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Assessment and Monitoring for Railway Tracks Reliability and Safety using Nondestructive Testing Measurement Systems

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A B S T R A C T

The deterioration of railway tracks raises great concerns about the integrity of assessments and evaluations of railway tracks currently in service. Integrated inspection strategies coupled with innovations in inspection technology can lead to significant improvements in operational cost efficiency and reliability without the requirement of a fundamental shift in the existing understanding of the inspection process and standards. This review provides a discussion of the current state-of-the-art in nondestructive testing (NDT) for inspection, testing, and monitoring approaches for internal and surface defects, and condition assessment of railway tracks in general. A critical analysis is made between NDT and visual approaches, including a review of background theory and the techniques used to incorporate condition data into maintenance procedures. Various image processing techniques, along with their applications to different NDT imaging methods and some specific applications in railway tracks, with a discussion of their advantages and shortcomings, as well as future developments and novel inspection methodologies in the field are also presented, in order to show the potential of these approaches for rail infrastructure.

Keywords: reliability inspection, safety, railway tracks, nondestructive testing, internal and surface

1. Introduction

Maintaining the serviceability of infrastructure is quite costly, particularly for railway infrastructure, and this trend is expected to intensify as infrastructure continues to age. A primary challenge is the effective allocation of funding for the maintenance and repair of transportation networks, such as roads, highways and railways. Consequently, the development of more sophisticated nondestructive testing techniques and state-of-the-art repair assessment methods of infrastructure has become a major subject of interest within the structural engineering community [1].

Over the last few decades, many nondestructive Testing (NDT) methods have been developed and applied to inspection and monitoring tasks, such as radar, infrared thermography, acoustic techniques, and even optical imaging. These methods of inspection, which generate waveform or image data, have several advantages, such as the ability to detect elements at the surface, near-surface and beneath the surface of the structure [2]. In infrastructure imaging for detection and monitoring, however, acquiring data is only the first step in evaluating structures. This data has to be processed and interpreted in order to present the information in a more meaningful and useful format. Various image processing methods can be employed to interpret image data, such as statistical and signal processing approaches. The current use and development of image processing techniques employing NDT is limited due to the unavailability of

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enough experimental data and field applications. This is largely due to technical limitations, and the fact that engineers are generally unfamiliar with these techniques and lack knowledge of the available methods. However, many technological obstacles have been greatly reduced over the years, such as computer efficiency, resolution of imagery, equipment transportability, as well as the price of equipment [2].

2. Visual inspections and nondestructive testing (NDT) techniques

One of the most pressing problems facing the management of infrastructure is the lack of accuracy and the variability between assessments obtained through traditional investigation methods and the actual condition of a given structure. Conventional approaches are subjective in nature and strongly depend on the experience and skill of the inspectors [3]; the lack of objective and quantitative information can produce significant differences between the estimated and the actual condition of a structure, and the amount of repair work needed. Although such methods have been employed with some degree of success, they have not demonstrated the ability to predict deterioration problems in advance of a desired time period necessary for project planning [4]. Certain imaging methods have proven to be very efficient in collecting infrastructure data. However; acquiring data is only the first step in assessing and evaluating infrastructure deterioration. This data has to be processed and interpreted in order to present the information in a more meaningful and useful format. Various image processing techniques can be employed to efficiently and effectively obtain reliable information concerning the actual condition of infrastructure, which can be used to predict the safety and serviceability of infrastructure. Evaluation methods based on visual inspections depend on trained inspectors to examine various components using nondestructive testing (NDT) techniques, evaluate the condition of the components, and determine the level of damage. Although visual inspection may be effective in many cases, it is costly, time-consuming, and often a disruption to normal activities. Also, this evaluation is subjective in nature and strongly depends on the experience and skill of the inspectors; the lack of objective and quantitative information can produce significant differences between the estimated and the actual condition of a structure and the amount of repair work needed [5]. On the other hand, traditional NDT methods based upon radiography, ultrasound, eddy currents, and dye penetrating tests have been used in the industry for decades. With the continuous evolution of technology, the above methods have undergone various improvements, leading to a further reduction in NDT costs and better accuracy. With the rapid development and inevitable aging of infrastructure, it is vital to monitor infrastructure health to ensure the system's or component's integrity by detecting the onset of damage, such as fatigue cracks and corrosion in rail tracks [6].

3. NDT and Railway tracks

In order to increase the reliability of the railway network and improve the efficiency of maintenance procedures, rail tracks are inspected at regular intervals for internal and surface defects, as well as rail profile irregularities and wear, missing fastenings, failed sleepers, and abnormal variations in rail gauges. Rail tracks are usually inspected visually by appropriately trained personnel walking along the tracks and noting down defects, which is a relatively subjective procedure that may occasionally involve errors and omissions, and does not provide any information with regards to the presence of internal defects or failed sleepers [7].

Nowadays, accelerating degradation of railway tracks is creating many problems for railway engineers, since railway structures are deteriorating due to everyday service. Moreover, the irregularities of wheels, rails, or track properties, greatly influence the damage. Thus, assessing and determining the condition of rail tracks is of great concern to track engineers, especially in potential risk zones. However, data on the structural integrity and deterioration of railway tracks is very limited. Apart from regular visual inspections by track officers, track corrugation tests are regularly performed at track sites. Corrugation testing deals only with individual rails and only superficial railhead surfaces. Therefore, in order to ascertain the condition of railway tracks constantly subjected to train-induced vibrations, dynamic testing must be performed on tracks in which the dynamic properties can be extracted and estimated from the vibration responses of track structures. It should be noted that these parameters are important to dynamic analysis and design of structural systems, which are compliant with dynamic loadings, such as railway tracks, bridges, or high-rise buildings. The resonances can cause serious damage to such systems [8].

The structural condition of railway tracks is typically not known either before or after maintenance procedures. Therefore, in practice, the maintenance and renewal operations are usually based on empirical criteria. There is a need for better understanding on the structural conditions and the deterioration rates, which can lead to improved strategic planning and implementation of railway tracks. To maximise safety while minimising the costs of track maintenance and renewal, evaluation and monitoring of the structural integrity of railway tracks and its components are imperative.

Various research and models for the prediction of fatigue life and crack propagation in the railway wheel, have been conducted due to the stress field caused by mechanical loads and press fitting process of a railway wheel, such as, using 3-D nonlinear stress analysis model and element analysis model [9].

Rails are often systematically inspected for internal and surface defects using various nondestructive testing (NDT) techniques. During the manufacturing process, rails are inspected using automated optical cameras and eddy current sensing systems for any surface damage, while the presence of internal defects is assessed through ultrasonic inspection. Similarly, ultrasonic transducers and magnetic induction sensors have been extensively used by the rail industry for the inspection of rails in service. More recently, automated vision techniques and hybrid systems based on the simultaneous use of pulsed eddy current probes and conventional ultrasonic probes have been introduced for the high-speed inspection of rail tracks. Other NDT techniques, such as electromagnetic acoustic transducers, laser ultrasonic, guided waves, and alternating current field measurement probes, are also under development for application in the rail industry [10].

Rail networks across Europe are getting busier with trains travelling at higher speeds and carrying more passengers and heavier axle loads than ever before. Although, severe rail accidents are relatively rare within the EU, their frequency of occurrence is still at an intolerable level. Rail accidents can be due to human error, infrastructure defects or train equipment failure [10].

Several countries in Europe and Asia are seeing increased spending in railway infrastructure. The national economy of Turkey has been steadily growing stronger; it is currently the 16th largest economy in the world, and the sixth largest economy relative to the EU. Turkey is increasingly being recognised as a country that is modernizing rapidly and is moving up the skills chain with improved capabilities. Railways are enjoying a period of significant and sustained investment in Turkey, with major investments in high-speed rail lines, rail-led solutions to freight and distribution, and urban transportation in major cities across the country. A commitment to invest US $45 billion has been made (US $23.5 billion before 2023), in a programme of expansion up until 2035 [11]. Outside of Europe, countries such as Saudi Arabia are also seeing tremendous investments in rail networks. The scope of the planned Saudi rail projects and required investment are massive at an estimated $45 billion. One third of the GCC rail budget is allocated to upgrading existing lines and building new rail networks across the Kingdom before 2030. However, with Saudi Arabia's vast land mass, varied geographical features, as well as the plan's ambitious deadlines and objectives, a unique set of financing, logistical and engineering challenges will require innovative and equally ambitious solutions [12]. Thus, improvements to a massive rail network along with the existing rail infrastructure, will lead to increased demands in inspection and maintenance of rail assets due to the higher risk of catastrophic failure. The expenditure for inspection and maintenance has thus grown steadily over the last few years [7].

The current inspection intervals in Norway are based on experience from other countries, international recommendations, etc., but currently these intervals have not been evaluated based on cost benefit analysis. The yearly cost of inspecting the Norwegian network comprises several hundred thousand Euros. On the other hand, there are significant costs if cracks are overlooked leading to rail breakage and a possible derailment [13]. The rails are primarily constructed to have a strength that ensures an approximately infinite life span. However, high axle loads, wheel failures, and substructure failures can compromise this significantly. To ensure safe railway operation, it is important that the rails are free from defects such as cracks, geometry failures etc. In modern railway operation there exist two types of monitoring cars for the rails: ordinary measurement cars that measure rail geometry and surface deterioration and ultrasonic inspection cars that measure rail breakages and internal cracks [13].

4. Rail flaw detection

With the constant increase of railway use and loading capacity, the contact between the wheels of the trains and the rail tracks becomes more frequent, which increases the rail load. This makes the rail surface prone to fatigue and damage, which is likely to evolve into transverse and horizontal cracks internally. In order to avoid accidents, human casualties, and loss of service, the early non-destructive safety evaluation of rail surface is very important.

Non-destructive testing is one of the most important testing methods. The following are some non-destructive testing methods applied in rail flaw detection. Although visual detection is the simplest and oldest method used in rail flaw detection, it is time consuming and subjective, which may lead to erroneous conclusions. Currently, the most popular rail testing methods are the ultrasonic and the eddy current testing methods [14]. Ultrasonic testing involves the reflection of acoustic waves to detect internal defects [15]. It is quick, extremely reliable, and reaches deep into the structure. However, the display of the ultrasonic testing results is not easy to understand; moreover, this method often requires treatment of the surface under examination [16].

Other detection methods in rail testing have been recently developed. The ultrasonic testing of the weld inside the rail head has the advantages of accuracy and intuition, but it is incapable of detecting the defect on the surface or near the surface. The detection method which combines ultrasonic wave and eddy current tests uses multiple sensor probes and is able to detect the rail flaws inside and on the surface of the rail track. However, its analytical performance on the degree and type of flaws is unsatisfactory [17]. High-speed flaw detection using eddy currents can be used to evaluate the location and extent of the rail damage. However, there are difficulties in intuitively displaying the different types of rail defects [18]. One research employed eddy current testing in order to distinguish and quantitatively analyze different types of rail surface defects. The sensitivity of the amplitude of the eddy current signal phase was used to evaluate the rugged surface and side cracks of a rail track that was actually in use.

5. Non-destructive testing (NDT)

NDT Based-on Ultrasound

Sound with high frequencies, or ultrasound, is one method used in NDT, where ultrasonic waves are emitted from a transducer into an object and the returning waves are analyzed. Ultrasonic measurements can be used to determine the thickness of materials and determine the location of a discontinuity within a component or structure by accurately measuring the time required for an ultrasonic pulse to travel through the material and reflect from the back-surface of the material or the discontinuity. If a crack or defect is present, the ultrasonic pulse or sound will bounce off of it and be detected in the returned signal. Analysis of the pattern created by the signal will reveal the position of the defect [19].

Ultrasonic inspection is carried out by a variety of different instruments ranging from hand-held devices, through dual-purpose road/track vehicles to test fixtures that are towed or carried by dedicated rail cars. Unfortunately, the performance of existing conventional ultrasonic probes in detecting small surface defects such as head checks and gauge corner cracking is inadequate during high-speed inspections, generating a number of false alarms and hence resulting in higher inspection times and associated costs. This is also one of the reasons that the current international practice is to combine non-destructive evaluation of the rail network with preventive maintenance procedures, such as rail head grinding, in order to optimize the trade-off between maintenance cost and structural reliability. Furthermore, the quality of ultrasonic inspection can be adversely affected by rail corrugation.

Over the last 50 years, the application of customized ultrasonic techniques for the examination of railroad components has increased compared with conventional ultrasonic techniques used until the end of the 20th century. Nevertheless, some accidents have occurred. Consequently, more than ever, high-speed modern trains require modern and advanced examination techniques [20].

NDT Based-on Radiography

Digital radiography technology is one method that has had an impact on the inspection process, as it is economical, saves time, and is eco-friendly. This is attributed to the fact that it reduces radiation energy by 50% and exposure time by 60% - 70%. Digital radiography provides a new, innovative method that replaces X-ray films, darkroom processing, and conventional archives with computer systems, electronic archiving and x-ray capture using direct or reusable digital imaging plates. The flexible imaging plates are used just like ordinary films in jackets and can be placed inside or outside of the component or structure under inspection. These plates are exposed in a similar manner to a standard radiographic setup but with reduced radiation energy and exposure time. The radiographs are then electronically reported, archived, or accessed, as needed. Digital radiography can be employed for safety assessment and monitoring of railway tracks and associated components. This approach also integrates and embeds the knowledge of engineering, reducing the subjective nature of other techniques, such as visual inspection.

Radiographic inspection of rails can be carried out using either gamma or X-ray sources. In the past, radiography was carried out more often using a gamma-ray source; with the advent of portable digital X-ray detectors, however, the use of X-ray sources became more commonplace. Radiography, although a particularly efficient non-destructive testing (NDT) method for inspecting rails for internal flaws, inherently involves health and safety drawbacks. Therefore, it is only employed as a means of verification in places where defects have already been detected using other non-destructive evaluation techniques or in rail areas, such as aluminothermic welds, and switches and crossings, where inspection with other NDT methods is unreliable and not very efficient in detecting transverse rail defects [7].

Acoustic Emission (AE) Techniques

Acoustic emission (AE) techniques have been tested in the laboratory and in the field regarding their suitability for the detection of surface rail defects at high speeds by various researchers at AEA Technology Rail (now DeltaRail) and Cranfield University [21]. This technique has also been investigated by researchers in Birmingham University and elsewhere to evaluate the applicability of the technique for structural health condition monitoring of rail sections where structural defects have already been identified by other means and where their further growth requires attention [22].

Eddy Currents

Eddy current testing is applicable for the inspection of the surface and near-surface areas of rail heads; however, the operation of eddy current probes is sensitive to lift-off variations. Consequently, the probes need to be positioned at a constant distance (no more than 2mm away) from the surface of the rail head and particular attention needs to be given to any lift-off variations that may occur during inspection. The performance of eddy current sensors can therefore be adversely affected by the presence of grinding marks on the rail [7].

Magnetic Flux Leakage

The application of Magnetic Flux Leakage (MFL) sensors is mainly focused on the detection of near-surface or surface-breaking transverse defects, such as RCF cracking. However, transverse fissures are not the only types of defects found in rails, which can include deep internal cracks and rail foot corrosion. These defects are not detectable with the MFL method either because the fissures run parallel to the magnetic flux lines and hence they do not cause sufficient flux leakage, or they are too far away from the sensing coils to be detected (i.e. the rail web and foot). MFL is also adversely affected by increasing inspection speed. With increasing speed the magnetic flux density in the rail head decreases, and as a result, the signal becomes too weak for the detection of defects at speeds that exceed 35km/h. Inspection systems based on the simultaneous use of conventional ultrasonic transducers with MFL sensors have a higher probability of detecting smaller near-surface and surface-breaking defects in the rail head. However, as inspection speed increases, the performance of MFL sensors tends to deteriorate rapidly due to a reduction in the magnetic flux density. More recently, Pulsed Eddy Current (PEC) probes have been added on certain ultrasonic test trains to offer increased sensitivity in the detection of surface defects at high inspection speed. PEC probes perform better than MFL sensors at higher inspection speeds but are affected more by lift-off variations [7].

Alternating Current Field Measurement

Alternating Current Field Measurement (ACFM) is an electromagnetic inspection method capable of both detecting and sizing (length and depth) surface breaking cracks in metals. The basis of the technique is that an alternating current can be induced to flow in a thin skin near the surface of any conductor. By introducing a remote uniform current into an area of the component under test, when there are no defects present the electrical current will be undisturbed. If a crack is present, the uniform current is disturbed and the current flows around the ends and down the faces of the crack, thus allowing its detection and sizing. ACFM sensors are less affected by lift-off variation than eddy current probes and can operate even at 5mm away from the rail surface [7].

Automated Vision Systems

Automated vision systems can operate at very high velocities; speeds up to 320km/h are possible depending on the nature of the inspection. They are typically used to measure the rail profile and percentage of wear of the rail head, rail gauge, corrugation and missing bolts. Certain advanced vision systems can be used for the detection of RCF and other types of surface damage such as wheel burns at slower inspection speeds (<10km/h). Despite the usefulness of automated vision systems, their applicability is restricted to the detection of surface features only and therefore the inspection needs to be repeated using ultrasonic sensors for the detection of internal defects [7].

6. Other methods

Other rail inspection techniques, which are currently at different stages of development, include the use of long-range ultrasonic, electromagnetic acoustic transducers (EMATs) and laser ultrasonics. These techniques, however, have their own technical problems and limitations, and consequently have found limited applications in rail inspections thus far. There is also a lack of standards, which needs to be addressed before these techniques can be adopted by the rail industry. The main problems restricting the use of these techniques are of a technical nature. Furthermore, a fundamental shift to inspection techniques where new inspection standards may be required and on which existing maintenance staff personnel has limited expertise would be undesirable. Therefore a prolonged period of trials is likely to be required before these new techniques can be approved for widespread application [7].

Imaging in NDT

Approaches based on imaging in NDT are generally used to improve inspection reliability, to improve damage detection and characterization, to automate inspection tasks, and to generate information about the material properties in order to assist in assessing the remaining life of a structure [24]. Innovative methods for precise and timely condition assessment, performance prediction, and maintenance management are constantly being developed for the cost-effective rehabilitation of aging and deteriorating infrastructure. To this end, imaging techniques are being increasingly employed due to their high potential to provide reliable information about the condition of a structure. Various nondestructive testing techniques are used to obtain infrastructure imagery, such as optical images, which present image data of the surface, infrared thermography and acoustics, which are used for subsurface conditions, and ground penetrating radar, which is employed to obtain below-surface information of a structure [24].

Recent developments in other single imaging methods have tried to achieve improved imaging quality and better detectability, such as ultrasonic imaging used for detecting defects or hidden objects inside a structure [25], and thermal imaging methods for mapping the length and shape of cracks, as well as crack depth [26]. In order to find a way to improve the imaging capability of each single imaging technique and to reach beyond the physical diffraction limit, the multi-wave imaging concept was proposed in recent years [27], which consists of combining two different waves generated sequentially and taking advantage of the capacity of each wave. For example, with the combination of thermal and acoustic imaging, the acoustic waves provide image contrast while the thermal absorption provides superior spatial resolution. Because of the way the waves are combined, multi-wave imaging produces a single but enhanced image with the best contrast and resolution. Another method that shares the same goal of enhancing image quality is Hybrid imaging, which simply combines two single methods; however, data fusion and image registration are usually necessary [6].

Significance of Imaging for Infrastructure Applications

Surface damage, such as cracks, in images are usually treated as objects, and are thus quantified through techniques that first segment the objects from the background to extract shape or object features, and then classify the images based on those features. However, in their study on the classification of pits and cracks in corrosion images, it was found that segmentation approaches worked well on individual images, but proved unsatisfactory when applied to a large set of samples due to the variability in the background. So they adopted a method based on analysis of the textured appearance of the pits and cracks in the images, which was successfully employed to discriminate between the two types of damage. The present research aims at finding a new application for texture methods in the analysis of infrastructure damage from NDT imagery. Different types of infrastructure damage each have a specific texture typical of the type of deterioration, which should permit their discrimination through texture analysis methods.

There are few studies that have applied image processing techniques, such as texture analysis, to extract textural features in order to obtain infrastructure deterioration information from optical imagery and there have so far been even fewer efforts to combine two approaches, such as statistical methods and signal processing methods. Since, there are no obvious quantitative measures to characterize texture, texture analysis can prove to be quite difficult to implement. Nevertheless, a good understanding or a more satisfactory interpretation of an image should include the description of both spectral and textural aspects of the image [27]; thus, the door for research in computer vision remains wide open. Consequently, texture analysis techniques, usually used in the field of medical imagery and remote sensing, can find new and original applications in civil engineering.

The use of image processing methods on NDT imagery for the extraction of infrastructure deterioration information can be compared with visual inspection approaches that were traditionally employed to evaluate the condition of infrastructure in service. Contrary to visual inspections, which, in most cases, remain qualitative, the proposed methods employ classification techniques, which present the greater advantage of providing quantitative information due to their capacity to analyze images, pixel by pixel, based on their numerical properties. Also, acquiring most of the types of NDT imagery is not relatively costly, time consuming, or a disruption to service, thus allowing for more frequent monitoring, which is another important factor in effective maintenance [28].

As a result, the information obtained from the approaches described in this study can be used to supplement visual inspections. The quantitative nature of this data and its regular collection can promote the establishment of deterioration criteria through the determination of correlation between deterioration factors and damage within infrastructure. Furthermore, these techniques present the potential to be incorporated into an automated monitoring system for infrastructure. Up to now, automated recognition of deterioration modes in infrastructure from monitoring data has been the object of very few research projects. In this context, better understanding of automated image analysis, and knowing how such tools can be used to assist inspectors in the assessment of the condition of infrastructure can provide more reliable infrastructure monitoring and decision making.

7. Conclusion

The deterioration of railway tracks raises great concerns about the integrity of assessments and evaluations of railway tracks currently in service [8]. Integrated inspection strategies coupled with innovations in inspection technology can lead to significant improvements in operational cost efficiency and reliability without the requirement of a fundamental shift in the existing understanding of the inspection process and standards [29]. Consequently, this comprehensive discussion on state-of-the-art in NDT methods currently employed in the inspection of rail tracks and their components, along with their advantages and drawbacks, can be used to develop appropriate inspection and maintenance strategies that are supplementary to visual inspection methods, resulting in a combination of experienced evaluations and quantitative assessments of the structural health of railway infrastructure.

References

[1] X. Dérobert, C. Aubagnac, and O. Abraham, Comparison of NDT techniques on a post-tensioned beam before its autopsy. NDT&E International, 35 (2002) 541 – 548.

[2] Sh. Kabir, Imaging-based detection of AAR induced map-crack damage in infrastructure structure, NDT&E International 43 (2010) 461–469.

[3] N. Carino, Nondestructive test methods to evaluate concrete structures. Proceedings of the 6th CANMET/ACI International Conference on Durability of Concrete, Thessaloniki, Greece, 2003.

[4] U.S. Department of Transportation, Federal Highway Administration, National Technical Information Service, Springfield, VA 22616, NTIS publication no. PB255322, 2003.

[5] Sh. Kabir, Image Processing In Infrastructure Applications: Review And Prospective, CSCE Annual Conference Québec, 2008.

[6] Y. Cheng,, Y. Deng, J. Cao, X. Xiong, L. Bai, and Z. Li , Multi-Wave and Hybrid Imaging Techniques: A New Direction for Nondestructive Testing and Structural Health Monitoring, Sensors (Basel), 13(12) (2013), 16146–16190.

[7] Mayorkinos Papaelias, Clive Roberts and Claire Davis, Rail inspection technology, Centre for Rail Research and Education, University of Birmingham, 2010.

[8] S. Kaewunruen, and Remennikov, Non-destructive testing (NDT): A tool for dynamic health monitoring of railway track structures, Materials Australia, 39 (6) (2006) 14-16.

[9] G.H. Farrahi, S. Sohrabpoor, S.M. Salehi, R. MasoudiNejad, Prediction of Fatigue Life in the Railway Wheels Under the Influence of Residual Stress Field, International Jounal of Railwa Resaerch, 1 (6) 2015.

[10] M Ph Papaelias, C Roberts, C L Davis, A review on non-destructive evaluation of rails: State-of-the-art and future development, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit July 1, 222 (4) (2008) 367-384.

[11] UK Trade and Investment, Railway Sector Fact-Finding Mission to Turkey, UK Trade and Investment, 2011.

[12] Saudi Rail, An Engine for Growth in the Region, http://saudirail-expo.com/home.php, 2015.

[13] J. Vatn and H. Svee, A Risk Based Approach to Determine Ultrasonic Inspection Frequencies in Railway Applications, 6th Proceedings of the 22nd ESReDA Seminar, Madrid, Spain May (2002) 27-28.

[14] D. Hur, M. Choi, D. Lee, S. Kim and J. Han, A Case Study on Detection and Sizing of Defects in Steam Generator Tubes Using Eddy Current Testing, Nuclear En-gineering and Design, 240 (2010) 204-208.

[15] R. Raisutis, R. Kazys, E. Zukauskas, L. Mazeika and A. Vladisauskas, Application of Ultrasonic Guided Waves for Non-Destructive Testing of Defective CFRP Rods with Multiple Delaminations, NDT&E International, 43 (5) (2010) 416-424.

[16] Z. Song, T. Yamada, H. Shitara, and Y. Takemura, Detection of Damage and Crack in Railhead by Using Eddy Current Testing Journal of Electromagnetic Analysis and Applications, 3 (2010) 546-550.

[17] R. Pohl, A. Erhard, H. J. Montag, H. M. Thomas and H. Wustenberg, NDT Techniques for Railroad Wheel and Gauge Corner Inspection, NDT&E International, 37 (2) (2004) 89-94.

[18] NDT.Net

[19] B. Rockstroh, F. Walte, and W. Kappes, Modifizierte Radpru¨fsysteme fu¨ r neue Eisenbahnra¨der und Radsa¨tze fu¨ r Schienenfahrzeuge. Proceedings of the International Symposium on Rail Vehicles. Dresden, Germany; 2002.

[20] K. Bruzelius, An initial investigation on the potential applicability of Acoustic Emission to rail track fault detection, NDT & E Int.,37 (7) (2004) 507-516.

[21] P. Yilmazer, A. Amini, M. Papaelias, The structural health condition monitoring of rail steel using acoustic emission techniques, in the Proceedings of NDT, September 2012.

[22] Sh. Kabir, Transform- and Statistical-based Image Analysis for Assessment of Deterioration in Concrete Infrastructure, ISBN0494426268, 9780494426265, Publisher: Library and Archives Canada, Ottawa, Canada, 190 p, 2009.

[23] M. Turqueti, V. Kunin, B. Cardoso, J. Saniie, E. Oruklu, Acoustic Sensor Array for Sonic Imaging in Air. Proceedings of IEEE Ultrasonics Symposium (IUS); San Diego, CA, USA. (2010) 1833–1836.

[24] C.C. Tai, J. Moulder, Bolt-hole corner crack inspection using the photoinductive imaging method. J. Nondestruct. Eval. 19 (2000) 81–93.

[25] M. Fink, M. Tanter, Multiwave imaging and super resolution. Phys. Today, 63 (2010) 28–33.

[26] D-C. and L. Wang, Texture features based on texture spectrum. Pattern Recognition, 24 (5) (1991) 391 – 399.

[27] O. Abudayyeh, M. Al Bataineh, and I. Abdel-Qader, An imaging data model for concrete bridge inspection. Advances in Engineering Software, 35 (2004) 474 – 480.

[28] M. Papaelias, S. Kerkyras, F. Papaelias and K. Graham , The future of rail inspection technology and the INTERAIL FP7 project, Centre for Rail Research and Education, The University of Birmingham, UK, NDT 2012.