A Review of the State-of-the-Art on Combining Multiple NDT Techniques in Terms of Precise Fault Detection

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Abstract

The present industrial scenario demands optimum quality, feasible processing time and enhanced machine availability to cope-up with continuously increasing customer expectations. To achieve this target, it is mandatory to ensure the optimum performance and higher availability of machinery. Therefore, the present work begins with, review of the research work of different researchers, which includes the applied combinations from year 2000-2016 proceed with discussion on the parameters being checked before making combination of NDT and finally, covers the maintenance performance parameters for quantifying improvement in performance after combining NDT. The result indicates that very few researches uses combination of NDT's, in areas like aeronautical, compressors etc., and most of the works done in composites to be tested without using any decision making technique. The researchers and practitioners can use the outcome of this work as a guideline for combining multiple NDT technique to achieve precise fault prediction and forecasting of upcoming failures.

Keywords: condition monitoring, corrective actions, fault detection, non-destructive testing

1. Introduction

The precise fault detection [1, 2] at early stages is vital for machine life expectancy to plan corrective measures accordingly and it is essential for optimum performance of machinery/components. Non destructive testing (NDT) as the name suggests, is a technique in which component are tested for flaw without disintegrating or altering its present structure. NDT is an efficient fault detection technique [3-5] for identification of fault cause and location and thus, which leads to reduction of Mean Time to Repair (MTTR) and increases Mean Time between Failure (MTBF). The applications of these techniques [6] are in the field of material testing and defect detection in welding, casting, forging and in many applications.

Although various non-destructive testing techniques have several advantages, while there are some disadvantages too. Therefore, a single NDT technique cannot give highly reliable fault detection. To achieve this objective, it is necessary to combine multiple techniques of NDT's. The organization of this research paper is as follows: In section 2, the review part of NDT techniques are covered. In section 3, the result and discussion part covered and then, conclusions are drawn in the last section. The contribution and significance of this research study is of three-fold; firstly, review the research work of different researchers related to NDT combinations from year 2000-2016; secondly, check the parameters for making combination of NDT and finally, a covers a discussion on the maintenance performance parameters for quantifying improvement in performance after combining NDT.

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2. Review of NDT Techniques

This section signifies the objective and it has three sub-sections. The first part of this section covers the research work of various researchers related to combination of NDT; the second part covers the list of performance parameters to check before making combination and the later part suggests parameters being quantified for measuring the performance improvement because of combining multiple NDT's.

2.1. Research work related to combination of NDT

Yong-Kai Zhu et al.(2011) [7] reviewed optical NDT technologies for testing of various materials. The author highlighted that fiber optics features easy integration and embedding, electronic speckle focuses on whole-field high precision detection, infrared thermography has unique advantages for testing of composite materials, endoscopic technology provides images of the internal surface of the object directly, and terahertz technology opens a new direction of internal NDT because of its excellent penetration ability to most of non-metallic materials.

Suhaila Abd Halim et al. (2012) [8] applied radio-graphic image with recognition techniques in automated detection system for weld defect detection. The author highlighted that automated inspection of weld defect improves objectivity, consistency, accuracy and efficiency of fault detection, therefore, gives advantages in term of results and time.

S. Khangar et al. (2012) [9] applied multiple NDT techniques for shaft failure analysis along with SEM, XRD. This research paper extensively covered various methodologies that are applied for the failure analysis of the shaft. This innovative work provides guidelines for selecting the best failure analysis methodology suitable for the shaft to prevent repetitive failure.

Bo Li et al. (2012) [10] applied X-ray detection (defects on the surfaces or sub-surface of the friction stir welding joints), ultrasonic C-scan testing (to reveal inner voids and tunnels), ultrasonic phased array inspection (for the small, tight voids and tunnels examination) and fluorescent penetrating fluid inspection (used for the hidden-type defects) to examine different weld-defects in aluminum 2219-T6 thick butt friction stir welds. Apart from this, author also showed the use of micro structural for the analysis of characteristics related to particular defect through its micro-structure.

R. Ambu et al. (2006) [11] used holographic procedure and electronic speckle pattern interferometry technique to investigate the feasibility of the optical methods for detecting impact damage in composite. The investigation showed that both optical methods were able to identify the impact damage presence, but there efficiency depends on the through-thickness location of the delaminations produced.

Malcolm K. Lim et al. (2013) [12] showed the way to improve concrete bumper wall testing, using Ground Penetrating Radar (GPR), Ultrasonic Pulse Velocity (UPV), Impulse Response (IR). The author highlights the fact that if the scope of work is straight forward, then it is acceptable to use a single test method. However, when a single test method does not provide enough information of the problem, the combining different methods is essential thereby. The information about the advantages and limitation of each test method is the key to apply the right combination of test methods for evaluation. This research paper provides insight into the different test methods and case history whereby combining different nondestructive test methods were used in the evaluation.

X. De´robert et al. (2002) [13] covered testing of weak post-tensioned beam using Ground penetrating radar, Ferroscan (cover-meter), gamma-ray radiography and impact-echo methods. Their results were discussed after the hydro-demolition autopsy of the beam. This work describes the extent of NDT surveys, respond to the needs of structural engineers, through the use of complementary NDT approaches.

Thomas. Aastroem (2008) [14] covered evolution of NDT from very beginning including visual inspection at 10500 B.C.to till 2008. The paper sets out to give an idea of the incredibly fast proliferation of NDT methods that has taken place during the fifty years till 2008. This work showed the review of interaction between the most important machine diagnostic methods and these NDT methods. This work gives a short glimpse of the early history, i.e. the discoveries leading to the first classical NDT-methods. Some facts are also given out the standardization development and the operator's certification. The paper lists that abundance methods are available today for being tested either in the field or in a laboratory environment to use the abbreviations for the methods in question without any attempt to explain their background or working principles.

Zhongqing Su et al. (2006) [15] comprehensively reviewed damage identification approach based on lamb wave for composite structures. This work also provides comparison of lamb wave transducers with other NDE transducers. As per the author, artificial intelligence is a very promising approach, but it needs vast input training data preparation. These are major limitation and for practical uses, these must be addressed for improvements.

D. Horn et al. (2000) [16] combined eddy-current testing (ET) and ultrasonic testing (UT) for reliable fault detection in Zr-Nb (2.5%) pressure-tube billets. This work also outlines the concepts of probability density functions (PDFs), cumulative probability (e.g. of detection), and relative operating characteristics (ROCs), as they apply to the individual inspection campaigns (ET and UT) of our data set. Also, it gives Gaussian fits to probability as an ET or UT signal amplitude function, normalized to unity for each depth. The Dempster–Shafer method used in this work includes assigning probability masses to propositions (rather than to hypotheses).

John W. Wilson (2007) [17] applied Metal Magnetic Memory(MMM) Or Residual Magnetic Field(RMF) method for stress measurement in steel sample weld crack, investigated the phenomena in diverse conditions and explained this through experimentation. The author also prepared multiple setups for experimental evidences and covers stress generation in various cases like in the case of the clamping of tools. This research showed that the unique passive field technique incorporated with analysis of the magnetic field pattern and magnetic field variation rate would prove beneficial in certain conditions.

Kaphle, M. et al. (2011) [18] reviewed acoustic emission technique and covers its three important namely; source location, source identification/discrimination and severity assessment. The author outlines that these three requires innovative and intelligent use of several signal processing tools combined with the study of AE signal parameters and their statistical distribution. This combination also provides an efficient way to process large volumes of generated data, which is a vital area of ongoing research in the field of acoustic emission testing.

Y.Y. Hung et al. (2009) [19] reviewed shearography and active thermography including its theoretical part and then, its practical applications. The author stated the salient features of these technique viz., full-field, non-contact and quick detection of material defects in metal, non-metal and composites. The author also took an example of pressure vessel defect detection. Furthermore, the two techniques of NDT applied on the same sample to make visible their inimitable merits and restrictions to compare them.

Prayaswal Pratesh Wadhwani et al. (2008) [20] applied vibration signature analysis for failure in rolling element bearing. The author also provided a comprehensive table on typical defects that detected with this type of analysis. Ashutosh Verma et al. (2014) [21] applied oil analysis, thermography and vibration analysis for the fault detection in rolling element bearing. The author also tabulated the above mentioned techniques in a systematic manner.

T.H. Loutas (2011) [22] covers effective condition monitoring of gear box with oil analysis, thermography and vibration analysis. Briefly discusses the advantages of AE over vibration testing. Futuremore, variable loading conditions to check the sensitivity and effect of the methodology mentioned in the paper. Multiple condition parameters extracted from the saved AE and vibration data. The conventional parameters were used from the time or frequency domain used in addition to the wavelet-based parameters. A series of natural gear tests performed to evaluate its performance. A certain subset of parameters has shown superiority in differentiating monotonically and thus identifying gear damage throughout the tests.

R. Raišutis et al. (2008) [23] reviewed vibration analysis, thermography, x-ray imaging, acoustic emission, and ultrasound as on-site testing technique for wind turbine blades taking into account its complicated structure. Pierre Tchakoua [24] reviewed and classified wind turbine condition monitoring (WTCM) methods and techniques using combination of NDT's with an emphasis on current scenario and potential challenges. The outcome of this research can used to point out the pros and cons in current WTCM industry and define research priorities needed for the industry to meet the challenges in wind industrial evolution and market expansion.

D. Breysse (2012) [25] applied ultrasonic pulse velocity measurement (UPV) and rebound hammer measurement (RHM) for fault detection in concrete. The author suggested that replacing one NDT technique with a semi-destructive test may also provide an interesting alternative to some cores. This work also covered in-depth critical review of existing models, an analysis of experimental data of multiple authors in laboratory studies as well as on site. This work also covered the key factors identification that influencing the strength quality estimate. To achieve understanding of the effect of strength range and the measurement error, synthetic simulations also developed to get a better understanding of the role played.

Z. Hameed et al. (2009) [26] reviewed different techniques, methodologies and algorithms that developed to monitor the wind turbine performance. To keep away the wind turbines from catastrophic conditions due to sudden breakdowns. To keep the wind turbine in operation, implementation of a condition monitoring system (CMS) and fault detection system (FDS) is paramount. For this purpose, ample knowledge of these two types of systems is mandatory. So, maximum approaches related to the CMS and FDS were reviewed in this paper.

Pter Bieder (2008) [27] applied 3-dimensional ultrasonic tomography with high-resolution discontinuous images comprising all arbitrary scan angles at standard inspection speeds for neutron Irradiation inspection at nuclear power plant. This work covered quantification of inspection outcomes regarding flaw type, flaw location and flaw size, at high inspection speeds. This research helps to conquer limitation of conventional inspection, such as, ultrasonic examination of non-accessible component areas.

M. Winkelmans (2002) [28] applied electrochemical noise measurements, acoustic emission (AE) technique, acousto-ultrasonics (AU) and fiber optics for analyzing general corrosion of carbon steel (CS) and stainless steel (SS), pitting of SS, stress corrosion cracking of CS and SS. The four measurement techniques incorporated in the same sensor body to reveal and quantify the corrosion.

Dag Horn (2006) [29] applied combination of eddy current and ultrasonic testing in the case study of the Canadian nuclear industry through a number of statistical techniques. Moreover, he provides a good discussion about the pros and cons of combining multiple techniques. As field data are scarce, therefore, it may be necessary to establish a scaling relationship between signals from artificial flaws and real defects to permit use of the former in qualification work.

D.M. McCann (2001) [30] applied combination of NDT techniques for testing concrete and masonry. The basic principles of NDT methods were described with particular reference to the five major factors that influence the success of a survey: depth of penetration, vertical and lateral resolution, contrast in physical properties, signal to noise ratio and existing information about the structure. The author described the NDT surveys integration into the investigation of the structural investigatio n.

Bruce W. Drinkwater et al. (2006) [31] reviewed ultrasonic arrays and showed details of modeling with algorithms, tables, figures. This work has also highlighted the modeling importance in the arrays selection to fulfill a given performance specification. This work brings together the most relevant published work on arrays for non-destructive evaluation applications, comment on the state-of the art and discuss future directions. The focus of this work is on their application to non-destructive evaluation (NDE) using bulk waves. There is also a significant body of published literature referred to use arrays in the medical. Besides, sonar fields and the most relevant papers from these related areas are also reviewed.

Roman Ruzek et al. (2006) [32] covered impact defect identification and wing composite barely visible impact damage (BVID) using ultrasonic C-scan and shearography. This work also compares the results of visual, ultrasonic C-Scan, laser shearography impact damage assessment, and determination of sandwich panels, which took out from the sandwich skins of this developmental wing.

Ahmad El Kouche et al. (2012) [33] described ultrasonic-based non-destructive testing (NDT) integration with wireless sensor networks (WSNs) to continuously monitor material integrity during run-time. Odile Abraham et al. [34] stated case study of Mont-Blanc Tunnel used Ground-penetrating radar (GPR) and Seismic Refraction. In the case of the Mont-Blanc Tunnel, these non-destructive methods have been tested in three zones: heavily damaged, moderately damaged, and sound. This feasibility study has shown that a zone classified moderately deteriorated is in fact more heavily damaged than that are classify as very deteriorated.

Gerd Dobmann et al. (2001) [35] covered ultrasonic absorption, ultrasonic back scattering, positron annihilation testing for material aging determination under European network project.. This work presents results obtained in a round-robin action organized in a concerted action of ten partners in the EURATOM program of the European Community. This research documented the state of the art of available NDT techniques to characterize material aging phenomena based on a Charpy-V energy reduction and a shift in the fracture appearance transition temperature.

A.Mccrea (2002) [36] surveyed automation potential of surveyed NDT methods for inspection and restoration of steel bridges along with considering their applicability and versatility in terms of some tailored criteria. To simplify a comparative analysis, the main characteristics of each method presented in a table. This work also provides grading for various NDT methods in terms of their effectiveness for different applications. Also, it covers existing automated and partially automated restoration systems. This work covered data collection related to tools and systems, critically reviewed them, and identified their range and feasible limitations.

Fereidoon Marefat (2011) [37] covered the possibility in substituting the new approach (Phased Array Ultrasonic) with the former laborious methods with special emphasis on welding defect detection. This work focused on each method’s weak points.

C.Colla et al. (2002) [38] applied radar, impact echo and ultrasonic-echo methods for defect detection in different railway slab-track constructions. The paper covers limitation and advantages, comparability and complementary of these methods. The used acoustic and electromagnetic methods, were found being complementary.

Zoubir-Mehdi Sbartaïet al. (2012) [39] applied electrical resistivity methods (Wenner and four-probe square array), GPR (Ground Penetrating Radar), direct wave analysis (arrival time and amplitude), Capacitive Method (3 frequencies of measurement), Ultrasonic surface wave method, with and without contact (velocity, attenuation, quality factor), Ultrasonic waves in direct transmission (UPV), Impact echo (first peak frequency) for evaluation of concrete properties. Several indices were defined for the evaluation of the quality and the degree of sensitivity of each NDT measurement regarding each concrete property. The indices were defined using two statistical approaches (variance analysis and multiple regression). A limited set of NDT parameters used and correlated with complementary between NDT parameters were evaluated using principal component analysis (PCA) and MATLAB.

F. Zastavnik (2014) [40] applied shearography and scanning laser vibrometry using an algorithm for testing of aluminum beams. Generally, curvature and moment distributions derived from the modal shape of a beam vibrating at resonance, but in this work it was derived with the help of NDT's. Damage accumulation in structures could be associated with the stiffness reduction and expressed mathematically as a stiffness factor or a damage variable related to the stiffness. The use of shearography for the local 2D stiffness distribution will provide additional difficulties in compared with 1D case of beams presented in this paper. A major difficulty to overcome is, computing all six components of the plate stiffness for each point, in the case of the assumed anisotropy.

Zoubir Mehdi Sbartaïet al. (2012) [41] covered concrete properties evaluation using Ground-penetrating radar (GPR), electrical resistivity and ultrasonic pulse velocity to predict more accurately concrete properties such as strength and water content. This work excellently shows statistical fusion of multiple NDT's using two techniques, namely Response Surface Method (RSM) and artificial neural networks (ANNs). The result obtained, supports fusion of NDT measurements to achieve effectiveness of the statistical modeling for predicting the properties of concretes.

J. P. Balayssac (2012) [42] covered analysis of concrete structures using multiple NDT's and showed analysis of a very large amount of data (about 200,000 measurements). This work shows relationships between each NDT measurement and the targeted indicator in a systematic manner. Several NDT methods involving different techniques (ultrasonic transmission and surface waves, electromagnetic, electrical and capacitive) were used and provided nearly 60 NDT measurements (attenuation, velocity, resistivity, frequency, etc.). This work describes a French project named SENSO (Strategy of non-destructive evaluation of the monitoring of concrete structures) devoted to developing a methodology for the non-destructive evaluation of concrete based on a multi technique approach.

Yiming Deng et al. (2011) [43] provided comprehensive review of electromagnetic imaging methods for NDE applications supported with summary and discussions on future directions. Furthermore, it is superior to integrate graphics processing units (GPU) and this will redefine the computational related works for imaging methods and thrust advances the imaging sensors development through parallel data processing, fast image acquisition, enhancement, and compression.

Mohammed Cherfaoui (2012) [44] applied multiple NDT's in the whole process of maintenance of pressure equipment, in a systematic manner. This research work covers a case study and shows all the stages, including making an accurate diagnosis of the sphere condition of storage, and to evaluate its lifetime and to ensure this structure's restoration.

D.G. Aggelis et al. (2011) [45] discussed the complementary use of the two techniques (thermography and ultrasound) as a potential robust methodology for evaluation of difficult sub surface cracks in concrete before it is visible. Thermography is initially used to locate the defects, in the form of vertical cracks beneath the surface. Due to the variation of the temperature field and consequently, ultrasound propagation applied to estimate the depth, using firm correlation between wave transmission and damage characteristics.

Ł. Wierzbicki et al. (2010) [46] described development of a real-time non-invasive technique using pulsed infrared (IR) thermography to measure the temperature of polymer materials and ultrasonic testing as a type of non-destructive testing commonly used to find flaws in materials and to measure the object's thickness. In experimental part, subsurface defects made in specimens of polymeric materials such as PE, PMMA, laminate then experimentally detected and directly displayed in ultrasonic and thermographic images. In this study 16 specimens preheated during specific time using infrared lamp. After that a thermo-vision camera used to scan the specimen's surface temperature during cooling down process, and then, thermographic image analysis applied for defect detection. The experimental results have demonstrated that application of ultrasonic and thermographic testing are effective methods to visualize and reveal defects in the polymeric materials.

Pertti Auerkari (2002) [47] stated defect detection in gas turbines using multiple NDT's. Furthermore, the technical development, especially in ET (Eddy Current Testing) suggests widening applications for metallic surfaces. Simultaneously, new challenges for NDT have emerged, e.g. from ceramic coatings, complex coated cooling channels and wide arrays of very small cooling holes.

Sanjay Kumar et al. (2013) [48] reviewed different works in the area of NDT and tries to find out the latest developments and trends available in industries and other fields to minimize the total equipment cost, minimize damage and maximize the safety of machines, structures and materials.

Christian Garnier (2011) [49] combined ultrasonic testing, infrared thermography and speckle shearing interferometry for detecting aeronautical defects. The testing was done on composite specimens that had a variety of defects. The general visual inspection technique applied to evaluate size and position of defects. Their result shows that only the ultrasonic method enables accurate determination of the depth of a defect.

M.C. Carnero (2005) [50] covered diagnostic techniques and instrumentation for screw compressors (Petrochemical Plant) using lubricant and vibration analysis. After explaining the basic concept, a case study of a screw compressor with the integration of lubricant and vibration analyses is also explained in this paper. In this article, a model is proposed that uses a combination of tools belonging to operational research, such as: analytic hierarchy process (AHP) and factor analysis (FA) and carries out the decision making for the selection of the diagnostic techniques and instrumentation in the predictive maintenance programs. The model has been tested in screw compressors when lubricant and vibration analyses are integrated.

A.Goel (2006) [51] covered Principle, advantages and disadvantages of various NDT's techniques commonly used in Gujarat refinery. R D Finlayson (2000) [52] covered defect detection in aerospace Structures using acoustic emission and acousto-ultrasonics. Also, discuss several applications and monitor scenarios in a very effective way.

Rosmaini Ahmad et al. (2012) [53] provided useful information regarding the time based maintenance (TBM) and condition-based maintenance (CBM) techniques application in maintenance decision making and explores the challenges in implementing each technique from a practical perspective. The paper compares the challenges of implementing each technique from a practical point of view, focusing on the issues of required data determination and collection, data analysis/modeling, and decision-making.

Dimla E. Dimla Snr. (2000) [54] reviewed some methods that have been employed in tool condition monitoring using sensor signals analysis. Particular attention is paid to the manner in which sensor signal from the cutting process have been harnessed and used in the TCMS development.

Y.Y. Hung et al. (2009) [55] comprehensively reviewed advantage, disadvantage and flaw detection capabilities of shearography and active thermography in a very effective way. It mentioned in the paper that ultrasonic testing is inferior than these two techniques, but no working evidence explained. To compare both techniques, numerous experiments conducted to look like a real-life industrial NDT applications. Artificial flaws were deliberately implanted in the test samples. This phase-shifting performed using a computer-controlled variable wave retarder made of liquid crystal.

G. Sposito et.al. 2010) [56] covered testing of power plant steels using nonlinear ultrasonics, X-ray diffraction, eddy current and acousto-ultrasonics. This work compares destructive methods with some promising NDT's in a very effective way. There are results that show potential drop techniques that can detect incipient creep damage. A decisive assessment of the main results obtained in the secondary and tertiary stages of creep offered in this paper, and the benefits and disadvantage of each metho d discussed.

Mph Papaelias (2008) [57] comprehensively reviewed NDE methodologies for rail defect detection in countries including Europe and North America. It also reviewed current state-of-the-art in NDE of railways including future developments. This work shows that capabilities of each of the techniques which reveal that certain techniques have advantages ov er the other, but there are always certain disadvantages which cannot be overcome either due to the restrictions posed due to the nature of the technique or due to the lack of sufficient technical development; therefore, combination of NDT gives reliable results.

Sumit P.Raut et al. (2014) [58] covered study of the various methodologies used for the shaft failure analysis, and to choose appropriate methodology that is suitable for the failure analysis of the shaft used in gear box which mounted on the overhead crane to prevent repetitive failure. The author covered work of various researchers for comparing different methodology, there application and limitation.

S.N. Dwivedi et al. (2003) [59] covered diagnosis of defects in Cylinder Blocks Casting using magnetic, dye penetrant inspection, and ultrasonic. The expert system mentioned in this work incorporates the knowledge in the form of IF–THEN. Module 1, using the integrated approach, not only diagnoses the defect, but also suggests its cause as well as remedial measures to avoid the future defects recurrence. In module 2, the author applied magnetic method, dye penetrant and ultrasonic test to solve the complex problems of inspection and interpretation of defects and, thus, will be useful as an aid for qu ality control.

Kyung-Suk Kim et al. (2003) [60] applied electronic speckle pattern interferometry (ESPI) and shearography for detection of an internal crack of pressure pipeline. This paper clearly shows that the amount of shearing is an important factor and if it is more than crack size, then there is a possibility of size overestimation. Here, shearography and ESPI used for quantitative analysis of an internal crack of the pipeline and both of them have proved being suitable to qualitatively detect insid e the crack. In this study, the effective factors in shearography optimized for quantitative analysis and the size of inside crack determined. In this st udy, the interferometer is sensitive to the out-of-plane displacement used and then, four-step phase shifting and unwrapping method applied to measure the surface displacement of an object.

G. Mroz et al. (2014) [61] reviewed optical NDT methods for testing of combined materials covering eddy-current array technology and induction thermography. A program written in Matlab 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 being graphically represented. In this work, load sensitive specimens united with sensor fields and a newly developed method is experimentally implemented to identify the loading magnitude and direction. Investigations of the loading have shown that, on exceeding the local yield stress of the direction sensitive lineal sensors, the martensite formed due to the loading stresses producing plastic deformation.

S. M. Tabatabaeipour et al. (2010) [62] applied ultrasonic time-of-flight diffraction (ToFD), X-ray Radiography for testing of AISI 316L welds made prepared using shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) processes. The measurements also showed that the probe positioning is very important in the detection of diffracted echoes when using the ToFD technique. It was observed that the amplitude of the back wall echoes in the SMAW sample is higher than the GTAW sample in all principal directions. Results obtained shows that GTAW is more isotropic than SMAW's sample. Moreover, it is 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 the specimen inspection prepared with the SMAW process is easier than the one made with the GTAW process due to higher scattering of waves in the latter.

Maierhofer Christiane et al. (2015) [63] covered the development and application of optical and thermographic methods for the nondestructive evaluation of delaminations, cracks and further substructures in connection with bulging along with two case studies. A good deal of experimentation were conducted on two different days, this work concluded that the moving clouds in alternation to direct solar radiation is better suited to detect inhomogeneities of the structure as compared to continuous direct solar radiation.

Iliopoulos Sokratis N. et al. (2015) [64] covered the monitoring crack initiation and evolution of super container which designed for the geological disposal of the high-level and heat emitting radioactive waste for six months. The author applied Digital Image Correlation (DIC), Acoustic Emission (AE) and Ultrasonic Pulse Velocity (UPV) on the scaled model to obtain further insight about the crack formation probability. The paper outlined the benefits of using combination of the three NDT techniques for condition monitoring.

Alwash Maitham et al. (2015) [65] covered a methodology for regression model fitting between combination of NDT's like rebound hammer (RH) and ultrasonic pulse velocity (UPV). In this paper, a synthetic simulation approach was applied to study the effects of the number of cores, the NDT measurements quality, the variability in concrete strength, the existence and magnitude of possible uncontrolled factors (like saturation rate), and the combination of techniques, and then a methodology was developed for improving the quality of strength assessment. This work also outlined that there is a critical minimal number of cores which makes the efficient combination.

Balageas D. et al. (2016) [66] reviewed and highlighted that thermal nondestructive testing (TNDT) is better than other conventional techniques such as X-ray, ultrasonic, eddy current, liquid penetrant, etc. This work also outlined the limitations of TNDT and highlighted the need of combining thermal method with other NDT techniques; so that one may take advantage of both.

Raju Sumathy et al. (2016) [67] experimented about the influence of combination of Fly Ash (FA) and Copper Slag (CS) on the mechanical properties of concrete. For this, the researcher applied the destructive tests to determine the compressive strength, split tensile strength and flexural strength. On the basis of results obtained from both NDT and DT techniques, the paper concluded that the results are favorable for concrete with industrial wastes such as Fly Ash and Copper Slag, and it is also superior to control concrete properties

2.2. Parameters being checked before combining NDT's

It is necessary to compare various NDT's before making their combination as if we made the combination in random way. It may not result in higher reliability of fault detection and may leads to wastage of resources (man-machine-time). Various researchers suggest various parameters (see table 1) be considered before making combination.

Table 1 Details of attributes used in for combining multiple NDT

Attribute	Description	Author (Year)
Principle	A rule or a theory that technique is based on;	S. Khangar et al. (2012), A.Mccrea (2002)
Equipment	The things that are needed for this technique;	S. Khangar et al. (2012), A.Mccrea (2002)
Applications	The defects that can be detected using this technique;	S. Khangar et al. (2012), Prayaswal Pratesh Wadhwani et al. (2008), D.M. McCann (2001), Roman Ruzek et al. (2006), A.Mccrea (2002)
Accuracy	The state of being correct;	Malcolm K. Lim et al. (2013), Ashutosh Verma et al. (2014), D.M. McCann (2001), Roman Ruzek et al. (2006), A.Mccrea (2002)
Process Lead Time	The time between start and end of a process	Malcolm K. Lim et al. (2013), Ashutosh Verma et al. (2014)
Process Cost	It includes resources needed like support structure, sensors, surface cleaners etc.	Ashutosh Verma et al. (2014), D.M. McCann (2001), A.Mccrea (2002)
Power Needed	Amount of energy needed for operating the equipment.	A.Mccrea (2002)

2.3. Parameters being quantified for measuring the performance improvement

After combining multiple NDT's, the next part is to quantify the effect of combining multiple NDT's. For this purpose, key performance indicators of maintenance needed to measure. Basically, if after combination, the following parameters don't get improved then it means either combination is not appropriate or single NDT'S is better. As per Namboothiri (2011) [68] and Kumar et al. (2007) [69] following are the most commonly used maintenance performance indicators.

- Availability - The availability is expressed as the percentage of the plant availability.

$$Availability = \frac{MTBF}{(MTBF + MTTR)} \tag{1}$$

- Mean Time Between Failures (MTBF) - It is an arithmetic average of how fast the system is failing.

$$MTBF(Hrs) = \frac{(Total\ Up\ Time\ per\ unit\ Time - Total\ Down\ Time\ per\ unit\ Time)}{Total\ Number\ of\ Failures\ per\ unit\ Time} \tag{2}$$

- Mean Time to Repair (MTTR) - It is an arithmetic average of how fast the system is repaired.

$$MTTR\ (Hrs) = \frac{Total\ Down\ Time\ per\ unit\ Time}{Total\ Number\ of\ Failures\ per\ unit\ Time} \tag{3}$$

- Failure Rate (FR) - It is the reciprocal of MTBF.

$$Failure\ Rate\ (FR) = \frac{1}{MTBF} \tag{4}$$

3. Result of Review

For the purpose of this research, an exhaustive and systematic search of the literature related to a combination of non-destructive testing done. The time frame for this literature review was from 2000 to 2014. The below table (see Table 2) shows the details of research work covered in this review.

Table 2 Details of papers used in critique review of combination of NDT

Author	Year	Domain	Technique
Yong-Kai Zhu et al.	2011	Review	Optical NDT technologies, including fiber optics, electronic speckle, infrared thermography, endoscopic and terahertz technology
Suhaila Abd Halim et al.	2012	Review	automated detection system
V. S. Khangar et al.	2012	Shaft	Comparison of various NDT's
Bo Li et al.	2012	aluminum 2219-T6 thick butt friction stir welds	X-ray detection, ultrasonic C-scan testing, ultrasonic phased array inspection and fluorescent penetrating fluid inspection
R. Ambu et al.	2006	composite laminates	holographic procedure and electronic speckle pattern interferometry technique
Malcolm K. Lim et al.	2013	concrete bumper wall	Ground Penetrating Radar (GPR), Ultrasonic Pulse Velocity (UPV), Impulse Response (IR)
X. De´roberta et al.	2002	beam	Ground penetrating radar, Ferroscan (cover-meter), gamma-ray radiography and impact-echo Methods
Thomas. Aastroem	2008	Review	15 to 200 NDT discussion
Zhongqing Su et al.	2006	Composites	Guided Lamb waves Detection Technique
Roberto Suárez-et al.	2004	Review	Magnetic Memory Method
D. Horn et al.	2000	Zr-Nb(2.5%) pressure-tube billets	Eddy-Current and Ultrasonic Testing
John W. Wilson et al.	2007	Steel sample	Metal Magnetic Memory (MMM) Or The Residual Magnetic Field (RMF)
KAPHLE, M. et al.	2011	Review	Acoustic Emission Technique
Y.Y. Hung et al.	2009	Review	Shearography and Active Thermography
Pratesh Jayaswal et al.	2007	Rolling Element Bearing	Vibration Signature Analysis
Ashutosh Verma et al.	2014	Rolling Element Bearing	Oil Analysis, Thermography and Vibration Analysis
T.H. Loutaset 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
Pierre Tchakoua et al.	2014	wind turbine blades	Ultrasonic testing, Visual Inspection, Acoustic Emission, Thermography, Radiography
D. Breysse	2012	Concrete	Ultrasonic Pulse Velocity Measurement (UPV), Rebound Hammer Measurement (RHM)
Z. Hameeda et al.	2009	Wind Turbine	Vibration Analysis, Acoustic Emission, Thermography, Radiography
Fausto Pedro García Márquez et al.	2012	Wind Turbine	Ultrasonic testing, Vibration Analysis, Acoustic Emission, Thermography, Radiography
Peter BIEDER et al.	2008	Neutron Irradiation	3-Dimensional Ultrasonic Tomography
Dag HORN	2006	Review	Multiple NDT
M. Winkelmans Et al.	2002	General Corrosion Of Carbon Steel (CS) and Stainless Steel (SS)	Electrochemical noise measurements, acoustic emission (AE) technique, acousto-ultrasonics (AU) and fiber optics
D.M. McCann et al.	2001	Concrete and Masonry	Ultrasonic testing, Vibration Analysis, Acoustic Emission, Thermography, Radiography
Bruce W. Drinkwateret al.	2006	Review	Ultrasonic Arrays
Roman Ru°zˇek et al.	2006	Wing composite Barely Visible Impact Damage	Ultrasonic C-Scan and Shearography
Ahmad El Kouche et al.	2012	CBM industrial equipment	UT with WSN
Odile Abraham et al.	2003	Fired tunnel walls	Ground-penetrating radar (GPR) and Seismic Refraction
Gerd Dobmann et al.	2001	Material Aging Determination	Multiple NDT
A. McCrea et al.	2002	Steel bridges corrosion	Multiple NDT's

Table 2 Details of papers used in critique review of combination of NDT (continued)

Author	Year	Domain	Technique
Fereidoon MAREFAT et al.	2011	Welding Defects	Radiography and Phased Array Ultrasonic
C. Collaa et al.	2002	Railway Tracks	Radar, Impact-Echo And Ultrasonic-Echo Methods
Zoubir-Mehdi Sbartaïet al.	2012	Concrete Properties	Electrical resistivity methods (Wenner and four-probe square array), GPR (Ground Penetrating Radar), direct wave analysis (arrival time and amplitude, Capacitive Method (3 frequencies of measurement), Ultrasonic surface waves method, with and without contact (velocity, attenuation, quality factor), Ultrasonic waves in direct transmission (UPV), Impact echo (first peak frequency).
F. Zastavnik et al.	2014	Beams	Shearography and Scanning Laser Vibrometry
Zoubir Mehdi Sbartaïet al.	2012	Concrete Properties	Ground-penetrating radar (GPR), electrical resistivity and ultrasonic pulse velocity
J.-P. Balayssac et al.	2012	Concrete Structures	Multiple NDT's
Yiming Deng et al.	2011	Details of EIM	Electromagnetic Imaging Methods (EIM)
Mohammed Cherfaouia	2012	Pressure Equipment	Multiple NDT
D.G. Aggelis et al.	2011	concrete	Thermography and Ultrasound
Ł. Wierzbicki et al.	2010	Fired tunnel walls	Multiple NDT
Pertti Auerkari et al.	2002	Gas Turbines	Multiple NDT
Sanjay Kumar et al.	2013	Review	Multiple NDT's
Christian Garnier et al.	2011	Aeronautical Defects	Ultrasonic Testing, Infrared Thermography and Shearography
M.C. Carnero	2005	Screw Compressors	Lubricant and Vibration Analyses
A. Goel	2006	Review	TOFD, IRIS , AUS LFET, AET , RFET, OLCM
R D Finlayson et al.	2000	Review	Acoustic Emission And Acousto-Ultrasonics
Rosmaini Ahmad et al.	2012	Review	CBM
Dimla E. Dimla Snr.	2011	Tool-Wear Monitoring	Sensor signals analysis
Y.Y. Hung et al.	2009	Review	Multiple NDT's
G. Sposito et al.	2010	Steel Creep	Nonlinear ultrasonics, X-ray diffraction, Eddy Current and acousto-ultrasonics
MPh Papaelias et al.	2008	Rail defect	Multiple NDT's
Sumit P.Raut et al.	2014	Shaft Failure Analysis	Multiple NDT's
S.N. Dwivedia et al.	2003	Cylinder Blocks Casting	Magnetic, dye penetrant, and ultrasonic
Kyung-Suk Kima et al.	2003	Internal crack of pressure pipeline	Electronic Speckle Pattern Interferometry (ESPI) and Shearography
G. Mroza et al.	2014	Review	Eddy-current array technology and induction thermography
S.M. Tabatabaeipour et al.	2010	AISI 316L welds made with shielded metal arc welding and gas tungsten arc welding processes	Ultrasonic time-of-flight diffraction (ToFD), X-ray Radiography
Maierhofer Christiane et al.	2015	Delaminations, cracks and further substructures in connection with bulging	Optical and thermographic NDT's
Iliopoulos Sokratis N. et al.	2015	Monitoring crack initiation and evolution in super container	Digital Image Correlation (DIC), Acoustic Emission (AE) and Ultrasonic Pulse Velocity (UPV)
Alwash Maitham et al.	2015	Concrete Testing	Rebound hammer (RH) and ultrasonic pulse velocity (UPV)

Table 2 Details of papers used in critique review of combination of NDT (continued)

Author	Year	Domain	Technique
Balageas D. et al.	2016	Review	Thermal NDT, X ray, ultrasonic, eddy current, liquid penetrant
Raju Sumathy et al.	2016	Influence of combination of Fly Ash (FA) and Copper Slag (CS) on the mechanical properties of concrete.	Ultrasonic Pulse Velocity (UPV) and Digital Schmidt Rebound Hammer (RH)

As per Fig. 1, it is evident that very few researches combined the NDT's except in year 2011 and 2012. Apart from this, the below figure also highlights the wide gap in research work related to NDT's. Therefore, researchers can use the below graph as a base for their literature review work.

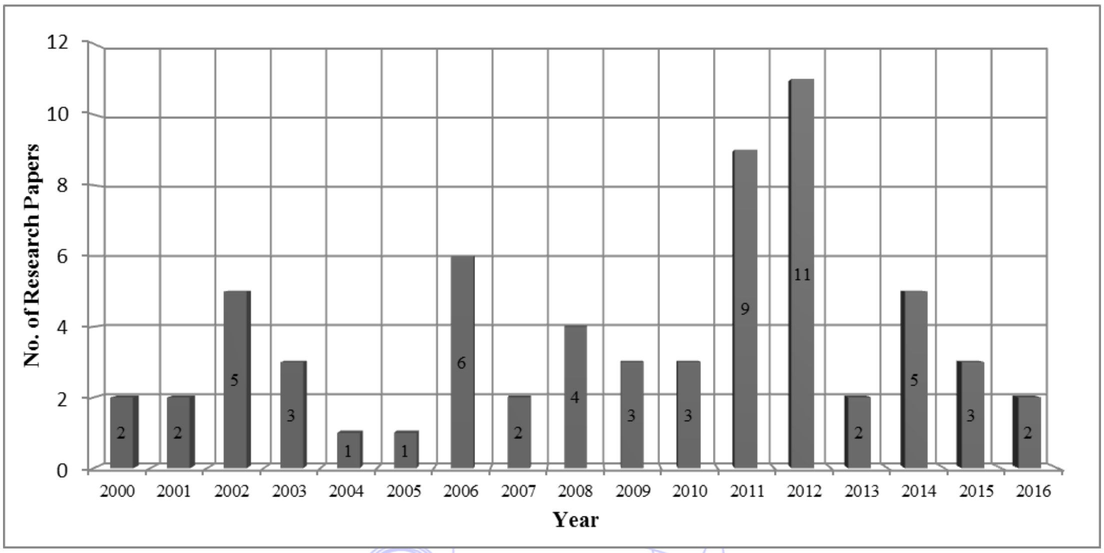

Fig. 1 Article time distribution

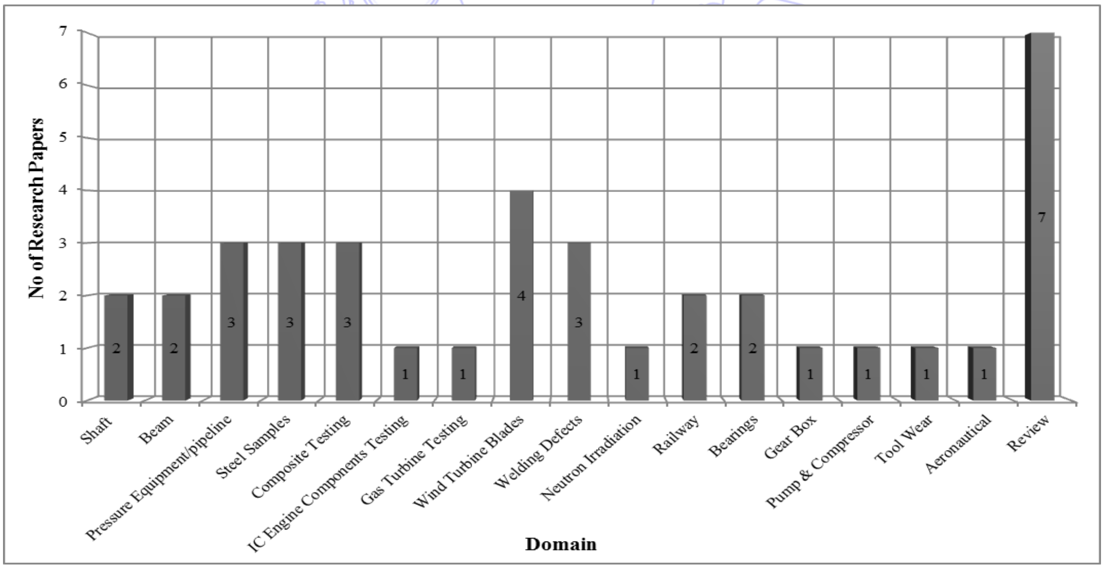

Fig. 2 Graph between domain and number of research paper

As per Fig. 2, most of the work done in composites testing and apart from this, less focus on researchers is on gears, bearings etc. Therefore, the researchers may consider least covered areas for further research work and use the below graph to identify the domain of research.

As per Fig. 3, the NDT & E International journal covers research papers which are based on combination of NDT's. Apart from this, it is also evident that the number of peer-reviewed journals welcomes the research work related to NDT's. Therefore, researchers can use the below graph for selecting the journal for publishing their research work.

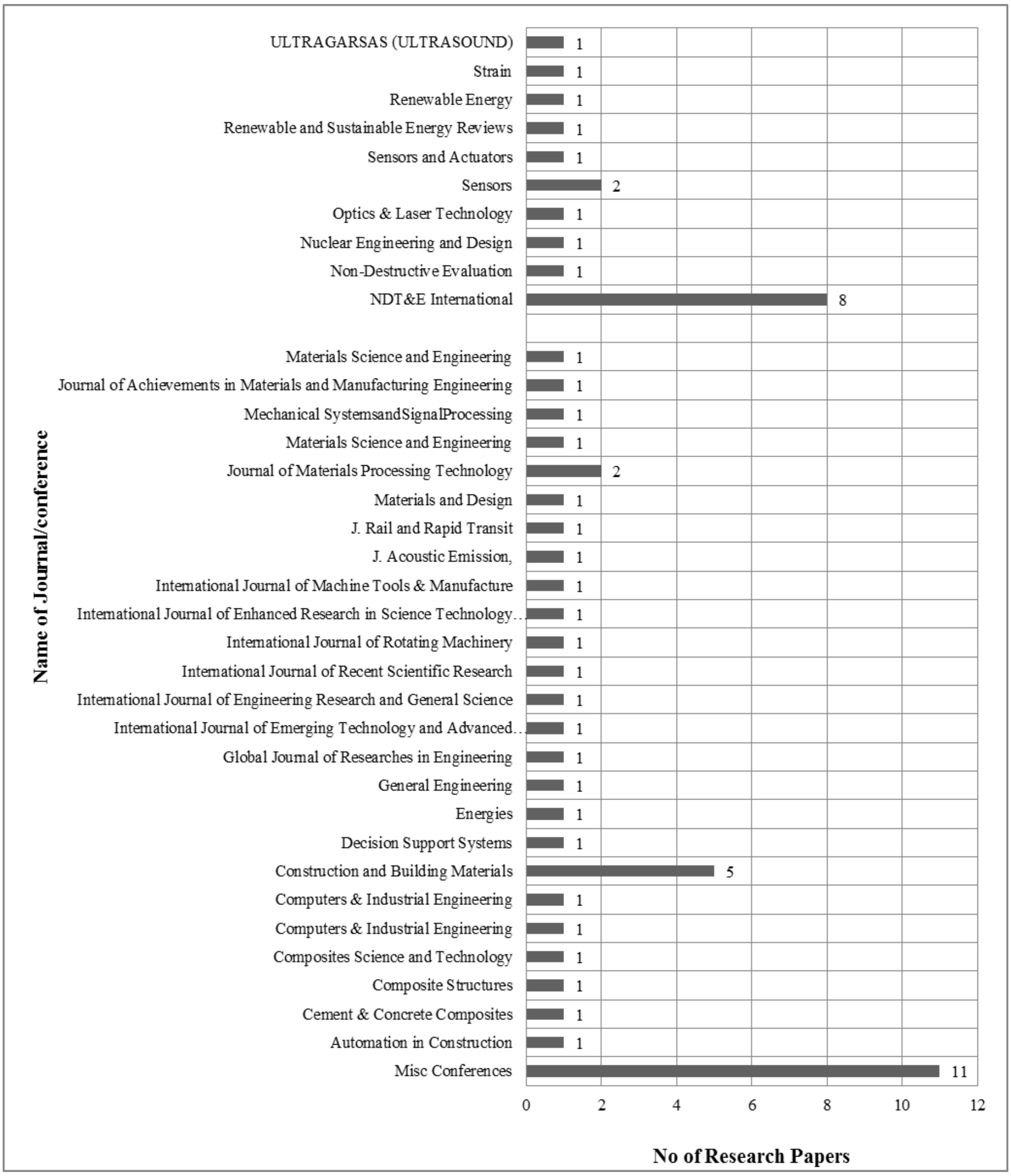

Fig. 3 Graph between name of journal/conference and number of research paper

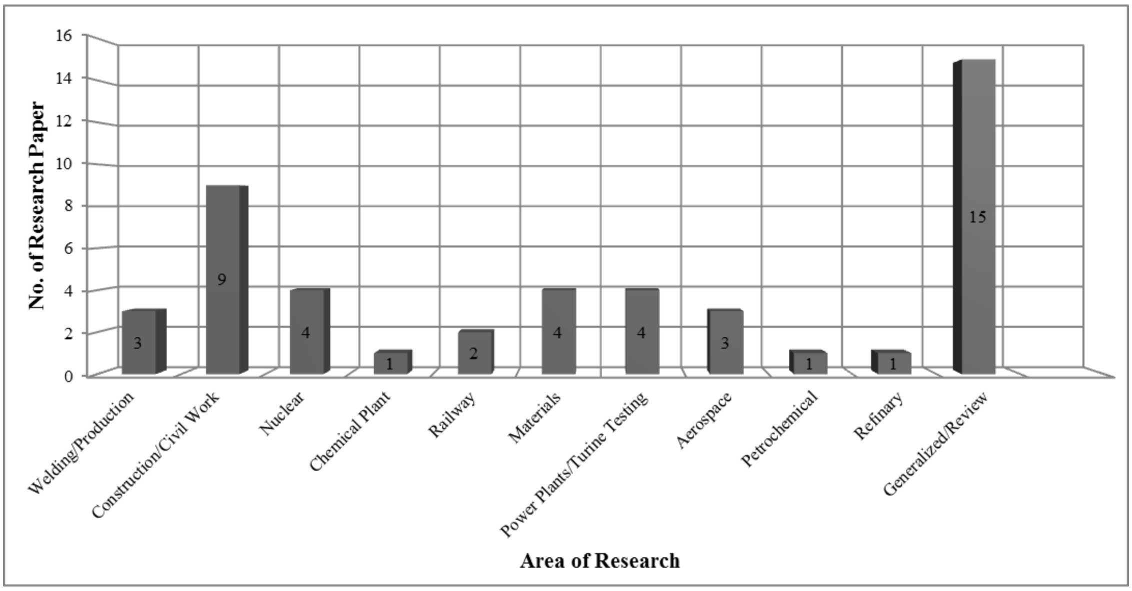

Fig. 4 Graph between area of research and number of research paper

As per Fig. 4, most of the work has done in the areas of review and in construction industry. Apart from this, it is also evident that less work is done in chemical plants, petrochemical and refineries. Therefore, researchers can use the below graph for selecting the area their research work.

As per Fig. 5, it is clear that most of the work done without using decision-making technique for combining multiple NDT's. Apart from this, it is also evident from the below graph that some decision-making techniques like graph theory, Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) method etc. are not covered. Therefore, researchers can use the below graph for selecting the suitable decision making for their research work.

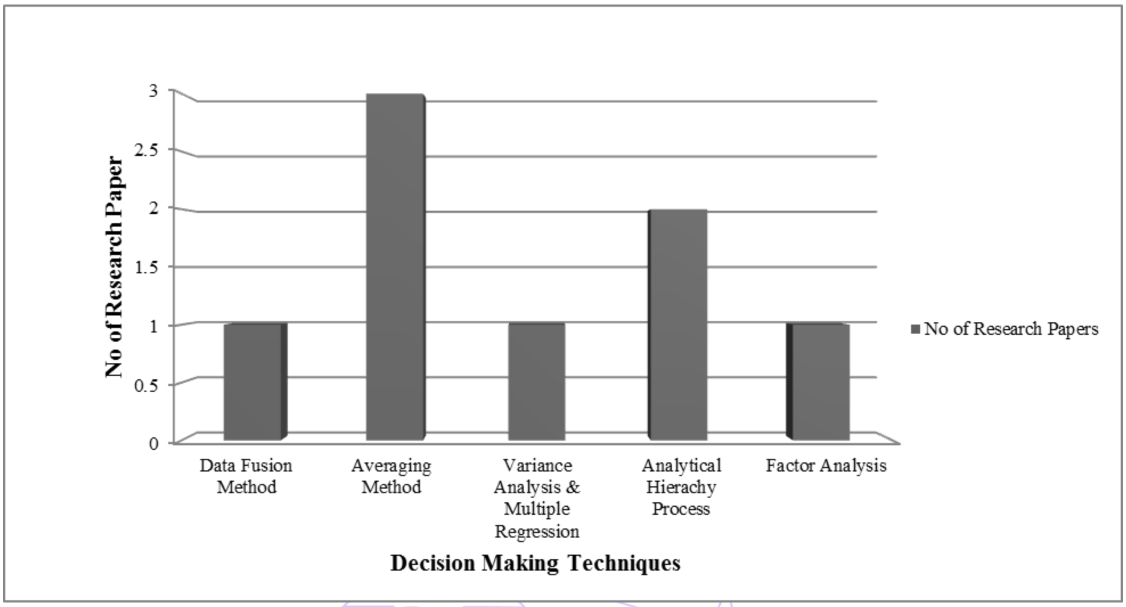

Fig. 5 Graph between decision making techniques and number of research paper

4. Conclusions

As per the objective discussed in the abstract, this research work is contributed in review of research papers dealing with NDT (Non Destructive testing) techniques combination along with some practical examples. This work outlines that although NDT is an effective tool and can replace destructive testing, the NDT combination gives better reliability in fault detection/assessment of defects in industrial equipment/components in multiple applications. Basically, each technique has some hindrances; therefore, making combination helps in countering these hindrances. Multiple works reviewed in this work highlights the increase in reliability, reduction in MTBF etc. because of combining multiple NDTs. The importance of this research is that, this work covers the parameters being considered before and after combining multiple NDT's, following are some more outcomes.

(1) Very few of the research papers use the decision-making approach. If they use a proper decision-making approach then it will save time and increase the fault detection reliability.

(2) Most of the work done in composites testing and least work is on gears, bearings etc.

(3) These research papers clearly proved the advantage of combining multiple NDT's for reliable fault detection.

(4) Apart from this, before combining multiple NDT's, it is better to compare then in terms of their characteristics and then, measure the maintenance performance improvement due to this combination. If the performance enhances, it means combination is fruitful.

The future work includes -

(1) The incorporation of qualitative fault tree analysis for fault diagnostics can be used.

(2) The mitigation of the challenge in the implementation of multiple-technique inspection is the extensive set of data required for qualification and the detailed analysis of flaws needed to be validated the NDT results.

(3) The incorporation of logical combinations (AND, OR) and averaging are appropriate to limited data sets where detailed probability distributions are not known.

(4) Better understanding of material properties, better understanding of complex structures, improved tomographic imaging, forward modeling etc. can be performed.

(5) A number of possible future areas for development are adaptive arrays, data fusion and harmonic and elastic imaging.

(6) The integration of the two technologies, wireless sensor networks (WSNs) based NDT, can bring about new applications in the field of low cost wireless material examination in real-time.

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