

A State of the Art Critical Review of NDT Techniques and Its Development: A Review of more Than a Decade of Research

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Abstract: Manufacturers are affected by continuously varying customer needs and high competition, which demands best quality, low processing time, cost effectiveness and low rejections. Non destructive testing plays a pivotal role as there is no need to destruct the product for testing and failure can be detected at earlier stages, planning for repair can be done. Therefore, this paper is attempt to provide a detailed critical review number of NDT techniques and their development in period from Year 2000-2014, which is also the most productive phase of NDT development as multiple improvements in existing techniques, development of new ones, research for further improvements under process. This review shall be helpful to the practitioners for current trends, at the same time this critical review will enable the researchers to find out the research gap.

Index terms-Non destructive testing, Fault Detection, Condition Monitoring, Reliability, Machines, Flaw, Wind Turbines, Composites, Welding Defects.

I. INTRODUCTION

Excessive maintenance (Escaler et al., 2011) severely affects the machine performance, its working efficiency and useful operating life. So it is better

(Garnier et al., 2011) to detect failure at early stages and plan for corrective measures. It is prerequisite to long-term reliability. Non destructive testing (NDT) implies Inspection or measurement of surface or internal flaws without destructing it. NDT is an effective technique (D'Orazio et.al, 2008; Krautkramer, et.al, 1990; Wilcox Mark et.al, 2003), and reduces Mean Time to Repair (MTTR) by improving trouble shooting capabilities and increase Mean Time between Failure (MTBF) due to proactiveness. These techniques (Shull Peter J., et.al, 2002) can be applied in manufacturing processes such as welding, casting, forging, surface treatment, etc. in which flaws or defects are prominent.

II. DETAILS OF NDT TECHNIQUES

Table 1 (Khangar et.al, 2012; Lim et.al, 2013; Khaira Aashish et.al, 2001; McCrear et.al, 2002; Verma et.al, 2012) covers the insights of some popular NDT techniques so that the researcher or a beginner become familiar with these NDTs before starting to study the critique review part of this paper.

Table 1 Detail of NDT Techniques

Techniques	Application	Advantages & Disadvantages	Cost
Visual Inspection (VT) It is based upon the detection of surface defects by naked eye. Normally applied without the use of any additional equipment, Effectiveness and scope of VT can be improved by using aids such as a borescope.	-Surface crack in gears, pulleys, crank shafts, Geometrical defects	Advantages - Immediate data for viewing and analysis. - Modest skills required - It does not require sophisticated apparatus. Disadvantages - Superficial - Only for surface defects - High interpretation skills	-Low

Liquid penetrant Testing

Used to reveal surface defects by using colored or fluorescent dye to increase the see ability of small discontinuities. It requires pre cleaning to allow access to cracks.

- Surface crack
- Porosity
- Checking for crack in weldments and leak testing of thin walled vessels.

needed
- Uncontrolled offset affects field of view and crack width & length.

Advantages-

- Simplicity
- No sophisticated equipment needed.

- Low

Disadvantages-

- Multiple stages in complete process so difficult to automate
- Reliability of inspection process relies upon experience and high observing skills of tester combined with the visual accuracy and intelligence.
- Requires particular type of testing conditions like suitable light arrangement and surface cleanliness required.

Ultrasonic Testing

Used for the detection of surface and sub-surface defects in sound conducting materials. Ultrasonic wavelengths are of shorter range and higher frequency, as it gives better resolution. A void in the testing specimen reflects some energy back to the transducer, which is detected and displayed

- Thickness Measurement, with accuracy 2% and thickness range 1-200 mm.
- Delaminations Identification/cold joint/honeycomb
- Flaw detection in welds, plates, castings, mechanically joined splices and connections etc.
- Detection of location of porosity, voids and corrosions
- Detectable defect size min 1.3 mm deep and 2.5 mm long

Advantages-

- High Penetration
- Portable Instrument, light weighted units
- Accurate absolute value, such as depth of delaminations.
- Can evaluate thickness up to 3-4 ft.
- Relatively quick
- One sided access needed
- Comparative accuracy in determining defect's size and depth.

- Moderate

Disadvantages-

- Coupling medium needed
- Trained Professional Needed
- Good surface condition needed means it is free from rust & excessive paints, smooth and clean.
- Small and thin parts are difficult to inspect
- Probe alignment is critical
- Requires point by point search, hence expensive on large structures

Eddy Current

ET can be applied on coated and uncoated objects and the testing can be carried out on all accessible surfaces on welds of almost any configuration. Eddy currents are based on the principle of electromagnetic induction.

- Cracks, Porosity detection
- Defect discontinuities such as seams, laps, pits, cracks, voids and Inclusions
- Material thickness measurements
- Seams and cracks as shallow as 0.03 mm can be detected

Advantages-

- Rapid testing
- Easily automated
- Little or no surface preparation needed.
- No contact needed
- No special operator skills needed

Disadvantages-

- Probe size affects sensitivity
- For simple geometries
- Shallow depth of penetration

- Low

Magnetic Particle Testing

The principle is to induce magnetic flux in the testing specimen, while the flux lines running along the surface at right angles to the suspected defect. If there is any discontinuity the flux will stay out in to the air at the opening of the crack. The crack edge becomes magnetized and magnetic attractive poles North and South formed. These have the power to attract finely divided particles of magnetic material such as iron powder.

- Subsurface defects
- Checking pipes for crack
- Cast and welds
- Defects up to 1.5 mm below surface and in welds up to 12.5 mm below surface

Advantages-

- Rapid testing
- Easily automated
- Little and no surface preparation
- Cheap and robust probes

Disadvantages-

- Every component needed to be tested twice
- Diagonal defects are difficult to detect
- Probe must be near to the surface and its size affects sensitivity

- Moderate

Radiography

It is based on using short wavelength radiation passing through the testing specimen. X-rays, produced electrically, and Gamma rays emitted from radioactive isotopes. The sensing method is of photo-emulsion, phosphor screen and conversion to video, while through photochemical processing and permanent film imaging the output becomes processed and recorded. The interesting fact is the greater the

- Hidden flaws
- Inclusions
- Porosity, voids, cracks and cavities
- Weld inspections, imperfections within the thickness of materials
- Detectable defect size min 1.4 mm deep and 2.5 mm long in 15-25 mm thick steel sections

Advantages-

- Equipment is portable and suitable for field use
- Film radiography leads to permanent records of results and compatible to computer analysis
- Large areas can be inspected in one time.

Disadvantages-

- Access to opposite side is needed
- Density or thickness variations of 1% to 2% only can be sensed.
- Extensive expertise needed for testing and interpretation of results
- Sensitivity decreases with

- High

thickness, the greater the absorption. Furthermore, the denser the material the greater the absorption. The radiation used in radiography testing is a high frequency and lower wavelength version of the electromagnetic waves.

thickness.

- Cracks must be parallel to beam
- Source and film geometry and alignment is critical

Thermography

Thermographic cameras detect radiation in the infrared range of the electromagnetic spectrum and produce images of that radiation, called thermograms. The amount of radiation emitted by an object as per the law of radiation, increases with increase in temperature, therefore, thermography process identifies variations in temperature.

- Detection of near surface defects
- Rolling element bearing fault detection
- Bridge deck survey without lane closure

Advantages-

- Time efficient
- Remote sensing
- Scanning system provides real time pictorial display
- Test can be carried out from distance

- High

Disadvantages-

- Affected by weather conditions
- Expensive
- Effective only up to 3 inches.
- The camera only measures surface temperature.

Vibration Analysis

The main process in vibration analysis is conversion of the mechanical vibrations into an electronic signal and then signals analysis by means of computer. The causes of vibration as imbalance, bent shaft, misalignment and looseness

- Rolling element bearing fault detection
- Vibration Measurement in Motor, Gear Box, Bearing life measurement

Advantages

- Time efficient
- Give some indirect measure of current condition.

- High

Disadvantages-

- Difficult to quantify data

III. CRITICAL REVIEW OF NDT TECHNIQUES

This section covers the key papers related to specific techniques as discussed in Table 1. The research papers related to online condition monitoring covered in different section.

A. Eddy Current Testing

Deqiang Zhou et al. (2010) investigated current feature extraction techniques for pulsed eddy current testing including peak value and peak time, spectral characteristics analysis, principal component analysis (PCA) projection coefficient and response shape curvature. Experimental study has been undertaken on samples with artificial surface and subsurface

defects. Based on a comparative study of the feature extraction techniques, the most suitable features and their combination are discussed. This paper provides a framework for future applications comprising the characterization of real defects and stress profiles in engineering components. Further improvement will be obtained using wavelet-based principal component analysis (PCA) feature for defect classification and quantification in particular.

Ali Sophian et al. (2003) stated new PCA-based feature extraction method which reduces the dimensionality of the response signals and extracts relevant features, which allow effective classification of defects. The performance of classification has proven to be better than the conventional method using the response peak characteristics. By extracting principal components with highest variances, the effect of noise has also been reduced as data that contained in first components are mostly free of noise and results in better repeatability of the system. Furthermore, investigation can be carried out for the lift-off effect (a well-known problem with eddy current instrument) mitigation to increase the reliability of the technique.

Gui Yun Tian et al. (2005) presented a new potential feature of defect classification that can be gained from the pulsed eddy current (PEC) NDT technique. The new feature, called as the rising point time, offers some benefits viz independence of coil dimensions and ability to produce the depth of a defect regardless the defect type or shape. This new feature can be integrated with other features, such as peak value and time and PCA-based features to enhance the accuracy in classification of defects. Further work can be undertaken on the mathematics modeling of the rising time by using theoretical analysis and their application for defect location and quantification.

Ali Sophian et al. (2002) reported a simple pulsed eddy current system for surface and sub-surface crack detection in aircraft lap-joint structures using hybrid features. The software compensation techniques employed have improved the measurement resolution and stability. The technique presented in the paper requires no amplification circuitry and uses pure undistorted data.

Yong Li et al. (2011) stated fast analytical modeling using pulsed eddy current testing. The simulations using Extended Truncated Region Eigen function Expansion (ETREE) for modeling PEC inspection on two-layered and three-layered specimens have been conducted. Good agreement can be found in not only PEC responses to specimens but

also PEC differential signals between experiment and ETREE. The comparison with respect to computational time was also carried out. According to the results of comparison in terms of speed and accuracy, ETREE exhibits superiority to time-stepping finite element analysis (TSFEM), and supplies solutions to PEC problems at high speed without loss of accuracy.

Tianlu Chen et al. (2008) stated defect classification using PEC testing. A new time domain feature, termed as arrival time of descending (TD) point of PEC differential response, is extracted by Hilbert transform and analytic representation. Six shape features (three for the rising part: response segments (RS), the arrival times of peak point derivatives (TPDER), and the means of R curvatures (RCUR); three for the descending part: DS, trough point derivatives (TTDER), and the means of D curvatures (DCUR) are extracted and explained. The performances of these features are compared and illustrated as the good and fast combinations, are recommended and the performance similarity of rising and descending part features is validated. The effectiveness and robustness of features for defect classification, natural defects in particular, are validated further by experimental tests. Furthermore, the method can be testified by real applications and the work can be extended to interpretation and quantitative analysis of different defect e.g. lift-off plus sub-surface defect, metal loss plus sub-surface defects and multiple layers with air gap problem, where hidden corrosion is presented.

Javier García-Martín et al. (2011) excellently reviewed the state-of-the-art methods of eddy current testing which is one of the most widely used non-destructive forms of testing. More research in eddy current techniques, in terms of sensors, equipment and signal processing, can lead to even more applications of these techniques.

B. Liquid Penetrant Testing

J.W.C. Pang et al. (2005) stated promising and interesting approach i.e. biomimetic approach to develop and demonstrate a damage visualizing, self-repairing, bleeding composite which provides an effective way to highlight concealed damage and recover mechanical strength after an impact damage event. The release and infiltration of an UV fluorescent dye from fractured hollow fibers into damage sites within the internal structure of the composite has been successfully demonstrated. The approach taken was to develop a material which can enhance visibility of a damage site and restore mechanical properties by a healing process. The results of flexural testing shown that a significant

fraction of lost mechanical strength is restored by the self-repairing effect of a repair agent stored within hollow fibers. Also, efforts are being made to correlate the visible damage area with impact energy.

Jason Y.L. Goh et al. (2004) covered micro deformation analysis using correlation (MDAC) as an alternative to Scanning Acoustic Microscopy (SAM) and dye penetrant testing for defect detection possessing advantages over both techniques. A non-contact displacement measurement technique (MDAC) has been applied to the problem of measuring thermally induced strain in IC devices. More specifically, two stacks of images with different axial positions (through focus, Z) are taken—one before (cold) and one after deformation (hot) and also covers displacement and strain map results of IC devices that highlight the advantages of using MDAC over/in conjunction with SAM and dye penetrant testing. Sample preparation for MDAC is minimal, needing only cross-sectioning and finishing of the sample such that some surface features remain (residual roughness) unaffected. Hill-Climbing Algorithm was also used which is effective method but rarely seen in other papers. Only lapse is for low light level conditions in which regions of the image contain only a few grey levels (<4 bits), the correlation algorithm has fewer features to lock-on to, leading to reduced accuracy. To overcome this problem, a camera with a larger number of grey levels may be used. Alternatively, if this is not possible, a scheme may be implemented that combines a number of images with different exposures into a single extended dynamic range image.

S.N. Dwivedi et al. (2003) stated testing of cylinder blocks casting using magnetic, dye penetrant, and ultrasonic testing. The criteria for diagnosing these defects, which have been classified into different groups, include location, shape of defects and whether the defects appear before or after machining. This paper also showed an expert system adviser for detection and interpretation of defects by NDT, based on the appearance of pattern/echo characteristics during the test. This expert system incorporates the knowledge in the form of IF-THEN. A knowledge-based engineering system can be defined as an intelligent computer program that uses rule-based knowledge and inference procedures to solve problems that are difficult and require significant human expertise for their solutions. It could be even defined as software whose purpose was to control thoughts and other software representing the knowledge. The traditional approach tends to precede data through the algorithm to obtain a solution to a specific problem in a finite

number of steps. Module 1, an expert system adviser is used using the integrated approach, not only diagnoses the defect, but also suggests its cause, as well as remedial measures to help avoid the recurrence of future defects. Module 2 knowledge-based engineering module is used, which solves the complex problems of inspection and interpretation of defects by combination of mentioned NDTs and, thus, will be useful as an aid for quality control.

J.Pitkanen et al. (2001) effectively described variety of methods such as dye penetrant, eddy current, radiography and ultrasonic methods for crack detection in gas Turbine blades.

C. Magnetic Analysis

Aldo Canova et al. (2008) covered a methodology based on 2D and 3D numerical magnetic field analysis for the design of a non-destructive device for metallic ropes with particular attention being given to the influence of field sensor and damage positions. In the 3D simulation real local damage to the rope is considered and the leakage fluxes around it plotted. A parametric simulation was performed by considering variations of the main geometrical parameters that in a real test can affect the results, such as the air gap between the rope and the measuring point (the position of the field sensors) and the radial position of the sensor itself, experimental results on the real prototype on many different commercial ropes are provided. Moreover, the development method is always the same; the presented results are valid only for the configuration considered in this paper. The experimental results of the signal to noise ratio are reported only for a reduced number of ropes.

Yong Li et al. (2007) covered 3D magnetic field sensing using magnetic flux leakage (MFL) testing. The study is undertaken used extensive finite element analysis (FEA) focused on the 3D distribution of magnetic fields for defect characterization and employed a high sensitivity 3-axis magnetic field sensor in experimental study. Several MFL tests were undertaken on steel samples, including a section of rail track. The experimental and FEA test results shows that data from not only the x-axis and z-axis but also y-axis can give comprehensive positional information about defects in terms of shape and orientation, being especially advantageous where the defect is aligned close to parallel to the applied field. The work concludes that 3D magnetic field sensing could be used to improve the defect characterization capabilities of existing MFL systems, especially where defects have irregular geometries. These initial tests indicate that the use of a 3-axis system would be

advantageous in certain situations to give orientation information, especially where irregularly shaped defects or defects orientated close to parallel to the applied field are expected but this approach affected by geometric shape. Furthermore, an investigation can be carried out into the implementation of the 3-axis system to detect defects in components with irregular surface geometries, e.g. free curvature surface, and evaluation of feature extraction techniques for three axis signals via experimental effort and FEA.

D. Radiography

Hernández D.Benítez et al. (2009) stated composite samples defect characterization using infrared non-destructive testing and dynamic principal components analysis (DPCA) & k-nearest neighbor algorithm as optimization technique. Three learning machines viz multilayer perceptron (MLP), radial basic functions (RBF) and support vector machine (SVM) were trained and validated with a reference-free thermal contrast. The study of the thermal diffusivity impact on the modified differentiated absolute contrast (DAC) curves and the MLP classification error shows that affects more severely the DAC curves and the MLP classification errors than a variation. The disadvantage of using learning machines is that this approach requires at least one sample with a known set of defects to obtain the training dataset and that once the system is trained this can only be used for the same material with the same experimental platform.

Tosapolporn Pornpibunsompop (2012) investigated and evaluated launch tube weld using radiography with AWS D1.1 standards. The paper started with preparation of launch tube, then radiographic and X-ray inspection was done. The finding of inspection results were evaluated by certified person and the evaluation with AWS D1.1 standards were performed as well.

H. Kasban et al. (2010) covered Welding defect detection using radiography as testing technique and neural network as optimization technique. The image is lexicographically ordered into a 1D signal. The Mel Frequency Cepstral Coefficients (MFCCs) and the polynomial coefficients are extracted from either the 1D signal, one of its transforms, or both of them. The Discrete Cosine Transform (DCT), Discrete Sine Transform (DST), and Discrete Wavelet Transform (DWT) can be used for this purpose. An artificial neural network (ANN) is trained with the extracted features to create a database. Through experiment it is shown that proposed approach can be used in a reliable way for

automatic defect detection from radiography images in the presence of noise and blurring.

E. Shearography

Y.Y.Hung et al. (2009) presented a comprehensive review of shearography and active thermography and their applications in nondestructive evaluation of materials. A comparison of the advantages, limitations, characteristics and defect detection ability were presented. Also covered defect detection in case of various objects like pressure vessel etc. Both techniques have qualities of full-field, non-contact and faster detection of material defects in metal, non-metal and composites materials. Nevertheless, they are basically different in terms of law detection mechanism.

Y.Y. Hung et al. (2005) reviewed shearography and compared this with ultrasonic, proved superiority of shearography in specific applications. Shearography is a practical technique and therefore, it has gained rapid acceptance by the industries as a useful tool for measurement.

Jung-Ryul Lee et.al (2004) investigated elementary behavior of carbon/epoxy plain-weave fabric composite with large unit cells under uniaxial tension using digital phase-shifting grating shearography. Grating shearography is a combination of three techniques, which are a phase-shifting technique, shearography and diffraction grating metrology. Practically, the shear distances of about 100 mm are used in this paper and analyzed heterogeneous strain fields in fabrics under uniaxial tension. Tensile strain of the fill yarn in the matrix dominant direction is higher than the value of the warp yarn in the fiber dominant direction. Due to the feature of the excellent signal to noise ratio (SNR) of grating shearography, the phase change maps can be directly converted into the six displacement derivative maps. The fundamental interest of the slope mapping is clearly enlightened.

Jung-Ryul Lee et.al. (2004) covered quantitatively composite material made of micro structural NC2, using grating shearography and speckle shearography. Apart from this the author also shows comparison between these two methods in terms of its capability and limitation. Here four kinds of performance indices considered, which were signal to noise ratio (SNR), spatial resolution, resolution and sensitivity. The chosen specimen was an open-hole tensile specimen fabricated with a non-crimped fabric. In these comparative experiments, grating shearography had superiority in signal-to-noise ratio and spatial resolution to speckle shearography except

the labor of the non-trivial specimen preparation. This comparative study offered mechanical engineers a guideline for the reasonable selection of a technique of shearography for a particular test object.

Kyung-Suk Kim et al. (2003) covered methodology for quantitative analysis of an internal crack in pressure pipeline using Electronic Speckle Pattern Interferometry (ESPI) and shearography. In this study, the effective factors in shearography were optimized for quantitative analysis and the size of inside crack has been determined. In this study, the interferometer sensitive to the out-of-plane displacement has been used and the surface displacement of an object was measured and evaluated by using the four-step phase shifting and unwrapping method. The out-of-plane surface displacement was measured by ESPI and the displacement was differentiated numerically. The results were the spatial derivatives of out-of-plane displacement, which can be an equivalent to those of shearography. Shearography can be related with the first derivative of ESPI due to the difference of interferometers. The paper indicates clearly that the size of cracks can be obtained quantitatively lacking any detail of a crack by using ESPI and if amount of shearing is more than crack size then size of the crack may over estimated. Also shows that the induced pressure has influenced the determination of crack size but the influence was so little and also the shearing direction must be paralleled to crack direction.

Y.H. Huang et al. (2009) stated testing of fabric composites under tension using digital phase-shifting grating shearography. This study covered novel impulsive thermal stressing method using high-power flash lamps for convenient nondestructive testing and evaluation in both laboratory and industrial environment. By incorporating a novel clustering phase extraction method, the movement of the continuously deforming object is obtained using only one single deformed speckle image at each deformed stage, thus enabling both qualitative and quantitative measurement. A series of experiments were conducted to demonstrate that the proposed impulsive thermal stressing method is effective and practical for industrial applications, and the clustering phase extraction method is ideal for NDE of continuously moving object. The proposed method employs a high-power heat flux to excite the specimen under test, and being more convenient and practical than conventional stressing methods. A special clustering phase extraction method has also been proposed for quantitative phase evaluation during continuous movement of the object. With further development, the technique may be applicable

for in-situ industrial nondestructive testing and evaluation.

F. X Ray Testing

Domingo Mery (2013) presented a general overview of computer vision methodologies that have been used in X-ray testing. It also concluded that there are some areas like casting inspection where automated arrangements are incredibly effectual, and other application areas for instance baggage screening where human interaction is still used; there are certain areas like weld and cargo inspections where the course of action is semi automatic; and there is a few research areas including food analysis are still remain untouched. This paper highlights need of a public database of X ray images that can be used for testing and assessment of image and computer vision algorithms.

Ion Tiseanu et al. (2005) covered testing of high-density metallic (steel) and low-density materials (graphite and ceramic) using X-ray microtomography. It has been demonstrated that this system can be used for a large range of samples with regards to size, material and complexity. For the individual miniaturized samples, the microtomography analysis is guaranteed for feature recognition down to a few micrometers. The detection system is placed on a precise motorized stage additionally provided with a vertical and transversal manually adjustable table. The investigated sample is placed on a motorized micrometric manipulator to assure maximum degree of freedom in sample positioning. A supplementary manually adjustable positioning device for supporting the X-ray source and the X-ray detection system was added in order to enable oblique view of flat samples or components. Image acquisition, 3D reconstruction and reconstructed volume visualization are performed by two networked Dual CPU (2 GHz, 2GB RAM) Windows workstations. The 3D tomographic reconstructions are obtained by a proprietary highly optimized computer code based on a modified Feldkamp algorithm. A numerical simulation procedure time-independent multi material and multidimensional coupled electron/photon Monte Carlo transport – was developed. An instrumented dummy capsule was scanned in order to accurately determine the positioning of the specimens, heaters and thermocouples. Main elements of the dummy capsule are: SUS specimens (2mm diameter), bronze pipes (1.2mm diameter) and cladding materials.

G. Fedorko et al. (2013) presented experimental measurements of selected properties of textile rubber

pipe conveyor belts, which are dynamically damaged using X-Ray Tomography, ultrasonic measuring system and Precision Thickness Gauges. Apart from results of experimental measurements, new experimental analysis of inner structure of conveyor belt by computer tomography is used. In transversal direction of the conveyor belt, 65 measuring points were marked in distance of 20 mm from each other, where the first and the last measuring point is located on the edge of the belt. Measured values show that conveyor belt carcass is not mechanically damaged and wear of upper and lower covering layer of belt sample occurs mainly on edges, which is typical for pipe conveyors. For comparison, same measurements with unused conveyor belt EP 1250/5 5 + 2 AA of the same width was carried out. Analyzed sample of conveyor belt 1250/5 when compared to reference sample EP 1250/5 5 + 2 AA has lower values of trough shape coefficient. Low values of trough shape coefficient results from dynamic damage and cause insufficient contact with idlers and the belt did not hold proper pipe shape. Experimental verification provided the monitoring of undamaged sample and sample after mechanical damage claims to compare obtained dimension changes in the internal structure and material homogeneity. Interesting information comes from the comparison of value of elastic elongation. Elastic properties of the conveyor belt help to compensate the trajectory and speed of belt straining, its resistance to dynamic fatigue, ability to absorb additional side forces which are created by passing through the curves and change of operational situation (start of the conveyor, operation with conveyed material, change of conveyance capacity and stopping the conveyor).

G. Thermography

Yong-Kai Zhu et al. (2011) reviewed optical NDT technologies, including fiber optics, infrared thermography, electronic speckle, endoscopic and terahertz technology. Fiber optics has easy integration and embedding, electronic speckle covers whole-field high precision detection, infrared thermography has unique features for tests of combined materials, endoscopic technology offer images of the internal surface of the object directly, and terahertz technology unlock a new direction of internal NDT because of its outstanding penetration ability to most of non-metallic materials. Representative engineering applications of these technologies are demonstrate, with a short summary of the history and discussion of current progress.

G. Mroz et.al. (2014) reviewed optical NDT methods for testing of combined materials using eddy-current array technology and induction thermography. Based on the physical material

properties of metastable austenitic steels, a novel design is developed for implementing local, component inherent load sensors; so-called directionally-sensitive yield-stress sensors. The appropriate strengths and yield stresses, corresponding to the component loading to be monitored, can be specifically set by locally heat treating the selected, cold worked sensor's region using a fiber-laser. Electromagnetic testing methods, such as eddy current technology and imaging induction thermography are developed to rapidly collect the technical data of such microstructures which possess modified physical material properties. The measuring technology is developed and adapted to the testing task via modeling. Finite element analysis (FEM) computation are also performed both for describing the domain's scope and the eddy current distribution, as well as for simulating the magnetizing processes as well as the chronological formation of temperature fields in the component's edge region. A program written in Matlab was employed to evaluate the data obtained with the aid of the eddy-current technology. Using this program, the sensor off-set can be corrected and the measured values graphically represented. During the simulation, consideration is given to the geometry and material size effects as well as to the excitation and testing frequencies.

Laura Vergani et.al. (2014) presented overview of the principles and methodologies at the basis of thermography as experimental non-destructive technique, especially dealing with composites. Different methods mentioned in the literature, initially applied to homogeneous materials, and also to composite structures. The attention is focused on the correlation between the thermal response of composites under mechanical loads, either static or dynamic, and the fatigue behavior of the studied materials: Mainly focused on fiber-reinforced composites (FRC) made of natural or synthetic fibers, impregnated into polymer matrix, and arranged in different stacking sequences. A series of case studies also explained.

Anna Runnemalm et al. (2014) covered testing of resistive spot welded metal sheets (automotive Industry) using thermograph. This paper showed a single-sided setup of a thermography incorporating with a flash lamp as excitation source. The analysis algorithm targets to find the spatial region in the obtained images analogous to the effectively welded area, i.e., the nugget size. Experiments showed that the system is able to identify spot welds, assess the nugget diameter, and based on the information also distinguish a spot weld from a stick weld. The system is proficient to inspect more than four spot welds per

minute. The set-up is arranged to be possible to mount on an industrial robot in order to achieve a fully automatic inspection system. The analysis algorithm aims to find the spatial region in the acquired images that corresponds to the successfully welded area (the nugget size). The results were compared to the results from a peel test for each piece. In order to avoid uncertainties in the comparative measurement, the peel tests were performed by a skilled person with experience of measuring spot weld diameters. With the suggested setup of an automated thermography system, the inspection can be operator-independent, and with a stationary inspection cell, as suggested here, the time, test place and situation can be controlled.

Roberto Montanini et al. (2012) investigated the detection limits associated to defects geometry and depth as well as recognition of barely visible impact damage over the external gel-coat finish layer using optically excited lock-in thermography. The obtained results demonstrated the effectiveness of lock-in infrared thermography as a powerful and non-contact full-field measurement technique for the inspection of large glass fiber reinforced polymer (GFRP) structures. In particular, results showed that, by using a transmission set-up instead than a reflection one, accurate assessment (standard uncertainty < 1.4%) of impact damages could be attained, whereas estimation of delaminations depth is critically influenced by the actual area and aspect ratio of the discontinuity. A simple model to account for this dependency proposed in this paper. Three GFRP plates were prepared by manual lay-up of six layers of bi-axial [0/90] and randomly arranged glass fiber combi wovens (800/300 g/m²) embedded in a polyester resin matrix. The laminated plates had a total thickness of 9 mm. The GFRP-1 plate was used to assess depth detection limits. The GFRP-2 plate instead, was used to investigate the influence of defect aspect ratio. For this reason, four different geometries were considered: circular (C), triangular (T), rectangular (R) and square (S). The GFRP-3 plate was prepared to study the possibility of identifying and sizing barely visible impact damages (BVIDs). Each defect has been identified by an alphanumeric code in which the first number indicates the plate (either 1 or 2 or 3), the letter specifies the defect geometry and the last number designates the depth (in mm) or the indenting load (in KN). Experimental tests were performed using optically excited lock-IN thermography (OLT), either in reflection (R) or in transmission (T) mode. The threshold value was determined by taking into account the background noise of the phase image, which was estimated, for each excitation frequency, by means of the standard deviation of the phase angle

measured over the sound region of the material. The threshold frequency was determined, for each defect, by performing a linear interpolation between the coordinates (fx, Cx) of the two closest experimental points and by calculating the exact frequency at which the interpolation line crosses the threshold value. The obtained results proved the effectiveness of OLT as a practical and contactless full-field NDE tool, but also highlighted some limitations. An important conclusion of this study has been the correlation found between flaw depth assessment and flaw geometry.

John Wilson et al. (2011) reported experimental investigation into the application of PEC thermography to the detection and characterization of multiple cracks caused by rolling contact fatigue (RCF) initiated defects in a section of rail track is reported. In the experiment, a square coil is positioned normal to the sample surface, near the edge of the rail head, where the RCF induced cracking is known to be concentrated. This configuration mimics a line inductor, with localized heating in the area under the coil. The system deploys an induction heating control box that is used to supply power to a coil positioned over the sample under test. This induction of the eddy currents results in the heating of the sample. When the flow of current is changed by the defect, it leads to an increase of current density in specific areas of the sample and as a result, an increase in Joule heating. The thermographic images are captured by an infrared (IR) camera and the thermal distribution pattern analysis is conducted by appropriate software. The merits and hindrances of various rolling contact fatigue detection technique like ultrasonic testing, non-contact eddy current, and alternating current field measurement, low frequency eddy current is properly explained.

H. Ultrasonic Testing

Sergey A. Titov et al. (2008) covered pulse-echo ultrasonic testing technique based on comparing the output waveform with a previously recorded reference for the first metal sheet is developed to detect disbonds and voids in the adhesively bonded joints with sufficient resolution. The developed decomposition algorithm has been used in the study of steel and aluminum specimens having various adhesive layer thicknesses in a range of 0.1–1 mm. The developed technique was also tested on real automotive adhesively bonded joints. Also, the technique presented in this paper involves processing the experimental reference waveform and does not require an exact quantitative model. To improve the lateral resolution of this method, the probe was equipped with a special collimator in effort to narrow

the ultrasound beam. As the mechanical load produced by the delay line on the metal sheet is relatively small, the frequency of the first through-thickness resonance of the structure can be readily measured and reliably related to the integrity of the join.

Q. Liu et al. (2007) covered anisotropic weld testing using Ultrasonic Testing and Ray Tracing Algorithm as an optimization technique. In order to enable ultrasonic measurement of anisotropy and the directivity of dendrites in a weld, a forward formulation is presented in this paper. In simulations, the numerical method is applied in the calculation from an incident ray to a transmitted ray. In order to further investigate the ray distribution from the probe through the weld, two additional rays are included to each ray on both sides. Numerical examples are also included to show the capability of this developed model is illustrated in numerical examples. In the simulations, only the transmitted ray is followed and only the same type of ray as the incident one is considered. In one of the examples, the ultrasonic rays are assumed to start from the same fixed source at the upper surface of the weld parent material, but with different incident angles. In other examples, the process of moving a probe along the upper surface is simulated in this example. In the next example, the instance of a partitioned probe model is considered. This hybrid model of the forward formulation will later be applied to solve the inverse problem. It is based on the discretization of the simulated volume and well suits modeling objects with complicated material structure.

S.M. Tabatabaeipour et al. (2010) covered testing of AISI 316L welds made by shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) processes, using ultrasonic time-of-flight diffraction (ToFD) and X-ray Radiography. An artificial flaw was machined by electro-discharge machining (EDM) process in each weld. The depths of each of these flaws were approximately 6mm from the top surface of the base material. Austenitic characteristics consisting of grain orientation distribution and anisotropy show that the GTAW specimen is more isotropic than the SMAW due to the orientation of its grains. Moreover, comparison of echo amplitudes shows higher attenuation for the weld prepared by the GTAW process. After welding, X-ray radiography was performed on both specimens to characterize the artificial flaws and to ensure the absence of additional flaws. After inspecting the samples by radiographic testing, ultrasonic time-of-flight diffraction measurements were carried out on both specimens. The inspection was done parallel to the centerline of the welds by two 65°, 6MHz

longitudinal angle beam probes in pitch-catch configuration. To study the anisotropy of the base and weld materials, samples with dimensions of 15mm×15mm×15mm were cut from the base metal and welded sections. Ultrasonic wave velocities were measured at various directions along principal and non-principal axes (45° with respect to principal axes). The measurements were conducted by both contact and immersion techniques. To study the grain orientation of welds, samples with dimensions of 40mm×25mm×5mm were cut from the welded part of the specimens. These samples were subsequently ground, electro polished, and etched. To expose the grain orientation of welds, an etching solution made from 1.5 g ammonium per sulphate, 7.5 ml H₂O, 25 g iron per chloride, 10 ml HCl, and 3ml HNO₃ was used. Maximum error in the measurement of densities and velocities are estimated as 2% and 0.5%, respectively. The amplitudes of the back wall echoes in weld samples are compared with the back wall echo of the base metal along principal directions. It can be observed that the amplitude of the back wall echo in the SMAW sample is higher than the GTAW sample in all principal directions. Results obtained show that GTAW is more isotropic than SMAW sample. Moreover, it was shown that wave attenuation in GTAW sample is higher than the SMAW. B-scan images obtained from ToFD measurements of the two welds indicate that inspection of the specimen prepared by the SMAW process is easier than the one made by the GTAW process due to higher scattering of waves in the latter. In this paper TOFD technique and its advantages over conventional ultrasonic testing explained properly.

Sung-Jin Song et.al. (2002) covered testing of turbine blade root of nuclear power plant using newly developed Phased Array Ultrasonic Inspection (PAULI) to attain electronically scanned ultrasonic images of nuclear power plant components. A medical ultrasound imaging system (SA-8800, Medison, Korea) was modified for the development of intelligent PAULI system. Two PCs are installed for the real time image display and the intelligent flaw characterization. The system has 64 independent transceiver channels that can drive 64 or 128 individual array elements with time delay. The frequency range of the system is 2–8 MHz. A sample mockup of turbine blade root with EDM notches was fabricated and the detection ability was verified. The developed system can give electronically scanned ultrasonic images in real time fashion and very much enhance the effectiveness and reliability in the flaw revealing and location in comparison by classical ultrasonic testing (UT) using A-scan signals. To predict ultrasonic beam radiation from array transducers, a complete 3-D radiation beam models is

developed based on the boundary diffraction wave model. Based on the model-based optimization, array transducers were fabricated and tested in the initial experiments with artificial flawed specimens. Finally, the feature extraction from A-scan flaw signals with the phased array system at various steering angles was performed to demonstrate the capability of the flaw classification. Modeling and simulation of radiation beam from phase array transducers also done. The simulation studies confirmed that there would be no grating lobes when the ultrasonic beam is steered up to 45° .

A.Badidi Bouda et al. (2003) performed experimental study on thermally processed steel samples to study the evolution of some ultrasonic parameters such as wave velocities and attenuation coefficients as function of the steel grains size using Ultrasonic Testing. The experimental results obtained are discussed and analyzed in order to develop an ultrasonic technique for grains size determination. A thermal processing device was used in order to have a continuous quenching simply with a suitable water flow, and this, only on one side of the sample. The samples were taken from the same steel bar. The metallographic analysis has shown a ferritic perlite structure on all the sample length. Ultrasonic measurements are undertaken in immersion technique at oblique and normal angles of incidence by using a 10 MHz immersion focused probe. The inaccuracy of these results does not allow exploitation at this stage of the attenuation coefficients in the characterization of the grains size by ultrasounds.

I. Vibrations

N. Tandon et al. (2000) covered testing of rolling element bearing using vibration and acoustic measurement along with detection of both localized and distributed categories of defect. Vibration measurement in both time and frequency domains along with signal processing techniques such as the high-frequency resonance technique covered. Other acoustic measurement techniques such as sound pressure, sound intensity and acoustic emission have been reviewed. Recent trends in research on the detection of defects in bearings, such as the wavelet transform method and automated data processing, have also been included. An explanation for the vibration and noise generation in bearings is given in this paper.

Pratesh Jayaswal et al. (2008) showed recent developments in the field of machine fault signature analysis with particular regard to vibration analysis and testing of rolling element bearing. Covers various condition based monitoring especially vibration

testing. This paper also provides a comprehensive table on typical defects that can be detected with this analysis

T.H. Loutas et al. (2011) covered fault detection in gear box, using oil analysis, thermography and vibration analysis. Conventional parameters from the time or frequency domain as well as wavelet-based parameters were utilized. Their performance was checked through a series of natural gear tests. A certain subset of parameters has shown an excellence in differentiating monotonically and thus diagnosing gear damage throughout the tests. Independent component analysis applied on the fused data revealed independent components capable of monitoring the basic damage modes of the gearbox.

R. Raišutis et al. (2008) reviewed different NDT techniques including vibration analysis, thermography, x-ray imaging, acoustic emission and ultrasound for testing of wind turbine blades, taking into account the complicated structure of the wind turbine blades as well as possibility to make non-destructive testing in harsh on-site conditions.

M.C. Carnero (2005) proposed a model that carries out the decision making in relation to the selection of the diagnostic techniques and instrumentation in the predictive maintenance programs related to condition monitoring of screw compressors, using lubricant and vibration analyses. The model uses a combination of tools belonging to operational research such as: analytic hierarchy process (AHP) and factor analysis (FA).

M. Thirumalai et al. (2009) covered the vibration monitoring and analysis case studies, where vibration analysis and modification/repair performed. In following three cases, early identification of the impending failures not only saved maintenance cost and down time but also prevented the catastrophic failure-

(a) Sodium pump, a critical component in Steam Generator Test Facility, where malfunction of hydrostatic bearing was detected

(b) Centrifugal pump of 1200 m³/h flow capacity used in a water test loop for circulating DM water in 1:4 scale model of Prototype Fast Breeder Reactor, where rolling element bearing failure was detected.

(c) Sodium pump in a 500 kW sodium loop used for various experimental studies, where bearing pedestal crack was identified.

M.R. Nasiri et al. (2011) presented a method to automate the cavitations fault detection in centrifugal pumps using vibration signature analysis. A neural network was used to identify three healthy/faulty conditions namely normal, moderate and fully

developed cavitations. Experiments were also conducted to evaluate the presented model. Also the number of sensors and the best sensor positions are studied.

Sadettin Orhan et.al. (2006) covered the vibration monitoring and analysis case studies; examined in machineries that were running in real operating conditions. Failures formed on the machineries in the course of time were determined in its early stage by the spectral analysis. It was shown that the vibration analysis has much advantage in factories as a predictive maintenance technique.

IV. REVIEW OF NDT APPLICATION AS AN ONLINE CONDITION MONITORING TOOL

In online condition monitoring, machine or a component is continuously observed while it is in running condition by taking help of sensors. This section will cover the research work related to online condition monitoring.

A.A. Carvalho et al. (2010) covered detection and classification of welding defects by using magnetic testing. In this research work, pattern nonlinear classifiers were applied by artificial neural networks, to make sure the possibility to detect and categorize defects in pipelines inspected through magnetic pigs (MFL technique). Numerous tests were performed on samples with defects artificially created (internal and external corrosion and lack of penetration). Also covers possibility to detect and classify defects in pipelines inspected through magnetic pigs (MFL technique).

D. Dinakaran et al. (2009) presented monitoring of crater wear in turning, using ultrasonic technique as a testing technique and Adaptive Neuro-Fuzzy Inference System (ANFIS) as an optimization technique. An ultrasound online condition monitoring of crater wear of the uncoated carbide insert in turning operation is demonstrated. The method is based on inducing ultrasound waves in the tool, which are reflected by side flank surface. The quantity of reflected energy is associated with crater wear depth. Diverse ultrasonic parameters measured for defining the crater wear and individual part of each parameter is analyzed. The ultrasonic

parameters, amplitude, pulse width and root mean square (RMS) of the signal are utilized to quantify the crater depth and width. The power spectrum analysis of received signals shows the significance of frequency components in defining the tool wear.

E. Mendel et al. (2009) covered condition monitoring of oil extraction rigs using vibration analysis, pattern recognition techniques. This paper presents vibration analysis techniques for fault detection in rotating machines more specifically rolling element bearing defects inside a motor pump is the subject of study. Signal processing techniques, like frequency filters, hilbert transform, and spectral analysis are used to extract features used later as a base to classify the condition of machines. Also, pattern recognition techniques are applied to the obtained features to improve the classification precision. Further investigations on others faults, such as unbalance, misalignment, flow turbulence, and cavitations.

Mindaugas Jurevichius et.al. (2007) covered testing of machines and buildings using vibrations measurement. Computerized system for vibrations measurement and algorithms for analysis of vibrosignal are presented in this paper. The vibration measurement system includes accelerometers or displacement sensors, amplifier for sensor signal amplification and signal integrator for apparatus calculation of vibration speed and displacement, data acquisition device and personal computer. The vibration signals are analyzed in frequency and in time domain by estimating spectral distribution, statistics, RMS for different time intervals of vibration signal. Examples of results of vibration measurement and data analysis in buildings and machines with rotating parts are included also. The software used for data acquisition is ebiol-LT and for data analysis is Origin 7.0.

V. RESULT OF REVIEW

This research work is based on in-depth and orderly investigation of the literature related to non destructive testing. The time duration for this literature review was from 2000 to 2014. In total, 59 articles were reviewed for this paper. The below table 2 shows details of those papers that are used in critique review part of NDTs.

Table 2 Details of papers used in critique review of NDTs.

Name of Author	Year	Domain	NDT
Deqiang Zhou et al.	2014	Optimal Features Combination	Pulsed Eddy Current

Ali Sophiana et al.	2003	Principal Component Analysis	Pulsed Eddy Current
Gui Yun Tian et al.	2005	Defect Classification	Pulsed Eddy Current Sensors
Ali Sophiana et al.	2002	Defect Detection In Aircraft Lap-Joint Structures.	Pulsed Eddy Current
Yong Li et al.	2008	Fast Analytical Modelling	Pulsed Eddy Current
Tianlu Chen et al.	2008	Defect Classification	Pulsed Eddy Current
Javier García-Martín et al.	2011	Eddy Current Testing	Eddy Current Testing
J.W.C. Pang et al.	2005	Composite	Dye Penetrant Testing (UV Fluorescent Dye)
Jason Y.L. et al.	2004	IC Chip	Scanning Acoustic Microscopy (Sam), Dye Penetrant Testing
S.N. Dwivedia et al.	2003	Cylinder Blocks Casting	Magnetic, Dye Penetrant, And Ultrasonic
J. Pitkänen et al.	2000	Gas Turbine Blades	Dye Penetrant, Eddy Current, Radiography And Ultrasonic Methods
Aldo Canova et al.	2014	Ferromagnetic Ropes	Magnetic Analysis
Yong Li et al.	2007	3D Magnetic Field Sensing	Magnetic Flux Leakage
Herna'n D.Beni'tez et al.	2009	Composite Samples Defect Characterization	Infrared Non-Destructive Testing
Tosapolporn et al.	2012	Launch Tube Welds	Radiography
H. Kasban et al.	2011	Welding Defect Detection	Radiography Images
Y.Y. Hung et al.	2009	Review	Shearography And Active Thermography
Y.Y. Hung et al.	2005	Review	Shearography
Jung-Ryul Lee et al.	2004	Fabric Composites Under Tension	Digital Phase-Shifting Grating Shearography
Jung-Ryul Lee et al.	2004	Composite Material Made Of Microstructural NC2	Grating Shearography And Speckle Shearography
Kyung-Suk Kima et al.	2004	Internal Crack Of Pressure Pipeline	Electronic Speckle Pattern Interferometry (ESPI) And Shearography
Y.H.Huang et al.	2009	Fabric Composites Under Tension	Digital Phase-Shifting Grating Shearography
Domingo Mery	2013	Review	X-Ray Testing
Ion Tiseanu et al.	2005	High-Density Metallic (Steel) And Low-Density Materials (Graphite And Ceramic).	X-Ray Micro-Tomography
G. Fedorko et al.	2013	Textile Rubber Conveyor Belt (Pipe Conveyor)	X-Ray Tomography, Ultrasonic Measuring System Precision Thickness Gauges
Yong-Kai Zhu et al.	2011	Review	Optical NDT Technologies, Including Fibre Optics, Electronic Speckle, Infrared Thermography, Endoscopic And Terahertz Technology

G. Mroza et al.	2014	Review	Eddy-Current Array Technology And Induction Thermography
Laura Vergani et al.	2014	Fibre-Reinforced Composites (Frc)	Thermographic Techniques
Anna Runnemalm et al.	2011	Resistive Spot Welded Metal Sheets (Automotive Industry)	Thermography
Roberto Montanini et al.	2012	Thick Glass Fiber-Reinforced Composites	Optically Excited Lock-In Thermography
John Wilson et al.	2011	High Speed Trains	Pulsed Eddy Current (PEC)Thermography Or Induction Thermography
S.N. Dwivedi et al.	2003	Cylinder Blocks Casting.	Magnetic, Dye Penetrant, And Ultrasonic
Sergey A. Titov et al.	2008	Adhesively Bonded Joints In Automotive Assemblies	Pulse-Echo NDT
Q. Liu et al.	2011	Anisotropic Weld	Ultrasonic Testing
S.M. Tabatabaeipour et al.	2010	AISI 316L Welds Made By Shielded Metal Arc Welding And Gas Tungsten Arc Welding Processes	Ultrasonic Time-Of-Flight Diffraction (Tofd), X-Ray Radiography
Sung-Jin Song et al.	2002	Turbine Blade Root In Nuclear Power Plant	Phased Array Ultrasonic Inspection (Pauli)
A. Badidi Boudaa et al.	2003	Thermally Processed Steel Samples	Ultrasonic Testing
N. Tandon et al.	2000	Rolling Element Bearing	Vibration Signature Analysis
Pratesh Jayaswal et al.	2007	Rolling Element Bearing	Vibration Signature Analysis
T.H. Loutas et al.	2011	Gear Box	Oil Analysis, Thermography And Vibration Analysis
R. Raišutis et al.	2008	Wind Turbine Blades	Vibration Analysis, Thermography, X-Ray Imaging, Acoustic Emission And Ultrasound
M.C. Carnero	2005	Screw Compressors	Lubricant And Vibration Analyses
M. Thirumalai et al.	2009	Sodium Pump, Centrifugal Pump	Vibration Diagnostics
Sadettin Orhan et al.	2006	Rolling Element Bearings	Vibration Monitoring
M.R. Nasiri et al.	2006	Centrifugal Pumps	Vibration Signature Analysis
Sadettin Orhan et al.	2008	Element Bearings	Vibration Monitoring
A. A. Carvalho et al.	2010	Detection And Classification Of Welding Defects	Magnetic Testing
D. Dinakaran et al.	2009	Monitoring Of Crater Wear In Turning	Ultrasonic Technique
E. Mendel et al.	2009	Oil Extraction Rigs	Vibration Analysis, Pattern Recognition Techniques
Mindaugas Jurevichius et al.	2011	Machines And Buildings	Vibrations Measurement

It is necessary to know the distribution of year wise paper in order to know the actual state of NDT development.

Figure 1 shows a crescent tendency in the articles time distribution. The graph clearly indicates that most of the work done in 2011 & least in 2001.

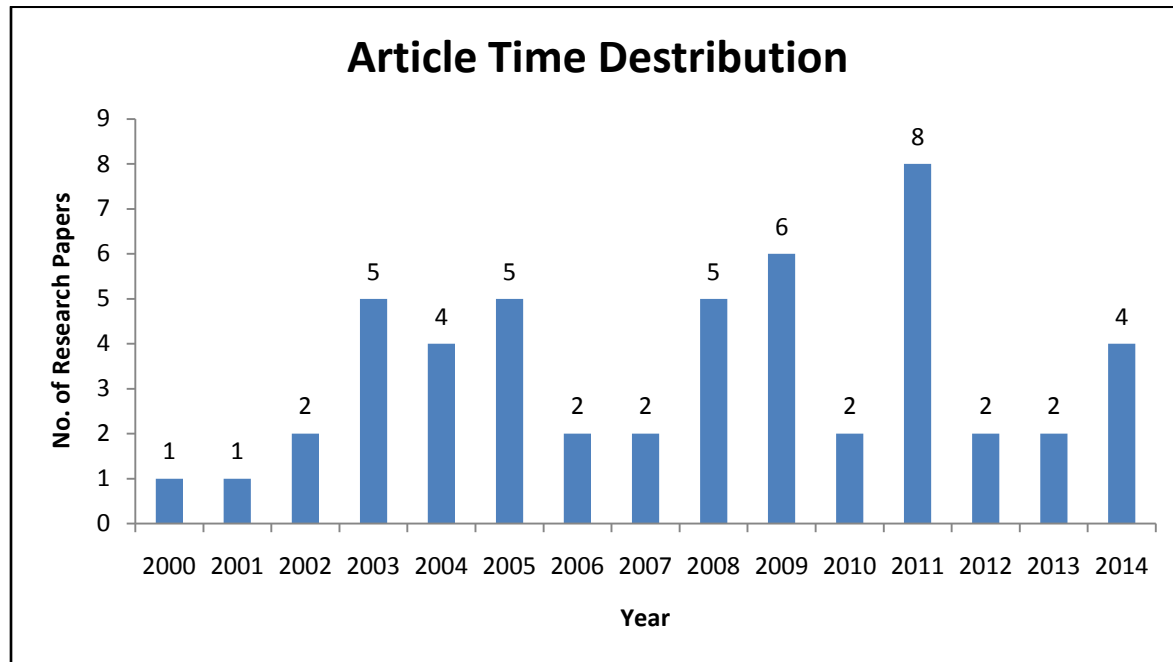


Figure 1 Article Time Distribution

Now it is necessary to know the technique wise distribution is essential as it will helps the researchers to identify the NDT techniques in which least work has been undergone. The fig. shows graph between no. of research papers and

Non-destructive testing. This graph in figure2 shows that most of the work is undergone in field of vibrations and least work done in X-ray detection and radiography.

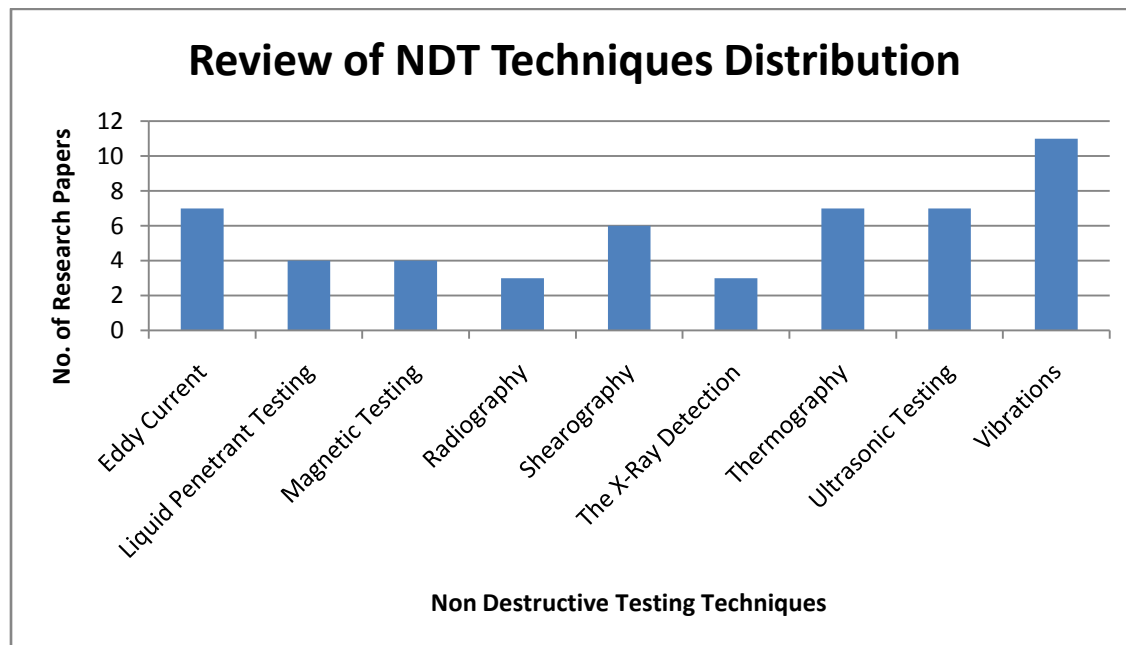


Figure 1 Review of NDT Techniques Distribution

For a researcher it is essential to know the areas in which these techniques are used and areas in which are remains untouched. This figure shows graph between

number of research papers and domain. This graph shown in figure 3 clearly indicates that most of the work done in composites testing and least work is on gears, bearings etc.

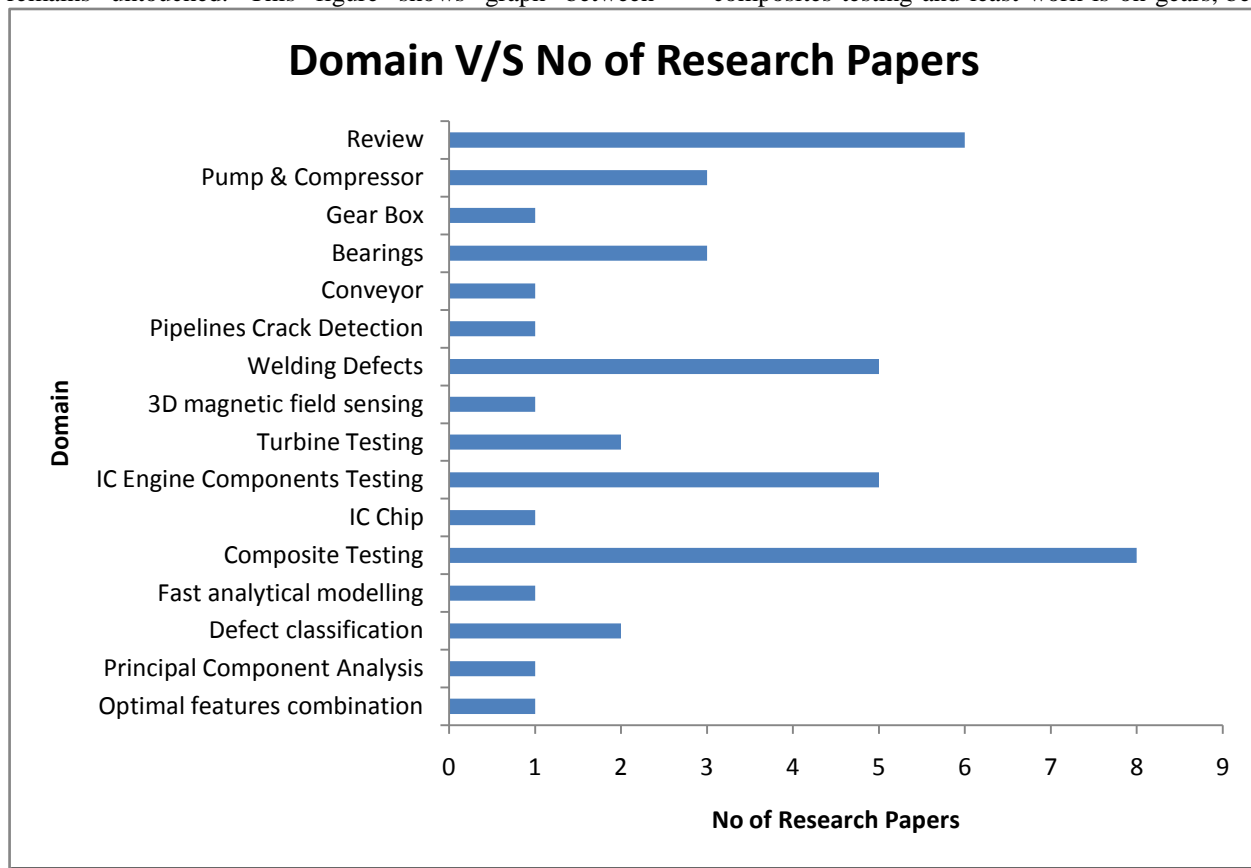


Figure 3 Domain V/S No of Research Papers

VI CONCLUSION

Total literature papers are 100 out which approx 60 having more concern with NDTs. As per the objective discussed in abstract, this state of art review covered the current trends, at the same time this critical review covered research gaps which can be helpful for researchers to find out the future research areas. Also shows that NDT can be an effective tool in the inspection and condition assessment of industrial machinery/equipments. It can provide knowledge that may not be possible to deduce from visual observation alone. The following are more outcomes:-

- Most of the research papers lacks in decision making part for selecting the combination of NDT.
- Mostly vibration technique is used with artificial intelligence, there is a wide scope for in corporatizing combination of other NDTs along with AI for optimization
- In application part mostly bearings, wind turbine transmission and concrete testing covered. There is a scope left for couplings, machines gear box, pulleys, guide ways, cylinders, Automobile parts etc.
- Few papers outline the significance of combining multiple NDTs for reliable fault detection.
- Some papers also highlighted the significance of optimization techniques.
- It is also concluded that a proper decision making technique is strongly needed at very beginning when NDTs combination made.

ACKNOWLEDGEMENTS

We are thankful to the department of mechanical engineering of MANIT Bhopal, India for providing the required facilities needed for the successful completion of this paper.

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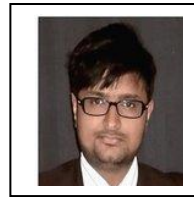
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