FEDERAL UNIVERSITY OF TECHNOLOGY MINNA

PROBLEMS TO SOLUTIONS OR SOLUTIONS TO PROBLEMS: REVERSE ENGINEERING IN A DYNAMIC WORLD

By

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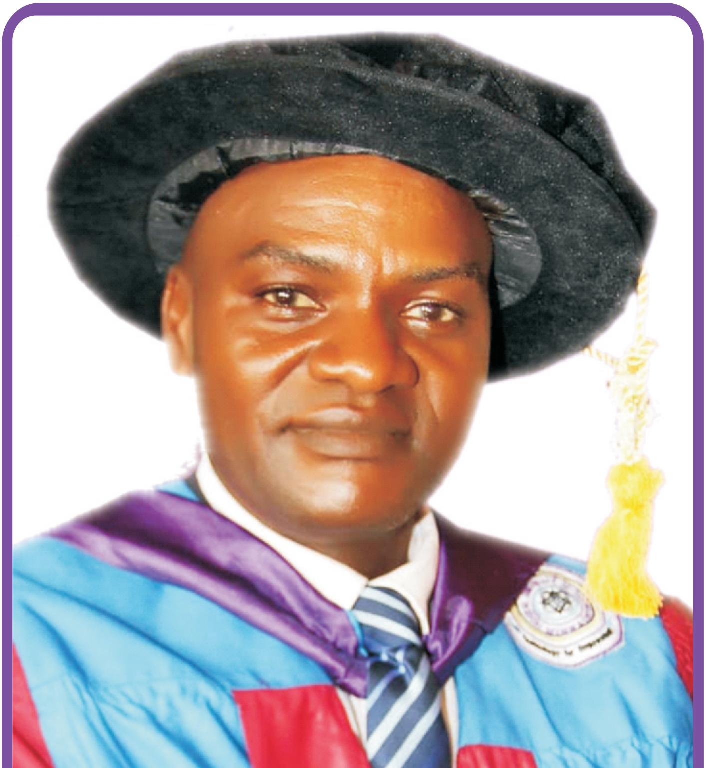

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1.0 Introduction

I feel most gratefully honoured today by the special grace of almighty God to deliver the 95th Inaugural Lecture of this great citadel of learning, the Federal University of Technology, Minna.

Mr. Vice-Chancellor, Sir; Deputy Vice-Chancellors; Registrar; Bursar; Librarian; Dean of Postgraduate School; Dean of Students Affairs; my Dean, School of Infrastructure, Process Engineering and Technology; Deans of various Schools; Directors of Units and Centres; Professors and members of University Senate; other members of academic and non-academic staff; distinguished guests; the greatest FUTMINNA Students; ladies and gentlemen.

The term "Problems to Solutions or Solutions to Problems" can be clearly conceptualized from historical, religious, scientific and even our daily human existence perspectives. Specifically, most major religious beliefs about the creation of man noted that the problem of loneliness of the first man (Adam) led to a solution which was in the creation of the woman (Eve). For those more scientifically inclined, modern forensic science Fingerprint Matching have been used to detect perpetrators (solution) of crimes such as murder (problem) by using several information from the crime scene. In addition, the development of vaccines (solution) as a result of the Corona virus pandemic (problem) involved moving from the "problems to solutions."

Reverse engineering, sometimes called inverse engineering, is a process in which software, machines, aircraft, architectural structures and other products are deconstructed to extract design information from them. The interplay of mathematical modelling with experiments is one of the central elements in science and engineering, and the aim of reverse engineering is to infer, analyse and understand, through this interplay, the functional and regulatory mechanisms of various systems (Villaverde & Banga, 2014). Reverse engineering has been studied in different areas, such as inverse problem theory, machine learning, nonlinear physics, biochemical kinetics, control theory and optimization, etc. On the other hand, inverse problem is the process of calculating from a set of observations the causal factors that produced them, by starting with the effects and then calculating the causes (Idowu, 2015).

1.1 Direct and Inverse Problem

As an example, Figure 1 shows a simple explanation of a direct and an inverse problem based on Newton's laws.

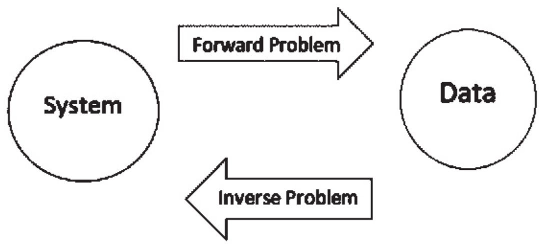

Figure 1: Forward and inverse problems (Mahdi Sadri, Seyed M. Shariatipour, Andrew Hunt, Masoud Ahmadinia et al 2019)

The direct problem here is the computation of the trajectories of bodies from the knowledge of the forces whereas the inverse problem is the determination of the forces from the knowledge of the trajectories. Sir Isaac Newton solved the first direct/inverse problem: the determination of the gravitation force from the Kepler laws describing the trajectories of planets.

1.2 Inverse Problems and Modelling: Application to Pipeline Monitoring

Although, pipelines are regarded as one of the surest and safest solution to the problem of petroleum products transportation, the attended problems of occasional natural damages (erosion, earthquakes) or third-party mechanical damages(terrorist attacks, vandalisation, heavy duty equipment, etc) cause pipeline failure (Posakony & Hill, 1992). Vandalisation refers to illegal or unauthorised destruction of petroleum pipelines to appropriate crude oil or its refined products for personal use or for sale in the black market (Akintola, 2006). This includes oil bunkering, scooping fuel from burst oil pipes and the deliberate act of oil terrorism. These damages are mostly due to accidental impact of heavy-duty equipment, ageing, and corrosion in developed countries; while in developing countries, theft, vandalisation and sabotage are the most significant factors (National Transportation Safety Board Pipeline Accident Report for Texas Eastern Transmission Corporation, Natural Gas Pipeline Explosion and Fire, 1994). Incidences of theft and sabotage have been reported in countries such as Mexico, Turkey, Kenya, China, Pakistan and Nigeria.

As the largest producer of oil in Africa, oil is the main stay of the Nigerian economy contributing about 90 % of the nation's foreign exchange earnings and about 25 % of the gross domestic products. A large proportion of the oil is produced offshore and transported using pipelines, and a major associated problem is pipeline vandalisation which has become rampant in recent times. Between January, 1999 to December 2005, there were 6,369 cases of pipeline vandalism as against 335 cases of natural causes (Yo-Essien, 2008). Furthermore, vandalisation has resulted in several economic, human, and environmental problems. Statistics gathered from the Nigeria National Petroleum Company reveals that Nigeria loses at least 2 billion US dollars annually due to vandalisation of the pipelines (Yo-Essien, 2008). Many lives are lost in a most sudden, tragic and violent manner and several pollutions of the land, air and aquatic lives occur due to this problem.

Also, this damage occurs mostly in remote areas where third party damages are rampant causing the supply of petroleum products to be disrupted. Even in situations where it had been known that damage has occurred along the pipelines, it has actually been difficult to pin-point the exact/region location of the damage. This has also resulted in the Nigerian government wasting huge amount of money using excavators to dig every part of the community where it is suspected there had been damage to a pipeline to locate it without spotting the particular area of the damage.

All effort to move from this problem to the solution proffered by the use of local community leaders, police, regular aerial surveillance at critical sections of the pipelines, and local security guards have proven abortive. Since most of this damage is caused by impulsive events, these generate a form of pressure pulse that propagates in both directions through the fluid in the pipe. This can be detected and measured at points remote from the event and the measured pulses which contain information about the event can potentially be used to locate and characterize what must have caused it. This information might then be used to assess the damage, its possible cause, and solutions needed (Olugboji, 2012).

1.3 Wave Propagation in Guided Media

During pressure pulse propagation along pipelines, the pipes through which the pulses propagate act as a wave guide and by so doing enable the pulses to propagate in one dimension. A waveguide can be defined as a structure that guides waves, such as electromagnetic waves or sound waves. There are different types of waveguides for every type of wave, and a good example is hollow conductive metal pipe which is often used for radio waves (microwave) (Nigeria National Petroleum Corporation, Annual Statistical Bulletin, 2005). The first mathematical analysis of electromagnetic waves in a metal cylinder was performed by Lord Rayleigh in 1897 (Nigeria Pipe Blast Kills over 500, 2006). The guiding of sound waves through a taut wire has been a well-known phenomenon for a long time now, as well as sound through a hollow pipe. Other applications of waveguides are in transmitting power between the components of a system such as radio, radar or optical devices. A propagation mode in a waveguide is one solution of the wave equations, or, in other words, the form of the wave Somerfield and Debye (Balanis, 1989) suggested that due to the constraints of the boundary conditions, there are only limited frequencies and forms for the wave function which can propagate in the waveguide.

1.4 Pipeline Damage Detection

It is quite oblivious that pipelines dangers and damages exist from the building of them to their use. They traverse large distances, which make them vulnerable to damage and their complexity makes it difficult to detect and locate faults. Moreover, this medium of transportation is usually attributed to very sensitive products such as crude oil, natural gas, and industrial chemicals, in which an unintended pause in their operation result in the loss of millions of dollars. Thus, it is of great importance to set up reliable mechanisms or systems in keeping a close watch at every inch of their length, in order to sustain normal operation and prevent loss of significant amount of those products. The design and application of pipeline detectors is made around the properties of the product that is being transported and expected nature of damage to the system. There are several methods in use that can detect and locate pipeline damage, ranging from simple visual inspection to complicated satellite based hyper-spectral imaging (Carlson, 1993; Scott & Barrufet, 2003), each with its own advantages and disadvantages. These methods are categorised under three headings; optical methods, electrical methods and acoustic/vibration based methods.

1.4.1 Optical methods

- **Visual inspection**

The use of visual inspection is probably one of the oldest, simple and direct methods of monitoring pipelines for damages (Bray & Stanley, 1989). The technique involves the use of personnel frequently walking along the path way of the pipeline to monitor damage and the use of trained dogs which are sensitive to the smell of substances released from a leak. Simple visual observation is reliable and forms part of everyday pipeline patrolling and monitoring. However, the limitation is that it cannot provide real-time detection of damage and it is an expensive and stressful means of detecting damages along pipelines.

- **Thermal imaging**

This is a form of passive optical system used for monitoring leaks on natural gas pipelines. This technique involves the detection of temperature differential between the leaking natural gas from pipelines and immediate surroundings (Weil, 1993; Kulp, Powers & Kennedy, 1998). This method requires the installation of very expensive thermal imagers on moving vehicles, helicopters or portable systems to monitor long lengths of pipeline within a short time. In addition, useful thermal imaging cannot be achieved if the temperature of the natural gas is not different from that of the surroundings. This method is largely immune to false alarms but cannot provide real time monitoring.

- **Fibre- optics**

Fibre-optics is an optical method of detecting in pipelines. The operating principle is the sensitivity of the fibre to applied stress. Commercial optical fibre intrusion detection system has been tested and used for the detection of encroachments on pipelines (Huebler, 2002). A long optical fibre, similar to those used in telephone systems, is buried above the pipeline. Light pulses are sent down the optical fibre and any discontinuity (damage) along the fibre results in a small amount of light being reflected back to the source. When there is an encroachment near a buried pipeline, the soil above the fibre is compressed and vibrates, which changes the optical properties of the fibre and hence the amount of light reflected back to the source, where it is detected. The location of the encroachment is obtained by measuring the time it takes for the reflected light pulse to return. It is actually not necessary for the fibre to be broken before damage is detected. The possibility of monitoring a few miles of pipeline from a single location was reported by Francini, *et al.*, (1997).

Another optical method monitors the changes in the fibre's light transmission, which may be detected and located by the use of Optical Time Domain Reflectometry (OTDR) (Doctor & Dunker, 1995). Commercial OTDR systems have been designed for the purpose of characterizing optical fibres (Huebler, 2002) and it has been shown that a backhoe loader passing over a buried fibre creates a detectable damage. It was found possible to monitor long distances because of the low attenuation of this type of fibre. The limitations of this technique are that the fibre spans across the entire pipeline, making it expensive, and the detection system only measures changes to the fibre along its length. This often results in false alarms due to large but benign disturbances, such as a slow-moving train or highway traffic crossing a section of fibre, and this will dominate the signal preventing detection of other problems (Huebler, 2002). They also require sophisticated and expensive instrumentation and signal processing.

- **Satellite monitoring**

The use of satellites to monitor pipelines for ground motion and encroachment was reported by Fung and Randell (2002). An example of this is the use of Synthetic Aperture Radar (SAR) to provide RADARSAT images that can be processed to detect any obstruction close to the pipelines. Satellites are used to visually monitor the right-of-way where these pipelines are located. Black and white satellite visual images one-metre resolution can be taken to locate and track disruptions to pipelines (Huebler, 2002). A limitation of the technique is the difficulty in interpreting the images when they are affected by weather. Similarly, due to the use of advanced satellite technology, such pipeline monitoring is expensive, requires a high degree of skill to operate and are slow due to the time taken to analyse related images.

1.4.2 Electrical Methods

- **Cathodic Protection Monitoring**

The cathodic protection monitoring system detects a breakage on the pipeline coating, resulting in shorting of the pipeline to electrical ground. This method was developed in Japan and the US (Hosokawa, Masuda, Ohira, & Sasaki, 2000). It involves the superimposition of a 220 Hz AC current on top of the normal DC cathodic protection current. This then requires monitoring of the AC pipe-to-soil voltage and the AC current, from which the pipe-to-soil resistance is calculated. Whenever there is an infringement on the pipe, this causes the resistance value of the pipe-to-soil to change, indicating potential damage. The limitation includes its non-applicability to older pipelines since it requires very few breaks in the coating, short detection range (Rocha, 1989) and reduced sensitivity due to breaches in pipe coating.

- **Impressed Alternating Cycle Current (IACC)**

IACC is an electrical based method of damage detection in pipelines that involves impressing electrical signals on the pipeline by the generation of a time varying voltage between the pipe and the soil at various locations where pipeline access is available. The generated signal which travels upstream and downstream of the pipeline from the transmitter, consists of a time-dependent waveform that is designed to maximize the impressed alternating current system performance in the presence of various sources of external noise. The resulting voltage signal between the pipe and ground is monitored continuously at a transmitting station. When there is a breakage in the coatings, this changes the impedance seen at the transmitting station and the signals received at the IACC which is located in the segment of the pipe being damaged (SWRI Report, 2003). The limitations here are that damage detection range may be short, reduction in sensitivity due to pre-existing breaches in pipe coating, possible interference due to cathodic protection systems, and the problem of accurate location of the damage.

1.4.3 Acoustic/Vibration Method

The acoustic technique of pipeline damage monitoring is based on the detection of the sound pulse created by impacts against the pipeline (Nakamachi, Uchida, Hosohara, Okada & Nagashim, 1992). The use of this technique dates back to the early 1990s. The impact against the pipelines generates acoustic signals within the pipe wall and in the fluid that is flowing inside the pipeline. These acoustic signals attenuate very fast in the pipe wall as a result of frictional interaction with the surrounding soil. The attenuation rate is smaller in the fluid and acoustic signals can propagate for up to 30 km (Francini *et al*., 1997). Past works involving acoustic technique have shown that the acoustic signals of a pressurized fluid escaping through a leak in a pipeline comprises various range of frequencies, and only the relatively low frequencies are useful for practical detection techniques as a result of the significant attenuation of the higher frequencies present in the signal (John, *et al*., 2004).

Rocha (1989) discovered that acoustic frequencies in the range 0.05 Hz to 10Hz can propagate in a gas for distances of about 160 km. On this basis, Rocha concluded that the amplitude of the acoustic wave is related to the properties of the gas, the operating pressure of the pipeline and the size of the leak. The detectable acoustic pressure of a leak can be as small as 5 mbars in a pipeline but this requires a special noise cancellation technique which is very complex so as to increase the signal to noise ratio (Rocha, 1989).

Leis (2003) with his team carried out experiments to determine how far an acoustic step function impact could propagate through a pipe wall in a 609.6 mm diameter pipeline. They did this by dropping weights ranging from a few kilograms up to 40 kg several metres into the pipe wall. The impacts were detected up to 3.2 miles away. The researchers speculated that the impacts could be detected as far as 40 km away. They also found that signals with frequencies greater than 500 Hz were completely attenuated in their tests.

Jolly, *et al*., (1992) reviewed several researches on different acoustic based leak detection methods and discovered that the most promising method for impulse detection are the low frequencies. The impulse method uses sensors mounted along the pipeline. This method could detect the transient acoustic event associated with a rapid rupture event.

A commercial acoustic based method called ThreatScan is currently being used to monitor pipelines providing early warning of third-party damage using hydrophones penetrating through the pipe wall. According to the manufacturers (www.ge.com/pii), ThreatScan is quick in detecting and assessing the severity of the damage, eliminating any false alarms and sending the information to the pipeline operator within 30 minutes. British Gas first used the pipe wall as an acoustic carrier with a sensor attached to the pipe wall (Gary & Alfred, 2003).

2.0 Proffered Solution

2.1 Pulse Reconstruction Method

Two techniques including digital filtering and inverse techniques are types of pulse reconstruction methods that were formulated and developed. Digital filtering is desirable in many situations in engineering and embedded systems. For example, in radio communication the signals become distorted and corrupted with noise.

2.2 Digital Filtering

Digital filtering is desirable in many situations in engineering and embedded systems. For example, in radio communication the signals become distorted and corrupted with noise. A good filtering algorithm can remove the noise while retaining the useful information. Many digital filters are based on the Fast Fourier Transform (FFT), a mathematical algorithm that quickly extracts the frequency spectrum of a signal, allowing the spectrum to be manipulated (such as to create band-pass filters) before converting the modified spectrum back into a time-series signal using the inverse FFT. Two types of digital filters are discussed because of the relevance to this work: deconvolution filters and linear filters.

- **Deconvolution Filter**

Deconvolution filtering techniques are widely used in digital signal processing and image processing (O'Haver, 2007). They are of great significance in scientific and engineering applications. The technique, as developed in this research for pulse reconstruction, is based on the principle of the deconvolution filter used in communications to recover a distorted signal. In mathematics, **deconvolution** is referred to as an algorithm-based process used to reverse the effects of convolution on recorded data (O'Haver, 2007). In optics and imaging, deconvolution is applied in correcting the optical distortion that is associated with optical microscope, electron microscope, telescope and other imaging instruments. It is usually done in the digital domain by a software algorithm (Cheng, 2006), as part of a set of techniques in microscope image processing.

Deconvolution has also been a very useful and well-studied problem that is commonly encountered in seismology (Webster, 1978). During exploration for underground hydrocarbon (oil and gas) reservoirs, seismic receivers (geophones) measure a noisy version of the earth's blurred response and the measured data may be interpreted using methods such as wavelet analysis. Similarly, in earthquake seismology the receivers measure the seismic waves that are generated by the earthquake. In this situation, deconvolution is used to isolate the earthquake source time function that characterizes the faulting underground process from the propagation effects (Bertero *et al*., 1997) using various deconvolution techniques such as Weiner, homomorphic, maximum-likelihood, and Kalman. The application of Weiner filters theory to deconvolution problems has been extensively described by Peacock and Trietel (1969), and Robinson and Silvia (1979). The method is based on the assumption of a time invariant system and stationary data. It has been shown that there is a possibility of applying the Weiner filter theory to model time varying systems with nonstationary statistics, but the resulting integral equations obtained are difficult to solve (Crump, 1974).

- **Linear filters**

All real measurements are disturbed by noise. This includes electronic noise, but can also include external events that affect the measurements taken, such as vibrations, variations of temperature, variations of humidity, etc., depending on what is measured and on the sensitivity of the device. It is often possible to reduce the noise by controlling the environment. Otherwise, when the characteristics of the noise are known and are different from the signals, it is possible to filter or to process the signal as mentioned above. Linear filters are useful in eliminating such unwanted frequencies (noise) from an input signal or to select a desired frequency among many other frequencies present in the signal. Several kinds of linear filters that are commonly used in signal filtering include:

(i) A low pass filter blocks high frequencies and passes low frequencies

(ii) A high pass filter blocks low frequencies and passes high frequencies

(iii) A band pass filter passes a limited frequency range and blocks all frequencies above and below

(iv) A band stop filter blocks a specified frequency range but passes high and low frequencies

(v) Anti-aliasing filter is a low pass filter type used before a signal is sampled, to restrict the bandwidth of a signal to satisfy the Nyquist sampling theorem.

This technique is computationally expensive, requiring the computation of multiple sets of sensitivity equations and gradients, but modern digital signal processing hardware makes the use of digital filters very fast.

2.3 Inverse Techniques

Inverse methods can be basically considered as an approach for interpolating or smoothing a data set in space and time where a model acts as a dynamical constraint. Some examples of inverse problems follow: Earthquake location, earth structure from surface or body wave inversion, plate velocities (kinematics), curve fitting and satellite imaging applications. For instance, a satellite is measuring ultraviolet radiance, being absorbed, emitted, or scattered by the atmosphere. From the radiances, it is desired to retrieve atmospheric, pressure, temperature, or trace gas concentrations, medical tomography.

For example, in medical imaging, if the exact properties of some internal organ were known, then on doing a scan, i.e., targeting that area with radiation or ultrasound, the resultant reflection/ attenuation map would be known. That would be the forward problem. But it is nearly always the properties of the internal organ that we are trying to find, and ideally without invasive surgery. Thus, an inverse problem needs to be solved.

In geophysics, inverse problems require an understanding of the "forward process" that relates the model to its geophysical response. They also require knowledge of the statistical reliability of the observed data. Aspects that must be considered in inverse problems include the formulation and parameterization of the problem, the existence, uniqueness and resolution of solutions, strategies for dealing with over-determined and under-determined model parameters, and strategies for introducing independent constraints into the solutions (Ferguson, 2005).

Forward Theory: This is the (mathematical) process of predicting data based on some physical or mathematical model with a given set of model parameters (and perhaps some other appropriate information, such as geometry, etc.). As an example, consider a two-way vertical travel time t of a seismic wave through M, *layers* of thickness h_i and velocity v_i.

Then t is given by: $t = 2\sum_{i=1}^{M} \frac{h_i}{v_i}$

The forward problem consists of predicting data (travel time) based on a (mathematical) model of how seismic waves travel.

Suppose that for some reason thickness was known for each layer (perhaps from drilling). Then only the M velocities would be considered model parameters. One would obtain a particular travel time t for each set of model parameters one chooses. As an example, one might invert the travel time t above to determine the layer velocities. Note that one needs to know the (mathematical) model relating travel time to layer thickness and velocity information. Inverse theory should not be expected to provide the model itself.

In addition, the model is the (mathematical) relationship between model parameters (and other auxiliary information, such as the layer thickness information in the previous example) and the data. It may be linear or nonlinear, etc. The model parameters are the numerical quantities, or unknowns, that one is attempting to estimate. The choice of model parameters is usually problem dependent, and quite often arbitrary. For example, in the case of travel times cited earlier, layer thickness is not considered a model parameter, while layer velocity is. There is nothing sacred about these choices. Data are simply the observations or measurements one makes in an attempt to constrain the solution of some problem of interest. Travel time in the example above is an example of data.

The transformation from data to model parameters is a result of the interaction of a physical system, e.g., the Earth, the gravity etc. Geophysics uses inverse methods to analyse the propagation of seismic waves through the Earth's crust and around its surface. There are two main uses here: earthquake analysis and oil/gas prospecting (Belishev & Blagovestchenskii, 1999).

- Vibration pulses are measured by arrays of geophones on the surface. These arrays are quite dense (many in a small area) for prospecting where the objective is to map a small sub-surface region with high spatial resolution, and very sparse for earthquake monitoring where the objective is to cover the whole Earth.

- In both cases models of seismic wave propagation are used to interpret the data, but the thing to be established is different in each case:
  - in prospecting the source of pulse is known and the inverse method is used to determine the structure of the sub-surface rock formations,
  - in earthquake monitoring the structure of the earth is known from a huge database of previous earthquakes, large and small, and the inverse method is used to determine the location and size of the current earthquake.

In the above two cases the problem is made easier by repetition (by successive explosions for prospecting and by use of many years of past earthquake data).

This lecture therefore elaborates on the application and the development of mathematical techniques for reconstructing a pressure pulse at its source from measurements made remotely from an event that has taken place along a pipeline, so as to detect, locate and predict the possible cause. This was achieved by the two techniques of digital filtering and inverse techniques earlier discussed. The experimental validation of the mathematical techniques is discussed and guidelines for practical implementation of impact damage detection systems based on the methods were developed and proposed.

3.0 Methodology

3.1 Event Location

Locating an event on a pipeline requires the use of two sensors on opposite sides of the event. The location of an event on a pipeline was carried out by considering two situations, with and without gas flowing through the pipe. With gas not flowing through the pipe, the calculations are quite straight forward. But with flowing gas, it becomes a bit more complex and requires the pulse propagation velocity to be calculated in both directions of the propagating pulse.

3.1.1. Location of an event on a pipeline

The location of an event such as impact or explosion along pipelines can be determined from knowledge of the pulse arrival times and sensor positions. Given a pipeline with three pressure sensors denoted by 1, 2 and 3 at distances $x_{1,}$ x_2 and x_3 from some datum. An impulsive event occurs at some unknown location and the pulse generated is recorded by the three sensors, arriving at times $t_{1,}$ t_2 and t_3 respectively. Clearly, if the sensors are spaced at approximately equal intervals the event will be located between the first two arrivals; between sensors 1 and 2 in this case.

3.2 Event Reconstruction by Digital Filter

The digital filtering technique developed used the theory of digital filtering in communications to remove distortion in long telephone links.

3.2.1. Digital filtering theoretical formulation

One of the basic elements of Digital Signal Processing (DSP) is the action of one-time domain signal on another by convolution. Convolution is a formal mathematical operation, just as multiplication, addition and integration. Basically, addition takes two numbers and produces a third number while convolution takes two signals and produces a third signal. Supposing an input signal, x[n], enters a linear system with an impulse response, h[n], resulting in an output signal, y[n]. In equation from this can be written as;

$$x[n] * h[n] = y[n] \tag{1}$$

This is to say, the input signal convolved with the impulse response is equal to the output signal. Where $*$ represent the convolution operator.

Generally, the objective of deconvolution is to find the solution of a convolution equation of the form:

$$f_i = h * f_o \quad (2)$$

where, f_i is some recorded signal, f_o is the signal to be recovered, which has been convolved with some other signal h before it was recorded, and * is the convolution operator as mentioned earlier.

The function h might represent the transfer function of an instrument or a driving force that was applied to a physical system. If it is possible to know h, or at least know the form of h, then deterministic deconvolution can be performed on the signal. However, if h is not known in advance, then an estimate of it is required. This is most often done using methods of statistical estimation (McLachlan, 1964). In physical measurements, the situation is usually closer to

$$f_i = h * f_o + \varepsilon \quad (3)$$

Where, ε is noise that has entered the recorded signal. If it is assumed that a noisy signal or image is noiseless when trying to make a statistical estimate of h , the estimate will be incorrect, and so the estimate of f_o will also be incorrect. The lower the signal to noise ratio, the worse the estimate of the deconvolved signal will be. However, if it is possible to have some knowledge of the frequencies of the noise in the signal, it is possible to improve the estimate of f_o through filtering. Although signals are always delayed during the passage through a filter, it is usually of no significance. The signal delay can be different for different frequencies (McLachlan, 1964), which mean that signals consisting of different frequency components suffer delay or time distortion.

3.2.2. Pulse reconstruction by deconvolution filter

During the propagation of the pulse along the pipeline it gets distorted in various unknown ways before getting to the sensors where it is measured. This may be considered as the action of a filter. In DSP terms, this can be related to equation 2 as:

$$f_2(t) = h_k(t) * f_3(t) \qquad (4)$$

Where, f_2 is the measured pulse at sensor 2, f_3, is the measured pulse at sensor 3, f_k, is the required digital filter kernel. All these are discrete functions in the time domain, representing the true functions of time at a suitable sampling rate. If h_k is known, then the original pulse at the event, $f^{(E)}$ can be reconstructed from the measured pulse signal f_2. This filter function h_k is obtained by the deconvolution of f_2 and f_3.

This is actually difficult to do in the time domain, but fortunately very easy in the frequency domain (Rayleigh, 1945). It is another foundation of digital signal processing that convolution in the time domain is equivalent to multiplication in the frequency domain, so $f_2 = h_k * f_3$ is the same as $F_2 = H_k \times F_3$, using the usual convention that an upper-case function represents the Fourier transform (DFT) of the equivalent lower case time domain function. Then the deconvolution filter function in the frequency domain is simply obtained by the division $H_k = F_2 / F_3$, which is then transformed into a time domain function h_k using the inverse discrete Fourier transform. H_k is the frequency

spectrum of the desired filter kernel, F_2 and F_3 are the frequency spectra of the measured pulses at sensors 2 and 3, respectively.
In situations where the propagation path affects the phase as well as the magnitude of the propagating pulse signal, some manipulations of the time domain function will be required so as to take into account the nature of the discrete Fourier transform which covers the frequency range $\pm$ the Nyquist frequency and so transforms into an aliased time domain function. Extracting the deconvolution filter function under these conditions is described fully in Rayleigh (1945). The pulse reconstruction was implemented in an m-code program, using the FFT and convolution functions available within MATLAB.

3.3 Event Reconstruction by Inverse Method

Inverse problems may be described as problems where the solutions are known, but not the causes. Alternatively, where the results, or consequences of the problem are known but not what must have actually caused it. For example, if x streams join to form a river, and it is known that y factories are adding known amounts of pollutant into the streams, then it is possible to calculate the resultant pollutant in the river. This would be the forward problem. A more likely problem however is that only the pollutant in the river is known, and it is required to establish which factory is adding what into which stream. This is the inverse problem.

3.3.1 Inverse method theoretical formulation

Inverse theory is inherently mathematical and as such does have its limitations. It is best suited to estimating the numerical values of model parameters for some known or assumed mathematical models. It is good for extracting the model parameters that best fit the data. The basic theory of inverse methods is fully explained by Menke (Balanis, 1989). Briefly, it can be summarised as follows. Suppose in the course of an experiment *N* measurements are obtained, these numbers may be considered as the elements of the vector **d** of length *N.* Also, the model parameters can be represented as the elements of the vector **m**, of length *M.*

Thus, we can write,

data: $\mathbf{d} = [d_1, d_2, d_3 ..., d_N]^T$ (5)

model parameters:

$\mathbf{m} = [m_1, m_2, m_3, ..., m_M]^T$ (6)

In the statement of an inverse problem there is a relationship between the model parameters and the data. This relationship is referred to as the model. The model usually takes the form of one or more formulas that the model parameters and data are anticipated to follow. For example, in trying to determine the resistance of a wire by measuring its voltage and current, there will be two data sets, voltage $\mathbf{d}_1$ and current $\mathbf{d}_2$ respectively, and one unknown model parameter, resistance (m_1). The model statement would be the resistance times the current equals voltage, which can be represented compactly by vector equation (7),

$\mathbf{d}_1 = \mathbf{d}_2 m_1$ (7)

In more realistic situations the relationship between the data and model parameter is more complicated. In the most general case, the data and model parameters are related by one or more implicit equation such as in equation (5.4),

$$l_1(\mathbf{d}, \mathbf{m}) = 0$$

$$l_2(\mathbf{d}, \mathbf{m}) = \qquad (8)$$

$$l_3(\mathbf{d}, \mathbf{m}) = 0$$

where, N is the number of equations.
In the above problem concerning the measurements of the resistance, $N = 1$ and $d_2 \ m_1 = d_1$ would constitute one equation of the form

$$l_1(\mathbf{d}, \mathbf{m}) = 0 \qquad (9)$$

These implicit equations, which can be compactly written as the vector equation **l (d, m) = 0**, summarize what is known about how the measured data and the unknown model parameter are related. The goal of inverse theory, therefore, is to solve, or invert, these equations for the model parameters. For a given application there is no guarantee that equation (9) contains sufficient information to specify the model parameters uniquely. Inverse methods provide the means of dealing with this type of problem.

3.4. Experimental Test Rig

Figure 2 shows the test rig that was developed to validate the theories of event location and reconstruction. It consists of an air-filled pipe along which pressure pulses propagate, a pressure pulse generator and an instrumentation system to capture and record the propagation of the pressure pulses.

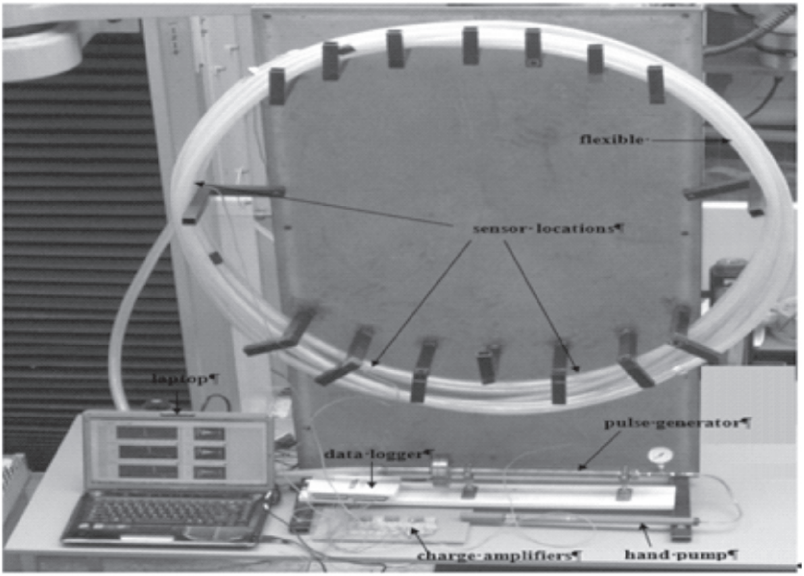

Figure 2: Experimental test rig showing the various components of the rig (Olugboji, 2012).

3.4.1 Air-filled pipe

The air-filled pipe is a smooth bore flexible hose pipe of internal diameter of 19 mm coiled on a circular framework at a diameter approximately 1.5 m, having established that at this curvature the pressure pulses would propagate through it unimpeded, as a waveguide.

(http://www.pulsation-dampeners.com). That is, the radius of curvature should be greater than ten times the diameter of pipe. An advantage in this arrangement is that even though the pressure measurement sensors attached to the pipe of the test rig are located at long distances along the hose pipe they are still physically close together for convenience of monitoring using a single data logger without the need for long cables.

3.4.2. Modification of experimental test rig

Modification of the developed test rig as shown in Figure 3 became necessary as some of the experiments to involve the use of both static and flowing air. The experiments with static air were undertaken with the test rig shown in Figure 2, as the generated pressure pulse enters from one end of the pipe. With flowing air, the experiments become a bit complex as the ends of the pipe must be unrestricted to allow the flow of air, and so the pressure pulse must be injected at an intermediate point. This modification was also necessary to verify the theory of event location, which requires determination of the time delay between arrivals at two sensors on sides of the event (i.e. the position of the pulse injection).

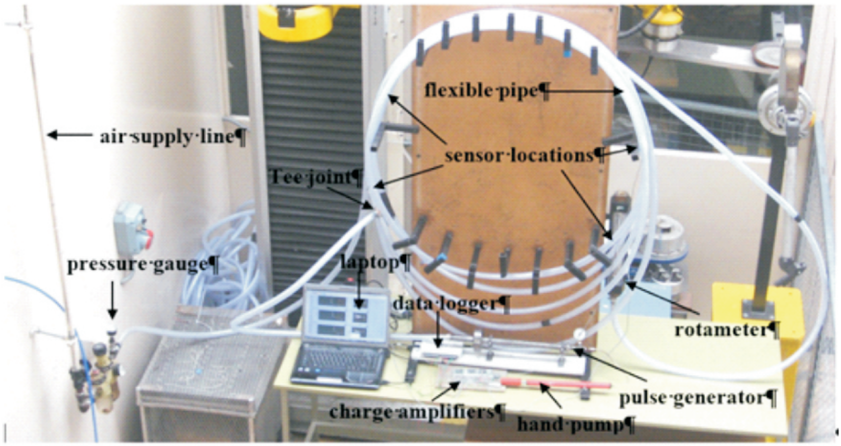

Figure 3: Modified test rig (Olugboji, 2012).

3.5. Calculation of Flow Velocity along Pipe

As the air flowed through the pipe it expanded as the pressure dropped from the measured inlet pressure to atmospheric pressure at the exhaust, and so its velocity increased steadily. It was necessary to estimate the velocity throughout the pipe in order to use the event location theory. In order to calculate this velocity distribution two assumptions were made; linear pressure drop along the pipe and isothermal flow.

The first assumption was made for ease of analysis and because the difference made by a more realistic assumption such as exponential pressure drop would make very little difference to the calculated results. The second is based on the flow regime. For a flow velocity of 395 m/s measured at exhaust in a 19 mm diameter pipe, Reynold's number for air at normal temperature and pressure is in the region of 50,000 and so is turbulent. This will promote good convective heat transfer and limit the temperature fall due to the expansion.

3.6 Data Acquisition

Data acquisition involves sampling analog signals from sensors, and converting them into digital values that can be displayed, analysed, manipulated, and stored by a computer. The data acquisition is performed using an analog to digital (A/D or ATD) converter. At the initial stage of the experiments a TDS 2014 digital oscilloscope was used for data recording of the pressure pulse signals and the data stored on a computer via an RS232 cable using WSTRO software. The limitation of the digital oscilloscope was the short duration data capture which was limited to 1000 data points. Nevertheless, these data were then analysed in Excel and used to define the specification for a more suitable data acquisition system. Based on this analysis a data acquisition system comprising a laptop computer and data acquisition module communicating via USB was selected. This comprised a 6215 USB data acquisition device from National Instruments, which has 16 analog input channels with 16-bit resolution and a 250 kHz single-channel sampling rate, and a laptop computer running LabView software. LabVIEW is a graphical programming language that is particularly well suited for use with National Instruments data acquisition devices.

3.7 Pipeline Detection System

Figure 4 shows a schematic representation of the communication set up. Each monitoring unit (S1 – S3) on the pipeline is tagged for easy identification of the sensors transmitting to the central processing unit. The detection system involves two stages:

- Stage one - involves the continuous monitoring of the sensor signal in order to detect and record the pulses that come very occasionally, and then transmit them to the central processing unit for analysis.
- Stage two - involves the processing of the received data at the central processing unit to determine the causing event, reconstruct the pulse and analyse the probable damage caused.

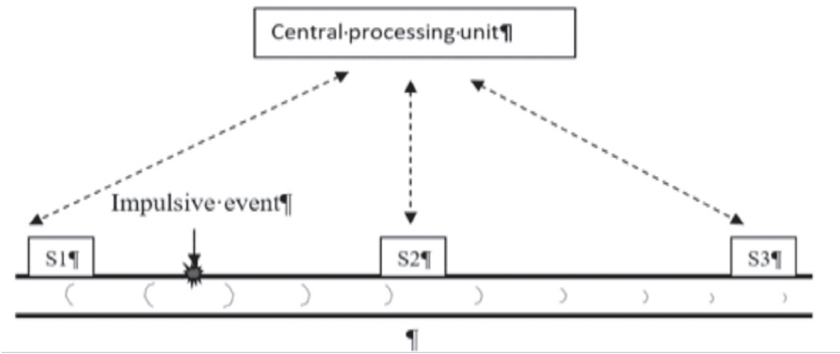

Figure 4: Pipeline communication set up (Olugboji, 2012).

Figure 5 shows the systems flow diagram for the second stage of detection. The first two arrival times will be determined (as there could be a lot of arrivals from one big event). From one of these and its neighbour the pulse propagation velocity will be calculated and from this the event location will be calculated using the first two arrival times. If less than three monitors have been triggered, this process cannot be followed, but it is a sign that the event was not very large. If two monitoring units on both sides of the event have been triggered this can be done from both directions, which will give two independent reconstructions and so provide more information on the reliability of the reconstructed pulse shape and magnitude. Then the reconstructed pulse will be analysed automatically to determine the type and magnitude of the event that caused it, and so to estimate the damage that is likely to have occurred. Finally, it will make a decision on whether to raise an alarm (dangerous condition detected), pass on the problem to an operator (doubtful condition) or do nothing (safe condition).

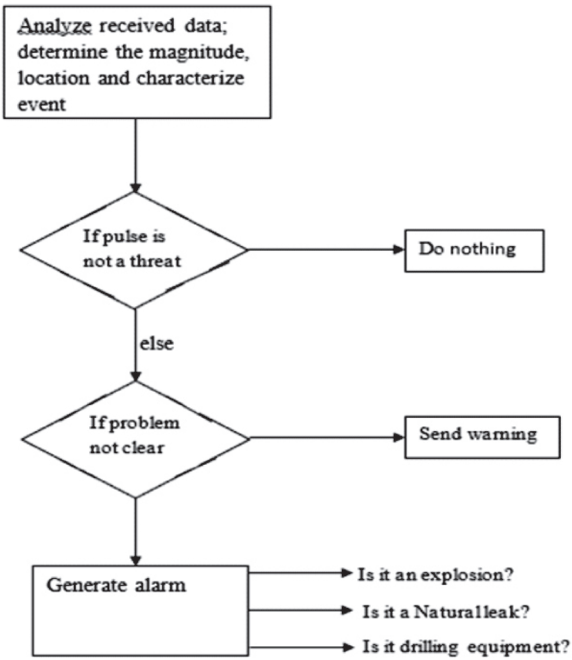

Figure 5: Flow chart of the second stage of the monitoring system (Olugboji, 2012).

By this means an identified and located event is immediately communicated to a pipeline operator for appropriate actions to be taken. The information will contain the estimate of the calculated magnitude, location of the event and its possible cause.

3.8. Hardware Composition

The monitoring unit consists of six components; a sensor, instrument amplifier, microcontroller, radio transmitter, a GPS module and the power supply. Figure 6 shows a schematic representation of the monitoring unit. The sensor and instrument amplifier measure the pressure pulses, which are detected and recorded by the microcontroller and then transmitted to a main station by the radio transmitter. The GPS module is used to provide the highly accurate time synchronisation required for measuring delay between sensor locations. The power supply provides power for the system.

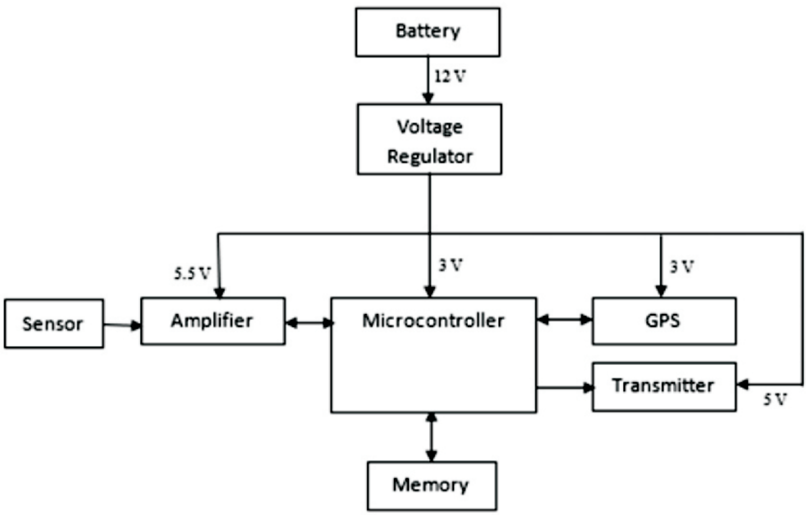

Figure 6: Block diagram for monitoring unit (Olugboji, 2012)

4.0 Results and Discussion

4.1 Event reconstruction in static air

Figure 7 shows the pressure pulse signals recorded at the three sensors and subsequently moderated. The analysis of the data was done off-line using a program written and developed in the MATLAB m-code programming language. The pulse measurements at sensors 2 and 3 are denoted f_2 and f_3 respectively. These were extracted from the long data stream by testing for the first threshold crossing and saving the next 10 ms of data (830 data points, which was established to be a sufficient time for the pulse to decay to a low level). These are typical of fifteen repeat tests performed.

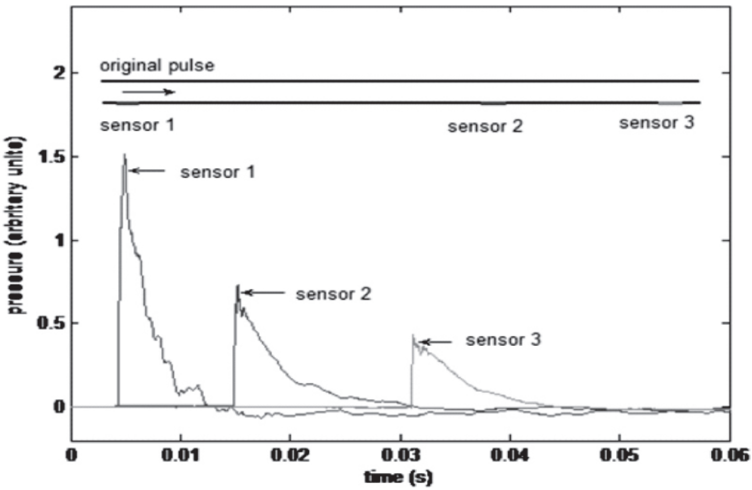

Figure 7: Typical pressure pulse measured at three sensors (without air flow) (Olugboji, 2012)

4.2 Event reconstruction by digital filtering

To test the effectiveness of the event reconstruction by digital filtering, the extracted pulse measurements f_2 and f_3 were used.

The discrete Fourier transform of the pulses were calculated using the fast Fourier transform (FFT) function in MATLAB, from which the discrete deconvolution function *h* was calculated. Figure 8 shows a representative measurement of the pulse functions f_2 and f_3 from which the deconvolution function *h* was obtained, truncated at 100 data points and padded to 830 with zeros. As can be seen, there is no apparent relationship between the measured pulse at sensors 2 and 3 and the deconvolution function obtained from them. The filter could not have been obtained except by means of the transformation into the frequency domain.

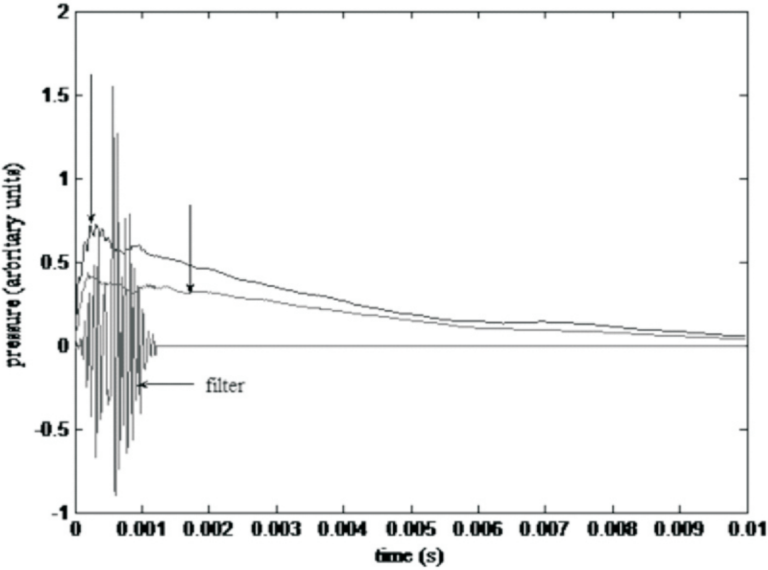

Figure 8: Filter function obtained from pulse measurements at sensors 2 and 3 (Olugboji, 2012)

The pulse function at the position of sensor 1 was then reconstructed using the convolution $f_1(R) = h * f_2$ and scaled according to the different distances between the sensors. The reconstructed pulse is shown in Figure 10, compared with the true function f_1 measured by the sensor.

The shape of the reconstructed pulse is broadly similar, but is distorted by high frequency noise at the start of the pulse. These may be attributed to the discrepancy in the calculated deconvolution filter function which is a finite length approximation to the true filter, the noise on the signals f_2 and f_3, and the neglection of the non-linearities inherent in the propagation. The problem of the filter can be reduced to some extent by increasing its length, though the improvement quickly reduces with further lengthening and is inherent in the use of the digital filters. The noise problem is also inevitable, particularly in a pipeline with flowing gas and when the sensors are well separated to keep down costs, making the signal at the most remote sensor fairly small. This noise was easily removed by means of a low pass filter. A linear phase Blackman window filter of 100 points was found to work well as shown in Figure 9.

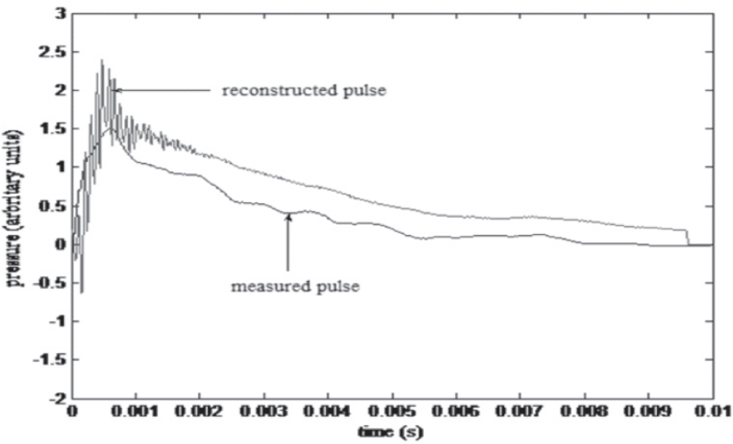

Figure 9: Typical Reconstructed pulse at sensor 1 using the deconvolution filter method (Olugboji, 2012)

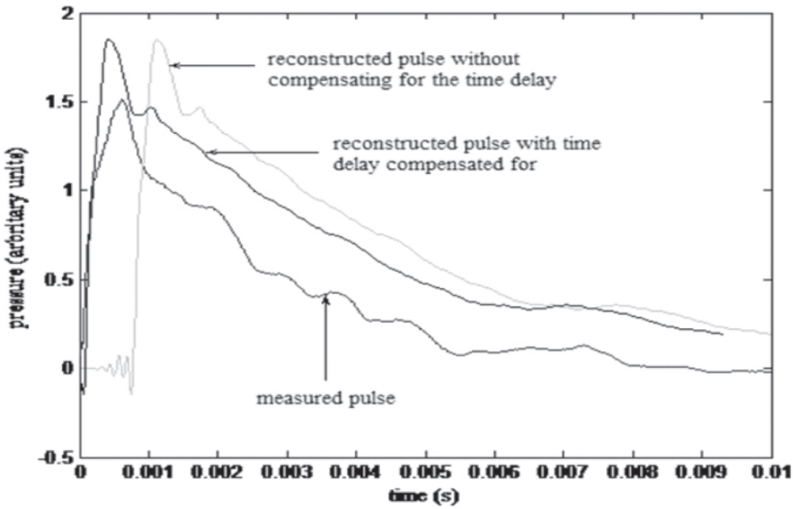

Figure 10: Reconstructed pulse signal at sensor 1 with low pass filtering (Olugboji, 2012)

The form of the final reconstructed pulse shown in Figure 10 is a fair approximation to the true measured pulse at sensor 1. There are two main discrepancies: the peak magnitude is overestimated by about 17 %, and the pulse shape is different in detail, most notably the introduction of an anomalous second peak. The delay which can be seen in the reconstructed pulse before it was compensated for is a normal effect of filtering and as such, is of no significance. This is evident from the reconstructed pulse when the delay was compensated for; moreover, the purpose of the reconstruction is to determine the pulse size and shape which carries the information required about cause of the event. Also, the small oscillations before the rise are an artefact of the Blackman window used in the low pass filter. These results are for one out of the fifteen repeat tests and are typical. The range of magnitude overestimation was between 17 % and 23 % compared to the measured true pulse at sensor 1.

3.3 Event Reconstruction by the Inverse Method

To investigate the use of inverse methods in the reconstruction of the pulse at the event site, the event to be reconstructed was similarly taken as the pulse as it passes through the first sensor. As before, the pressure pulse data at the first sensor was recorded but not used in the subsequent calculations. The same pressure pulse measurements obtained from sensors 2 and 3, f_2 and f_3, in the previous section were used and later transformed into the frequency domain using the fast Fourier transform (FFT) function in MATLAB to obtain their respective Fourier spectra. Based on the Fourier spectrum of the measured pressure pulses, a solution to the least square inverse problem was obtained to determine the estimate of the required model parameter m_{LS} following the procedures outlined in section 3.3.1. This value of the estimated model parameter was then used to calculate the Fourier spectrum of the pressure pulse to be reconstructed. The exponential of the log Fourier spectrum was then taken and transformed into the time domain using the inverse fast Fourier transform (IFFT) function in MATLAB. The reconstructed pulse is shown in Figure 11, together with the original measured pressure pulse at sensor 1.

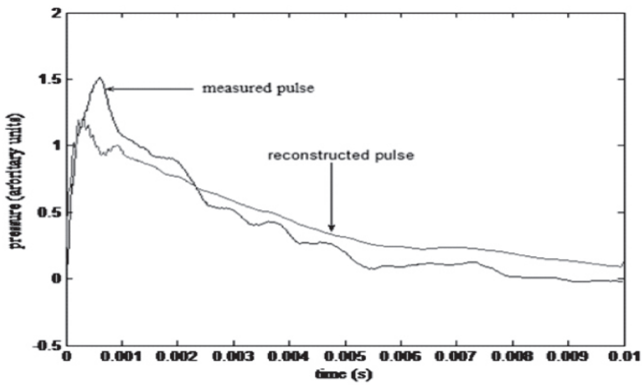

Figure 11: Reconstructed pulse at sensor 1 by inverse method (Olugboji, 2012)

From Figure 11 the shapes of the reconstructed and measured original pulse at sensor 1 agree quite well. The magnitude of the reconstructed pulse in this case can be seen to have underestimated the measured pulse by 20 %. This result is typical of the fifteen repeat tests, in which the underestimate ranged between 20 % and 22 %.

4.4 Event Location and Reconstruction with Static Air

The experiments in this section were done using the modified test rig illustrated in Figure 3. The simulation here is more realistic since the event location is first determined from arrivals at sensors 1 and 3, and then the pulse is reconstructed from the sensor 2 and 3 signals using this calculated location. The tests validate the event location technique, the digital filtering, and inverse methods. The pulse signals at the four sensors were measured and recorded at a sampling rate of 60 kHz. As before, the signal from sensor 2 was recorded for comparison with the reconstructed pulse, but was not used in that reconstruction.

Figure 12 shows a typical pressure pulse from one of the test results obtained at the four sensors located along the pipe of the modified rig. The sensor 2 was located as close as possible to the tee connector, and hence to the point of arrival of the pulse in the main pipe which defines the event location because this is the place where the pulse enters the main pipe and sets off in both directions, arriving first at sensor 2, followed by sensor 3, then sensor 1 and finally sensor 4. These times of arrival are associated with the distances of the sensors from the position where the generated pressure pulse enters the pipe. Sensor 2 is the best possible independent measurement of the event (the pulse as it enters the main pipe) because it is close to it and there will be little distortion/attenuation before the pulse propagating from the tee reaches it. The other three sensors are spread out along the pipe to locate and reconstruct the event.

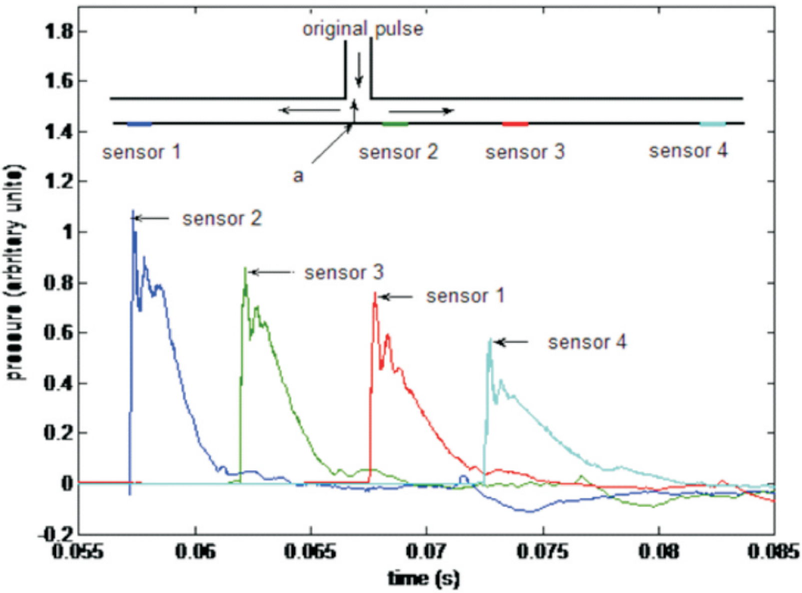

Figure 12: Typical pressure pulse measured at all four sensors of modified rig (without air flow) (Olugboji, 2012)

4.6 Event Location in Static Air

In this section, calculation of the location of an event on the pipe of the test rig was performed using a programme written in the MATLAB m-code language. The estimate of the location of the real event, that is, the point where the original pressure pulse enters the main pipe was determined from the measured data at sensors 1 and 3, and later compensated for the small offset to sensor 2. This compensation is necessary because the true source of the pulses is the tee joint and this should have formed the basis of all the calculations about the location of the event. But the measurement at sensor 2 was used for the purpose of comparing the results of pulse reconstruction, and hence the need to compensate for the small difference.

The computed estimates in the location of the event for the 75 measurements taken ranged between 1.770 m and 1.772 m, a scatter of just 2 mm, as against the actual measured event location of 1.760 m. The small discrepancy may be accounted for by the assumption of uniform velocity between the sensors in the calculation.

4.7 Event Location and Reconstruction with Flowing Air

The previous experiments discussed in **section 3.4.2** using the modified test rig were conducted on static air, but this is not representative of real pipeline applications as the gas in the pipeline is expected to be flowing. The tests in this section address this by investigating the effects of air flow velocity on event location and reconstruction. A compressed air supply with pressure control valve was attached to one end of the pipe as shown in Figure 3. This was used to control the pressure of the air at the inlet, and hence the flow rate through the pipe. The two cases of measurements of air flow velocity through the pipe considered are:

- A pressure drop of 0.1 bar along the pipe, giving a computed mean flow velocity between sensors 3 and 4 of 26 m/s as calculated using the methods in Section 6.11
- A pressure drop of 0.2 bar along the pipe, giving a mean flow velocity between sensors 3 and 4 of 34 m/s.

Figure 13 shows a typical result for the pressure pulse measurements obtained with the pressure pulse entering the main pipe between sensors 1 and 2 and the directions of air flow and pulse propagation. The slight differences may be attributed to the assumption that the pressure drop along the pipe and hence the change in air flow velocity, varies linearly with distance along the pipe.

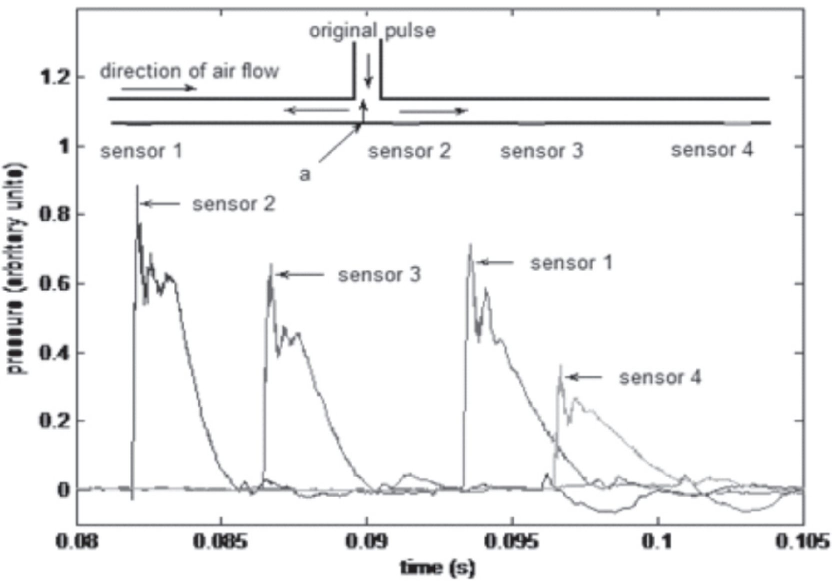

Figure 13: Typical pressure pulse measurements at all four sensors with pressure pulse entering between sensors 1 and 2 along the pipe with flowing air (Olugboji, 2012)

4.8. Event reconstruction by deconvolution and inverse methods with flowing air

Figures 14 and 15 show the form of the reconstructed pulses obtained using the digital filtering and inverse methods of event reconstruction, respectively. These reconstructions are typical of a quantity of measurements under the conditions of cases 1 and 2.

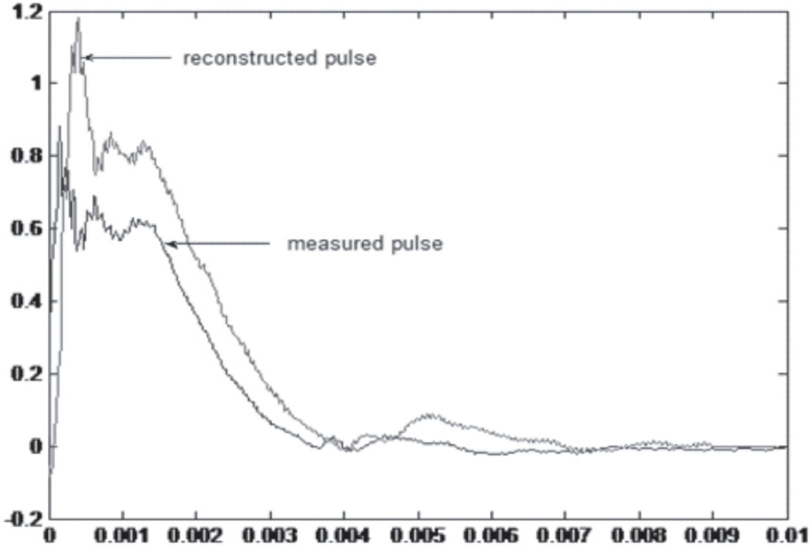

Figure 14: Reconstructed pulse using digital filter method (with air flow) (Olugboji, 2010)

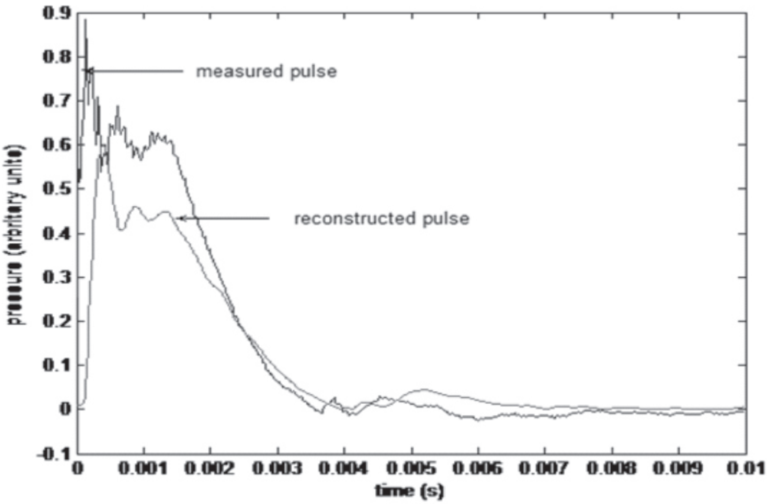

Figure 15: Reconstructed pulse using inverse method (with air flow) (Olugboji, 2012)

From Figures 14 and 15 it is seen that the pulse reconstruction using the digital filtering method gave a better representation of the true measured pulse at sensor 2 compared with that obtained using the inverse method. The higher quality is due to the high frequency components which are present in the digital filter reconstruction, but absent from the inverse method. Nevertheless, the inverse method reconstruction is still of value because it gives an underestimate of the pulse size in the range 30-35 %, compared to the consistent overestimate of 18-23 % made by the digital deconvolution filter method.

4.9 Summary on the Two Developed Techniques

Methods of reconstructing the form of a pressure pulse at the site of the event causing it were developed using digital filtering and inverse techniques. These were tested initially using computer modelled pulse propagation, and subsequently validated experimentally in both static and flowing air. It was found that the digital filter (deconvolution) methods-based technique gave generally better reconstruction of the event, but consistently overestimated its magnitude. The inverse technique also reconstructed the general shape of the pulse quite well, but with less good higher frequency components. However, it consistently underestimated the pulse magnitude, and so the two techniques might be used together in a practical application of this work.

Also, it was discovered that the temperature change within the pulses due to the pressure rise accounted for the high measured pulse velocities that were observed. The effect of noise addition on the measured pressure pulses showed that for moderate noise levels up to the level of the pulse magnitude, noise had very little effect on the calculated location of the event. The quality of

reconstruction was found to be inversely proportional to the level of noise, with good reconstruction achievable up to signal to noise ratio up 0.9. The results obtained showed their suitability to reconstruct the form of pressure pulse propagating along a gas filled pipeline from its source using both static and flowing air.
An outline design for a practical monitor system based on this work has been developed. The principle of operation is set out and the principal components are identified from currently available commercial sources. Based on these components, it was established that the cost of a monitor unit would be small compared with either the budget for new pipeline or the cost of a major leak. Furthermore, the power requirement was established and it was shown that a monitor unit might be powered by a conventional battery for more than a year. From this analysis, it was shown that a monitoring system of the type described could be constructed at a realistic price and used for a realistic time without maintenance, so that commercial exploitation of the work described here is a realistic proposition.

5. 0 Other Contributions to Knowledge

5.1 Sampled published works

5.1.1 Petroleum pipeline monitoring using an internet of things (IoT) platform (Aba, *et al.*, 2021).

In this study, the use of the internet of things (IoT) analytics platform service was used to mimic real-time pipeline monitoring and determine the damage location on a pipeline. Based on the principle of vibration in pipes, pressure pulses are used for pipeline monitoring in this study. The principle of time delay between pulse arrivals at sensor positions is also adopted in this study. An Arduino and a Wi-Fi module were combined, programmed and used to produce a wireless communication device that communicates with the ThingSpeak internet of things (IoT) analytics platform. A total of five channels were created on the platform to collect data from the five sensors used in the experimental test rig that used wireless communication devices. Signal data was collected once every 15 s and all the channels were updated every 2 min. ThingSpeak provided instant visualizations of data posted by the wireless communication device. Online analysis and processing of the data were performed as it came in.

5.1.2 Problems of Calculating Time Delay between Pulse Arrivals (Olugboji *et al.*, 2015a).

This work compares the performance of four different methods of estimating the time delay between pulse arrivals at the sensors subjected to different attenuation, distortion, and noise levels. The accuracy of the calculated time between the pulse arrivals at the sensors is determined and analyzed for each of the methods based on the ideal attenuation (no change in shape), ideal attenuation with added noise to the pulse signal and ideal attenuation but with distortion. Based on the analysis carried out, it is clear that the cross-correlation method gives the best estimate of the delay in pulse arrival times irrespective of the signal to noise ratio and so is the preferred technique used in the remainder of this research.

5.1.3. Event Reconstruction by Inverse Methods (Olugboji *et al.*, 2014a).

This work deals with an inversion technique that was developed to reconstruct a pulse after it has propagated along a pipe; a complex pulse that is progressively distorted. The technique developed makes use of the theory of inverse problems.

5.1.4. Event Reconstruction by Digital Filtering (Olugboji *et al.*, 2013).

This work deals with a digital filtering technique that was developed to reconstruct a pulse after it has propagated along a pipe; a complex pulse that is progressively distorted. The technique developed makes use of the theory of digital filtering used in communications to remove distortion in long telephone links.

5.1.5. Development of a Steam Powered Incubator with Solar Supported System (Rafiu *et al*., 2021).

This research work deals with the development of an incubator powered by steam generated from boiled water. The inner components and micro – controller are powered by solar system. The performance evaluation of the developed system was 85 %.

5.1.6. Design, Construction and Testing of a Poultry Feed Pellet Machine (Olugboji *et al*., 2015).

With increasing emphasis on self-employment as a means of improving the standard of living, there is consequently a diversification of human occupation notably in the agro-allied industries. Fish-feed machines are therefore important for the production of pelletized feed. The work involved the design, construction and testing of a cheap, electrically operated feed pellet machine with locally available materials. The operation capacity of the machine was found to be 50 kg/hr.

5.1.7. Design and Fabrication of Rice De-Stoning Machine (Olugboji & Jiya, 2014b).

This work aims at meeting the ever increasing demands of quality rice, avoiding losses and improving the income of local farmers. Mild steel was used in the construction of the machine. Standard equations were used to determine the dimension of the parts. The machine has a capacity of 47.39 kg/hr and an efficiency of 82.47 %.

5.2. Ongoing projects

(i) The development of smart ventilator for Covid-19 response. An Automated Smart Respirator that can check the pulse of patient and select for the patient the best breathing mode for the patient, either fast mode, slow mode, or regular breathing mode.

(ii) The Use of Maggot as alternative to egg incubation media. This involves culturing of maggots and using them to provide the heat required for incubation.

6.0 Conclusion and Recommendations

6.1 Conclusion

Methods of reconstructing the form of a pressure pulse at the site of the event causing it were developed using digital filtering and inverse techniques. These were tested initially using computer modelled pulse propagation, and subsequently validated experimentally in both static and flowing air. It was found that the digital filter (deconvolution) methods-based technique gave generally better reconstruction of the event, but consistently overestimated its magnitude. On the other hand, the inverse technique also reconstructed the general shape of the pulse quite well, but consistently underestimated the pulse magnitude; hence, the two techniques might be used simultaneously. Besides, the results obtained showed their suitability to reconstruct the form of pressure pulse propagating along a gas filled pipeline from its source using both static and flowing air.

An outline design for a practical monitor system based on this work has been developed. The principle of operation is set out and the principal components were identified from currently available commercial sources. Based on these components, it was established that the cost of a monitor unit would be small compared with either the budget for new pipeline or the cost of a major leak. Furthermore, the power requirements were established and it was shown that a monitor unit might be powered by a conventional battery for more than a year.

From the foregoing, it has been established that a monitoring system of the type described could be developed at a realistic price and used for a realistic time without maintenance, so that commercial exploitation of the work is a realistic proposition.

6.2 Recommendation

From the design guide developed for the practical monitoring system, it can be inferred that the cost of a monitor unit would be small compared with either the budget for new pipeline or the cost of a major leak. Hence, making the practical application of the current work at industrial scale is viable and cost effective. However, successful application of a potential solution depends on the support of relevant government policies and stakeholders. Therefore, it is recommended that joint investigation and application of the proposed approach with relevant government agencies be explored so as to assist in solving the problems of pipeline vandalization in our nation and wastage of water due to leakages/damages to water pipelines. In addition, irrespective of the problems and challenges we face in life, either personal, social or economic, we can work from the problem to solution as long as the will backed by relevant work is in place.

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To my lovely boys, Folorunsho Obafemi Joseph and Damilare David, I say a big thank you for understanding with me throughout my PhD programme. May God almighty make you greater than what I am today.

Finally, to this wonderful audience, without you here today, my inaugural lecture would have been of no value. Thank You All and may God almighty grant you all journey mercies back to your respective homes.

As a final note "in the womb of a problem lies the birthing of its solution", hence, never give up in your quest to overcome life's challenges or problems.

Mr. Vice-Chancellor, Sir, I rest my case.

References

Aba, E. N., **Olugboji, O. A.**, Nasir, A., Olutoye, M. A., & Adedipe, O. (2021). Petroleum Pipeline Monitoring Using an Internet of Things (IoT) Platform. SN *Applied Sciences, Springer Nature Journal*, 3 (180), pp, 442-451.

Akintola, T. (2006). Pipeline Vandalization and Oil Scooping in the Niger Delta and others in Nigeria. *<http:www.african conservation.org/dcforum/D2g/ll.html>.*

Balanis, C.A. (1989). *Advanced Engineering Electromagnetics*. John Wiley and Sons.

Belishev, M.I., Blagovestchenskii, A.S. (1999). *Dynamic Inverse Problems in Wave Propagation* (Russian). St. Petersburg University Press.

Bertero, M., Bindi, D., Boccacci, P., Cattaneo, M., Eva, C., & Lanza, V. (1997). Application of the Projected Landweber Method to the Estimation of the Source Time Function in Seismology. *Inverse Problems*, 13, 465–486.

Bray, D.E., & Stanley, R.K. (1989). *Non-destructive Evaluation: A Tool for Design, Manufacturing, and Service*. McGraw-Hill College, McGraw-Hill Series in Mechanical Engineering.

Carlson B. N. (1993). Selection and Use of Pipeline Leak Detection Methods for Liability Management into the 21st Century, Pipeline Infrastructure II, *Proceedings of the International Conference of the American Society of Chemical Engineers, ASCE*.

Cheng, P.C. (2006). *The Contrast Formation in Optical Microscopy. Handbook of Biological Confocal Microscopy* (Pawley JB, ed.) (3rd ed.). Berlin: Springer.

Crump, N. D. (1974). A Kalman Filter Approach to the Deconvolution of Seismic Signals. *Geophysics,* 39 (1), 1-13.

Doctor, R. H., & Dunker, N. A. (1995). Field Evaluation of a Fiber Optic Intrusion Detection System—FOIDS". GRI Final Report GRI-95/0077.

Ferguson, I. J. (2005). *Theory and Application of Geophysical Inversion Methods.* Department of Geological Sciences, University of Manitoba.

Francini, R. B., Leis, B. N., Narendran, V.K., & Stulen, F. B. (1997). Real-Time Monitoring to Detect Third-Party Damage: Phase II. GRI Final Report GRI-97/0141.

Fung, K. B. (2002). *Application of Remote Sensing Data for Monitoring of Gas Pipeline Right-of-Way.* www.semantic scholar.org/paper/Application.

Gary, L. B., & Alfred, E.C. (2003). Realtime Monitoring of Pipelines for Third Party Contact. A paper prepared for the United State Department of Energy, National Energy Technology Laboratory, Morgantown, West Virginia, 26507-0880.

Hosokawa, Y., Masuda, T., Ohira, H., & Sasaki, N. (2000). On-line Monitoring System for Detecting Third-Party Damage on Cathodically Protected Pipelines. *Pipeline Technology*, 2, pp, 205-221.

Huebler, J.E. (2002). Detection of Unauthorized Construction Equipment in Pipeline Right of Ways. Presentation given at U. S. Department of Energy, National Energy Technology Center Natural Gas Infrastructure Reliability Industry Forums, Morgantown, W.V.

Idowu, A. M. (2015). Instantaneous Modelling and Reverse Engineering of Data Consistent Prime Models in Seconds. *Procedia Computer Science*, 61, 373 – 380.

Jolly, W. D., Morrrow, T. B., O'Brien, F. F., Spence, H.F., & Svedeman, S. J. (1992). New Methods for Rapid Leak Detection in Offshore Pipelines. Final Report for U.S. Department of the Interior Minerals Management Service, 1-84.

John, L. L., George, M. P., Richard, G. & Patrick, B. (2004). *Coustic Detecting and Locating Gas Pipe Line Infringement,* West Virginia University, Department of Mechanical and Aerospace Engineering, G-70 Engineering Sciences Building, Evansdale Drive Morgantown, WV 26506.

Kulp, T. J., Powers, P. E., & Kennedy, R. (1998). Remote Imaging of Controlled Gas Releases using Active and Passive Infrared Imaging Systems." *Proceedings of Infrared Technology and Applications XXIII*, SPIE, 3061, 269-278.

Leis, B. (2003). Real Time Monitoring to Detect Contact, Product Loss, and Encroachment on Transmission Pipelines," *54th API Pipeline Conference*.

Mahdi Sadri, Seyed M. Shariatipour, Andrew Hunt, Masoud Ahmadinia (2019) Effect of systematic and random flow measurement errors on history matching: a case study on oil and wet gas reservoirs. Journal of Petroleum Exploration and Production Technology. http://doi.org/10.1007/s13202-019-0665-2

McLachlan, N. W. (1947). *Theory and Applications of Mathieu Functions* (reprinted by Dover: New York, 1964).

Nakamachi, K., Uchida, Y., Hosohara, Y., Okada, M., & Nagashim, S. (1992). Damage Detection System by Monitoring Audible Sound in Pipeline and Its Application. *International Conference on Pipeline Reliability*, Alberta, Canada; Calgary.

National Transportation Safety Board Pipeline Accident Report for Texas Eastern Transmission Corporation Natural Gas Pipeline Explosion and Fire (1994). Edison, New Jersey.

Nigeria National Petroleum Corporation, (2005) Annual Statistical Bulletin -11.

Nigeria Pipe Blast Kills over 500. Prensa Latina, December 26, 2006. Nigerian Guardian Newspaper.

O'Haver, T. (2007). *Intro to Signal Processing - Deconvolution*. University of Maryland at College Park

Olugboji, O. A. (2012). Development of an Impact Monitoring System for Petroleum Pipelines. *Au Journal of Technology,* 15(2), 115 – 120.

Olugboji, O. A., & Jiya. J. Y. (2014a). Event Reconstruction by Inverse Methods. *International Journal of Electronics, Mechanical and Mechatronics Engineering*, 4 (3), 791 – 801.

Olugboji, O. A., & Jiya. J. Y. (2014b). Design and Fabrication of Rice De-Stoning Machine. *Food Science and Technology*, 2(1), 1 – 5.

Olugboji, **O.A.,** Abolarin, M.S., Owolewa, M. O., & Ajani, C. K. (2015). Design, Construction and Testing of a Poultry Feed Pellet Machine. *International Journal of Engineering Trends and Technology (IJETT)*, 22 (4), 168 – 172.

Olugboji, O. A., Jiya, J. Y., & Ajani, C. K. (2015a). Problems of Calculating Time Delay Between Pulse Arrivals. *American Journal of Engineering Research (AJER)*, 4, 132 – 142.

Olugboji, O.A., Jiya, J. Y., & Hale, J. M. (2013). Event Reconstruction by Digital Filtering. *Advances in Signal Processing*, 1(3), 48 – 56.

Peacock, K. L., & Treitel, S. (1969). Predictive Deconvolution: Theory and Practice. *Geophysics*, 34 (2), 155-69.

Posakony, G.J., & Hill, V.L. (1992). Assuring the Integrity of Natural Gas Transmission Pipelines. Tropical Report, Gas Research Institute, GRI-91/0366.

Rafiu, O., **Olugboji, O. A.**, Adedipe, O., & Okoro, U. (2021). Development of a Steam Powered Incubator with Solar Supported System, *Conf. Ser.: Earth Environ. Sci.* 730 012028

Rayleigh, J.W.S. (1945). *The Theory of Sound.* Dover Publications.

Rocha, M. S. (1989). Acoustic Monitoring of Pipeline Leaks. Paper # 89-0333, ISA. www.digital.liberary.unit.edu.

Silvia, M. T., & Robinson, E. A. (1979). *Deconvolution of Geophysical Time Series in the Exploration for Oil and Natural Gas*. New York: Elsevier.

Scott, S. L., & Barrufet, M. A. (2003). Worldwide Assessment of Industry Leak Detection Capabilities for Single & Multiphase Pipelines. Project Report Prepared for the Minerals Management Service, OTRC Library Number: 8/03A120, University of Texas, Austin. SWRI Final Report, Project 14.1791 (2003). Evaluation of the Use of Impressed Currents for On-Line Monitoring of Gas Pipeline for PRC International.

Villaverde, A. F., & Banga, J. R. (2014). Reverse Engineering and Identification in Systems Biology: Strategies, Perspectives and Challenges, *Journal of Royal Society Interface* 11:201 30505.

Webster, G. M. (1978). Deconvolution Society of Exploration Geophysics. Geophysics Reprint series; No. 1.

Weil, G.J. (1993). Non-contact, Remote Sensing of Buried Water Pipeline Leaks using Infrared Thermography, Water Resources Planning and Management and Urban Water Resources, 404-407. www.ge.com/pii

Yo-Essien, L. P. E. (2008). Oil Spill Management in Nigeria: Challenges of pipeline Vandalism in the Niger Delta Region of Nigeria.

Brief Profile of the Inaugural Lecturer

Engr. Prof. Oluwafemi Ayodeji Olugboji was born on 24th November, 1971 into the family of Late Mr and Mrs. J. O. Olugboji of blessed memory in Kaduna State. He hails from Ise Emure Orun in Ekiti State.

Prof. Olugboji has always been an educationist; he started his educational pursuit at Command Children School in Kaduna State and thereafter proceeded to the Federal Government College, Kaduna, Kaduna State for his secondary education. He furthered his educational pursuit at the Federal University of Technology, Minna and graduated with a Second Class Upper Division in Mechanical Engineering in 1995. He did his National Youth Service Corp (NYSC) programme at the Nigeria National and Petroleum Corporation (NNPC), Kaduna, where he served as a Trainee Engineer and finished in November 1996.

His quest for knowledge and willingness to solve complex human and machine problems motivated him take up a Masters degree in Mechanical Engineering at the prestigious Federal University of Technology, Minna and graduated in April 1999.

He got his first appointment at the Federal University of Technology, Minna in October 1998 and served as an Assistant Lecturer at the Department of Mechanical Engineering till April 1999. In the same April 1999, he became a Lecturer II and was on the rank till October 2004 when he became Lecturer I. In February 2007, Prof. Olugboji moved to the United Kingdom where he had his PhD in Mechanical Engineering at the University of Newcastle upon Tyne. There in the United Kingdom he also served as an Examination Invigilator Officer and a Teaching Assistant at the Newcastle College from 2007 to 2012. On completion of his PhD studies in 2012, he returned to Nigeria and was promoted the rank of Senior Lecturer. He rose to an Associate Professor in October, 2015, and Professor of Mechanical Engineering in October, 2018.

Professor Olugboji has been privileged to supervise many research projects both at the undergraduate and postgraduate levels.

Prof. Olugboji has been saddled with administrative and academic responsibilities and never relegated himself and his personal development to the background. In 1998, he was appointed a member of the Engineering School Board and by the year 2000, he became a member of the University Sports Committee till 2007. He was reappointed to same position and served from 2012 till date. In 2001, he was Departmental Level Officer, Assistant Departmental Examination Officer and Seminar Coordinator for Departmental Undergraduate Projects. In 2002, given his good works, he was appointed member of University Students' Welfare Committee and member Committee of Congregation to Investigate the State of Allegations against the University Students' Union Executives. In 2003, Professor Olugboji was appointed the Seminar Coordinator for Departmental Postgraduate Diploma Projects. He was appointed the Departmental Examination Officer from 2004 to 2006. In 2005, Prof. Olugboji was appointed Departmental Students' Work Experience Programme (SWEP) Officer, member of University Seminar Committee, Coordinator of the School of Engineering and Engineering Technology, FUT Minna Students Work Experience Programme all in same year.

Having served meritoriously in the offices placed in his hands, in 2012, shortly after his return from PhD studies, Professor Olugboji was appointed the Departmental Postgraduate Coordinator. He doubled as a member of Utilization of Education Trust Fund for locally based postgraduate students in School of Engineering and Engineering Technology. He was also made the Chairman of the 3rd Biennial Engineering Conference, School of Engineering and Engineering Technology Fund Raising Committee for the 2012/2013 Academic Session. Engr. Prof. Olugboji was appointed the Head of Department of Mechanical Engineering in October, 2013 and member of the University Senate, a position he held till January 2018.

Professor Olugboji's love for the community cannot be down played; he started serving the community as a member of the Mechanical Engineering Welfare Committee from the year 2000 to 2007. He served as Staff Adviser to the National Association of Mechanical Engineering Students, FUT Minna Chapter from 2002 to 2007. He was the University Football Coach from 2003 to 2007 and re-appointed in 2012 and is still serving to date. His love for the community extends beyond the University as he has served in different committees at St. Peters Anglican Church, Minna.

Prof. Olugboji also gives back to humanity by offering consultancy services. He has been a member of the PTDF scholarship interview panel from 2012 till date, he is a Council for the Regulation of Engineering in Nigeria (COREN) and National Board for Technical Education (NBTE) representative for programme accreditation to various institutions in Nigeria, has being engaged in various project designs and fabrication for the Federal University of Technology, Minna and many more. He has received various awards which include the Postgraduate Student Scholarship Award at Newcastle, Petroleum Technology Development Fund (PTDF) PhD Scholarship Award, Best Research Project exhibited at 2015 first ever FUT Minna Convocation Exhibition.

He is an external assessor at Tshwane University of Technology, Pretoria, South Africa and other universities within Nigeria. He is a two time recipient of the Tetfund Institution based research invention grant. He is a member of different professional bodies which include Nigerian Institution of Mechanical Engineers and Nigerian Society of Engineers (MNSE). He is also a member of Council for the Regulation of Engineering in Nigeria (COREN), American Society of Mechanical Engineers, United States of America and Institution of Mechanical Engineers, United Kingdom.

It might excite you to know that Engr. Professor Olugboji is a fan of football, chess and adventurous travelling. He is a multi-lingual, who speaks English, Yoruba and Hausa fluently and has published copiously in international journals and journals within the shores of Nigeria. He is blessed with 2 wonderful sons.