International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 03 Issue: 08 | Aug-2016 www.irjet.net p-ISSN: 2395-0072

Survey on Impedance Measurement Technique based Structural Health Monitoring

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Abstract - *The present paper is a comprehensive survey on Impedance measurement technique for Structural Health Monitoring (SHM). There are a plenty of research studies from civil engineering domain on various techniques to monitor the health status of a structure – these have been reviewed to provide a glimpse of their advantages and disadvantages as compared to impedance based technique. In particular focus is on their utility in wireless SHM where reliability, compactness and cost-effectiveness are the primary concerns. The Electrochemical processes in corrosion process is mathematically analyzed and based upon it impedance based measurement technique is described. The second section considers advances in basic techniques in EMI method and then goes on to explore hardware innovations in designing compact, miniaturized and energy efficient sensor nodes. Finally various studies on present state of art in impedance based SHM are described.*

Key Words: SHM, EIS, Sensor node, Corrosion, WSN

1.INTRODUCTION This paper provides a synopsis of a review [1] that will summarize structural health monitoring studies that have appeared in the technical literature between 1996 and 2016. The primary purpose of this review is to update a previous literature review [1] on the same subject. As with these previous documents, this summary will not address structural health monitoring applied to mechanical engineering domain. Instead, this review, as well as the previous one, focus on global structural health monitoring. This review begins by defining structural health monitoring process in civil structures and physical and chemical processes involved in corrosion.

1.1 *Electro-chemical processes in corrosion*

The modern age physical infrastructure for civil, mechanical, aerospace and railways etc. involves a huge construction and maintenance cost. With ageing phenomenon due to environmental conditions like moisture and high temperature, mechanical stresses induced fatigue and corrosion of metallic and concrete structures, it becomes all the more imperative to constantly monitor the health status. The basic principle in corrosion induced degradation is pitting phenomena due to constant electrochemical reactions taking place in the presence of free radicals in the air (Fig.1).

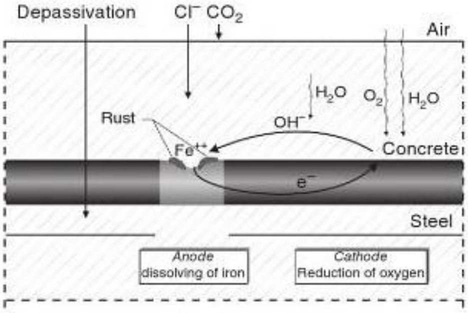

Fig -1: Chemical reactions taking place at the surface leading to pitting (corrosion) phenomenon[1]

Corrosion begins as moisture penetrates the protective barrier of a surface, starting the electrochemical process which leads to surface pitting [2]. It is commonly caused by either the presence of sufficient concentrations of chloride ions or carbonation. (Fig. 2)The most important cause of corrosion initiation of reinforcement steel is ingress of chloride ions and carbon dioxide to the steel surface. After initiation of the corrosion process, iron oxides and hydroxides are usually deposited in the restricted space in the concrete around the steel. Their formation within this restricted space sets up expansive stresses, which crack and spall the concrete over. This in turn results in progressive deterioration of the concrete structure [3]. Integrity of structure reduces as pits enlarge to form surface cracks which deepen into the thickness of the structure. The enhanced growth of pits into deep thickening cracks could lead to non-trivial loss of mass and hence reduction in structural integrity. The rate at which cracks develop with time is much faster than the pitting phenomena. This points to the need to early detect the damage due to corrosion so that serious damage to the whole structure could be avoided. Corrosion is a serious threat for structures. Traditional visual inspection often fails to provide accurate surveillance regarding the occurrence of corrosion. This usually leads to serious damages in case of aircrafts, ships, buildings, bridges etc. (early studies on corrosion). Precise pre-crack surface corrosion monitoring is critical to prevent any catastrophic failure in future.

Recently research and development activities on structural health monitoring (SHM) led to the development of smart sensors and IT–based monitoring/evaluating systems in the

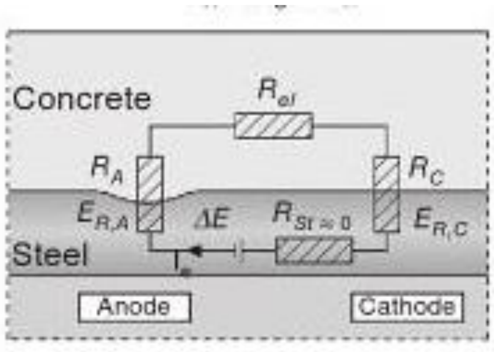

Fig -2: Electrical cathode and anode formation leading to change in EMI value [1]

fields of mechanical, aeronautical and civil engineering. SHM technologies are basically aimed at development of autonomous systems for continuous monitoring and integrity assessment of structures with minimal manual labour. Therefore, a smart wireless monitoring system using flexible, low-cost and highly efficient smart sensors such as piezoelectric, optical fibre and micro-electromechanical system (MEMS) sensors need to be developed. [4]

1.2 Electro-chemical processes in corrosion

SHM is a process targeted at providing in-time quantitative assessment of structural components and performance on a proactive basis. It consists of (i) permanent continuous, (ii) periodic or (iii) periodically continuous; recording of representative parameters, over short or long terms [5]. The information so obtained is used to calculate whether damage has started, the level of damage, ways to reduce it and to enhance knowledge concerning the structure being monitored.

The sensing component of the monitoring system includes sensors, recorders, servers and all other necessary firmware to measure the presence of the building, collect the data and transits it to an onsite server in real-time[6]. Several existing SHM system use wireless communication to allow devices to coordinate and collaborate to more effectively measure a structure, whether the goal is improved spatial resolution, network resilience, or advanced in-situ analysis [7]. The bottom line is to altogether avoid or at the least, reduce to the minimal, instances of sending complete data sets to the base station. The measuring node should be able to autonomously decide the damage condition by processing the sensed data with optimum energy consumption.

Wireless sensor networks are the key enabler of the most reliable and durable systems for long-term SHM and have the potential to dramatically increase public safety by providing early warning of impending structural hazards. The continuous miniaturization and cost-reduction achieved by these systems has the potential to expand the practice of SHM to a significantly higher number of existing and newer infrastructures [8]. These improvements have led to increased safety along with long-term effective maintenance and monitoring of structures.

A tabular representation of the different techniques in corrosion detection is shown in Table 1. It shows the advantages and disadvantages of different techniques. In particular it highlights the importance of impedance measurement technique in sensor nodes of practical significance. This is required to design autonomous active sensor nodes which are flexible, cost-effective and have real-time SHM utility.

Table -1: Different SHM Techniques and their significance

Visual Inspection	Simplest method that does not make use of any instrument; used where structure to be monitored is physically accessible. The type and degree of corrosion can be found out with this method. However, thinning of material and pre-crack stage cannot be determined. Advanced visual inspection employs magnifying glasses etc.
Radiography	Short wave electromagnetic beams like X-rays or γ-rays penetrate the material. The waves attenuate when passing through the material. The degree of attenuation depends upon the thickness of material. Pit growth and thinning of material can be measured by this method.
Eddy currents	Eddy current NDT methods use sinusoidal excitation and measure response as impedance or voltage changes on impedance plane display. The magnitude and phase changes are interpreted to detect flaws.

Electro impedance spectroscopy (EIS)	Corrosive reactions produce an anodic (i_a) and cathodic (i_c) current, and i_a is proportional to the corrosion rate [9][10].Only the net current can be directly measured. In EIS an AC voltage is applied to the material, and the magnitude and phase changes are interpreted to detect flaws.
Ultrasonic waves	An ultrasound scans the material by passing ultrasonic waves through material and measuring its reflection to create 2-D mapping of surface. It detects material loss and voids.[11]
Infrared Imaging/ Thermography	Corroded and non corroded structures have different thermal and magnetic properties. Materials are rapidly heated or cooled. Corroded materials show higher heating and cooling rates.IR cameras are used to measure temperature gradient. It mainly detects surface corrosion [12].
Impedance Method	When piezoelectric materials are bonded to a structure, the mechanical impedance of the structure couples with the electric impedance of the piezoelectric. As cracks or corrosion occur on the structure, the mechanical impedance changes, and the corresponding electrical impedance change in the piezoelectric is measured. The method is very sensitive to changes in damage [13].

1.3 Significance of EIS Technique

An alternative to visual inspection is automated monitoring using corrosion sensors. Monitoring is cheaper, less time consuming, and can be deployed where visual inspections are impossible.[14] Electrochemical Impedance spectroscopy (EIS) has been used to interrogate corrosion sensors, but at present large laboratory test equipments are required. As per [15] and [16], Electrochemical impedance is usually measured by applying a small AC excitation signal of known frequency to an electromagnetic cell and then measuring the current through the cell. The response is an AC current signal of same frequency but shifted in phase.

The excitation signal can be expressed as:

$$E_t = E_0 \sin(\omega t)$$

Where E_t is the potential at time t, E_0 is the amplitude of the signal, and ω is the radial frequency. The relationship between frequency ω (radians/second) and frequency f(Hz) is $\omega = 2\pi f$. In a linear system, the response signal, I_t, is shifted in phase (ϕ) and has a different amplitude than I_0.

$$I_t = I_0 \sin(\omega t + \phi)$$

An expression analogous to Ohm's Law allows us to calculate the impedance of the system as:

$$Z = E_t / I_t = (E_0 / I_0) \sin(\omega t) / \sin(\omega t + \phi) = Z_0$$

The impedance is therefore expressed in terms of a magnitude, Z Z_0 and a phase shift, ϕ.

The AD5933 impedance measurement chip offers a precise and compact solution for this type of measurement, enabling the development of field deployable sensor systems that can measure corrosion rates autonomously. Typically, the frequency ranges for the impedance measurements are chosen to have high peak densities that are sensitive to damage.

Mathematically, the corrosion of aluminium is modelled using an RC network that typically consists of a resistance, R_S, in series with a parallel resistor and capacitor, R_P and C_P. A system metal typically has values: R_S in 10Ωto10kΩ, R_P is 1kΩ to 1MΩ, and C_P IS 5µF to 70 µF. To make accurate measurements of these values, the impedance needs to be measured over a frequency range of 0.1Hz to 100 kHz. To ensure that the measurement itself does not introduce a corrosive effect, the metal needs to be excited with minimal voltage, typically in the range of ±20mV. A nearby processor can take charge at this stage – it would log a single impedance sweep from 0.1 kHz to 100 kHz every 10 minutes and download the results back to a control unit.

2. STUDIES ON VARIOUS APPLICATIONS IN SHM

Overly et al. [18] presented an impedance method based Active Sensor node (ASN-2), which works autonomously. Three methods were incorporated to save power. First, considering that transmission cost is much higher than processing cost, entire data processing is performed on-board. A substantial reduction in data that needs to be transmitted leads to a lot of cost cutting in energy consumption. . Second, a rectangular pulse train was used by ASN-2 to excite a PZT patch instead of a sinusoidal wave. This eliminates a digital-to-analog converter and reduces the memory space. Third, the phase of the response signal is used to detect damage instead of the magnitude. Sensing the phase of the signal eliminates an analog-to-digital converter and Fast Fourier Transform operation. This is useful as it not only saves power, but also enables us to use a low-power processor. Sensor node ASN-2 uses a TI MSP430 microcontroller. The sensor node is in the form of an evaluation board and several such nodes form a cluster. Thus several ASN-2 nodes form a wireless network for SHM. The researchers implemented a sleep mode whereby each node wakes up at a predetermined interval, such as once in four hours and performs sensing and reporting operation. Rest of the time it is in sleep mode. The power consumption of the sensor node is found to be 0.15 mW during the inactive mode. Also during the active mode it is a minimal 18 mW as compared to 60 mW reported by Mascraneas et al. 2007.

Bhuiyan et al.[19] presented the concept of designed pre stress force and its importance for the safety of pre stressed concrete bridge. They emphasized that loss of pre stress force in tendon could significantly reduce load carrying capacity of the structure. Thus a design is presented for an automated pre stress-loss monitoring system for pre stressed concrete girder. It employs a specially designed PZT-interface with a high-performance Imote2 sensor platform. The wireless impedance sensor node thus deployed has to fulfil the objective of high operating speed, low power requirement and large storage memory. A novel approach is used in implementation so as to carry out the twin objectives. The wireless impedance sensor nodes are designed for automated impedance-based monitoring technique. To predict pre stress-loss, a linear regression model has been effectively used. Finally, the system is evaluated from a lab-scale tendon-anchorage connection of a pre stressed concrete girder.

Bhuiyan et al. [20] This paper presents a technique for local structural health monitoring (SHM) of multiple structural connections by using multi-channel wireless impedance sensor nodes based on Imote2 platform. To achieve the objective, following approaches are implemented. Firstly, an Imote2-based multi-channel wireless impedance sensor node is designed for automated and cost efficient impedance-based SHM of structural connections. Secondly, an interface washer associate with impedance measurements is designed to monitor bearing stress which is considered as main effect on structural connections. Finally, performances of the multi-channel wireless impedance sensor node and the interface washer are experimentally validated for a bolted connection model. A damage monitoring method using RMSD index of electro-mechanical impedance signatures is used to examine the strength of each individual bolted connection.

Gyekenysi et al. [21]implemented and studied the applicability of wavelet-based compression techniques which compresses bandwidth over unimportant parts of the spectrum. This is known to overcome limitations imposed by low power requirements of wireless radios. Since structural health monitoring is the collection and analysis of structural response to ambient or forced excitations, it has important applications. Wisden is implemented as a data acquisition systems of networked embedded sensing elements. Wisden incorporates two novel mechanisms, reliable data transport using a hybrid of end-to-end and hop-by-hop recovery, and low-overhead data time-stamping that does not require global clock synchronization. The proposed node is in fact implementation of these mechanisms on the Mica-2 motes. The researchers evaluated the performance of Wisden when deployed on large structures.

Yang et al. [22] presented the power systems used in sensor nodes such as AAA batteries have finite/limited operational lives. This necessitates a low-cost wireless sensing unit to be fabricated and deployed in real-time applications. This requires special techniques for optimization of the wireless sensing unit design. Since such units act like building blocks of a large wireless network, the goal is to attain a design with overall energy efficiency. On the contrary we employ wireless radios that have very large communication ranges that require significant amounts of power. As a result, transmission cost is unfavourably posed against processing cost. It is rarely useful to transmit raw time-history records since at disposal are scarce system resources of battery power and bandwidth. Still another choice is to design an optimal computational core. Such a strategy implies local processing of collected raw data in the embedded core. Now the wireless channel is used to send the reduced data analysis reports rather than data intensive time-history records. The researchers have explored the ability of the computational core to perform such embedded engineering analyses. This is done by a two-tiered time-series damage detection algorithm. The algorithm employs a lumped-mass laboratory structure to achieve its objectives.

Lynch et al. [23] investigated a promising technology for robust and cost-effective structural monitoring which could be used for active diagnostic purposes. Due to limited energy sources, battery-powered wireless sensors can only perform limited functions and are expected to operate at a low duty cycle. Conventional designs are not suitable for sensing high frequency signals, e.g. in the ultrasonic frequency range. More importantly, algorithms to detect structural damage with a vast amount of data usually require considerable processing and communication time and result in unaffordable power consumption for wireless sensors. In this study, an energy-efficient wireless sensor for supporting high frequency signals and a distributed damage localization algorithm for plate-like structures are proposed, discussed and validated to supplement recent advances made for active sensing-based SHM. First, the power consumption of a wireless sensor is discussed and identified. Then the design of a wireless sensor for active diagnosis using piezoelectric sensors is introduced. The newly developed wireless sensor utilizes an optimized combination of field programmable gate array (FPGA) and conventional microcontroller to address the tradeoff between power consumption and speed requirement. The proposed damage localization algorithm, based on an energy decay model, enables wireless sensors to be practically used in active diagnosis. The power consumption for data communication can be minimized while the power budget for data processing can still be affordable for a battery-powered wireless sensor.

Peairs et al. [24] on the effect of applying axial load on impedance signatures, there are interesting results for damage detection capability using resonant peaks, when transverse and extensional(axial) vibration modes are considered for this effect separately. They have presented analytical, Finite Element and experimental evaluations. In the extension mode experiment, a progressive rightward shift in resonant frequency upon increase in tensile load occurs. The amount of shift from 0 to 10 kN is relatively small, about 0.3 kHz. This value is less than half of the transverse mode induced peak’s shift, which is 0.8 kHz. The additional peak shift observed in the experimental test, but absent from the analytical and FE analyses, is most likely caused by the interaction at the boundary condition during the application of axial load.

CONCLUSIONS

Thus we find that the field of SHM using impedance based technique is steadily maturing and many researchers are taking pains-taking efforts . More and more studies are being conducted to improve the state of art technologies for SHM. A robust hardware platform in which battery management, sensing unit and data storage synchronization, clock rate flexibility according to operational needs and optimum program and data memory availability is emerging for the processor unit. Also energy harvesting techniques are being incorporated to enhance the life-time of sensor node. Similarly, damage detection algorithms are being adapted to bring reliability to damage detection. Still more research is required to bring the laboratory experiences to real-time damage detection scenario.

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