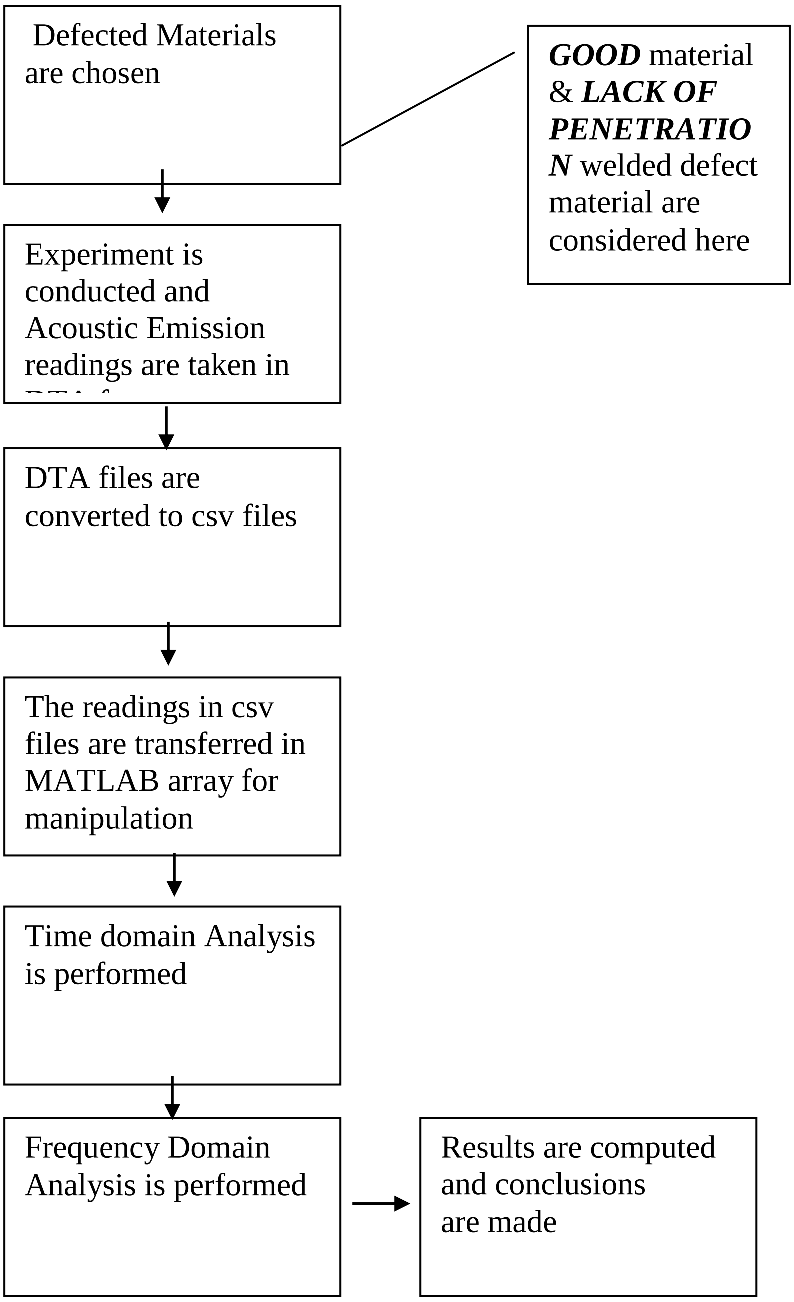
“Digital Signal Processing of Acoustic Emission Signatures”

CHAPTER 1: INTRODUCTION

Using the MATLAB’s exhaustive Digital Signal Processing toolbox and it complier vast capability a perfectly working and result oriented MATLAB codes which are out of sincere efforts and expert consultation have formulated. These codes are capable of manipulating the acoustic emission data into time domain and frequency domain and perform their analysis using Digital Signal Processing Techniques.

CHAPTER 2: BLOCK DIAGRAM



CHAPTER 3: BLOCK DIAGRAM DESCRIPTION

1. Welded defect Materials are chosen

The welded materials possess various defects such as

- Lack of Penetration
- Lack of Side fusion
- Porosity
- Slag
- Pin Hole

Here a ***GOOD*** sample (sample with no defect is chosen) and sample with ***Lack of Penetration*** welded defect is chosen.

2. Experiment is conducted and Acoustic Emission readings are taken in DTA format

- Sensors such as PK6I and R6α sensor are chosen.
- Sensors are connected to USB Acoustic Emission node which in turn is interfaced with the Computer.
- The other end of sensors is connected to the welded material so as to collect readings.
- Load/ Stress is applied to the material using mechanical jig.
- The Acoustic Emission data is collected in DTA form with the help of AE-Win Software.

3. Converting DTA to csv extension

- The acoustic emission readings cannot be imported into MATLAB in DTA form.
- Now they are converted into csv format for analysis in MATLAB using AE-Win Software.

- Then these Acoustic Emission signatures are imported into MATLAB arrays for further processing and analysis.

4. Readings in csv files are transferred in MATLAB array
This is done by using the following loops

```
p=dir('D:\B.Tech\Mini Project\AE ANSII DATA\Series 01\Good\*.csv');
num=cell(size(p));
for i=1:length(p)
num{i}=xlsread(['D:\B.Tech\Mini Project\AE ANSII DATA\Series 01\Good\',p(i).name],'A13:A1036');
end
```

5. Time Domain Analysis

- The values in a MATLAB array are used to generate a time domain plot.
- Various trends are observed.

6. Frequency Domain Analysis

- The time domain sequence is converted in frequency domain by using fourier transform
- Plotting in frequency domain is done.
- The absolute value (magnitude) is plotted separately.
- Dominant Frequency is observed.

CHAPTER 4: EXPERIMENTAL PROCEDURE EMPLOYED

1. First the sample to be tested is chosen which is either the GOOD sample or sample with Lack of Penetration (LOP) welded defect.

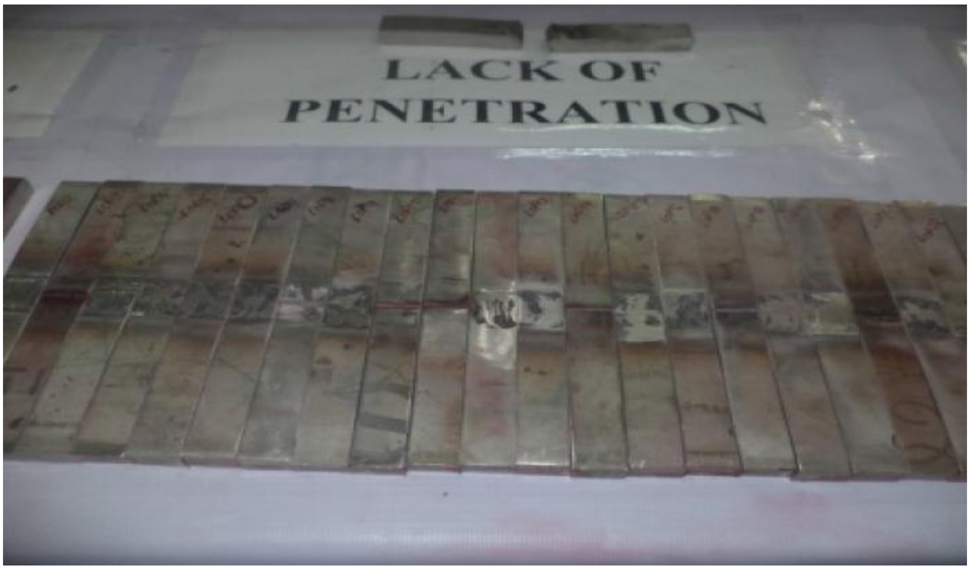


Figure 1: Samples of Lack of Penetration Defected Materials

2. The Acoustic Emission(AE) sensors are placed on the either sides as shown in figure

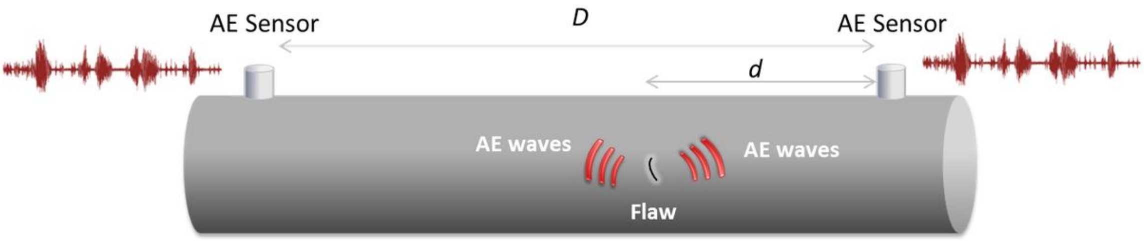


Figure 2 Acoustic Emission Sensor Placement

3. Force is applied on the material using the mechanical jig shown

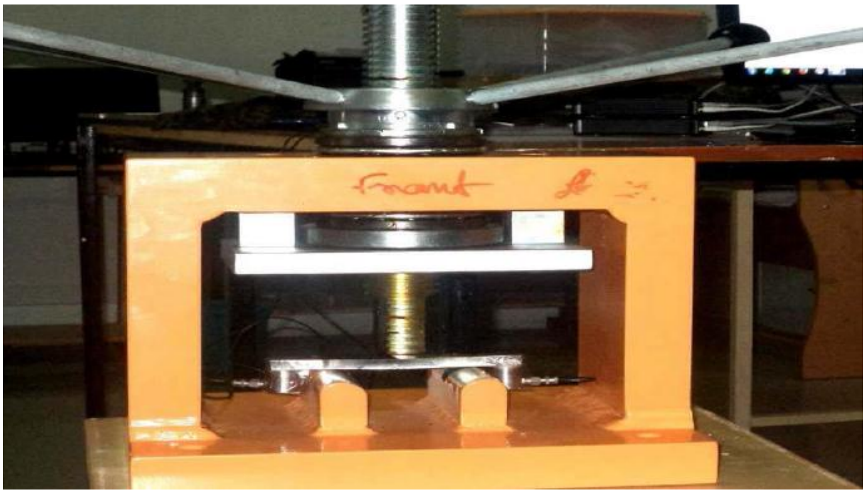


Figure 3 Mechanical Jig

4. The crack break opens giving rise to acoustic waves which are sensed by the Acoustic Emission (AE) Sensor in form of electrical impulses. The sensors used here are R6-α and PK6I sensors.
5. The electrical signals generated by sensors will have small amplitude levels and its difficult to analyse them, hence their magnitude is amplified by the preamplifier and amplifier then given into the measurement circuitory in order to assign the relative level to the Acoustic Emission waves measured, then into data buffers and finlly into the computer.
6. These results are in .DTA extesion and can be accessed by in the following way

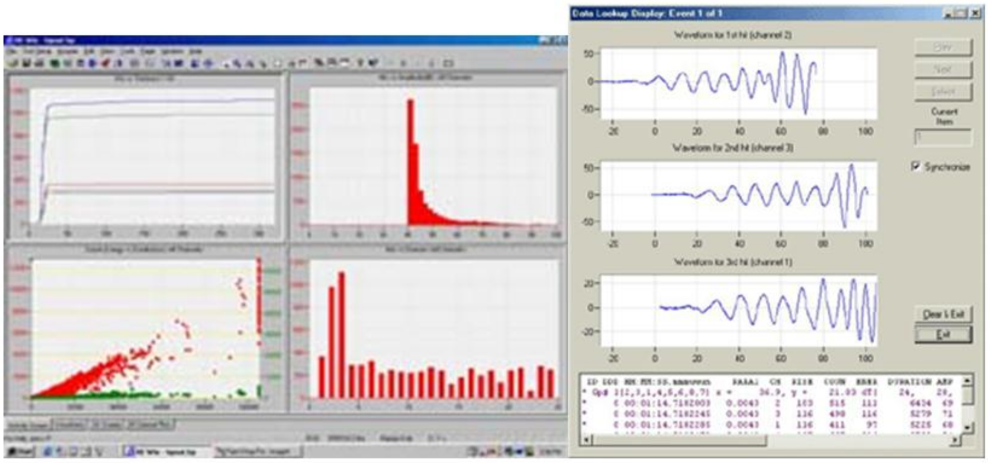


Figure 4 AE-Win results display

5.Since the data generated is in .DTA extension and so it is converted to into a format accessible by MATLAB, i.e comma seperated values (.csv) format.

7. A huge amount of data is generated in .csv formats around 100-200 files and each file may contain around 600-700 readings.

8. These amplitude values are now plotted in a time domain using MATLAB and various trends can be analyzed.

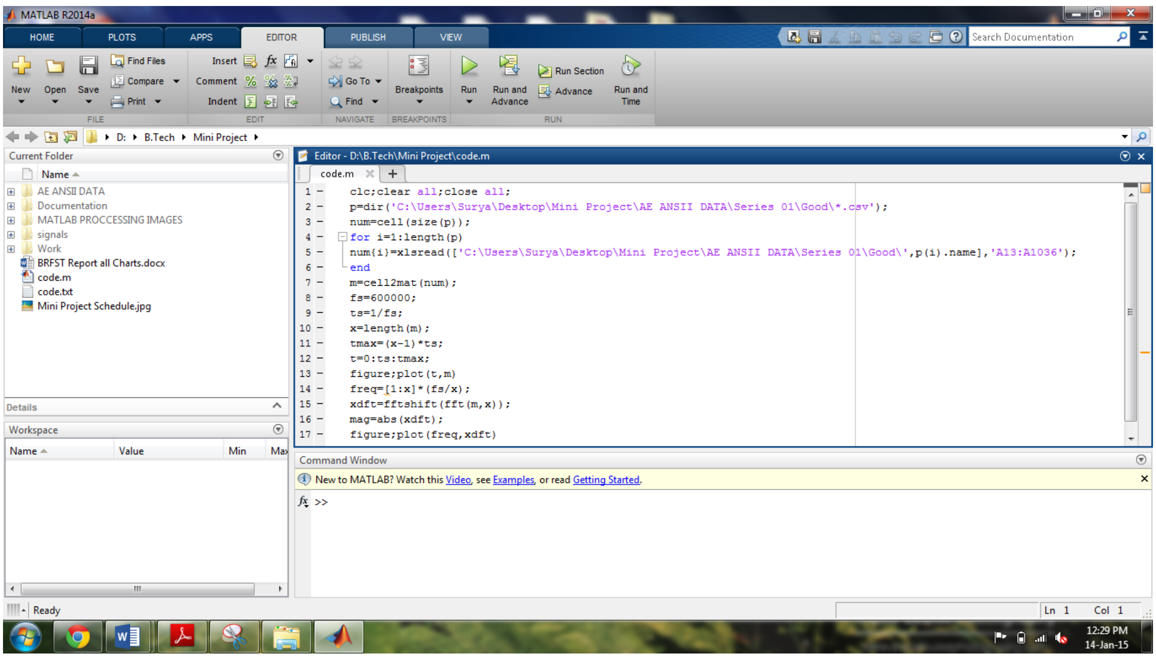


Figure 5 The screenshot of functional MATLAB window

9.Then fast fourier transform is perfomed for analysis in frequency domain

10. The trends in dominant frequecy for GOOD Sample and defected sample with Lack of Penetration (LOP) welded defect are established.

CHAPTER 5: MAIN FEATURES

5.1 Acoustic Emission:

5.1.1 Background

Acoustic Emission (AE) is the study and practical use of elastic waves generated by a material subjected to an external stress. The phenomenon was recognized by early miners who exited a mine when the rocks or supporting timbers started groaning. Tin cry, the sound produced when a tin bar is bent, was known soon after the production of metallic tin. More recently, C.S. Barrett mapped a low temperature phase transition in Lithium-Magnesium alloys by sticking a phonograph needle into the crystal and recording the output as the temperature was changed. J. Kaiser investigated the signals produced by samples undergoing tensile testing and discovered the Kaiser effect, i.e. that no signals were generated by a sample upon the second loading until the previous maximum load was exceeded. After Kaiser’s thesis was published in 1950, several groups investigated the phenomena for possible use in testing structures. In the early 1960s, Allen Green and a group at Aero Jet Corporation started using AE in the testing of Saturn Rocket propellant tanks. They used a form of triangulation based on the arrival times of the acoustic pulse at several acoustic emission sensors. This was the direct precursor of the work that is described in this paper.

5.1.2 Generation of Acoustic Emission Waves

Despite its longstanding use, the definition of "acoustic emission" has been a source of controversy for the last fifty years. Strictly, "acoustic" refers to the pressure waves detected by one's ear. However, elastic waves in solids are not limited to pressure waves, and all types of vibrational modes are generated by acoustic emission sources. Even so, the term "acoustic emission" has become almost universally used for the phenomena of elastic waves generated by an internal event in a media. In this monograph, "acoustic" will refer to any elastic wave generated by an acoustic emission source. Acoustic emission, then, is the generation of an elastic wave by the rapid change in the stress state of some region in the material. This change is usually caused by the application of an external stimulus to the material. The material can be a solid, liquid, gas or plasma and the external stress can be applied mechanically, thermally, magnetically, etc. The stress change must be rapid enough to transmit some energy to the surrounding material and dissipates as an elastic wave. On a macroscopic scale this definition includes earthquakes and thunder, while on a microscopic scale it includes the fracture of crystallites and Martensitic phase transformations. The occurrence of the burst of energy is completely determined by the local conditions, the local stress field, and the physical state of the region. As a result, neither the exact time when the energy burst occurs nor the exact details of the generated wave can be determined beforehand. In general, the event generating the emission is irreversible; neither a ruptured geologic fault nor a fractured crystallite in a metal plate will heal spontaneously.

Once the elastic wave is generated, it then travels throughout the material and can be detected at considerable distances from its point of origin. Traveling from its source to the point of detection, the wave is subjected to all the characteristics and variations of its acoustic path. Its energy is attenuated by geometric spreading and scattering by both microscopic and macroscopic variations in the material's structure. Other kinds of attenuations may also be present. The wave's frequency content is generated by the source and modified as it travels the acoustic path. The primary information carried by the wave is the time of arrival and the elastic energy detected at each sensor on the structure. The excitation of a sensor indicates that something happened in the specimen at a specific time, while the amplitude indicates the level of the disturbance. The apparent location of the source and all other characteristics of the detected signal are modified by the characteristics of the wave's path to each sensor as well as the characteristics the sensor. As a result, in a highly controlled laboratory experiment, a reasonable estimate can be made of the characteristics of the emission source; however, in a test on an actual structure, we are limited to what are basically statistical estimates from multiple emissions to tell us what is happening in the specimen. Statistical analysis is not generally used in the study of acoustic emissions, but the state of the specimen and the location coordinates of the sources are inferred from averages of calculated values from multiple emissions.

5.1.3 Reasons for employing Acoustic Emission Testing (AET)

Elastic energy is ubiquitous. It travels through all materials where there is an interaction between atoms. Only a hard vacuum does not transmit elastic energy. The distance from its source over which an acoustic signal can be detected depends on its initial amplitude and the acoustic characteristics of the material through which it is traveling. For many structural materials, acoustic emission signals can be detected from almost anywhere on the structure. This allows an AE test to cover an entire structure instead of only a small region. However, many acoustic signals which have nothing to do with the test can be present and detected. Acoustic isolation of the test object is highly desirable. Most acoustic emission testing filters out acoustic signals at frequencies below 20 KHz, thus ignoring background noise and verbal communication in the test area.

An acoustic emission test occurs in real time. The test does not find preexisting defects, but detects flaw growth as it occurs. If the stress application simulates the conditions that the test structure is designed to experience in actual operation, serious acoustic emission will indicate pathological flaws that could lead to failure of part or all of the structure. The amount of emission detected and the locations of the emission sources will depend both on the design of the structure and the materials used in its fabrication. For example, compare The bending of a strip of glass and a strip of FRP (Fiber Reinforced Plastic) with identical dimensions. The strip of glass will likely give a single high-amplitude burst of emission just at failure while the FRP will show a period of low level emissions followed by a few higher level emissions and then one or more high amplitude emissions as the strip starts to fail and then tears apart or snaps. Interpreting detected emissions is the test engineer's job. The value of the information obtained from a test is determined first by the design of the test and second, by the analysis of the detected emission. For complex structures, both the test design and interpretation are seldom simple. It is the purpose of this monograph to aid the test engineer in both areas.

5.1.4 Sources of Acoustic Emission

Acoustic emissions are acoustic waves generated by a rapid change in the stress state of a region in a material. Acoustic waves are one of two non-electromagnetic methods of transmitting energy through a material; the other method is thermal diffusion. A difference between the two is that thermal diffusion involves direct energy transfer between individual atoms, while an acoustic wave transfers energy by a cooperative motion of many atoms. An acoustic wave can be as simple as a pressure pulse in a gas or liquid, or as complicated as the many modes of transmission in a bounded solid. The generation of an acoustic wave invariably involves a large region of atoms.

The most common acoustic waves are sound waves in air and water. These are produced by vibration of a surface such as the vocal apparatus of an animal, a leaf in the wind, or the diaphragm of a speaker. These sources are quasi-continuous, involving a modulated vibration of an interface between the generating region and the transmitting medium. Another type of acoustic wave is generated by a sudden disturbance in or on the material itself, a transient event that produces a transient acoustic wave. Such a transient wave is what we define as acoustic emission. It may have the form of a single damped wave with complex frequency content or it may appear as many small transient events which sum into quasi-continuous noise. Its primary characteristics are that it is generated in the medium which transmits it, and it is transient in nature. Any sudden movement of a group of atoms at velocities near the sound velocity in a material can produce a transient acoustic wave. The apparent quasi-continuous signals which are often seen can be generated by the overlap of many transient events instead of a continuous vibration of a surface. Figure 1-1 shows waveforms both from a transient event and from a superposition of many transient events. The long decay of the transient event is produced by reflections of the original wave in the complex metal specimen.

The size of the region generating an emission can vary from a relatively small row or plate of atoms moving simultaneously into a new crystal position during a Martensitic phase transition to a fracture in a subduction zone between two continental plates. The energy released in an acoustic emission event will be roughly proportional to the volume of the source. Energy from these waves ranges from smaller than an electron volt to the energy contained in a thunder clap or that of a magnitude 9 earthquake. Wave frequencies are generally related inversely to the volume of the generating region, ranging from thousandths of a Hertz for earthquakes to several MHz in fine grain metals. An important characteristic of acoustic emission in solids is that the fracture of the region occurs when the local stress vector exceeds the strength of the region to withstand that vector. In other words, the exact time when the emission occurs strictly depends on the local conditions. In a metal, for example, the precise environment of every crystallite differs, and the fracture of one crystallite or of the boundary between two crystallites will make small changes in the local stress vectors in the other crystallites. This complete dependence on local conditions means that it is impossible to predict the exact time of any one emission or the time interval between any two emissions. Acoustic emissions occur unpredictably in time. They are a response not to the applied external stress but to the local stress fields produced at each position throughout the material. The parameters of the detected emission depend not only on the characteristics of the emission source, but also on the characteristics and geometry of the medium between the source and sensor, and on the characteristics of the sensor and of the couplant between sensor and medium.

5.1.5 Detection of Acoustic Emissions by sensors

The signal characteristics detected by individual identical sensors located at various positions on a specimen will often vary greatly for a single emission. The more complex the medium in which the emission is generated and transmitted, the more likely there will be large differences between detected signals from the same emission at different sensors. The unpredictable time of origination and the wide variety of waveforms in separate emissions are fundamental characteristics of acoustic emission. As such, these factors have a profound effect on the type of analysis used on the detected emissions.

In structural metals, both inter-granular and trans-granular cracking of metal crystallites can generate low level acoustic emission. Emission will also be generated at inclusions both by fracture of the inclusion and the breaking of the bonds between the inclusion and metal. Crack growth where at least several crystallites are involved can generate emission of moderate to large amplitudes. The presence of corrosion on a metal surface can be detected by the fracture of brittle corrosion byproducts while active corrosion can generate emission from bubble formation. In high stress environments, twinning (a form of crystalline distortion) can occur in some metals and this can produce emission. Room temperature creep in metals may involve the movement of dislocations in the metal. Laboratory experiments have claimed to be able to detect very low amplitude emission from creep, but the author is not aware of its use in structural flaw detection. The creep rate in structural materials under normal usage is usually far too slow to generate acoustic emission useable for flaw detection.

Source mechanisms in FRP include matrix cracking debonds between the matrix and fibers, fiber fracture, and crack propagation. These source mechanisms can all be activated by the application of an external stress. Based on the idea that the emission amplitude is related to the volume of the source, matrix cracking should produce the lowest amplitude emission, followed by matrix-fiber debonding. Fiber breakage would be louder still, partly due to the amount of energy released by the fracture of a high strength fiber. Finally, crack propagation, which includes all three of the previous mechanisms, would produce the highest amplitude emissions. This appears generally to be the case, but trying to quantify it as a rule has never worked very well, probably because FRP is usually laid up by hand and never comes close to the structural uniformity of a well annealed metal. The first loading of an FRP structure will generate acoustic emission at loads well below the strength of the structure. The most likely cause of this emission is the relief, by minute fractures in the FRP during the first loading, of high residual stresses which developed in local regions during the curing process. The fractures have little effect on the strength of the material, and the emission usually stops before the design loads are reached. This emission is seldom seen upon the second and subsequent loadings. Another source of emission in FRP structures is often seen during cyclic loading. This emission appears in the middle ranges of the cyclic load when the rate of change in applied stress is highest, instead of at the peak loads. It appears to be caused by friction between small regions in the structure which are not bonded. This type of emission can be present during the entire cyclic load test; however, it does not correlate with structural damage in the test object. Structural damage is associated with emission that occurs near the peak loads, especially during the rising load.

As discussed above, most acoustic emission mechanisms involve a permanent change in the micro structure of the material. Once a micro fracture occurs, it will not happen again unless there is some sort of healing mechanism. Therefore, acoustic emission appears irreversible. The Kaiser effect, where the re-stressing of a specimen will not generate acoustic emission until the previous load level has been exceeded, is caused by this irreversibility. The Kaiser effect holds very well for the immediate re-stressing of a metal specimen, but less well for composites. The problem is that the reapplication of an external stress does not necessarily take the specimen along the same micro-stress path. One often sees emission on subsequent loadings at loads lower than previously reached. The ratio of the load value, when emission starts on subsequent loadings, to the maximum load value reached on the previous loading, known as the Felicity ratio, indicates possible damage induced by the previous loading. Many NDT tests of FRP structures apply the test load in a series of steps, returning to zero between each step. The appearance of Felicity ratios much less than 1.0 is a good indication that significant damage occurred in previous loadings.

5.1.6 Characteristics of Acoustic Waves

Acoustic emission signals generate complexity as the wave travels through the medium. Understanding acoustic emission signals requires knowledge of the wave characteristics, starting with the properties of the medium through which the wave travels. All materials are collections of atoms held together by attractive forces while simultaneously prevented, by short range repulsive forces, from approaching each other too closely. The superposition of these forces results in an equilibrium position for the atom at its lowest energy, the material's most stable configuration. In crystals, for example, long range forces between the atoms result in defined locations for these equilibrium positions. The result is a crystal structure. In a liquid the structure is amorphous, but an approximate distance between atoms results in a uniform density. In a liquid, only the density is defined. There are no fixed positions for the atoms as there are in a crystal lattice. The ability of the atoms to change position is measured by the viscosity of the liquid, which can range from very low to extremely high. At the two extremes are a gas and a solid. A gas is a liquid with very low viscosity, and glass is a liquid with very extremely high viscosity. The density of a gas can be defined by its total mass and the volume of its container.

The acoustic properties of a material depend on its density and the long-range coupling constants between its atoms.
The long-range correlations in an acoustic wave result in many atoms in a small region being displaced in the same direction from their equilibrium positions. This displacement is a local dynamic strain in the crystal; the strain's direction and magnitude are constantly changing as the atoms move. When the atomic motion is pseudo-oscillatory, so is the strain. An acoustic wave is an oscillating strain moving through a material. Because stress and strain are always directly related in a material, there is also an oscillating stress field. Therefore, an acoustic wave can be described as either a dynamic stress or strain field in a material.

The three major applications of AE techniques are:

1) Source location - determine the locations where an *event* source occurred;
2) Material mechanical performance - evaluate and characterize materials/structures; and
3) Health monitoring - monitor the safety operation of a structure, i.e. bridges, pressure containers, and pipe lines, etc.

5.2 Welded Defects:

Welding defects can greatly affect weld performance and longevity. Having an understanding of the various defects, their causes and remedies can help to ensure higher-quality and longer lasting welds. Upon detection of welding defects, an evaluation should be carried out to determine its severity, and appropriate action taken. Even the most inconspicuous weld defect can render a welded structure unfit to carry out its intended purpose.

There are various welded defects such as

- Lack of Fusion
- Porosity
- Slag
- Incomplete Penetration
- Toe Crack
- Root Crack

We mainly focus on weld defect of type "**LACK OF PENETRATION**" and a **GOOD** (ideal) sample with no defects.

From the different mechanisms for the detection of cracks and crack-like defects in ductile material by AE examination, it is obvious that details of the defect are important for the detectability.

Some examples for good detectable defects are:

• Flaws or poorly bonded regions caused by the welding process: They result in large AE activity during the first pressurization test after the fabrication. It has to be noted that also
very small flaws and inclusions may result in considerable AE activity.

• Cracks or crack-like defects with layers and fillers produced due to the operational environment, e.g. corrosion layers.

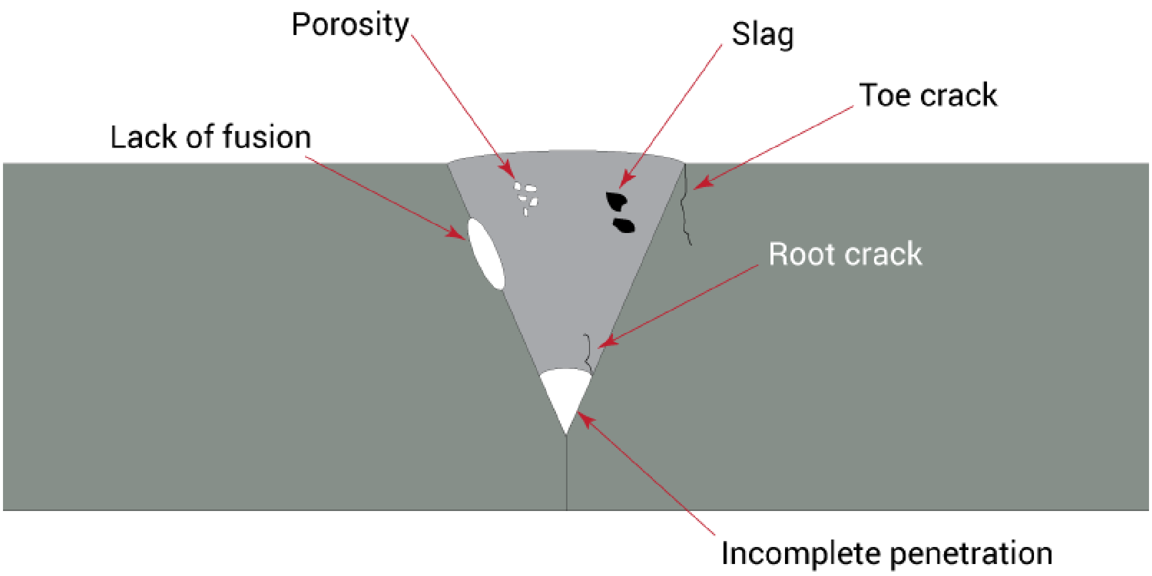


Figure 6 Various welded defects

5.2.1. Good Sample:

This is perfectly welded metal and it has no defects

5.2.2 Lack of penetration (Incomplete penetration):

It can be characterized in the following manner
This type of defect is found in any of three ways:

1. When the weld bead does not penetrate the entire thickness of the base plate.
2. When two opposing weld beads do not interpenetrate.
3. When the weld bead does not penetrate the toe of a fillet weld but only bridges across it.

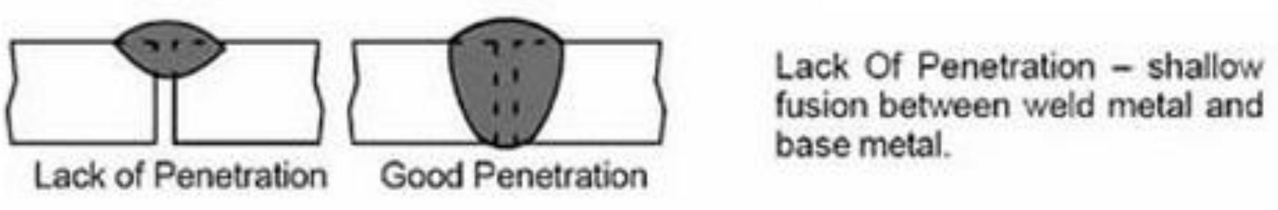


Figure 7 Lack Of Penetration (LOP) & GOOD

5.3 The Analysis methodologies which are employed in this project:

Using the MATLAB's exhaustive Digital Signal Processing toolbox and it complier vast capability a perfectly working and result oriented MATLAB codes which are out of sincere efforts and expert consultation have formulated. These codes are capable of manipulating the acoustic emission data into time domain and frequency domain and perform their analysis using Digital Signal Processing Techniques such as Discrete Fourier transform, Discrete-time Fourier transform, Power Density Spectrum, Dominant Frequency Evaluation and various other quantities have been evaluated for various defects in the nuclear grade stainless steel material SS316L.

These Acoustic signals which are generated by the Stainless Steel material under pre-stressed conditions of welded material are analog in nature. These analog signal are converted into digital signals with help of an A/D Converter present inside USB Node which is the interface between sensors and The Computer. The digital signals are processed by pre-amplifier and fed into proper form that can interface with the AEwin software on the Computer Device.

The various amplitude readings and further test results are collected from AEwin software in DTA format, which are then converted into csv (comma separated values) format for easy transfer into MATLAB

These are then imported to MATLAB Software using a MATLAB code section that is specially formulated to read the .csv files and import only the numerical data into MATLAB array for Digital Signal Processing.

The data which is now in a format that can be easily manipulatable in MATLAB software is plotted as time domain plot and later in frequency domain plot for further analysis and data procuring. After this process is completed the areas of analysis that could be focused are as summarized here under in the following tree diagram.

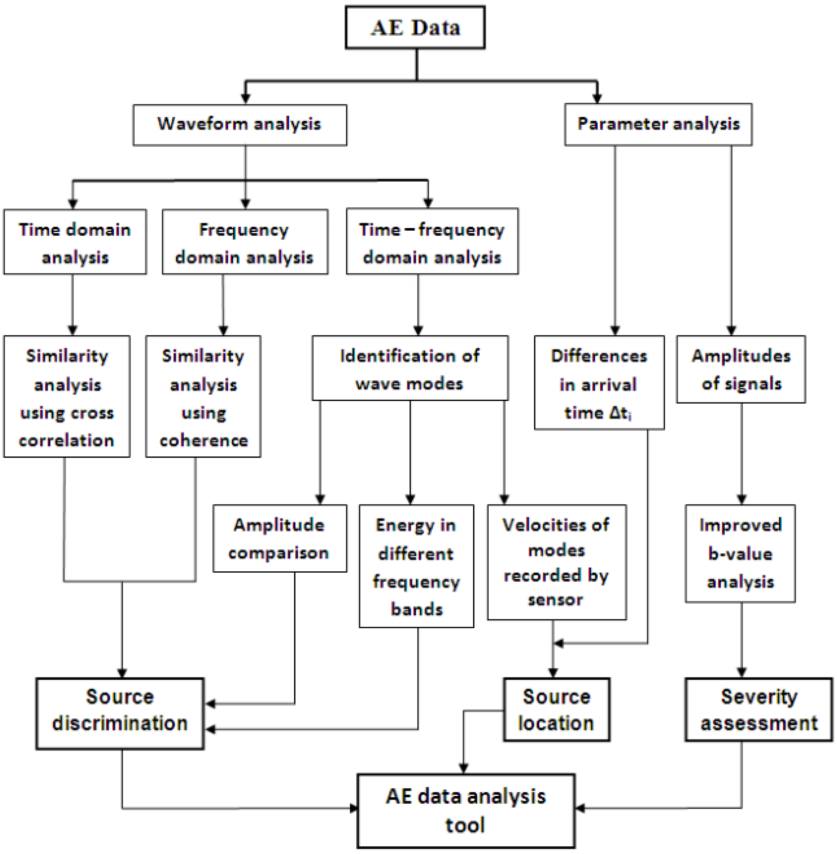


Figure 8 Tree Diagram of possible analysis of Acoustic Emissions

5.4 AEwin Software:

AEwin is a 32 bit WINDOWS, Data Acquisition and Replay program capable of running DiSP, SAMOS, PCI-2, MISTRAS or SPARTAN based products. Utilizing full WINDOWS resources including; Setting of any WINDOWS available screen resolutions, Printing, Networking, Multi-Tasking, Multi-Threading, etc., the program runs under WINDOWS 98/2000/ME/XP operating systems. However, the best performance will be obtained using WINDOWS 2000/XP. AEwin is fully compatible with standard (DTA) data files, which allows you to replay and analyse all your previously collected AE files.

AEwin is easy to learn, operate and use. The software has all the acquisition, graphing and analysis capabilities that you have come to expect in your AE system, plus many more new and enhanced features to ease your data analysis and visualization tasks. Multiple copies of AEwin can be run at once, one for acquisition with full display and analysis capabilities and one or more as Replay for additional analysis purposes. Contains many built in, enhanced features including Graph zooming and panning, more flexible graph setup, more graphs, and filtering functions.

5.5 MATLAB:

MATLAB (matrix laboratory) is a multi-paradigm Computing environment and fourth-generation programming language. Developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran.

MATLAB Consists of various toolboxes which are a package of function related to specific application. Few of them are as listed hereunder

- Signal Processing Toolbox
- DSP System Toolbox
- Communications System Toolbox
- Wavelet Toolbox
- RF Toolbox
- Phased Array System Toolbox
- LTE System Toolbox

5.5.1 DSP System Toolbox (A component of MATLAB):

DSP System Toolbox provides algorithms for the design and simulation of signal processing systems. These capabilities are provided as MATLAB functions, MATLAB System objects, and Simulink blocks.

The system toolbox includes design methods for specialized FIR and IIR filters, FFTs, multirate processing, and DSP techniques for processing streaming data and creating real-time prototypes. You can design adaptive and multirate filters, implement filters using computationally efficient architectures, and simulate floating-point digital filters. Tools for signal I/O from files and devices, signal generation, spectral analysis, and interactive visualization enable you to analyze system behavior and performance. For rapid prototyping and embedded system design, the system toolbox supports fixed-point arithmetic.

Various features of DSP System toolbox have been extensively used for acoustic emission signal processing.

5.6 Digital Signal Processing Techniques Used

5.6.1 Fourier Transform

The Fourier transform is important tool in engineering many other disciplines. Its discrete counterpart, the Discrete Fourier Transform (DFT), which is normally computed using the so-called Fast Fourier Transform (FFT), has revolutionized modern society, as it is ubiquitous in digital electronics and signal processing. Radio astronomers are particularly avid users of Fourier transforms because Fourier transforms are key components in data processing (e.g., periodicity searches) and instruments (e.g., antennas, receivers, spectrometers), and they are the corner stores of interferometry and aperture synthesis.

5.6.2 Continuous Time Fourier Transform

The Fourier transform is a reversible, linear transform with many important properties. For any function f(x) (which in astronomy is usually real-valued, but f(x) may be complex), the Fourier transform can be denoted F(s). The product of x and s is dimensionless

x is a measure of time t (i.e., the time-domain signal) s corresponds to inverse time, or frequency ν (i.e., the frequency-domain signal).

The Fourier transform is defined by

$$F(s) \equiv \int_{-\infty}^{\infty} f(x)\, e^{-2\pi i s x}\, dx$$

which is usually known as the forward transform, and

$$f(x) \equiv \int_{-\infty}^{\infty} F(s)\, e^{2\pi i s x}\, ds$$

which is the inverse transform.

In both cases, $i \equiv \sqrt{-1}$. Alternative definitions of the Fourier transform are based on angular frequency ($\omega = 2\pi\nu$), have different normalizations, or the opposite sign convention in the complex exponential. Since Fourier transformation is reversible, the symmetric symbol $\Leftrightarrow$ is often used to mean "is the Fourier transform of"; e.g., $F(s) \Leftrightarrow f(x)$.

The complex exponential is the heart of the transform. A complex exponential is simply a complex number where both the real and imaginary parts are sinusoids. The exact relation is called Euler's formula

$$e^{i\phi} = \cos\phi + i\sin\phi$$

Complex exponentials are much easier to manipulate than trigonometric functions, and they provide a compact notation for dealing with sinusoids of arbitrary phase, which form the basis of the Fourier transform. Complex exponentials (or sines and cosines) are periodic functions, and the set of complex exponentials is complete and orthogonal. Thus the Fourier transform can represent any piecewise continuous function and minimizes the least-square error between the function and its representation.

Thus an analog electronic filter will convert a sine wave into another sine wave having the same frequency (but not necessarily the same amplitude and phase), while a filtered square wave will not be a square wave. This property of complex exponentials makes the Fourier transform uniquely useful in fields ranging from radio propagation to quantum mechanics.

5.6.3 Discrete Time Fourier Transform

The continuous Fourier transform converts a time-domain signal of infinite duration into a continuous spectrum composed of an infinite number of sinusoids. In astronomical observations we deal with signals that are discretely sampled, usually at constant intervals, and of finite duration or periodic. For such data, only a finite number of sinusoids is needed and the Discrete Fourier Transform (DFT) is appropriate. For almost every Fourier transform theorem or property, there is a related theorem or property for the DFT. The DFT of N uniformly sampled data points x_j (where $j=0,\ldots,N-1$) and its inverse

$$X_k = \sum_{j=0}^{N-1} x_j \, e^{-2\pi ijk/N}$$

and

$$x_j = \frac{1}{N} \sum_{k=0}^{N-1} X_k \, e^{2\pi ijk/N}$$

5.6.4 Sampling Theorem

For a DFT to represent a function accurately, the original function must be sampled at a sufficiently high rate. The appropriate rate for a uniformly sampled time series is determined by the Nyquist-Shannon Theorem or Sampling Theorem. This theorem states that any continuous baseband signal (signal extending down to zero frequency) may be identically reconstructed if the signal is bandwidth limited and the sampling frequency is at least twice the bandwidth of the signal (i.e. the highest frequency of a baseband signal). That critical sampling rate, $1/\Delta t$, where Δt is the time between successive samples, is known as the Nyquist rate, and it is a property of the time-domain signal based on its frequency content. Somewhat confusingly, if a time-domain signal is sampled uniformly, then the frequency corresponding to one-half that rate is called the Nyquist frequency,

$$\nu_{N/2} = 1/(2\,\Delta t)$$

The Nyquist frequency describes the high frequency cut-off of the system doing the
sampling, and is therefore a property of that system. Any frequencies present in the original signal which are at higher frequencies than the Nyquist frequency will be aliased to other lower frequencies in the sampled band as described below. If that signal was band-limited and then sampled at the Nyquist rate, in accordance to the Sampling Theorem, no aliasing will occur.

5.6.5 Dominant Frequency:

There are many situations when the observed data show a periodic behavior due to one frequency, called the dominant frequency, which carries the maximum energy among all frequencies found in the spectrum.

$$(f \star g)[n] \stackrel{\text{def}}{=} \sum_{m=-\infty}^{\infty} f^*[m]\ g[m+n].$$

5.7 Characteristics of Apparatus used

5.7.1 Type and Dimensions of Defected Material:

Lack of penetration defect is implanted in weld bead region of the materials. Tungsten Inert Gas Welding (TIG) is adopted to weld the Stainless Steel (SS316L) nuclear grade materials. The material is fabricated with dimensions of 140 × 16 × 10 mm and AE signatures are studied under preload conditions.

5.7.2 Mechanical Jig (For applying stress)

Mechanical Jig is fabricated to maintain constant load in concentrated weld region. When external load is applied on the weld region, the deformed specimen experiences acoustic emission signals form the weld defect region which are potential source of releasing stress energy. The generated signal is processed by 2-channel USB-AE node and AE-WIN software. The Digital Signal Processing and Analysis are conducted on two different samples i.e. the Good Sample and the sample with Lack of Penetration welded defect.

5.7.3 Acoustic Emission Sensors:

The sensitivity of the sensor depends not only on frequency but also on the direction of motion accelerometers which are carefully designed to measure only the component of motion parallel to the axis acoustic emission sensors respond to motion in any direction.

- There are numerous sensors but all of them commonly are
- Enclosed in a case
- They contain the crystal, which acts a transducer.

Two sensors of prime importance in this project

- PK6I Sensor
- R6α Sensor

Introduction to Acoustic Emission Sensors:

The sensor constitutes the first part in an AE measurement chain and as of this is of particular importance. A subsequent measurement system can only process signals which the AE-sensor picked up. Anything an AE-sensor does not pick up is lost for analysis. An AE-sensor converts the surface movement caused by an elastic wave into an electrical signal which can be processed by the measurement equipment. The piezoelectric element of the AE-sensor should pick up faintest surface movements (i.e. have high sensitivity) and convert this movement most efficiently to an electrical voltage.

AE-sensor size and frequency response

The size of the piezoelectric element affects the resonance frequency of the AE-sensor. In general the resonance frequency is higher for smaller piezo-elements. Therefore the desired resonance frequency has a major influence on the sensor size; i.e. the lower the frequency range of an AE-sensor the larger its size.

Adhesive mount (bonding)

An AE-sensor may also be bonded directly to the object's surface. Care should be taken choosing the right adhesive which should not attack the surface it is applied to. The adhesive will also act as a couplant.

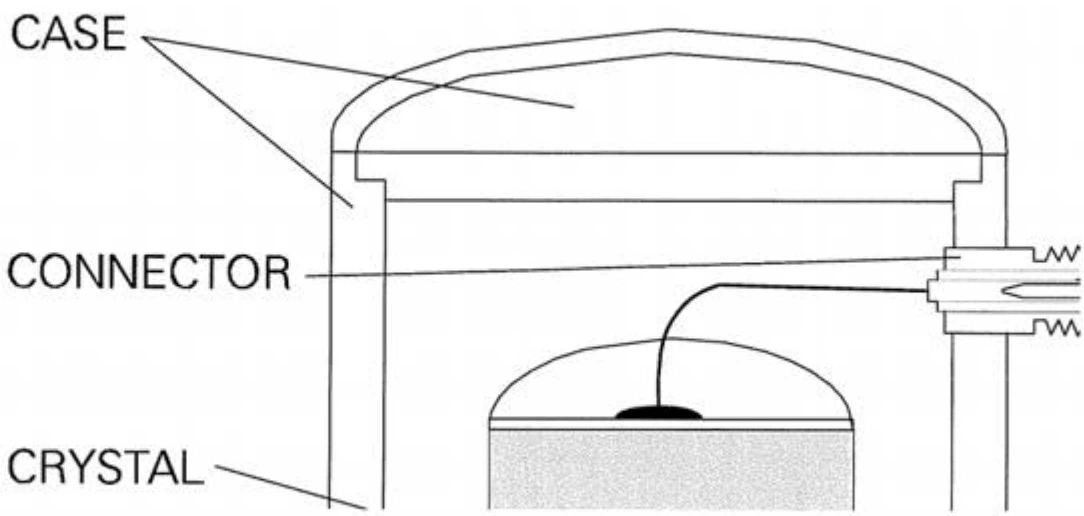


Figure 9 Acoustic Emission Sensor Schematic

5.7.3a PK6I Sensor:

The PK6I sensor is a medium frequency, resonant, acoustic emission sensor with an integral, ultra-low noise, low power, filtered, 26dB preamplifier, which can drive up to 200 meters of cable. This sensor represents an improvement in both noise and low power consumption performance, with noise level below 3 µV and power consumption of 25 mW. The PK6I features a strong stainless steel, integrated body structure.

Figure 10 PK6I Accoustic Sensor

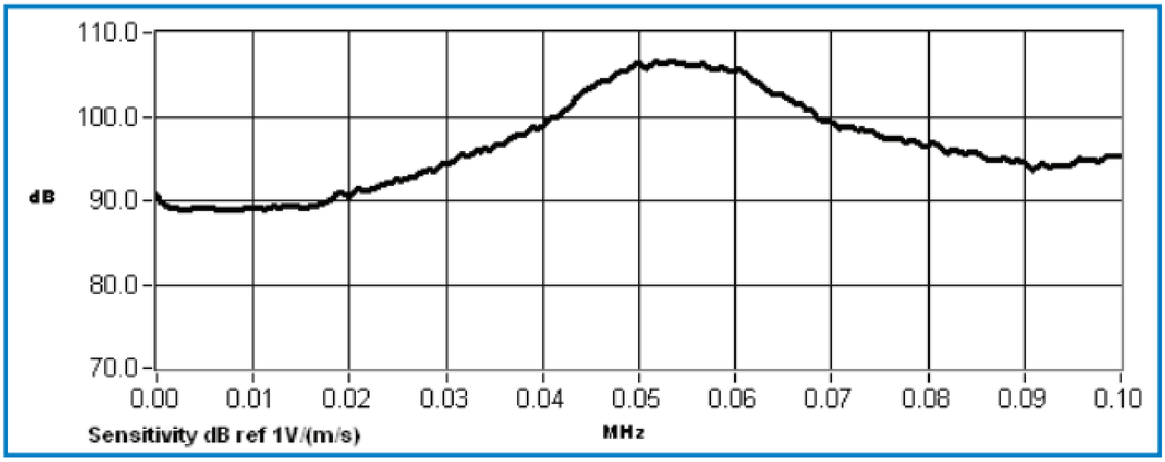


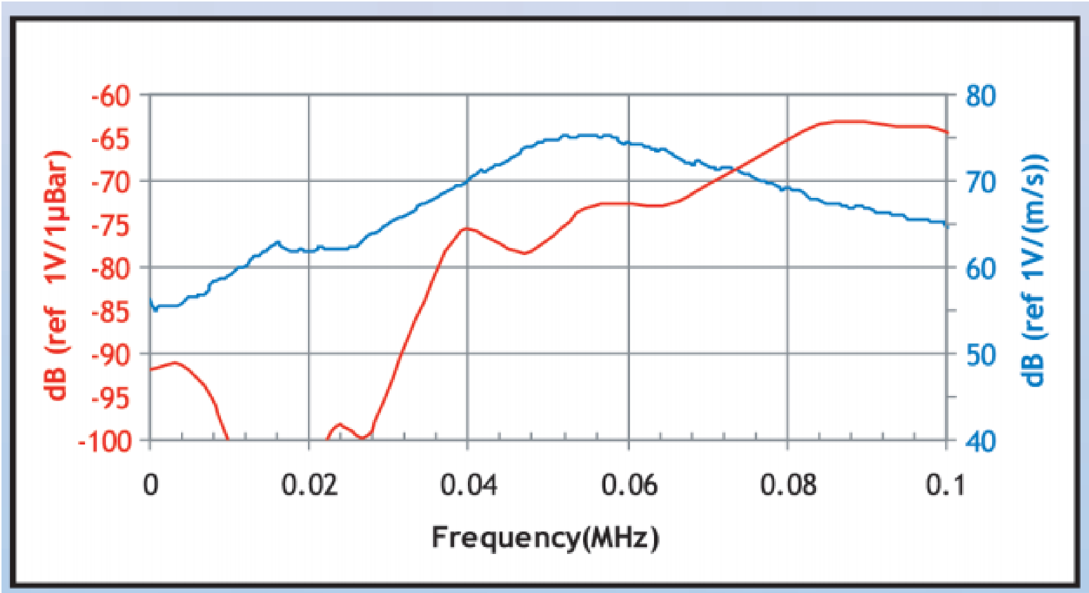
Figure 11 Plot of sensitivity of the PK6I sensor (dB)

5.7.3b R6α Sensor:

This sensor has as Peak Sensitivity 75 [-64] dB and its Operating Frequency Range is 35 - 100 kHz with Resonant Frequency 55 [90] kHz. This sensor can be used on metal and FRP structures such as pipelines or storage tanks in petroleum, refineries, chemical plants, and offshore platforms, due to its high sensitivity

and low resonance frequency properties.

Figure 12 R6α Accoustic Sensor



Frequency response of the R6α. Calibration based on ASTM E1106; Calibration based on ASTM E976.

Figure 13 Frequency response of the R6α sensor.

5.7.4 USB Acoustic Emission Node:

The USB AE Node is a single channel Acoustic Emission (AE) Digital Signal Processor with full AE hit- and time-based features, including waveforms. Through the USB Connector, the AE Node is easily interfaced to a Notebook or PC running Windows 7, 8 and XP and Physical Acoustics Corporation’s (PAC) well known AEwin. The USB AE nodes can be connected to available USB ports of a notebook which also supplies the power needed to operate the USB AE Node.

Features:

• Powered and operated through USB Port

• Rugged surface mount (SMT) construction

• Built-in internal preamplifier and power for external preamplifiers

• 18 bit resolution, 20MHz sampling frequency

• With analog and programmable digital filters

• Waveform and Location Options

Figure 14 USB Accoustic Emission Node seperately(left)
In connected state(right)

CHAPTER 6: THE LAYOUT DIAGRAM

Layout of Experimental setup for acoustic emission testing:

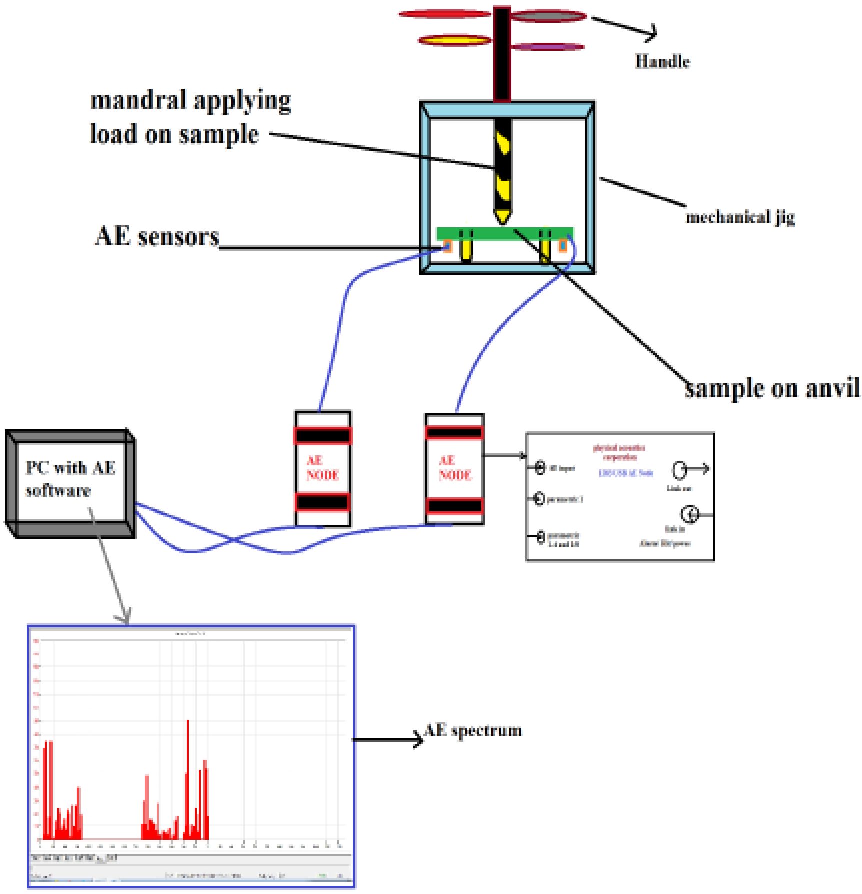


Figure 15 Layout diagram of Acoustic Sensors, USB Node and PC

- The sensor is mounted to the sample to be tested

- When stress is applied Acoustic Emission waves are generated and these are sensed by the sensors and converted into small electrical signals are generated

- The electrical signals generated by sensors will have small amplitude levels and its difficult to analyse them

- Their magnitude is amplified by the preamplifier and amplifier then given into the measurement circuitory.

- The relative level to the Acoustic Emission waves measured, then into data buffers and finlly into the computer.

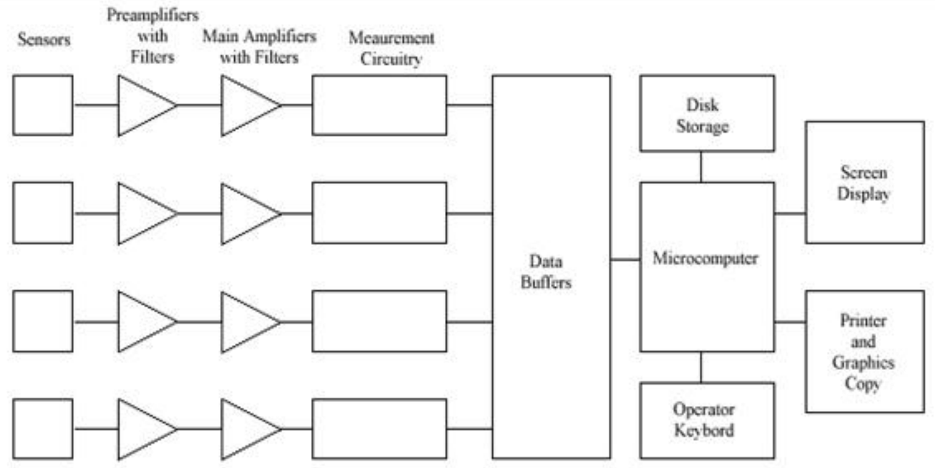


Figure 16 Block Diagram of Sensor Functionality

- The sensors cannot be connected directly to Computer for analysing the signals hence the sensors need to be interfaced with the help of Interfacing device which interfaces the sensor(transducer) to the Computer.

- These Acoustic Emission nodes and synchronised with the help of a Time Synchronization cable.

- The data from Acoustic Emission sensor is shown in understandable form in AE-Win software.

CHAPTER 7: THE ORIGINAL MATLAB CODE

7.1 Collecting the acoustic emission signatures:

- The Acoustic Emission signatures from good and defected sample with welded defect which is classified as lack of penetration in Stainless Steel material (SS316L) are collected from the acoustic sensors and then collected into a single channel AE system is just palm size. The USB AE Node is a single channel Acoustic Emission (AE) Digital Signal Processor with full AE hit- and time-based features, including waveforms. Through the USB Connector, the AE Node is easily interfaced to a Notebook or PC running Windows 7, 8 and XP and Physical Acoustics Corporation’s (PAC) well known AEwin Software.
- The data is stored in .DAT, .xls and .csv extensions in computers hard disk.

7.2 Importing the data into MATLAB for signal processing and analysis:

The data in csv format is imported into MATLAB arrays using xlsread function (ignoring the first 13 unwanted data lines) in the .xls file and plotting it using the following piece of MATLAB Code for “Good” sample as well as “Lack of Penetration” acoustic signatures.

Program:

```
clc;clear all;close all;
p=dir('D:\B.Tech\Mini Project\AE ANSII DATA\Series 01\Good\*.csv');
num=cell(size(p));
for i=1:length(p)
```

```
num{i}=xlsread(['D:\B.Tech\Mini Project\AE ANSII DATA\Series 01\Good\',p(i).name],'A13:A1036');
end
m=cell2mat(num);
fs=600000;
ts=1/fs;
x=length(m);
tmax=(x-1)*ts;
t=0:ts:tmax;
figure;plot(t,m)
freq=[1:x]*(fs/x);
xdft=fftshift(fft(m,x));
mag=abs(xdft);
figure;plot(freq,xdft)
```

From the above code we can observe that

1. The cell size is generated based on the no. of files in specifies and
2. The data is read and imported in MATLAB arrays for manipulation.

The data in csv format is imported into MATLAB arrays using xlsread function.

3. The first 13 unwanted data lines are ignored in the .xls file using the following piece of MATLAB.
3. The time axis is generated and the values are plotted as function of time.

Analysis in frequency domain:

Here the after the signal is generated in time domain it is converted into frequency domain for further analysis using the predefined function fftshift in MATLAB.

Program:

```
freq=[1:x]*(fs/x);
xdft=fftshift(fft(m,x));
mag=abs(xdft);
figure;plot(freq,xdft)
```

```
figure;plot(freq,mag)
```

7.3 Computing various signal parameters.

Parameters such as time, amplitude, frequency and magnitude for various signatures are computed from the signals generated by the above MATLAB codes. These signal parameters helps us in finding out the defect of a given signature.

The frequency domain plot is obtained.

The magnitude plot is generated.

CHAPTER 8: RESULTS

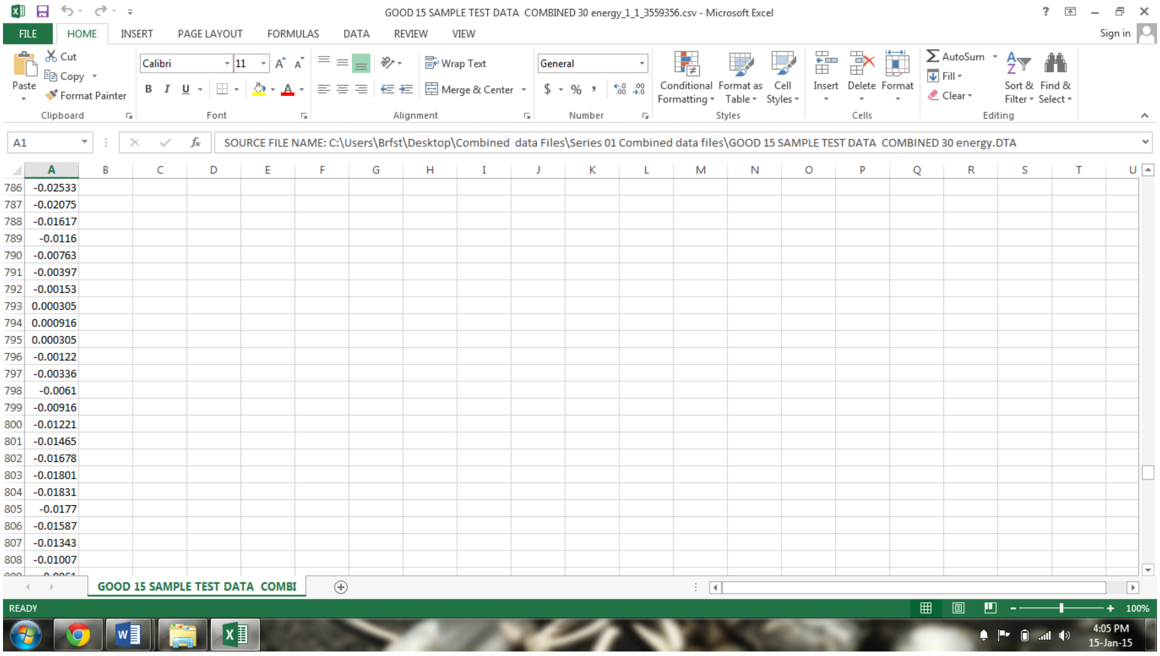


Figure 17 Sample test data of GOOD sample showing various amplitude values

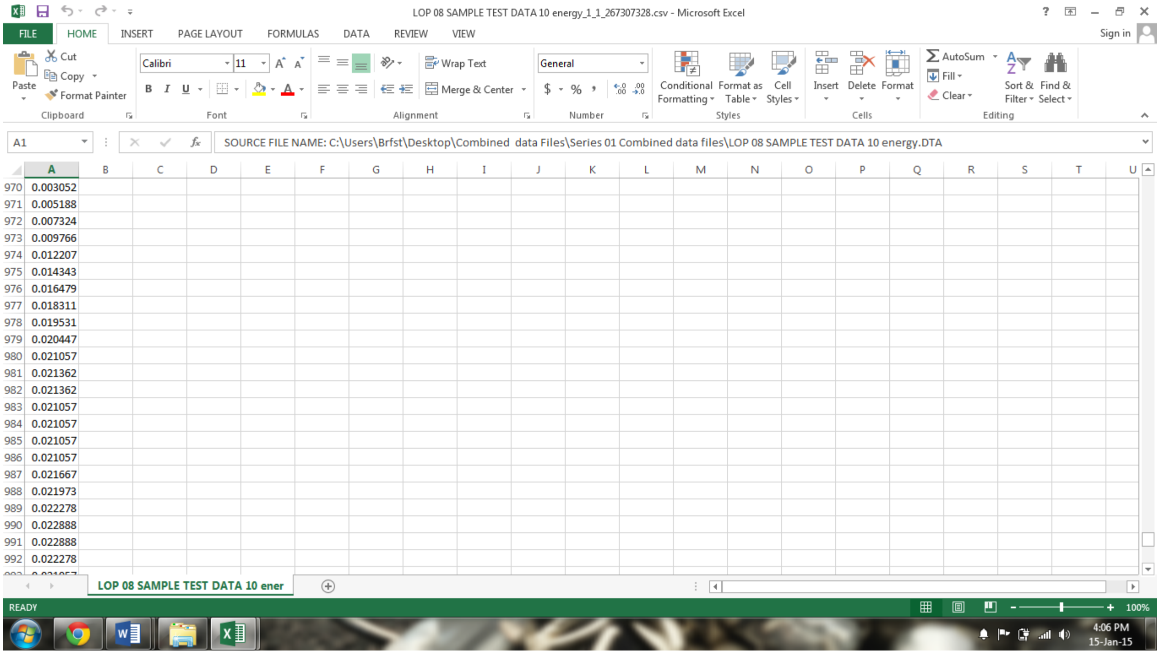


Figure 18 Sample test data of LOP Defect showing various amplitude values

8.1 "Good" Sample Waveforms:

8.1.1 Time domain signal:

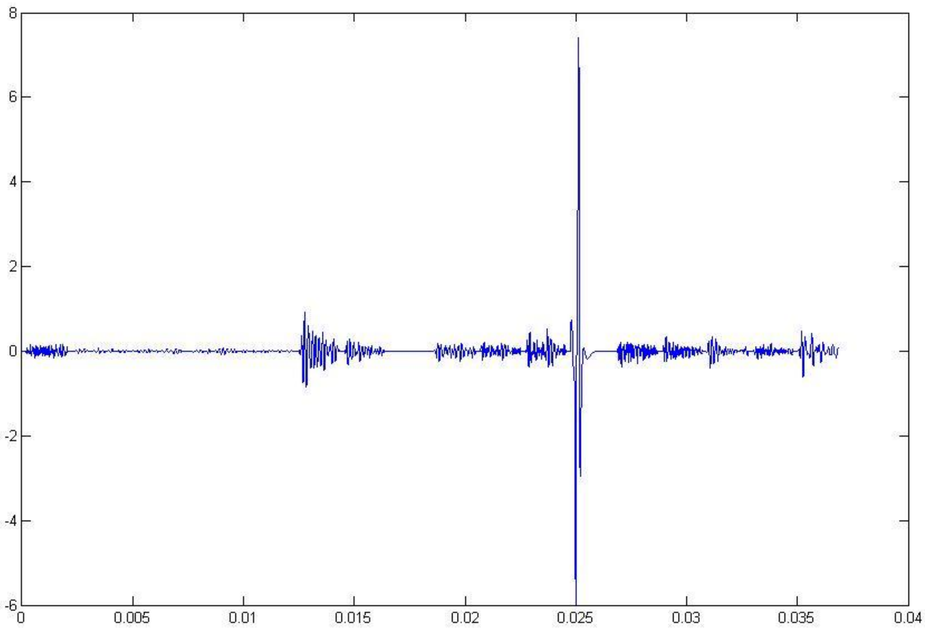


Figure 19 Time vs Amplitude plot of GOOD Sample

Observations

The variations of amplitude between the extreme values during entire time period of load application is noted. Since dominant frequency needs to be evaluated we consider fourier transform for analysis in frequency domain.

8.1.2 Frequency domain signal:

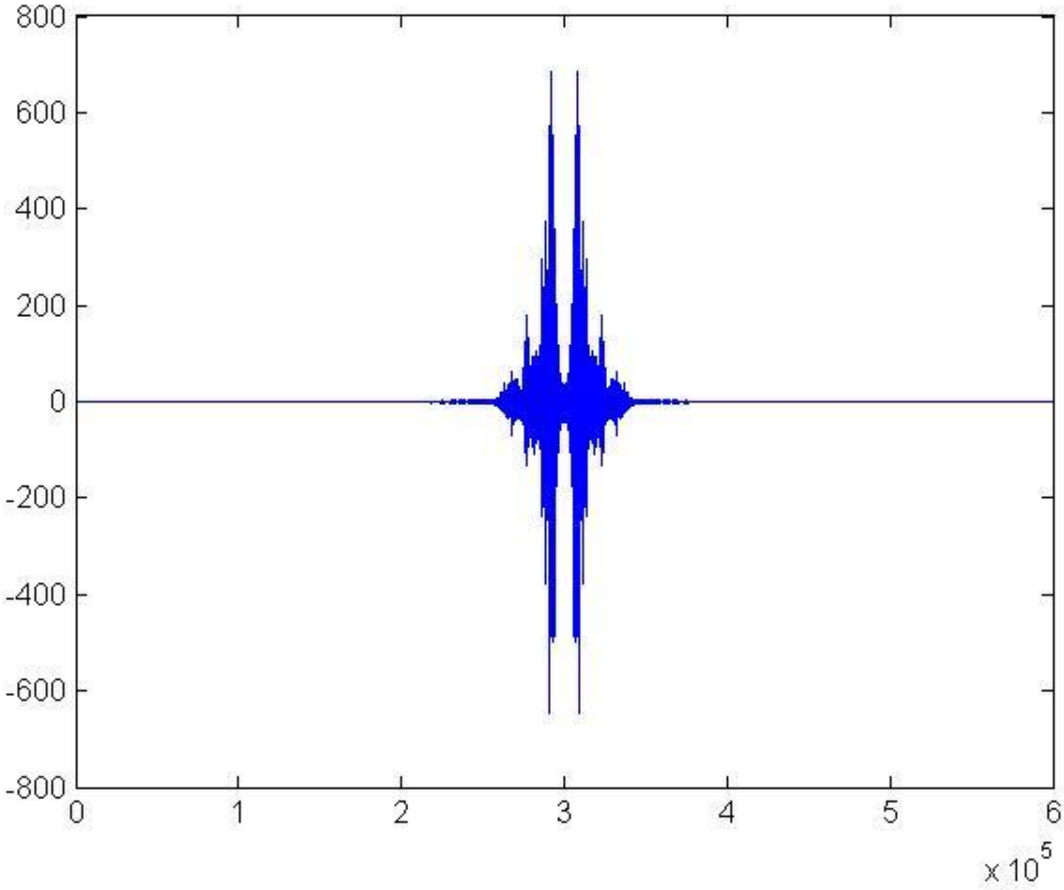


Figure 20 Frequency vs Magnitude plot of GOOD Sample

Observations

The frequency response of Acoustic Emission values for the GOOD sample during entire time period of load application can be seen. The frequency response are observed to be in the order of 10^5 for this GOOD sample. Almost all of the frequency response is the range of 2.5×10^5 to 3.5×10^5

8.1.3 Magnitude Plot in frequency domain:

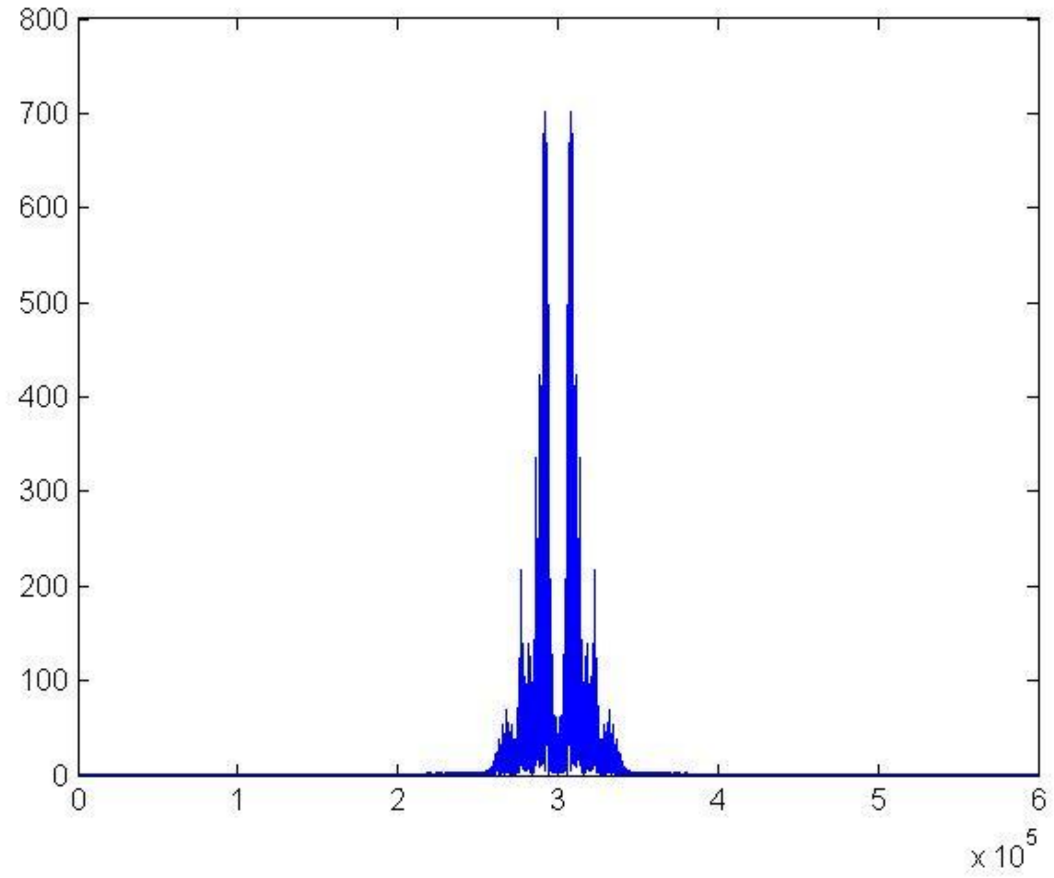


Figure 21 Frequency vs Magnitude (abs) plot of GOOD Sample

Observations

The magnitude of frequency response has been considered for better identification and isolation of dominant frequencies present in Acoustic Emission values for the

GOOD sample during entire time period of load application.

The dominant frequency is found to be 3.2 x 10^5 Hz.

8.2 Lack Of Penetration

8.2.1 Time domain signal:

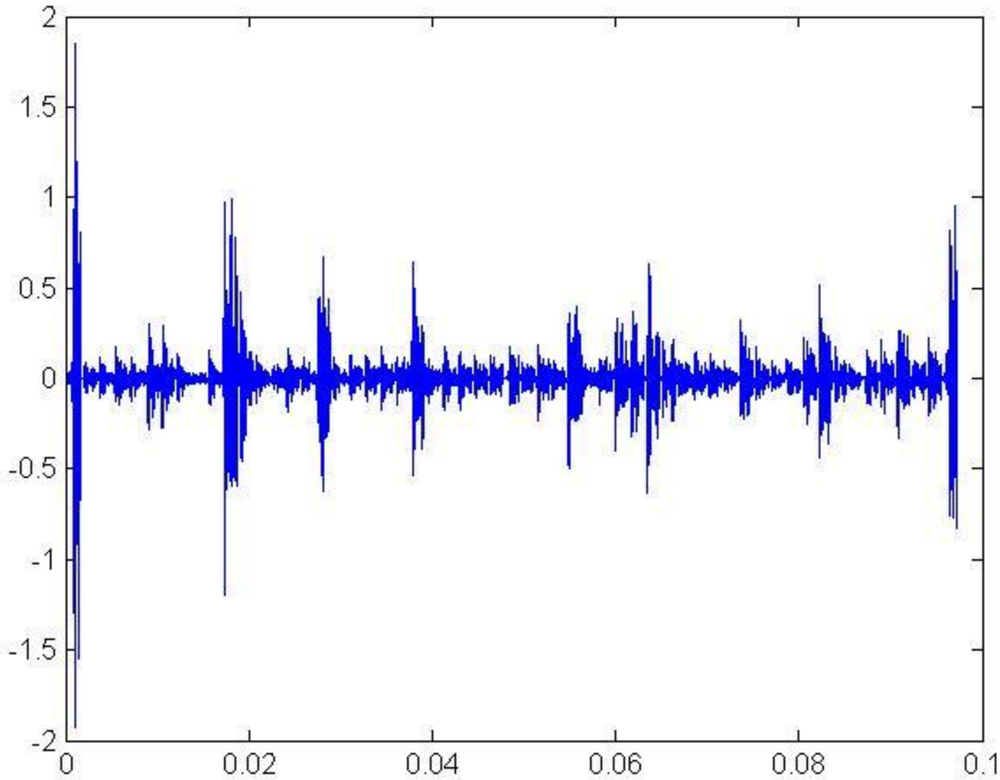


Figure 22 Time vs Amplitude plot of LOP Sample

Observations

The variations of amplitude between the extreme values during entire time period of load application is noted. Since dominant frequency needs to be evaluated we consider fourier transform for analysis in frequency domain.

8.2.2 Frequency domain signal:

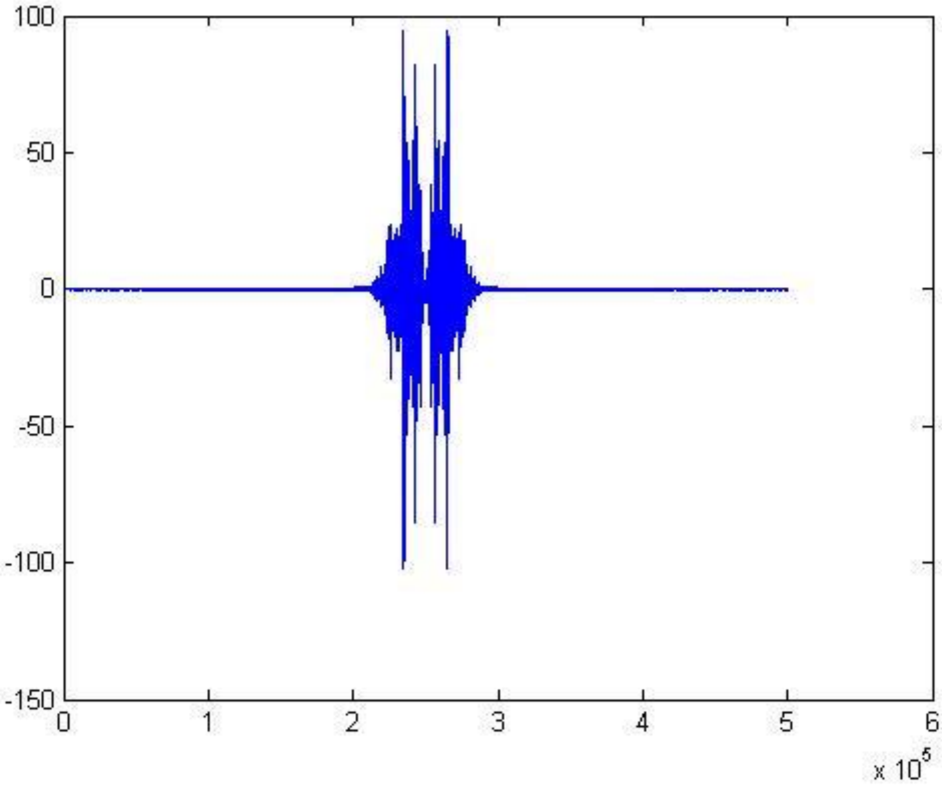


Figure 23 Frequency vs Magnitude plot of LOP Sample

Observations

The frequency response of Acoustic Emission values for the LOP sample during entire time period of load application can be seen. The frequency response are observed to be in the order of 10^5 for this LOP sample. Almost all of the frequency response is the range of 2.0 x 10^5 to 2.8 x 10^5 Hz

8.2.3 Magnitude Plot in frequency domain:

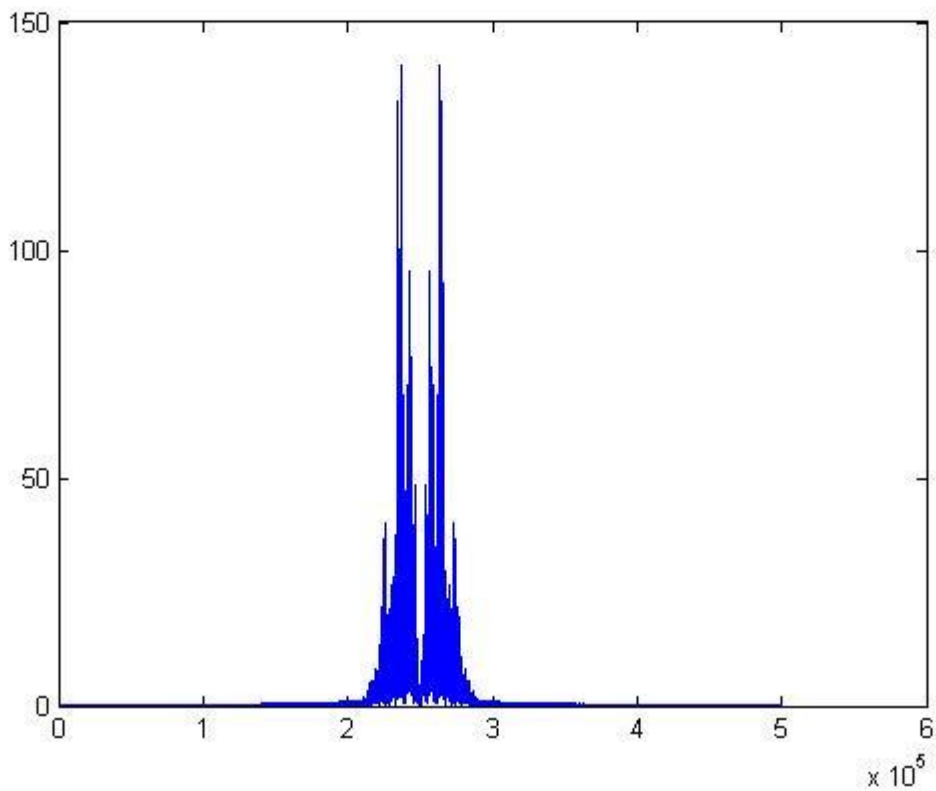


Figure 24 Frequency vs Magnitude (abs) plot of LOP Sample

Observations

The magnitude of frequency response has been considered for better identification and isolation of dominant frequencies present in Acoustic Emission values for the LOP sample during entire time period of load application. The dominant frequency is found to be $2x10^5$ Hz.

CHAPTER 9: CONCLUSIONS

Acoustic Emission signatures of welded defect samples are obtained by using 4-Channel AE nodes and sensors namely PK6I and R6α. These sensors are having resonant frequency 90/100 KHz signatures are obtained by AEWin software. Processed AE signatures are analyzed in time domain and frequency domain methods using MATLAB software. The salient features are mentioned below for analysis of these Acoustic Emission Signatures for ***GOOD*** and ***LACK OF PENETRATION*** defected materials.

- The overall plot of large amount of data generated by Acoustic Emission Sensors in many trials and plot it in one graph in time domain has obtained.
- The ***fftshift*** mode of Fourier Transform which moves the zero-frequency component to the center of the array has been performed. It is useful for visualizing a Fourier transform with the zero-frequency component in the middle of the spectrum.
- The magnitude plots of this data has also been obtained.
- Trials are made to identify the dominant frequency for each of the defects.

- Trials are underway to obtain wavelet transform which is used to obtain dominant frequency, this type of approach is used in major research fields to analyze large chunks of data.

CHAPTER 10: FUTURE SCOPE

- The use of Acoustic Emission will become more prevalent because it can provide unique insights into damage processes. The problems of Acoustic Emission including noise reduction, reliability, and difficulty in solving the inverse problems of wave propagation in source-function and waveform analyses—represent areas of future endeavor in Acoustic Emission science and technology. There is also a great need for work to develop Acoustic Emission theories for new applications.

- Trials are made to identify the dominant frequency for each of the defects.
- Trials are underway to obtain wavelet transform which is used to obtain dominant frequency, this type of approach is used in major research fields to analyze large chunks of data.

CHAPTER 11: APPLICATIONS

The application of acoustic emission to non-destructive testing of materials, typically takes place between 100 kHz and 1 MHz. Unlike conventional ultrasonic testing, Acoustic Emission tools are designed for monitoring acoustic emissions produced within the material during failure or stress, rather than actively transmitting waves, then collecting them after they have travelled through the material. Part failure can be documented during unattended monitoring. The monitoring of the level of Acoustic Emission activity during multiple load cycles forms the basis for many Acoustic Emission safety inspection methods that allow the parts undergoing inspection to remain in service.

The technique is used, for example, to study the formation of cracks during the welding process, as opposed to locating them after the weld has been formed with the more familiar ultrasonic testing technique. In a material under active stress, such as some components of an airplane during flight, transducers mounted in an area can detect the formation of a crack at the moment it begins propagating. A group of transducers can be used to record signals, then locate the precise area of their origin by measuring the time for the sound to reach different transducers. The technique is also valuable for detecting cracks forming in pressure vessels and pipelines transporting liquids under high pressures. Also, this technique is used for estimation of corrosion in reinforced concrete structures.

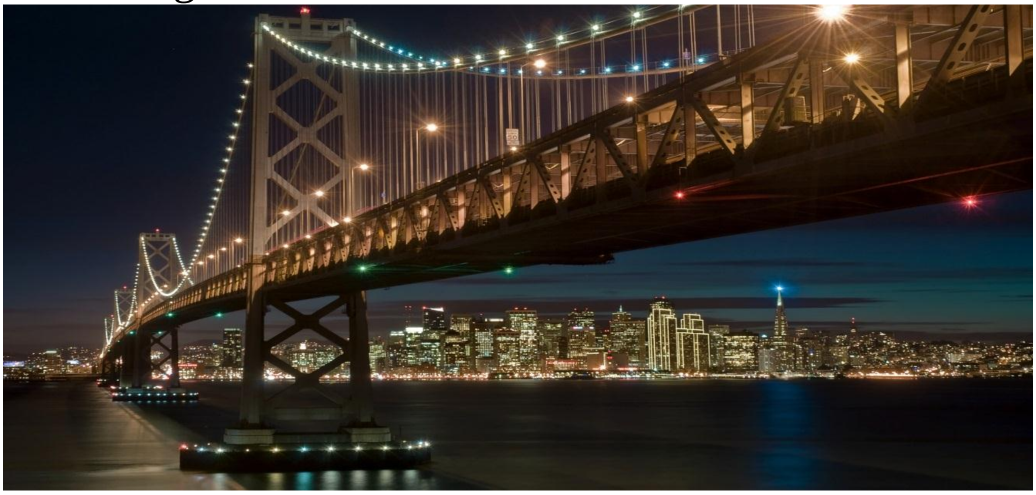
In addition to non-destructive testing, acoustic emission monitoring has applications in process monitoring. Applications where acoustic emission monitoring has successfully been used include detecting anomalies in fluidized beds, and end points in batch granulation.

11.1 Gas Trailer Tubes

Acoustic emission testing on pressurized jumbo tube trailers was authorized by the Department of Transportation in 1983. Instead of using hydrostatic retesting, where tubes must be removed from service and disassembled, Acoustic Emission Testing allows for in situ testing. A 10% over-pressurization is performed at a normal filling station with AE sensors attached to the tubes at each end. A multichannel acoustic system is used to detection and mapped source locations. Suspect locations are further evaluated using ultrasonic inspection, and when defects are confirmed the tube is removed from use. AET can detect subcritical flaws whereas hydrostatic testing cannot detect cracks until they cause rupture of the tube. Because of the high stresses in the circumferential direction of the tubes, tests are geared toward finding longitudinal fatigue cracks.

11.2 Bridges

Bridges contain many welds, joints and connections, and a combination of load and environmental factors heavily influence damage mechanisms such as fatigue cracking and metal thinning due to corrosion. Bridges receive a visual inspection about every two years and when damage is detected, the bridge is either shut down, its weight capacity is lowered, or it is singled out for more frequent monitoring. Acoustic Emission is increasingly being used for bridge monitoring applications because it can continuously gather data and detect changes that may be due to damage without requiring lane closures or bridge shutdown. In fact, traffic flow is commonly used to load or stress the bridge for the AE testing.



11.3 Aerospace Structures

Most aerospace structures consist of complex assemblies of components that have been design to carry significant loads while being as light as possible. This combination of requirements leads to many parts that can tolerate only a minor amount of damage before failing. This fact makes detection of damage extremely important but components are often packed tightly together making access for inspections difficult. AET has found applications in monitoring the health of aerospace structures because sensors can be attached in easily accessed areas that are remotely located from damage prone sites. AET has been used in laboratory structural tests, as well as in flight test applications. NASA's Wing Leading Edge Impact Detection System is partially based on AE technology. The image to the right shows a technician applying AE transducers on the inside of the Space Shuttle Discovery wing structure. The impact detection system was developed to alert NASA officials to events such as the sprayed-on-foam insulation impact that damaged the Space Shuttle Columbia's wing leading edge during launch and lead to its breakup on reentry to the Earth's atmosphere.

11.4 Damage assessment of composites using Acoustic Emission

Project Aims

The aim of the project is to investigate acoustic emission (AE) from composites and to develop a technique to assess impact damage. Specific aims are:

- Manufacture a buckling a test rig and confirm loading conditions through finite modelling.
- To characterize the damage mechanisms of composites in terms of AE signals.
- Investigate the use of AE to identify buckling patters of composite plates.

11.5 Medical applications for Acoustic Emission

Project Aims

Quality control in orthopaedic diagnostics requires methods of non-destructive processes which do not harm the patient either by radiation or by an invasive examination. There is currently no non-invasive evaluation method for the state of wear regarding human joints, and it is not possible to quantify joint condition from patient report as every patient has different levels of tolerance to pain.

Initial trials shows that the analysis of Acoustic Emission (AE) signals from sensors attached to human joints that it may be possible to grade levels of joint degradation.

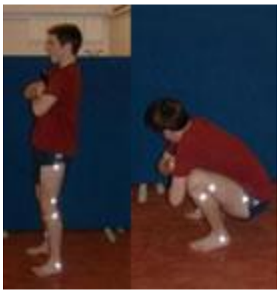
Initial Trials

Sensor Selection

Although there is a desired frequency range for AE signals sensor selection was determined by size of sensor. A large sensor limited knee movement and was difficult to attach. Noise due to sensor slipping was also problematic (above). A sensor with a small height was selected for practicality.

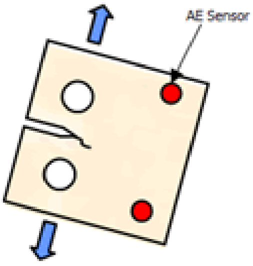
Sensor Attachment

Sensor attachment was achieved using medical tape, a medical grease was used as a couplant. As the sensor is attached to the skin near to the joint there is no evasive process also the process causes no pain and no harm to the body unlike x-rays.



Loading of Joint

The joint was loaded by natural body movements. The loading of the knee was achieved by a simple squat process. The rotation of the knee joint was monitored using motion analysis (fluorescent balls above). Results showed that the greatest AE signals occurred at the point of maximum load of the joint.



Bone Cement Samples

Samples of bone cement cast into compact test specimens were fatigued under conditions found in the human body. AE showed that it was possible to detect and locate small changes in crack length.

CHAPTER 12: REFERENCES

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