

# DEVELOPMENT OF EPOXY RESIN CARBON BLACK SMART COATING MATERIAL FOR STRUCTURAL HEALTH MONITORING OF PETROLEUM PIPELINES

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## ABSTRACT

*The service life of a structure can be extended by periodic monitoring of its integrity; every structure subjected to excitation will vibrate at its natural frequency, a deviation from this value is an indication of damage. Structural health monitoring offers the prospective for regular and periodic appraisal of the safety and reliability of structures. This study presents the use of epoxy resin / carbon black nanocomposite as a smart coating for the capturing of vibration data of an excited petroleum pipeline. The laboratory rig used was modeled using parameters from an existing petroleum Pipeline. The damage indices obtained in the research reveal a damage of 10.22 % defect on the damaged pipeline. Data obtained using the nanocomposites were successively decomposed using the Hilbert Huang transform, the integrity of the proposed method was checked by data captured using an accelerometer. The damage index obtained from the vibration data captured by the accelerometer is rather too high (14.53 %); this could be attributed to the sensor location and may require additional number of accelerometers to capture the vibration data that will generate accurate damage index of the entire pipeline. The study recommends the calibration of the data obtained with the view to optimized the use of the nanocomposite for structural health monitoring.*

**Keywords:** Vibration, Epoxy Resin, Carbon Black, Structural Health Monitoring, Piezoresistive

## 1 INTRODUCTION

Structural health monitoring (SHM) offers the potential for constant and cyclic evaluation of the safety and reliability of structures or systems [1, 2]. The service life of the structure can be prolonged by decisive preventive measures based on data of the state of the structure as provided by the SHM system. SHM is a Damage detection strategy that can eventually ease life-cycle. cost and prevent awful failure. For instance on 20<sup>th</sup> April, 2010, a pipeline carrying methane gas leaked into the deepwater Horizon oil rig operated 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 recognition methods which can use the benefit of distributed computing settings obtainable by smart sensor technology are greatly required, but presently inadequate. Lately, advancement of smart sensors has produced the prospect of crowded array of sensors in SHM. However, using conventional system such as wired sensors to execute SHM system with a large collection of sensors is pretty demanding because of the challenges in deploying and maintaining the linked wiring [3, 4]. Existing 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 extensively employed in numerous nondestructive techniques for damage detection in SHM applications. Amid 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]. The increase in petroleum product exploitation makes the world economy deeply reliant upon widespread networks of pipelines for petroleum energy sources and transmission [7]. These Petroleum pipelines have a noteworthy safety record owing to high-quality design, they are however open to a range of damage and other aging defects [8, 9, 10, 11, 12]. It has been the routine to review the dependability of underground oil and gas pipelines in the presence of extreme 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 made of 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.

## **2 EXPERIMENTAL PROCEDURE FOR PRODUCTION OF EPOXY RESIN/ CARBON BLACK NANOCOMPOSITE**

EpoxyAmite® 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 °C using a hot air blower and a magnetic stirrer to evaporate the methanol. 4.8g 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 as done by Aldraihem *et al.* [20].

## **3 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 030.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 as suggested by Aldraihem *et al.* [20]. 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 to capture the variation in resistivity of the nanocomposite when excited by the flowing water under the action a pump also used was a commercial accelerometer made by Landtek to capture vibration data. To experiment the structural health monitoring of the smart coat two different vibration data was captured. The first was captured when the pipeline has no damaged and the second was captured after holes were created on the pipeline as shown in Figure 3. The commercial accelerometer was placed at 600 mm from the first hole and used to capture vibration data (for comparison) from both the damaged and healthy pipeline. The pump was used as the excitation force; the damaged pipeline was simulated by drilling 2 holes (10 mm diameter each) as shown in the Figure 3 below. A flexible hose was attached to the drilled holes to redirect leakage to the reservoir tank.

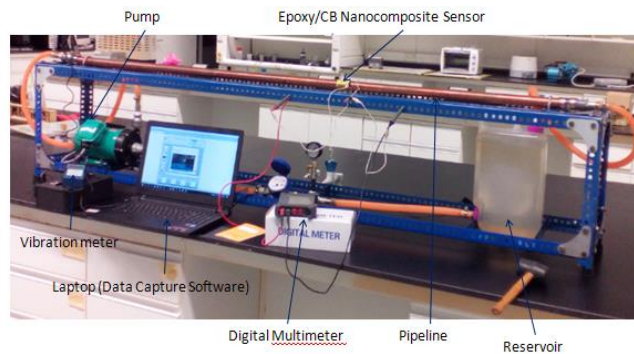


Figure 1. Experimental Rig for the Capture of Vibration Data

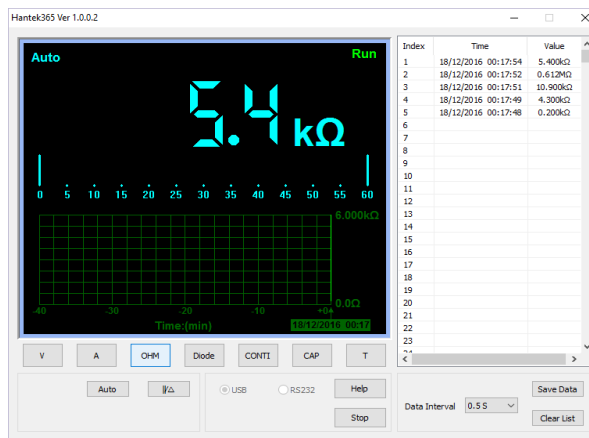


Figure 2. Hantek 365A Software Interface

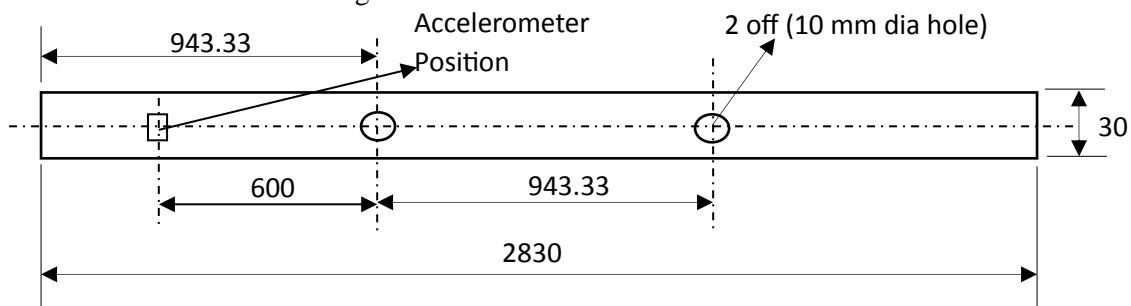


Figure 3. Sketch of the Damaged Pipeline

#### 4 MATHEMATICAL MODEL OF SMART COAT

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 4. 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 [21].

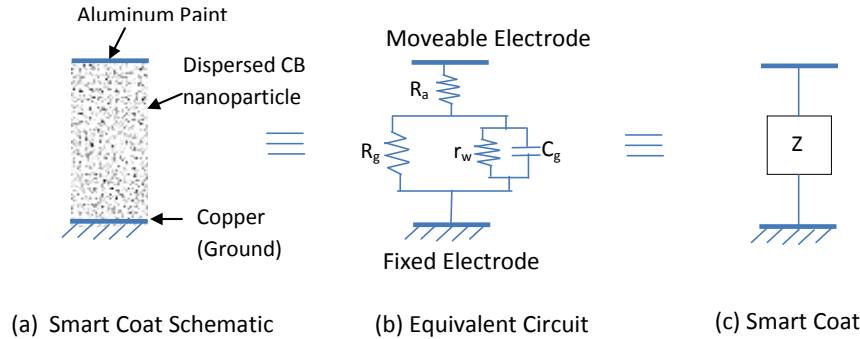


Figure 4. Equivalent Electric Circuit of the Nanocomposite Sensor

From the equivalent electric circuit shown in Figure 3 the real and imaginary impedance is given by equations 1 and 2 respectively.

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

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

Where  $R_a$  is the overall resistance of the CB nanoparticle aggregate,  $R_g$  is the resistance of the overall gaps of the nanocomposite,  $\omega = 2\pi f$ ,  $\tau_\omega$  is the frequency dependence characteristic time of the equivalent circuit and is given by equation 3 below,  $Z$  is the impedance,  $C_\omega$  is the frequency dependence capacitance of the gap.

$$\tau_\omega = R_e C_\omega \text{ and } R_e = \frac{R_g \tau_\omega}{R_g + \tau_\omega} \quad (3)$$

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 4.

$$K_d = \frac{Q_{dc}^2}{2\epsilon A} \rightarrow x_{dc} = x_0 - \frac{Q_{dc}^2}{2K\epsilon A} \quad (4)$$

Where  $Q_{dc}$  is the charge in the electrodes due to dc bias  $\epsilon$  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 equation 5, we have [22].

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{z}_i} \right) + \frac{\partial D}{\partial \dot{z}_i} + \frac{\partial L}{\partial z_i} = P_i \text{ and } \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{Q}_k} \right) + \frac{\partial D}{\partial \dot{Q}_k} + \frac{\partial L}{\partial Q_k} = E_k \quad (5)$$

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 6 [22].

$$D = \frac{1}{2} (b\dot{x}^2 + (R_0 + R_a)\bar{Q}_1^2 + R_g(\bar{Q}_1 - \bar{Q}_2)^2) \quad (6)$$

and the virtual work [22] is shown in equation 7.

$$\delta W_{nc} = F(t)\delta x + u_{in}\delta \bar{Q}_i \text{ or } \delta W_{nc} = \sum_{i=1}^n P_i \delta \dot{z}_i + \sum_{i=1}^l E_k \delta \dot{Q}_i \quad (7)$$

The electrical charge in the nanocomposite is given by equation 8 [22].

$$\dot{Q}_1(t) = Q_{1dc} + Q_1 \text{ and } \dot{Q}_2(t) = Q_{2dc} + Q_2 \quad (8)$$

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.

$$L = T'' - V - W_e \quad (9)$$

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  $\frac{1}{2C_g}Q_2^2$ . Substituting equations 6, 7 and 8 into equation 5, we have Equations 10 and 11 is the model equation of the nanocomposites.

$$m\ddot{x} + b\dot{x} + Kx - \frac{Q_{2dc}}{\partial A} Q_2 = F \quad (10)$$

$$\left. \begin{aligned} (R_0 + R_a)\dot{Q}_1 - R_g(\dot{Q}_2 - \dot{Q}_1) &= 0 \\ R_g(\dot{Q}_2 - \dot{Q}_1) + \frac{x_{dc}}{\partial A} Q_2 - \frac{Q_{2dc}}{\partial A} x &= 0 \end{aligned} \right\} \quad (11)$$

## 5 DETERMINATION OF DAMAGE INDEX OF THE PIPELINE

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

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

The inverse of equation 11 is given by.

$$x(t) = \int_{-\infty}^{+\infty} X(f)e^{-j2\pi ft} dt \quad (13)$$

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 14.

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j(\frac{2\pi}{N})kn} \quad (14)$$

For  $k = 0, 1, 2, \dots, N-1$ ,  $n$  is the time sample index,  $n = 0, 1, 2, \dots, N-1$ , 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 15.

$$E_{xx} = \int_{-\infty}^{+\infty} |X(k)|^2 dk \quad (15)$$

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  $E_{xx}^{damaged}$  and the equivalent energy index will be taken as in equation 16.

$$FRF - E(k) = \sum_k \left| \frac{E_{xx}^{damaged}}{E_{xx}^{healthy}} \right| \frac{2}{N} * 100 \quad (16)$$

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 17.

$$I_x = \int_{-\infty}^{+\infty} |X(k)| dk \tag{17}$$

The damaged index of the of the FFT integration [25] is shown in equation 18.

$$FRF I_k = \left| \frac{I_x^{damaged} - I_x^{healthy}}{I_x^{healthy}} \right| * 100 \tag{18}$$

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 vibration data. 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.

## 6 RESULTS AND DISCUSSION

A sample rate of 50 Hz, frequency resolution of 80 Hz and time resolution of 200 s was used in the analysis. Figure 5 and 6 shows the time history of the healthy and damaged Pipeline, higher amplitude of resistance (ohm) above the peak amplitude line of the healthy pipeline was exhibited by the damaged pipeline. This phenomenon was also observed by Owolabi *et al.* [26] and they state that measured frequencies and response amplitudes are distinctive values and should remain the same for a unique structure. However, amplitude is more valuable as indicators of impact on the structure and do not take into account the time duration and the energy in the pipeline.

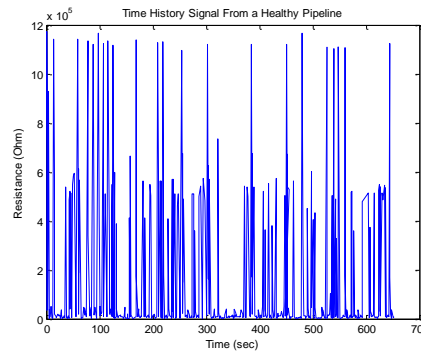


Figure 5. Time History of Vibration Data from the Healthy Pipeline (Nanocomposite)

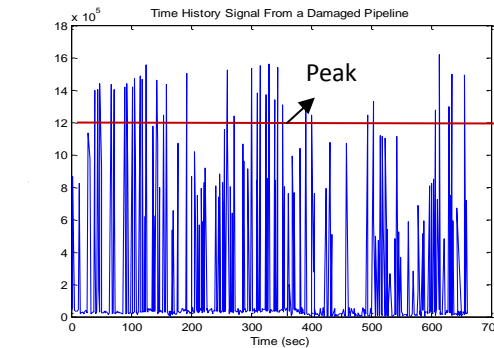


Figure 61. Time History of Vibration Data from the Damaged Pipeline (Nanocomposite)

Variation in frequency and amplitude for the damaged and healthy pipeline with time is captured by the EMD energy spectrum as shown in Figures 7 and 8.

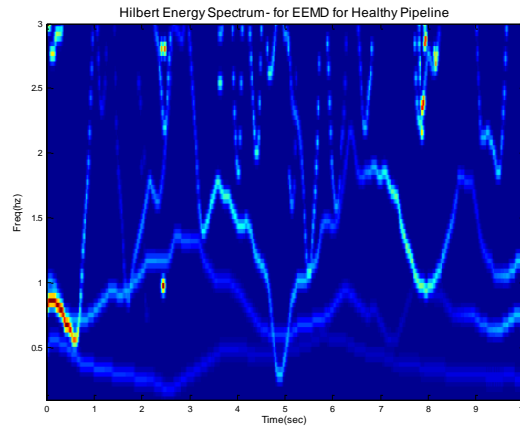


Figure 2. EMD Hilbert Energy Spectrum for the Healthy Pipeline (Nanocomposite)

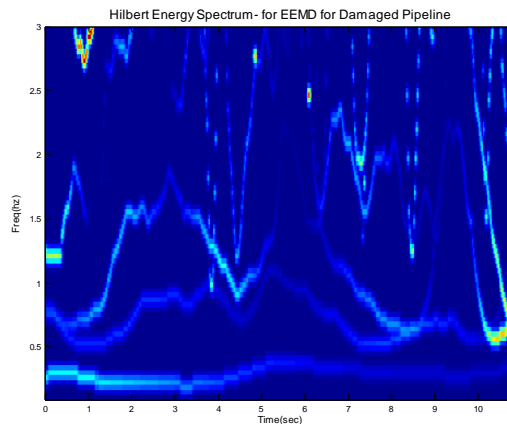


Figure 8. EMD Hilbert Energy Spectrum for Damaged Pipeline (nanocomposite)

The energy spectrum for the healthy pipeline is marked by lower frequency peak over a longer period occurring after 500s. The higher frequency peak at 500 s of Figure 8 is an indication of damage on the pipeline coupled with difference in the energy spectrum over the entire period. The EMD damaged based index (EMD-EDI) has a high level of sensitivity to very slight damages, making it as an efficient method for detecting sensitive damages in structures. The MATLAB program takes the vibration signals acquired via the nanocomposites smart coating, corresponding to the healthy and the damaged states of the pipeline as inputs. The code breaks the vibration data into elemental signals (IMFs) at different energy levels using the EMD procedure and use the EMD-EDI to establish the damage indices

## 7 CONCLUSIONS

The research introduced a new health monitoring approach based on sensing of the vibration response of a pipeline using smart piezoresistive epoxy nanocomposites, and then evaluating the vibration response of the pipeline using the data obtained by the use of the nanocomposites. The damage indices obtained in the research reveal a damage of 10.22% defect on the damaged pipeline.

Data obtained using the nanocomposites were successively decomposed using the Hilbert Huang transform, the integrity of the proposed method was checked by data captured using an accelerometer. The damage index obtained from the vibration data captured by the accelerometer is rather too high (14.53%); this could be attributed to the sensor location and may require additional number of accelerometers to capture the vibration data that will generate accurate damage index of the entire pipeline. The use of smart paint (conductive epoxy nanocomposite) provides a better health assessment; the numerical results confirm that the proposed approaches could effectively identify the existence and intensity of defects in the entire length of pipeline.

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