves led to work by Voß et al. [43]where numerical modelling of non-contact testing was developed to study the interaction between Lamb Waves and composite materials. The study developed a numerical simulation model of lamb waves propagation in multi-layer CFRP laminates throughout Finite Elements Analysis. Additionally, several experimental validations were carried out with a CFRP specimen in which a piezo transducer was embedded to generate the guided waves. The cross-validation contributes to a better understanding of the interaction.

Similarly, in Gao et al. [44] laser-induced lamb waves generation was implemented as the main method for damage detection in composite laminates. The method interprets the responses affected by the damage throughout an algorithm called sparse imaging which is based on the assumption that few damage locations are presented on the structure. The experimental section was carried out on CFRP laminate with an attached magnet on both sides to simulate delamination. The system characterized the damage with high accuracy.

A different approach is presented in Wang et al. [45] where lamb waves were applied for damage detection in pipelines. The propagation of helical waves was previously modelled in a finite element analysis to validate the performance of the method. Helical waves, which can generate better results, were generated throughout a non-contact electromagnetic acoustic transducer (EMAT). The novel design was experimental tested on a pipeline where a pitch-catch system was employed to validate the design. Both experimental and simulation showed potential applications for Helical waves, however further study should be conducted to register damage in structures.

Radar vibration-based

As mentioned before, vibration-based techniques are global approaches to detect potential damage. Moreover, they are the most widely applied method [46]. In these sections, only radar-based methods are discussed.

In radar systems, a known frequency radio signal is transmitted and subsequently reflected onto the object and captured by the system again for data processing [47]. Radar technology has been employed in many remote sensing applications in SHM [48]. For instance, in Ochieng, Hancock & Roberts [49] the state of the art of ground-based radar applications for in-field monitoring of wind turbines was presented. Moreover, in-field experiments with ground-based radar to measure blade tip deflection was employed. The signals were measured in a time-domain approach to obtain changes in the blade deflection. Radar sensing has many advantages, for instance, it can work up to a few kilometres or propagate through non-conducting materials.

The high cost of damage presented in wind turbines (develop more) [50] has also led to work by Nikoubin et al. [51] where a low-cost portable radar sensor was originally utilized to acquired Doppler signatures from which blade's physical features can be determined. This system was employed on in-field experiments where Doppler signatures with different angles and locations were obtained and compared. Additionally, Munoz-Ferreras et al. [52] reported the same approach with two designed radar prototypes that operate at the C and K bands for in-field acquisition experiments. Moreover, in Munoz-Ferreras et al. [53] simulations of the exact experimental set-up were performed. The simulated results validated the preliminary experimental data, concluding that Doppler information has a great potential for real-time monitoring applications of wind turbines.

For instance, in Moll et al. [54] a non-contact mechanical vibration sensing was reported. The proposed method employs a millimetre-wave doppler radar sensor to measure mechanical vibration in non-conducting materials. MM-wave radiation is capable to penetrate barriers such as foams, ceramics, plastics etc. The time-series measurement is used to assess structural defects. Consequently, the system was tested in a laboratory setup to measure vibration data from a structure behind an 80mm thick polystyrene foam. Good reliability and repeatability were found when a 20mm crack was detected in various experiments.

In Rice et al. [55] another radar technology for vibration-based monitoring was reported. The investigation was conducted

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with a low-cost wireless radar sensor to obtain dynamic structural response data. The sensor uses dual measurement modes (i.e., periodic and non-periodic) the arctangent demodulated interferometry and the nonlinear vibrometer modes were utilized to generate sub-millimetre accuracy. The system was tested in three laboratories set-ups to evaluate the accuracy. Although experimental in-field data was not acquired, this low-cost sensor presented high accuracy and feasibility in the measurements for both modes and future applications in SHM.

Bennett & Rutz [56] presented another radar technology for bridges health assessment. The named Image by Interferometric Survey (IBIS) technology is capable to monitor deflections with a high precision i.e., 1/100mm, making it a great option for non-contact measurement applications. The proposed system was experimentally tested on laboratory and in-field set-up. The former was conducted to measure the accuracy of the method with cables and the later was performed in a cable-stayed bridge. Additionally, a contact accelerometer was utilized to cross-validate the measurements. This interferometric radar was capable to monitor structural deflections and vibrations.

Laser ultrasound-based

Ultrasound is a Nondestructive test method, however, is widely employed in structural health monitoring in local approaches [57]. Early-stage damage sometimes is difficult to detect as these fatigues produce nonlinear characteristics within the structure. A need to detect early-stage damage led to work by Liu et al. [58], which investigated nonlinear wave modulation spectroscopy (NWMS) to detect early fatigue cracks by exploiting nonlinear ultrasonic signatures. A fully non-contact technique is proposed by the implementation of a pulse laser beam for ultrasonic wave generation, and a laser Doppler vibrometer for ultrasonic wave detection. This method, unlike usual nonlinear techniques, exploits a feature called sideband peak count (SPC) as a means to identify potential damage. The peak variations showed in SPC determines the presence of the fatigue cracks. The system was tested with three aluminium plates and aircraft fitting-lugs. Resulting in a robust technique to detect material defects in metallic materials. (The finding suggest a very robust technique)

The same system, pulse laser and laser vibrometer were reported in An, Kwon & Sohn [59]. This fully non-contact ultrasonic wavefield imaging ultrasonic system is used to detect surface cracks in plate-like structures with special complexities. Additionally, a frequency-wavenumber (f-k) algorithm is implemented to extract crack ultrasonic features. The f-k algorithm enables to extract only cracks features without the necessity of baseline data from the undamaged system. The system was numerically and experimentally tested in two aluminium specimens, asymmetrically and vertical stiffened plates. (This image demonstrated a robust technique, In the same manner, imaging was reported in).

In Flynn & Jarmer [60] laser doppler vibrometry (LDV) was implemented to measure and visualize ultrasonic signature responses to characterize hidden defects in plate-like structures. The single-tone ultrasonic waves are generated throughout an attached piezoelectric transductor in the structure. The working principle of the method is that single-tone waves are steady thus extracting time-invariant properties of the wave that are indicative of damage is faster. Furthermore, the method exploits the wavenumber property of the waves from which damage can be detected. This approach was tested with an aluminium plate with three corrosion spots and two composite specimens with a high-speed projectile impact and two slow-speed impact damages respectively. The data acquired processed with the attributes of the waves clearly showed the spots of the damages in the three specimens.

Ultrasound system was also reported in Lee et al. [61], in which mechanical impedance was studied for monitoring pipelines in nuclear power plants. Pulse laser beam and laser Doppler vibrometer is also implemented to enable health monitoring of pipelines under high temperatures. In this study, a statistics tool named outlier analysis, which enables autonomous damage detection, is implemented for data processing. The chemical corrosion in an elbow pipeline was successfully detected in a lab-scale experiment.

Acoustic based

Acoustic emission is also an NDE technique, which is commonly known as the most simples method to deploy yet difficult to implement [62]. The necessity to obtain vibration measurements lead to work by Jiang, Zhang & Maxwell [63]. The feasibility to obtain modal parameters measurements through infrasound measurements was investigated. A cascading pre-processing technique was employed for identifying low-frequency modal properties. The method was tested with a small-scale structure and a microphone. Also, in Lobo-Aguilar et al. [11] infrasound approach was reported. A single microphone was used as a means of a noncontact method to capture dynamic properties on bridge structures. The method was validated with the data obtained from traditional accelerometer sensor. Besides, both methods deployed machine learning-based extraction technique to increase the signal-to-noise ratio. These techniques successfully demonstrated the applicability of infrasound in SHM.

In a study by Arora, Wijnant & De Boer [64] damage detection and localization were accomplished using an acoustic-based method. The proposed technique combines acoustic emissions and vibration signatures to acquire vibro-acoustic responses as a means of damage characterization. In experimental studies, an aluminium with fixed-fixed boundary conditions was studied. The system consists of a loudspeaker which emits an acoustic field and a microphone to measure the pressure response of the plate. First, the undamaged eigenvalue and eigenvector data was obtained

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from the acoustic pressure response and subsequently a crack was introduced and the eigendata was obtained. The changes in the natural frequencies are used to determine damage. Moreover, the flexibility matrices, derived from eight data, determine the exact location of the damage (non-contact method).

Similarly, damage detection with acoustic emission is presented in Poozesh et al. [65]. Sound radiations are used as the main method to characterize and localize damage in wind turbine blades. The working principle is that sound radiation characteristics variates when structural damage is present i.e., cracks, delamination, holes, etc. The experiments carried out in the study enclosed an acoustic microphone array with 62 microphones and an acoustic camera to characterize the radiation. The data acquired was further analyzed with a CLEAN algorithm, which unlike traditional beamforming, produces higher spatial resolution. This non-contact method effectively detected and located holes an cracks within the structure.

In another study by Qiu & Lau [66] a hybrid acoustic-laser based method is presented to characterize damage in FRP concrete specimen. The method encloses a loudspeaker, laser, photoreceiver, laser and a computer. Experimentally a CFRP-retrofitted concrete specimen and an FRP-reinforced concrete with an artificial defect were constructed. This technique evaluates damage throughout the following process: acoustic waves, emitted by the loudspeaker, excite the surface specimen. The laser is used to characterize the vibration and the photoreceiver captures the laser reflected response. The measurement response, through Fourier transform, a frequency domain spectrum of damaged and undamaged states is acquired. Comparison between both data was effectively used to indicate the presence of damage.

Magnetic properties

Magnetic methods are widely used in many ways to evaluate structures, many magnetic properties of the materials and transducer are exploited to acquire reliable data [67]. In Christopoulos et al. [68] an inductive sensing method to measure strain in composite materials was presented. Magnetostrictive wires were embedded in carbon/epoxy specimens to act as structural and sensor elements. These specimens were tested under tensile experiments to study inductive variations and their relation to the strain. Four types of non-contact transducer/sensor (i.e., coaxial coils, c-shaped inductive, circular coil Hall, and c-shaped inductive Hall.) were constructed to acquire experimental strain measurements. The experimental data showed a minimum detectable strain value of 0.25mStrain with a high resolution of 0.1mStrain. (High sensitivity embedded small size and does not increase the weight in the structure)

A similar approach was presented in Coatney et al. [69]. Where nano magnetostrictive particles were embedded in a composite structure for nondestructive damage detection. Terfenol-D magnetostrictive powder was embedded in a CFRP sample as a means of damage characterization. Experimentally the specimen was tested under tensile stress and with the usage of a non-contact magnetic field sensor, fluctuations in magnetization flux density were captured. The load and fatigue cycles produce clearly variations in the magnetic field due to Terfenol-D particles, which is an indicator of early-stage damage detection (The specimen reduced its strength with the inclusion).

Similarly, in Zagrai & Akan [70] magneto-mechanical impedance (MMI) method was reported as a means to obtain structural dynamic responses and diagnosis in metallic structures. The approach compromises the usage of a non-contact magneto-elastic active sensor (MEAS), with two different configurations, to emit electromagnetic and elastic waves. First, an aluminium beam with free-free boundary conditions was tested to identify a structural dynamic response. The MEAS sensors were placed 1mm away from the beam, and through and impedance analyzer the impedance variations were obtained and the dynamic responses characterized through the software LabVIEW. Moreover, the system was tested on three different structures evaluation scenarios i.e., loose bolts, adhesive deterioration, and cracks in honeycomb panels. These scenarios change the mechanical properties of the structure and therefore the inductance peaks in the dynamic response can be exploited for damage evaluation.

In another study presented by Chen et al. [71] magnetic field interference measurements are investigated as a means of monitoring scour in bridges. The method incorporates smart rock usage containing strong magnets in their structure. Although the study primarily presents the feasibility of the smart rock's magnetic field measurements through a magnetometer, the potential field application is revealed. The smart rocks would be placed underneath the sensitive zones of the bridge piers, thus, when a scour events occurs, the wholes, started by the flood, increase and eventually the smart rocks will automatically roll down to the bottom of the whole. Thus, damage detection would be characterized by tracking the movement of smart rocks through a magnetic field with, for instance, high precision global positioning system.

Displacement based

In the work presented by Giri & Kharkovsky [72] a novel approach to detect surface cracks in concrete was presented. The non-contact system consists of a laser displacement sensor (LSD), a scanner and a control centre. The LSD, mounted on the scanner, performs raster scanning over concrete specimens. Two concrete specimens were used to test the system i.e., cylindrical and concrete slab. Damage characterization is achieved through the triangulation principle onto the specimen surface. The effects of the specimen's geometry were further analyzed with different incident angles. The readings demonstrated this method is a robust technique to detect cracks in concrete and other nonconducting materials.

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Laser displacement sensor (LSD) was equally implemented as means of damage detection in Lee & Kim [73]. The non-contact system encloses a single LSD installed on wind towers to characterize damage in the rotating blades. A multi-sensing approached to characterize blade deflection due to bolt loosening, nacelle tilting and, mass loss-damage was proposed. Moreover, the effects of the temperature on the data monitored were analyzed. Overall, the results showed feasibility to characterize such damages. Besides, the system showed a relative easy damage evaluation from the field experiments.

Rodrigues, Félix & Figueiras [74] developed a hybrid system to measure bridge deflections. The non-contact system encloses a hydrostatic liquid levelling with a fibre optic engaged for displacement variations measurements. The fibre-optic-based transducers were installed along the bridge in crucial locations to obtain vertical displacements through liquid's level changes; these changes are measured throughout a fibre optic sensor placed in the transducer system. Laboratory tests were executed to study the prototype performance. Additionally, field tests in the Leziria bridge were performed obtaining a high sensitivity with an error of less than 0.2%. (Robust system, capable to read in environment conditions)

Similarly, Li et al. [75] proposed a multi-target method for 3-D non-contact displacement measurements. The system encompasses a frequency modulation continuous wave (FMCW) radar sensor. Mathematical and analytical modelling was developed to further analyzed the working principle of the technique. Moreover, the radar prototype system was constructed with a data acquisition card (DAQ). Outdoors experiments were conducted to test the feasibility of the new system. Although no structural damage was investigated with the system, it showed high accuracy and potential use in structural heal monitoring.

Optical methods

In another recent study, Pang, Chen, Yu, et al. [76] investigated the use of laser speckle optical sensor (LSOS) for *in-situ* strain measurements. This fully non-contact method replaces traditional contact methods i.e. resistive gauges, fibre optic, and extensometers. The LSOS was modified with a field-of-view subsystem to extend sensor gauge length. The method was validated through field test for strain monitoring of rail tracks. Data comparison between strain gauge and laser speckle confirms the high accuracy and the robustness of the proposed method, moreover, contact sensors can be replaced for LSOS sensors where mirror surfaces or transparency materials are not utilized. (Finally, the outcomes suggest a strong sensor capable to be used for strain-based and other applications).

In the work by Yang & Oyadiji [77] a fibre optic sensor was developed for structural health monitoring applications. The sensor was modified with multiple layers of transmitters for large amplitude vibration measurements. Better read range and sensitivity was achieved with two-layers of transmitters. This non-contact sensor was tested to measure dynamic displacement in small scale cantilevers. The experiment validated the information with a contact accelerometer and non-contact laser sensor. The data suggest an extremely high concordance with conventional techniques. Moreover, the fibre optic sensor data is less noisy and free from electromagnetic interference.

In the work presented by García et al. [78] different configurations of the optical sensor were tested to measure the tip clearance (TC) in turbines. Four configurations of optical fibres were built and tested to obtain at least 30um of precision. Three configurations were tested further in the turbine in a wind tunnel, resulting in the third and fourth configuration have the best precision. Although the third configuration showed the best precision, 25um, the maximum working temperature is 60C limiting its applicability. Finally, the fourth configuration, capable of working at 350C, showed a precision of 28um making it suitable for tip clearance and vibration frequency measurements in structural health monitoring applications.

Similarly, Dhawan, Dikshit & Kawade [79] developed a two-dimensional fibre optic position sensor. The method is capable to produce vibrations measurements in a 2-D plane for structural health monitoring applications. The system includes a CCD camera where the data measurements are collected and further analyzed. The working principle is that the axial and the lateral changes are measured through the change in peak intensity and the centroid of image spot at CCD camera respectively. Although reliable measurements were acquired, this non-contact method should be further tested in field application.

Thermal testing

Infrared thermography or thermal imaging is considered a non-destructive examination method which allows observing the heat patterns on an object surface [80]. In a study by Mulaveesala et al. [81] defects in reinforcement concrete structures (RCS) are characterized throughout Thermal Nondestructive Testing (TNDT). A non-contact thermal wave imaging method was implemented to expose corrosion in reinforcement bars (rebar) within the concrete. This active technique implemented a frequency modulated thermal wave imaging (FMTWI) method to control two halogens lamps to generate thermal waves, and an IR camera to capture the temperature distribution in the sample. Phase based and correlation-based post-processing approaches were chosen to reveal subsurface features i.e., corrosion. Both processing approaches clearly indicate the amount of corrosion.

In Hwang, An & Sohn [82] continuous laser thermography is proposed as a newly damage visualization method of wind turbine blades. The fully non-contact thermography is capable of detecting surface and subsurface damage under rotating condition. The *in-situ* apparatus includes a line laser beam for thermal waves generation and an infrared (IR) camera for capturing the thermal

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responses. The working principle is that the obtained images from the IR camera are post-processed with a damage imaging algorithm. The statistical pattern recognition algorithm recognizes internal delamination throughout, first, a collection of thermal responses for each blade are built, then system continuously produces thermal images for comparison, once an abnormality is detected, the algorithm removes the noises and clearly shows the exact defect location.

Better post-processing techniques led to work by Pena & Rapun [83] which a post-processing technique was exploited for detecting defects and inclusions in two-dimensional plates. The study combined active infrared thermography and topological derivatives as a post-processing tool for damage detection in aluminium plates. The method is capable to process time-harmonic thermographs capable to detect interior defect with no prior knowledge about the size or shape of the defects. Moreover, the mathematical tool is extremely robust concerning noise.

Higuera et al. [84] investigated a steady active thermographic method which incorporates a post-processing algorithm capable of detecting defects and inclusions from synthetic thermographs. The mathematical tool, topological derivatives, as opposed to traditional algorithm approaches, does not reduce the physical information obtained from thermal imaging, generating a robust damage detection method capable of identifying and locating internal flaws of diverse sizes and shapes. The method is also capable to process noisy thermographs.

Wireless

A bio-inspired wireless sensor is reported in Tata et al. [85]. The proposed technology encloses an antenna for strain measurements. Printed on a flexible substrate, the patch antenna functions as both, transducer and as the broadcasting device. Although essentially the sensor is contact based i.e., embedded, the data acquisition procedure is a wireless non-contact method. Furthermore, the backscattering principle was utilized to interrogate the strain data from the antenna attached to a cantilever exposed to mechanical loads. The electromagnetic resonant cavity, generated by the patch antenna, radiates specific known resonance frequencies which are distorted when elongation is present. Moreover, the reflection coefficient (S11) presents changes in its frequency for different strain percentages which is the principal method to evaluate the state of the structure.

Similarly, wireless strain-based technology was presented in Zhang & Bai [86]. A passive RFID tag was embedded in truss elements to assess the overall structural condition. The working principle was that a brittle bar is connected to the tag short-circuiting the chip and changing the impedance. This brittle bar is designed to break out when a strain threshold previously calculated is exceeded. Once the pre-set brittle bar is broken the RFID tag starts data broadcasting throughout a non-contact RFID reader. Additionally, building information modelling (BIM) is introduced to the method in order to identify and highlight the failing truss element (yielding and bulking added to the method to bring a more graphical way to help decision-makers to identify the truss element which is under strain. identifying the truss element).

A study by Abedin & Mehrabi [87] presented a novel approach to investigate the accuracy of wireless sensors in structural condition assessment in girder bridges. Moreover, self-powered wireless sensor suitability was investigated for SHM applications. Energy harvesting through solar and thermal gradients are broadly employed. However, vibration-based energy, generated from the bridge under live loads, was examined to discover whether they create enough energy to power the sensors. Additionally, stress/strain vibrations were analyzed as a means for the damage detection method. Thus, laser vibrometer was utilized to assess wireless sensor accuracy and finite element analysis was realized to validate the field data. The findings suggest that first, non-contact laser vibrometer is an effective and economical method. And that the vibration generated under normal loads is enough to power the wireless sensors.

In Zahedi, Yao & Huang [88] a fully wireless passive technology for structural health monitoring is demonstrated. The ultrasound-based system includes a wireless interrogator, wireless actuator and an embedded sensor mounted on the structure. The system exploits the amplitude modulation and demodulation to produce a passive pitch-catch system. The ultrasound signal is generated wirelessly throughout the interrogator. Then, the signal is received by the actuator which transforms the signal a generates the ultrasound. The results demonstrated a 0.5m reading range.

A studied by Amies et al. [89] incorporated radio frequency (RF) technology to gauge floor displacements in civil structures after earthquakes. The novel method encloses several RF transceivers embedded to fixed locations nodes in the structure. Frequency-modulated continuous wave (FMCW) radar through a non-line of sight (NLOS) technique emits and reflects signals which are computer analyzed to measure the transceivers displacement. Displacement data is used to calculate interstorey drift ratios (IDRs) which are used to study the stress and hence the condition of the structure.

In Iervolino & Meo [90] another wireless approached is presented to detect barely visible impact damage (BVID), delamination and cracks. A spiral passive electromagnetic sensor (SPES) is investigated for damage characterization in composite materials. The 2-D sensor is specially designed and fabricated to resonate at a specific frequency. Experimentally, the sensor was investigated on two specimens, conductive (CFRP) and non-conductive (GFRP) composite materials. Different samples were fabricated and their resonant frequency obtained. Two types of damage (i.e., drilled holes and impacts) were introduced to the samples. Through the usage of a spectrum analyzer, resonant frequencies of the damage samples were obtained and compared. The clear variation of the frequency showed in the analyzer makes

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the approach feasible and reliable.

Microwaves

Overall, microwave techniques have been tested in nondestructive evaluation. However, it has been mostly employed in cemented based and metallic based. Structural health monitoring in many cases is challenging as the structures often perform in harsh environments and conditions. Moreover, the SHM method must be capable to detect minimal structural changes before failure occurs [91]. For instance, in the aero industry, gas turbine components operate in very high temperatures and health monitoring is extremely essential. This necessity has led to the work by the National Aeronautics and Space Administration (NASA) reported in [91]. NASA developed two new non-contact microwave sensing technology for rotating blades in gas turbine engines. Microwave based blade vibration sensor was utilized to perform frequencies and vibration measurements. They were compared with previous data gathered from capacitive sensors, showing high accuracy and reliable readings. (Both technologies have the potential to withstand harsh environments and produce highly accurate measurements. Microwave's vibration sensing it's a worthy technology as it can stay at high temperatures. The technology is under evaluation, but they have developed this technology)

Similarly, Li et al. [92] presented a microwave imaging method to detect delamination of wind turbine composite blades. Delamination is the most critical failure mode for composite materials and especially in fibre-reinforced composites [93]. An open-ended waveguided technique was implemented as the method for obtaining microwave imaging of T-joints in wind turbines. Glass-fibre reinforced polymer (GFRP), widely employed for wind turbine components, was utilized for delamination test. A highly accurate delamination characterization i.e., existence and extent was achieved during the experiments. This new approach could be further taken for health assessment un other parts of the wind turbines.

Nadakuduti, Chen & Zoughi [94] presented a microwave method for crack detection in cement-based materials. A non-contact near field microwave method is employed to characterized surface-breaking cracks, its width and depth. The project presented two studies of surface-breaking cracks for mortar and hardened cement samples. The successful crack detection method was accomplished using an open-ended rectangular waveguided probe. Cracks characterization i.e. width and depth were effectively reported throughout the measurements. This method could be extremely useful as depth characterization and damage evaluation can be easily evaluated in cement structures for instance, after seismic events.

Gentile & Cabboi [95] evaluated the use of microwave remote sensing for vibration response measurements on cable-stayed bridges. This radar technology utilized microwave interferometers to performs dynamic and static measurements under operational conditions. Contact accelerometers were employed to validate the data acquired from the non-contact technique. Two cable-stayed bridges were analyzed during the tests; periodic measurements on the cables to obtain local natural frequencies and damping ratios is the technique to evaluate deflections and structure condition. Based on the comparison between both data and its high accuracy is suggested that microwave remote sensing is a quite consistent technique for condition assessment on cable-stayed bridges in SHM applications.

Tomography

Magnetic Induction Tomography is an ideal technique to be applied for contactless applications [96]. A study by Renner, Fischer & Marschner [97] presented a new tomography imaging approach for *in-situ* and non-contact applications. Magnetic Induction Tomography (MIT) is proposed to evaluate the condition of the fibre-reinforced composite. This contactless technology is capable to produce 2D or 3D inhomogeneity images from where damage can be localized and detected. MIT differs from conventional techniques as it can produce 3D spatial interior images. A further study by Renner, Marschner & Fischer [98] was conducted to evaluate MIT for conductive fibre-reinforced composites. This method is proposed as an autonomous tool in SHM of conductive composites (too much data collected).

Another study by Park et al. [99] similarly employed additional algorithms to improve non-contact tomography methods. Difference Hilbert Back Projection (DHB) algorithm was implemented to improve the tomography imaging accuracy of plate structures imperfections. Pulse laser and air-coupled transducers were used as the main non-contact detection method. The automatic detection system includes a robotic arm with a hybrid technology containing the laser and the air transducer for image acquisition. Overall, the technique was found successfully to predict faults in large plate structures. However, it has clearly stated that there is space for improvements in image quality and DHB algorithm.

Gupta et al. [100] developed and validated an electrical capacitance tomography (ECT) method to characterize subsurface composite damage. Planar array electrodes configuration, unlike conventional circular arrays, was implemented to obtain a volumetric distribution of the specimens. The portable method was tested in two different scenarios. First 3-D PLA specimens with internal voids of different configuration and CFRP specimens after an induced hammer impact were investigated. Throughout mapping change in electrical permittivity, the method was capable of identifying the delamination-like and delamination damage in both procedures. Although the image quality resolution is not desirable the delamination on the subsurface was identified. Moreover, the data were further compared with a C-scan finding high accuracy.

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Strain based

Strain based methods are widely used to assess the condition of the structures as they produce key data from the structures. Many sensors have been developed throughout the years. This sensor has some drawback as they must be attached to the structure and have to be maintenance etc. Some structures are hard to access for such installations. Thus, other technologies have been used to overcome these drawbacks.

In a work, by Jo et al. [101] strain measurements were accomplished using light detection and ranging (LiDAR) as a non-contact method. This 3D laser technology was used to obtain 3D shape information data for a steel plate. The data were evaluated using regression analysis and the strain was calculated using a finite element analysis (FEA) simulation. Also, the obtained strain measurements were compared to measurements obtained with contact strain gauges sensors. The findings suggest that data from LiDAR were quite similar to the strain gauges sensors. Thus, this non-contact technique can be an effective tool in structural health monitoring applications.

A similar approach was described in Pang et al. [102] where a laser speckle imaging system (LSIS) was used to obtain strain measurements in fastener holes. Additional digital image correlation (DIC) algorithms were used to optimize the performance of LSIS technology. Uniaxial tensile stress was performed on an aluminium alloy specimen as it is widely used in fuselage structures. In addition, an extensometer was utilized in the test to validate the LSIS performance. The measurements showed high consistency with previous FEA simulation. The data obtained from both approaches were extremely correlated. (Thus, this approach seems quite practical for structural health monitoring applications).

In Christopoulos, Hristoforou & Tsamasphyros [103]strain-based magnetic sensing capabilities were investigated. An epoxy polymer matrix dispersed with ferromagnetic particles (iron) was used to study the sensitivity of magnetic properties exposed to tensile stress. The composite material was exposed to an external mechanical load. The obtained elongation produced changes in the sample geometry and its magnetic properties. The alteration in the magnetic properties is observed in variations in the magnetic resistance (reluctance). The non-contact method used a Hall sensor to measure reluctance fluctuations. The proposed method found a strong relationship between strain and reluctance which can be further exploited in SHM applications where iron materials are employed.

Spectroscopy

Withey et al. [104] investigated non-contact strain measurements using photoluminescence spectroscopy. A polymeric coating embedded with single-walled carbon nanotubes (SWCNTs) was applied to a substrate. Strain applied to the substrate is transmitted to the coating producing shifts in SWCNT fluorescent spectra due to electronic changes. These fluctuations are measure optically with a non-contact spectrometer. The fluorescence peaks are large enough to measure strain in structural health monitoring applications using SWCNTs as nanoscale sensors. The proposed method, strain painting, although under complex working principles, its deployment is quite simple and versatile. (Complexity discussed of the principle, the laboratory should see in real word but suitable for practical applications however see the 87 for steel, also many instruments required).

In a study by Hanhan et al. [105] portable spectroscopy is proposed for *in-situ* and non-contact stress detection. This technique explores the piezospectroscopic effect of certain photo-luminescent materials. For instance, alumina-containing materials under laser excitation, emit spectral peaks. These spectral emissions are sensitive to stress and strain. The photo-luminescent mapping and analysis instrumentation was designed to be a portable piezospectroscopic system (PPS). They tested an alumina nanocomposite coating sample with the PPS, the measurements were compared against a FEM simulation data. The experiment showed potential applications for non-contact structural health monitoring.

Hybrid methods

A deeper damage characterization could be achieved with the combination of several methods or sensors. Combination of non-contact methods or combining non-contact and contact techniques can greatly enhance the reliability and accuracy of the procedure. However, this approach is only justifiable if the benefits are correctly balanced with additional time, cost and complexity generated [67].

Khan et al. [106] presented a hybrid non-contact and contact method for damage assessment of concrete masonry walls subjected to cycling loads. The multi-sensing approach combined infrared thermography (IRT), acoustic emission (AE) and ultrasonic method (UT). The Infrared thermography non-contact method was capable to detect the presence of moisture in the porous wall which appears in the form of temperature fluctuation on the surface. AE was proven to be a suitable method to monitor damage progression when active ultrasonic methods confirm the existence of cracks. This efficient method utilized cross-validation within the above methods to validate damage progression.

A work by Vakhguelt, Kapayeva & Bergander [107] incorporated a mixture of non-contact and contact ultrasonic methods for condition assessment for boiler tubes. Overheating and wall thinning are two major issues in boiler tubes failures. EMAT (Electro-Magnetic Acoustic Transducer) was used as a non-contact ultrasonic technique to evaluate the wall thickness. Standard ultrasonic measurements were obtained to compare the reliability of the non-contact measurements. A further correlation between wall thickness and overheating was attempted for the overall method (Economic advantages see in the paper).

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In a study by Alamdari et al. [108] three different non-contact sensing techniques were examined to monitor the integrity of a cable-stayed bridge. Namely laser scanning, robotic total station and digital levelling were deployed to acquire displacement profiles at four discrete points. Although the data gathered from the three sensor techniques is very consistent and sufficient to identify the changes in the structure, damage localization and characterization are only possible with multiple measurements points. Nevertheless, this multi-sensing approach verified that changes in the displacement profiles between undamaged and damaged state are a reliable damage detection method (much sensors, need more measurement points).

Lai et al. [109] presented a combination of full-field infrared thermography (IRT) and laser shearography. Both non-contact methods were used to detect flaws between carbon fibre-reinforced polymer (CFRP) and concrete materials. CFRP is used to rehabilitate concrete structures. Imperfections in such materials interfaces can be critical for the overall bond strength. Thus, the IRT technique was implemented to detect surface flaws due to a distinct rate of heat diffusion and shearography method to measure the mechanical response of surface displacement through the application of thermal stresses. The experiments were carried out on 6 CFRP-concrete samples with 17 different flaws. Field data were compared after opening the samples resulting in, infrared thermography achieving 93% of accuracy whereas shearography 90.5%, however, both techniques tend to underestimate and overestimated the measurements respectively. (However, both methods could be combined and further algorithm could be used to achieve better accuracy for structural health monitoring)

In the study presented by Chen et al. [110] a hybrid method is proposed as a means to characterize structural defects. The combined method merges Finite Element Analysis (FEA) simulations and optical shearography. Finite Element simulations are used to simulate different loading scenarios to obtain deformation data and a prediction algorithm to determine shearographic fringes patterns. Experimentally an acrylic sample is exposed to the same loading scenarios, and real-time patterns are obtained and compared with the predicted fringes patterns thus the abnormalities are detected. Besides, the shearographic patterns are also projected to the sample to improve the method and make it more obvious.

Conclusion

This document reviewed the most relevant methods and tools that exhibit many different contactless methods taken for structural health monitoring in the last 25 years. The most important technique was discussed including vision-based, radar, laser, embedded, wireless, hybrid sensing among others. There is a clear trend in utilizing vision-based tools like the computer become more powerful and algorithms (i.e., artificial intelligence, deep learning, neural network) are capable to accurately post-process the data. Global methods are undoubtedly the more applied method used with different types of sensors and tools deployed. Mainly because the vicinity of the potential damage is not needed beforehand. However, small-scale damage might not be detected in these vibration-based approaches. Thus, local methods (e.g., strain-based,) are preferred when high sensitivity is essential. For these particular cases, the wireless embedded sensor seems to be the most feasible techniques. Additionally, hybrid sensing has the potential to detect damage in a more accurate approach, however, its implementation needs to be considered as an extra cost and massive data would be generated. Also, there is still room for improvement in all contactless approaches. To conclude non-contact methods are being widely employed to characterize many defects (e.g. cracks, delamination, spalling) in metallic, concrete and composite structures, nevertheless, the chosen technique should be carefully chosen as early damage detection is imperative.

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