Non-Contact Quantification of Longitudinal and Circumferential Defects in Pipes using the Surface Response to Excitation (SuRE) Method

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Abstract

Rapid screening and monitoring of hollow cylindrical structures using active guided-waves based structural health monitoring (SHM) techniques are important in chemical, petro-chemical, oil and gas industries. Successful implementation of the majority of these techniques in the SHM of pipes depends on the identification of the appropriate guided-waves modes and their frequencies for each application. The highly dispersive nature of the guided-waves and presence of multi modes at each frequency makes the mode selection and the interpretation of signals a challenging task. The surface response to excitation (SuRE) method was developed to detect the defects and loading condition changes on plates with minimum dependence on the excitation of particular modes at certain frequencies. In the present study, the SuRE method is proposed for quantification of longitudinal and circumferential defects, with varying severities, as common examples of axisymmetric and non-axisymmetric defects in pipes. The results indicate that the SuRE method can be used effectively for damage quantification in hollow cylinders.

1. Introduction

Hollow cylindrical structures (pipes) are typically used in the distribution of liquids and gases in chemical, petro-chemical, oil and gas industries. In these industries, monitoring the mechanical integrity of pipes is extremely important as any mechanical defect can potentially have adverse impacts on their safe operability throughout their service life and/or lead to costly and deadly leakages (Alamilla, Sosa, Sánchez-Magaña, Andrade-Valencia, & Contreras, 2013; Caleyo, Alfonso, Alcántara, & Hallen, 2008; Kishawy & Gabbar, 2010). Structural health monitoring (SHM) methods can be divided into two groups: active and passive (Baqersad, Poozesh, Niezrecki, & Avitabile, 2016; Demetgul, Senyurek, Uyandik, Tansel, & Yazicioglu, 2015; Mueller et al., 2009; Staszewski, Mahzan, & Traynor, 2009). Passive methods (Olund & DeWolf, 2007; Sabra & Huston, 2011; Zaleha, Mahzan, & Idris, 2014), like acoustic emission based methods, use sensors to collect signals caused by creation/growth of damages, such as cracks, debondings, and corrosions. Active methods use sensors for collecting the response of a structure to a known excitation imposed by actuators (Giurgiutiu et al., 2012; G. Park, Farrar, Scalea, & Coccia, 2006; Zhao et al., 2007). Active (SHM) methods have gained popularity for damage detection in hollow cylindrical structures because of the known input and simpler analysis of the response.

Some groups of active SHM methods use guided-waves for monitoring of structures. Guided-waves are a group of mechanical waves that require boundaries for their propagation. Three types of wave modes that exist in the hollow cylinders are longitudinal axially symmetric, torsional axially symmetric and non-axially symmetric (flexural) modes. Guided-waves are generated on the surface with a bonded actuator(s) and the response of the surface is monitored using the same or other transducers (Bhuiyan, Shen, & Giurgiutiu, 2016; Lu, Ye, Wang, Zhou, & Cheng, 2010; Siqueira, Gatts, Da Silva, & Rebello, 2004). Guided-waves move along the hollow cylindrical structures with very little loss of their energy. Active guided-waves based methods have been extensively used for monitoring the mechanical integrity of different types of structures. However, there are yet shortcomings to be addressed in the detection of defects with these methods.

Guided waves are dispersive. That means the group and phase velocity of propagating guided-waves depends on the frequency and mode of excitation (Nishino, Yoshida, Cho, & Takemoto, 2006; Rose†, 2003; Smelyanskiy et al., 2011; Wilcox, Lowe, & Cawley, 2001). It should be noted that different modes can exist in each frequency. Therefore, even in single frequencies, a wave can propagate with different speeds and as a result, a wave distorts during its propagation from the exciter to the sensor which makes data interpretation and analysis in the time domain a challenging task. Pitch-catch (Ihn & Chang, 2008; Stoyko, Popplewell, & Shah, 2014), pulse echo (Carandente & Cawley, 2012; Ma, Wu, Wang, & Liu, 2015), and Electromechanical impedance spectroscopy (EMIS) based methods (Annamdas & Radhika, 2013; Kamas, Giurgiutiu, & Lin, 2015; Lim & Soh, 2013) are the most well-known linear active guided-waves based SHM techniques for defect detection in hollow cylindrical structures.

To minimize problems due to dispersion, in pitch-catch and pulse-echo methods, the surface is typically excited with a carefully selected single/limited range frequency. In these methods, reflections and transmission of guided waves are monitored, respectively. In limited frequency methods, such as pulse-echo and pitch-catch, selection of the proper mode and frequency plays a very important role in the performance of the method (Giurgiutiu, 2005; Zhang & Yu, 2011). The proper mode has to be selected by considering the characteristics of defects that are yet to be detected. Thus, the mode and excitation frequencies that are selected for detection of a certain type of defect may not be applicable for other types of defects.

In EMIS based methods, the mechanical impedance of the structure is coupled to the mechanical impedance of the bonded piezoelectric transducer and in the transducer, the mechanical and electrical impedances are coupled together. In the monitoring process, it is assumed that the PZT remains intact during monitoring process while specific characteristics of the structure such as stiffness, damping, and dynamic mass of structure change in presence of damage. Because of the existing coupling between the mechanical impedance of the structure and electrical impedance of the PZT sensor element, defects alter the measured impedance of the bonded piezoelectric element. However, EMIS in high frequencies is only sensitive to the very adjacent areas of the transducer. Therefore, high numbers of transducers are required for monitoring a large area.

In EMIS based methods, the surface is excited in a wide frequency range using a bonded piezoelectric element. Typically, an EMI analyzer simultaneously excites the surface in a broad frequency range using the piezoelectric element and measures the impedance of the same piezoelectric transducer (Kamas, Lin, & Giurgiutiu, 2013; Min, Park, Yun, Lee, & Lee, 2012; Venu Gopal Madhav Annamdas & Chee Kiong Soh, 2010). Alternatives have been proposed to eliminate the need for the bulky EMI analyzer, which also can be costly (Bhalla, Gupta, Bansal, & Garg, 2009; S. Park, Yun, & Inman, 2008). In addition, to date, bonded sensors have been the inevitable part of EMIS systems. That is, EMIS cannot be used in non-contact mode since it depends on the impedance changes of the bonded piezoelectric transducer. However, bonded sensors cannot be used in some applications due to design considerations or rugged environment of in-service structures.

The Surface Response to Excitation (SuRE) method eliminates the need for the EMI analyzer by attaching a secondary piezoelectric element(s) to the surface and using the frequency response of the second piezoelectric element(s) for evaluating the health of the entire system. Instead of a second piezoelectric element, any contact or non-contact sensor may be used as long as they can measure the surface responses at the selected frequency bandwidth. Spectrum analyzers, simple data acquisition systems, and DSPs may be used for data collection and analysis. Applications of the SuRE method include the detection of defects on plates, finding loose bolts on robotic devices, and estimation of load distribution on plate surfaces (Fekrmandi et al., 2015; Fekrmandi et al., 2014, 2016; Tashakori et al., 2017; Shervin Tashakori et al., 2016, 2017)

The purpose of this research is to demonstrate a non-contact SHM strategy for pipes with minimum dependency on the selection of proper excitation modes and frequencies. To achieve this, the SuRE method is applied in a non-contact mode using a scanning laser vibrometer. The performance of the SuRE method is evaluated when axisymmetric and non-axisymmetric defects were created in an aluminum pipe and their severities increased in three increments.

2. MODE SELECTION AND EXCITATION FOR GUIDED WAVES

In practice, there is no a priori knowledge about the size, shape, and orientation of a defect in an in-service pipe.

Characteristics of a wave, such as the wave mode, frequency, dispersion and propagation characteristics, determine the types of defects that are detectable through excitation of that mode. Therefore, selection of a certain mode and frequency would not necessarily lead to a successful inspection of the target structure, in real applications. For example, both longitudinal and torsional modes are axisymmetric. However, due to different wave structures and propagation behaviors, their sensitivities to identical defects are different. For example, by using longitudinal modes, the chance of detecting a longitudinal defect with a much smaller width compared to its length and depth is very low in comparison to using torsional modes. At the same time, the probability of detecting a circumferential damage with the same characteristics but oriented in a circumferential direction is much higher using longitudinal wave modes. In short, the performance of the conventional methods depends on the match between the selected excitation mode and geometrical parameters of the damage.

When applying the SuRE method, the surface of a structure is excited in a broad frequency range which excites multiple wave modes on the structure. This provides a means for the method to be highly sensitive to defects with different sizes, orientations, and configurations. In the SuRE method, only the frequency response of the structure is obtained and used for monitoring the state of health. Typically, the appropriate excitation frequency range is selected to cover at least 20-30 peaks in the frequency response. Therefore, the appropriate range could be determined with a single test at any point for any new specimen.

3. PROPOSED METHOD

The SuRE method is an active structural health monitoring technique in which the surface of a structure is excited over a certain frequency range using surface bonded piezoelectric elements. Typically, one piezoelectric element is used for excitation and one or more piezoelectric sensors or other types of transducers are used to acquire the response of the system. In order to monitor the dynamic response of the system, Fast Fourier Transform (FFT) of the acquired signal is obtained. This frequency spectrum remains fixed, provided the mechanical integrity of the structure does not change. The frequency response matrices of the system obtained from the FFT in intact and damaged states are shown in equation (1). The response at each frequency has the unit of voltage, where f is frequency, B and D indicate the baseline and damage states, m is the number of scanned frequencies, and n is the number of sensor locations in the network. In other words, every column in the matrices represents the frequency response spectrum of a certain sensor location over the acquired frequency range.

$$V_B(f) = B_{m*n}$$
$$V_D(f) = D_{m*n} \tag{1}$$

When damage occurs or loads are applied on the structure of interest, the dynamic response of the structure is altered. In the SuRE method, for sensor locations of j = 1,…,n in the sensing network, sum of squares of differences (SSD) of the frequency response matrix of the damaged part with respect to the pristine structure (baseline state) is used as the damage metric and is calculated, as shown in equation (2). Therefore, it can be speculated that SSD is capable of quantifying between different severities of defects.

$$SSD_{j=1,\dots,n} = \sum_{i=1}^{i=m} \left(B_{ij} - D_{ij}\right)^2 \tag{2}$$

4. EXPERIMENTAL SETUP

To validate the SuRE method for pipes in non-contact mode, an experimental setup was assembled that focused on evaluating an aluminum pipe having the dimensions: 226 mm (length), 26 mm (outside diameter) and 3 mm (wall thickness). The schematic of the experimental setup used in this experiment is shown in Figure 1.

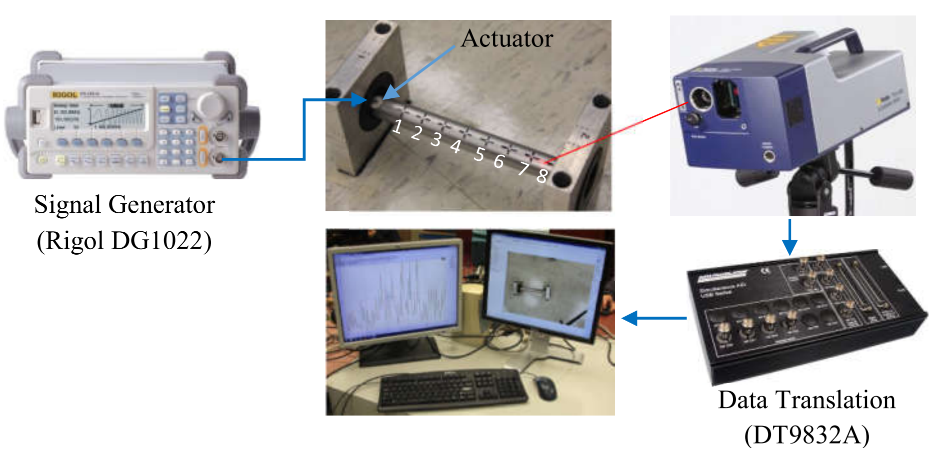

Figure 1. Experimental setup for implementation of the SuRE method for pipes in non-contact mode

Two metallic supports with plastic bushes with the inner diameter of 37 mm were used to hold the pipe in position. A 15 mm disk-shaped piezoelectric transducer was permanently bonded to the surface of the pipe section and was excited by a 20 volt continuous sweep sine wave in the range of 20-250 kHz. In the present study, initially, it was aimed to detect the presence of axisymmetric and non-axisymmetric damages and then to identify the increase in the severity of each damage. Initially, an artificial circumferential cut was created with three different depths. Then, a longitudinal cut was created and the length and the depth varied in three different levels.

The Responses of the pipe to the excitation in the pristine state and after each increase in the severity of the damage were monitored at eight different points along the axis of the pipe using a Polytec 3D Laser Scanning Vibrometer PSV400. The points are shown by cross marks in figure 1. The laser signals were collected with a 10^6 sample/s sampling rate by using a DT9832A data acquisition card. A 4096 points size Fast Fourier Transform (FFT) was used to calculate the FFT of the acquired signals. The collected data were in the form of Voltage-frequency.

5. Results And Discussion

Two different types of defects were created on the pipe to evaluate the performances of the SuRE method. The artificial longitudinal and circumferential defects were created by using a milling machine with a 4.76 mm diameter end mill. The length of the non-axisymmetric longitudinal defect was increased from 40.84 mm to 81.68 mm in increments of 20.42 mm. Additionally, the depths of the circumferential and longitudinal defects were increased in 0.5 mm steps.

Initially, it was important to show that benign environmental and experimental changes, such as temperature variations and slight changes of pipe position on supports, have a negligible effect on the acquired response. For that purpose, the frequency response of the test pipe to the excitation was obtained on separate days. Prior to acquiring the data, the experimental setup was completely disassembled and then re-assembled and the experiments were repeated.

Also, three different responses of the system at the same location were acquired and the average response of the pipe was used in the analysis. As can be seen in Figure 2, there is negligible difference between the responses acquired in the two sets of tests. However, the frequency response changes dramatically upon introducing the defects. For instance, the frequency responses of the pipe before and after different levels of the circumferential damage in reading point 1 are shown in Figure 3.

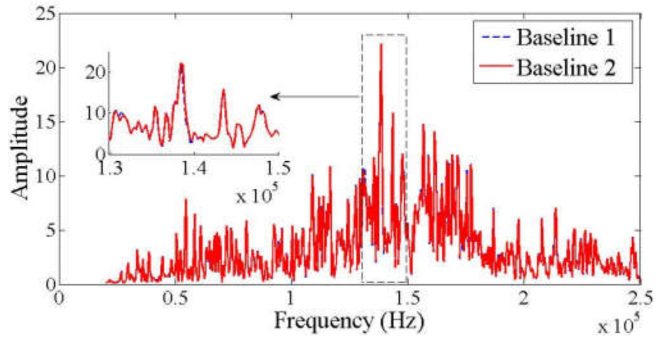

Figure 2. 1st Baseline spectrum vs. 2nd Baseline spectrum

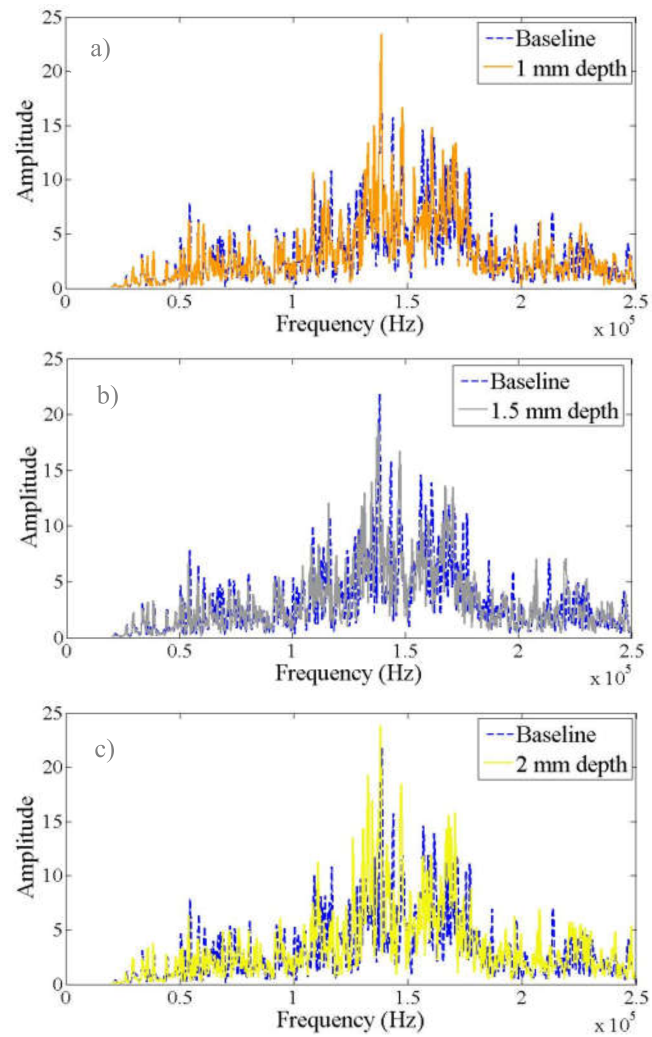

Figure 3. Frequency responses of the pipe before and after the three levels of the circumferential damage at sensor location 1: a) 1 mm b) 1.5 mm c) 2 mm

In the following sections, the SSD values are calculated for the responses collected by the laser vibrometer with respect to the baseline responses in all eight reading points for the circumferential and longitudinal damages.

5.1. Circumferential Defect

The initial circumferential cut with the depth of the 1 mm was created in the middle of reading points four and five. The depth was then increased to 1.5 mm and 2 mm in the subsequent tests. The dynamic responses of the pipe at the eight sensing locations were acquired before and after increasing the damage depth. By using equation (2), the SSD values were calculated with respect to the baseline frequency spectrums. In addition, to provide a basis for comparison between the changes of SSD damage indexes in a pristine and damaged structure, SSD values for two different sets of baselines are also calculated in all sensing locations. All SSD values are shown in Figure 4. The figure shows that the SSD value increased by the increase in the depth of the circumferential damage and the SuRE method successfully distinguished between the three damage states in all of the sensing points.

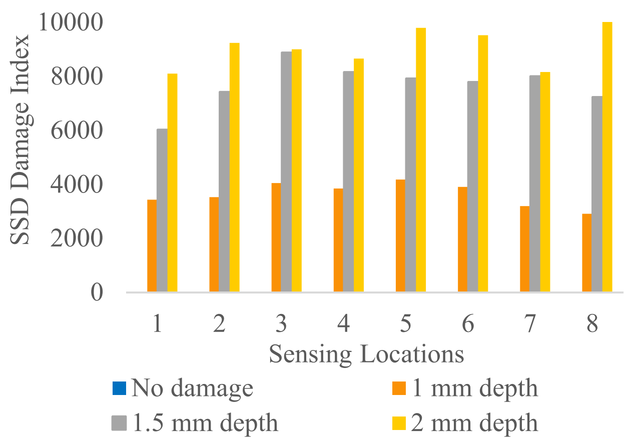

Figure 4. SSD damage index values at eight sensory points before and after the increases in depth of the circumferential damage

5.2. Longitudinal Defect

The second set of tests was conducted to investigate the effectiveness of the SuRE method for quantification of the longitudinal defects. The response of the pipe to the excitation without any damage (baseline) was studied at different test locations. The same tool, which was used for creating the circumferential damages, was then used to create the longitudinal damages along the pipe axis. The length of the initial longitudinal defect was equal to 40 mm. The length was then increased to 60mm and 80 mm. The depth of the cut was held constant and equal to 0.5 mm for all three lengths. The SSD values were again determined using the equation (2) by comparing the test cases with the baselines collected in the pristine state. The SSD values referring to the different levels of the damage at each test point are presented in Figure 5. Similar to the circumferential defects, the SSD values increased in all the sensing locations when the length of the damage was increased.

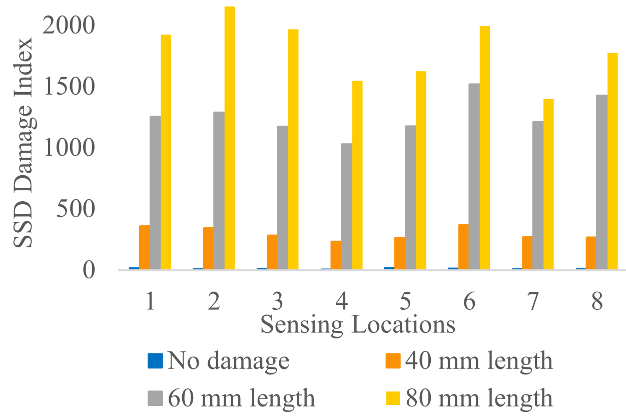

Figure 5. SSD damage index values in all sensing locations before and after the longitudinal damages

In addition, the performance of the SuRE method was evaluated when a linear damage was created with three different depths. The same tool was used to create the 100 mm length linear damage with 1 mm, 1.5 mm and 2 mm depths. The SSD values are plotted in Fig.6. The SSD values increased drastically in Fig. 6 when the linear defect was created and its depth was increased. A similar trend was observed in all sensing points. The study verified that the SuRE method is also sensitive to the wall thickness loss in the longitudinal direction.

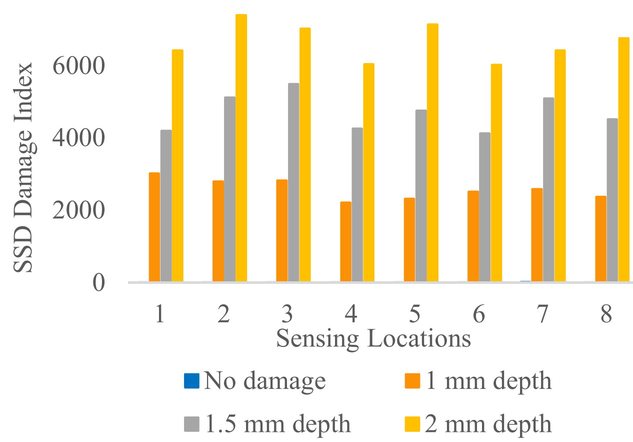

Figure 6. SSD damage index values in all sensing locations before and after the increases in depth of the 100 mm length longitudinal damage

6. CONCLUSION

A piezoelectric element excited the structure in a broad frequency range and a scanning laser vibrometer was utilized for reading the responses of the structure in eight different sensing points before and after the creation of circumferential and longitudinal defects. The frequency responses collected from the structure remained the same as long as no damage was introduced into the pipe. However, the responses drastically changed after creation of damages. A part of the change was due to the alteration of the mechanical impedance of the structure after creation of damages. The other part of the change was a result of the scattering, reflection, and diffraction of waves in presence of the defects. The sum of the squares of the differences (SSD) was used for quantification of damages with different severities.

The SuRE method was able to successfully quantify between different severities of longitudinal and circumferential defects in pipes in non-contact mode, in all sensing locations. Therefore, even readings from one sensing point were enough for quantification of damages in the tests. The broad excitation frequency makes the SuRE method sensitive to different varieties of defects in different distances from the actuator. As a result, it can be effectively used for monitoring of pipes without any need for a priori knowledge about characteristics of potential defects and their locations. Unlike the EMIS method, in high frequencies, the sensing point(s) does not need to be in a very close proximity of the damages and also the SuRE method can be used in non-contact mode. These characteristics make the SuRE method a promising approach for quick assessment of pipes in different engineering applications. Future studies regarding the SuRE method should focus on selection of optimal sensing location(s) for increasing the sensitivity of the method in detection of different types of damages.

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