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ORIGINAL PAPER

Sensors Used in Structural Health Monitoring

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Abstract In the last years, the occurrence of natural hazards around the world has evinced the necessity of having structural health monitoring schemes that can allow the continuous assessment of the structural integrity of the civil structures or infrastructures, in order to avoid potential economic or human loses; further, it also allows the application of new sensing technologies and signal processing algorithms. An important step in a structural health monitoring strategy is the appropriate selection of the sensor used to measure the required physical variable. Although several reviews have been published, they focus on presenting and/or explaining the methodologies and signal processing techniques used in structural health monitoring. This article presents a state-of-the-art review of the sensing technologies used in structural health monitoring. Further, some candidate sensor technologies with potential of use in this area are also reviewed, where the main issues that affect their implementation in real-life schemes are also discussed.

1 Introduction

The modern lifestyle of the society would not be the same without the existence of the civil infrastructures, as they are used to transport people or products between cities or even countries. Moreover, they are also employed to create offices or homes, or to construct water reserving places, just to enumerate some of their applications. Even when they are designed to operate into severe ambiental conditions, the unpredictable occurrence of natural phenomena, i.e., tornadoes, strong winds, small seismic waves, as well as their natural aging, can cause an important concern to their physical integrity, making the continuous measurement of some physical properties an imperative task, since any significant change may be detected and thus, allowing taking remedial actions in a timely fashion to restore the functionality required by the structure.

Structural Health Monitoring (SHM) is a procedure that aims to estimate the structure condition by means of the evaluation of some measured physical features. According to Amezquita-Sanchez and Adeli [1], a damage-based SHM involves three stages: signal monitoring, processing, and its interpretation (Fig. 1a). The first stage uses a wide range of sensors to measure physical properties of structure, which can be classified in three groups [2]: kinematical (displacements, velocity, and acceleration), mechanical (forces, deformations, stress), and ambient (wind and temperature). Also, the signal monitoring stage requires an instrumentation or signal conditioning circuitry and a data acquisition system (DAS) for storing and later processing them (see Fig. 1b). Evidently, the sensor output determines the instrumentation required; further, it also influence the quality of the measured signal. A poor instrumentation might lead to have two undesirable consequences: a potential loss of information and the need of a more complicated signal processing technique in order to compensate the lost information, thus avoiding a misinterpretation of them. Hence, knowing the main characteristics of sensors used in SHM is a highly desirable feature, as this knowledge will help

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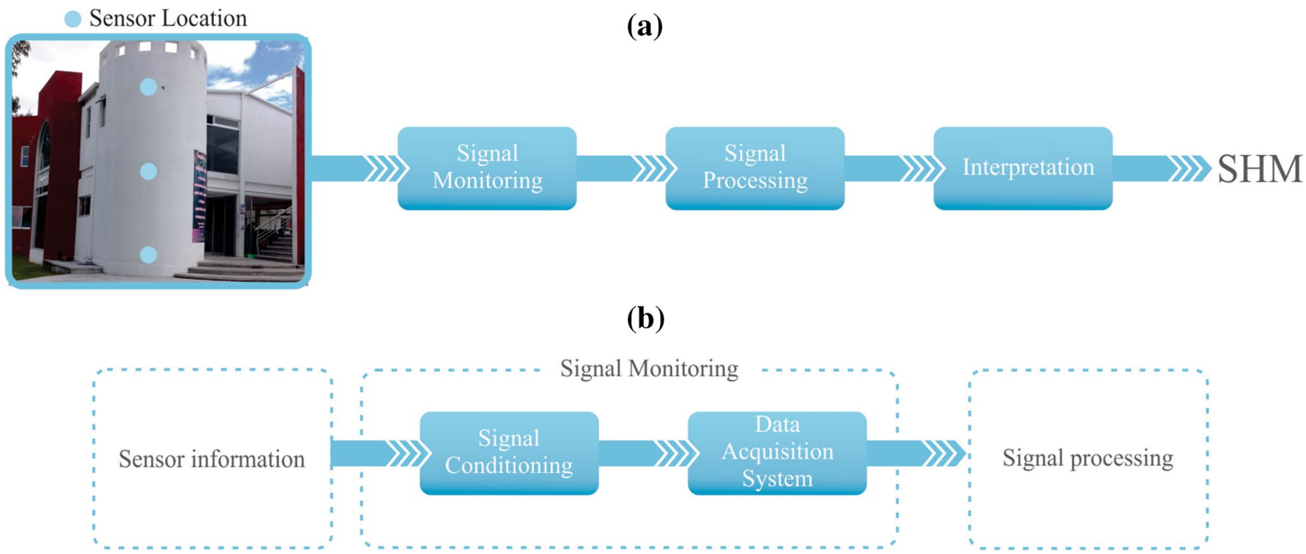

Fig. 1 A SHM scheme: **a** a damage-based approach, **b** steps required in the signal acquisition stage

to make the best-suited decision for the sensor selection and its deployment in the in-test structure.

Recently, different articles have reviewed the main signal processing and interpretation algorithms used in SHM [1–6], lasts steps in a damage-based approach (Fig. 1a). In this regard, and despite of previous works that superficially deal with the sensors features [2, 6], to the best of the authors knowledge, an article that describes the main sensors used in SHM for civil engineering is still missing. This article presents a state-of-the-art review of the sensor technologies used on journal articles for SHM in civil engineering. The focus is on civil structures including buildings and bridges, which are by far the most used structures for satisfying the abovementioned necessities. The rest of this paper is organized as follows: in Sect. 2, the used sensors for obtaining the kinematic variables (acceleration, velocity, and displacement) as well as their operating principle are presented; then, in Sect. 3, the measurement of the most representative mechanical features, fatigue, strain, and force measurement, is explained; further, the sensors used to detect the most frequently mechanical failures, corrosion and crack, which are important into the SHM of civil infrastructure, are also presented. On the other hand, Sect. 4 discusses both the way that the main environmental variables are sensed and the used devices to this purpose. The main features of the sensors used in SHM applications are resumed in Sect. 5. Next, Sects. 6 and 7 present some recommendations to ensure an adequate instrumentation and some candidate sensors to be used in SHM applications, respectively; finally, the article ends with some concluding remarks.

2 Kinematic Sensors

Broadly speaking, the term kinematic refers to the study of the motion of particles or bodies without regarding the cause that induced the movement. In this regard, a kinematic sensor, for SHM applications, measures the motion induced by an external force which can be, for instance, moderate or strong winds, seismic waves, traffic and human-induced vibrations, among others. This motion can be captured by measuring the displacement, velocity or acceleration of the in-test structure. This section presents the most common kinematic sensors used in SHM along with the structures and the applications where they are deployed.

2.1 Acceleration

An accelerometer is a device that measures an oscillatory movement due to the presence of induced vibrations, which cause changing accelerations in the in-study structure. In general, there are four types of accelerometers that are used in SHM: capacitive, piezoelectric, force balance, and microelectromechanical (MEMS) devices [2].

Conceptually, a capacitive accelerometer (shown in Fig. 2a) measures the capacitance between two plates, one that can be moved by an inertial mass and the other fixed to the internal case of the sensor. Evidently, when the sensor is subjected to vibrations, the inertial mass and its attached plate will move, thus varying the distance to the fixed plate, causing that the capacitance value changes as well. This type of sensor has the advantage of being able to detect subtle movements that other technologies cannot [2].

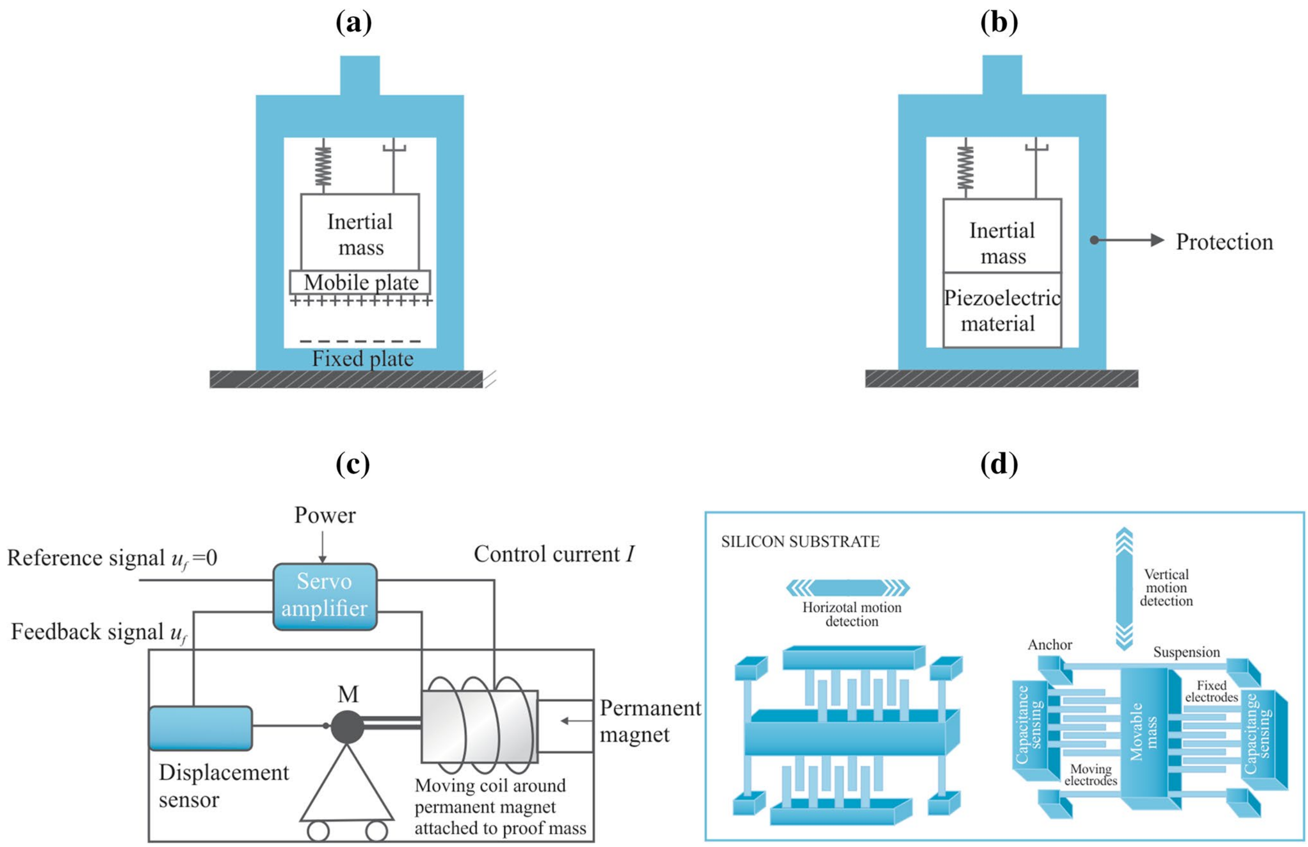

Fig. 2 Accelerometer types: **a** capacitive, **b** piezoelectric, **c** force-based, and **d** MEMS-based

A piezoelectric accelerometer replaces the two plates by a piezoelectric material (usually a crystal) (depicted in Fig. 2b) that produces an electrical current, which is proportional to the pressure applied to the material. In this regard, the higher the pressure, the higher the output signal will be. Compared with the capacitive approach, this kind of accelerometers has a slightly reduced sensibility making them less suitable to measure low frequency vibrations [2].

Regarding the force-based or servo accelerometer (Fig. 2c), it is composed by three different parts: a sensor to measure the displacement of a seismic mass, an actuator that calculates the aforementioned force to maintain the mass in its position, and a servo amplifier that decodes the signals created by the actuator to produce the required electrical signals in order to have the necessary force. In general terms, its operating principle can be described as follows: since any slightly perturbation (force) can move the seismic mass, the actuator (magnet) estimates the necessary counter force to try to keep the mass in its initial position, which is produced by the amplifier by injecting current to the coil attached to the magnet according to the sensed position by the displacement sensor. It should be pointed out that the output signal is the measured position, which is equivalent to the mass displacements produced by the external acceleration.

On the other hand, a MEMS-based accelerometer is usually made of several capacitors that are micro-fabricated, thus allowing a reduction in the capacitor size. As the MEMS-based accelerometer share the same sensing technology, its functioning principle is similar to the capacitive accelerometer. The development of new techniques for micro-fabricating technologies has led to a considerable price reduction, making them more accessible to the researchers and engineers, thus they have become in one of the most used accelerometers sensors in SHM applications [2]. Figure 2d illustrates the mechanical model of a MEMS-based accelerometer.

In recent years, several real-life structures have been equipped with accelerometers in order to measure vibrations to implement SHM schemes. For instance, the Green Building, a reinforced concrete (RC) building of 21 stories, located at the MIT, is instrumented to update a finite element model (FEM) [7]. They record the responses when the structure is subjected to ambient vibrations using uni-axial servo accelerometers, with a range of ±4 g. They extract the impulse response functions (IRFs), using seismic interferometry, to estimate the parameter (stiffness) that connects the IFRs with the FEM model. The update is performed by using a probabilistic approach. The obtained results show that their proposal can accurately update the FEM model, as the estimated IRFs are very similar to their experimental counterparts. Other RC buildings that have been instrumented with tri-axial MEMS-based, servo, and piezoelectric accelerometers are a hospital [8], bridges [9–12], scholar offices [13], among others.

Civil infrastructure including bridges for both pedestrian and traffic [14–17], working offices [18], frame structures [19], 3D truss structures [20, 21] have also been instrumented using either piezoelectric, servo, or MEMS-based sensors. It should be pointed out that the piezoelectric or the servo accelerometers are uniaxial, whereas the MEMS are often tri-axial. Uniaxial accelerometers are usually chosen for monitoring real-life structures due to some directions are not properly excited because of the direction in which excitation force is applied; thus, even the most sensitive sensor could only acquire noise.

On the other hand, historical buildings [22–25] have also installed accelerometers, especially servo and piezoelectric ones, to assess their dynamic performance under ambiental conditions. Some of these works perform the modal parameters identification to update FEM models, while others make damage detection once a natural hazard has occurred. One feature they share is that the modal parameters have a closely relationship with the ambiental conditions (mainly temperature), concluding that a method to decouple them is highly recommended if they are going to be used for damage detection.

A major trend that has taken impulse is the instrumentation of super tall buildings in order to assess its behavior among different scenarios. In this regard, the measurements of the Lotte World Tower [26] (acquired with piezoelectric accelerometers), the Taipei 101 Tower [27], and Canton Tower [28] (which are obtained with servo accelerometers), have been analyzed to find their modal parameters. The authors of the aforementioned works make use of well-known techniques such as peak-picking (PP) and frequency domain decomposition (FDD) methods or proposes the utilization new methods, like the Synchrosqueezing Wavelet Transform (SQWT). The papers show a good correlation between the experimental values and the predicted ones using a FEM-based model.

2.2 Velocity

Another form to capture the movements induced by the abovementioned sources is through the velocity sensors. In general terms, there have been used two different types of velocity sensors in SHM: those based on the Doppler effect and its electromechanical counterparts [2].

An electromechanical-based velocity sensor is composed by a permanent magnet and two coils suspended around it. This concept is illustrated in Fig. 3a. According to the Faraday law, when the wires of a coil interact with a permanent magnet, it will be produced an electrical current whose intensity depends on the velocity which the coils cut the magnetic field of the permanent magnet, that is, the more the coils move, the higher the produced current will be; thus, the output of this sensor is obtained by subtracting the signals created by the two coils.

A laser Doppler-based vibrometer (LDV) is a device that is formed by a photo detector and a signal processor, as seen in Fig. 3b. The LDV operates as follows: a frequency-modulated laser beam is reflected in the in-test structure, causing a frequency shift (Doppler shift) in the bounced beam. This shift is compared with the reference frequency, where the difference is demodulated and processed by the signal processor to estimate the velocity of the in-test object.

Over the past years, the use of velocity sensors has been expanded in the SHM field. For instance, an 11-story RC building is instrumented using a LIDAR (Light Detection

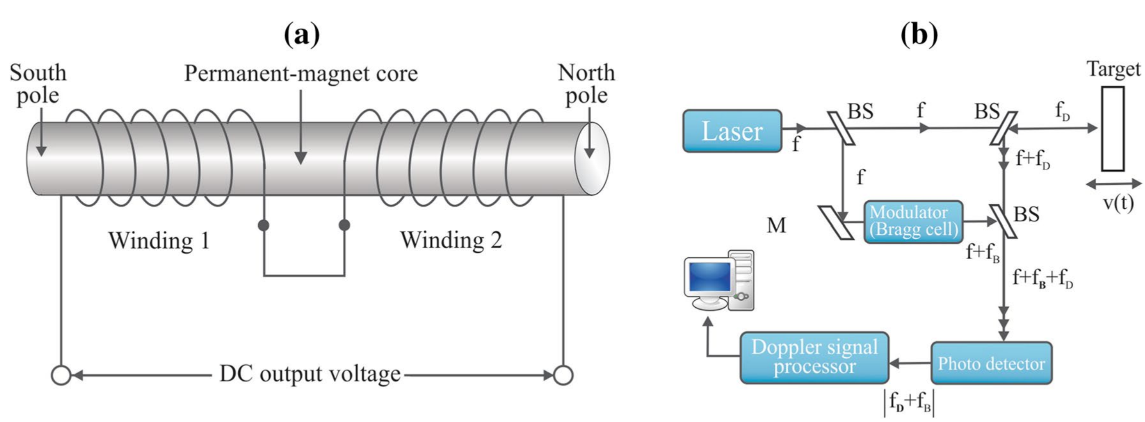

Fig. 3 Velocity sensor types: **a** electromechanical and **b** LDV

and Ranging)-based vibrometer and the Lennartz 3D 5 velocimeters [29]. The authors processed the obtained samples from both sensors by estimating the natural frequencies and mode shapes using the FDD method. They conclude that the LIDAR-based vibrometer results are very similar to those obtained by the velocimeters, with the advantage that the vibrometer can be used for remote monitoring, as no physical contact is required between the sensor and the in-test structure. On the other hand, electro-mechanical-based velocimeters (or geophones) have been used to damage detection of a five-girder, three-span bridge [30]. The velocimeters were used to measure the vertical vibration of the bridge. A damage detection algorithm is proposed using an autoregressive with exogenous inputs (ARX) model. They are able to detect multiple damages with their proposal; yet, the noise in the measurement affect their proposal, as the proposed algorithm cannot detect the damage in an external girder.

Another application of the velocity measurements is the modal parameters identification. An eight-storey steel frame is excited with broadband signals to analyze its response [31]. They propose a wavelet packet-based approach to deal with the inherent noise of the measured responses. The obtained results show that the proposal is robust against the noise, as the identified modal parameters (natural frequency and damping ratio) have an absolute error within 2% and 20%, respectively. Further applications of the velocimeters are also found in bridges [32–36], RC buildings [37], masonry structures [38], among others.

Recently, it has been proposed the use of the angular velocity as a form to detect if a civil structure has a damage or not. Liao et al. [39] also use MEMS-based gyroscopes to perform damage detection in a three-story single bay steel frame. They propose a damage indicator based on the difference on the coefficients of an ARX model. They conclude than the gyroscope has an increased sensibility compared with the accelerometer to detect damages near of their location. Sung et al. [40, 41] have explored the potential use of the MEMS-based gyroscopes as a substitute of accelerometers to detect and locate where a damage has occurred in a supported beam. They propose a damage indicator based on the modal flexibility matrix. The obtained results show that the gyroscope measurements have an enhanced sensibility for detecting the damage; further, the damage indicator proposed has a greater noise-robustness with the gyroscope measurements than with the accelerometers ones. They also note that a hybrid scheme, where both accelerometers and gyroscopes are used, can lead to have a SHM system that potentially can outperform other sensors.

2.3 Displacement

Some applications might require the use of the displacement measures to detect additional features than can be used for the damage or structural identification algorithm enhancement, such as the interstory drift ratio (IDR) [42]. In this regard, SHM schemes have made use of a resistive-based transducer, linear variable differential transformer (LVDT) or global positioning satellites (GPS) to measure the displacement of a civil structure.

A resistance-based transducer is formed by a variable resistor, either a linear or rotational one, which has three physical pins, denoted by the numbers 1, 2, and 3, respectively in Fig. 4a. The adjust pin is directly connected to the in-test structure, as the variation of this pin will change the total resistance value (R_1+R_2); consequently, the voltage value will also change [43]. For practical reasons, it is convenient to treat this transducer as a potentiometer, to eliminate the resistance changes produced by temperature. Figure 4a shows the graphical description of this transducer.

The LVDT schematic representation is depicted in Fig. 4b. It is composed of a nickel-iron-based core surrounded by a primary winding and two secondary ones, which are connected in a series way. When a voltage is applied to the primary winding, it is induced a voltage to the secondary windings; thus, when the core moves over the windings, it will create two different voltages (V_1 and V_2) depending of its position to the secondary windings. In this regard, the output signal of the sensor (V_s) will be the difference between V_1 and V_2 [43].

Regarding the GPS-based displacement measure, its operating principle can be described as follows: once located a GPS-receiver, it connects with four satellites, each one sending its position. By estimating the time that require the information send by the satellite to be received in the receptor, its absolute position can be found; thus, by using basic triangulation schemes, the position of the receiver is estimated. It should be pointed out that it is necessary to use high-precision receptors, to achieve a reasonable sensibility for measuring the displacements [44].

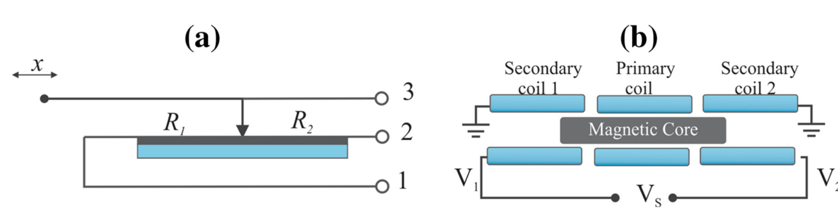

Fig. 4 Displacement sensor types: **a** potentiometer and **b** LDVT

The modal parameters (natural frequencies, damping ratios, and mode shapes) of an eight-storey steel frame using displacement measurements, obtained by potentiometers, are calculated in [45]. This article proposes a novel scheme that combines a time-variant ARX model and the use of the wavelet transform to perform the abovementioned task. The obtained results show that this proposal can identify accurately the modal parameters, as the maximum errors for the natural frequencies and damping ratios are below of 2% and 20%, respectively, even in the presence of a high-level of noise. They also can identify the stories that have a damage by using the identified natural frequency and the stiffness of the floor. Further applications of potentiometers can be found in Saisi et al. [46], McGetrick et al. [47], and He et al. [48].

LVDTs have been used as a part of damage identification, location, and quantification of a three-story steel structure [49]. The authors propose a novel hybrid scheme that combines the use of an AR model, second order blind source separation (SOBI), and principal component analysis (PCA) to perform the abovementioned task. The obtained results show that the proposal can successfully perform this task; but, they note that an appropriate choice of the AR model order yields to influence the accurateness of the damage quantification. LVDTs are also used to instrument Elevated Viaducts [50], a masonry building [51], a three-story, one-bay, 1/5-scaled RC building [52], and road bridges [53], among others. The obtained results in these works show that LVDT can be used to detect low-frequency modes, as there is an inherent limitation in terms of the measurement range they can capture.

Im et al. [44] presented a review of applications of GPS in SHM. They conclude that GPS can be used to measure static or quasi-static displacement with a reasonable accuracy, allowing the detection of low-frequency modes. These findings are confirmed by determining the modal parameters of a cable-stayed bridge [54] and suspension bridge [55].

An emerging technique to measure displacements is the utilization of optical-based instruments. Unlike the abovementioned sensors, an optical instrument can be easily installed in the in-test structure; further, its cost is greatly reduced compared with the utilization of GPS receptors. In this regard, the article presented by Chatzis et al. [56] point out that higher order modes can be successfully detected using this kind of sensor, which is an improvement compared with the other sensors; but, it is necessary to perform further studies to overcome a troublesome issue, which is the presence of low order spurious modes. Additional applications of this type of sensor can be found in [57, 58].

3 Mechanical Sensors

Measuring mechanical features, such as fatigue, force, strain, corrosion, cracks, among others, has become a very important task in civil infrastructure, especially in bridges, as they are closely related to their safe operation: a sudden failure might cause important consequences in terms of the potential loss of human lives and economic distortions. Moreover, the early detection of the failure will require, potentially, a lower budget, which also is a desirable item nowadays. In this regard, over the last years, novel schemes that make use of well-known and new sensor technologies have been proposed. In this section, the most common ones are reviewed.

3.1 Fatigue Detection

Fatigue detection is one of the most common failure found in civil infrastructure, especially bridges [59]. In general terms, this failure begins in the zones that experiment significant stress that have microscopic imperfections that lead to the appearance of fine cracks whose length and depth evolve negatively until they no longer have the integrity required.

Over the past years, several approaches to measure the fatigue level supported by the civil structure have been developed. Gokanakonda et al. [59] develop a sensor for fatigue detection based on the utilization of slots and stripes, named by the authors as ligaments, that are impressed in a metal plate (Fig. 5). These ligaments have a different strain magnification, as they have different strain magnification factors when compared with a nominal reference. The used ligaments fail in a sequentially order, where the first one that breaks is the one that received the greatest amount of stress and so on. They note that the ligaments failure occurs before the complete collapse of the in-test part. They propose that the fatigue can be detected by measuring the plate resistance, where increments in this property will indicate the severity of the fatigue level. This concept is further explored in [60], where they test a specimen that has two stripes and one slot in a steel beam. They note that slot separation must be optimized in order to have a better estimation of the fatigue value. Other approaches such as

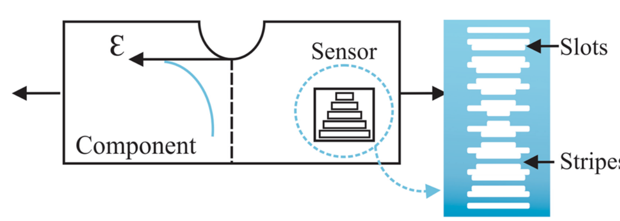

Fig. 5 Fatigue sensor composed by lots and stripes

eddy currents [61], acoustic emission (AE) [62, 63], ultrasonic waves [64] and strain-based methods [65], among others have been used for fatigue detection. These sensors have been used to monitor RC beams and steel bridges. The obtained results show that although good results are obtained, as all the used sensors can detect and quantify the amount of fatigue, it is still necessary to develop long-term monitoring to test them in real-life conditions.

3.2 Force Measurement

The measure of the applied force in critical parts of a civil structure is sometimes required, as these parts are designed to deal with up to a maximum value; if the applied force exceeds this value, it is likely to generate unnecessary cycles of stress, which in consequences will lead to an accelerated deterioration. To this purpose, cell loads have been used. They are a transducer device that converts the applied force into an electrical signal; although different types of load cell can be used, the most common one is a cell composed of strain gauges (Fig. 6a), where the electrical signal is obtained using an instrumentation circuit known as the Wheatstone Bridge (Fig. 6b). The operating principle can be resumed as follows: the higher the applied force, the greater the resistance; thus, the resulting voltage will decrease its value. This type of load cells is preferred as they can perform dynamic and static measures.

Rajan et al. [66] designed a system of load cells to measure how section of bridge decks behave under heavy windy conditions. They measure the forces that impact critical points in the bridge, to estimate all the three properties that occur in the bridge: lift, drag, and moment. They show that the proposed system can successfully estimate the above-mentioned properties; further, they also note that their system behaves in a linear way. On the other hand, the measure of the span deflection in a bridge deck is done using a load cell [67]. Their proposal consists of steel cable fixed to the deck, the load cell, a coil spring, and a weight that keeps the cable connected with the ground (Fig. 7c). As the load cell is subjected to a fixed force (given by the spring), any weight that passes through the deck will change the fixed force, thus by using the equations provided by the authors, the deflection can be estimated. They test their proposal in a steel bridge, obtaining noticeable results, as their sensor can estimate deflections with an accuracy of 0.05 mm. They note that their proposal behaves in a linear way and can be used in places where the access to the ground down the deck are troublesome; but, low wind conditions and low water level are required to not affect the fixed force. Additional applications using strain-based load cells are reported by Sideris et al. [68], Okazaki et al. [69], Lin et al. [70], Abdullah et al. [71], and Astroza et al. [72].

3.3 Strain

One of the most common consequences of applying a force in any solid object is its deformation. The measurement of the strain is one of the possible forms to measure the deformation of an object, and is usually sensed by using strain gauges, piezoelectric transducers, and vibrating wire strain gauges [73]. A strain gauge,

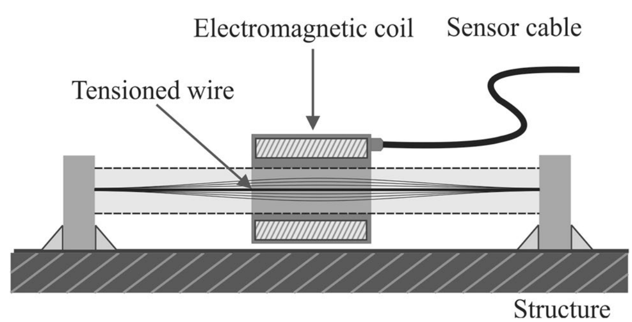

Fig. 7 Overall description of the vibrating wire strain gage

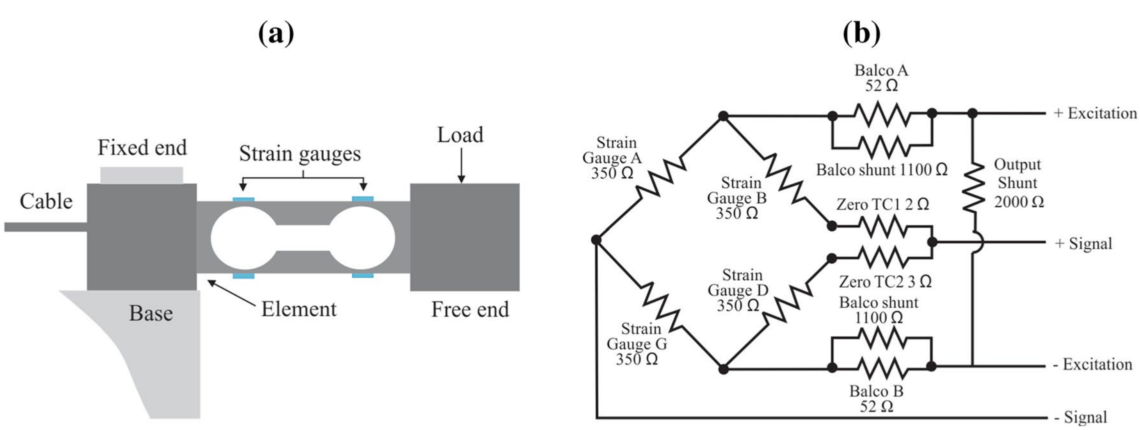

Fig. 6 Strain gauge load cell: **a** schematic overview, **b** wheatstone bridge

as abovementioned, changes its resistance value once it is subjected to an external force that deforms the in-test object. Regarding the piezoelectric transducer, also abovementioned, it is produced an electrical signal that is proportional to the deformation of the object. On the other hand, the vibrating wire strain gauge (Fig. 7a) uses the resonant frequency of the wire to estimate the strain. This device consists of two plates that have a tensioned wire between them; by applying an external force, the plates move causing a change in the tension of the wire, and thus, changing its resonant frequency. An electronic circuit, which could be a coil and a lock-in amplifier, can be used to both activate and measure the frequency.

Moreu et al. [74] installed a wireless monitoring system capable of measuring vibrations and strain using accelerometers and strain gauges, among other sensors. They use the obtained measurements to calibrate a FEM-based model of a double-track steel truss bridge located in Chicago, USA. They also compare the measurements of a magnetic strain gauge (the strain is measured as a change in the friction) and the reference ones, to verify if the former ones can be used as an alternative of the traditional ones. The obtained results show promising advances; but, it is required further test to verify the obtained values in variable ambiental conditions. Santini Bell et al. [75] also used the measurements of the strain to calibrate the FEM model of The Powder Mill Pond Bridge, a three-span continuous composite steel-girder bridge with a RC deck. Fu and Zhang [76] use the strain measurements of the Millard E. Tydings Memorial Bridge (a truss one) to investigate the causes of the bridge expansion joint failure. They found that higher values of stress, due to unexpected slide movements in the joint, that the expected ones caused the failure.

Since excessive strain can produce cracks and thus fatigue, it has been also used for this purpose [77–79] as well as performance evaluation and prediction [80–83] of bridges, among others applications.

3.4 Corrosion

Corrosion is one of the most important parameters that affect the performance and serviceability life of modern civil infrastructure, in particular of bridges. It can pass unnoticed for years or even decades, until severe failures that affect the structural integrity of the structure occur. Hence, it is necessary to develop sensors and methodologies that can be capable of a continuous monitoring of this property in order to be able to detect it in its earliest state, so the remedial actions required do not consume excessive amount of time and money.

According to Modares and Waksmanski [73], the objective of corrosion sensors is to detect its initiation and the rate of change. To this purpose, several technologies have been proposed. For instance, an electrochemical impedance-based sensor is used in [84]. It basically consists of a two-electrode cell (depicted in Fig. 8a), which are fed using a fixed-frequency sine wave. The corrosion is measured by calculating the difference of the impedance generated when two sine waves with different frequencies (10 mHz and 10 kHz) are applied to the sensor. Once obtained the resulting impedance, its reciprocal is related to the current that flows through the structure, and thus, the rate of corrosion can be estimated. This sensor is used to estimate the corrosion rate of two steel bridges in Japan. Another type of sensor technology is the utilization of radio-frequency identification (RFID) waves to detect how the corrosion affects the structure [85]. They use a circuit (tag), composed by a coil, capacitors, and resistances (Fig. 8b) to generate a magnetic wave with a specific frequency (above 10 MHz); then, a reader (who is another coil), by means of the induction principle, produces an electrical current that is proportional to the signal intensity. In this way, by positioning the tag under the surface to be analyzed, the signal strength will change, thus the induced current will also change. The corrosion is measured by analyzing the real and imaginary parts of the impedance. Although interesting results are obtained, sometimes the initial stage cannot be detected;

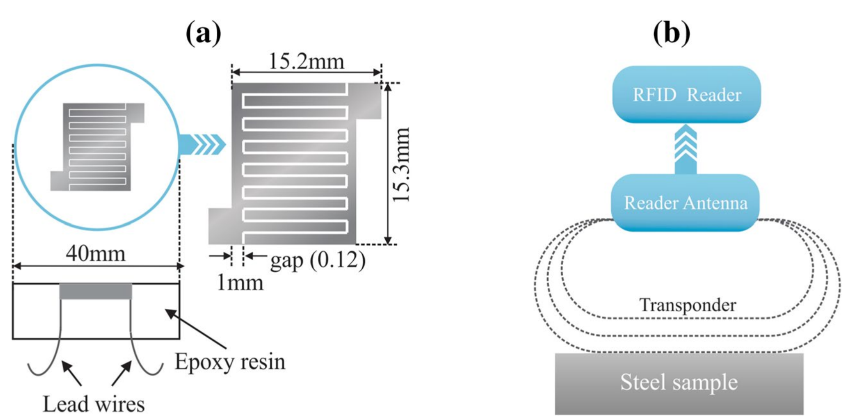

Fig. 8 Corrosion sensor technologies: **a** electrode cell and **b** RFID-based sensor

in this regard, the use of a varactor diode into the reader has been proposed [86], allowing the early detection of the damage in steel and reinforced concrete sections.

Further technologies that include the utilization of eddy currents [87], acoustic emission [88], and magnetic waves [89], among others, have been employed for monitoring and quantifying the corrosion in steel and concrete bridges.

3.5 Crack Detection and Quantification

Over the past decades, the crack detection and its quantification are an attractive area for experimentation. Cracks are provoked by corrosion, parts of the structure have been consumed, or due to excessive forces that cause fatigue in the structural parts, among other reasons. The most used sensors for detecting crack are AE, strain measure, and thermography [90, 91]. AE can be defined as the utilization of high-frequency sound waves, whose range varies from 100 kHz to 1 MHz to detect and create a graphical representation of the in-test surface and its cracks. In particular, both active and passive types of AE have proposed. An active AE-based sensor uses a piezoelectric transducer whose signal intensity depends on if the structure has cracks or not. In contrast, the passive sensor applies a sound wave to the in-test structure, and measures the rebounded wave to quantify its strength; in theory, the lower the signal is, the deeper the crack, the weaker the signal.

Yapar et al. [92] used an AE-based active sensors to detect and locate cracks in prestressed concrete bridges. They point out that is necessary to filter the acquired signals, as the noise contained in them causes potential miscalculations of the crack localization; hence, they make use of the discrete wavelet transform and the symlet wavelet (8th order) to denoise the signal. The crack localization in the in-test structure is done by means of a neural network, fed by some features such as the arrival time, frequency, among others. The obtained results show that their proposal is accurate, as it can locate the crack in concrete bridges within a maximum error of 5.5%. On the other hand, Zárate et al. [89] propose the utilization of a two-stage scheme for quantifying the crack length and its prognosis in RC bridges, that is, how many stress cycles does the structure have. They construct the probabilistic function with the acquired data; then, using a multivariate analysis (with all the acquired sensors), they perform the prognosis task by predicting a stress intensity factor. They test their proposal using samples of RC bridges, showing that it can quantify the crack length and its prognosis with an accuracy of 99%. An application that makes use of ultrasonic wave can be found in [93]. Further sensing technologies to detect cracks include the utilization of ground penetrating radar [94], piezoelectric transductors [95], vibrations [96], Hall-effect movement sensor [97].

4 Ambiental Sensors

The influence of ambiental variables, such as the temperature and wind, plays an important role in the estimation of the physical properties in civil structures cannot, in most cases, be neglected. For instance, it is well known that an increase of the temperature will produce an increase into the materials length; thus, modifying the stiffness and, in consequence, changing the value of the modal parameters [3]. On the other hand, the measurement of the wind speed in very important in civil infrastructure, as it can impose an excessive force that could, potentially, generate zones with a greater concentration of stress that the originally planned, among other effects. In this regard, the continuous monitoring of these ambiental variables can lead to have better algorithms to estimate the desired mechanical properties. In this section, the used sensors for measuring temperature and wind are presented; also, some applications that make use of theses variables are discussed.

4.1 Wind

An anemometer is a device that measures the wind speed in a reliable and simple form. There are four common technologies that are commercially available. A mechanical anemometer is usually constructed with several coups, that are attached to the horizontal arms, which are connected to a vertical rod. Thus, the stronger the wind blows, the faster the rod moves. This movement is translated to an electrical signal using a generator, which is then converted into the instant value of the speed. Other mechanical anemometers count how many rotations occur during a specific interval and then apply a relationship to estimate the velocity. An ultrasound-based anemometer has several pairs of sound transmitters and receivers that are mounted forming 90-degree angles. As the wind, will affect some of the sound beams, that is, will cause a deviation of their path, they will arrive slightly before or after that the others; thus, the speed difference can be used to detect the wind speed. The laser technology has also used to construct anemometers. One of them is the laser interferometer-based one, which measures the speed as follows: by using a laser beam and dividing it in two using a mirror, it can be generated two beams, one of them is used as the reference and will not be subjected to the wind, whereas the other (measurement beam) is affected; then, by recombing the two beams, a reference pattern can be obtained. Every time the measurement beam is affected by the wind, a slightly alteration of the pattern is produced, which is known as a set of interferences fringes. The wind speed is estimated by measuring the spaces of the aforementioned fringes.

In civil structures, wind has been used as an excitation force in real-life buildings, especially tall and super-tall ones, and bridges, as it is cheap and can excite properly these kind of structures [3]. Hong et al. [98] realize a study to a suspension bridge to estimate its modal parameters, natural frequencies, damping ratios, and mode shapes, and to calibrate a FEM-based model, using as excitation force the measured wind (obtained using a NRG Systems 40H mechanical anemometer). They obtain a good agreement between the estimated and measured responses (using a MEMS-based accelerometers). Kim et al. [99] analyze the structural responses of two parallel cable-stayed bridges, subjected to winds that create vortex-induced vibrations. The bridges' responses are measured with MEMS-based accelerometers, whereas the wind's speed is obtained using an ultrasonic anemometer. It is worth noticing that the bridges are equipped with tuned mass dampers (TMDs) to control the displacement of the bridge. They find out that the TMDs degrade its performance with low-speed winds as the damping ratio of the first mode does not increase enough its value to mitigate the displacements. They conclude that for the TMD can work ideally with wind speed above 10 m/s. The wind speed is also used to analyze the multimode coupled buffeting response of long-span bridges [100], to perform the preliminary design of tall buildings [101], to also analyze wind-induced pressure processes on tall buildings [102], and to assist the design of long-span bridges [103].

4.2 Temperature

The temperature can provide information regarding the inner conditions of the structure, such as fatigue, cracking, and yielding. Further, since some sensors are affected by the temperature, its measuring becomes an important concern in order to apply the appropriate corrections in order to have reliable measurements. To this purpose, several sensors including thermocouples, resistance temperature detector (RTD), and thermography, among other technologies are used. Thermocouples use the seebeck effect to measure the temperature. This effect describes that when two different metals are jointed at their ends and are subjected to a difference of temperature (T1), a voltage will be produced (Fig. 9a). The magnitude of the voltage will depend on the metals used (T2 y T3). The resulting current needs to be conditioned as it has a very low amplitude. In general, it is required to know the temperatures T2 and T3 in order to estimate T1; besides that, it is usually employed a specific operational amplifier-based circuit to instrument this transducer. The RTDs are sensors that are composed by a length of fine wire (usually a platinum one) surrounded by a ceramic or glass shell (Fig. 9b). These sensors are one of the most accurate as they have a linear relationship between resistance and temperature. Its conditioning circuit uses a voltage-fixed source, and because of the abovementioned relationship, any change in the voltage will indicate a variation of the temperature. Finally, the infrared energy can be considered as a measure of the temperature of an object. To measure this energy, thermographic cameras are used. They can be made of charge-coupled devices (CCD) that capture the emitted photons in the range of wavelength desired (9–14 μm). The obtained images are known as thermograms.

Wang et al. [104] study the effects that temperature causes in curved steel box girder bridges. They place displacement and temperature sensors all along a three-span continuous curved steel box girder bridge, where they note that non-linear temperature gradients cause self-restrained stresses in steel girders, thus stressing the whole structure and modifying the curvature of the bridge. They note that an exponential relationship can describe the temperature field, which can be used for similar bridges. Farreras-Alcover et al. [105] propose regression models that make use of temperature, strain, and traffic patterns to perform the structural health monitoring of welded bridge joints. They instrument the Great Belt Bridge, a suspension bridge, with strain gauges and temperature sensors, and generate a regression model using a weighed least-square approach to estimate the missing variables (a strain-based stress indicator that also depends on the temperature). The obtained results show that the proposal can be also used as a prognosis tool, in order to estimate the remaining fatigue life and also as performance assessment tool. Yarnold et al. [106] propose a temperature-based model for structural identification of long-span bridges. They use displacement sensors, vibrating wire strain gauges, and thermistors to acquire the required data. They find that the relationship between the abovementioned variables follows a bilinear response. Bearing this in mind, they propose the optimization of a FEM-based model using an iterative approach.

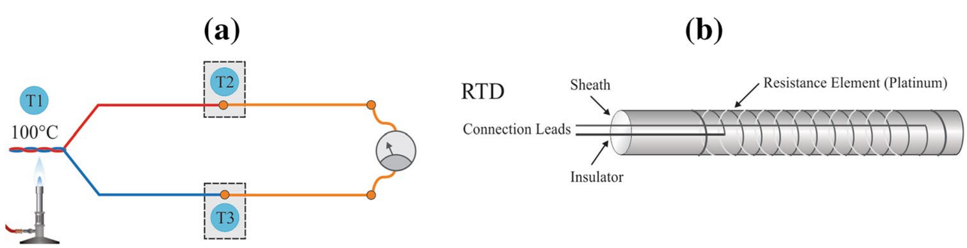

Fig. 9 Temperature sensors: **a** thermocouple, **b** RTD

The obtained results show that the response of the proposed model (displacement) is very similar to the obtained measurements. Further applications of temperature in SHM can be found in [107–111].

5 Main Features of the Sensors Used in SHM

The sensors presented in this article mostly measure primary physical properties, which in most SHM schemes, can be used to assess the actual condition of the structure; however, some mechanical properties require the measurement of secondary properties. Table 1 resumes some of the most widely used sensors in SHM schemes; further, it is also presented the type of application in which they are used.

6 Instrumentation Strategies for the Most Common Used Sensors in SHM

Another important feature of the sensors used in SHM is described by the type of output that the sensor has, that is, if the sensor produces current or voltage as its output. In any case, the following steps can be employed in order to secure a correct communication with the DAS:

1. If the sensor used produces a current output signal, a current-to-voltage operational amplifier-based scheme should be employed, so the produced current can be converted to a proportional voltage which can be further processed by additional stages.
2. An additional amplifier could be employed so the input range of the analog-to-digital converter (ADC) can be fully used. This avoids the loose of information of the sensor due to an improper input voltage range to the ADC.
3. The knowledge of the impedance levels between the different conditioning stages is important, so the voltage levels do not change their value due to different impedance levels. Thus, if the voltage output sensor has a lower impedance value compared with the next processing stage, a buffer must be used in order to avoid the loose of amplitude or inducing distortions to the measured signal.
4. The use of an antialiasing filter is required so the frequency range that is measured cannot be distorted.

Whereas the abovementioned recommendations can be used for all type of analog sensors, some of them might require special configurations in order to be used. For instance, to utilize strain gages, the Wheatstone bridge must be used as an instrumentation circuit. On the other hand, if a digital output sensor is used, then the communication protocols used to interface with it must be explored. The most popular are the serial peripheral interface (SPI) and inter-integrated circuit (I^2C), which are available in modern digital signal processors.

7 Novel Sensor Technologies Trends in SHM

The continuous development of new materials, which in most cases are smaller than the existing ones, has allow introducing novel sensors that in preliminary tests have been demonstrated to be potential solutions for SHM applications. This sections presents some of these technologies as well as potential applications where they can be used.

7.1 Vision-Based Sensors

Most of the presented sensors in previous sections require to have physical contact with the in-test structure in order to be capable of measuring the desired responses. Further, wired-based sensor systems must consider how distant will the data acquisition be placed, so the space, transportation, and length of cables have to be considered. Even when the utilization of wireless systems can avoid this calculation, the power consuming remains as issue. In this regard, the utilization of vision-based sensors does not impose the utilization of wires nor require physical contact between the sensor and the structure.

In the last years, applications of vision-based sensors have been proposed for system identification [112–114]. Although they present a significant step of innovation, some features remain as an interesting opportunity area to further investigate them. For instance, the amount of light present in the workspace can limit the accuracy of the measurements, as the tracked object can be wrongly located. This effect can have undesired consequences, as the mapping to the adequate reference system cannot be done properly, inducing an error in the estimated modal parameters. For this reason, these works have been used for academic structures. Further investigation of algorithms that can isolate the tacking point regardless of the luminosity of the picture will allow the utilization of these type of sensors in real-life structures. In this way, some interesting results are presented for crack detection [115, 116].

7.2 Fiber-Optic-Based Sensors

Another emerging technology is the utilization of fiber-optic-based sensors (FOS). Broadly speaking, FOS sensors operate according the amount of light that passes thorough the fiber optic, which is affected by either modifying the core reflection index, or generating

Table 1 Features of the presented sensor technologies

Type of sensor	Variable	Sensor technology	Relevant features	Main applications	Ease of installation
Kinematical	Acceleration	Capacitive	Can detect low-frequency oscillations Not affected by external conditions	Damage detection System identification	Easy
		Piezoelectric	Ideal to detect oscillations above 0.5 Hz Requires temperature compensation		
		MEMS	Reasonable compromise to detect low and high-frequency oscillations Inexpensive		
		Servo	Can detect ultra-low-frequency oscillations Excellent sensibility		
	Velocity	Doppler effect	High sensitivity Contactless	Damage detection System identification	Complex
		Electromechanical	Used primary to measure high-frequency vibrations Low-noise floor		
		Gyroscope	Can enhance algorithms to detect the site where damage occurred Drift	Damage detection	Easy
	Displacement	Resistive	High linearity Good resolution	Crack length detection System identification	Easy
		LVDT	Not affected by external conditions	Damage detection System identification	
		GPS	Poor resolution Low-frequency modes are only detected	System identification	Medium
		Optical	Enhanced resolution compared with GPS-based instruments Spurious modes can be induced		
Mechanical	Fatigue detection	Strain	Sensor fails before the collapse of the part Further studies to determine the best compromise in the stripes length is required	Damage detection	Easy
		Eddy currents	Can detect the initial state of the crack Can measure subtle changes in the crack length		
		AE Ultrasonic waves	Can detect the initial state of the resulting crack The crack length estimation is more complex, as the sensor does not follow a linear relationship		
	Force measurement	Load cells	Require temperature compensation Output is proportional to the load applied	Lift Drag moment Deflection	Medium
	Strain	Strain gage	Deformation is proportional to the deformation Usually used for static applications	Deformation Performance evaluation and prediction	Medium
		Piezoelectric	Improved sensitivity Mostly used in dynamic applications		
		Vibrating wire strain gauge	Offers noise isolation Samples can be read several kilometers far from the instrumented structure		
	Corrosion	Impedance	Uses two different frequencies to measure the corrosion rate Can detect the initial stages	Damage detection	Medium
		RFID	The original version cannot detect the early stages A varactor diode-based sensor is used for performing the abovementioned detection		
		Eddy current	Cannot detect the initial stages of the damage Follows a linear relationship		
		AE	Need of filtering schemes to avoid miscalculations in the rate of corrosion		
		Magnetic waves	Further tests are required to determine the best frequency to detect the corrosion in its earliest stage		
	Crack	AE	Need of filtering schemes to avoid miscalculations Complex algorithms are required to locate the site of the crack if weak signals are acquired		Medium
		Strain	It is necessary to use various sensors to have an adequate coverage of all the structure surface		Medium
		Thermography	A laser should be used to enhance the detectability of the crack Contactless		Complex
		Ultrasonic waves	Surface treatment is required Complex algorithms are needed		

Table 1 (continued)

Type of sensor	Variable	Sensor technology	Relevant features	Main applications	Ease of installation
		Ground penetrating radar	Excellent spatial resolution Requires a powerful implementation platform as it uses a great amount of memory		Medium
		Piezoelectric transducers	It is necessary to use various sensors to have an adequate coverage of all the structure surface Work better in metal structures		Easy
		Vibrations	Fusion of complex algorithms are required to detect, locate, and quantify the cracks It is necessary to use various sensors to have an adequate coverage of all the structure surface		
		Hall-effect movement sensor	It is necessary to use various sensors to have an adequate coverage of all the structure surface		Medium
Ambiental	Wind	Anemometer	Used to measure the excitation forces for system identification algorithms	Design System identification Vibration control	Easy
	Temperature	Thermocouples	They are only linear in a certain operation range Require compensation circuits to mitigate the environmental temperature	System identification Vibration control Prognosis	Easy
		RTD	Linear range of operation		
		Thermography	Expensive		Medium

interference patterns, among others, being the most used the interferometric, the Fiber Bragg Grating (FBG), and the Fabry–Perot interferometers [117]. One of the most important advantage of FOS over other sensing technologies is that they can be used for both sensing and transmission purposes simultaneously. They have been widely used for strain estimation [117], although deflection measurements, acceleration, angular velocity, corrosion, and displacement applications have been also reported [118–122]. FOS have been also used to create distributed sensors, which also have used for strain and crack detection [117, 123].

It should be pointed out that most of FOS sensors are not affected by environmental factors [117]; however, FBG in the majority of the cases requires temperature compensation. A possible solution is the utilization of the Long Period Fiber Grating (LPFG) [124], as they share the sensing principle without requiring the aforementioned compensation. Evidently, further studies are required in order to find out the if LPFG has the same sensibility and frequency range measurement than FBG.

7.3 Piezoceramic-Based Sensors

This type of sensor is a human-made version of the traditional piezoelectric materials, e.g. quartz. They are constructed by using one of two components: Barium Titanate and Lead Zirconate Titanates or PZTs [125, 126]. In their natural form, these compounds do not have the piezoelectric effect; but, by applying an electrical field with a significant amplitude, they acquire the aforementioned effect, which is stronger than the natural one [127]. Applications of this type of sensor have been reported for detecting cracks [128, 129], bolt inspection [130], and acceleration and force measurement [129], among others. Since they can be embedded into the material, allowing the creation of a type of "self-sensing" structure. The presented applications report promising results in academic structures; thus, it is necessary to perform further tests in real-life structures in variable ambiental conditions to examine their efficacy on real-life environments.

8 Concluding Remarks

Modern civil structures require a continuous assessment of their structural integrity in order to avoid catastrophic failures that can lead to economic and potential human loses. In this regard, the knowledge of SHM schemes, in particular of sensors and signal processing algorithms, has become a necessity for civil and structural engineers. This article presents a state-of-the-art review of articles focused on sensors used to measure key properties to determine the actual state of the structures. While other review articles barley mention the sensors used in SHM, as their focus is other, to the best of the authors' knowledge, this is the first article that presents an overview of the sensors used in SHM.

In general, three types of physical variables are measured: kinematical, mechanical, and environmental. Kinematical variables are widely used to determining the global state of health of the structure, where the use of angular velocity sensors is becoming popular to perform damage localization in specific localizations of the structure.

Regarding the mechanical variables, they are mostly used in SHM for civil infrastructure, as it is measured some material properties such as fatigue, strain, and the applied force, which are important to assess the material integrity and operation limits. Further, as the materials degrade due to the applied force or the environmental conditions, the measure of corrosion and cracks is also performed. In combination, these properties can be used to estimate the remaining serviceable life of the critical parts of the structure, and thus, of the structure. On the other hand, environmental variables, in particular temperature and wind, are used to compensate the deviations that some properties have under changing conditions.

While some the newer sensor technologies have been used for SHM in civil engineering applications, they must be further explored in real-life environments, in order to fully assess the potential benefits and challenges that they have. In this regard, for vision-based sensors, the amount of light in the working space has a fundamental role in some of the segmentation algorithms used; hence, the exploration of other algorithms that do not depend on this condition is an opportunity for further development. Fiber-optic and piezoceramic sensors can be embedded into the vital parts of the structure in order to develop self-sensing materials.

In spite of the vast work done in developing new sensor technologies, there is still a great potential for improvement. New sensor technologies must be as eco-friendly as possible, consume as lower power as possible, have an improved noise immunity, and be capable of being integrated into the materials to develop the new generation of smart materials. These features will allow to construct the next generation of smart structures.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Amezquita-Sanchez JP, Hojjat A (2016) Signal processing techniques for vibration-based health monitoring of smart structures. Arch Comput Methods Eng 23:1–15. doi:10.1007/s11831-014-9135-7
2. Gattulli V, Lepidi M, Potenza F (2016) Dynamic testing and health monitoring of historic and modern civil structures in Italy. Struct Monit Maint 3:71–90. doi:10.12989/smm201631071
3. Perez-Ramirez CA, Amezquita-Sanchez JP, Hojjat A, Valtierra-Rodriguez M, Romero-Troncoso RJ, Dominguez-Gonzalez A, Osornio-Rios RA (2016) Time-frequency techniques for modal parameters identification of civil structures from acquired dynamic signals. J Vibroeng 18:3164–3185. doi:10.21595/jve201617220
4. Amezquita-Sanchez, JP, Hojjat, A (2015) Feature extraction and classification techniques for health monitoring of structures Sci Iran Trans A Civ Eng 6:1931–1940. Available at http://www.scientiairanica.com/en/ManuscriptDetail?mid=3227. Accessed 25 Sep 2016
5. Webb GT, Vardanega PJ, Middleton, CR (2015) Categories of SHM deployments: technologies and capabilities. J Bridge Eng 20:04014118. doi:10.1061/(ASCE)BE1943-55920000735
6. Wijesinghe B, Zacharie S, Mish K, Baldwin J (2013) Design and development of in situ fatigue sensors for structural health monitoring of highway bridges. J Bridge Eng 18:297–307. doi:10.1061/(ASCE)BE1943-55920000361
7. Sun H, Mordret A, Prieto GA, Toksöz MT, Büyüköztürk O (2017) Bayesian characterization of buildings using seismic interferometry on ambient vibrations. Mech Syst Signal Process 85:468–486. doi:10.1016/jymssp201608038
8. Karapetrou S, Manakou M, Bindi D, Petrovic B, Pitilakis K (2016) “Time-building specific” seismic vulnerability assessment of a hospital RC building using field monitoring data. Eng Struct 112:114–132. doi:10.1016/jengstruct201601009
9. Santos A, Silva M, Santos R, Figueiredo E, Sales C, Costa JC (2016) A global expectation-maximization based on memetic swarm optimization for structural damage detection. Struct Health Monit 15:610–625. doi:10.1177/1475921716654433
10. Dilena M, Morassi A (2011) Dynamic testing of a damaged bridge. Mech Syst Signal Process 25:1485–1507. doi:10.1016/jymssp201012017
11. Gomez HC, Ulusoy HS, Feng QM (2013) Variation of modal parameters of a highway bridge extracted from six earthquake records. Earthquake Eng Struct Dyn 42:565–579. doi:10.1002/eqe2227
12. Franco JM, Marulanda J, Caicedo JM (2015) Modal identification of a full-scale building under seismic excitation using the fast mode identification technique. Exp Tech. doi:10.1111/ext12164
13. Foti D, Gattulli V, Potenza F (2014) Output-only identification and model updating by dynamic testing in unfavorable conditions of a seismically damaged building. Comput Aided Civ Infrastruct Eng 29:659–675. doi:10.1111/mice12071
14. Chang K-C, Kim C-W (2016) Modal-parameter identification and vibration-based damage detection of a damaged steel truss bridge. Eng Struct 122:156–173. doi:10.1016/jengstruct201604057
15. Bursi OS, Kumar A, Abbiati G, Ceravolo R (2014) Identification, model updating, and validation of a steel twin deck curved cable-stayed footbridge. Comput Aided Civ Infrastruct Eng 29:703–722. doi:10.1111/mice12076
16. Zhou HF, Ni YQ, Ko JM (2011) Structural damage alarming using auto-associative neural network technique: exploration of environment-tolerant capacity and setup of alarming threshold. Mech Syst Signal Process 25:1508–1526. doi:10.1016/jymssp201101005
17. Moser P, Moaveni B (2013) Design and deployment of a continuous monitoring system for the dowling hall footbridge. Exp Tech 37:15–26. doi:10.1111/j1747-1567201100751x
18. Morovati V, Kazemi MT (2016) Detection of sudden structural damage using blind source separation and time–frequency approaches. Smart Mater Struct 25:055008. doi:10.1088/0964-1726/25/5/055008
19. Dragos K, Smarsly K (2016) Distributed adaptive diagnosis of sensor faults using structural response data. Smart Mater Struct 25:105019. doi:10.1088/0964-1726/25/10/105019

20. Jang S, Spencer Jr BF, Sim S-H (2012) A decentralized receptance-based damage detection strategy for wireless smart sensors. Smart Mater Struct 21:055017. doi:10.1088/0964-1726/21/5/055017
21. Osornio-Rios RA, Amezquita-Sanchez JP, Romero-Troncoso RJ, Garcia-Perez A (2012) MUSIC-ANN analysis for locating structural damages in a truss-type structure by means of vibrations. Comput Aided Civ Infrastruct Eng 27:687–698. doi:10.1111/j1467-8667201200777x
22. Ubertini F, Comanducci G, Cavalagli N, Pisello AL, Materazzi AL, Cotana F (2017) Environmental effects on natural frequencies of the San Pietro bell tower in Perugia, Italy, and their removal for structural performance assessment. Mech Syst Signal Process 82:307–322. doi:10.1016/jymssp201605025
23. Saisi A, Gentile C, Guidobaldi M (2015) Post-earthquake continuous dynamic monitoring of the Gabbia Tower in Mantua, Italy. Constr Build Mater 81:101–112. doi:10.1016/jconbuildmat201502010
24. Lorenzoni F, Casarin F, Modena C, Caldon M, Islami K, da Porto F (2013) Structural health monitoring of the Roman Arena of Verona, Italy. J Civil Struct Health Monit 3:227–246. doi:10.1007/s13349-013-0065-0
25. Elyamani A, Caselles O, Roca P, Clapes J (2016) Dynamic investigation of a large historical cathedral. J Civil Struct Health Monit. doi:10.1002/stc1885
26. Li QS, Zhi L-H, Tuan AY, Kao C-S, Su S-C, Wu C-F (2011) Dynamic behavior of Taipei 101 tower: field measurement and numerical analysis. J Struct Eng 137:143–155. doi:10.1061/ASCEST1943-541X0000264
27. Li Z, Park HS, Adeli H (2016) New method for modal identification of super high-rise building structures using discretized synchrosqueezed wavelet and Hilbert transforms. Struct Des Tall Spec Build. doi:10.1002/tal1312
28. Ni YQ, Xia Y, Lin W, Chen WH, Ko JM (2012) SHM benchmark for high-rise structures: a reduced-order finite element model and field measurement data. Smart Struct Syst 4–5:411–426. doi:10.12989/sss2012104_5411
29. Gueguen P, JolivetV, Michel C, Schveitzer A-N (2010) Comparison of velocimeter and coherent lidar measurements for building frequency assessment. Bull Earthquake Eng 8:327–338. doi:10.1007/s10518-009-9137-2
30. Farahani RV, Penumadu D (2016) Damage identification of a full-scale five-girder bridge using time-series analysis of vibration data. Eng Struct 115:129–139. doi:10.1016/jengstruct201602008
31. Su WC, Huang CS, Chen CH, Liu CY, Huang HC, Le QT (2014) Identifying the modal parameters of a structure from ambient vibration data via the stationary wavelet packet. Comput Aided Civ Infrastruct Eng 29:738–757. doi:10.1111/mice12115
32. Dai K, Boyajian D, Liu W, Chen S-E, Scott J, Schmieder M (2014) Laser-Based Field Measurement for a Bridge Finite-Element Model Validation. J Perform Constr Facil 28:04014024. doi:10.1061/(ASCE)CF1943-55090000484
33. Sung Y-C, Lin T-K, Chiu Y-T, Chang K-C, Chen K-L, Chang C-C (2016) A bridge safety monitoring system for prestressed composite box-girder bridges with corrugated steel webs based on in-situ loading experiments and a long-term monitoring database. Eng Struct 126:571–585. doi:10.1016/jengstruct201608006
34. Benedettini F, Dilena M, Morassi A (2015) Vibration analysis and structural identification of a curved multi-span viaduct. Mech Syst Signal Process 54–55:84–107. doi:10.1016/jymssp201408008
35. Lin T-K, Chang Y-S (2017) Development of a real-time scour monitoring system for bridge safety evaluation. Mech Syst Signal Process 82:503–518. doi:10.1016/jymssp201605040
36. Farahani RV, Penumadu D (2016) Full-scale bridge damage identification using time series analysis of a dense array of geophones excited by drop weight. Struct Control Health Monit 23:982–997. doi:10.1002/stc1820
37. Valla M, Gueguen P, Augère B, Goular D, Perrault, M (2015) Remote modal study of reinforced concrete buildings using a multipath lidar vibrometer. J Struct Eng 141:D4014005. doi:10.1061/(ASCE)ST1943-541X0001087
38. Bergamo O, Campione G, Donadello S, Russo G (2015) In-situ NDT testing procedure as an integral part of failure analysis of historical masonry arch bridges. Eng Fail Anal 57:31–55. doi:10.1016/jengfailanal201507019
39. Liao Y, Kiremidjian AS, Rajagopal R, Loh, C-H (2016) Angular velocity-based structural damage detection. In: Proceedings of the sensors and smart structures technologies for civil, mechanical, and aerospace systems conference, Las Vegas, Nevada, United States, March 20, 2016, Jerome P Lynch, SPIE. doi:10.1117/122219398
40. Sung SH, Lee JH, Park JW, Koo KY, Jung HJ (2014) Feasibility study on an angular velocity-based damage detection method using gyroscopes. Meas Sci Technol 25:075009. doi:10.1088/0957-0233/25/7/075009
41. Sung SH, Park JW, Nagayama T, Jung HJ (2014) A multiscale sensing and diagnosis system combining accelerometers and gyroscopes for bridge health monitoring. Smart Mater Struct 23:015005. doi:10.1088/09641726/23/1/015005
42. Li H, Dong S, El-Tawil S, Kamat VR (2013) Relative displacement sensing techniques for postevent structural damage assessment: review. J Struct Eng 139:1421–1434, doi:10.1061/(ASCE)ST1943-541X0000729
43. Antonelli K, Astakhov VP, Bandyopadhyay A et al (1999) Displacement measurement, linear and angular. In: Webster JG, Eren H (eds) The measurement, instrumentation and sensors handbook on CD-ROM. CRC Press, Boca Raton
44. Im SB, Hurlebaus S, Kang YJ (2013) Summary review of GPS technology for structural health monitoring. J Struct Eng 139:1653–1664. doi:10.1061/(ASCE)ST1943-541X0000475
45. Su WC, Liu CY, Huang CS (2014) Identification of instantaneous modal parameter of time-varying systems via a wavelet-based approach and its application. Comput Aided Civ Infrastruct Eng 29:279–298. doi:10.1111/mice12037
46. Saisi A, Gentile C, Ruccolo A (2016) Pre-diagnostic prompt investigation and static monitoring of a historic bell-tower. Constr Build Mater 122:833–844. doi:10.1016/jconbuildmat201604016
47. McGetrick PJ, Kim C-W, González A, O Brien EJ (2015) Experimental validation of a drive-by stiffness identification method for bridge monitoring. Struct Health Monit 14:317–331. doi:10.1177/1475921715578314
48. He L, Lian J, Ma B (2014) Intelligent damage identification method for large structures based on strain modal parameters. J Vib Control 20:1783–1795. doi:10.1177/1077546312475150
49. Loh C-H, Chan C-K, Chen SF, Huang S-K (2016) Vibration-based damage assessment of steel structure using global and local response measurements. Earthquake Eng Struct Dyn 45:699–718. doi:10.1002/eqe2680
50. Murià-Vila D, Sánchez-Ramírez AR, Huerta-Carpizo CH, Aguilar G, Camargo Pérez J, Carrillo Cruz RE (2014) Field tests of elevated viaducts in Mexico City. J Struct Eng 141:04016074. doi:10.1061/(ASCE)ST1943-541X0001527
51. Li S, Zuo Z, Zhai C, Xu S, Xie L (2016) Shaking table test on the collapse process of a three-story reinforced

concrete frame structure. Eng Struct 118:156–166. doi:10.1016/jengstruct201603032
52. Stavridis A, Ahmadi F, Mavros M, Shing PB, Klingner RE, McLean D (2016) Shake-table tests of a full-scale three-story reinforced masonry shear wall structure. J Struct Eng 142:D4014001. doi:10.1061/(ASCE)ST1943-541X0001086
53. Le HX, Hwang E-S (2016) Investigation of deflection and vibration criteria for road bridges KSCE. J Civ Eng. doi:10.1007/s12205-016-0532-3
54. Han H, Wang J, Meng X, Liu (2016) Analysis of the dynamic response of a long span bridge using GPS/accelerometer/anemometer under typhoon loading. Eng Struct 122:238–250. doi:10.1016/jengstruct201604041
55. Erdogan H, Gülal E (2013) Ambient vibration measurements of the Bosphorus suspension bridge by total station and GPS. Exp Tech 37:16–23. doi:10.1111/j1747-1567201100723x
56. Chatzis MN, Chatzi EN, Smyth AW (2015) An experimental validation of time domain system identification methods with fusion of heterogeneous data. Earthquake Eng Struct Dyn 44:523–547. doi:10.1002/eqe2528
57. Islam MN, Zareie S, Alam MS, Seethaler RJ (2016) Novel method for interstory drift measurement of building frames using laser-displacement sensors. J Struct Eng 142:06016001. doi:10.1061/(ASCE)ST1943-541X0001471
58. Park J-W, Lee K-C, Sim S-H, Jung H-J, Spencer BF Jr (2016) Traffic safety evaluation for railway bridges using expanded multisensor data fusion. Comput Aided Civ Infrastruct Eng 31:749–760. doi:10.1111/mice12210
59. Gokanakonda S, Ghantasala MK, Kujawski D (2016) Fatigue sensor for structural health monitoring: design, fabrication and experimental testing of a prototype sensor. Struct Control Health Monit 23:237–251. doi:10.1002/stc1765
60. Priyantha Wijesinghe BHM, Zacharie SA, Mish KD, Baldwin JD (2013) Design and development of in situ fatigue sensors for structural health monitoring of highway bridges. J Bridge Eng 18:297–307. doi:10.1061/(ASCE)BE1943-55920000361
61. Papazian JM, Nardiello J, Silberstein RP, Welsh G, Grundy D, Craven C, Evans L, Goldfine N, Michaels JE, Michaels TE, Li Y, Laird C (2007) Sensors for monitoring early stage fatigue cracking. Int J Fatigue 29:1668–1680. doi:10.1016/jijfatigue200701023
62. Nor NM, Ibrahim A, Bunnori NM, Saman HM, Saliah SNMS, Shahidan S (2014) Diagnostic of fatigue damage severity on reinforced concrete beam using acoustic emission technique. Eng Fail Anal 41:1–9. doi:10.1016/jengfailanal201307015
63. Li H, Huang Y, Chen WL, Ma ML, Tao DW (2011) Estimation and warning of fatigue damage of FRP stay cables based on acoustic emission techniques and fractal theory. Comput Aided Civ Infrastruct Eng 26:500–512. doi:10.1111/j1467-8667201000713x
64. Mutlib NK, Baharom SB, El-Shafie A, Nuawi MZ (2016) Ultrasonic health monitoring in structural engineering: buildings and bridges. Struct Control Health Monit 23:409–422. doi:10.1002/stc1800
65. Deng Y, Liu Y, Feng D-M, Li A-Q (2015) Investigation of fatigue performance of welded details in long-span steel bridges using long-term monitoring strain data. Struct Control Health Monit 22:1343–1358. doi:10.1002/stc1747
66. Rajan SS, Jaya KP, Lakshmanan N (2009) Development of load cells for simultaneous measurement of drag, lift, and moment for section models of bridge decks under wind load. Exp Tech 33:38–45. doi:10.1111/j1747-1567200900532x
67. Ferreira JG, Branco F (2015) Measurement of vertical deformations in bridges using an innovative elastic cell system. Exp Tech 39:13–20. doi:10.1111/j1747-1567201200852x
68. Sideris P, Aref AJ, Filiatrault A (2014) Large-scale seismic testing of a hybrid sliding-rocking posttensioned segmental bridge system. J Struct Eng 140:04014025. doi:10.1061/(ASCE)ST1943-541X0000961
69. Okazaki T, Lignos DG, Hikino T, Kajiwara K (2013) Dynamic response of a chevron concentrically braced frame. J Struct Eng 139:515–525. doi:10.1061/(ASCE)ST1943-541X0000679
70. Lin Y-C, Sause R, Ricles J (2013) Seismic performance of a large-scale steel self-centering moment-resisting frame: MCE hybrid simulations and quasi-static pushover tests. J Struct Eng 139:1227–1236. doi:10.1061/(ASCE)ST1943-541X0000661
71. Abdullah ABM, Rice JA, Hamilton HR, Consolazio, GR (2016) Experimental and numerical evaluation of unbonded posttensioning tendons subjected to wire breaks. J Bridge Eng 21:04016066. doi:10.1061/(ASCE)BE1943-55920000940
72. Astroza R, Ebrahimian H, Contel JP, Restrepo JI, Hutchinson TC (2016) System identification of a full-scale five-story reinforced concrete building tested on the NEES-UCSD shake table. Struct Control Health Monit 23:535–559. doi:10.1002/stc1778
73. Modares M, Waksmanski N (2013) Overview of structural health monitoring for steel bridges. Pract Period Struct Des Constr 18:187–191. doi:10.1061/(ASCE)SC1943-55760000154
74. Moreu F, Kim RE, Spencer Jr BF (2016) Railroad bridge monitoring using wireless smart sensors. Struct Control Health Monit. doi:10.1002/stc1863
75. Santini Bell E, Lefebvre PJ, Sanayei M, Brenner B, Sipple JD, Peddle J (2013) Objective load rating of a steel-girder bridge using structural modeling and health monitoring. J Struct Eng 139:1771–1779. doi:10.1061/(ASCE)ST1943-541X0000599
76. Fu CC, Zhang N (2011) Investigation of bridge expansion joint failure using field strain measurement. J Perform Constr Facil 25:309–316. doi:10.1061/(ASCE)CF1943-55090000171
77. Liu R, Ji B, Wang M, Chen C, Maeno H (2015) Numerical evaluation of toe-deck fatigue in orthotropic steel bridge deck. J Perform Constr Facil 29:04014180. doi:10.1061/(ASCE)CF1943-55090000677
78. Chen Z, Xu Y, Wang X (2012) SHMS-based fatigue reliability analysis of multiloading suspension bridges. J Struct Eng 138:299–307. doi:10.1061/(ASCE)ST1943-541X0000460
79. Siriwardane SASC, Ohga M, Dissanayake PBR, Kaita T (2010) Structural appraisal-based different approach to estimate the remaining fatigue life of railway bridges. Struct Health Monit 9:323–339. doi:10.1177/1475921710361320
80. Seo J, Hosteng T, Phares B, Wacker J (2016) Live-load performance evaluation of historic covered timber bridges in the United States. J Perform Constr Facil 30:04015094. doi:10.1061/(ASCE)CF1943-55090000852
81. Gokce H, Catbas F, Gul M, Frangopol D (2013) Structural identification for performance prediction considering uncertainties: case study of a movable bridge. J Struct Eng 139:1703–1715. doi:10.1061/(ASCE)ST1943-541X0000601
82. Saiidi M, Vosooghi A, Nelson R (2013) Shake-table studies of a four-span reinforced concrete bridge. J Struct Eng 139:1352–1361. doi:10.1061/(ASCE)ST1943-541X0000790
83. Srinivas V, Sasmal S, Ramanjaneyulu K, Ravisankar K (2014) Performance evaluation of a stone masonry–arch railway bridge under increased axle loads. J Perform Constr Facil 28:363–375. doi:10.1061/(ASCE)CF1943-55090000407
84. Nishikata A, Zhu Q, Tada E (2014) Long-term monitoring of atmospheric corrosion at weathering steel bridges by an electrochemical impedance method. Corros Sci 87:80–88. doi:10.1016/jcorsci201406007
85. Zhang H, Yang R, He Y, Tian GY, Xu L, Wu R (2016) Identification and characterisation of steel corrosion using

passive high frequency RFID sensors. Measurement 92:421–427. doi:10.1016/jmeasurement201606041
86. Perveen K, Bridges GE, Bhadra S, Thomson DJ (2014) Corrosion potential sensor for remote monitoring of civil structure based on printed circuit board sensor. IEEE Trans Instrum Meas 63:2422–2431. doi:10.1109/TIM20142310092
87. Shaikh H, Sivaibharasi N, Sasi B, Anita T, Amirthalingam R, Rao BPC, Jayakumar T, Khatak HS, Raj B (2005) Use of eddy current testing method in detection and evaluation of sensitisation and intergranular corrosion in austenitic stainless steels. Corros Sci 48:1462–1482. doi:10.1016/jcorsci200505017
88. Jirarungsatian C, Prateepasen A (2010) Pitting and uniform corrosion source recognition using acoustic emission parameters. Corros Sci 52:187–197. doi:10.1016/jcorsci200909001
89. Carkhuff B, Cain R (2003) Corrosion sensors for concrete bridges. IEEE Instrum Meas Mag 6:19–24. doi:10.1109/MIM20031200279
90. Zárate B, Caicedo J, Yu J, Ziehl P (2012) Probabilistic prognosis of fatigue crack growth using acoustic emission data. J Eng Mech 138:1101–1111. doi:10.1061/(ASCE)EM1943-78890000414
91. Yao Y, Tung S-TE, Glisic B (2014) Crack detection and characterization techniques—an overview. Struct Control Health Monit 21:1387–1413. doi:10.1002/stc1655
92. Yapar O, Basu PK, Volgyesi P, Ledeczi A (2015) Structural health monitoring of bridges with piezoelectric AE sensors. Eng Fail Anal 56:150–169. doi:10.1016/jengfailanal201503009
93. Wolf J, Pirskawetz S, Zang A (2015) Detection of crack propagation in concrete with embedded ultrasonic sensors. Eng Fract Mech 146:161–171. doi:10.1016/jengfracmech201507058
94. Benedetto A (2013) A three dimensional approach for tracking cracks in bridges using GPR. J Appl Geophys 97:37–44. doi:10.1016/jjappgeo201212010
95. Alavi AH, Hasni H, Jiao P, Borchani W, Lajnef N (2017) Fatigue cracking detection in steel bridge girders through a self-powered sensing concept. J Constr Steel Res 128:19–38. doi:10.1016/jjcsr201608002
96. Xiang J, Liang M (2012) Wavelet-Based Detection of beam cracks using modal shape and frequency measurements. Comput Aided Civ Infrastruct Eng 27:439–454. doi:10.1111/j1467-8667201200760x
97. Krakhmal'ny TA, Evtushenko SI, Krakhmal'naya MP (2016) New system of monitoring of a condition of cracks of small reinforced concrete bridge constructions In: Proceedings of the International Conference on Industrial Engineering (ICIE), Chelyabinsk, Russian Federation, May 19–20, 2016, Andrey A. Radionov. Procedia Eng. doi:10.1016/jproeng201607322
98. Hong A, Ubertini F, Betti R (2011) Wind analysis of a suspension bridge: identification and finite-element model simulation. J Struct Eng 137:133–142. doi:10.1061/(ASCE)ST1943-541X0000279
99. Kim S, Park J, Kim H (2016) Damping identification and serviceability assessment of a cable-stayed bridge based on operational monitoring data. J Bridge Eng. doi:10.1061/(ASCE)BE1943-55920001004
100. Chen X (2014) Analysis of multimode coupled buffeting response of long-span bridges to nonstationary winds with force parameters from stationary wind. J Struct Eng 141:04014131. doi:10.1061/(ASCE)ST1943-541X0001078
101. Kwon D, Spence S, Kareem A (2014) Performance evaluation of database-enabled design frameworks for the preliminary design of tall buildings. J Struct Eng 141:04014242. doi:10.1061/(ASCE)ST1943-541X0001229
102. Huang M, Lou W, Chan C, Lin N, Pan X (2013) Peak distributions and peak factors of wind-induced pressure processes on tall buildings. J Eng Mech 139:1744–1756. doi:10.1061/(ASCE)EM1943-78890000616
103. Diana G, Rocchi D, Belloli M (2015) Wind tunnel: a fundamental tool for long-span bridge design. Struct Infrastruct Eng 11:533–555. doi:10.1080/157324792014951860
104. Wang J, Xu Z, Fan X, Lin J (2016) Thermal effects on curved steel box girder bridges and their countermeasures. J Perform Constr Facil. doi:10.1061/(ASCE)CF1943-55090000952
105. Farreras-Alcover I, Chryssanthopoulos MK, Andersen JE (2015) Regression models for structural health monitoring of welded bridge joints based on temperature, traffic and strain measurements. Struct Health Monit 14:648–662. doi:10.1177/1475921715609801
106. Yarnold M, Moon F, Aktan AE (2015) Temperature-based structural identification of long-span bridges. J Struct Eng 141:04015027. doi:10.1061/(ASCE)ST1943-541X0001270
107. Zhang Y, O'Connor S, van der Linden G, Prakash A, Lynch J (2016) SenStore: a scalable cyberinfrastructure platform for implementation of data-to-decision frameworks for infrastructure health management. J Comput Civ Eng 30:04016012. doi:10.1061/(ASCE)CP1943-54870000560
108. Torres-Arredondo M-A, Sierra-Pérez J, Tibaduiza D-A, McGugan M, Rodellar J, Fritzen C-P (2015) Signal-based nonlinear modelling for damage assessment under variable temperature conditions by means of acousto-ultrasonics. Struct Control Health Monit 22:1103–1118. doi:10.1002/stc1735
109. Santos J, Cremona C, Orcesi A, Silveira P (2016) Early damage detection based on pattern recognition and data fusion. J Struct Eng. doi:10.1061/(ASCE)ST1943-541X0001643
110. Hedegaard B, French C, Shield C (2016) Effects of cyclic temperature on the time-dependent behavior of posttensioned concrete bridges. J Struct Eng 142:04016062. doi:10.1061/(ASCE)ST1943-541X0001538
111. Kromanis R, Kripakaran P, Harvey B (2016) Long-term structural health monitoring of the Cleddau bridge: evaluation of quasi-static temperature effects on bearing movements. Struct Infras Eng 12:1342–1355. doi:10.1080/157324792015117113
112. Yang Y, Dorn C, Mancini T, Talken Z, Kenyon G, Farrar C, Mascareñas D (2017) Blind identification of full-field vibration modes from video measurements with phase-based video motion magnification. Mech Syst Signal Process 85:567–590. doi:10.1016/jymssp201608041
113. Oh BK, Hwang JW, Kim Y, Cho T, Park HS (2015) Vision-based system identification technique for building structures using a motion capture system. J Sound Control 356:72–85. doi:10.1016/jjsv201507011
114. Chen C-C, Wu W-H, Tseng H-Z, Chen C-H, Lai G (2015) Application of digital photogrammetry techniques in identifying the mode shape ratios of stay cables with multiple camcorders. Measurement 75:134–146. doi:10.1016/jmeasurement201507037
115. Yeum CM, Dyke SJ (2015) Vision-based automated crack detection for bridge inspection. Comput Aided Civ Infrastruct Eng 30:759–770. doi:10.1111/mice12141
116. Andreaus U, Baragatti P, Casini P, Iacoviello D (2016) Experimental damage evaluation of open and fatigue cracks of multi-cracked beams by using wavelet transform of static response via image analysis. Struct Control Health Monit. doi:10.1002/stc1902
117. Enckell M, Andersen JE, Glisic B, Silfwerbrand J (2013) New and emerging technologies in structural health monitoring: part I civil and environmental engineering. In: Kutz M (ed) Handbook of measurement in science and engineering. Wiley, Hoboken, pp 1–78. doi:10.1002/9781118436707hmse001
118. Mukhopadhyay SC, Ihara I (2011) Sensors and technologies for structural health monitoring: a review. In:

Mukhopadhyay SC (ed) New developments in sensing technology for structural health monitoring. Springer, Berlin, pp 1–14, doi:10.1007/978-3-642-21099-0_1
119. Helmi K, Taylor T, Zarafshan A, Ansari F (2015) Reference free method for real time monitoring of bridge deflections. Eng Struct 103:116–124. doi:10.1016/jengstruct201509002
120. Rodrigues C, Félix C, Lage A, Figueiras J (2010) A development of a long-term monitoring system based on FBG sensors applied to concrete bridges. Eng Struct 32:1993–2002. doi:10.1016/jengstruct201002033
121. Antunes P, Lima H, Varum H, André P (2012) Optical fiber sensors for static and dynamic health monitoring of civil engineering infrastructures: abode wall case study. Measurement 45:1695–1705. doi:10.1016/jmeasurement201204018
122. Tan CH, Shee YG, Yap BK, Mahamd Adikan FR (2016) Fiber Bragg grating based sensing system: early corrosion detection for structural health monitoring. Sens Actuators A 246:123–128. doi:10.1016/jsna201604028
123. Sahay P, Kaya M, Wang C (2013) Fiber loop ringdown sensor for potential real-time monitoring of cracks in concrete structures: an exploratory study. Sensors 13:39–57. doi:10.3390/s130100039
124. Perez-Ramirez CA, Almanza-Ojeda DL, Guerrero-Tavares JN, Mendoza-Galindo FJ, Estudillo-Ayala JM, Ibarra-Manzano MA (2014) An architecture for measuring joint angles using a long period fiber grating-based sensor. Sensors 14:24483–24501. doi:10.3390/s141224483
125. Sirohi J, Chopra I (2010) Piezoceramic actuators and sensors. In: Blockley R, Shyy W (eds) Encyclopedia of aerospace engineering, vol 6. Wiley, Hoboken, pp 1–14. doi:10.1002/9780470686652eae231
126. Ruiz D, Bellido JC, Donoso A (2016) Optimal design of piezoelectric modal transducers. Arch Comput Methods Eng. doi:10.1007/s11831-016-9200-5
127. Kong Q, Robert RH, Silva P, Mo YL (2016) Cyclic crack monitoring of a reinforced concrete column under simulated pseudo-dynamic loading using piezoceramic-based smart aggregates. Appl Sci 6:341. doi:10.3390/app6110341
128. Guofeng D, Linsheng H, Qingzhao K, Gangbing S (2016) Damage detection of pipeline multiple cracks using piezoceramic transducers. J Vibroeng 18:2828–2838. doi:10.21595/jve201617040
129. Wang RL, Gu H, Song G (2013) Active sensing based bolted structure health monitoring using piezoceramic transducers. Int J Distrib Sens Netw 9:583205. doi:10.1155/2013/583205
130. Yan S, Wu J, Sun W, Ma H, Yan H (2013) Development and application of structural health monitoring system based on piezoelectric sensors. Int J Distrib Sens Netw 9:270927. doi:10.1155/2013/270927