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Epoxy Resin Carbon Black Smart Coating for Structural Health Monitoring of Petroleum Pipelines

R. M. Joshua [1*] & O. B. Mamat[2]

[1,2]Mechanical Engineering Department, Universiti Teknologi PETRONAS (UTP), 32610 Seri Iskandar, Perak Darul Ridzuan, Malaysia.

[*]Corresponding email: raphbari@yahoo.ca

ABSTRACT

The service life of a structure can be maximized by intermittent monitoring of its integrity; every structure exposed to excitation will vibrate at its natural frequency, an aberration from this value is a sign of damage. Structural health monitoring (SHM) provides a platform for periodic and consistent assessment of the safety and reliability of structures. This study presents the use of epoxy resin / carbon black nanocomposite as a smart coating for the harvesting of vibration data of an excited petroleum pipeline. The laboratory rig used was modeled to reflect parameters from an existing petroleum Pipeline. The vibration data harvested was compared with the data obtained using a commercial vibration meter. The vibration data was analyzed using a MATLAB code developed by Thomas Irvine. The analyzed time history obtained using the nanocomposite shows maximum resistance amplitude at 35.92 Hz and a low resistance amplitude at 2.65 Hz representing the natural frequency of the pipeline.

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INTRODUCTION

Structural health monitoring (SHM) Provides the opportunity for consistent and repeated assessment of the safety and reliability of structures or systems [1, 2]. The service life of the structure can be extended by significant preventive measures based on data describing the state of the structure as provided by the SHM system. SHM is a damage identification approach that can ultimately reduce life-cycle cost and avert unpleasant failure. For instance on 20th April, 2010, a pipeline carrying methane gas leaked into the deep-water horizon oil rig ran by Transocean, contracting for British Petroleum (BP), causing a big blast, damaged and sank the rig, killing some of the workers and polluting the Gulf of Mexico with millions of gallons of oil [3].

Damage identification procedures which can exploit the use of distributed computer settings, attainable by the use of smart sensor technology are significantly required, but presently inadequate. Recently, progression of smart sensors and their technology has fashioned the possibility of teeming array of sensors in SHM. However, using conservative system such as wired sensors to execute SHM system with a huge collection of sensors is really challenging, this can be as a result of challenges in deploying and maintaining the linked wiring [3, 4]. Prevailing monitoring methods include but not limited to acoustic monitoring system (AMS), fiber optic system (FOS), satellite monitoring (SM), cathodic protection monitoring (CPM), on-call system (OS) and impressed alternating cycle current monitoring (IACC) [5]. Piezoelectric transducers are widely used in many nondestructive techniques for damage detection in SHM applications. Among the several techniques for damage detection, the electromechanical impedance method is well-known for employing thin piezoelectric ceramics working both as actuators and sensing element [6]

Increase in energy demand with consequent increase in petroleum product exploitation makes the world economy intensely dependent upon widespread networks of pipelines for petroleum energy sources and transmission [7]. These Petroleum pipelines have a notable safety record due to high-quality design, yet they are open to a range of damage and other aging defects [8-12]. It has been the humdrum to access the reliability of underground oil and gas pipelines in the presence of life-threatening loading and corrosion effects, this is to rightly supervise the pipeline and to make certain a leak-free conveyance of harmful materials occur [13]. Its state or serviceability should be consistently assessed for condition or serviceability assessment. SHM has been well thought-out to offer useful data on the recent condition of a structures by measuring structural vibration responses and other physical phenomena [14].

The enormous network of pipeline for the distribution of petroleum product runs through variety of terrain and covers several kilometers of vast areas, therefore deploying sensors to monitor the entire length of the pipeline is challenging. Several attempts have been made with various degree of outcome. Felli et al., [15] proposed a smart-pipeline system equipped with an improved Fiber Bragg Gratings (FBG) based on fiber optics neural network for monitoring of displacement and acceleration of petroleum pipeline. The network offers measurement at hundreds of points along a single fiber with enormous precision of each point of measure. Hence, deployment of existing sensors is point or section located on the pipeline thereby introducing the challenge of optimal sensor placement (OSP) [16].

SHM technologies based on polymer matrix composites have for the past two (2) decades become a subject of special interest [17], nanocomposites based on a choice of nano-scale carbon fillers, such as carbon black (CB), are gradually being considered as a pragmatic option to traditional smart materials, mainly owing to their better electrical properties [18] and low cost. When electrically conducting nanoparticle is dispersed into a dielectric polymer a piezoresistive material is formed capable of sensing vibration. Therefore, this research considers the existing fusion bonded epoxy coating over the petroleum pipeline [19] to develop an epoxy resin/carbon black nanocomposite for vibration monitoring of the petroleum pipeline.

Experimental Procedure for Production of Epoxy Resin/ Carbon Black Nanocomposite

EpoxAmite® 100 and 102 Medium hardener manufactured by Smooth-On Inc was used as the two epoxy resin–hardener system; the epoxy resin/hardener weight ratio used is 100:29 as advised by the manufacturer. The CB used is Vulcan® X72 manufactured by Cabot Corporation. 2.4 g of CB nanoparticle was dissolved in methanol and sonicated for 15 minutes using a digital ultrasonic bath with 42 KHz frequency. 20g of epoxy resin was then poured into the mixture and further sonicated for 30 minutes. For good dispersion, the sonicated mixture was subjected to magnetic stirring at 750 rpm. The mixture was further stirred using a pensonic PM-112 hand mixer at 500 rpm for 5 minutes, the mixture was heated to 76 ^{0}C using a hot air blower and a magnetic stirrer to evaporate the methanol. 4.8 g of hardener was added and stirred using a magnetic stirrer at 750 rpm for 10 minutes to obtain a homogenous suspension. The suspension was then degassed to remove trapped air; the paint is then applied to the copper pipeline and allowed to cure at room temperature for 24 hours. To provide an electrical terminal the surface of the nanocomposite was painted with aluminum paint.

EXPERIMENTAL SET UP

The experimental rig shown in Figure 1 consists of a copper pipeline chosen to represent an existing pipeline transporting crude oil. The pipeline is a reduced model of an existing pipeline and has a dimension of θ30.x1x180 mm, for safety consideration water was used as the transported fluid in place of crude oil. A pump of rating of 86/87 l/min, head of 4 m and rated power of 180 w was used to transport the fluid through the copper pipe from the reservoir; the copper pipe was isolated for vibration effect by using flexible piping at both ends of the pipe. The epoxy resin/carbon black nanocomposite paint was applied over the pipe; electrically conducting aluminum paint was then applied over the nanocomposite. The terminal of Hantek 365A USB multimeter data Logger was connected to the copper pipe surface and the ground was connected to the aluminum paint. The pipeline was excited with a pulse force from a hammer and the piezoresistive effect was captured as a data using the Hantek 365A software with an interface as shown in Figure 2.

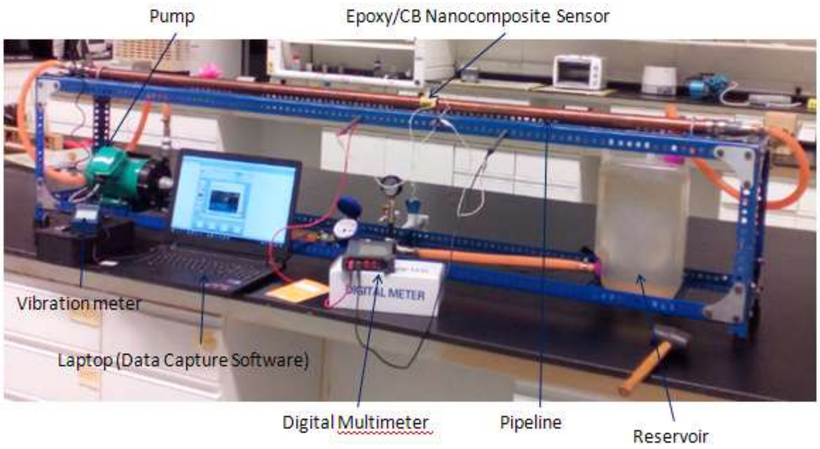

Figure 1: Experimental Rig for the Capture of Vibration Data

MATHEMATICAL MODELLING

Epoxy resin/carbon black nanocomposite is known to display intergrain and grain boundary impedances and thus they can be represented by the equivalent circuit shown in Figure 3. The circuit consists of RC element connected in parallel, applying the Cole-Cole model we have the real and imaginary parts of the Cole-Cole impedance [20] as equation (1) and (2) respectively

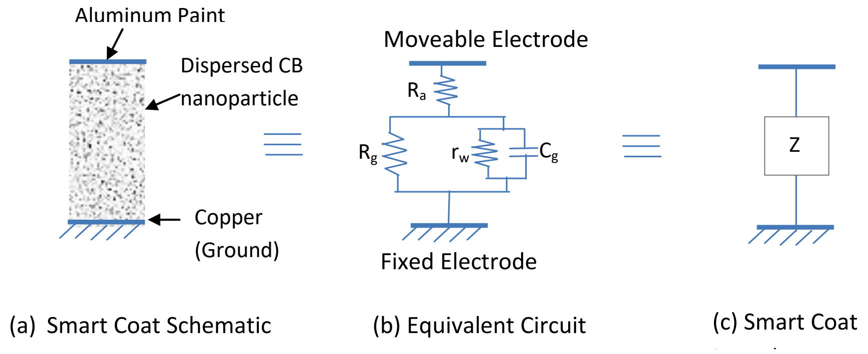

Figure 2: Equivalent Electric Circuit of the Nanocomposite Sensor

$$z' = R_a + \frac{R_e}{1+(\omega\tau_\omega)^2} \quad (1)$$

$$z" = -\frac{\omega R_e \tau_\omega}{1+(\omega\tau_\omega)^2} \quad (2)$$

Where R_a is the overall resistance of the CB nanoparticle aggregate, R_g is the resistance of the overall gaps of the nanocomposite, $\omega = 2\pi f$, τ_ω is the frequency dependence characteristic time of the equivalent circuit, Z is the impedance, C_ω is the frequency dependence capacitance of the gap and $\tau_\omega = R_e C_\omega$ and $R_e = \frac{R_g \tau_\omega}{R_g + \tau_\omega}$

When the pipeline was excited by a force F(t) from the hammer, the mass m of the nanocomposite is displaced through a distance X(t). This mechanical disturbance is converted to an electrical signal, when the disturbance is removed; the distance between the electrodes is x_0 and the distance becomes x_{dc} when the voltage from the Hantek 365A USB multimeter data logger is applied. If K is the stiffness and b the damping coefficient of the nanocomposite then the stiffness force [21] is given by equation (3)

$$K_d = \frac{Q_{dc}^2}{2\ni A} \rightarrow x_{dc} = x_0 - \frac{Q_{dc}^2}{2K\ni A} \quad (3)$$

Where Q_{dc} is the charge in the electrodes due to dc bias ∋ is the effective permittivity of the nanocomposite and A is the surface area of the electrodes. Applying the Hamilton principle for electromechanical systems and considering the Cole-Cole equations we have [22]

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{z}_i}\right)+\frac{\partial D}{\partial \dot{z}_i}+\frac{\partial L}{\partial \dot{z}_i}=P_i \text{ and } \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{Q}_k}\right)+\frac{\partial D}{\partial \dot{Q}_k}+\frac{\partial L}{\partial \dot{Q}_k}=E_k \quad (4)$$

Where P_i includes all non-consecutive mechanical loads which are not included in the dissipation function and E_k is the non-consecutive voltage [22]. The dissipation energy function D is given by equation (5)) [22]

$$D=\frac{1}{2}\left(b\dot{x}^2+(R_0+R_a)\bar{Q}_1^2+R_g(\bar{Q}_1-\bar{Q}_2)^2\right) \quad (5)$$

and the virtual work [22] is shown in equation (6)

$$\delta W_{nc}=F(t)\delta x+u_{in}\delta\bar{Q}_i \text{or } \delta W_{nc}=\sum_{i=1}^{n}P_i\delta\dot{z}_i+\sum_{i=1}^{l}E_k\delta\dot{Q}_i \quad (6)$$

The electrical charge in the nanocomposite is given by equation (7) [22]

$$\dot{Q}_1(t)=Q_{1dc}+Q_1 \text{ and } \dot{Q}_2(t)=Q_{2dc}+Q_2 \quad (7)$$

Where Q_{idc} (i = 1, 2) is the charge due to a DC bias and $Q_i(t)$ is the charge created by the excitation. The Lagrangian is given by equation (8)

$$\mathrm{L}=\mathrm{T}''-\mathrm{V}-\mathrm{W_e} \quad (8)$$

Where T" is kinetic energy given by $\frac{1}{2}m\dot{x}^2$, V is the potential energy given by $\frac{1}{2}(x+d)^2$, and W_e is the internal electrical energy given by $\frac{1}{2C_g}\bar{Q}_2^2$. Substituting equations (5), (6) and (7) into equation (4), we have

$$m\ddot{x}+b\dot{x}+Kx-\frac{Q_{2dc}}{\ni A}Q_2=F \quad (9)$$

$$\left.\begin{aligned}(R_0+R_a)\dot{Q}_1-R_g\left(\dot{Q}_2-\dot{Q}_1\right)=0\\ R_g\left(\dot{Q}_2-\dot{Q}_1\right)+\frac{x_{dc}}{\ni A}Q_2-\frac{Q_{2dc}}{\ni A}x=0\end{aligned}\right\} \quad (10)$$

Equations (9) and (10) is the model equation of the nanocomposites

Determination of Damage Index of the Pipeline

If the vibration signal is $x(t)$ then the Fourier transform is given by

$$X(f) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft}dt \tag{11}$$

The inverse of equation 2.4 is given by

$$x(t) = \int_{-\infty}^{+\infty} X(f)e^{-j2\pi ft}dt \tag{12}$$

Where t is time, f is frequency, X(f) is the Fourier transform of the vibration signal and $x(t)$ is the vibration signal, The analog continuous vibration signal will be digitized for the computer to read using a converter to generate an N number of samples from a function x(n) [23]. Then the discrete Fourier transform of x(n) is shown below in equation (13)

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j\left(\frac{2\pi}{N}\right)kn} \tag{13}$$

For k = 0,1,2….N-1, n is the time sample index, n = 0,1,2 ….N-1, where N is the number of sample and x(t) is the periodic function containing the response signal captured by the epoxy-carbon black-silica nanocomposite sensor. The equivalent energy can be represented as in equation (14)

$$E_{xx} = \int_{-\infty}^{+\infty} |X(k)|^2 dk \tag{14}$$

Equation (14) can be used to calculate energy index of the frequency response of the pipeline when it is healthy $E_{xx}^{healthy}$ and when it is damaged E_{xx}^{damged} and the equivalent energy index will be taken as in equation (15)

$$FRF - E(k) = \sum_k \left|\frac{E_{xx}^{damaged}}{E_{xx}^{healthy}}\right| \frac{2}{N} * 100 \tag{15}$$

The damage index which is a representation of the pipeline's health condition can be taken as the integral of the amplitude of the Frequency response function (FRF) evaluated over various frequency range [24] as shown in the equation (16)

$$I_x = \int_{-\infty}^{+\infty} |X(k)| dk \tag{16}$$

The damaged index of the of the FFT integration [25] is shown in equation (17)

$$FRF\ I_k = \left|\frac{I_x^{damaged} - I_x^{healthy}}{I_x^{healthy}}\right| * 100 \quad (17)$$

Where $I_x^{healthy}$ and $I_x^{damaged}$ are the damaged index from vibration signal at the healthy state and damaged state of the pipeline respectively. The damaged state is simulated by drilling 3 holes at a depth of 0.5 mm and at 45 mm from each other. MATLAB code called vibrationdata.m generated by Tom Irvine was used to analyzed the vibration data captured using the nanocomposite. The result was compared by result captured by a piezoelectric sensor from a vibration meter (VM-6320) made by landtek.

RESULT AND DISCUSSION

Ambient vibration of the laboratory modeled pipeline under the hammer-force excitation is obtained through transient analysis using MATLAB code named vibration data. The pipeline acceleration and resistance response is sampled for 21 s at a sampling rate of 50.47 samples/s.

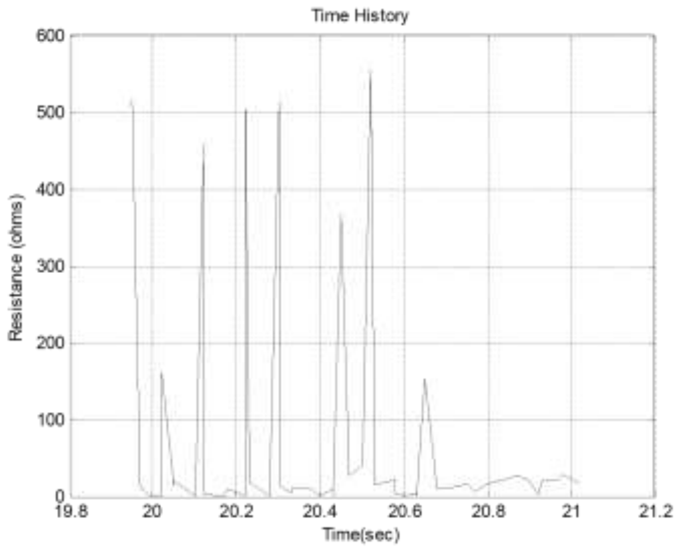

Figure 3: Time History of the Vibration Data Captured using the Nanocomposite Sensor

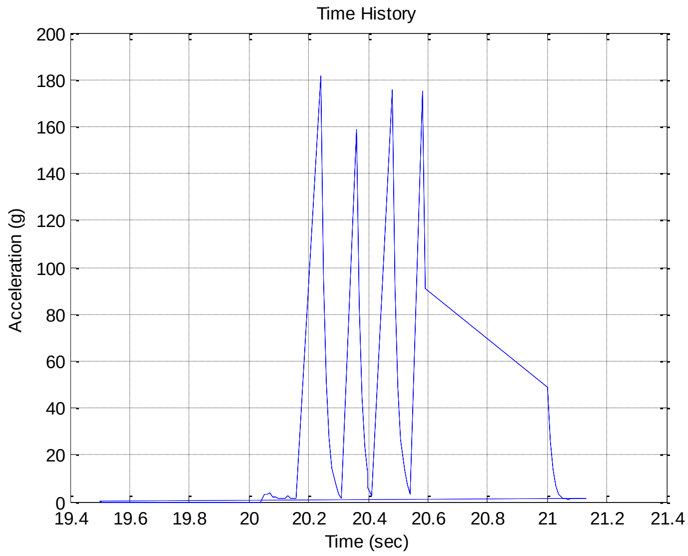

Figure 4: Time History of the Vibration Data Captured using the Vibration meter

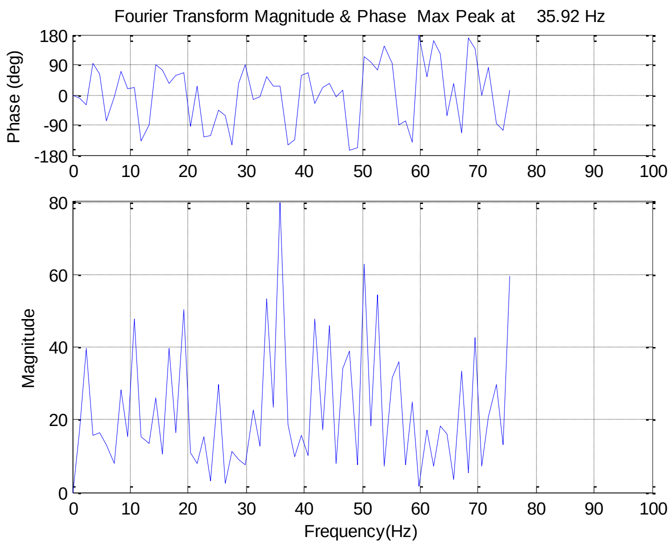

Figure 5: Fourier Transform Magnitude and Phase Maximum Peak of the Vibration Data Captured using the Nanocomposite Sensor

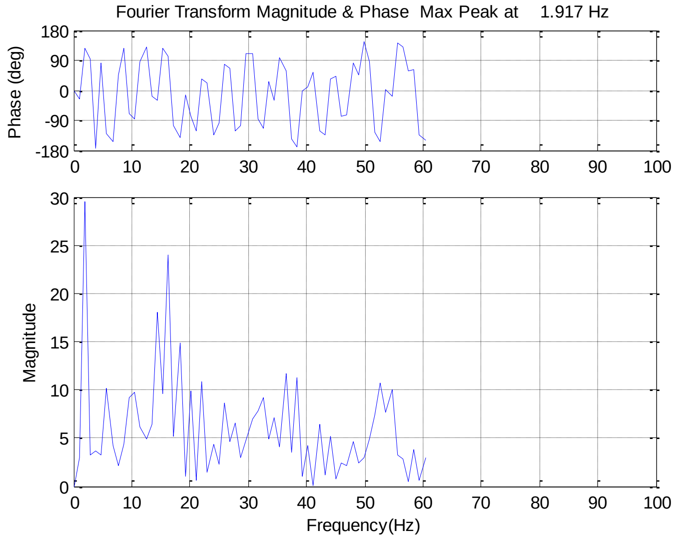

Figure 6: Fourier Transform Magnitude and Phase Maximum Peak of the Vibration Data Captured using the Vibration meter

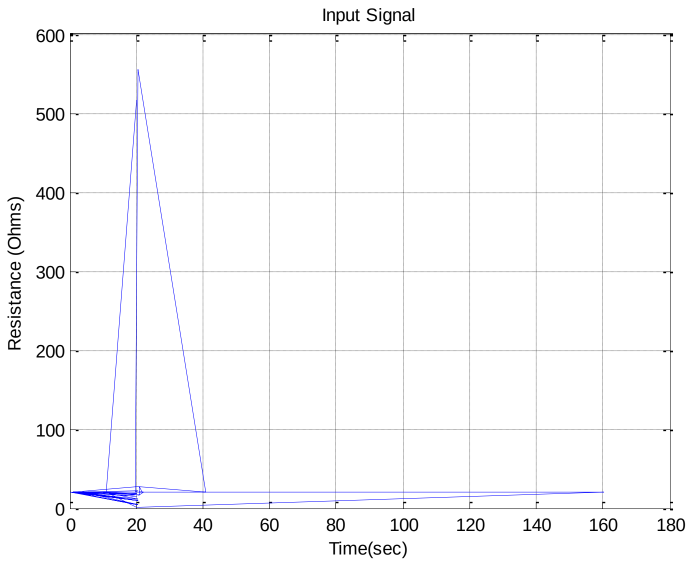

Figure 7: The Transmissibility between an Input and Resistance value of the Vibration data captured using the Nanocomposite Sensor

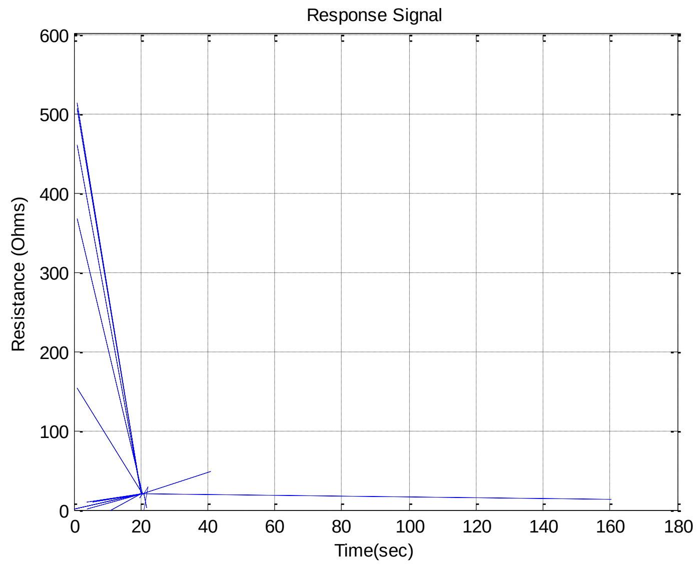

Figure 8: The Transmissibility between the response and the Resistance value of the Vibration data captured using the Nanocomposite Sensor

The maximum resistance amplitude for the vibration data from the nanocomposite in the frequency domain is at 35.92 Hz, it is pertinent to note that unlike acceleration unit a maximum resistance peak is indicative of vibrational force, A low resistance amplitude occurs at about 2.65 Hz representing the Natural frequency of the pipeline, Comparatively the maximum amplitude for the vibration data captured by the vibration meter in the frequency domain is 1.92 Hz representing the natural frequency of the same pipeline . This slight variation in the value of the natural frequency as recorded by the two techniques can be explained by the piezoresistive characteristics of the nanocomposites and location coverage of the two sensors. The accelerometer is a point location sensor and will require a combination of a number of sensors and a well define location for them, on the other hand the smart coating covers a wider area and can use the piezoresistive property to capture a better representation of the natural frequency of the pipeline . A high resistance value indicates least disturbance of the pipeline, when the pipeline is excited the nanoparticle distance is reduced and the conductivity is increased with a consequent reduction in the resistance.

Transmissibility is a measurement used in the classification of materials for vibration management characteristics. It is a ratio of the vibrational force being measured in a system to the vibrational force entering a system. Figure 6 shows the transmissibility relation between the input signal or vibration force and the resistive response of the nanocomposite with a maximum resistive response of 550 0hms occurring after 20 seconds. This is reflected by the transmissibility curve of Figure 7 which shows the response signal transmissibility. The transmissibility is calculated to be 90.91 % , which is indicative of a rigid structure.

CONCLUSION

The nanocomposite sensor was successfully fabricated and was found to be piezoresistive; the nanocomposite was a smart material with the ability to capture vibration data when connected with the Hantek 365A USB multimeter data Logger. The analysis of the vibration data shows maximum resistance amplitude at 35.92 Hz and a low resistance amplitude representing a natural frequency of the pipeline at 2.65 Hz representing 27.54 % variation of the natural frequency captured by the accelerometer.

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