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Development of Novel Rail Non-destructive Inspection Technologies

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Abstract: Despite rapidly developing real-time manufacturing process inspection systems and maintenance procedure modeling, their reliability and precision is not sufficient to eliminate the need for non-destructive inspection of rails in-service. The train derailments happened and the speeding up train running under higher dynamic axle load reaffirm the importance and necessity to develop non-destructive evaluation (NDE) technologies. In order to obtain an entire inspection of rails, how to keep reasonable sensitivity and resolution at a high speed without missing inspection and avoid false reading are the critical techniques must be considered. This article firstly describes the basic problems in traditional ultrasonic testing and basic results false flaw reading through experiments. Then mainly emphasizes on providing a comprehensive review on the current state-of-the-art in NDE methodologies of rail inspection in order to solve and complement conventional ultrasonic inspection. The corresponding theories, analysis solutions and approaches of signal processing are also mentioned to some extent. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Basic problems, Novel rail inspection, Guided waves, ACFM, EMATs, Hybrid system.

1. Introduction

Rails in-service are subjected to intense bending, shearing, thermal and residual stresses, plastic deformation and wear, resulting in deterioration of structure integrity in time. Moreover, rails unqualified owing to manufacturing problems, in operation under complex and volatile environment compose the combination factors leading to different defects eventually. Jeong presented an overview of the common defects [1, 2] and provided the relevant analysis of the formation [1]. Conventional ultrasonic testing uses wheel or sled installed piezoelectric transducers filled with adaptable fluids. Though ultrasonic testing occupied an indispensable position in the filed of NDE, the fatal weakness existing make the methodology not all-inclusive due to the attenuation originating from shelling weaken the power that causes the missing inspection of transverse defects [2, 3]. Secondly, the excessive attenuation resulted form the weld's coarse component when propagating through the structure prevents the high frequencies from penetrating the alumino-thermic welds completely [4]. Broken rails turn up now and then, but they don't remarkably enough lead to derailments. Nevertheless, the reports from the Federal Railway Administration (FRA) Safety Statistics Data indicate that 3,386 derailments happened among 1998-2008 while the rail defects account for at least 1,242 cases that cost more than $297 M [3]. Synthesized factors form the motivation to promote research group tackling key technical problems on promising inspection systems. In order to avoid causing huge personal and property losses, a lot of portable or vehicle techniques [2] have been developed worldwide.

2. Normal Ultrasonic Inspection Problems

Conventional Ultrasonic wheel probes or sled installed probes normally use piezoelectric transducers configured with different angles and positions taking responsibilities of relevant regions in order to achieve best detecting effects. Several aspects should be taken into consideration so as to conduct the inspection more efficiently and effectively. Signal to noise ratio (SNR) decides the integrated performance which must be guaranteed for the missing fatigue may lead to rail fracture. Near surface detecting accuracy and the restriction of blind area confine the effective range of the whole rail that fatal defects should be detected. Eventually, false flaws complex the judgement with the complicated constructure in the process of rail track detection. The experiments below conducted by using a portable digital ultrasonic device are aimed at revealing the specific phenomena that we should attach importance to during inspection and analysis.

2.1. Influence of Noise

Noise in rail track inspection can be classified to two main aspects: constructure noise and electrical noise. The unenvitable element distributes the energy which results in the amplitude of defect signal. Furthermore, the interfering noise leads to misreading at some extent.

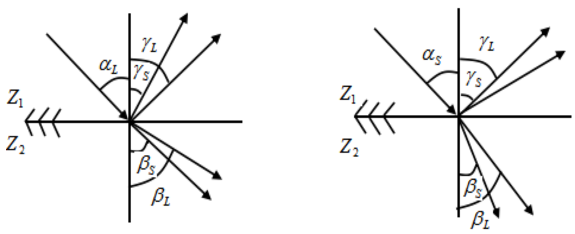
2.1.1. Constucture Noise

Most noise resulting from reflection, refraction and dispersion decrease SNR and may lead to false judgement.

In Fig. 1 c_{L_1}, c_{L_2} are the longitude wave speed in two medium, c_{S_1}, c_{S_2} are the shear wave speed in two medium, γ_L, γ_S are the reflection angles of longitude and shear wave, β_L, β_S are the refraction angles of longitude and shear wave, α_L is the incident angle of longitude wave, α_s is the incident angle of shear wave, Z_1, Z_2 ate the acoustic impedance in two medium.

$$\frac{\sin\alpha_L}{c_{L_1}} = \frac{\sin\gamma_L}{c_{L_1}} = \frac{\sin\gamma_S}{c_{S_1}} = \frac{\sin\beta_L}{c_{L_2}} = \frac{\sin\beta_S}{c_{S_2}}, \quad (1)$$

$$\frac{\sin a_S}{c_{S_1}} = \frac{\sin\gamma_L}{c_{L_1}} = \frac{\sin\gamma_L}{c_{S_1}} = \frac{\sin\beta_L}{c_{L_2}} = \frac{\sin\beta_S}{c_{S_2}}, \quad (2)$$



(a) (b)

Fig. 1. (a) Incident longitude wave, (b) Incident shear wave.

Equation (1) and (2) demonstrate the path of ultrasonic transmitting along the detecting structure and compose the basis of wave mode conversion while the incident angle reaches a particular value. The angle is relevant to speed in both medium. The experiment of 61 degree will instruct the analysis of mode conversion computing process. Dispersion brings about attenuation accompanying with complicated reflection, refraction when grains of the organization is coarse.

2.1.2. Electrical and Impulse Noise

Electrical noise has a broadband frequency distribution range. Property of inspection system decides the level of the noise. By means of comparing experiments, level range can be acquired. Random, full amplitude and single peak incorporates the characteristics of impulse interruption. The features indicate measurable and recognizable method of the noise.

2.2. Near Field Region and Blind Area

Setting aside the attenuation from the medium, sound pressure of point sound source field spreading in liquid can be expressed as below [5]

$$P = \frac{P_0 dS}{r}\sin(wt - kr), \quad (3)$$

where r is the Arbitrary point distance from acoustic source, w is the angular frequency, $k = 2\pi/\lambda$, dS is the Area of point sound source, P_0 is the Original pressure of point sound source, t is the Transmitting time from point source to position r, P is the Pressure in position r.

Via integration of the whole surface of the disk acoustic source, sound pressure formula of arbitrary point in pressure axis of disk acoustic source spreading in liquid is converted as below [5]

$$P = \left\{2P_0 \sin\left[\frac{\pi}{\lambda}\left(\sqrt{R_s^2 + a^2} - a\right)\right]\right\}\sin(wt - ka), \quad (4)$$

where R_s is the radius of disk acoustic source, P is the Pressure away axis at a distance of a .

Fig. 2.(a) and Fig. 2(b) shows the pressure distribution of disk acoustic source spreading in liquid.

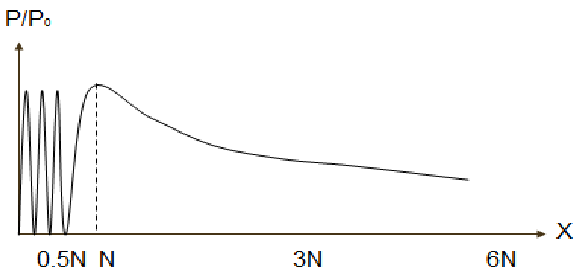


Fig. 2 (a). Axis pressure of acoustic source.

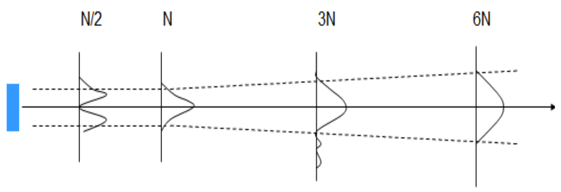


Fig. 2 (b). Pressure in the cross section of disk field.

$$\frac{\pi}{\lambda}(\sqrt{R_s^2 + a^2} - a) = (2n+1)\frac{\pi}{2}(n = 0,1,2,3...)$$

While $a < N$, position of maximum sound pressure in axis can computed through the formula below [5]:

$$a_m = \frac{4R_s^2 - \lambda^2(2n+1)^2}{4\lambda(2n+1)}, \quad (5)$$

It concluded that defects in Near field region may miss inspection because of minimums pressure points.

The scope of blind area depends on the capability of the device, transducer and outline of the inspection constructure. Blind area in regular structure normally means disability of detecting the flaws near surface which causes missing inspection.

3. Novel Rail Track Inspection Techniques

The motivation to develop novel rail inspection techniques is to complement conventional ultrasonics testing in a cost-effective, high efficiency way and reduce the influence of normal ultrasonic problems. In the following paragraphs, latest development of representative novel methodologies such as techniques using Guided waves, electro-magnetic acoustic transducers (EMATs) and AC Field Measurement (ACFM), hybrid system will be introduced while existing tough issues and new attempts will also be discussed.

3.1. Inspection Techniques Using Guided Waves

Guided waves are originally used for detecting corrosion of petroleum and gas pipelines. They are formed when the body wave propagates between the boundaries along the waveguide such as rail tracks. Wave mode and frequency selections are the critical techniques in guided wave detection as dispersion and multiple wave modes are the principal characters that makes the inspection extremely complicated because excited wave modes transmit at different speeds in both directions and the speeds are influenced by the frequency components [4].

In order to figure out the dispersion properties of the rails, a range of numerical analysis models are Constructed such as finite element models, analytical finite element models, and semi-analytical finite element (SAFE) models [7]. Coccia [7] uses forced high frequency SAFE approach for a rail head which indicated reasonable match between theoretical and experimental in time and frequency domains and successfully calculated the strain energy distribution in the rail crossing section using a mode tracking algorithm. The study also comes to conclusions that it is better to inspect internal defects in the rail head gage and field sides using anti-symmetrical excitation while symmetrical excitation for detecting surface flaws. On the other hand, so as to generate appropriate wave modes that can achieve better effects, transducers are designed and placed [4, 7-8]. Signal processing algorithms aimed at automated defect classification and denoising are also subtly designed [8].

A system as shown in Fig. 3 developed in South Africa by the Institute of Maritime Technology shows potential of guided waves to monitor rail. Permanent transmit and receive stations installed alternately to detect the damages by noise level when trains approach and depart. The principle analysis was proved by Ryue, et al. [9]. The system can be solar powered and recognize valid signals according to criteria as signal frequency, burst length and burst repetition interval. The technical problem is concentrated on how to achieve a reasonable distance with capability of processing small signal. Along 34 km inspection rail, three breaks were detected in 15 months [10]. New receiver will drastically improve performance and adaptability for different rail types (frequencies) with low power digital signal processor technology. It should be able to work reliably at low signal to noise ratios and faster operation to cope with metro train intervals will also be possible. As an implementation of detection system, it anticipates the combination of defects detecting and monitoring of rails in-service [9].

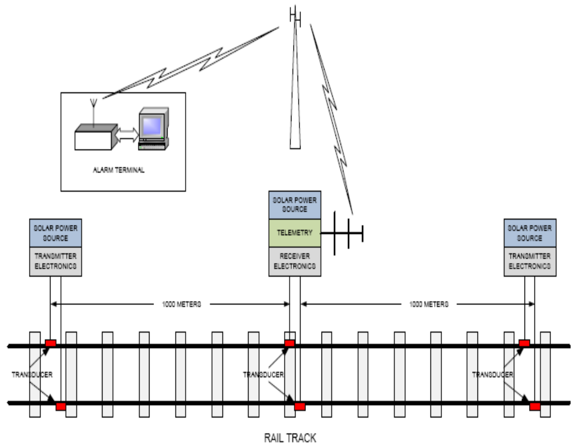


Fig. 3. System Diagram [taken from Ref. 10].

3.2. Inspection Techniques using ACFM

AC Field Measurement technique was originally developed at the aim of accurately measuring the depth of surface-breaking fatigue cracks at welds underwater. The technique is capable of detecting and sizing surface breaking cracks in metals based on the principle that AC can be induced to flow in a thin skin near the surface of any conductor. The introduced remote current into the component will not be disturbed when there is no crack present. If there is a crack present, the uniform current is disturbed and the current flows around the ends and down the faces of the crack [11, 12]. As shown in Fig. 4, the field component denoted by Bz corresponds to the poles generated as the current flows around the ends of the crack introducing current rotations in the plane of the component is indicative of a crack length. While the field component denoted by Bx corresponds to the reduction in current surface density as the current flows down the crack and is indicative of the depth of the defects [11].

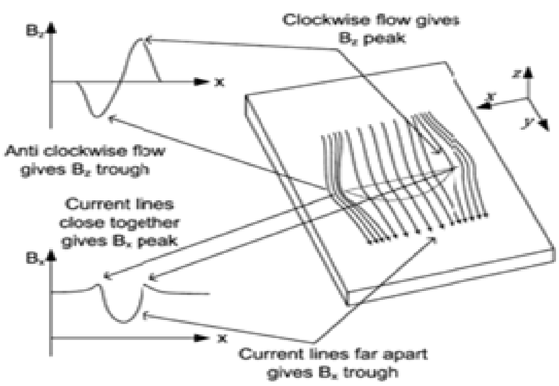


Fig. 4. Definition of field directions and co-ordinate [taken from Ref. 12].

ACFM technique was initially applied for rail surface detection using a walking stick carrying an ACFM probe by TSC and Bombardier Transportation [12]. Nicholson [13, 14] compared COMSOL model results and experimental measurements using an ACFM pencil probe for calibration defects. COMSOL Multiphysics software was used to construct a FE model to simulate the response of ACFM sensor. The experimental data of normalized Bx and Bz field distributions at zero lift off was reconstructed through grid scanning. Compared results validated that the COMSOL model predictions of $\Delta B/\Delta x$ can stands for the ACFM signal variation and predicted changes using semi-elliptical approximation to represent the RCF is reasonable[14]. Hasanzadeh [15] built a fuzzy recursive least square algorithm as a learning methodology along with a set of fuzzy linguistic rules for probe signals of a crack (data) providing a means to compensate for the lack of sufficient samples in available crack databases [15]. The algorithm was checked by using several semi-elliptical cracks and relative ACFM signals with 140 samples and the results showed that it manages to size a wide range of unknown elliptical cracks including five cracks with the same length but different depth.

Along with the progress of theoretical model and process algorithms , a newly developed integrated robotic system as introduced in Fig 5 is designed by Hamed Rowshandel, et al. [12] in the interest of automatically locating and obtaining detailed information of rolling contact fatigue cracks by employing a novel combined threshold and signature match (CTSM) method. Graphical user interface made by C++ has been designed which serves as the core of the robotic system where all the real-time data process and decision-making take place. The detection process consists of dynamic part which is aimed at locating defects at a controlled speed between 4km/h and 20km/h while the static part takes responsibility for characterizing the defects [12].

Fig. 5. The developed integrated robotic system [taken from Ref. 12].

3.3. Inspection Techniques using EMATs

EMATs rules as an electromagnetic coupling mechanism that generates the ultrasound by passing a large current pulse through an inductive coil in close proximity to an electrically conducting or a magnetic material surface in the presence of a strong static magnetic field supplied by permanent magnet, electromagnet or pulse electromagnet, and detect within skin depth [13]. Relative components and the principle are shown in Fig. 6. The inspection allows for more reproducible generation and detection characteristic as the lack of physical couplant reduced the degree of variations in coupling condition. Instead, numerous parameters and complicated geometry lead to the complexity of the testing process.

Dixon, et al. [16] designed a lab-based laser-EMAT system in order to investigate the ultrasonic surface wave's generation, propagation and interaction on the rail head with a Michelson interferometer measuring the out-of-plane displacement. The Rayleigh-like wave generated by EMAT can flood the whole curve makes it capable to detect the gauge corner cracking. A suitable fixed distance between generation and detection transducers is suggested to ensure the Rayleigh-like signal is well separated from other wave modes. Crack depth gauging technique based on wideband Rayleigh waves in pitch-catch geometry and on rail track sample are also demonstrated [17]. Rosli [18] proposed a study for defect charactering both in depth and angel by analyzing the B-scans alongside the ratio of enhancement in the in-plane to the out-of-plane velocity components of a Rayleigh wave. Results of the study concludes that machine slots can't simulate surface crack because the transmission of the wave underneath a surface-breaking defect is affected by both the slot angle and depth, while under certain experimental conditions the technique is capable of characterizing surface cracks [18]. Acoustic nonlinearity related to fatigue damage accumulation was also studied [19].

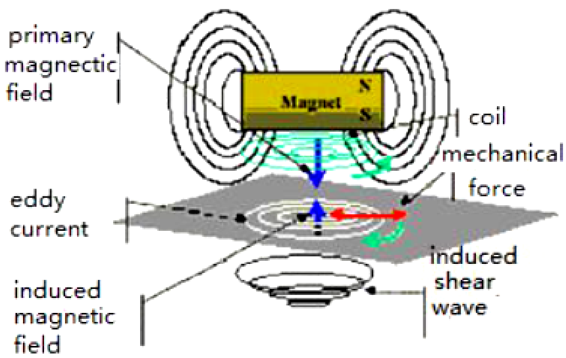


Fig. 6. EMAT components and principle [taken from Ref. 16].

EMATs technique has the potential to detect internal defects as different kinds of waves can be generated according to changing the folding shape of coil, magnetic field and drive mode. Tektrend (now NDT Olympus) in Canada [20, 21] designed an EMAT system called RailPro.

The commercial system can generate surface and bulk ultrasonic waves so as to inspect the entire rail and has been successfully examined on a sample track including transverse fissures, horizontal and vertical head splits, split webs, bolt hole cracking, and RCF damage at testing speeds between 5–9 km/h[20, 21]. A Russian company VIGOR designed a system as shown in Fig. 7 called UD-EMA-RWT-01M with 8 channels and 10 EMATs. Through reasonable configuration, the equipment can inspect head, web and foot of the rail at the same time without dead zone at the Speeds between 0.1-1 m/s [22].

Fig. 7. Scheme of carriages arrangement with EMAP [taken from Ref. 22].

3.4. Inspection Techniques using Hybrid System

As many advanced techniques applied for the rail inspection system, it brings about interests of improving reliable hybrid systems which is considered to be an inevitable methodology of rail inspection. Ministry of Chinese railway developed an inspection train GTC-80 incorporate multiple ultrasonic wheel probes with high definition linear array CCD that can achieve an inspection speed about 80 km/h. Ultrasonic wheel probes for each track consists of 15 transducers mainly take responsibility for internal defects. While the CCD routing inspection system realized automated identification of defects such as surface scratches, fastenings missing, malposed or fractured [23].

Another novel system developed by Interrail managed to inspect at the speed up to 48 km/h, comprises optical module scanning corrugation, rail head profile, missing parts, and defective slippers, ACFM module detecting and quantifying the severity of surface damages, ultrasonic phased array module assessing internal defects and high frequency vibration analysis [24]. Lift off variations limited the performance capability at a higher speed.

4. Conclusions

As an individual inspection method can't manage to perform efficiently and comprehensively under constantly acceleration of the train and increasing rail load conditions, it comes to be an inevitable trend to attach paramount importance to bring about dependable and innovative hybrid systems, whilst strive for improving unitary detection system. Apart from hybrid systems, the partly successful measurement system in application anticipates combination track monitoring with detection is a feasible and reasonable method which can seek out the undetectable defects and breakage occurrence through real-time monitoring so as to improve efficiency and accuracy of the testing. Assisting with maintenance procedure models and manufacturing process inspection, robust signal processing algorithm and effective data fusion combining techniques are playing critical roles in reliability and accuracy of the future detection system.

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