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Abstract

The repetitive cyclic loading are the main cause of fatigue in metals and consequently their failure. Furthermore, the defects due to fatigue such as surface breaking and sub-surface, drastically effects the integrity of the structures. Therefore, to achieve high-quality performance and profitability of the structure or a component, they need to be detected and characterize on time concerning their type, location, length, depth, width, and orientation. For this purpose, a lot of detection techniques have been introduced and employed widely. However, the role of Non-Destructive Testing (NDT) methods is vital in this regard due to its high reliability and versatility.

This thesis work aims to evaluate the different types of NDT techniques, to detect the fatigue cracks in metals. For this reason, several most common NDT techniques including electromagnetic and contact/non-contact types are thoroughly described and compared in the light of the previous researches done by many researchers. Namely Ultrasonic Testing (UT), Magnetic Particle Inspection (MPI), Radiographic Testing (RT), Acoustic Emission (AE), Eddy Current (EC), Liquid/Dye Penetrant Testing (DPT), Alternating Current Field Measurement (ACFM), Visual Inspection (VI) and Thermographic Testing.

Moreover, efforts are made to bring out the detection capabilities and limitations, primarily to enable the selection of an appropriate technique for a specific application such as automated testing capability, derived from an operator-independent concept, with the potential of complete characterization of defects in a material.

Acknowledgements

I have gained valuable knowledge in the detection of fatigue cracks in metals using several non-destructive testing techniques, while writing this master thesis.

Throughout the project, my supervisor *Fredrik Bjorheim* has helped me a lot in getting good literature by suggesting different authentic sources. Therefore, I am very grateful to him in this regard.

Finally, I dedicate this thesis work to all the researchers and inspectors, who have worked and constantly working in the development of non-destructive testing techniques. Thus, providing reliable structures to the society.

Table of Contents

Chapter 1: Introduction 6

1.1 Historical Perspective 6

1.2 Crack detection Methods 8

Chapter 2: Theory of fatigue and NDT 9

2.1 Fatigue in Metals..9

2.2 The Fatigue process 9

2.3 Importance of well-defined inspection strategy 11

2.3.1 Inspection procedures and outcomes 12

2.4 NDT Reliability 13

2.5 Methods of Assessment of NDT Reliability 13

2.5.1 What is Probability of Detection (POD)? 13

2.5.2 Measuring POD Curve 16

Chapter 3: Non Destructive Testing (NDT) Techniques....................................20

3.1 Literature Review..20

3.2 Benefits of NDT inspection 22

3.3 The detection Techniques 23

3.3.1 Ultrasonic testing 23

3.3.2 Magnetic Particle Inspection 32

3.3.3 Radiographic Testing 37

3.3.4 Acoustic Emission 40

3.3.5 Eddy Current 43

3.3.6 Dye Penetrant Testing 49

3.3.7 Alternating Current Field Measurement 50

3.3.8 Visual Inspection 53

3.3.9 Thermography 54

3.4 Summary of detection techniques 58

Chapter 4: Discussion & Comparison 59

Chapter 5: Conclusion..63

Chapter 6: Suggestions & Recommendations..63

Chapter 7: Reference List 64

List of figures

Figure 2.1 The classic curve of fatigue crack development [11] unmodified, CC BY 3.0 10
Figure 2.2 POD curves for EC, MPI, ACFM & UT [23] unmodified, CC BY 4.0 14
Figure 2.3 Illustration of Ideal and Real POD curve [25] unmodified, CC BY 3.0................................... 15
Figure 2.4 Depiction of POD curve with 95% confidence level [25] unmodified, CC BY 3.0................. 18
Figure 3.1 Showing Ultrasonic beam focusing on a defect ∅ with area A[25] unmodified, CC BY 3.0.... 23
Figure 3.2 POD curves of defects classified as a) LF and b) LP [25] unmodified, CC BY 3.0 25
Figure 3.3 ToFD arrangement showing defect’s edges diffracting incident waves[55] unmodified, CC BY 4.0 26
Figure 3.4 Illustration of the shape of a defect in ToFD method [55] unmodified, CC BY 4.0 26
Figure 3.5 Illustration of Echoes detected in ToFD [55] unmodified, CC BY 4.0 27
Figure 3.6 Illustration of Pulsed-Echo technique [57] unmodified, CC BY 3.0.. 28
Figure 3.7 Illustration of an ultrasonic wave passing in Pulse-echo UT method; without the defect and with the defect [58] unmodified, CC BY 4.0 29
Figure 3.8 Illustration of the multi-scanning array used in pulsed-echo UT method [58] unmodified, CC BY 4.0 30
Figure 3.9 Illustration of Through-Transmission technique [57] unmodified, CC BY 3.0 31
Figure 3.10 Showing MFL inspection of pipeline[62] unmodified, CC BY 3.0 34
Figure 3.11 The illustration of working arrangement of the SMLF technique [69] unmodified, CC BY 3.0 36
Figure 3.12 Illustration of an X-ray imaging system [72] unmodified, CC BY 3.0 38
Figure 3.13 Illustration of typical simulation steps of radiographic testing[73]unmodified, CC BY 3.0... 39
Figure 3.14 Illustration of AE receiving the waves generated from crack growth [75] unmodified, CC BY 3.0 40
Figure 3.15 Illustration of the methodology of determination of POD of a defect with AE [76]............... 42
Figure 3.16 Showing typical eddy current testing[79] un-modified, CC BY 3.0 45
Figure 3.17 Possible experimental arrangement of SQUID based eddy current [80] un-modified, CC BY 3.0 47
Figure 3.18 Showing the indication of a defect in the test specimen in DPT[61] unmodified, CC BY 3.0 49
Figure 3.19 The ACFM’s defect detection system[88] unmodified, CC BY 3.0 51
Figure 3.20 The Schematic representation of ACFM with ‘Butterfly plot’[88] unmodified, CC BY 3.0.. 52
Figure 3.21 A possible arrangement of active thermographic inspection [93] unmodified, CC BY 3.0.... 56
Figure 4.1 Depiction of different NDT method’s 90% pod and required crack depth............................... 61

Chapter 1: Introduction

The repetitive cyclic tensile loadings are the main factor of fatigue crack initiation and its growth in metals. Consequently, the member fails if a crack extends in an unstable mode because then it will not allow member to resist the internal stresses anymore. However, in fracture mechanics, existing flaws and tensile stresses are the two primary conditions considered for crack growth in metals.

The engineering structures such as steel bridges, gantry girders, crane support structures, marine structures and machine's components are more susceptible to fatigue cracking. However, they are exposed to four different types of loads. Such as.

- Fixed.
- Variable.
- Environmental.
- Seismic.

The fixed and variable loads are generally present in all engineering structures. Whereas, the environmental load like wind load is also of great importance while designing of marine structure, because in such cases, steel or any other metal are required to sustain an infinite number of loading cycles at low stresses during service life.[1]

1.1 Historical Perspective

The materials used in construction before the 19th century or industrial revolution was primarily stone, timber, mortar, and brick, because the production of metals especially steel and iron was limited. As a result, it was not widely and readily available for construction purposes at that time. For this reason, ancient structures were usually comprised of columns and arches, which were all made up of brittle material that were known to carry compressive loads only. Therefore, exploiting the materials characteristics. However, with the mass production of steel and iron during the industrial revolution, this restriction was removed and metals were incorporated to withstand the tensile stresses in load-bearing structures.

Steel is a metal that has very high tensile strength. However, it was noted that the structures built using steel is getting failed unexpectedly at stresses well below its expected tensile strength. For instance, the rupture of the molasses tank in January 1919 at Boston, USA is a famous example of fatigue failure. Consequently, the disaster resulted in 12 deaths, several injuries, property damage/loss in addition to 2 million gallons of molasses were wasted.

Similarly, another incident happened in 1842 at Versailles, France, due to the fatigue damaging. However, a German scientist *August Wohler* (1819-1914) discovered that it was due to repeated 'low level' cyclic stress in locomotive's axle. Moreover, he also discovered that fatigue life of metal increases with decreasing in applied stress and decreases drastically in the presence of notches or cracks. He represented his results in tabular form. Later, *Spangenberg* (1874 and 1879) plotted the *Wohler's* data into curves along linear abscissa and ordinate, known as 'Wohler curves'.

Furthermore, the famous Liberty ships incident during World War II are the indication of unexpected and undesirable failure due to the application of a new design and fabrication procedure in the vessel structure, without proper skills and the knowledge of fracture mechanics. During the early phase of World War II, the German navy destroyed the supply line of the British at a much faster rate. On the other hand, the ship building was taking a long time. For this reason, a famous American construction engineer '*Henry Kaiser*' developed a new strategy to pace up the process of building vessels. Therefore, he started welding the ships instead of riveting them, as opposed to traditional design. However, it was a great success until one vessel broke into two while navigating in 1943, between Siberia and Alaska. Correspondingly, several other ships were also severely damaged under the same condition and causes.

The following factors came out to be responsible for the investigation of the Liberty Ships incident.

- There was a local stress concentration on the deck at square hatch corners, where fracture initiated.
- The steel used in shipbuilding is of inadequate quality i.e. poor toughness.
- The welds contain crack-like flaws.

In contrast to previously designed riveted hulls. The material (steel) was inappropriate to function properly in the newly designed welded structure because it started acting like one plate, having no barrier to stop the crack growth from one plate to another, also welding flaws further accelerated the crack growth. However, in riveted hulls, crack was limited to the plate, it initiated in. [2, 3]

The disaster of semi-submersible '*Alexander L. Kielland*' happened on 27th March 1980 is one of the most famous and recent examples of fatigue failure crack propagation, due to manufacturing fault. According to investigation reports, the sequence of failure occurs due to the fatigue crack propagation, originated from the previous one, located in the weld joint among the brace and hydrophone support. The crack propagation starts around and inside the insert and brace that causes it to fail due to overload. Subsequently, other braces of columns that joining them to rig broke off due to overload and the platform couldn't keep its balance and capsized. As mentioned above, the main cause of the disaster came out to be a manufacturing fault i.e. the welding defects in the fillet welds around the hydrophone. Moreover, during an inspection, it was found that the circular hole carved in the brace to connect the hydrophone was poorly done and was not as per specifications. Therefore, while installing hydrophone, the welding defects like porosity, slag, and incomplete penetration was unintentionally introduced in the heat-affected zones (HAZs) of the hydrophone. Furthermore, the stress concentration factor (k) in the fillet weld of the hydrophone was also found to be higher than the normal ones. [4]

Thus, the examples above depicted the vitality of proper and detailed inspection of structures by using modern tools, to prevent the major structural failures. Following this, researchers accelerated their research in fracture mechanics and defect detection fields such as NDT, which led to the development of CTOD, stress intensity factor (K) by Irwin, J integral by Rice, etc. As a result, now a days, the inspection is carried out at much more advanced level particularly due to NDT. However, they also contain some uncertainties and limitations but it highly depends upon their application and reliability of specific technique. [2] Moreover, modern tools, and international standards were also developed for instance ISO 2394 (ISO 1998), ISO 19901-9 (ISO 2017), and ISO 19902 (ISO 2007). [5]

1.2 Crack detection Methods

The defect detection methods can be categorized as destructive and non-destructive. However, only non-destructive testing (NDT) methods will be discussed here. Furthermore, the selection of NDT method highly depends upon the type of joint and type defect to be detected. They can also split into contact and non-contact methods i.e. some methods needs to be in touch with the surface of the material to perform testing, as shown in table 1. For instance, fatigue life can be drastically reduced due to surface-breaking defects in a material. For this purpose, Magnetic Particle Inspection (MPI) technique can be employed to identify it. Because it is a fast, reliable, and inexpensive method. Similarly, the detection of internal flaws in a material can be done by Ultrasonic testing (UT) or Radiographic testing (RT) method. In addition, some other conventional non-destructive methods are Visual Inspection (GVI), Eddy Current (EC), Liquid/Dye penetrant testing (DPT), Alternating Current Field Measurement (ACFM), and Acoustic Emission (AE). [5]

Table 1 The conventional contact and non-contact NDT methods.[5]

Contact Methods	Non-Contact Methods
Ultrasonic testing	Radiographic testing
Eddy Current	Visual Inspection
Magnetic particle inspection	Alternating Current Field Measurement
Dye penetrant testing	Thermography
Acoustic Emission	

Chapter 2: Theory of fatigue and NDT

This chapter briefly explains the theory of the Non-Destructive Testing (NDT) methods, used in the detection and inspection of fatigue cracks in metals. It also demonstrates the concept of POD, reliability and different methods and equations (if any), used in their evaluation.

2.1 Fatigue in Metals

The industrial revolution was closely related to the development in the transportation industry, especially in rail transport. However, means of transportation such as vehicles are more exposed to variable loads. Likewise, they are more susceptible to an unexpected premature failure of the components of machines due to fatigue that can lead to sudden rupture of the whole structure. Certainly, as discussed earlier, the first accident due to fatigue failure happened in Versailles in 1842, which was investigated by a famous German scientist, *August Wohler*. In the late 19th and early 20th century, the subject of fatigue of materials was of paramount importance among researchers and scientists. Therefore, extensive investigation was carried out, particularly in the manufacturing and development of anti-fatigue components for the automotive and aircraft industry. [6]

The concept "Fatigue in metals" defines the degradation of a material under cyclic loading, introduced during 1837-1839 by a famous scientist, author, and mechanic; *J. B. Poncelet* in his lectures. [7] Similarly, in 1843, a famous Scottish mechanical engineer *W. J. M. Rankine,* and in the same period, a French engineer *Morin* also illustrated the phenomenon of fatigue fracture of cars and stagecoaches axles. [8, 9].

In addition to above, a German scientist, *August Wohler* has also done a lot of work in the field of fatigue of materials. For instance, he presented the concepts of the material's response under repeated loading and fatigue limit under the influence of residual strains, etc. Moreover, his investigations and experimental results were used as the guiding principles in the late 1800s and beyond. Furthermore, in 1870, he presented a general law, which states that "The rupture cause due to steady load and cyclic stresses that are beyond the carrying strength of a material. The difference of these stresses is the measure of the disturbance of the continuity, so far as by their increase in the minimum stress, which is still necessary for rupture diminishes". [10]

2.2 The Fatigue process

The two most important parts of any material's fatigue life are the fatigue crack initiation and its growth.

In fact, the development of fatigue crack can be classified into three parts, such as.

- Crack Initiation (Region I).
- Crack Propagation (Region II).
- Final failure (Region III).

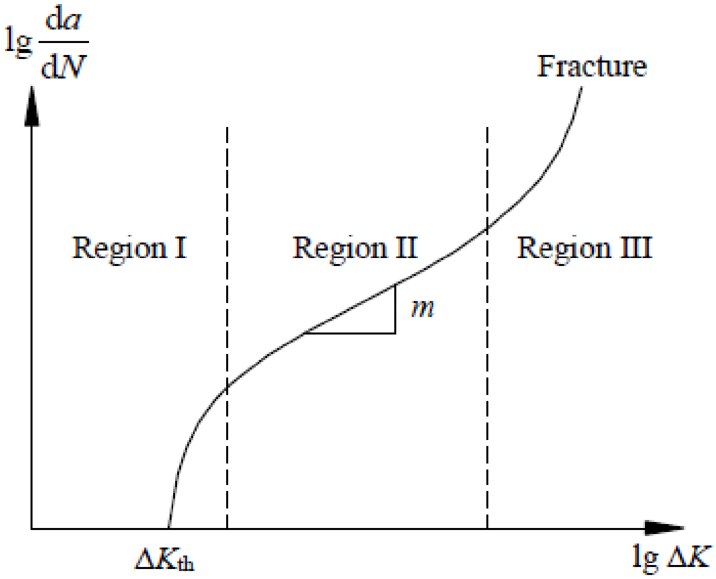


Figure 2.1 The classic curve of fatigue crack development [11] unmodified, CC BY 3.0

1. *Crack initiation*: The crack initiates in this regime due to induced stress that goes above the threshold level at any free surface particularly at hotspots or areas of localized stress concentration such as keyways, bolt holes, tool marks, etc. in a structure or component. However, in homogenous materials, the main cause of the formation of a fatigue crack is the cyclic straining results in the formation of persistent slip bands (PSBs), a structural dislocation of the bands of localized slip. Its detection in bulk is common for surface grains because they are less restrained as bulk material. In contrast, in heterogeneous materials, crack usually starts from pre-existing defects or intrusion in a material.

2. *Crack propagation*: The crack continues to grow in this regime due to induced stress. However, several other parameters like location, stress range, geometric properties of the structure also deeply influence the crack growth. Correspondingly, the *Paris law*, as shown in equation (1) is commonly incorporated to predict the length of the crack used in fracture mechanics. Yet, it can also be used to express the fatigue crack rate in metals and is only valid in region II.

$$\frac{da}{dN} = C(\Delta K)^m \qquad (1)$$

Where a, N, and ΔK represent the crack length, a number of cycles, and stress intensity factor respectively. Furthermore, C and m are material parameters.

3. *Final failure*: The failure occurs when the applied stress makes the cross-sectional area to reach the ultimate level. Where its resistance becomes inadequate to withstand any more load and any further induced stress will cause a fracture to the component. [1, 12-14]

Moreover, the fatigue life of structure under a constantly applied stress ratio can be expressed by the *stress life method*, as shown in equation (2).

$$NS_{max}^{m} = C \tag{2}$$

Where N and S_{max} represents the cycle number under S_{max} and maximum stress. And m and C are parameters of the material. However, due to a small variation in 'm', it can be treated as a constant value. Although, It is effected by several factors such as material properties, temperature, design geometry, etc.[15]

2.3 Importance of well-defined inspection strategy

Inspection is one of the main activities to minimize and mitigate uncertainties and risks in structures. The main purpose is to ensure that structural integrity is maintained and monitoring the status of degradation of a material. [12] However, corrosion and fatigue crack growth are two main parameters involved in degradation and consequent failure of structures. Comparatively, corrosion can be controlled by incorporating different techniques such as by using corrosion allowance in design calculation, using the protection system by anodes and coating/painting. Whereas fatigue crack growth is more critical because it causes sudden failure of structure or component and difficult to detect due to its rapid growth. [16].

Since inspection and repair cost of structures particularly marine or offshore structures like wind turbines are very expensive and unreliable, when in service. Therefore, it is always preferred to inspect such structures before putting them into the operation or service. The behavior of structure concerning fatigue cracking depends upon the amount of data available, the more information available the more predictable and reliable behavior will be and vice versa. But due to the nature of fatigue and uncertainties involved, the detection of a fatigue crack is always a challenge. In inspection planning, if the inspection is not yet been made then it doesn't influence the outcome of the estimated future probabilities. However, the terms Inspection planning and reliability or inspection updating are co-related to each other, they can be defined as 'The inspection updating is using the information collected through the previous inspection whereas inspection in future can be termed inspection planning". And reliability updating is "the usage of the information collected at different time intervals over the service life of structure". [17]

Ojha et al. (2014) [1] in their paper "*Fatigue: A disastrous failure of welded structure*" concluded that according to research in the field of fatigue failure, it is now a well-known fact that the inappropriate structural design is not solely responsible for the failure of the structure. There are also some other factors involved such as geometric factors and structure's imperfection. Therefore, detailed and proper inspection of the structure, done by well-trained inspectors with the latest tools is necessary, before putting it into service. However, the incident of '*Alexander L. Kielland',* as discussed earlier, happened due to the manufacturing flaw in a structure that seemed to be overlooked or neglected due to improper inspection, edifies the importance of using NDT techniques during an inspection.

Although, several NDT methods are available during an in-service inspection, to detect different types of defects in structures or components such as pipeline, offshore structure, etc. However, due to the high cost and lengthy procedure, it is vital to fully understand the type of defect and location before choosing any technique. For this purpose, the *risk-based inspection* (RBI) method is widely employed since 1970s. It can be defined as, it is a risk-based decision-making tool used in inspection planning that evaluates the probability of failure (POF) of a structure. The strategy is used to determine the optimum inspection intervals, inspection details, and a suitable technique. Moreover, the procedure consists of establishing the ranking table based on the evaluation of the risk of POF of structure and its consequences. Afterward, the inspection interval range is determined through a level of risk of potential failure and thus, the best NDT technique is employed for inspection. Furthermore, the capability of any NDT technique is usually expressed by a term called the *probability of detection* (POD). Although, many modern and advanced NDT techniques are available during an in-service inspection but 90% of conventional NDT techniques such as MPI, DPI, EC, RT, and UT are frequently used, which are less effective and less expensive. Comparatively, techniques such as AE (if used along with other techniques) and TOFD are costly but highly effective. [18, 19]

2.3.1 Inspection procedures and outcomes

To evaluate the condition and status of degrading structure, quantitative data is required. It also provides the guidance tool to the technical staff, managers, and owners to analyze the cost-effective optimum maintenance strategy to increase the service life of the structure. Furthermore, in inspection year, usually two types of inspections are carried out, either determined through RBI or any other method. The purpose of the first type is to detect a defect only and if a defect is successfully identified then the second inspection is carried out to determine the defect size. Moreover, the simulation of maintenance and repair of the structure can be expressed through different methods such as *Markov matrices* and *Reliability-based* methods. According to the *Markov matrices* method, if the size of the defect is above the threshold value than repair work is carried out. However, due to uncertainties present in inspection during detection and assessment, problems may occur that can lead to failure of structure or component. Consequently, upon the first inspection in the detection of a defect, two options are available 1. Carry out further assessment 2. Do nothing. Similarly, after the second inspection, again two options are available 1. To repair 2. Not to repair. These probabilities of detection and repair can be expressed using matrices. [20] According to the *Reliability-based* method, upon inspection of structure or component, three different types of information are available 1. No detection 2. Detection with Unknown size 3. Detection with size measurement.

Detection can be expressed as:

$$H(t_i) = a_d - d(t_i) \tag{3}$$

Where a_d represents the detectable crack size that can be obtained from POD curve of inspection equipment used and $d(t_i)$ express the level of damage at timet_i. If $H < 0$, it signifies that the size of the crack is larger than the smallest detectable crack size. Conversely, if $H > 0$, it shows that detection is impossible because the size of the crack is smaller than the detection capability of the inspection tool.

The crack size can be formulated as:

$$D(t_i) = a_m - d(t_i) \tag{4}$$

Where a_m is the measured crack size.[17]

2.4 NDT Reliability

The NDT reliability has gone through several stages since the late 1960s. Many researchers have put their efforts into its development intending to improve the life prediction's efficiency in the parts that highly depend upon the reliability and competence of NDT methods [21]**.** Moreover, the efficiency of the NDT method is measured by the term reliability. It is usually expressed in terms of flaw size having a probability of detection of 90%[18]. However, it can also be expressed in terms of Reproducibility, Repeatability, and Capability of the technique used and the technique that predicts NDT's capability is termed as POD [18]. Although, every NDT methods have certain specialty in detecting a certain type of defect. However, they have both detection and dimensioning inherent uncertainties as well. According to the program '*Have Cracks Will Travel*' of the US Air Force, the probability of detection varies even among the cracks of the same size.[19]. Therefore, to describe such uncertainty in the NDT method, the term 'Probability of Detection' (POD) is proposed.

2.5 Methods of Assessment of NDT Reliability

2.5.1 What is Probability of Detection (POD)?

The probability of detection (POD) can be expressed as 'the proportion of defects of a given size that could be detected by the NDT technique, when applied by inspectors to structural elements in a defined environment'[22]. Moreover, POD is articulated by the concentration of the damage for time-dependent crack size under uncertainty. It increases with the increment in crack size after fatigue damage. [13] And indicates a strong correlation with crack length. However, it is also deeply influenced by physical and operational parameters such as type of material, geometry, type of defect, NDT method applied, testing environment, and inspector's condition.

According to *DNV GL*, The calculation of the probability of detection for non-destructive testing techniques such as eddy current, ultrasonic, magnetic particle inspection, and ACFM techniques can be expressed through equation (5).

$$P(a) = 1 - \frac{1}{1 + (\frac{a}{X_0})^b} \tag{5}$$

Where a represents crack depth (mm) and X_0, b represents the distribution parameter, as shown in table 2. They are highly depend upon the accessibility of the part inspected and the type of NDT technique employed. The defects located at parts with difficult accessibility i.e. underwater are mostly less detected. However, parameters are set equal for these techniques except UT, irrespective of the accessibility of inspected parts.[23]

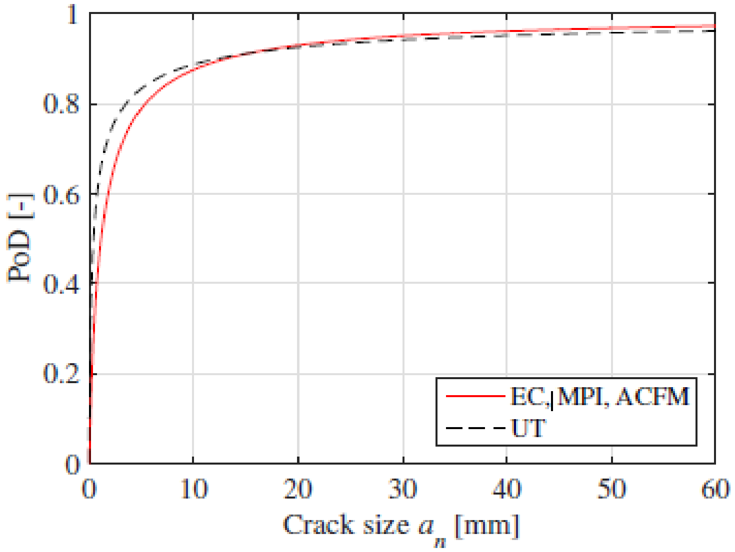


Figure 2.2 POD curves for EC, MPI, ACFM & UT [23] unmodified, CC BY 4.0

Table 2 The distribution parameters of POD curves. [23]

Distribution parameters	**X_0**	**b**
EC	1.160	0.900
MPI	1.160	0.900
ACFM	1.160	0.900
UT	0.410	0.642

Upon inspection of component or specimen, the following four possibilities (conditional probabilities) are encountered. [24]

- The specimen contains a defect and the NDT technique detect it. (True positive)
- The specimen contains no defect and the NDT technique detects nothing. (True negative)
- The specimen contains a defect and the NDT technique detect nothing. (False Negative)
- The specimen contains no defect and the NDT technique detects its presence. (False positive)

Currently, the evaluation of the POD curves is mostly used to assess the reliability and delicacy of the NDT technique. Furthermore, it is also used to determine the efficiency and scope of detection techniques regarding defect size. The ideal technique regarding POD curves is related to the critical size of a defect and its probability of detection. In this case, there will be no or false acceptance of defected piece (false negative) or elimination of good parts (false positive). However, in case, the size of the defect is lesser than the established critical size then its probability of detection will be zero and if it (defect size) is more than the established critical size then its probability of detection will be 1 or 100%. Comparatively, POD curves never depict such kind of behavior in reality because there is always a region of uncertainty with false acceptance and false rejection. Figure 2.3 shows the real and ideal POD curves.

Moreover, POD curves are usually established empirically and the most common method is known as *Round Robin Testing* (RRT). It involve an assessment of the fabricated specimen having artificial defects in various dimensions, similar to a real defect found in the welded joints. Afterward, the POD curves drawn may depend upon the findings of one inspector or group of inspectors. However, before the fabrication of test specimens, the following parameters must be known to avoid any difficulty during the process.

- Which defect's dimension will be focused?
- To what level, it will get inspect?
- How many intervals will be required within the range of defect dimensions?

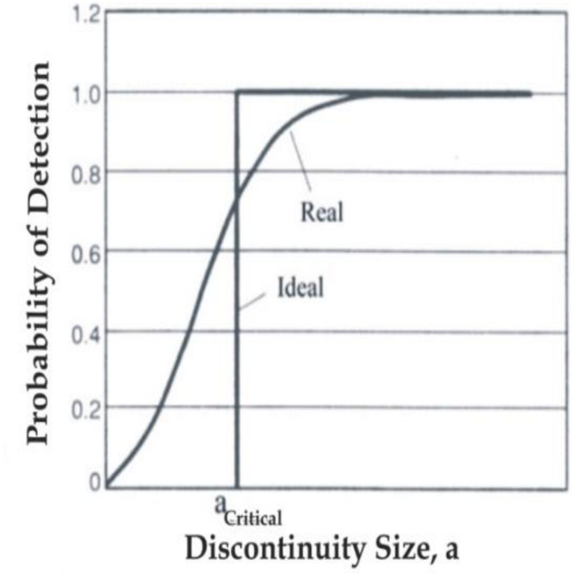


Figure 2.3 Illustration of Ideal and Real POD curve [25] unmodified, CC BY 3.0

In the *RRT method*, two problems are commonly encountered. First, the number of test specimens, which are used to ensure the analyzing reliability of the established curve. They must be sufficient enough to establish the POD curve and limit of the confidence interval. Second, the difficulties encountered during the fabrication of a test specimen in getting artificial defects, in similar to real ones, in different dimensions. These problems often provide poor sample space that hinders the possibility of getting statistic parameters of the POD curve that provides good data adjustment. Thus, it require highly skilled welders to create such accurate defected weld specimen.

On the contrary, in metal alloys, POD curves can be established through fatigue cracks, which can be initiated through a notch and grow in a controlled environment. However, it is economical and challenging at the same time. Moreover, the controlled system can be monitored through methods such as ultrasound and its growth can be controlled by consistent loading it at almost 70% material's yield strength.

In June 1997, a reliability model was presented at *'First American-European'* Workshop of reliability at Berlin. They provided the following three parameters that can affect the NDT reliability.

- The natural capacity of the NDT system.
- Aspects of a particular application.
- Human factor.

Furthermore, they concluded that the reliability of the NDT technique can never go beyond the idealized criteria. However, the reliability of the NDT technique, when applied to a particular type of defect can be described by equation (6).

$$Re = f(IC) - g(PA) - h(HF) \tag{6}$$

Where;

Re Represents the total reliability of a system.

$f(IC)$ Shows the natural capacity of the NDT system.

$g(PA)$ Shows the Aspects of a particular application like accessibility etc.

$h(HF)$ Shows the Human factor like skill etc.

These factors can only effect in case of manual inspection because they cause abrupt changes and divergence from the ideal condition as f governs the internal capability of the NDT technique, used in ideal condition, g represents the natural factors, h express the human factor (highly sensitive in manual inspection). This is why, the probability of detection is observed to be less in the manual inspection as compared to automatic inspection.[25]

2.5.2 Measuring POD Curve

The POD of discontinuity or crack of size, for instance "a" is determined through an average of all the discontinuities present with the same size in a specimen. Afterward, the average is used to establish the POD curve for a specific discontinuity for each of its dimension i.e. length (most commonly used), depth, or height. Moreover, there are several statistical models available to estimate POD curves. The two types of analysis methods that are commonly used to obtain data to run through these models are: a *versus* $\hat{a}$ *and hit/miss* method. In fact, both of them can be incorporated into applying POD curves. However, outcomes are distinctive, when applying on a similar data set.[25]

2.5.2.1 Hit/Miss Method

Several statistical distribution methods can be used to assess Hit/Miss cases. According to *log-logistics or log-probability* distribution, POD can be expressed as follows. The defect dimensions (preferred one) should be distributed in ascending order and must contain a minimum of 60 defects, to evaluate the POD curve parameters.

$$PoD = \frac{e^{\frac{\pi}{\sqrt{3}}(\frac{\ln a-\mu}{\sigma})}}{1+e^{\frac{\pi}{\sqrt{3}}(\frac{\ln a-\mu}{\sigma})}} \tag{7}$$

Where $a, \mu, \sigma,$ and e represent defect dimension, average, and standard deviation respectively.

The equation (7) can also be expressed as:

$$PoD = \frac{e^{(\alpha+\beta\ln a)}}{1+e^{(\alpha+\beta\ln a)}} \tag{8}$$

$$\ln\left(\frac{PoD(a)}{1-PoD(a)}\right) = \alpha+\beta\ln a \tag{9}$$

Where $\mu = -\frac{\alpha}{\beta}$ and $\sigma = \frac{\pi}{\beta\sqrt{3}}$,

Thus;

$$\ln(probability) \propto \ln(a) \tag{10}$$

In this method, 95% of confidence level usually practiced and it is considered mandatory that the flaws or discontinuities detected should be in binomial distribution and must be at least 29 in numbers in each concerning dimension. Figure 2.4 shows the instructive example of a 95% confidence level.

The confidence level can be estimated as follows (assuming it to be in a normal distribution).

$$P\left[-z\left(\frac{\alpha}{2}\right) \le \frac{\bar{x}-\mu}{\frac{\sigma}{\sqrt{n}}} \le z\left(\frac{\alpha}{2}\right)\right] = 1-\alpha \tag{11}$$

$$P\left[\bar{x}-z\left(\frac{\alpha}{2}\right)\frac{\sigma}{\sqrt{n}}, \le \bar{x}+z\left(\frac{\alpha}{2}\right)\frac{\sigma}{\sqrt{n}}\right] \tag{12}$$

Where $\alpha, \mu\ and\ \sigma$ shows significance level, average, and standard deviation respectively.[25]

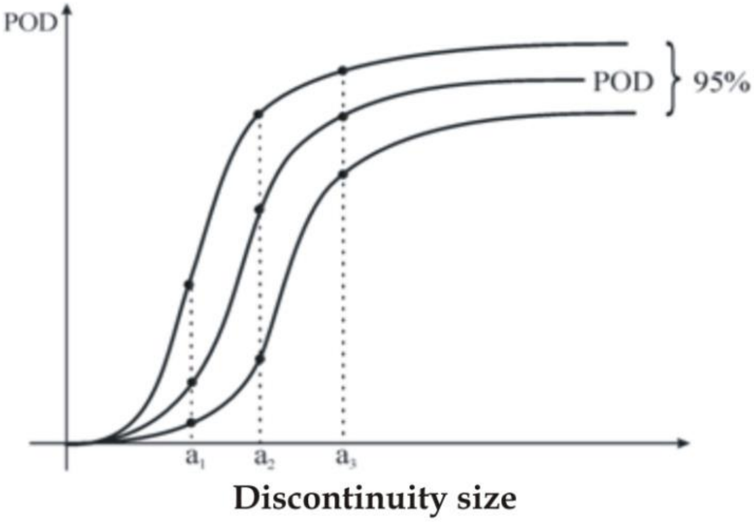


Figure 2.4 Depiction of POD curve with 95% confidence level [25] unmodified, CC BY 3.0

2.5.2.2 a Versus $\hat{a}$ Method

The response of the NDT technique employed is highly depend upon their characteristics and functional capability. However, some techniques can only detect a defect but don't give any clue regarding its size. Contrary to this, some techniques use signals as a response $\hat{a}$ to the actual size of a defect a.

Following relationships are used to analyze the response signal $\hat{a}$ of inspection technique and a as the actual size of a defect.

$$\ln(\hat{a}) = \alpha_1 + \beta_1 \ln(a) + \gamma \tag{13}$$

Where γ is an error with normal distribution, represents standard deviation constant that is equal to $(\sigma_1 = 0)$. In equation (13) $\ln(\hat{a})$ (in a normal distribution) and $\ln(a)$ are in a linear relationship. Furthermore, POD of response signal can be represented by the following equation.

$$PoD(a) = 1 - F\left[\frac{\ln(\hat{a}_{th}) - (\alpha_1 + \beta_1 \ln(a))}{\sigma_\gamma}\right] \tag{14}$$

Where $\ln \hat{a}_{th}$the limit of defect evaluation and F is the continuous cumulative function.

By normal distribution's symmetry, it can be written as:

$$PoD(a) = F\left[\frac{\ln(a) - \mu}{\sigma}\right] \tag{15}$$

It’s a cumulative *log-normal* distribution. Where $\mu(a) = \frac{\ln(\hat{a}_{th}) - \alpha_1}{\beta_1}$ and the standard deviation $\sigma = \frac{\sigma_\gamma}{\beta_1}$ and $\alpha_1, \beta_1,$ e and σ_γ can be calculated through the verisimilitude method.[25]

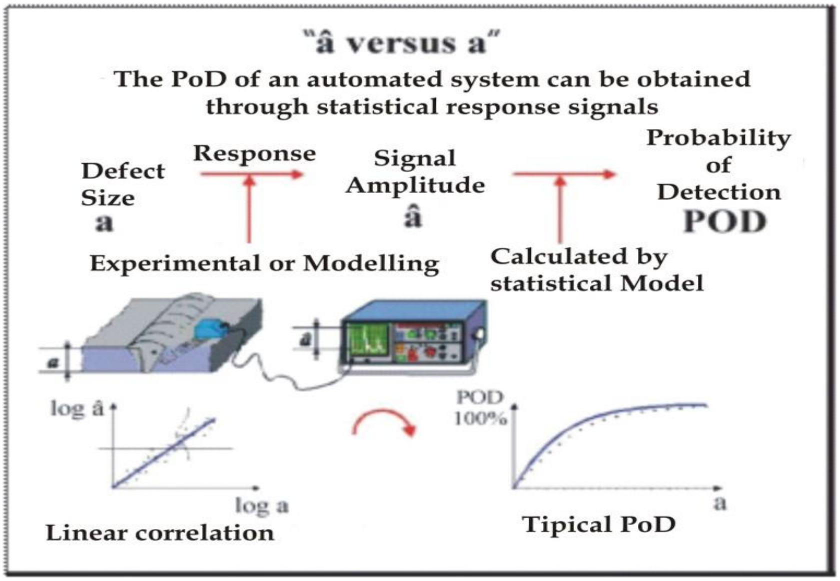


Figure 2.5 Showing implementation of a versus $\hat{a}$ method on PoD curves[25] unmodified, CC BY 3.0

As explained earlier that the detection capability of the NDT technique is preferably expressed in a statistical manner such as POD, because a repeated inspection of the same flaw size and type will not always give the same results. Moreover, *Lewis et al* in their paper illustrated through example that no crack could be detected by 100% of the time but its probability of detection increases with the increment in crack size. However, different cracks with different sizes have different detection probabilities. Therefore, the reliability of the NDT method depends on the undetected largest defect that could be undetected rather than the small one, which could be detected. [26] Furthermore, the probability of detection of each method depends upon two parameters i.e. crack size and accessibility of the inspected location. [27]

POD curves can also be described through Weibull distribution. In *Mello and Mattos* [27]**,** the *Weibull distribution* expressed POD as:

$$POD(a_d) = 1 - exp[-(\frac{a_d - a^*}{\lambda - a^*})^{a}] \quad (16)$$

Where a^*, λ, a depends on the inspection method and accessibility of the detail.

Chapter 3: Non Destructive Testing (NDT) Techniques

This chapter specifically describes the several NDT techniques. It involves the literature review, the benefits of employing NDT, and the detailed discussion about them.

The Non Destructive Testing techniques are employed to examine and characterize flaws without causing any physical harm to the system and specimen. However, some of these techniques are also be used as in situ inspection. [28] The NDT methods have evolved over the last several decades and used extensively due to its rapidness and effective operating procedures. Their implementation has drastically impacted the inspection procedures, concerning the time required to detect defects and their assessment. Furthermore, different methods are available and employed in different industries depending upon the type of material, type, and location of the defect, they are designed for. [29]

The methods are incorporated to ensure that the structure is free of defects that could lead it to failure. They are used in different industries such as automobile, offshore, aerospace, etc. However, every technique has some limitations in its effectiveness and accuracy. Therefore, care should be taken while selecting and evaluating the data received and must ensure that the techniques are performed by well-trained personnel. Moreover, the reliability and functionality of inspection methods or techniques generally depend upon the following aspects. [17]

- Metallurgy of the inspected area.
- Type of NDT technique and procedure employed.
- Capabilities of the equipment used.
- Flaw type and its orientation.
- Local geometry and accessibility.
- Working conditions like lighting.
- Operator skills and experience.

3.1 Literature Review

The NDT is frequently applied for the detection of defects in different materials, particularly in metals. Many researchers and scientists have made valuable contributions in the development of NDT such as *Rens et al. (1997)*[30] reviewed and unfilled their studies regarding major NDT methods and their applications concerning civil engineering structures like bridges. They reviewed different NDT methods such as acoustic emission, thermal methods, ultrasound, magnetic methods, and vibration analysis. *Rolander et al. (2001)[31]* have also comprehensively studied the usage of different NDT methods in civil structure's inspection. They concluded that the most used inspection technique is a visual inspection. Furthermore, they have found the five most commonly used NDT techniques, incorporated during the inspection of the bridge. Namely ultrasonic testing, magnetic particle testing, penetrant testing, and radiographic testing technique. *Van der Horst et al. (2013)*[32] after discussing and reviewing suitability, capability, and applicability of some NDT methods such as ultrasonic testing, radiographic testing, magnetic testing, and strain monitoring. They concluded that all four methods have different limitations in monitoring fatigue cracks, particularly in marine structures. Therefore, it is preferable to incorporate combined measurements of a single structural property due to uncertain environment conditions on marine structures.

In metals, surface defects are not always in 90^o to the surface of a specimen. However, previously, during an inspection of metals using the ultrasonic technique for the detection of surface-break defects, it was considered that defect is perpendicular to the specimen's surface. *Dutton et al.*[33] Investigated the interaction of Rayleigh waves with crack's depth and its wide angles relative to the surface, using a non-contact laser generation and detection system. Moreover, additional information was acquired by using the finite element model to get the 3D models.

It is very challenging to detect the defects in materials with the coarse-grain structure using ultrasonic non-destructive technique due to fault echoes or sometimes also called 'wrong calls'. The backscattered ultrasonic signals often consist of fault echoes that emerge from the material grains. Therefore, to measure the defects correctly, it is essential to reduce these fault echoes. *Vaclav Matz et al.*[34] Employed a method based on discrete wavelet transform to refine the ultrasonic signals. Furthermore, the pattern recognition method called support vector machines were used to categorize the ultrasonic signals in fault echoes, weld echoes, and back-wall echo in A-scan.

The usage of modern instrumentations such as latest sensors and other inspection equipment has provided the accuracy and time-saving in inspection processes. The eddy current technology is increasingly used in recent years due to rapid development in the field of electronics. *Javier Garcia Martin et al.*[35] Analyzed the basics and main variables of the eddy current method. Moreover, they also described the latest technologies used in eddy current methods like multi-frequency and pulsed systems.

The pulsed eddy current technology is considered to be a very informative, useful, and sensitive technique. It can detect defects and measure the thickness across the thickness of the non-conductive coating of a few millimeters in metals. However, its results are largely affected by many circumstances such as noise and lift-off effect. *Gui Yun Tian et al.* [36] Presented a solution to reduce the lift-off problem by using normalization and two reference signal technology.

Yi-Mei Mao et al.[37] Presented a method to measure the defect quantitatively in oil pipelines using *Hilbert-Huang Time-frequency analysis* (HHT) method, a method used to calculate the instantaneous frequency and amplitude of the signal by disintegrating the signals. The ultrasonic signals reflected from defected and defect-free pipelines were treated by using Hilbert-Huang transform, a signal processing technique.

Infrared Thermography (IRT) is the technique that is highly dependent on the structure's inspection situations such as heating or excitation source and infrared ray detector. It is a non-contact, non-invasive, expensive, and safe inspection method (because infrared radiations are not dangerous for human health). *D. J. Titman* [38] has worked extensively IRT field and explored a wide range of its applications. Furthermore, he described its usage, guidance and some limitations. *Carosena Meola et al*.[39] Experimented to analyze the several aerospace components and structures, made up of different materials such as metals and composites, used in the fabrication process of aircraft. They have employed lock-in thermography non-destructive testing and detected different kinds of damages including fatigue failure.

D. Bates et al. [40] Compared different thermal non-destructive techniques in an inspection of carbon fiber composite aircraft components, to detect flaws during the manufacturing process and in-service operations.
The experiment was performed by *Giovanni M. Carlomagno and Carosena Meola* [41] to examine the application of IRT technology in the field of architectural restoration. Moreover, different thermographic techniques were employed such as pulse thermography, lock-in thermography, lateral heating thermography, and pulse phase thermography to detect the artificial defects, induced in three samples made up of marble, brick, or tuff with covering plaster. *M. R Clark et al.*[42] Concluded that IRT technology can also be used accurately in material inspection even in low temperature i.e. low circulating temperature. They showed this experimentally by applying IRT in concrete bridge structural inspection and internal masonry structure.
P Cawley[43] Concluded that five ndt techniques are mostly used in inspection processes i.e. radiography, ultrasonic, eddy current, magnetic particle, and penetrant testing. This is why, extensive research is underway to incorporate them in the most optimal way to speed up the inspection processes, reduce the preparations and time required.
Sharad Shrivastava et al.[44] Discussed the usage and applicability of NDT techniques in the biomedical field. They investigated the disadvantages and their remedies through acoustic emission and acoustic-ultrasonic techniques. *Antonio J. Salazar et al.*[45] Described the effect of surface roughness on the characterization of steel samples (AISI-SAE 430) of varying surface roughness by using ultrasonic signals. *J. Hola et al.*[46] Performed survey of the state of the art non-destructive diagnostic techniques especially acoustic techniques in investigating and studying building structures.
I. Amenabar et al.[47] Investigated several non-destructive techniques such as ultrasonic, thermography, and x-ray CT techniques, for inspection of the wind turbine blade by determining their capabilities and competencies in different working conditions.
Christian Garnier et al.[48] Worked extensively in detecting, locating in site defects, and their size resulting from *Barely Visible Impact Damages* (BVID) or in-service defects, located at complex surfaces like wings, roads, etc. Furthermore, the visual inspection (VI) technique was employed in the determination of the size and location of all defects.

3.2 Benefits of NDT inspection

- Assessment of surface aspects.
- Detection of defects on time.
- Reducing time and material wastage/misuse.
- Determining material dimensions i.e. density assessments.
- Provide good quality products.
- Deceasing manufacturing costs and increasing production.
- Providing the capability of in-service inspection of components or structure.
- Getting a high-reliability level i.e. very low chances of overlooking of defects.
- Achieving customer satisfaction.
- Prediction of materials response.
- To assess the kind of a material without causing any harm to it and its surroundings.

- Assessment of the internal condition of structure or component is possible without causing it any harm [49].

3.3 The detection Techniques

There are many diverse ways of detecting fatigue cracks in metals, depending upon their accuracy and safety. However, the most suitable method must be chosen. Therefore, some of the most commonly used NDT methods are discussed here.

3.3.1 Ultrasonic testing

The ultrasonic testing (UT) technique is particularly used in detection of planar internal and surface defects, in sound conducting materials. The method consists of three modes: transmission, reflection, and backscattering of ultrasonic waves. The typical UT procedure starts with the production of ultrasonic wave. For this purpose, a short ultrasonic pulse wave, carrying an electric charge applies to a piezoelectric crystal that vibrates at a frequency relative to the thickness of the crystal, it could range between 1 MHz to 6 MHz. They can also be produced through the piezoelectric effect i.e. conversion of electrical energy into the mechanical energy of a transducer through a probe. Afterward, it allowed to travel through the material and after reflecting from the defect, if present in the material. They provides the information regarding its location. Moreover, the size, orientation, and other characteristics of a defect can also be easily determined, because the direction of the waves and signal traveling time are known. The velocity of the waves varies with the metal, like in steel it can travel at 5900 meters per second and in water, it is 1400 meters per second.

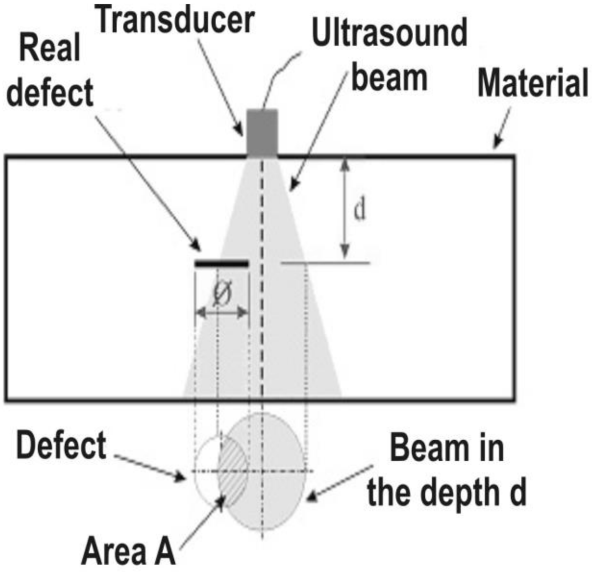


Figure 3.1 Showing Ultrasonic beam focusing on a defect Ø with area A[25] unmodified, CC BY 3.0

Furthermore, the instruments involved in typical UT are the transmitter, receiver circuit, transducer tool, and display monitor. However, in conventional UT method, angle of the beam used and its orientation relative to the defect is a major concern, because if it is not in the correct position then either no or very weak detection will be encountered. Therefore, it is always recommended to use different angles of the beam to ensure the detection of defects that are in different orientations. For this purpose, Time of Flight Diffraction (TOFD) is the latest technology that can be used. Moreover, the total sonic beam intensity that highly depends upon its position relative to defect can also be calculated, as expressed in equation (17).

$$S_{\emptyset} = \int\int_A e^{-\alpha d}.S_0.k(d_i).\exp(-a(\sqrt{x^2+y^2})^b) \tag{17}$$

Where,

S_0 = the intensity at the center of the sonic beam.

α = coefficient of material attenuation.

d = distance between defect and transducer.

a And b = constants (supplied by the manufacturer).

A = defect area reached by a beam.

x, y = beam intensity measured at (x, y) points.

Moreover, the three most commonly used and accurate approaches of ultrasonic testing are Pulse echo, Time of Flight Diffraction (ToFD), and Through-Transmission techniques. The pulse-echo technique is applied to detect large flaws, location, quality control, and imaging purposes. It can also locate defects instantly in homogenous materials. However, the transit time of the wave, energy loss and scattering of waves are of paramount importance in this method. In the through-transmission method, the transducer and receiver are placed at a certain distance, away from the sample unlike conventional way. This method is highly suitable when complex geometries do not allow the contact of the transducer and receiver to the material's surface. More explained later about these methods in this section.

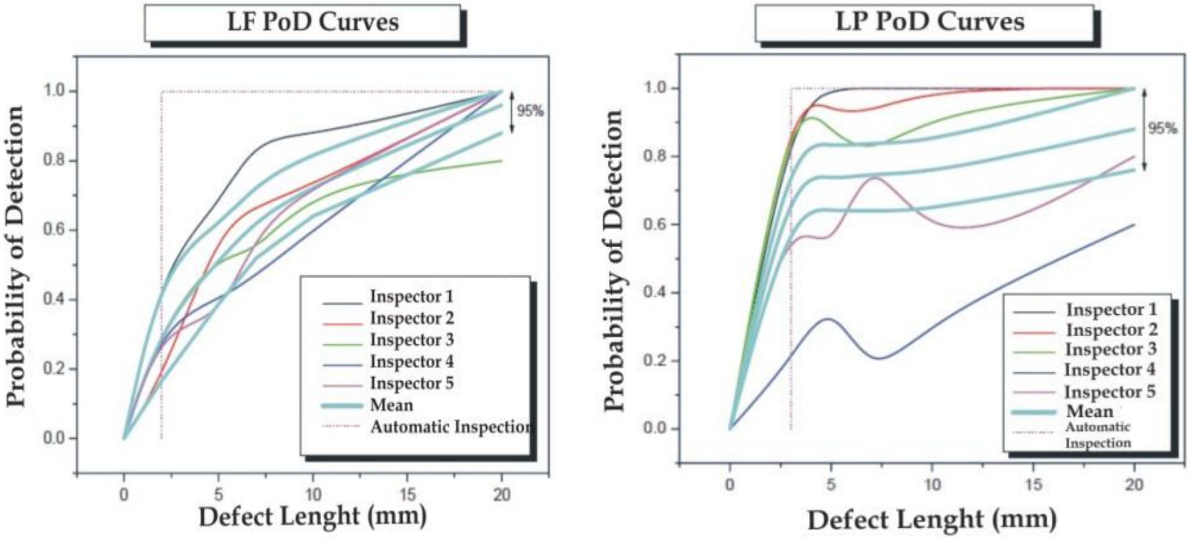
For instance, to get the POD 90 % using UT, the depth of a crack should be 13 mm (calculated from equation (5)), as shown below.

$$P(a) = 1 - \frac{1}{1 + (\frac{13}{0.410})^{0.642}}$$

$$= 0.90$$

According to *Fauske et al.[50]* Manual inspection through ultrasonic provides low POD than automatic inspection. It is considered that, in an inspection of a defect of a size of 10 mm and depth of 1 mm located on the opposite side of 80 mm thick sheet, the automatic inspection gives 80%

POD. Contrary to this, manual inspection provides only 60% POD. Furthermore, in one of the experiments performed, the POD of two defect classes: *Lack of fusion* (LOF) and *Lack of Penetration* (LOP) was inspected by five inspectors by using more advanced automated UT technique that works on the same principle, results are shown in figure 3.2. However, the pulse-echo and Time of Flight Diffraction (ToFD) technique are come out to be 100%, which is the classic case of ideal POD, where there is no detection below a threshold value.



a) **b)**

Figure 3.2 POD curves of defects classified as a) LF and b) LP [25] unmodified, CC BY 3.0

The Ultrasonic testing method has various advantages and disadvantages. The advantages include, fast scanning speed, high precision level in determining position and characterization of the flaw, highly sensitive to both surface and subsurface flaws, good penetration depth, provide instantaneous results, and have the capability of using in the field. Similarly, disadvantages include, the UT technology is only applicable to materials with thickness greater than 10-12 mm. Moreover, it is difficult to set up a system, scanning required highly skilled personnel because test sample required to ensure perfect scanning regarding angle of the beam, coupling medium is required to stimulate the transmission of sound energy into the test sample. However, the advantages of using automatic inspection carried out by ultrasonic is far more than the manual. *Passi et al.[51]* Concluded that the authenticity of manual inspection by ultrasonic is wholly based on the ability and knowledge of the inspector. The reliability of inspection may depend upon the three factors regarding the inspector's capability: lack of consideration in receiving echoes, the negligence of acoustic coupling, and the loss of preordained transducer's trajectory over the specimen. [17, 49-54].

Some of the commonly used and reliable UT methods are:

Time of Flight Diffraction (TOFD) UT Method

The Time of Flight Diffraction (TOFD) is one of the most accurate UT methods, with the highest POD, developed in the late 1970s. It has a strong potential to accurately detect and size mid-wall defects and less aligned defects. Furthermore, it provides more rapid linear scanning as compared to conventional UT technique because it uses the defect echo arrival time technique rather than echo amplitude that contains many deficiencies to determine the position and size of the defect.

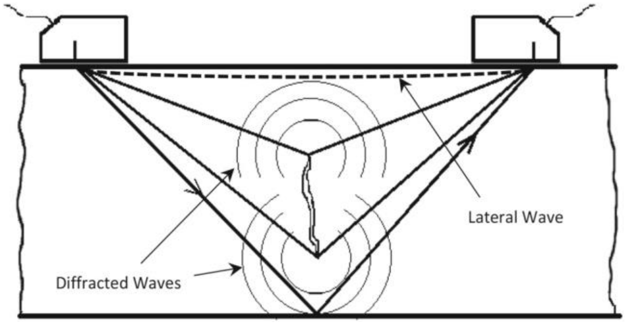


Figure 3.3 ToFD arrangement showing defect's edges diffracting incident waves[55] unmodified, CC BY 4.0

Afterward, the diffracted and reflected echoes are used in the sizing of the defect in the ultrasonic ToFD technique. The echo's arrival time can be calculated with high precision in nanoseconds. However, the receiver or detector receives the diffracted waves to create an A-scan ultrasonic signal that can be used to label the defect. The ToFD is a pitch-catch UT method, in which probes are engaged uniformly over the testing area to receive and transmit the angled-beam. The diffracted waves emitted from the edges of the flaw are analyzed that propagate in a wide-angle. Moreover, the high-frequency transducers such as longitudinal angled-beam transducers are employed to detect minor flaws like measuring the high-speed longitudinal waves. In the case of the incident longitudinal waves, diffracted waves have a high amplitude as compared to the incident shear wave. However, in the case of very small discontinuity, it may not be possible to discriminate between the top and bottom echoes.

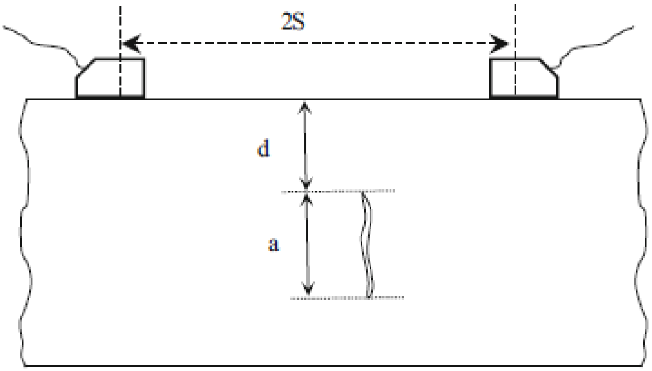


Figure 3.4 Illustration of the shape of a defect in ToFD method [55] unmodified, CC BY 4.0

In the figure 3.4, the depth of defect $'d'$ and size $'a'$ can be calculated by using the equation (18) and (19), knowing the time-of-flight (ToF) of defected echo and the distance between the two transducers $'2S'$.

$$d = \sqrt{\frac{(C_L \Delta T_U - 2S)^2}{4} - S^2} \tag{18}$$

$$a = \sqrt{\frac{(C_L \Delta T_B - 2S)^2}{4} - S^2} - d \tag{19}$$

Where, C_L represents the longitudinal wave velocity in the medium, ΔT_U and ΔT_B are ToF difference between lateral wave and defect's top and bottom echoes.

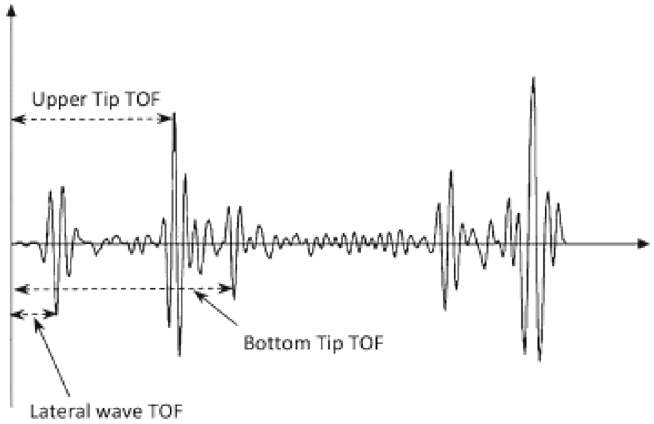


Figure 3.5 Illustration of Echoes detected in ToFD [55] unmodified, CC BY 4.0

In addition to the advantages of ToFD mentioned above, it is also a fast and highly effective method, usually one pair of the transducer can cover up to 50 mm or more of section thickness in one turn. Furthermore,, the probability of detection can also be increased by using several pairs in regions of thickness even less than 50 mm. However, the ToFD technique also has some limitations and dis-advantages such as it may not be able to detect small defects efficiently due to wrong calls and false echoes i.e. it has a low signal to noise ratio, highly-skilled inspector required to interpret the signals. Moreover, the typical ToFD is a 2D technique i.e. it is unable to detect a defect in 3D space. In addition, the ToFD also consist of two dead zones i.e. ID and OD, where it is unable to detect the defect and sizing also limited to 3 mm. The depth of the zones depends upon the frequency, ToFD settings, and damping. Low frequency and less transducer damping will create big dead zones and vice versa. Therefore, to improve the surface and near-surface detection and to get 100% detection coverage, the 'Pulse-Echo' technique is mostly employed. Moreover, many techniques, in addition to typical ToFD technique are also used to make it capable of detecting and sizing defects in 3D space. *Michael Moles et al.* Proposed from the fact that the estimation methods used in radar and acoustic positioning technology in 3D space can be used to extend the ToFD's capability by introducing and comparing active technique with a conventional passive technique based on source-positioning algorithms. However, in this new technique, to measure the time-of-flight echoes, several receiving transducers are employed. Alternatively, the mathematical models along with two linear minimization techniques such as *least squares and SI* methods were developed. The same action was performed by incorporating a passive technique. The result showed that in passive technique, useable signals must be received by at least four receivers at each transmitter location otherwise algorithm will not work. However, this was not the case with active technique. Moreover, their investigations showed that the active algorithm technique is more encouraging and the accuracy of defect detection in new technology can be increased by incorporating more pairs of transmitter-receiver. Furthermore, *Liu et al*. developed the method in which transient elastic waves were used to scan the surface cracks in reinforced concrete. Similarly, *Kimoto et al*. adopted the method of using several transducers to find two-dimensional coordinates of the tip of the surface-breaking defects. However, currently, the research and development work is underway to improve the readability of ToFD signals and reducing the dead zones.[55, 56]

Pulsed-Echo UT Method

The pulsed-echo ultrasonic method works on the same principle as ToFD. It also incorporates ultrasonic pulsed waves to identify the defects or thickness of the material. In this technique, the transmitter (T) transmits the waves and after reflecting from the defect or back wall of the test specimen, it is received by a receiver (R), as shown in figure 3.6.

Furthermore, a piezoelectric longitudinal axis transducer is placed on or near the surface, in the perpendicular direction to the test specimen. A transducer or transmitter transmits a pulse of ultrasonic waves that propagate through the material. Afterward, it is received by the receiver on reflecting by the defect, inclusion, void, or specimen's back wall, which results in A-scan. Moreover, their velocity depends upon the type of mode, in which they travel.

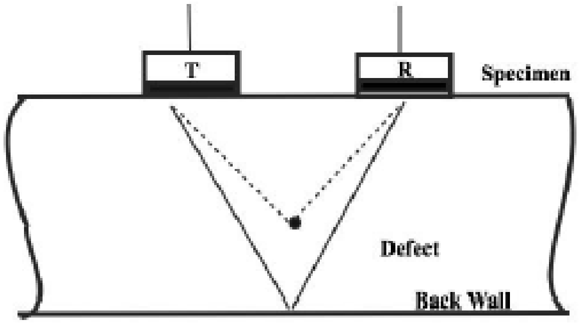


Figure 3.6 Illustration of Pulsed-Echo technique [57] unmodified, CC BY 3.0

The two types of modes: *longitudinal* mode and *transverse* mode are commonly encountered. However, in longitudinal mode, the particles fluctuate in a longitudinal direction to the direction of wave propagation. And in transverse mode, the particles fluctuate in perpendicular to the direction of propagation of the wave. Moreover, by considering the equation (19) and (20), it can be seen that the waves in longitudinal mode travel almost twice as faster in transverse mode.

Afterward, these waves are transformed into signals and analyzed which can be shown on screen. Likewise, there are many advantages of the Pulse-echo method such as it is simple in use, as only one transducer is sufficient to perform testing, thin dead zones, the maximum penetration depth, high resolution and sensitivity, location accuracy, and productivity. However, with the development of the latest techniques such as '*Dry point contact*' (DPC) transducer, it can also be used effectively in a situations, where only one side of the specimen is accessible.

Additionally, this technique allows us to determine internal flaws and thickness of the object from back wall reflection or echo, as shown in figure 3.7. Where 'D' and 'ΔT' represents the distance in the material and time-of-flight between transmitted and reflected waves

$$\text{Longitudinal mode:} \qquad V_L = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} \tag{20}$$

Where V_L shows the speed of sound in longitudinal mode (m/s), E is the young modulus (N/m^2) and σ is the poisons ratio.

$$\text{Transverse mode:} \qquad V_T = \sqrt{\frac{E(1-\sigma)}{2\rho(1+\sigma)}} \tag{21}$$

Where V_T is the speed of sound in transverse mode (m/s), E is the young modulus (N/m^2) that can be replaced by the Shear modulus of elasticity: $G = \frac{E}{2(1+\sigma)}$ and σ is the poisons ratio.

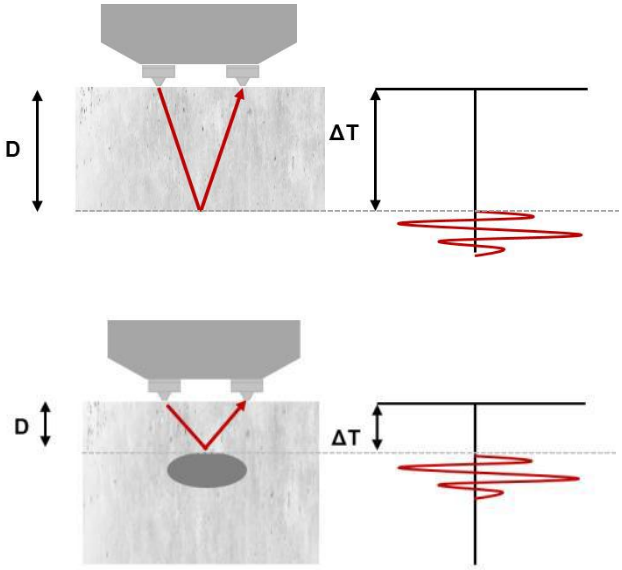


Figure 3.7 Illustration of an ultrasonic wave passing in Pulse-echo UT method; without the defect and with the defect [58] unmodified, CC BY 4.0

Furthermore, the pulsed-echo technique is very useful in inspecting large structures or objects due to its fast scanning capability, by using an array transducer with multiple channels. The working principle involved is that the one channel transmit waves and the others are receiving then the second channel transmits and others are receiving and so on, as shown in figure 3.8. This cycle continues, so that each receiver results in a separate A-scan that can be used to produce B-scan in real-time. However, it is a series of A-scan in one particular direction like in the x or y-axis.

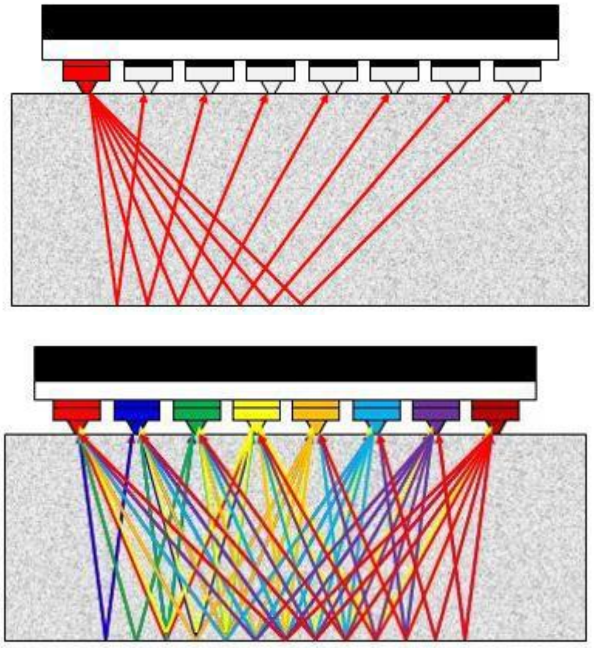


Figure 3.8 Illustration of the multi-scanning array used in pulsed-echo UT method [58] unmodified, CC BY 4.0

Lubos Misak et al. described the different scanning principles such as A-scan, B-scan, etc., and explained that how they can be combined to give 3D images. Moreover, they also mentioned the advantages of using modern imaging techniques such as *multi-head array systems*. They concluded that the 2D image is still more convenient in analyzing the object for non-specialists because high skills are required to interpret the images into 3D. Although, modern tools such as the '*Augmented Reality*' technique have made it possible to make better images. In fact, the transformation of the images is still the primary concern in a pulsed-echo ultrasonic scanning system.

A Madhusudanan et al. experimented to analyze the efficiency of the UT method by examining the '*time domain'* in a structural health monitoring system of a mechanical system by using two non-destructive testing techniques namely pulse-echo and through-transmission. In the pulse-echo method, the transducers were placed at the four sides of the specimen. The defect's aspects were analyzed by using a 5730PR transmitter and receiver with 1 MHz of 15 mm diameter, passing ultrasonic waves through the specimen to determine the time-of-flight between the transmitted and back-reflected waves. The distance (d) in the material was calculated by using the following equation (22).

$$d = vt/2 \tag{22}$$

Where v and t represent acoustic velocity and time between two peaks.

<u>Through Transmission UT Method</u>

The through-transmission UT method employs two transducer technique in a pitch-catch arrangement used to detect, size, and monitor the growth rate of cracks in particularly round and hollow shapes structures such as pipelines, cylinders, etc. and sometimes in non-cylindrical shapes. In fcat, in the case of weak signals and the presence of non-reflecting defects in a material, this technique can be very useful in analyzing them.

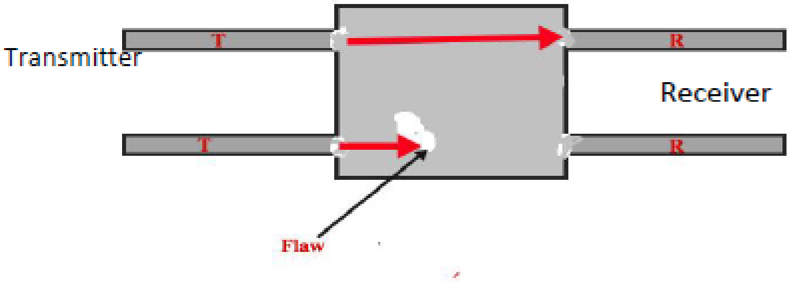


Figure 3.9 Illustration of Through-Transmission technique [57] unmodified, CC BY 3.0

Moreover, it is particularly useful in the inspection of multi-layered and multi-component materials that results in the position of impurity, defect, and inclusion in the XY plane. This method employs two transducers. The first transducer (ultrasonic transmitter) on one side of the material and the second one (detector) on the other side. Although, there are many inspection techniques to inspect the various type of objects with different shapes, sizes, and orientations of defects. Therefore, it is very helpful to have an alternative technique to verify like through-transmission technique.

The advantages of the through-transmission technique includes the absence of dead zone, no high noise problem, and very low dependence of single amplitude on flaw location in the material. Contrary to the pulse-echo method, this technique can detect finer defects throughout the material, particularly in parts of large thickness in metals. However, the limitation of this method lies in the complexity involved in the orientation of two transducers, placed on opposite sides of the material concerning their central beam of the directional pattern that results in low chances of getting exact defect's location and low sensitivity as compared to the pulse-echo method.

Similarly, in an experiment explained above, 5730PR transmitter and receiver with 1 MHz of 15 mm diameter were also used to determine the time-of-flight between the transmitted and back-reflected waves. In a material, the distance 'd' was estimated by using the equation (23).

$$d = v \times t \tag{23}$$

Where $'v'$ and $'t'$ represent the acoustic velocity and time between two peaks.

A Madhusudanan et al has concluded that both NDT techniques have also a strong potential for structural health monitoring (SHM). Their results were imperative. Moreover, they have shown effective defect detection, and characterization encompassing both complex signals and varying environmental conditions.

Jimmy Ellis et al. experimented to employ the through-transmission technique manually as a verification tool. Several ultrasonic techniques were employed to determine the size of the cracks on the outside edges of the mud drum of large diameter, inside the power boiler. They were open and directed in longitudinal and transverse directions. They appear to be not deep i.e. 0.25 inch approximately. However, some of them were old repair welds. The location of the edge of the cracks was verified using the through-transmission technique. The size of the crack positioned at 3 o clock was 0.5 inches approximately deep. Moreover, crack edges were located at a point where the transmitted signal was 50% of the sound wave transmitted in flawless areas. Therefore, they concluded that the manual trough-transmission UT technique is a very useful alternative technique that can be applied in many ways. It is also a very helpful crack growth monitoring tool during short shutdowns when an internal inspection is not possible.[57-61]

3.3.2 Magnetic Particle Inspection

The magnetic particle inspection (MPI) technique is widely used in many industries such as aerospace, automobile, etc. in the detection of surface-breaking and near-surface defects i.e. within 3 mm deep, particularly in ferromagnetic materials. In this method, magnetic field and magnetized ink (consist of tiny ferrous particles) are incorporated in the detection of flaws. In fact, the only criteria required, from an inspection point of view is that the component under inspection must be composed of ‘ferromagnetic’ material like Iron, nickel, cobalt or their alloys, because they can get magnetized easily and allows effective inspection. During operation, many factors can influence the magnetic field production. These may include the geometry of electromagnetic yoke, the shape, size, and orientation of specimen under inspection and the coil parameters. In its simplest way of work, specimen under inspection needs to be highly magnetized. However, this can be done successfully by using following directly or indirectly methods, either using AC, DC, rectified, or pulsed AC.

- *Current flow*: In this method, specimen considered to be the part of the electrical circuit. The magnetic field is produced by applying a large amount of current through the specimen.
- *Magnetic flow*: The permanent set of magnets or electromagnet handy yoke (connected with the coil) is used to magnetize the specimen.
- *Coil method*: A current-carrying insulated coil is used to produce a magnetic field. However, the specimen can be placed near or inside the coil.
- *Threaded bar and cable*: This method is used particularly in the examination of hollow components like tubes. The magnetization is done by threading an insulated current-

carrying conductor through the concerned place. Correspondingly, in a threaded bar and cable, a single conducting rod and flexible cable are used.

- *Induced current:* The magnetization of a specimen is done by electromagnetic induction in this method. It acts as a secondary winding of the transformer.

Afterward, ink (the blend of magnetic particles) is applied thoroughly to the specimen's surface. As a rule, the defect should in a perpendicular or up to 45 degrees to the direction of magnetization to get defect detected. Therefore, if there is any discontinuity or defect present in the component, magnetic flux will be broken and new south and north poles will be created at each of its edges, or in other words, magnetic particles will accumulate around such locations due to perturbation of flux lines. However, this happened due to rapid changes in the magnetic permeability of flux because the magnetic permeability is lower at discontinuities and higher at other places in the material, thus, lines takes different routes due to high resistance at such places.

In the mid-1990s *Thiokol Corporation* (USA) conducted a POD study on the reliability of MPI and Eddy Current method, in one of NASA's projects. It involved 23 inspectors, 100 test specimens, and defects include fatigue cracks in plates, holes and stress corrosion cracking. Regarding this project, *Hartman and Hibbert* concluded that a_{NDI} i.e. the smallest size of the defect that a particular type of NDT technique can detect accurately is usually the size of the defect in a structure for which POD is 90% at 95% confidence level, expressed by $a_{90/95}$. As a result, it was 4.4mm for *MPI* for corner cracks at 25 mm diameter holes in D6ac steel. Furthermore, in the late 1980s and early 1990s, *University College London* (UCL) coordinated a study and researched on the NDT's reliability of underwater inspection on offshore structures. In fact, the objective was to determine the reliability of MPI with other NDT techniques such as eddy current, ACPD, and, ACFM. The outcomes were, a_{90} = 50mm surface length for low light underwater MPI and in another case, $a_{90/95}$ = 7mm crack depth. Similarly, another project called '*Intercalibration of Offshore NDT'* (ICON) was conducted by six organizations from UK, France, and Italy with the same intentions and motivation. Additionally, this time ultrasonic was also present to compare it with MPI. The critical range was set to 10-50 mm in length. As a result, the probability of detection of defects using MPI and Liquid Penetration Inspection (LPI) was only 60 – 75% due to certain reasons like human errors. However, it can be improved by employing well-controlled automatic processes.

The POD curve primarily depends on the qualification and execution of work. However, the probability of detection for a particular type and size can be achieved by using equation (5) in MPI method. For instance, to get the POD of 90 % using MPI, the depth of a crack should be 14 mm, as show below.

$$P(a) = 1 - \frac{1}{1 + (\frac{14}{1.160})^{0.900}}$$

$$= 0.90$$

Furthermore, MPI also contain some advantages and limitations in its applicability. Hence, its high sensitivity and simplicity in usage, the short detection process, and preparations before inspection are not demanding are included in its advantages. On the other hand, disadvantages may include, it cannot inspect non-ferromagnetic materials like copper alloys, aluminum alloys, and austenitic stainless steels. Moreover, it can only detect flaws up to limited depth, it doesn't give measurable flux leakage in the proximity of flaw in a component. However, this can be solved by using latest tools. In the first place, to improve MPI, magnetic ink (wet method) can be incorporated instead of using the 'dry powder' method, to prevent human errors in assessing the defect. Second, to detect small flaws, 'fluorescent powder' can also be used to get a clearer image of a flaw under ultraviolet light. Finally, the magnetized tape can also be used to overcome the complications in geometries. It is achieved by placing the tape over the surface of a specimen and magnetized it by the strong surface magnetic field, then it is removed and can be inspected.

Magnetic flux leakage (MFL) Method

To estimate the leakage field effectively, the Magnetic flux Leakage (MFL) method (derived from MPI) can be adopted. It is also one of the most frequently used techniques in the static electromagnetic imaging process. Because it employs a 'magnetometer' instead of magnetic particles (ink) to analyze the perturbed flux lines. Furthermore, it can be employed effectively in calculating the field components that are perpendicular or parallel to the flaw and normal to the surface. Moreover, it is also very useful in inspecting the long pipelines, corrosion damages, and floors with thickness up to 15 mm. However, the inspection through 30 mm thickness is also possible after the development of '*saturation base low-frequency*' eddy current method.

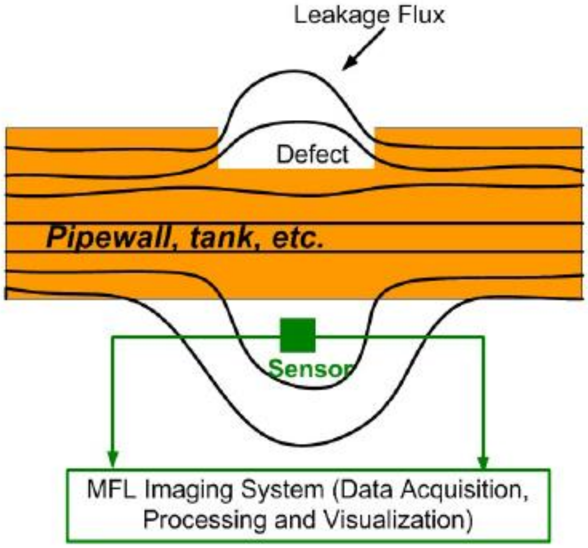


Figure 3.10 Showing MFL inspection of pipeline[62] unmodified, CC BY 3.0

Moreover, it's a fact that the MFL technique is unable to determine the accurate size of the near or far surface defects in a test specimen. Therefore, to increase the precision level and characterization ability, the new transducer needs to be involved in the inspection process. For this reason, a new approach *Pulsed Magnetic flux leakage* (PMFL) technique was introduced that provides more information about the flaws in components than any other MFL technique.

Ali Sophian et al. determined the capabilities of PMFL. They concluded that the PMFL is one of the best techniques in surface and sub-surface defect's detection. The different functions included in its time-frequency domain such as arrival time of the inflection pint, signal magnitude, and phase variation of frequency factor makes it very useful in determining the defect's size and location. Moreover, it is also capable to distinguish between crack locations and provides corresponding crack depths. However, the yoke plays a vital role in determining the penetration depth. In general, larger yokes give higher penetration depth. This technique is also effectively used in a material, where the defect is present on both sides of the metal but only one side is accessible.

Most commonly, two types of Pulsed MFL approaches are being incorporated i.e. DC PMFL and AC PMFL. Both techniques provide limited information regarding the size and position of defects. In fact, DC PMFL can only calculate magnetic flux leakage intensity. Therefore, it must be ensured before the inspection that specimen only carries one type of defect and at only one side, to get an accurate and precise measurement of defect size. However, AC PMFL also works at only one side of the sample, depending upon frequency applied. In this technique, the probe could be directed in a square wave pattern and the high-frequency component can provide extensive data at different skin depths. It is commonly known as penetration depth. It is governed by skin effect and can be defined as the depth below the surface of the conductive material, where the density of the current will reduce to 1/e or 37% of the current density at its surface, it can be expressed through equation (24). Furthermore, by using this technique, it is likely to inspect thicker material for near-surface and far side defects efficiently and can get information regarding the size and location of the defect. [17, 49, 53, 63-68]

$$\delta_o = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad (24)$$

Where σ is the electrical conductance of the material (S/m), $\omega = 2\pi f$ is the angular frequency (rad/s). This expression can also be used to estimate the amount of frequency to penetrate through the material.

Self-Magnetic Leakage Field (SMLF) Method

The working principle of Self-Magnetic Leakage Field (SMLF) is based on the assumption of naturally or self-occurring magnetic fields distribution on component's surface. It happened due to the presence of stress concentration zones (SCZs) and flaws in the material. Furthermore, it detects SCZs and positions of defects effectively by incorporating its pattern and gradient distribution

The methodology of SMLF starts with the application of magnetic field to the ferromagnetic material to magnetize it to the highest level. If there is no defect present in a material, the magnetic flux lines will pass through it freely. However, in the presence of defects, these lines will be disturbed because the resistance will be increased and magnetic permeability will be reduced in that particular area. Therefore, they start bending and leaking at the surface of the material. Afterward, the magnetic field leakage field will be formed in the defected area. It will then detected by sensors and corresponding signals will be formed and analyzed to check the status of the defect. Similarly, in the detection of corrosion in metals, particularly in steel, the principle of SMLF lies in the fact that the magnetic field excited in the ferromagnetic material by the magnetic field of the earth. In the presence of corrosion in a material, they will show irregular behavior in same manner as mentioned above. Thus, SMLF is a useful method in evaluating the areas of potential damage growth. This technique is the only passive and contact type technique in nature among all the magnetic NDT methods, which means it collects the information from radiations or waves emitted by the structure and the sensor is required to touch the component during an inspection. The advantages of SMLF is that, it can be used where access is limited due to its simple and small size equipment. Moreover, it doesn’t require surface preparation of component prior testing and the operational procedure is fast.

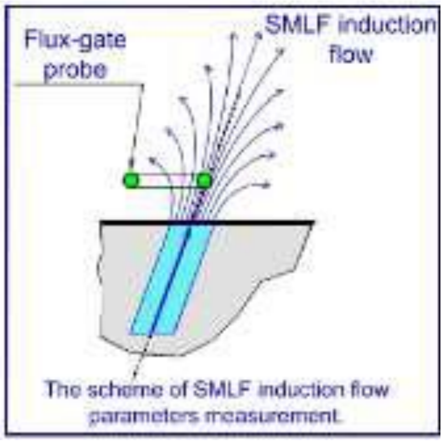


Figure 3.11 The illustration of working arrangement of the SMLF technique [69] unmodified, CC BY 3.0

Shuib Husin et al. discussed and experimented to show the application and verification of the SMLF technique in detecting defects in a thick material like P91. It is a ferromagnetic material used in the construction of the boiler and turbine structure and their accessories. They have concluded that this method can be successfully used to detect the defects in thick materials like P91. It can also trace out the location of a defect in a material with an accuracy of ±3 mm. Moreover, it is a fast, accurate, cost-effective, and practical technique.

Robert Stegemann et al. presented a new method of self-magnetic leakage field (SMLF) using magneto-optical (MO), a handy microscope instrument, and a GMR sensor. They have concluded that both methods are capable of detecting a minute change in the magnetic field in terms of field strength and spatial resolution and thus provide high-resolution magnetic field detectability. The MO technique is fast, direct, and can provide high-quality 2D images. In contrast, a GMR sensor takes more time, and results are largely affected by its sensing area and lift-off factors.[69-71]

3.3.3 Radiographic Testing

The Radiographic technique (RT) is one of the most reliable NDT technique to determine the weld defects, internal defects, and voids in the specimen, by using electromagnetic waves of short wavelengths such as x-rays and gamma-rays. They comprise of high energy photons, having the special ability to pass through the objects of certain thicknesses. The typical procedure involved in radiographic testing is the generation and transmission of x-rays or gamma rays through an x-ray emitter machine or radioactive source. Afterward, they travel and pass through the specimen. The specimen will absorb the rays and if some defect is present, more rays will pass through that area and eventually projected onto the film, producing an underlying image of different densities called a radiograph.

Furthermore, there are many other types of radiography methods available such as film radiography, computed radiography, x-ray computed tomography (XCT), x-ray backscatter tomography (XBT), and digital radiography. However, some of them are explained later in this section. They can be used in different capacities depending upon the thickness of the specimen. RT is particularly effective when the material is neither too thin nor too thick. For instance, low voltage radiography i.e. x-rays are used for thin parts varying from 1 to 5 mm and gamma rays are incorporated for thick parts due to its much shorter wavelength. The procedure starts with the emission of the x-rays through the emitter or gamma rays through the radioactive source. Then they are allowed to pass through the material and absorbed differentially depending upon its thickness, material with high thickness will absorb more rays. Moreover, the reliability of RT depends upon the delicacy of rays being used for radiography. The delicacy of x-rays is normally 2% of the material’s thickness, which means it could only detect the void up to 0.5 mm in the material of 25 mm thickness. Therefore, parts are often inspected in different planes. Likewise, gamma radiography also works in the same way. The only difference is the source of electromagnetic rays. As in this case, the radioactive isotope like Co 60 can be employed. However, this is highly dangerous to human health that’s why it is not a very preferable technique. In fact, it is very effective in the detection of internal defects in ferrous and non-ferrous materials. As similar to other NDT techniques, the probability of detection of flaws using the radiography method depends upon certain factors like human factor, orientation, and geometry of defect in respect to the beam direction, equipment’s delicacy, accessibility, resolution, the procedure applied and material’s selection. In radiographic testing, it is very important to expose a specimen to the radiographic beam at different locations and directions, to ensure a 100% detection probability, as in the ultrasonic testing.

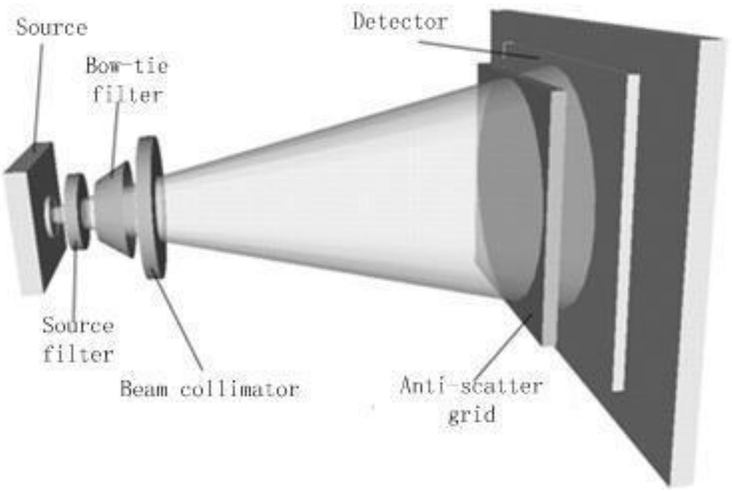


Figure 3.12 Illustration of an X-ray imaging system [72] unmodified, CC BY 3.0

Bikash Ghose has calculated the probability of detection of a planer flaw in a cylindrical object. Initially, the POD of crack was calculated for an arbitrary selected single exposure. Afterward, the same procedure adopted with many exposures. According to his mathematical formulation and derivation, the probability of detection of planer flaw can be expressed through equation (25):

$$P_N = \left(1 - \frac{\cos^{-1}(\frac{w \times 100}{s \times D})}{90}\right) \times N \tag{25}$$

Where w, s, D, N represents the width of the planer flaw, % sensitivity of radiographic technique used, Diameter of the grain, and numbers of exposures in equally spacing in terms of angles respectively.

Now, to get 100% of POD, P_N should be equal to one. The minimum number of orientations required is given by equation (26):

$$N_{min} = \frac{1}{(1 - \frac{\theta_{min}}{90})} = \frac{90}{90 - \theta_{min}} \tag{26}$$

Where; $\theta_{min} = \cos^{-1}(\frac{w \times 100}{s \times D})$

Moreover, he concluded that the number of orientations and crack width is directly proportional to the POD for a given object and % thickness sensitivity of the technique. However, POD is inversely proportional to the % thickness sensitivity of the technique and diameter of the object. Moreover, a minimum number of orientations required for 100% POD decreases with an increase in defect width, reduction in object diameter, and % thickness sensitivity. The figure 3.13.shows the simulation steps typically involved in the radiographic testing procedure

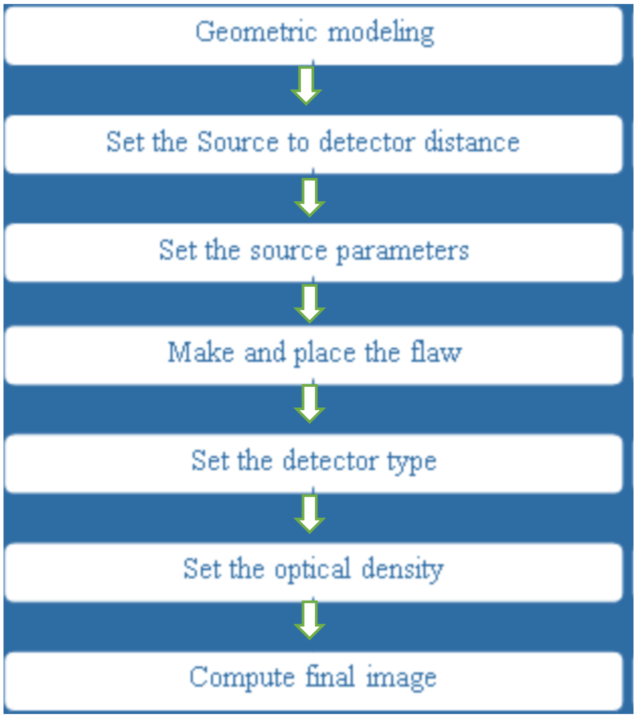


Figure 3.13 Illustration of typical simulation steps of radiographic testing[73]unmodified, CC BY 3.0

Some common types of radiographic testing are as follows.

<u>X-ray Computed Tomography (XCT)</u>

The X-ray Computed Tomography (XCT) is highly reliable and useful type of radiography as compared to conventional projection radiography regarding image production. XCT was developed to eradicate the difficulty in image production due to the superposition of structure between x-ray source and detector. Furthermore, it employs several transmission projections and mathematical models that creates ‘tomograph’. These 2D radiographic projections are then used to reconstruct the 3D images of the object. In XCT, data is readable and simple because it produces 3D images with a high resolution of nearly 1 μm. This technique is particularly useful in analyzing fatigue crack in the early stages of its nucleation and growth.

<u>X-ray Backscatter Tomography (XBT)</u>

In X-ray Backscatter Tomography (XBT) method, slim concentrated beam is used to investigate the different parts of the object, in parallel to getting backscatter signals by a large area detector. Eventually, it will provide an image similar to the radiograph. Moreover, these scattered x-rays carries informative data regarding the material’s properties. The scattered signal can be measured from the volume element (voxel) characterize by the intersection of both beams. The data from several measurements from each voxel in a plane within an object constructs a ‘tomograph’. However, this method has built-in limitations in both depth penetration and image production due to the scattering of x-rays in all directions. Therefore, it is limited to materials and inspection depths, from which measurable signals can be obtained. For instance, an inspection of a dense material like steel is limited to only 5 mm of the surface. Along with Radiographic testing technique, it is recommended to use UT technology in inspection of the material above 25 mm. Also, it is considered to be very difficult to detect planer defects using the radiographic technique but they can be detected when their depth is approximately in line with the beam path. [49, 52, 53, 74]

3.3.4 Acoustic Emission

The technology used in acoustic emission (AE) deals with the sound waves associated with the elastic or stress waves produced by a swift release of energy within a material, as a result of the crack, yielding, fiber pullout, breakage, etc. that may be due to fatigue or external loading. The AE energy released from these defects travel concentrically from the origin and detected by highly sensitive sensors/transducers, as shown in figure 3.14. Afterward, they converted to an electric signal and analyzed. Additionally, it is a very effective and efficient method of monitoring plastic deformation, creep, fatigue-induced damages, and fracture, particularly in metals. However, this method is particularly useful in detecting defects in large and complex structures, with exerted dynamic loading such as offshore structures and ships, because they require continuous monitoring. For this purpose, the controlled simulated non-destructive AE technique is used. Moreover, it covers the entire structure’s volume by using a few sensors, after properly analyzing their location, numbers, and signal-to-noise-ratio.

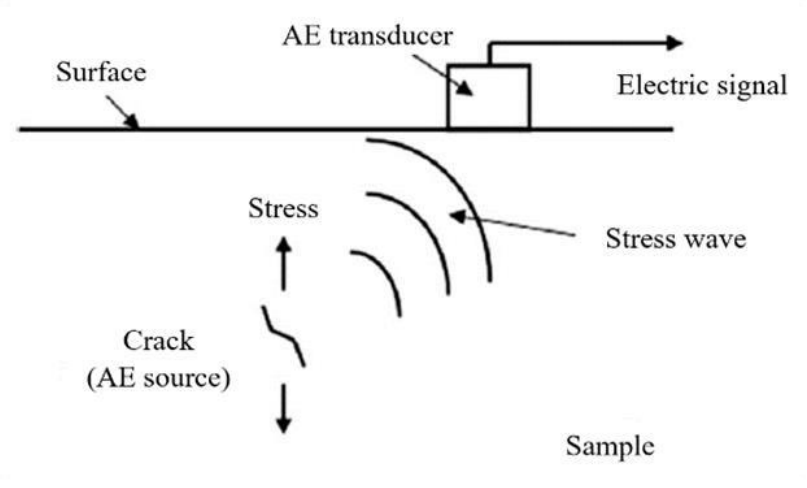


Figure 3.14 Illustration of AE receiving the waves generated from crack growth [75] unmodified, CC BY 3.0

In 2011, *Clarke et al*. performed a dynamic loading test in which artificial defect, in the form of wire rupture was induced on 6 m long riser under controlled laboratory conditions. AE along with other non-destructive techniques was incorporated to detect the possible damages. They suggested that it would be difficult to detect damage by using AE technology alone due to noise problems that lead to distraction and causes wrong calls. However, this problem may overcome by adjusting the sensor’s positions. Therefore, it is recommended to use other methods also along with AE to get better results.

Barat et al. experimented to calculate the POD of fatigue crack at its different stages in defined AE condition, in specimens made up of alloyed low-carbon steel 09G2S. They concluded that it is possible to determine the probability of detection of fatigue cracks and its accuracy against noise by using the AE technique. Moreover, it also allows determining the maximum spacing between the sensor and threshold value to get defined POD. However, the POD relies upon several factors like the stage of fatigue crack development, the distance between the sensor and the fatigue crack (source), the propagation's path properties, and noise level. Above all, the AE system must have adequate % sensitivity to detect defects in a material i.e. to record the impulses transmitted by the defect. The AE signal that is detected by a detector or sensor can be expressed by equations (27):

$$s(t) = u_{source}(t) \times h_{channel}(t) \times h_{sensor}(t) \tag{27}$$

$$AE\_data = Threshold(s(t), thr\_level) \tag{28}$$

Where $u_{source}(t)$ is the AE source function, $h_{channel}(t)$ is the transfer function of the propagation path and $h_{sensor}(t)$ is the AE sensor's impulse response. However, the equation (28) shows the detected AE signals expressed as several AE parameters as a result of threshold processing.

In 2009, *Kapptos* and *Darmatas* performed an experiment, based on radial-basis-function neural network and AE signal method. In this experiment, they modeled the side frame of the ship structure by using the steel-reinforced plate in a water tank along with piezoelectric pulse generator, as AE source and four piezoelectric sensors to detect waves in the plate. Likewise, in 2014 *Rogers* and *Stambaugh* also experimented on *UK naval platform* for one year to investigate the hull's integrity by using two arrangements of 16 global sensors and 4 local sensors. Both arrangements resulted in no crack growth in repaired ones, but figured out one more non-critical AE source.

In general, the AE method is frequently used to determine the marine structure's integrity. However, it is preferably used along with other non-destructive methods such as ultrasonic and strain monitoring to eliminate the background noises to achieve reliable data. The AE method can also be used for structural health monitoring (SHM) of the welded structure. It provides accessibility to detect and determine different weld defects. *Aboali et al*. experimented to detect the three types of welded defects such as porosity, slag, and lack of fusion (LOF) in butt welded carbon steel plates (Grade A36) of dimension 300×300×100 mm. They noticed an increase in AE in slag defects as compared to the other two. However, they were unable to differentiate between porosity and LOF defects. Similarly, *Lee et al.* inspected the defects in austenite stainless steel 316 material pipe using AE technology. The artificial defect (crack) of 20 mm length was induced in the middle of a welded region of the specimen using laser-guided wave, as a non-contact method to produce AE signal at one side of the steel pipe and connected sensors on the other side. They compared the findings regarding AE waveforms, frequency, and transmission, etc. of this experiment with the one of a defect-free specimen. As a result, they noticed many wave modes and conversions due to the present defects in a specimen.

Furthermore, *Adrian Pollock* conceded a model, as shown in figure 3.15, one of its kind for determining the POD by using AE on a project. In a project, AE technology was used to monitor the set of highly pressurized gas cylinders during 30 years of planned service life, including both pre-service hydro test and in-service monitoring. The model expresses the typical path from AE source to assess the data, in which all the variables along the path i.e. wave production & propagation, stress stimulus, source behavior, sensor sensitivity, instrumentation gain, and detection threshold were evaluated.

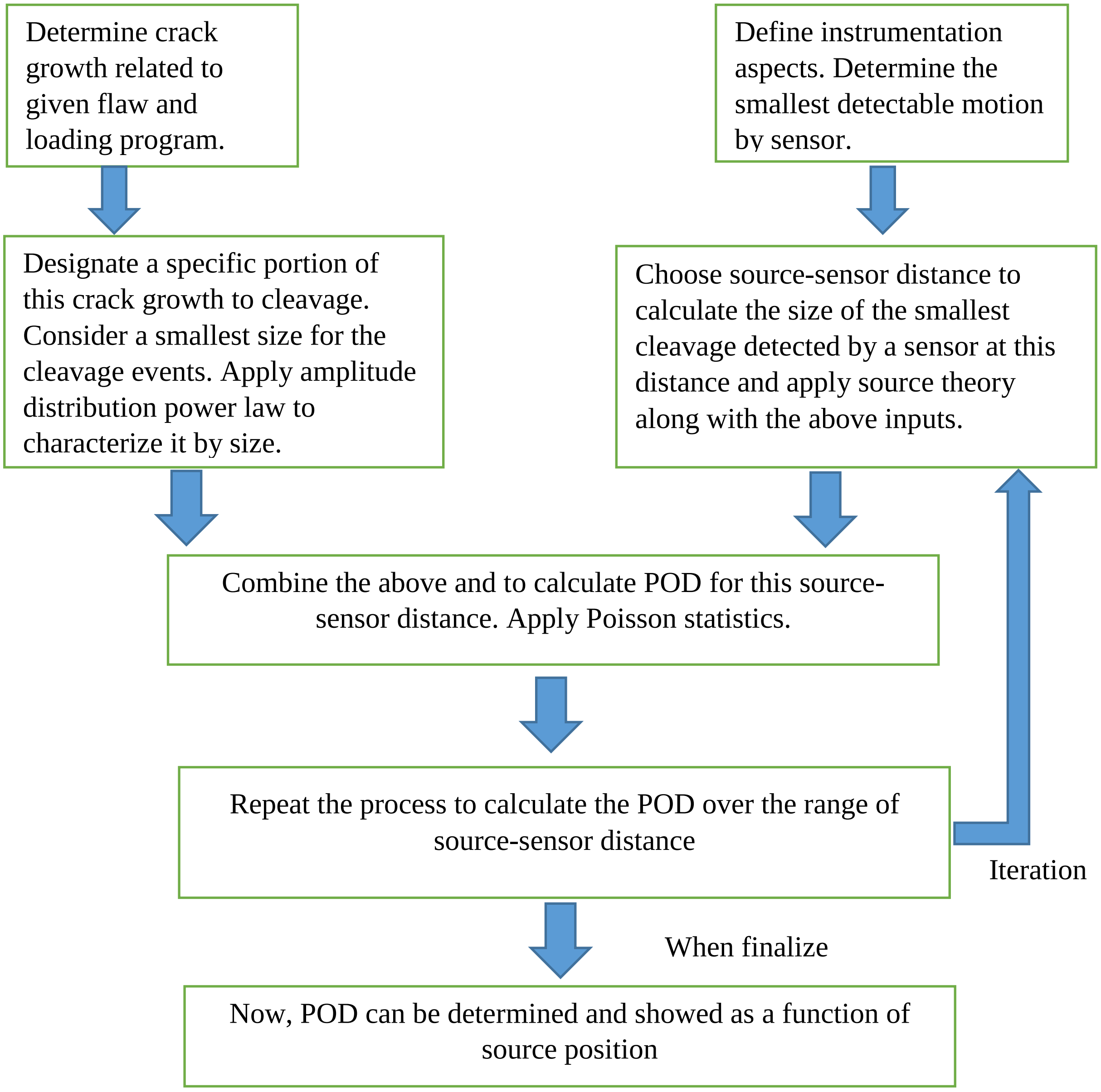


Figure 3.15 Illustration of the methodology of determination of POD of a defect with AE [76]

The Probability of detection (POD) is a significant method in determining the reliability of the non-destructive testing technique. It defines the probability of detection of defects that are considered to be present in a test specimen. Moreover, it depends upon several parameters of given defects such as flaw size, shape, class, and orientation. Previously, an empirical approach was followed to determine the POD, in which several test specimens (having artificial defect) were inspected by the number of inspectors employing the NDT technique, and results were formally present on a graph as the POD curve. The setback of this practice was that, it was arduous and expensive. Therefore, with the development in this field, several models for NDT techniques were introduced like the one shown above, to enhance the procedure of an empirical approach. These models reduced the number of test specimens and inspectors to develop POD, which eventually decrease the cost and provide improved results

Furthermore, the aspects of the Acoustic Emission (AE) method were quite different from other non-destructive methods. Firstly, this method deals with the origin of sound or signal generating and emitted inside the material instead of applying directly to the object. Secondly, it deals with the dynamic processes within a material i.e. the detectability of growing and inactive is crucial. However, the advantages of the AE technique include, it is highly sensitive and fast method, it can be used for global inspection using multiple sensors and permanent sensors, attached for continuous monitoring without maintenance. Additionally, it is a very useful technique to analyze the defects caused by fatigue loading e.g. fatigue cracks. In particular, this technique requires highly skilled personnel, to correlate AE data to a particular type of defect and also while using it along other NDT techniques.[32, 52, 76-78]

3.3.5 Eddy Current

The Eddy current (EC) and all other electromagnetic methods like a magnetic particle or ultrasonic method employ electromagnetic or sound waves to evaluate or inspect the conductive material such as steel, copper, aluminum, etc. to assess its properties and defect detection.

The principle of EC is primarily based on the interaction between the electromagnetic field, generated by a time-varying current passing through an excitation coil, and the test specimen. Eventually, it induces a magnetic field in the specimen, which must be in the proximity of the electromagnetic field, as per faraday’s law of electromagnetic induction that states; “a voltage will induce in an electrical conductor by a moving magnetic field”, mathematically shown in equation (29).

$$\vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{29}$$

Where, $\vec{E}$ represents an induced electromagnetic field, $\vec{B}$ is the magnetic flux.

Moreover, the main magnetic field generated by the coil will be opposed by a newly created electromagnetic field. Due to the interaction of these fields, the impedance of the coil will face possible changes. It depends upon the distance between the electromagnetic source and material, the surface and subsurface geometry, the conductivity and permeability of the material. Therefore, if the flaw is present in a material, by observing the minor changes in induced eddy current, the inspector can detect the flaw, efficiently and precisely. However, it should be noted here that, the crack needed to be detected must interrupt the surface eddy current. If it is happened to be in parallel with the eddy current then it will not create any major disturbance and crack may not be detected. Furthermore, this technique can detect surface cracks of 0.1 mm or less in-depth in ferrous or non-ferrous metals by using 100 kHz to a few MHz frequencies, depending upon the surface condition of a material. And for sub-surface crack detection, for instance in aluminum structure, EC can penetrate up to 10 mm depth. Hence, it can detect a crack in second or third layer with testing frequencies of 100 Hz to 10 kHz. *A. Sophian et al*. discussed one of the most crucial issue in EC testing that is the limited penetration depth due to skin effect. This effect occurs due cancellation of the main electromagnetic field by the one, induced by eddy current. It causes the alternating current to intensify near the surface. However, the standard penetration depth can be described as the depth, where the current's magnitude reduced by 1/e or 37% of its surface value. It primarily depends upon the frequency, permeability, and conductivity of the material as stated in equation (30).

$$\delta = 50\sqrt{\frac{\rho}{\mu . f}} \tag{30}$$

Where δ represents standard penetration of depth (m), μ is material's relative magnetic permeability (H/m) for non-ferrous=1, ρ is resistivity (mΩ.cm) where ρ = 172.41/material's conductivity and f is the frequency (Hz). Moreover, the effective penetration depth of the eddy current is suggested as '3δ' and the calculation will be affected if the thickness of the material is less than the effective depth. From the above equation, it can be concluded that the standard penetration depth is.

- Inversely proportional to permeability.
- Directly proportional to conductivity.
- Inversely proportional to frequency.

The EC method can be implemented successfully underwater as well as above water. Although, special arrangements are required in underwater operation. However, POD curves can be produced in both situations. Thus, the probability of detection of particular defect size, in both cases can be calculated using equation (5). For instance, to get the POD of 90 % using EC, the depth of a crack should be 14 mm.

$$P(a) = 1 - \frac{1}{1 + (\frac{14}{1.160})^{0.900}}$$

$$= 0.90$$

The EC method has many advantages over other non-destructive techniques like it can detect flaws or cracks in many conducting materials either ferromagnetic or non-ferromagnetic. In addition to this, it is a fast and sensitive method and provides results instantly and Inspection can be done without getting physically involve between the sensor or test specimen. It can also be used to differentiate among the pure material and alloy composition and to determine the test specimen's hardness after heat treatments. On the other hand, it also carries some disadvantages as well like this method can only be applied to the electrically conductive materials, high skills required to interpret the complex signals received on display instrument, the determination of field distance between the coil and material i.e. lift-off impose a big challenge in designing eddy current sensors, sensitivity to the irregularities in material surface or sub-surface can create a problem in flaw detection as they cover up the signals in noise.

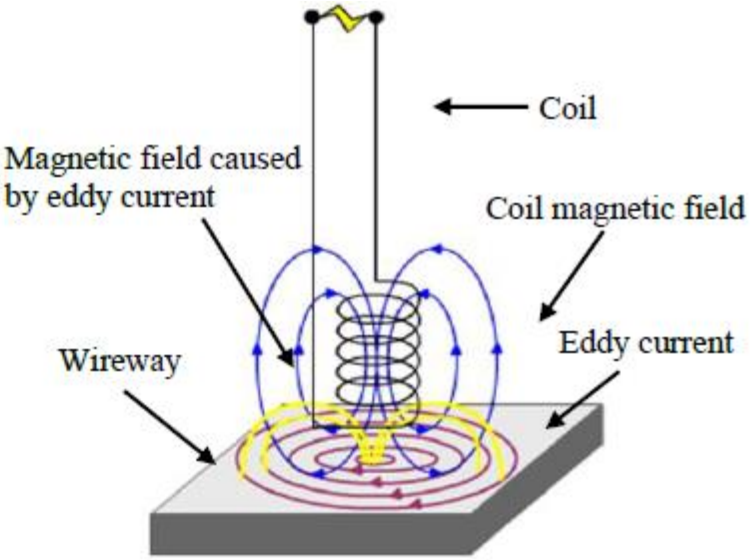


Figure 3.16 Showing typical eddy current testing[79] un-modified, CC BY 3.0

Currently, different types of eddy current techniques are used. Some of them are as follows.

<u>Eddy Current with Single Frequency</u>

EC with a single frequency system is the basic and currently the most frequently used non-destructive EC testing type for surface and sub-surface crack detection purposes. The equipment used in this system consists of an oscillator, sensors, excitation coil, signal processing system, and screen display for interpretation of impedance plane. In this method, the frequency is primarily depend on the type of material to be tested and the defect's depth. Usually, sinusoidal applied current with a frequency of a few hundred Hz to a few MHz is applied. However, it highly depends upon the depth of flaw, like for the detection of flaws with lower depth such as surface flaws, a high frequency is used. Likewise, in sub-surface flaw detection, low frequency is employed. The sensor must also induce the high eddy current density near the defect to achieve the desired results. Moreover, the excitation and sensors can be used in single-coil or separated coils by employing specific coil design. The various design models and the impedance bridge circuit that are used to modify, impedance variation into amplitude modulation together with the phase, gives the distinctive fluctuations in the test specimen.

Furthermore, in eddy current application, the most important step is to select or design a proper coil because getting the right signals from the probe is the main point of concern. The probe split into two major classes, *Absolute* and *Differential* probes, which can be used depending upon the defect's depth and testing condition. For instance, in the detection of defects in welds, a special uniform eddy current probe is used to assess the material properly by neglecting problems associated with the weld zone such as noise, lift-off variations, etc. Most commonly, it consist of a coil specially designed to produce straight lines current pattern in the material, rather than in circles by inducing uniform electromagnetic field. As they are highly sensitive to the defect location. Therefore, extra work and special probes are required to detect defects of all directions.

Eddy Current with Multi-Frequency

Multi-frequency eddy current works in the same way and similar in principle as conventional single frequency EC. However, it is more effective and efficient than single frequency EC. The main difference in them is the number of frequencies used in operation. In multi-frequency EC, different excitation frequencies can be used either simultaneously or sequentially, depending upon the type of material used. For instance, in unsaturated ferromagnetic material testing, frequency is applied sequentially, because in this type there is no variation in the power supply. Similarly, using frequencies simultaneously has also advantage of less time-consumption. However, there is no such option available in single frequency EC. Furthermore, Single frequency EC is only capable to identify defect of a few test conditions. Multi-frequency EC provides more information regarding the nature of the defect. It provides more accurate results in the detection of flaws in ferromagnetic material. Moreover, it can also evaluate the simple and complicated shape flaws by neglecting unwanted signals while having variations in different material parameters such as conductivity, permeability, geometry, and probe lift-off.

SQUID-based Eddy Current

Superconducting Quantum Interference Device (SQUID) is the latest and most advanced eddy current NDT technology, developed in the 1980s. These devices (superconductors) usually operate at cryogenic temperature i.e. very low temperature. Moreover, they would carry no resistance in conducting DC below a certain temperature, SQUID provides very sensitive and strong detection of magnetic flux, independent of frequency. It has many advantages against conventional eddy current technology especially when low excitation frequency required. Moreover, it gives very improved results in signal-to-noise ratio such as up to three orders of magnitude for a crack at high depth i.e. up to 13mm. It can also detect small changes in a magnetic field while having large background fields due to its high dynamic range of 140db/$\sqrt{hz}$ or more.

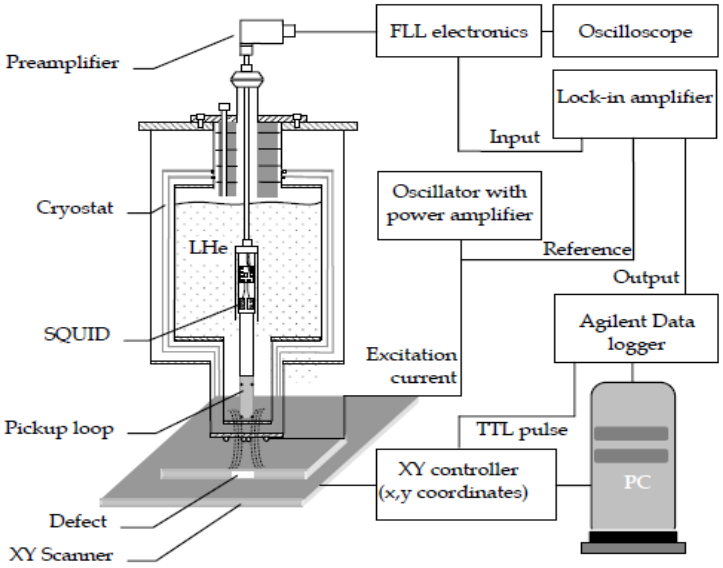


Figure 3.17 Possible experimental arrangement of SQUID based eddy current [80] un-modified, CC BY 3.0

Jenks et al. presented a thorough review of this technique. According to their research SQUID magnetometry technique can provide low noise and highly sensitive estimation of a magnetic field in the range of dc to 10 kHz. Moreover, it is also very useful in determining the quasi-static current of active corrosion in metallic structures. These capabilities enable the SQUID technique to be used as an alternative to conventional non-destructive testing techniques. Furthermore, they concluded that the SQUID has the best detection capability of magnetic flux among all the sensors because its sensitivity is unmatchable. However, improvement and development are required in this field. *Weinstock and Nisenoff* were the pioneers, they determined the capability of SQUID magnetometry in detecting the flaws in metals. They incorporated second-order gradiometer (an instrument used to measure the gradient of a physical quantity such as magnetic field) and a 1 A and 4.6 Hz AC injected into copper and iron pipes and proved that SQUID technique can be successfully employed to estimate the magnetic field disturbance, due to current variation produced by the flaw present in the structure.

In fact, recent research shows that the SQUIDs with the ability to work at room temperature are also developed and high transition temperature SQUIDs are capable of evaluating defects in 50 mm of thick aluminum layers. However, apart from all its advantages and capabilities, it is not frequently used due to its high cost.

Pulsed Eddy Current technique

Pulsed eddy current (PEC) is a useful modern technology in non-destructive testing. It poses many advantages as compared to the conventional eddy current method such as high penetration depth, more information about the defect, highly reliable anti-interference. Furthermore, it can classify many parameters such as defect size, location, and probe lift-off during an inspection. However, the conventional eddy current system is greatly influenced by the eddy current's depth of penetration because of single sinusoidal excitation. It allows them to determine the surface and near-surface defects i.e. up to few millimeters under the surface. PEC system employs one dual-function coil or two separated coils. It takes pulses for testing instead of excitation that reduces power consumption drastically. In contrast to conventional eddy current instruments, they produce waveforms in a square, triangular, or saw tooth shape. Since, eddy current's penetration depth is primarily based on the excitation frequency. Therefore, PEC can go deeper and fetch more information regarding defect properties. This technique has also the ability to test highly conductive materials such as copper. In addition to above, it allows to detect surface and near-surface flaws simultaneously without altering the operating frequency and changing the probe.

Furthermore, PEC supplies a large pulsed current into the excitation coil. However, the eddy current will induce in testing specimens only when there is a transient change in it. This is why, this technology is also called *transient eddy current*. As theses pulse travels through the material, they developed and scatter back due to present discontinuities in it. Each pulse contains continuity of frequencies particularly low frequencies components, hence, they can go deep below the material's surface. Moreover, in recent research, it is found that it can penetrate even through 100 mm of the non-conductive coating. As a result, each component gets more information from different depths, and the probability of detection can be increased.

Many researchers played a vital role in the development of PEC eddy current technology such as *C. S. Angani et al*. [81] performed an experiment using the fabricated differential probe and PEC technique, to detect artificial defects induced in insulated stainless steel pipe. The energy and the spectral power density of the defected pulse were calculated and derived by using different signal processing techniques such as pulse amplitude and other time-domain features i.e. time to zero to analyze the output. They concluded that the differential PEC technique is highly capable of detecting defects in insulated pipes. However, the spectral power density and the energy of the defected pulse can be described by using the following equations.

$$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} |f(t)e^{-i\omega t}|^2 \tag{31}$$

Where ω is the angular frequency and $F(\omega)$ is the Fourier transform of$f(t)$.

$$Energy = \int_{-\infty}^{\infty} |f(t)|^2 \tag{32}$$

Moreover, *Giguere et al.* made an important contribution in improving the defect detection using PEC technology. *Tian and Sophian* also conceded the concept of 'rising point time' in defect identification and lift-off. Basically, this feature provides an opportunity to evaluate the depth of defect irrespective of its shape and size and freedom of the coil dimension. Similarly, *Hoshikawa* designed a uniform eddy current probe to produce a rotating magnetic field with two sinusoidal excitations. *J.H. Rose et al.* has defined a method to detect a defect in time-domain for PEC probe with one plate coil, for both air-core and ferrite-core.[35, 82-85]

3.3.6 Dye Penetrant Testing

Liquid or Dye Penetrant Testing (DPT) is one of the earliest and most frequently applied non-destructive testing technique, used in different industries. It is successfully incorporated to identify surface-breaking defects in non-magnetizable materials such as aluminum, copper, titanium, magnesium, etc. and also in non-ferromagnetic materials such as glass, rubber, and ceramic materials. The principle of the technique relies on the ability of the liquid with low surface tension to infiltrate into the cleaned surface having flaws, by capillary action. The process of detection of defects in DPT involves the following steps.

- *Pre-cleaning*: Remove the dirt and stain with the help of wire brush or cloth that can shroud the defect, apply the cleaner solution on the specimen's surface to remove oil, dust particles, and others.
- *Penetrant Application*: Apply the penetrant either by spraying, brushing, or dipping on the test specimen and allow it to reside on the object's surface for about 10 minutes.
- *Removal of excess penetrant*: Using cloth, having some solvent on it, remove the excess penetrant. After removing and using the solvent, dry up the surface using a clean cloth.
- *Developer Application*: Apply the developer evenly upon the surface by spraying. Then Wait for about 30 minutes for the developer to react. It will help the penetrant to come out of the flaw to the surface.
- *Defect detection*: The defect may appear as a difference in color, as shown in figure 3.18. However, it can also be detected by using ultraviolet or white light, depending upon the type of dye penetrant used.
- *Post-cleaning*: Clean the surface of the specimen again using a clean cloth with cleaner.

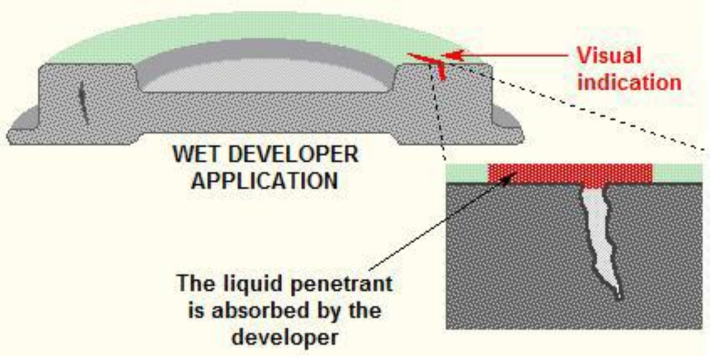


Figure 3.18 Showing the indication of a defect in the test specimen in DPT[61] unmodified, CC BY 3.0

The DPT method is used because of its advantages over the other non-destructive testing methods particularly MPI. Apart from the fact that it is considered to be a time-consuming method, as compared to MPI and it largely depends upon human experience, knowledge, and visual capability. Some of its advantages are; it is easy to use in principle because of its simple equipment, it is also very suitable in fieldwork. However, it is only capable to detect surface-breaking defects. And thorough surface preparation like cleaning is required before testing.

Many researchers have made significant contributions in the development of dye penetrant technology by performing different experiments like *Syed Mobin Baba et al.* experimented to figure out the delicacy and accuracy of liquid penetrant testing (LPT) or DPT in the detection of a defect in a sample of stainless steel and chromium-nickel, that gives good strength, durability, and resistance against corrosion. The sample was welded using Tungsten inert gas (TIG) welding. As a result, LPT appears to be very sensitive in detecting surface defects and also detected one significant flaw in the weld.

Michele Cevenini in 'Safety and Productivity innovations in Liquid Penetrants and Magnetic Particles Testing' has described the advantages of using automated Liquid Penetrant Inspection (LPI). According to him, the automated LPT inspection has largely benefited the automotive industry. Furthermore, it doesn't only increase the reliability of the LPT technique but also provided a safer working condition for the inspector involved in the testing process. Moreover, by using robots in the inspection process, it has drastically reduced the consumption of liquid penetrants and thus the cost of operation reduced.

Mohit Bector et al. performed three separate tests on stainless steel cylinder having V-butt welded joint to compare the efficiency and reliability of three non-destructive testing techniques: Ultrasonic Testing, Magnetic Particle Testing, and Liquid Penetrant testing. They concluded that MPI is very uncertain than UT and LPT. Moreover, it has limitations in detecting defects in welded joints. However, UT is very effective and efficient in finding deep flaws and LPT is cheaper than the other two. Furthermore, it is only capable of detecting surface flaws in weld zones. *Andrea Tonti et al.* also concluded that liquid penetrant testing technique can be very useful in detecting surface flaws even at high temperatures i.e. 50℃. [61, 86, 87]

3.3.7 Alternating Current Field Measurement

The Alternating Current Field Measurement (ACFM) is a non-contact electromagnetic NDT technique, used to determine and characterize the surface breaking and near-surface (in some cases) defects in magnetic and non-magnetic materials.

Its detection system comprised of two components, the hardware, and the software. The hardware component includes a scanner, ACFM board, and a computer. The scanner drives out the uniform alternating current on the specimen's surface and records the changes in the magnetic signal simultaneously. Afterward, the signals are processed, identified, and analyzed along with intelligent 'defect detection analysis software' to detect a defect in the test specimen.

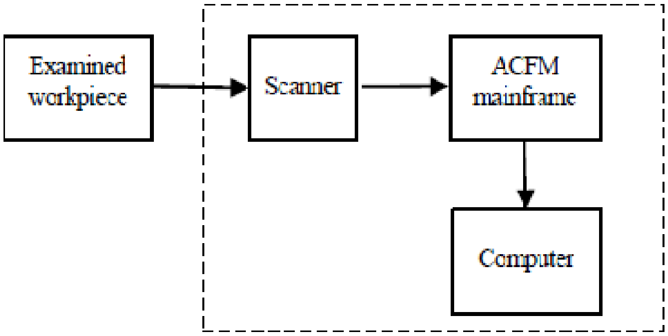


Figure 3.19 The ACFM's defect detection system[88] unmodified, CC BY 3.0

The ACFM probe consists of a large coil and sensors, used to induce uniform high frequency (5-50 kHz) alternating current into the test specimen's outermost surface and to detect a disturbance in the magnetic field (B), up to three orthogonal directions x, y and z. The AC that flows in a thin skin, following the surface near the surface of the conductor will get no disturbance while traveling through the defect-free area. However, if there's some defect present in a surface then the current will get disturbed and start to flow underneath and around it, disturbing the resultant magnetic field above the surface. Those perturbations are comparable to the defect's size and electrical disturbance. Afterward, the mathematical models are used to locate surface-breaking defects and to determine their parameters like depth and length from Bx or By and Bz. This is achieved by analyzing the magnetic field's directional disturbances Bx, By (Parallel to the input filed and defect's expected direction), and Bz (perpendicular to the surface) of the defect. However, to improve the probability of detection and to avert the dependence on the speed of the probe, the Bx and Bz are plotted against each other in a '*Butterfly shape*', as shown in figure 3.20. Since ACFM technology deals with the magnetic field disturbance in a material, it doesn't require any electrical contact with the specimen's surface. Thus, there's no need to remove any protective coating or paint from it. Moreover, to measure the defect's size, the calculated magnetic field's disturbance is fed into the mathematical model that gives a theoretical prediction of current flow around and beneath the defect. These types of models depict a strong correlation with the physical measurements made using ACFM equipment.

Furthermore, the probability of detection can be calculated by using equation (5). For instance, to get the POD of 90 % using the ACFM technique, the depth of a crack should be 14 mm, as shown below.

$$P(a) = 1 - \frac{1}{1 + (\frac{14}{1.160})^{0.900}}$$

$$= 0.90$$

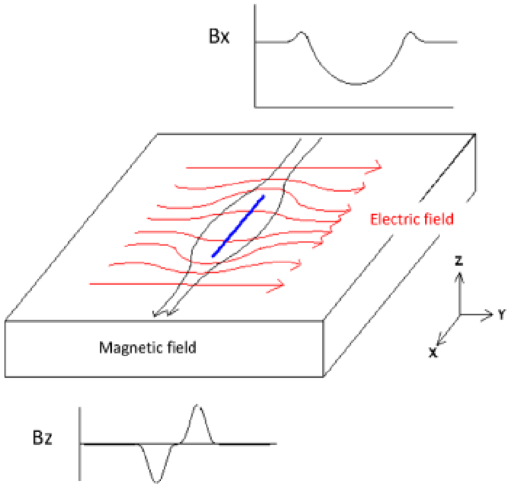


Figure 3.20 The Schematic representation of ACFM with 'Butterfly plot'[88] unmodified, CC BY 3.0

In the period 1986-1991, *University College London (UCL)* conducted many underwater experiments and investigations by using many non-destructive techniques such as magnetic particle inspection, eddy current testing, ACFM, etc. to determine their reliability and probability of detection (POD). In their report, after experimenting samples of 20 joints with defects varying from 2-9 mm in depth. They concluded that, the POD using ACFM on 1-2 mm of the epoxy coating was very much similar to the one without coating. Moreover, ACFM results positive in their experiments and all surface defects of 5 mm were detected. In fact, the POD for 2 mm deep depth was determined as 80%.

In the 1980s, the *oil and gas* industry of the UK investigated the underwater inspection using one of the conventional NDT technique i.e. Magnetic Particle Inspection (MPI). However, they require special preparation of specimen's surface before testing like cleaning, removal of paint, or any protective coatings on it, due to its limited detectability in coated materials. In addition to above, it also require that either diver need to be a skilled inspector or inspector need to be qualified diver. Moreover, MPI is highly dependent on the site conditions such as degree of accessibility, etc. as it is usually difficult to detect the defect on-site due to their location. Contrary to this, ACFM require very nominal cleaning and it can also be applied over paint and non-conductive coating of a few millimeters i.e. up to 5mm in thickness. Furthermore, it is independent of the probe's time and speed. Which means it allows the scanning of a defect in slow/high speed or steps. It will always present the 'butterfly' plot that makes it very suitable for underwater inspection, as it allows the inspector to view and analyze the data by staying above water in a standard working environment, while the diver moves the probe underwater. Additionally, ACFM's system can also determine the depth of the defect, storing the data for later stages like for audit. Another advantage of ACFM against other conventional non-destructive testing methods such as MPI, Dye Penetrant is its cost and time effectiveness, as mentioned earlier that they require paint removal, accessibility platforms, and sometimes required to even shut down the processor plant to reduce the temperature, before an inspection takes place. Contrarily, ACFM doesn't require such preparations before the inspection. Thus, it can drastically reduce the time and save the cost. By considering these aspects of ACFM, many certified authorities like DNV, Lloyds, and others have adopted ACFM technology. Even some industries have reported up to 60% of time and cost savings after employing this method.

As compared to ‘eddy current’ technique, ACFM can determine high depth defects because it employs uniform AC which goes further down to the defect’s surface. Moreover, it can measure defect depth without calibration, penetrate through thicker coverings and transition weld zones, and permits the change in signal due to low probe lift-off i.e. maximum 3 mm with an allowable reduction in the signal. Furthermore, ACFM can be easily set up with a mechanized system using array technology. It allows an automated interpretation that can reduce human error and increases the probability of detection. However, the ACFM technique also has limitations, like in carbon steel, it can only detect surface-breaking defects accurately in it, because only this can be found in ACFM’s calibration table. The ACFM’s calibration table is required to convert inspected depth into true depth to accurately measure the size of the crack in a material. Moreover, in high skin depth non-magnetic materials, the sub-surface defects and defects starting from another side can detect only either the skin depth is sufficiently high or the defect is positioned close to the top surface.[88-92]

3.3.8 Visual Inspection

The Visual Inspection (VI) technique is the simplest and the oldest NDT technique, used to detect defects in a material. VI is particularly used to identify macroscopic defects such as cracks, poor welds, the shape of the joint, and transition between the material and the weld like excess height and undercuts of the weld. These areas are commonly subjected to fatigue cracks initiation. Therefore, they need to be inspected thoroughly and attentively. Moreover, this technique is also useful in determining the physical dimension, surface finishing, stamps/logos of standardizations, and defect’s shape in an object.

According to *DNVGL-CG-0051*, the equipment required for typical visual inspection is a magnifying glass, radius gauge, light source, and lux meter (a gauge used to measure the brightness of the light). Furthermore, for assessment of defects with limited accessibility, several types of mirrors, endoscopes, borescopes, fiber optics, and cameras can also be employed. The inspection procedure involved proper cleaning of the object’s surface before inspection starts. It should be thoroughly cleaned and free from dust, mud, stains, slag, paint spots, and any other surface irregularity by using a clean cloth, cleaner compound, abrasive paper, or grinding machine (if required). Moreover, any temporary attachment with the object’s surface must be removed and all the sharp corners and edges must also be made round to get good accessibility and vision.

In 1996-1997 *Fujimoto et al.* presented some POD curves based on assumptions and experience. The assumptions were made by using a plate of moderate thickness with cracks of high depth on it. In addition, the accessibility to those cracks was also kept moderate. However, the result showed that the cracks were detected only after they have grown through half of the plate thickness. Hence, it showed that the probability of detection was very low while using only the VI method. For this reason, a well-experienced inspectors and the latest equipment like high-resolution cameras etc.

are used during inspection. Moreover, other non-destructive techniques can also be used along with visual inspection to get a high probability of detection.

Furthermore, the most important advantage of a visual inspection lies in its flexibility and simplicity during operation. Moreover, It is the fastest and easiest process of all NDT techniques regardless of the type of material used, structure's shape, and its size. The outcomes of testing are rapid, reliable, and sensitive upon repetition. In addition to above, employing VI also saves time and cost because it doesn't require expensive or a specific instrument. However, visual inspection technique has also many inherent restraints, due to limited human vision, the equipment's low resolution, poor accessibility, and environmental conditions that may cause the defect to be overlooked or neglected during the inspection process.[17, 52, 87]

3.3.9 Thermography

The thermographic testing technology is also termed as thermal imaging. The working principle of thermography relies on the fact that the defect present in material changes its thermal conductance. It is usually applied to low depth skin materials because there are fewer temperature variations when crack moves deeper underneath the surface than when it is close to it.

One of the predominant and newest applied types of thermographic testing is 'Infrared Thermography (IRT)'. It is particularly used to detect sub-surface defects but also employed for different purposes in many fields such as, in civil engineering (as an indicator of loss of heat in a building), mechanical engineering (as a signal of a defect in maintenance) and aeronautics, etc. However, several objects emit specific type electromagnetic radiations above absolute zero temperature. They have a longer wavelength than those of visible light. Those rays are called infrared radiations. Furthermore, there are three possibilities involved in the dissipation of radiant energy after striking from the object. They will either be absorbed, transmitted, or reflected. The amount of total radiant energy that is related to these possibilities are often expressed as absorptivity, transmissivity, and reflectivity of the object or body. These constraints are highly dependent on wavelength and their sum must be equal to 'one' of any wavelength.

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1 \tag{33}$$

Here$\alpha_\lambda, \rho_\lambda, \tau_\lambda$ represents the spectral, spectral reflectance, and spectral transmittance.

Moreover, IRT works by obtaining and processing infrared radiations of different wavelengths, depending upon the temperature variations on the material's surface with the help of non-contact infrared detecting and measuring devices such as pyrometer and infrared camera. These devices convert the emitted infrared radiations from an object into electronic signals. However, in the event of weak signals, data processing techniques are used to improve results and making detection of defects possible. Most commonly, two types of approaches are used in non-destructive testing using IRT: *Active* and *Passive* approach. The passive approach deals with the inspection of the material with temperature variations, for instance, the inspection of structures with inside water panel. In fact, the active approach is most commonly used in NDT inspection. In active thermography, data obtaining and external stimulating (heating) are done simultaneously. The objective is to produce thermal differences in sub-surface defects of the specimen by using different external excitation techniques such as optical simulation i.e. by using a halogen heat lamp and laser, electromagnetic sources i.e. through microwaves and induced eddy current. Afterward, stimulation generates heat energy as thermal waves that travel through the object. And when they encounter a defect, they change their traveling velocity, creating a thermal difference on the surface above the defect. Furthermore, the equipment typically involved in active thermography are infrared camera, excitation source like Halogen lamp, and data processing algorithms to improve the results, as shown in figure 3.21.

The probability of detection of defects using an active approach in NDT inspection are deeply rely upon the selection and type of equipment used. Therefore, here it is discussed the type of equipment that can increase the chances of flaw detection.

Infrared Sensor

They are used to convert infrared radiations into electronic signals. The selection of infrared sensors depends upon the different aspects of the object to be inspected and environmental conditions. However, mostly infrared cameras are used in NDT inspection for sensing infrared radiations. The material's spectral emissivity parameter is also one of the important parameters involved in the infrared sensor's selection. This parameter expresses the number of radiations emitted from the inspected object as compared to that from the black body at the equal temperature. In fact, the materials with high emissivity provide a better probability of defect detection because they give a low parasitic reflection.

Excitation Source

The most common and simple excitation sources available for IRT in NDT inspection are 'heat gun' and 'thermal blanket'. The thermal blanket is particularly used in the heating of medium and large size objects. They are mostly designed to provide an accurate heating source for different kinds of materials. However, in this method, only the cooling-down stage is analyzed, because the blanket covers the entire object during warming-up, blocking the passage of information. The heating gun is a manual, low cost, and rapid technique but with a low repeatability rate. It uses hot air to heat the area of interest particularly useful for small and medium-size objects.

Furthermore, to overcome these limitations and to increase the POD, new methods were developed such as optical methods. One of the most common and widely used technique are using flash lamps and halogen lamps. They can provide a continuous and modulated rate of heating on different sizes of objects with a high rate of repeatability and accessibility of getting information during warming and cooling down processes of an object. However, in some cases like in metallic and reinforced objects, the optical stimulation technique is unable to provide adequate thermal contrast. Therefore, to improve this technique latest equipment are available like in Vibro-thermography, heat is generated through mechanical means (friction of di-continuities), in Thermoinduction thermography, induced eddy current technique are employed for heat generation and defect detection, in pulsed thermography, the specimen is heated through the short pulse of thermal stimulation.

Data Processing technique

There are many mathematical models and data processing algorithms that are used to interpret the electronic signals in the IRT technique. It not only provides a better probability of detection but also used to describe the automatic detection procedure. However, following are some of the important and most common techniques that are used to process data in the IRT technique.

- Statistical moments.
- Principle component analysis.
- Dynamic thermal tomography.
- Polynomial fit and Derivatives.
- Pulsed phase tomography.

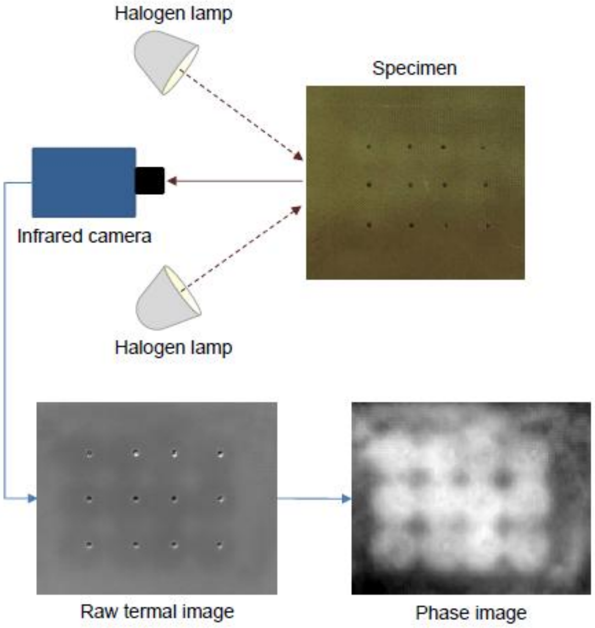


Figure 3.21 A possible arrangement of active thermographic inspection [93] unmodified, CC BY 3.0

Patrik Broberg performed an experiment to detect the artificial (in the form of notches) and real surface cracks in a metallic material i.e. weld by using optical and pulsed IRT technique. The notches were 12 in number with dimensions of between 0.25 and 1.7 mm long, 800 to 400 μm wide, and half of the length deep. Moreover, the width of real cracks was varied between 5 and 330 μm, found by using an optical microscope. As a result, all 12 notches were identified in the IR image. In fact, larger notches were detected without excitation but not those with a length shorter than 0.5 mm because in such cases, it was difficult to differentiate them with the noise. However, the signal to noise ratio can be improved by adjusting the wavelength. Furthermore, lamps were employed instead of a laser as an excitation source in the detection of real cracks. The results revealed that the size of the smallest defect identified using this technique was about 5-10 μm. He concluded that the smallest width of the crack that could be detected was 5-10 μm .

Moreover, thermography is a fast method. It can detect small cracks in the material and it can also be employed as an alternative of EC and MPI methods.

A. Runnemalm and P. Broberg employed thermography for automatic inspection in a welded plate made up of Inconel. They concluded that, by using a UV excitation source, a high signal-to-noise ratio can be achieved in metals. The surface defect with a width of 0.2 mm and a length of 2.9 mm was successfully detected during the experiment.

Thermographic testing preferably IRT has many advantages in employing it as an inspection method in non-destructive testing. The advantages include; it can inspect large bodies in single-shot and less time, it permits inspection of parts of an object, where there is only one accessible side i.e. it doesn't require coupling like many other NDT methods. Moreover, it is a non-contact technology like ACFM and radiography and non-invasive technology i.e. it doesn't affect or create changes in the specimen, it emits no harmful radiations such as x-rays. Therefore, it can be used frequently and for a long time, it can also provide two-dimensional images that allows the comparison of the areas of the object. From all these advantages thermographic testing is considered to be a very effective and efficient NDT inspection technique. However, despite all these advantages. It also carries some disadvantages as well like the inspection required expensive and sensitive instrumentation such as infrared camera, highly skilled and trained personnel are required to run the instruments and to interpret the infrared images as they are difficult to translate, the inspection must be performed in a controlled environment to avoid any external effect because thermography is highly dependent on testing conditions and surroundings such as temperature.[52, 93-95]

3.4 Summary of detection techniques

Table 3 shows a summary of the aforementioned detection techniques.

Table 3 Summary relative uses and merits of NDT methods.[96]

Description	**UT**	**MPI**	**EC**	**DPT**	**RT**
Capital cost	Medium to high	Medium	Low to medium	Low	High
Consumable cost	Very low	Medium	Low	Medium	High
Result timing	Immediate	Short delay	Immediate	Short delay	Delayed
Geometrical Effect	Important	Not very important	Important	Not very important	Important
Access issues	Important	Important	Important	Important	Important
Type of defect	Internal	External	External	Surface breaking	Most
Relative sensitivity	High	Low	High	Low	Medium
Formal record	Expensive	Unusual	Expensive	Unusual	Standard
Inspector skills	High	Low	Medium	Low	High
Training of the inspector	Important	Important	Important	-	Important
Training required	High	Low	Medium	Low	High
Equipment’s Probability	High	High to medium	High to medium	High	Low
Dependence on material composition	Very	Magnetic only	Very much	Little	Quite
Automation ability	Good	Fair	Good	Fair	Fair
Capabilities	Thickness gauging & some composition testing.	Defects only.	Thickness gauging & grade sorting.	Defects only.	Thickness gauging.

Chapter 4: Discussion & Comparison

Several non-destructive testing (NDT) techniques are reviewed in this thesis regarding their defect detection capabilities, operating procedures, and advantages/disadvantages, particularly in the light of previous researches, done by many researchers. Now, in this chapter, the discussion and comparison of those techniques will be deliberately examined.

Ultrasonic testing is one of the most frequently practiced and highly reliable testing method. It is capable of detecting and characterizing surface and sub-surface cracks in thick materials i.e. approximately greater than 10-15 mm, concerning the type, size, and location in a sound conducting material. Moreover, in conventional UT method, the angle of the beam used and its orientation relative to the defect is a major concern. For this purpose, the ToFD technique can be employed. It provides more accurate determination of the size of the flaw, irrespective of their orientation and position of the receiver probe. Furthermore, the position of a specimen can also be adjusted by analyzing beam intensity. However, equipment is expensive and the procedure is complicated, thus required skilled personnel to perform testing.

The MPI technique is useful in determining surface and near-surface i.e. within 3 mm deep defects in a material. However, the major concern in this method is its incapability to characterize the depth and orientation of defects. Moreover, its detection function cannot be enhanced and supported by a digital tool like signal processing technique that can be used in ultrasonic, eddy current, and other various NDT techniques. Therefore, when sub-surface and large discontinuities i.e. >1mm are expected then dry method is used and in shallow surface defects like fatigue cracks, wet fluorescent methods are employed. Furthermore, latest tool such as a resolution video camera and image processing methods can also be used. For improved results, extensive training is required to perform the testing.

Unlike MPI technique, sensors like magnetometer, inductive coils, and hall elements are used to detect magnetic leakage fields in the MFL technique. It allows automatic testing and evaluation without a human inspector. Furthermore, it is commonly used in underwater inspection and in testing of irregular structures or components. Moreover, as magnetization is local and levels are very low, therefore, it doesn’t require demagnetization. The reliability and characterization capability can be improved by using MFL together with UT or visual testing method.

Eddy current is a simple, less dangerous, reliable, and economical non-contact inspection technique, used to detect surface breaking and sub-surface flaws in a material, particularly useful in an underwater inspection. However, it cannot be applied in non-conducting materials. In this method, the sub-surface flaws are difficult to detect because of the low signal-to-noise ratio that happened due to ‘skin effect’. For this reason, SQUID sensors can be used to detect such type of defects with high penetration depth and the probability of detection. Furthermore, the conventional EC is time-consuming but the pulsed eddy current (PEC) technique is fast and more reliable. Moreover, methods like *intelligent image scheme* can be employed to perform fast processing and image scanning. In fact, this drastically reduced the time consumption in testing. Above all, in EC method, the detection of defects highly depends upon the properties of defects and electrical conductance of the material.

Radiographic testing (RT) technique is favorably used in the detection of volumetric flaws in a material either by using x-rays or gamma rays, depending upon the thickness of the material under observation. As compared to UT, the interpretation of its outcomes is easy to understand. However, it gives a very low probability of detection for planer flaws, because in this technique it is very difficult to convert the light source into a single point from the x-ray source. Therefore, to get a good probability of detection, it is always recommended to expose the object in different orientations to the rays. Moreover, the conventional RT technique is time-consuming and also require to stop any other work during an inspection. It is also unable to provide information about the depth of the defect, as it gives results in 2D. For this purpose, x-ray computed tomography (XCT) technology can be beneficial. It uses several transmission projections and mathematical models to construct 3D images of the object. In gamma rays radiography, because of the usage of an isotope as a radioactive source, it is not preferably used.

Acoustic Emission (AE) technique is used to analyze several types of defects and failure modes by analyzing emission signals or waves in a material. The two distinctive features of AE makes it different from other NDT techniques. First, it uses the signals or waves generated by the object instead of any external source. Therefore, it can be used on structures during service i.e. when damage propagation occurs. Second, the strain can be measured in AE testing. Furthermore, the inspection process is fast and can also be used precisely in the structural health monitoring (SHM) system. However, two main challenges commonly occurs during operation. Firstly, to differentiate between the several signals emitted by the specimen and secondly, high sound generation can affect the signals measured. They can be overlapped and the defect can go undetected, if the structure is not enough loaded to produce the elastic waves. For this reason, it is very important to have highly sensitive AE sensors to detect the signals.

The Liquid/Dye Penetrant Testing (DPT) is an inexpensive inspection technique, as compared to MPI and UT. However, it takes more time in setting up arrangements and requires surface preparation such as pre-cleaning and post-cleaning of the material surface. Moreover, it is easy to use and required simple instrumentation like Visual Inspection (VI). Therefore, it is a preferred technique for fieldwork. In this technique, the detection of defects is largely based on human experience and visual capability. Above all, it doesn’t provide an accurate depth of the defect and is only able to identify surface-breaking defects in a material.

The Visual Inspection (VI) is a fast, inexpensive, and flexible NDT technique. It can be applied to any material irrespective of its composition and size. However, its detection capability largely depends on the human experience and knowledge like in DPT. Therefore, there are very high chances of neglecting or over-looking of defects due to limited human vision.

The Alternating Current Field Measurement (ACFM) is a non-contact electromagnetic technique, employed to detect and characterize the surface breaking and near-surface defects in magnetic and non-magnetic materials. Furthermore, this technique can also be used successfully in underwater operations like inspection of offshore structures. As compared to MPI and DPI, it is cost-effective and fast, because it doesn’t require any removal of paint or coating. Moreover, it provides more accessibility options and no thorough cleaning required of the material’s surface. Contrary to MPI, it is independent of probe time and speed, which means, it allows the inspector to stay above water and analyze output instead of diving into the water. However, in low skin depth materials, it is only capable of detecting surface-breaking defects.

Thermographic testing is also a non-contact NDT technique like ACFM and Radiography. In fact, it is very effective and efficient inspection technique, as the smallest width of the crack that could be detected is 5-10 μm. In other cases, 2.9 mm long and 0.2 mm wide surface defect has also detected by using a UV excitation source. Moreover, it is non-invasive and non-hazardous as compared to x-rays, used in radiography. However, equipment involved could be expensive. Furthermore, the probability of detection highly depends upon the selection of the instruments like the infrared camera and inspection needs to proceed in a controlled environment, because external conditions such as high temperature, moisture can affect the testing procedure.

Although, the detectability of a crack deeply influenced by its orientation, testing environment, type of NDT technique used etc. However, by considering figure 4.1, it can be seen that, the POD of a crack of given size is also highly depend upon the application of specific technique. Therefore, as the depth of cracks are not largely vary in numbers, the POD of 90% of a cracks of given sizes, by four major NDT techniques can be achieved by altering the application procedure or execution of work. For example, in any case, if the execution of any technique is improvised to what extent that the crack needs, then it will detect it successfully, irrespective of depth of crack.

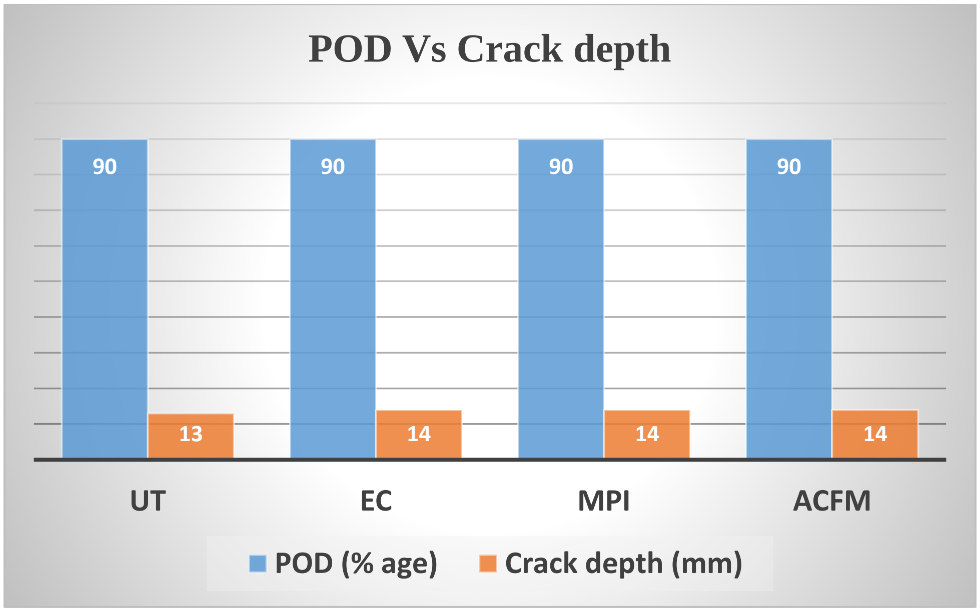


Figure 4.1 Depiction of different NDT method’s 90% pod and required crack depth.

Table 4 Brief comparison of NDT techniques. [96]

Method	Detectability	Advantages	Limitations	Example of use
Ultrasonic	Change in acoustic Impedance due to defects present.	Ability to penetrate through thick materials and can work automatically.	Mostly Coupling to material & Smooth surface required.	Inspection of Adhesive assemblies for bond integrity and hydrogen cracking.
Magnetic Particle Inspection	Magnetic flux leakage due to surface or near-surface defect present.	Sensitive to the surface and near-surface defects i.e. within 3 mm. Also In-expensive.	Surface preparation required like removal of the coating. Limited to the ferromagnetic material. De-magnetization may be required.	Inspection of large casted components like railroad wheels.
Eddy Current	Change in electrical conductance due to defects present in a material	Automate easily and quickly. Medium expensive.	Applicable to only electrically conducting materials and provide limited penetration depth.	Detecting defects in heat exchanger tubes.
Dye Penetrant testing	Surface opening of a material due to cracks, seams, etc.	Inexpensive, portable, simple, and sensitive o small surface defects.	It must be a surface flaw. Not applicable to a rough and porous surface.	Inspection of turbine blades
Radiography	Change in density due to defects..	Many materials can be inspected. A versatile, record of inspections also available.	Expensive, Radiation safety required, defects must be perpendicular to x-ray film.	Detection of faults in a pipeline.
Visual Inspection	Surface features like crack, finishing, color, etc.	It can be automated, in-expensive.	Only applicable to surface of a material.	Limited Inspection of any material like surface finish and uniformity.

Chapter 5: Conclusion

All NDT methods are equally important in testing, inspection, maintenance, and structural health monitoring (SHM) of the structures. Each one has its pros and cons and different requirements. Therefore, they should be selected appropriately, to maximize its quality, quantity, and workability. Moreover, the non-destructive testing methods are commonly used for determining and characterizing the defects in a specimen under observation through inspection and testing. In fact, they are extensively employed in evaluating the integrity of metals than any other material. Furthermore, some techniques are capable of providing the size and orientation of defects in addition to their detection, and others can only reduce human effort and provide a basic detection facility. However, the type and size of equipment required, the extent of simplicity in operating procedure and application, the time required, defect size and expenses involved in the process is always a major concern in this field.

Chapter 6: Suggestions & Recommendations

Further research work must be performed to determine more effective and efficient combinations of different Non-destructive testing techniques, which can give much better results of inspections in different types of metals. This would reduce the time and cost and further increase the reliability and confidence level of testing procedures.

- The process involved in estimation and calculation of the reliability of NDT techniques is particularly important for modern industries. Therefore, the latest methods should be established, which are cost and time-efficient.
- The introduction of the latest digital technologies like automation, digital signal processing, signal analysis theorems, and various mathematical models in the NDT field is the hour of need. They would make techniques more effective and capable of making effective management decisions at their operation and development stages.
- The structures, particularly the big ones like offshore platforms and ships must be thoroughly inspected before putting it into operation because it would reduce the cost of testing, effort, and repair (if required).
- The inspection and routine maintenance operations must be performed after regular intervals.
- Inspector's competence plays a vital role in the efficiency of NDT techniques. Therefore, training sessions and courses must be arranged after a regular interval to enhance their skills.

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