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VIABILITY OF APPLYING MECHANICAL IMPEDANCE BASED STRUCTURAL HEALTH MONITORING FOR PIPELINE: A REVIEW

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ABSTRACT

Damage detection in pipeline system is one of the most important goals for energy companies. As the pipeline network continues to age, monitoring and maintaining its structural integrity is needed. A few methods of nondestructive evaluation (NDE) are currently used for this purpose, but numerous accidents over the past several years have led to significant costs and fatalities, indicating that NDE techniques may not be sufficient. Researchers and owners believe that a structural health monitoring (SHM) system would enable pipeline operators to continuously monitor the structural integrity of their networks. This paper gives critical review about impedance-based structural health monitoring. Impedance method is one of the SHM system detection techniques that implemented using the piezoelectric patches, avoiding the necessity for two separate sensor arrays. Because piezoelectric patches are flexible and resilient, they can potentially be permanently bonded to the curved surface of a pipeline's main body. This permanent installation allows for the continuous monitoring of the pipeline system and reduces the costs associated with implementing NDE techniques, such as excavation to gain direct access to the pipeline.

Keywords: pipeline integrity, mechanical impedance, structural health monitoring.

INTRODUCTION

Definition of impedance methods

Impedance-based Structural Health Monitoring using piezoelectric wafer active sensors has been extensively developed as a damage detection method in structures (Sepehry, Shamshirsaz, & Bastani, 2011). Impedance methods involve monitoring the mechanical impedance of a structure. The mechanical impedance of a structure, is related to the dynamic behavior of the structure. In reality, the mechanical impedance is sensitive to changes in some structure's properties such as (mass, stiffness, and damping characteristics). Because damage to a structure affects these characteristics, the mechanical impedance of a structure can indicate the presence of damage in the system. Therefore, the integrity of a structure can be monitored by monitoring the structure's mechanical impedance.

Many instruments are available that can directly measure the mechanical impedance of a structure, some of them are typically expensive and cumbersome to employ. A simpler transducer which can be used to measure a structure's mechanical impedance is a piezoelectric patch, such as a Macro Fiber Composite (MFC) patch and piezoelectric wafer active sensors (PWAS). When mounted to the surface of a structure, such as a pipeline, the mechanical impedance of a piezoelectric patch is directly coupled to the mechanical impedance of the structure. The piezoelectric properties of the piezoelectric patch, in turn, couple its electrical impedance to its mechanical impedance. Therefore, the electrical impedance of a piezoelectric patch, when it's mounted to a pipeline system, is coupled to the system's mechanical impedance. The relative size and weight of a piezoelectric patch is negligible compared to that of it host structure, which in this case is a pipeline system. Accordingly, a piezoelectric patch introduces negligible impact on the dynamic characteristics of the host structure. This low impact allows the use of a piezoelectric patch to accurately measure the mechanical impedance of a structure.

IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING

An electromechanical model of a piezoelectric patch mounted to a host structure is shown in Figure-1. In the model, a piezoelectric patch (PZT) is shown directly bonded to a single degree of freedom system, as represented by a mass (m), spring (k), and damper (c). (Liang et. al.1994) show that the electrical admittance, Y(ω), of the piezoelectric patch is a combined function of the mechanical impedance of the piezoelectric patch, $Z_a(\omega)$, and the mechanical impedance of the host structure, Z(ω). The equation for the electrical admittance, which is simply the inverse of the electrical impedance, is as follows:

$$Y(\omega) = \frac{I}{V} = i\omega a\left[\bar{\varepsilon}_{33}^{T} - \frac{Z(\omega)}{Z(\omega) + Z_a(\omega)} d_{3x}^{2} Y_{xx}^{E}\right] \quad (1)$$

Where:

V is the input voltage, I is the output current from the piezoelectric patch and d_{3x}, Y_{xx}^{E}, and $\bar{\varepsilon}_{33}^{T}$ are the geometry constant, the piezoelectric coupling constant, Young's modulus, and the complex dielectric constant of the piezoelectric patch at zero stress, respectively. (Park et. al. 2003). Mechanical impedance of a structure is related to the mode functions and natural frequencies of the structure and is simply defined by ratio of an applied force to the resulting velocity.

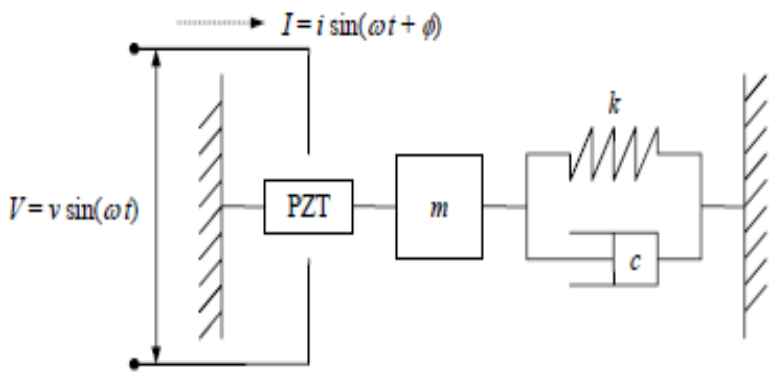

Figure-1. Electromechanical model of a piezoelectric patch mounted to a host structure (Park *et al*. 2003).

Testing parameters involved with impedance methods

In general the impedance methods aim to record impedance signatures of the structure in a healthy condition, and then estimating the state of the structure by comparing the electrical impedance taken at different times during the life of the structure, which follows the same philosophy of traditional vibration-based methods. The main difference is the frequency range that is used to detect the changes in structural integrity. To ensure high sensitivity to incipient damage, the electrical impedance is measured at high frequencies in the range of 30–400 kHz. Under this high-frequency range, the wavelength of the excitation is small and sensitive enough to detect minor changes in the structural integrity.

If we assume that the properties of the piezoelectric patch and its bonding conditions remain constant over the course of the structure's monitoring period, the above equation shows that the electrical impedance of the piezoelectric patch is directly related to the mechanical impedance of the structure. Therefore, the measured electrical impedance of the piezoelectric patch can be used to monitor the structure's mechanical impedance. As the electrical admittance is primarily capacitive, the imaginary part of the electrical impedance is dominant. However, only the imaginary part of the electrical impedance is affected by changes in the dielectric constant, which is temperature sensitive. Accordingly, the imaginary part of the electrical impedance is more sensitive to temperature variations than the real part. Therefore, the real part of the electrical impedance is commonly used for SHM applications. (Sun *et al*. 1995).

For SHM applications, impedance methods are similar to traditional vibrations techniques in that both methods aim to monitor the structural integrity of a structure by observing changes in its characteristic vibrations over time. An extensive review of SHM techniques based upon traditional vibrations is given in Doebling *et al*. (1998). The primary difference between the two methods, however, is the frequency ranges used for the measurements. Relative to the frequency ranges used for traditional vibrations techniques, impedance methods implement a much higher frequency range. The sensitivity to incipient damage of a particular vibration based approach to damage detection, whether traditional vibrations or impedance methods, is dependent upon the frequency of the excitation used. For a given method to be sensitive to incipient damage, the wavelength of the excitation must be smaller than the characteristic length of the damage to be detected (Stokes and Cloud, 1993). Because the impedance method implements such high frequency ranges when compared to traditional vibrations, the electrical impedance of an MFC is much more sensitive to incipient damage. At such high frequency ranges, the wavelength of the excitation is relatively small, depending on the wave speed of the structure's material, and sensitive enough to detect minor changes in the structure's integrity.

Impedance measurements typically involve using a stepped sine wave across a predetermined frequency range. At each frequency step of the sine wave, the corresponding voltage and current are recorded and used to estimate the electrical impedance of the piezoelectric patch at the particular frequency. In the area of impedance methods, there is a lack of analytical work available which addresses the modes of vibration of complex structures over ultrasonic frequency ranges. Therefore, the frequency range used for impedance measurements with a given structure is typically determined by trial and error. A frequency range with a high mode density, as observed as the number of peaks present, is generally favorable because it contains more information regarding the condition of the structure than a frequency range with lower mode density contains. For this reason, a few frequency ranges are normally chosen, and ideally each frequency range contains 20 to 30 peaks. (Sun *et al*. 1995). Because of the relatively high frequencies involved, impedance methods are generally more sensitive to local changes in a structure, and traditional vibrations techniques are generally more sensitive to global changes in the structure. With impedance measurements, "a frequency range higher than 200-kHz is found to be favorable in localizing the sensing, while a frequency range lower than 70-khz covers a larger sensing area."

(Park *et al*. 2003) With pipeline structures, therefore, the impedance methods can be used to detect local damage if a sufficiently high frequency range is chosen.

Previous works

Experimental implementation of the EMI-based structural health monitoring technique has been successfully conducted on several complex structures. The detection of cracks, loose connections of pipelines, damages in metallic structures, and in composites structures are reported by many researchers (Wang, Yan, & Wang, 2012). Several research efforts demonstrate the ability impedance methods to detect cracks, loosening of joints, delamination of composite structures, and corrosion of metallic structures, and can incorporated into SHM systems involving numerous complex structures. Liang *et al*. (1994) was the first who proposed the applying of impedance measurements to structure health monitoring, and subsequently developed by Chaudhry *et al.(*1995), Sun *et al.* (1995), Park *et al.* (1999, 2000a,b, 2001, 2003), Soh *et. al.* (2000), Bhalla & Soh (2003, 2004a,b), Peairs et. al. (2004) and their co-workers.

The leading attempt to implement impedance methods with a SHM system was performed by Sun *et al*. (1995). In this research, impedance methods were used to monitor damage in a simple truss structure. A damage metric based upon the root-mean-square deviation was used to assess the structural integrity of the truss system. The research also investigated the effects of the chosen frequency range and excitation level for the measurements. Chaudhry *et al.* (1995) demonstrated the localized sensitivity of impedance measurements. Impedance measurements were taken near the tail section of an airplane. Two types of damage were investigated, one which was local and a second which was distant. The local damage involved loosening the main mounting brackets of the tail section. Because this damage was close to the measurement location, the damage was easily identified. The distant damage involved alterations to the airplane's structure at other locations, such as a bracket for a wing, and was not as easily identified. The impedance measurements were shown to be relatively insensitive to the far-field damage compared to the near-field damage.

The effects of high temperature environments on impedance methods was investigated by Park *et al.* (1999). High temperature piezoelectric patches were used to monitor damage in a bolted joint structure subjected to a temperature range of 482 to 593 °C. The high temperature environment caused much greater variation in baseline measurements than previously had been observed at room temperature. However, the variation caused by damage, which is simulated by slightly loosening one of the bolts, was still much greater than the baseline variation.

One application related to pipeline systems was addressed by Park *et al.* (2001). In this research, impedance methods were used to monitor damage in the flanged joints of a simple pipeline system, as seen in Figure-2. Piezo-ceramic patches were mounted to the surface of the flanges and used locally to monitor damage in each flange. The impedance method was implemented to perform a rapid assessment of the structural integrity of the flanged joints. Such an application would be useful after an event of short duration, such as an earthquake or nearby excavation. In addition, the impedance methods were shown to be capable of making measurements while the structure is in service. Therefore, the methods developed in this research can easily be integrated into a SHM system. Because the piezoelectric patches were mounted to the flanges of the pipeline system, however, these methods cannot efficiently detect damage in the pipeline's main body.

The presented impedance methods in (Thien, 2006) demonstrated the ability to correctly identify and locate the presence of damage in the flanged joints of the pipeline system, including the loosening of bolts on the flanges. In addition to damage to the actual pipeline itself, the proposed methods were used to demonstrate the capability of detecting deposits inside of pipelines. Monitoring these deposits can prevent clogging and other hazardous situations. Damage detection of hollow cylinders by the electromechanical impedance (EMI) technique was performed on aluminum and steel specimens with different thicknesses (Hamzeloo, Shamshirsaz, & Rezaei, 2012). Finite Element Model of the EMI technique on hollow cylinders was developed and validated in order to study the influence of different damage types and damage location on EMI spectrum and resultant damage metrics. In (Ai, Zhu, Luo, & Yang, 2014), a new electromechanical impedance (EMI) technique using the united mechanical impedances (UMI) of the PZT sensor and the host structure is first theoretically derived. Then, the technique is applied to the experimental study that includes monitoring a steel beam with corrosion damage. The electromechanical (EM) admittance is measured with two surface-bonded PZT sensors at different moments. Then, the sensitivity of (UMI) is investigated through comparison with EM admittance. Finally, the severity of corrosion damage is also discussed. The results indicate that (UMI) is more sensitive to corrosion damage than (EM) admittance. Thus, the innovative (EMI) technique is effective in monitoring steel structural health.

Figure-2. Application of impedance methods to a simple pipeline structure (Park, *et al*. 2001).

Advantages of impedance methods comparison with other techniques

NDE techniques are the most common approaches which used for monitoring of pipelines structures, and they are include ultrasonic technology, acoustic emission, magnetic field analysis, penetrant testing, eddy current techniques, X-ray analysis, impact-echo testing, global structural response analysis and visual inspections. (Park et. al. 2000a, 2003; Giurgiutiu *et al.* 2002), have made detailed comparisons between the impedance method and other NDE approaches.

The main objective of impedance method is to appear changes in the dynamic properties or response of structures as in some NDE techniques. However, the impedance measurements are made at much high frequencies, which greatly improves the sensitivity to damage. Any NDE high-frequency testing methods may provide detailed information on anomalies in some structures, but these methods usually require complicated instruments and professional skills to interpret the measured data. Most of these methods require out of service periods, or can be applied only at certain time intervals, which may not be suitable for autonomous on-line structural health monitoring. The sensitivity of the impedance method to minor defects is comparable with that of ultrasonic methods, but the method does not require experienced technicians to discern details. The cost required for hardware and sensors/actuators would be much lower than that of NDE techniques, with the development and the implementation of low-cost impedance measuring circuits (Peairs et. al. 2004). The sensing regions of the impedance sensors are much larger than those of local ultrasonic or eddy current sensors, which are usually moved to scan over certain areas to detect damage in a structure.

Impedance-based structural health monitoring provides a compromise between global structural methods and traditional ultrasonic techniques. With a limited number of sensors and actuators, critical areas of a structure can be monitored which is one of the advantages of the global structural methods.

Damage in an incipient stage can be accurately identified, which prior to the impedance methods, only local inspection techniques could possibly detect. In addition, by using the actuation and sensing capabilities of PZT, the impedance sensors can also be used to measure global or ultrasonic vibrational response if a proper signal conditioning circuit is implemented, which makes the method attractive for integrated uses of several NDE approaches.

Moreover to address the damage in flanged joints in the pipeline, a different approach is required. Impedance methods, implemented to monitor the structural integrity of the flanged joints in a pipeline system. There are several reasons that impedance methods are an ideal choice for this application. The most significant advantage of impedance methods as applied to the proposed structural health monitoring (SHM) system is that MFC patches can be used to perform impedance measurements. Therefore, the. An additional advantage of the impedance method is that the relatively high excitation frequencies involved make it sensitive to local damage rather than global damage. Also, the impedance method is a form of active sensing which means that no external excitation is required.

CONCLUSIONS

Most of the researches have successfully demonstrated the benefit and feasibility of a structural health monitoring (SHM) system for pipeline networks. Previous studies have proven the potential application of impedance methods to SHM systems. They demonstrated the ability of impedance methods active-sensing techniques to correctly identify and locate the presence of damage in the flanged joints of the pipeline system. Further works are still necessary to check the feasibility of the proposed technique for monitoring the health of pipelines structures. Additional experimental works are needed to achieve more reliable results regarding the influence of structural mechanical impedance on PZT sensors caused by corrosion damage.

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