Journal of Applied Sciences

ISSN 1812-5654

science alert

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OPEN ACCESS Journal of Applied Sciences

ISSN 1812-5654
DOI: 10.3923/jas.2017.415.428

Review Article
Crack Inspection Using Guided Waves (GWs)/Structural Health Monitoring (SHM): Review

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Abstract
The Structural Health Monitoring (SHM) serves as an efficient and cost effective way to assist the guided wave study and the development of diagnostic algorithms before conducting time consuming experiments. In this paper introduce a review of Guided waves used for Structural Health Monitoring (SHM). Significant work has been done in guided wave modelling, guided wave generation and sensing and crack detection. In addition, presents the state of the art in these research areas with particular emphasis on guided waves in complex structures literature about guided waves and their applications in assessing the integrity of structures such as pipelines presented. Finally, the state of the art of Lamb-wave-based SHM technologies applied in pipeline structures, for the identification of crack and fatigue crack in science and industry.

Key words: Guided waves, structural health monitoring, crack detection, pipeline, piezoelectric

Received: April 18, 2017 Accepted: June 17, 2017 Published: July 15, 2017

Citation: Hatem Mostafa Elwalwal, Shahruddin Bin Hj. Mahzan and Ahmed N. Abdalla, 2017. Crack inspection using guided waves (GWs)/Structural Health Monitoring (SHM): Review. J. Applied Sci., 17: 415-428.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Increasing resources have been put into the development of various approaches for SHM applications. Some of these methods include fiber-optic sensing systems, the statistical pattern recognition methods, the vibration based approaches, the electromechanical impedance based methods and elastic wave based methods. For instance, the application of fiber-optic sensors, particularly Fiber Bragg Grating (FBG) sensors has rapidly accelerated in SHM in recent years[1,2]. By embedding fiber-optic sensors in structures, it is possible to acquire real-time data on structural variations such as stress or strain. Monitoring data can be utilized to identify deviations from a structure's original design performance to optimize its operation, repair and maintenance over time[3]. The SHM problems can also be cast in the context of a statistical pattern recognition paradigm[4]. Effective feature extraction is first performed by means of multivariate analyses and dimensionality reduction techniques. Here, feature extraction is a step of mining features, which are sensitive to crack of interest, from measured raw signals. Training data are then needed to build a statistical model in the inference stage and the model is used for subsequent decision making for classification and regression problems. Based on the data from uncrack or/and crack systems, supervised or unsupervised learning techniques can be used to identify crack. Data normalization is finally conducted to separate signal changes caused by operational and environmental variations of the system from those due to structural crack. The typical vibration based methods exploit the fact that a change in a structure influences the vibration signature such as the natural frequency of the structure[5,6]. Natural frequency variations can be used to identify structural vibrations, changes in structural stiffness and cracks. The natural frequency observation methods require a high level of crack and may not be effective in detecting deterioration over time or more subtle failure identification.

One of the most promising methods for active SHM is the integration of smart materials into the structures and utilization of these smart materials as sensors and actuators. Piezoelectric materials are representative among such type of smart materials. Through piezoelectricity and converse piezoelectricity, piezoelectric materials can act as both mechanical sensors and actuators to receive and generate signals[7-9]. Since the electrical impedance of piezoelectric sensors/actuators intimately bonded onto the structure is directly related to the structure's mechanical impedance, the variation of the electromechanical impedance is monitored over a large frequency spectrum in the high kHz frequency band[10]. In addition, elastic waves are a type of elastic perturbation that can propagate in a solid and reveal certain characteristics about the propagation medium[11].

This study focuses on review of using guided wave based methods for SHM applications. Moreover, more detail of guided wave propagations in crack inspection and wave interactions with structural discontinuities can be easily simulated. Finally, brief description of the important guided wave features such as dispersions and wave mode shapes can be acquired.

STRUCTURAL HEALTH MONITORING: CONCEPT AND APPROACHES

The emerging concept of Structural Health Monitoring (SHM) represents one of the enabling technologies that will overcome the aforementioned limitations[12-14]. The SHM often refers to the process of achieving the crack detection and characterization strategy for engineering structures. The idea of SHM is simply to make manufactured structures more like the human body and build a "Sensing skin" for those structures, which is practically implemented by permanently attaching an onboard network of actuators/sensors on the monitored structures[15]. The SHM process involves the observation of the system over time utilizing periodically sampled dynamic responses from the sensory network, the extraction of differential features caused by crack from these measurements and the comprehensive analysis of these features to determine the current state of structural health. The SHM can be either passive or active. Passive SHM infers the state of the structure by utilizing passive sensors, so this scheme only "Listens" to the structure without interacting with it. It has been shown that the reliability of SHM systems increases when the sensors do not just "Listen" but function as both actuators and sensors[16]. Active SHM utilizes active actuators/sensors that integrate the structure to identify the appearance of crack and its associated severity.

A complete SHM methodology should be able to (1) Identify crack occurrence in the structure, if any, (2) Locate structural crack and (3) Quantitatively describe the severity of crack. A more detailed general discussion of SHM can be found by Worden and Dulieu-barton[17].

The process of SHM is organized by the four steps as shown in Fig. 1[18]. All of researches in the field of SHM address some parts of the process. Operational Evaluation addresses life-safety and/or economic issues, definition of possible crack, environmental and/or operational conditions and data management constraints. The step of data acquisition, fusion and cleansing discusses how to select excitation and sensing methods and to configure data collection parameters such as strain, displacement and acceleration. In addition, for better feature extraction performance, the data cleansing process is

Table 1: Crack identification levels

Crack levels	Crack states	Description
Level 1	Detection	Qualitative indication of the presence of crack
Level 2	Location	Possible position of crack
Level 3	Classification	Estimate of the type of crack
Level 4	Assessment	Quantification of the extent of crack
Level 5	Prognosis	Estimate of the remaining useful life of structure

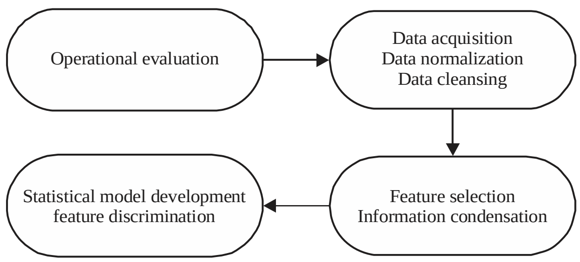

Fig. 1: Structural Health Monitoring (SHM) process

performed for noise removal, spike removal and outlier removal. The step of feature extraction and information condensation addresses data analysis parameters and signal processing methods like time and/or frequency analysis. The last step, statistical model development for feature discrimination, discusses how to determine changes between uncrack and crack structures and how to develop a model based on only uncrack structures.

This process is generally classified into two types, supervised learning and unsupervised learning mode. The supervised learning mode provides the information about crack presence and its possible location. The unsupervised learning mode is used for crack type discrimination, the extent of crack and the remaining lifetime of structures. For crack identification, SHM technology requires including all the crack information obtained from both supervised and unsupervised learning modes.

Crack identification level for SHM technology was first proposed by Rytter[19], separated into four steps. Farrar and Worden[18] divided the crack identification steps into five levels as shown in Table 1. Therefore the importance of the crack classification when multiple crack mechanisms are active, the type and the extent of the crack were organized into the separate steps for crack identification.

Each crack level requires all of the lower-level information. Levels 1 through 4 are associated with crack diagnostic process. On the other hand, level 5 is distinguished from others because this step is to develop validated simulation models to expect structural failure based on the understanding of the physics of failure. Hence, the remaining lifetime of structures/components can be predicted by the model development. For this study, the crack diagnostic process (Level 1~4) is focused on experimental investigation for the SHM technology.

STRUCTURAL HEALTH MONITORING

It is well established that structural health is directly related to structural performance that can be regarded as the primary factor in establishing the operational safety of the structure. There are different kinds of methods that can be used to detect the health of a structure and some of these are conventional methods such as vibration-based or parameter estimation methods, while others are based on new concepts. Many of the current methods for crack detection use the system or subspace identification technique; others use crack detection algorithms that bypass system identification and rely directly on the measured data to identify the crack. The vibration monitoring of a structure has gained popularity over the past decade due to the relative ease of instrumentation involved and the powerful system identification techniques developed for structural health monitoring. The main idea here is to replace the visual, systematic inspections by health monitoring systems that can continuously acquire and analyze vibration data and allow identification of crack at an early stage. More recently, a number of researchers have used neural networks for crack detection that can be considered to be a two-phase method involving a pattern generation/training phase and a pattern recognition phase. Another concept used for crack detection, known as the Precursor Transformation Method (PTM) is based on determining the causes (precursors) of change in the measured state of the structure under non-variable loading conditions (e.g., dead loads in bridges). Based on different methods and environments involved, a variety of parameters and criteria are used for measurement and crack detection. The different types of structural health monitoring, signal processing and analysis methods used (proposed) in the literature as indicated in Fig. 2.

System and subspace identification: The system identification technique is one that constructs a model of the cracked structure. By comparing the model of the cracked structure with that of the uncracked structure, the crack is detected. Lindner and Goff[20] did some research in this field. Liu and Rao[21] used a parameter identification method to determine the crack of a structure. With the subspace system identification algorithm, a structure state-space model was obtained. The identified state-space model was then

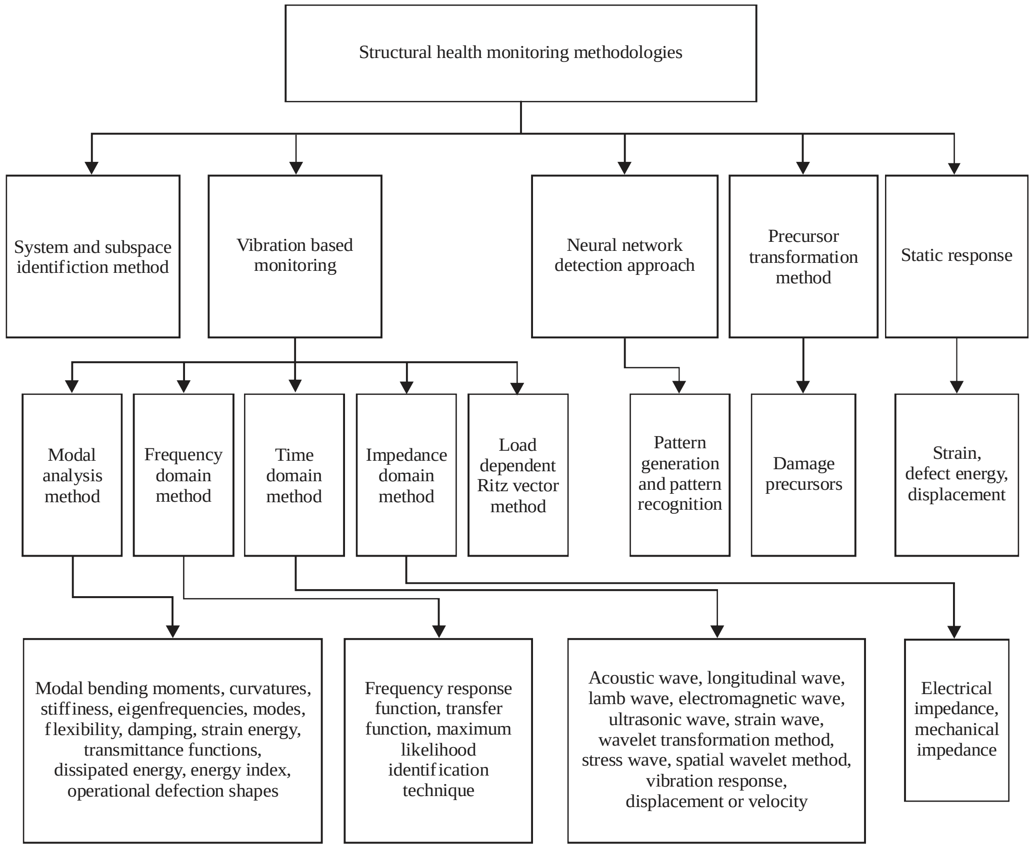

Fig. 2: Structural health monitoring

transformed into two special realization forms for determination of the equations of motion of the multiple degree-freedom structure. The parameters of the equations of motion, mass and stiffness matrices or crack indices were used to determine the location and extent of the crack. This method can also be extended for the health monitoring of substructural systems. Mevel *et al.*[22] used Hereto, a statistical local approach based on covariance-driven stochastic subspace identification, to detect the structural crack. The approach was applied to vibration data measured and ambient response data were measured right before and after applying a crack pattern. With the applications to a sports car and the vibration data measured on the bridge Z24 in Switzerland, it illustrated that the method allows the early detection of a vibration-induced fatigue problem. Mevel *et al.*[22,23] also did some research in a detection algorithm design with the statistical local approach based on stochastic subspace-based identification. This approach dealt with the early detection of slight deviations in usual working conditions. With output-only samples measured on a few industrially relevant examples, such as a steel subframe structure, the approach was proved to be efficient and capable of detecting slight changes in their eigenstructures. Tasker *et al.*[24] did some research on structural crack detection using subspace estimation. With an on-line subspace modal parameter estimation algorithm for crack detection, it showed that the method was able to detect small changes in structural properties through an innovation vector. Experimental evaluation demonstrated that the method could rapidly detect the occurrence of a change in the dynamic system using multiple sensors. The time-varying behaviour was captured in real-time via a graphical display of the norm of the innovation vector of the system.

GUIDED WAVE EXCITATION AND SENSING

For guided wave excitation and sensing, various transducers have been used, such as Piezoelectric Wafer Active Sensors (PWAS) (Fig. 3a), comb transducer (Fig. 3b), Macro Fiber Composites (MFC) (Fig. 3c), wedge transducers (Fig. 3d), fiber optics (Fig. 3e), electromagnetic acoustic transducers (EMAT)[25,26] (Fig. 3f), air-coupled transducers (Fig. 3g) and laser devices (Fig. 3h)[27,28]. Among these transducers, the low profile PZT are widely used for guided wave excitation and sensing. The PZT are small and light and suitable for integration into host structures (surface-mounting

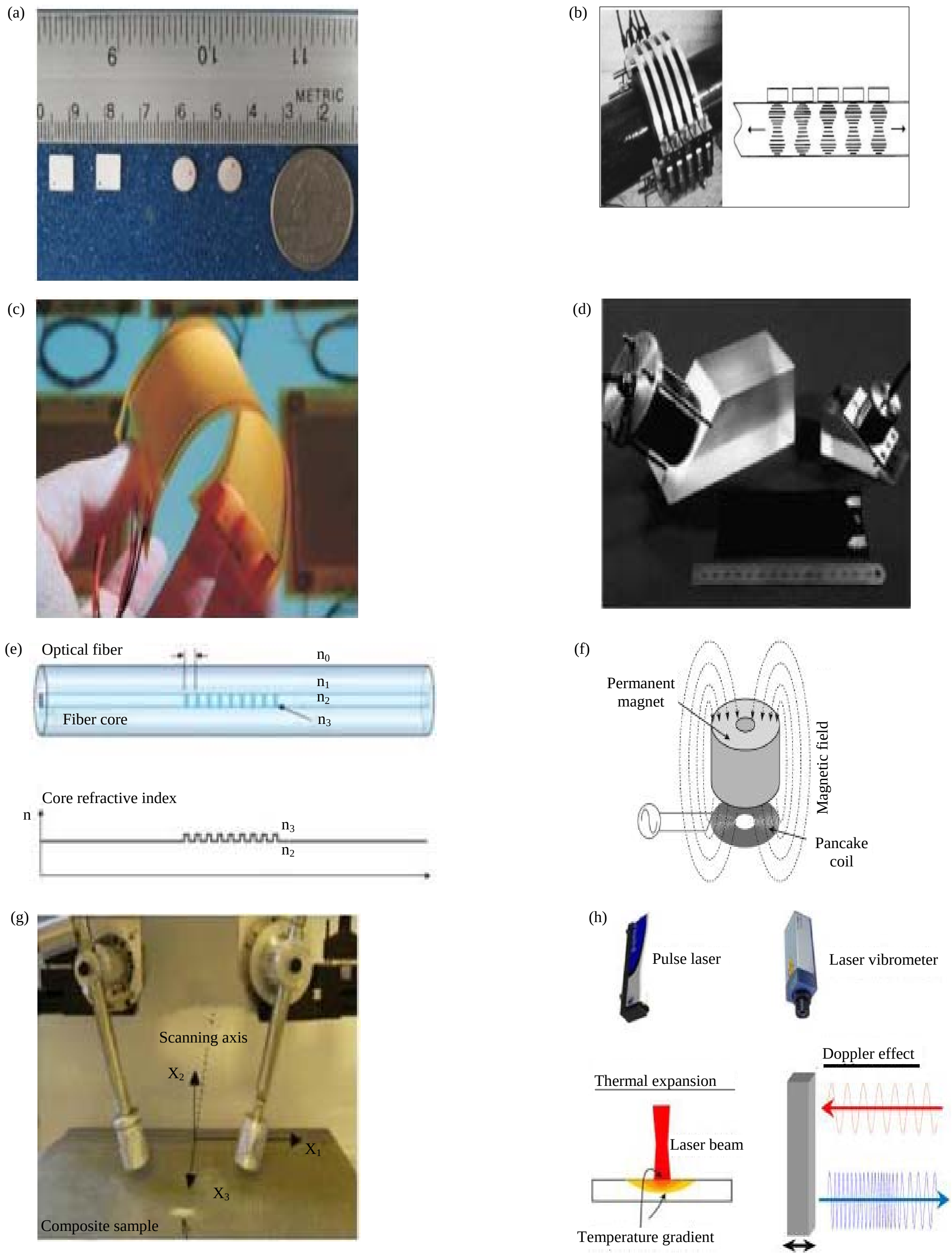

Fig. 3(a-h): Examples of various transducers (a) PWAS[29], (b) Comb transducer[30], (c) MFC[31], (d) Wedge transducers[32], (e) FBG[33], (f) EMAT transducer[27], (g) air-coupled transducer[34] and (h) laser transducers[35]

or embedding in composites) without significant intrusion, serving as good candidates for built-in transducers. Moreover, PZT can serve several purposes, such as high-bandwidth strain sensors and exciters, resonators and embedded modal sensors[12]. Recently, the laser devices, such as the high power pulse laser and the laser Doppler vibrometer, have emerged for non-contact guided wave applications[4]. The pulse laser can excite high energy wide band guided waves based on

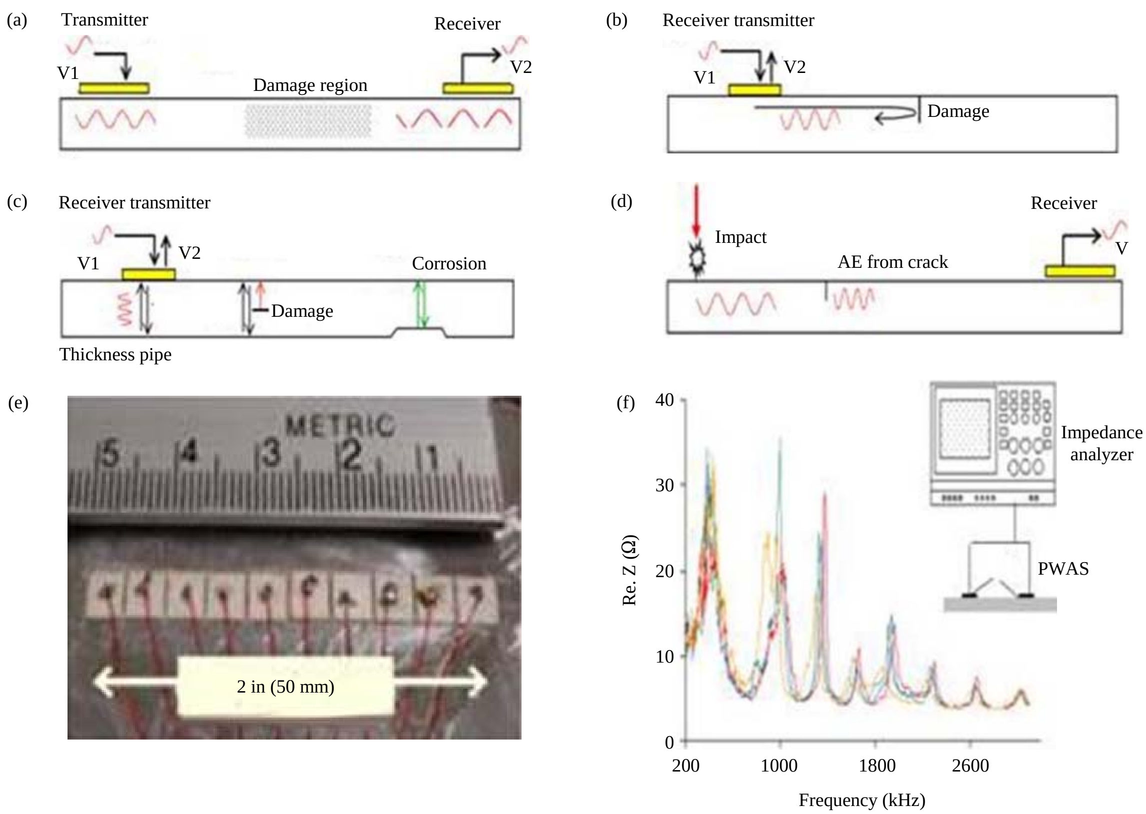

Fig. 4(a-f): Schematics of PWAS applications (a) Pitch-catch sensing, (b) Pulse-echo sensing, (c) Thickness sensing mode, (d) Impact/AE detection, (e) PWAS phased array and (f) E/M impedance method

either the thermal elastic effect or structure surface oblation. The laser Doppler vibrometer can measure the velocity or displacement at the sensing point on structural surface in the direction of the laser beam based on the Doppler effect. Their non-contact and remote sensing natures have attracted a lot of attention.

With the embedded guided wave excitation and sensing abilities, PWAS have be used for various SHM applications[8,29,36], such as (1) Active sensing of far-field crack using pitch-catch (Fig. 4a), pulse-echo (Fig. 4b) and phased array (Fig. 4e) methods, (2) Active sensing of near field crack using E/M impedance method (Fig. 4f) and thickness sensing mode (Fig. 4c) and (3) Passive sensing of Acoustic Emission (AE) events (Fig. 4d).

REVIEW OF CRACK MODELING

The crack or faults such as cracking, delamination, unbonding or the loosening of fasteners will change the physical properties of a structure[37]. A change in any one of the physical properties of stiffness, damping or mass will in general alter the behavior of the structure. Over the past 20 years, the idea of using physical properties and responses to assess the integrity of structures and machine elements has captured the attention of many researchers. Research in this area has been conducted on many fronts in a number of different disciplines are presented in Table 2.

REVIEW OF GUIDED WAVES FOR SHM SENSING SYSTEMS

Many researchers have used piezoelectric sheet elements as sensors in active controllable systems[57-60] and in structural health monitoring systems[61-63], since such piezoelectric sensors have advantages such as compactness, sensitivity over a large strain bandwidth in the monitored structure. It was demonstrated that for high frequency cases a dynamical piezoelectric sensor model should be used to consider dynamic sensing effects.

Among the most common sensing systems applied for GW-SHM, such as PZT transducers, PZT-based sensing systems in terms of GWs deliver excellent performance in detection and location of cracks.

The studies have verified that GW wave sensing systems for SHM have many advantages for identifying crack in structures, beam, plate and pipeline summarized in Table 3.

Table 2: Survey of guided wave crack detection technique

References	Methods proposed	Materials and sample shapes	Crack types	Remarks
Lowe *et al.*[38]	Propagate guided waves	Pipeline	Corrosion detection	Focused on sensitivity to defects of the propagation of the reflection and their modes. In addition, the work validate by finite element simulations and precise laboratory experiments
Liew and Veidt[39]	Neural networks damage identification	Bars	Laminar defects	The proposed neural network accurately predicated damage location and depth based on fusion data process that overlapping test
Lu[40]	Physical crack growth model	Pipeline	Corrosion detection	Investigate the liquid pipeline crack growth and it's controlled by the corrosion fatigue mechanism
Tan *et al.*[41]	Load-independent creep constraint parameter	Pipeline	Three-dimensional creep crack-tip	Focused on correlation between test specimens and the 3-D axially cracked pipelines. In addition more analysed done to check the effects of loading levels, crack sizes and geometries on pipeline crack
Wang *et al.*[28]	Shear horizontal guided waves propagating	Pipeline	Axial crack	The author also verified the proposed method by comparing with 3D numerical modelling FEM package for quantitative testing of axial pipeline cracking
Pan *et al.*[42]	A failure analysis	Stainless steel pipeline	Intergranular crack	Investigated pressure pipeline crack after two years servicing under elevated temperature by ABAQUS finite element software. The result show better understanding of effect of pipeline material mechanical properties and stress distribution on failure mechanisms
Cheng and Chen[43]	Hydrogen embrittlement	Pipeline carbon steels	Corrosion detection	The proposed method fatigue predicted crack growth rate and compared with experimental data
Liu *et al.*[44]	Linear magnetic dipole model	Pipeline	Axial crack	The author introduced a new relationship between geometry characteristics of axial cracks and magnetic flux leakage signals and show that detection accuracy depended on influence of magnetic fields near the magnetic poles
Eybpoosh *et al.*[45]	Unsupervised feature-extraction method	Aluminum pipeline	Different damage	The author focused on the effect of operational conditions and varying environmental on aluminum pipeline damage detection based on different wave modes propagation characteristics. In addition, empirical validation also conducted a pipeline structural abnormality including multiple small, different types and locations, in a steel pipe and under different temperature ranges
Xu *et al.*[46]	Generating longitudinal guided waves model	Pipeline	Different damage	Studied the effect on the excitation coil lift-off distances on alternating magnetic field strength generated in pipeline
Wang *et al.*[47]	Defect's geometric parameters	Pipeline	Different damage	Investigated the complexity of reflection signals features from defect edge for different defects geometric to determine the extraction signals to enable a quantitative and accurate pipeline defection
Cobb *et al.*[48]	Measure guided wave attenuation	Pipeline	Corrosion detection	Experimentally investigated the pipeline configurations (coated and uncoated) for corrosion detection based on guided wave attenuation with frequency range 10-140 kHz at ambient temperature

Table 2: Continue

References	Methods proposed	Materials and sample shapes	Crack types	Remarks
Peter and Wang[49]	Optimized matching pursuit method	Pipeline	Axial crack and corrosion	The author introduced a new optimized matching pursuit method for directly and accurately the pipeline axial defect detection. The analysis of the interference between the reflection components for efficient defect information extraction. In addition, proposed method enhances signal-to-noise ratio of reflection signal, but also characterizes
Clough *et al.*[50]	A screening technique	pipeline	Circumferential crack	The screening technique has good capability on defect sizing and detection. Also Finite element method has been used to simulate the pipeline focused on reflections that occur and the mode conversions
Lowe *et al.*[51]	Longitudinal ultrasonic guided wave	Pipeline	Different damage	The author for reduces the cost and weight on longitudinal guided wave mode for better inspection by adopting isolation transducers with 20-100 kHz operating range frequencies
Jiang and Chen[52]	Fatigue crack propagation	Pipeline	Mechanical damage	The author approved that fatigue crack propagation rate will increase by mechanical damage and the synthetic soil which led to shorten the pipeline service life
Koppe *et al.*[53]	Lamb waves	Pipeline	Different crack	Investigated the practicability of a Lamb Wave Generator (LWG) for differentiate and classify different defect types. In addition introduce a proper excitation, transmission and reflection of lamb wave characteristics based on relevant sample parameters (dimensions and specimen materials)
Sun and Li[54]	Liner sound source localization	Stainless steel pipeline	Different crack	The author introduced crack simulation model using Nielsen-Hsu Pencil Lead Break method identify Hit lockout time, Hit definition time, peak definition time and timing parameters for acoustic emission signal transducer
Kim *et al.*[55]	Small yoke-type magnetizer	Pipeline	Axis-directional crack	The DMF extracted crack for an arc-directional crack and an axis-directional crack
Piddubniak *et al.*[56]	The scattering of plane non-stationary sound wave	Steel shell	Long Crack	The author investigate echo-signals, directivity patterns of the scattered field and scattering amplitudes for the steel shell. in addition, the vibrations of steel shell are modelled based on Kirchhoff-thin shell-theory

Table 3: Guided wave for structural health monitoring

References	Methods proposed	Specific sensors	Materials detected	Remarks
An and Sohn[64]	Integrated impedance and guided wave (IIG)	Piezoelectric transducers	Deferent material such as steel, aluminium and composite	The author introduced IIG method to improve damage diagnosis under different temperature conditions. The proposed IIG technique shows good applicability on crack detection of a steel lap joint, with a complex geometry of aluminum specimen and a composite wing specimen
Rose *et al.*[65]	Robust leading edge technologies	-	Pipeline inspection	The author approved that scanning guided wave has significant enhancement on pipeline crack inspection using both and torsional longitudinal modes. In addition experimental data also presented to validate the proposed techniques
Na[66]	Electromechanical impedance (EMI)	Piezoelectric transducers	Pipeline wall thickness	The author investigated the reduction in wall thickness using the electromechanical impedance (EMI) method. Also, analysis effect of the resonance frequency range on detecting accuracy
Baltazar *et al.*[67]	Ultrasonic helical Lamb waves	Fiber composite (MFC) sensors		Cylinder aluminumThe author introduce wavelets technique to accurately perform mode identification of the ultrasonic captured signals. In addition, the experiment results shows that helical waves has better performance to monitor the damage in difficult to access areas
Yuan and Yan[68]	Combination of model electro-mechanical impedance (EMI) and RMM technique	Piezoelectric sensor	Timoshenko beams	The author derived a new expression of cracks impedance information with surface- bonded PZT sensor. The electro- mechanical impedance signatures extracted from the electro-mechanical impedance can be used to detect cracks in a structural system
Jing *et al.*[36]	Electro-Mechanical Impedance (EMI) method	Piezoelectric ceramic (PZT)	Concrete structures	The author proposed embedded PZT sensor on the surface-bonded for damage diagnoses under different conditions such as damage locations and extents. The experimental results approved that the proposed method are more accurate in detecting cracks in large-sized
Mahadevan *et al.*[69]	Domain of fatigue crack growth	-	Different crack	The author suggested several finite element present surrogate model and crack growth model. In addition three uncertainty types are such as (1) material properties and loading variability; (2) sparse data and measurement errors at different inspection scenarios (not detected crack, detected crack but not measured size and detected crack with measurement)size; finally (3) during crack growth analysis errors
Packo *et al.*[70]	Elastic	Wave propagation	Pipeline crack	The author presented subsequently methods for crack modelling. Also, review the relation of structure defects with elastic wave interaction transmission, reflection and other complex phenomena. The experimental results approved the proposed structure damage models has very good agreement with simulation model

Table 3: Continue

References	Methods proposed	Specific sensors	Materials detected	Remarks
Sun *et al.*[71]	Fatigue	Crack growth model	Different crack depths and locations	The author presented new relation of cracked beam natural frequency. The numerical simulation model with sceneries including different crack depths and locations also proposed. From the result, it can that the cracks deep closed to fixed end will lead to the faster rate of descent of the first order natural frequency and decrease of natural frequency
Gaith *et al.*[72]	Artificial Neural Network (ANN)	Solid cantilever beams	Different crack	The author proposed ANN model to predicted the cracks location and depths and size. In addition the ANN data training data collected from ANSYS software
Qatu *et al.*[73]	3-point	Pulse-echo technique	Aluminium plate	The author suggest wigner-ville distribution to eliminate noise and calculate the Time of Flight. Also, ABAQUS software used to simulate lamb wave propagation and determine the effect of damage size on the damage localization
He *et al.*[74]	Crack	Size quantification method	Different crack	The author studied Lamb wave propagation mechanism to predicate a crack size based on finite element method including two damage sensitive features: correlation coefficients and normalized amplitude. The simulation result verified the proposed model by series of coupon data caused environmental conditions and manufacture
Afzal *et al.*[75]	Detecting crack damage	Fiber Optic sensors (FOSs)	Concrete structures	The author presented review of various techniques used in crack damage detection using Fiber optic sensors. More information related to FOSs characteristics provided for more precise and accurate crack damage detection
Friswell and Penny[76]	Breathing cracks	-	Beam elements	The author investigated the effect of breathing cracks excitation where the beam stiffness is bilinear. In addition, crack modelling compares the different techniques using crack flexibility and low frequency vibration
Duan *et al.*[77]	Different structural health monitoring	Piezoelectric sensor	Plate, pipeline and beam structures for damage detection	The author focused proposer selection piezoelectric sensors and actuators types for crack detection including (beam, plate and pipeline damage detection). In addition, analysis of plain piezoelectric and inter digital transducer and their applications in pipeline, plate, beam and structures for damage detection technique are examined

CURRENT APPROACH IN INDUSTRY

In the pipeline industry, a single method for detecting or monitoring damage in a pipeline does not currently exist. Instead, industries typically implement a combination of several different techniques. For the oil and natural gas pipeline industry, destructive and non-destructive inspection techniques are commonly used together to ensure the integrity of transmission lines[78-82]. These techniques typically require the pipeline system to be temporarily taken out of operation. The most common destructive technique is a hydrostatic test. For oil pipelines, a hydrostatic test involves pressurizing the pipeline to a point greater than the maximum operating pressure. The pressure is then observed for several hours to determine if any leaks are present, because a hydrostatic test could potentially cause a leak or rupture, all the hazardous materials in the pipeline must be replaced with water to prevent environmental damage, because of service interruptions and water removal difficulties, hydrostatic testing is not used with natural gas pipelines.

When the geometry of the pipeline permits, non-destructive techniques are primarily used to ensure the structure's integrity. Such techniques commonly involve sending a magnetic flux or ultrasonic inspection device down the inside of the pipeline. The size of the device available limits the smallest size pipe that can be tested and the radius of bends also limits the ability to use a particular device. These devices perform best in oil pipelines because petroleum products act as a good coupling between the instrument and the pipe wall. Accordingly, these techniques do not require oil pipelines to be emptied, contrary to hydrostatic testing. However, natural gas pipelines are more complicated because a gas does not provide good coupling for the testing device. Therefore, operators of natural gas pipelines have turned to direct assessment procedures for the determination of the integrity of their systems.

As evidenced by the documented cases of pipeline accidents, the current approaches used in industry to monitor the structural integrity of pipelines is not 100% effective. Even though pipelines are one of the safest modes of energy transportation, there is still justification for seeking improvements. The associated costs of property damage from accidents are quite significant, not to mention the enormous loss from each and every fatality. Also, the implementation of both destructive and non-destructive inspection techniques requires the pipeline to be taken temporarily out of service, which adds to the costs to an operator. Therefore, the development of a more reliable, cheaper monitoring system would have countless advantages for pipeline operators.

Hence, innovative monitoring systems and defects diagnosis techniques should be in place to insure the sustainability of the infrastructure, i.e. pipelines and the associated equipment to insure their integrity and continuity[80,83].

CONCLUSION

This study focused on various vibration-based SHM methods, elastic-wave-based method, referred as guided wave method which employed as the fundamental tool for crack inspection. The GW method is an active SHM technology, which is a combination of Ultrasonic testing and Acoustic emission approaches. The technique is a global SHM method, which also has capability to detect local cracks of any structure. A complete SHM methodology should be able to identify crack occurrence in the structure, if any, locate structural crack and quantitatively describe the severity of crack. In addition, GW method has a number of advantages such as simple inspection methodology; time- and cost effectiveness; ability of wide area inspection with a limited number of transducers, fast and repeatable inspection capability; sensitivity to small cracks; and mode and frequency tuning capability.

SIGNIFICANCE STATEMENTS

This study presents a state-of-the-art review on various methodologies for the integration of GWs and SHM. A broad classification of important research works was presented along with their shortcomings and contributions. A comparative analysis in tabular form of various guided waves approaches has also been given. This study is very helpful for those who want to build up a level of understanding in the area of pipeline crack detection and classification based on different techniques including artificial neural networks.

ACKNOWLEDGMENT

Authors very thankful to Faculty of Mechanical and Manufacturing. Eng., University Tun Hussein Onn Malaysia (UTH) for financial support (RDU1503116) this project.

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