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Executive Summary

Nowadays, rails are systematically inspected for internal and surface defects using various non-destructive evaluation (NDE) techniques. During the manufacturing process rails are examined visually for any surface damage, while the presence of any internal defects is assessed mainly through ultrasonic inspection. Similarly, ultrasonic wheel probes have been extensively used by the rail industry for the inspection of rails in-service. Unfortunately, conventional ultrasonic wheel probes cannot reliably detect small (<4 mm) surface defects - particularly Rolling Contact Fatigue (RCF) cracks – in rails.

Despite the fact that several maintenance procedure models have been developed based on the rail damage present, their accuracy is not sufficient to eliminate the need for inspection. For that reason, the rail industry has invested considerably in the research and development of alternative NDE methodologies. The current international practice is to combine non-destructive evaluation of the rail network with preventative maintenance procedures, such as rail head grinding, in order to optimise the trade-off between maintenance cost and reliability.

Recently, hybrid systems based on the simultaneous use of pulsed eddy current probes and conventional ultrasonic probes have been introduced in Germany and elsewhere for the high-speed inspection of rail tracks. Pulsed eddy current probes are capable of accurately detecting RCF cracks of moderate size (~4 mm) and can operate at speeds of up to 72 km/h without significant variation in their performance. Nonetheless, eddy current probe performance is largely affected by lift-off variations, which means that certain surface defects can still be missed during inspection. For that reason extensive research is currently under way for the development of novel high-speed NDE equipment, involving high speed cameras, Alternating Current Field Measurement (ACFM) probes, Electromagnetic Acoustic Transducers (EMATs), Field Gradient Imaging (FGI), ultrasonic phased arrays, laser ultrasonics, and multi-frequency eddy current sensors. Some of the aforementioned methods, such as the ACFM, are already available for use by the rail industry but the inspection speeds currently achieved (~2 km/h) permit the quantitative inspection of only small rail segments, where damage is already known to exist.

This report comprehensively reviews non-destructive evaluation methodologies in use around the world for rail defect detection. This includes a detailed overview of non-destructive evaluation theory and the techniques used to incorporate condition data into maintenance procedures. It also presents a comprehensive overview of the current state-of-the-art in non-destructive evaluation of railways coupled with an extensive discussion of future developments and novel inspection methodologies in the field.

1. Introduction

Today, rail networks across the world are getting busier with trains travelling at higher speeds and carrying more passengers and heavier axle loads than ever before. The combination of these factors has put considerable pressure on the existing infrastructure, leading to increased demands in inspection and maintenance of rail assets.

The expenditure for inspection and maintenance has thus, grown steadily over the last few years without however being followed by a significant improvement of the industry's safety records. As a direct consequence the immediate key challenges faced by the rail industry are: a) the improvement in the safety of the railway system, b) the development of new railways to accommodate the continued growth in demand, and c) contributing to a more sustainable railway, in both environmental and financial terms, by delivering further efficiencies and exploiting technological innovation[1].

Rail flaw detection has an important part to play in ensuring the safety of the world's railways. Maximum reliability of the railway network can therefore be achieved only after sufficient and reliable inspection and maintenance of the rail network[2]. Figure 1demonstrates the risk of failure due to the propagation of a single crack in the rail head.

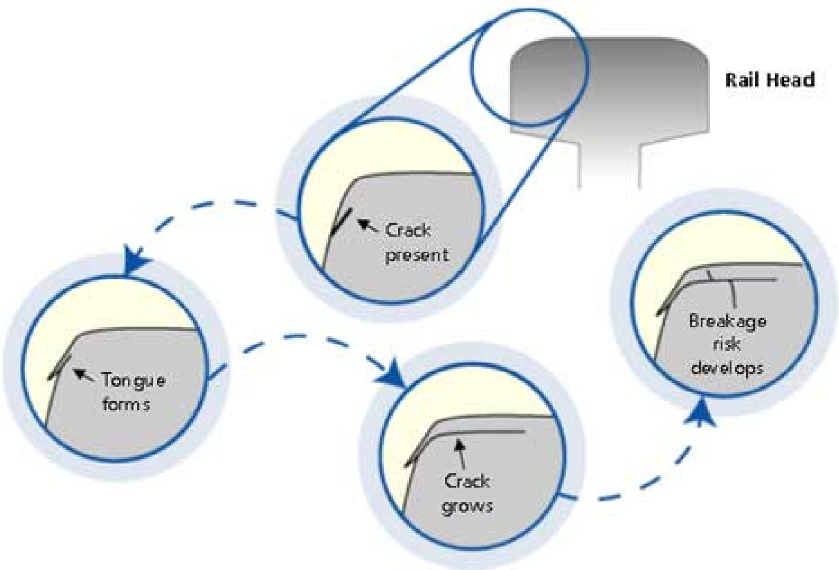

Figure 1 - Risk of failure due to crack propagation in rails.

Recent accidents caused by broken rails, such as the one that took place in Hatfield in October 2000, have focused industrial attention on the technologies that enable the detection of flaws in rail. The need for more reliable and improved rail flaw detection systems has increased further due to more stringent maintenance requirements levied by infrastructure managers (or their governing bodies)[2-3]. Figure 2 shows how a typical rail defect may develop.

Despite the fact that early rail flaw detection is of paramount importance for the safe and reliable operation of rail networks around the world, rail NDE technology has never received the funding required to practically eliminate rail fatigue failures. It appears that it is only when a serious accident takes place that funding becomes more readily available. The appropriate use of the limited funding is thus very important, and research effort should be directed for the development of new rail testing technologies in a coherent fashion.

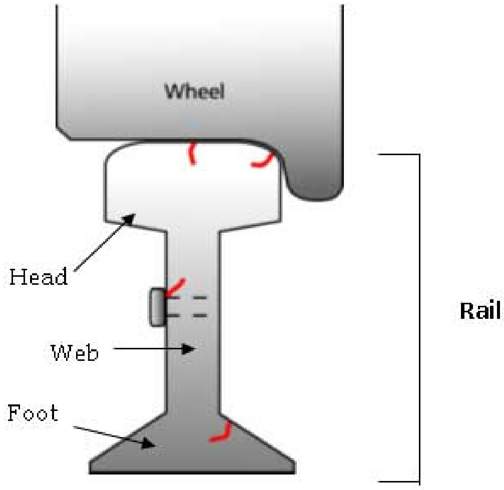

Figure 2 - Typical locations of defects in rails.

It should be noted that Figure 1 and Figure 2 show the possible crack locations in rails and not the actual crack directions.

The main issue in rail inspection from the industrial point of view is to develop improved inspection methods that will offer increased sensitivity to defects and higher resolution at increased inspection speed. On the other hand, the lack of qualified NDT engineers in other NDT technologies apart from standard ultrasonics makes the rail industry even more hesitant in taking the step to employ other NDT technologies.

The deficiency of current NDT methodology has been partly acknowledged by the rail industry through the general use of special grinding trains for rail maintenance. Grinding trains are employed systematically to machine down worn rails in order to remove surface damage in an early stage and ensure the geometry of rails[4]. Nevertheless, this type of practice does lead in a reduction in the overall operational lifetime of rails and does not remove the need for NDT inspection. For that reason, a considerable amount of research is currently under way to develop new improved steel grades for rail manufacturing that will be more surface-damage tolerant.

The majority of the technology development in rail flaw detection in the U.S. is currently undertaken by the rail testing service suppliers[4]. In a similar fashion this appears to be the case in Japan, Israel, Australia and Canada. However, in Europe the situation is slightly different, since the largest European rail network operators, namely Société Nationale des Chemins de fer Français (SNCF), Deutsche Bahn (DB) and Network Rail (NR), can demonstrate an active involvement in rail inspection research led by the academia and rail testing service suppliers.

The largest rail network operators have purchased their own test trains in order to perform rail inspections. Nonetheless, a significant number of operators still subcontract rail inspection of their networks to rail testing service suppliers. Existing rail testing trains achieve inspection speeds between 40km/h – 100km/h however, as the speed increases the system's sensitivity and resolution deteriorates significantly.

2. Non-destructive evaluation methods for rails

Rails are systematically inspected for internal and surface defects using various NDE techniques. During the manufacturing process rails are examined visually for any surface damage, while the presence of any internal defects is assessed mainly through ultrasonic inspection. Similarly, ultrasonic testing equipment has been extensively used by the rail industry for the inspection of rails in-service.

In most cases rail inspection is performed using special ultrasonic probes mounted on the undercarriage of the test train[5]. Sliding plate sleds or fluid-filled ultrasonic wheel probes are the common methods used to couple the piezoelectric transducers to the rail. Standard ultrasonic sensors have poor detection ability when surface-breaking or near-surface defects are involved. Therefore, multiple transducers need to be employed at various angles in order to allow detection of surface-breaking and near-surface defects as shown in Figure 3.

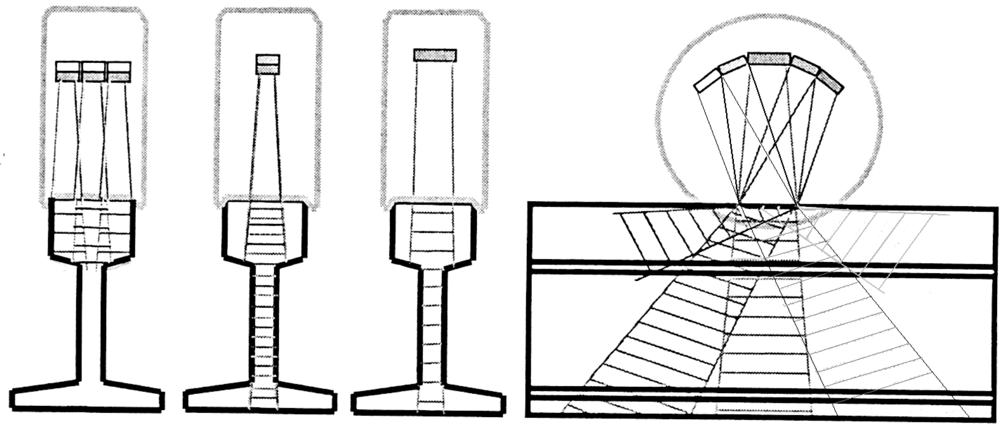

Figure 3 - Multiple ultrasonic transducers positioned at various angles in order to increase the overall detection capability of the system[6].

Magnetic Flux Leakage (MFL) testing is usually employed in certain Sperry models (100 and 900 series) for the detection of near-surface defects as complementary technique to ultrasonic testing[5]. The schematic in Figure 4 shows the principle of MFL inspection. The use of this technique is restricted at speeds below 35km/h as its performance deteriorates significantly at higher speeds.

More recently, hybrid systems based on the simultaneous use of pulsed eddy current (EC) sensors and conventional ultrasonic testing probes have been introduced in Germany, the Netherlands and elsewhere for the high-speed inspection of rail tracks. Pulsed EC sensors have a superior performance in comparison to ultrasonic testing probes when inspecting for near-surface or surface-breaking defects, such as Rolling Contact Fatigue (RCF), spalls and wheelburns. Pulsed eddy current sensors seem to offer a better proposition than MFL probes as they are more sensitive to near-surface and surface defects and can operate at significantly higher speeds (inspection speeds of up to 100km/h are possible)[7-12].

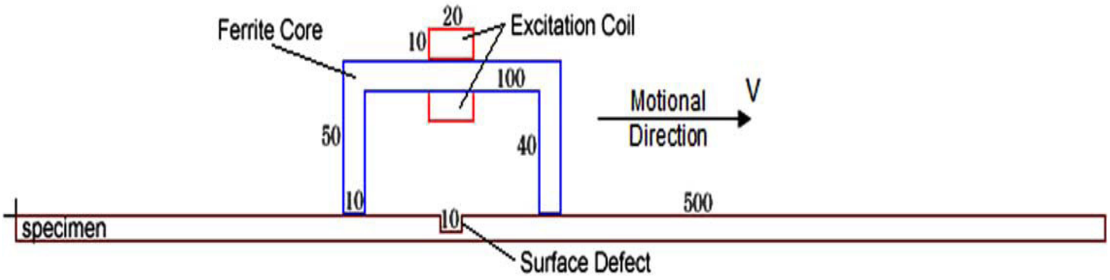

Figure 4 - Schematic showing the principle of MFL inspection.

However, eddy current sensors are strongly affected by lift-off variations and thus need to be positioned as close as possible and at constant distance from the surface of the rail head. Figure 5 shows an eddy current probe carrier used in the DB test train.

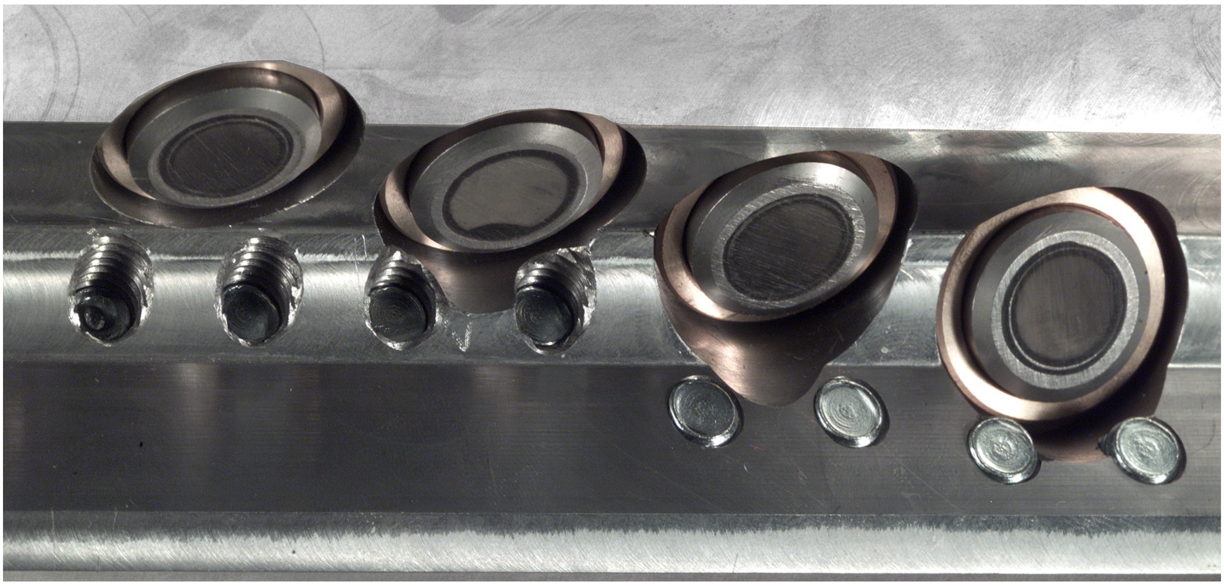

Figure 5 - The probe carrier with the eddy current sensors used by DB for the detection of RCF cracks (photo courtesy Deutsch Bahn).

Other NDE techniques that are currently under investigation for high-speed inspection of rails include laser-ultrasonics[13], Electromagnetic Acoustic Transducers (EMATs)[14-17], Alternating Current Field Measurements sensors (ACFM)[18-22], high-speed cameras[23], advanced multi-frequency eddy current sensors[24], Field Gradient Imaging (FGI)[25], high-resolution ultrasonic probes, ultrasonic phased arrays[26], and long range ultrasonics[27-28]. Most of these techniques have been already developed enough to be used in portable systems for the inspection of rails at lower speeds. Figure 6 shows a manual ACFM system employed for detection and automated quantification of RCF cracks on rails[21-22]. The sensor is being pushed by the operator along the rail head constantly looking for any changes in the signal caused by the presence of RCF cracks.

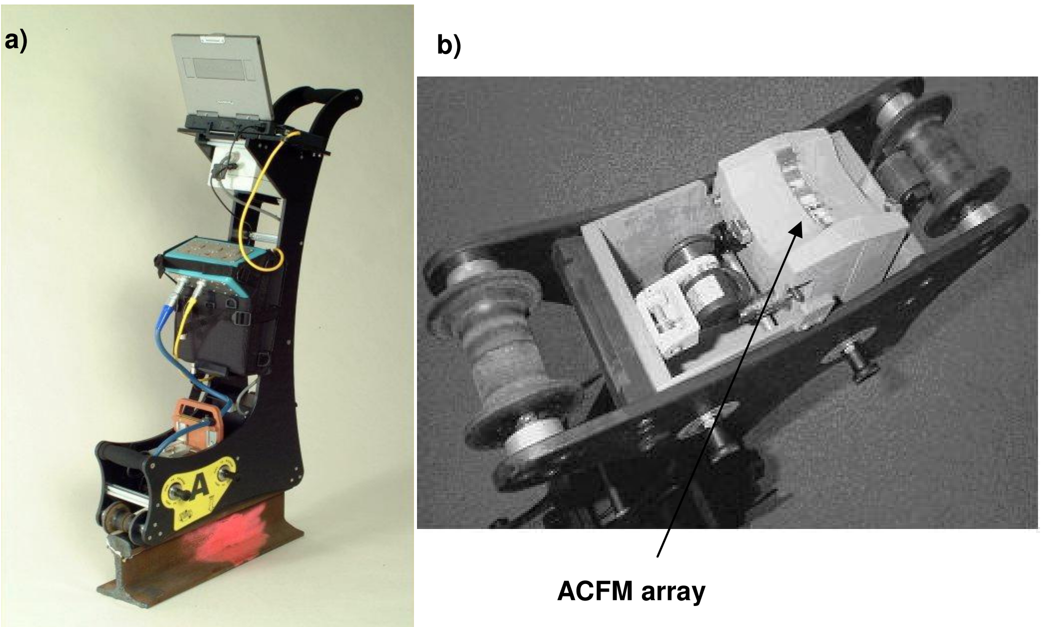

Figure 6 - a) The ACFM walking stick, b) the under-side of the ACFM walking stick.

In some cases high-resolution ultrasonic probes, laser-ultrasonics and EMATs have been loaded on hi-rail based vehicles that can achieve inspection speeds of between 20km/h and 35km/h[17]. Figure 7 shows an EMAT inspection system for automated rail inspection mounted on a hi-rail vehicle by Tektrend (now NDT Olympus).

Figure 7 - EMAT inspection system for automated rail inspection mounted on a hi-rail vehicle (Tektrend).

Some researchers have suggested the possibility of using long-range ultrasonics (guided waves) for rail inspection[27-28], however, it is doubtful whether this technique will ever find widespread application in the rail industry. Long-range ultrasonic methods were originally developed for the detection of corrosion and large cracks in long (up to 100m) pipe sections. The principle of this technique is based on the detection of reflected waves. The sensitivity of long-range ultrasonics systems is low since it can only detect relatively large transverse defects. Although, there is considerable research currently on-going in the field of guided waves, the research effort is mainly focused on the application of the technique for the inspection of pipes, off-shore structures, and wind-turbines. Figure 8shows a Waveinsolids hi-rail vehicle that uses long-range ultrasonics for the detection of transverse defects in the U.S.[27].

Figure 8 - Photograph of a hi-rail vehicle incorporating a long-range ultrasonics system for the inspection of transverse cracks.

2.1 Rail inspection using ultrasonics

During the inspection of rails using conventional ultrasonics probes a beam of ultrasonic energy is transmitted into the rail. The reflected or scattered energy of the transmitted beam is then detected using a collection of transducers. The amplitude of any reflections together with when they occur in time can provide valuable information about the integrity of the rail. Since defects are not totally predictable, the energy is transmitted at several different incident angles in order to maximise the Probability of Detecion (PoD) of any detrimental features present in the rail. The refracted angles generally used are 0, 37 or 45 and 70°. In addition, transducers are also positioned to look across the rail head for longitudinal defects such as vertical split heads and shear defects as previously shown in Figure 3[4-5].

In many countries, this technique is typically employed on Sperry trains (UTU1 and UTU2 models). The presence of detected defects by the UTU1 and UTU2 Sperry trains is confirmed through the deployment of portable ultrasonic inspection units known as Sperry Sticks[4-5]. Figure 9 shows a typical portable rail inspection unit.

Figure 9 - Portable ultrasonic rail inspection unit (Sperry stick)[4-5].

One of the original problems encountered with UTU1 was the too many “false” readings, each of which had to be investigated thus taking considerable staff time[4-5]. This has been partly addressed by setting more realistic detection thresholds and by a programme of comparing the train results with results from manual systems in order to refine the detection criteria. UTU2 has a greater probe array which enables wider ultrasonic coverage.

The probe array, which consists of 9 separate transducers, is contained within a liquid filled tyre, known as a Roller Search Unit (RSU). UTU2 has two of these units in order to ensure testing can continue should one RSU fail to function correctly. This is necessary as possession of the line for testing is already limited due to the demands on the system. The Sperry stick is a hand operated version of the RSU and is used as the manual method to check the output of both the ultrasonic trains. The comparison of results from unit UTU2 with those from the Sperry Sticks shows a 90-95% success rate of defect identification. A higher correspondence of results with this equipment has been achieved in the U.S. and further refinement of the system in the UK is underway in order to improve the success rate. UTU2 can run at speeds of up to 65km/h, however, for safety and accuracy the probes need to pulse the defect 4 times and so in practice they are operated at 45km/h. The equipment on the UTU trains does not size the defects. Currently the average distance completed in one night is between 150 and 210km.

Problems encountered by the UTU trains include:

- Very cold weather where ice interferes with testing by providing an intervening interface.
- Damaged rail where a sliver of rail can slice/puncture a tyre, which occurs on average once a week.
- Leaf mould, which drastically affects sensitivity of the probes.
- Sandite can be problematic as it provides an intervening interface.
- Heavily applied lubrication can affect results up to 100m from a trackside lubrication unit, which also produces an intervening interface.
- Identification of vertical/transverse defects.

Eurailscout[7-12] (Netherlands, Germany, etc.) and Scanmaster[29] (Israel) test trains use sliding plate sleds to accommodate the ultrasonic probes as shown in Figure 10. The Eurailscout test trains can incorporate pulsed eddy current probes in order to improve the system’s detection capability. These trains operate at a speed of 72km/h (inspection speeds of up to 100km/h are reported to be possible)[7-12].

Figure 10 - A five-sled arrangement shown lifted off the rail. Some of the sleds include two probes which allow a total of seven ultrasonic probes to be used. A four-sensor eddy current probe (not shown) can be similarly mounted[29] .

2.2 Rail inspection using magnetic flux leakage

Magnetic flux leakage method (MFL) is broadly used for NDE of structural components in the petrochemical, rail, energy and metal industries. In MFL, permanent magnets or DC electromagnets are used to generate a strong magnetic field in order to magnetise the ferromagnetic specimen under inspection to saturation. The magnetic flux lines are coupled into specimen using metal 'brushes' or air coupling. If there are any anomalies or inclusions, the magnetic flux lines will leak outside of the specimen close to the anomalies and the sensor or sensor array will detect the leakage magnetic field, which conceives information relating to anomalies or inclusions such as corrosions and cracks.

According to the distribution of magnetic flux lines coupled into the specimen, MFL systems that comprise magnetiser and sensors or sensor array are categorised into two types: (1) circumferential MFL excelling in detection and sizing of longitudinal defects; (2) axial MFL that is apt to volumetric or metal-loss defects with a significant circumferential extent or width. Both methods suffer from the probe velocity effect on MFL signals. It has been reported that velocity effects for circumferential MFL are more significant than for axial MFL and the speed at which probe velocity influences the circumferential MFL is much lower than that for axial MFL.

In rail inspection using MFL, search coils fixed at a constant distance from the rail, are used to detect any changes in the magnetic field that is generated by a DC electromagnet around the rail. In the areas where a near-surface or surface transverse defect is present in the rail, ferromagnetic steel will not support magnetic flux and some of the flux is forced out of the part. The sensing coil detects a change in the magnetic field and the defect indication is recorded[30].

Unfortunately, transverse fissures are not the only types of defects found in rail. Other manufacturing and service-related defects that can occur include inclusions, seams, shelling, and corrosion. Fatigue cracks can initiate from these defects, as well as normal features of the rail such as bolt-holes. If these defects go undetected, they can lead to rail head and web separations. Many of these defects are not detectable with the flux leakage method because the flaws run parallel to the magnetic flux lines or the flaws are too far away from the sensing coils to detect. MFL is mainly used by certain hi-rail and railbound Sperry vehicles as a complementary technique to ultrasonic inspection. The maximum speed achieved for the combined ultrasonic/MFL system is typically 35km/h[4-5].

In practice the following solutions are also realised:

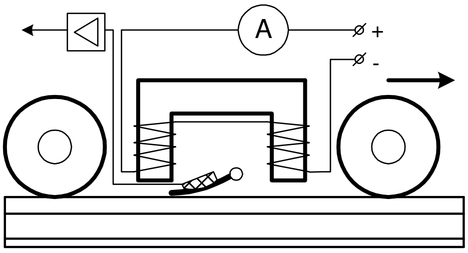

Figure 11 - U-shape electro magnetic (old solution)

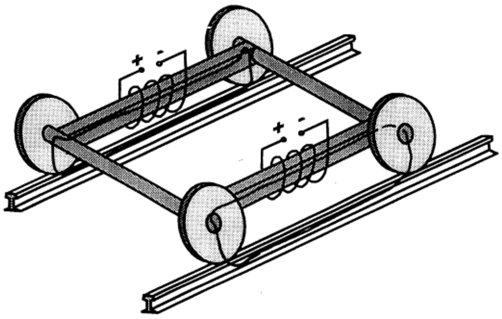

Figure 12 - Electromagnet on the frame of the measuring bogie (new solution first version). Disadvantage the small magnetic field.

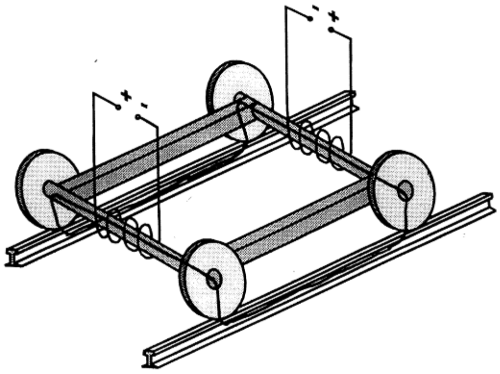

Figure 13 - Electromagnet on one axle of the measuring bogie. (new solution second version). Advantage: Big magnetic field.

2.3 Rail inspection using pulsed eddy currents

For several years, application of eddy current technology was limited for inspection of individual rail welds. More recently, eddy current systems were developed to perform inspections on rails at speeds of a few metres per minute in order to detect cracks due to Rolling Contact Fatigue. Figure 14 shows a manual eddy current system employed for detection of RCF cracks on rails and wheelburns. The sensor is pushed by the operator along the rail head who looks for changes in the signal caused by the presence of RCF cracks or wheel burns.

Figure 14 - EC sensor for detection of RCF cracks on rails (Hocking NDT).

As mentioned earlier, standard ultrasonics sensors have poor detection ability when surface-breaking or near-surface defects are involved. An eddy current sensor has a far better ability in detecting this type of defects. Nearly all relevant surface or near surface defects can be detected using eddy current inspection. Nonetheless, attention needs to be given to lift-off variations during eddy current inspection. Table 1 provides an overview of the detectability of eddy current sensors.

Category	**Detectability**	**Statement**
Head Checking	Very good	Quantity, location, depth
Indentures	Very good	Quantity, location, period
Wheel-burns	Very good	Location, extent
Grinding marks	Very good	Quantity, location, period
Rail joints	Very good	Location, kind
BelGroSpi's	Good	Quantity, location
Squats	Good	Quantity, location
Short/long pitch corrugation	Good	Location, period
Welds	Good	Location, Kind, Lack of fusion

Table 1 - Capability of eddy-current sensors in detecting various surface defects[11].

Significant developments in inspection of rails using eddy current technology have been reported by the German Federal Institute for Materials Research and Testing (BAM)[7-12].

The reported equipment was specifically developed for detection of RCF cracks and provides information on defect position and depth. At the moment this system is used in some rail test vehicles and manual rail test system in the Netherlands, Germany and elsewhere by Eurailscout.

To find specific positions of defects, a Global Positioning System (GPS) instrument is used in addition to the path data supplied by the train. The co-ordinates are saved as part of a fixed interrelationship with the measured data.

It is very important to guide the eddy current probes so that the signals are not influenced and the sensitivity does not fluctuate due to lift-off from the test surface. The rail inspection test situation is especially complex, since the probe has to be positioned at an angle relative to the guiding surface.

The first successful high-speed tests (72km/h) took place in a selected section between Magdeburg and Eilsleben in Germany (1999) were several areas with RCF cracks were known to exist. Near Magdeburg's main station remainders of RCF cracks were found in an approximately 800 mm long section of previously ground rails[7-12].

The indications detected by the Eurailscout test train were clearly confirmed during a manual inspection with an eddy current inspection trolley shown in Figure 15. The developed eddy current system has also been successfully incorporated on grinding trains to assess the quality of rail grinding[12].

Figure 15 - Manual inspection of rails with eddy current sensors (photo courtesy of DB).

2.4 Rail inspection using alternating current field measurement

Alternating Current Field Measurement (ACFM) is an electromagnetic inspection method which is now widely accepted as an alternative to magnetic particle inspection in the Oil and Gas Industry, both above and below water[18-22]. Although developed and patented by TSC Inspection systems initially for routine inspection of structural welds, the technology has been improved further to cover broader applications across a range of industries. Figure 16 shows the theory behind the operation of the ACFM sensor. Increases in inspection speeds (from a few centimetres per minute to a few metres per minute), application to non-planar crack morphologies and extension of sizing models to accommodate different crack types have all been achieved[20].

The technique is based on the principle that an alternating current (AC) 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. Because the current is an alternating current it flows in a thin skin close to the surface and is unaffected by the overall geometry of the component.

In contrast to eddy current sensors that are required to be placed at a close (<2mm) and constant distance from the inspected surface, a maximum operating lift-off of 5mm is possible without significant loss of signal when using ACFM probes. This is due to the fact that the signal strength diminishes with the square of lift-off, not with its cube which is the case for eddy current sensors. This enables the ACFM technique to cope with much greater lift-off and thicker non-conductive coatings. For larger threshold defects a higher operational lift-off (>5mm) is possible[22].

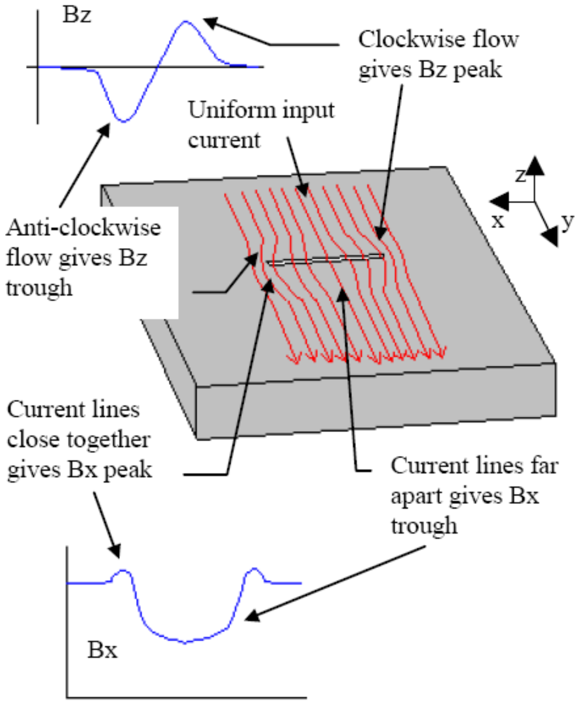

Figure 16 - Definition of field directions and co-ordinate system used in ACFM[20].

ACFM probes are available as standard pencil probes and multi-element array probes. These probes can be customised to optimise inspection of particular structural components and maximise the Probability of Detection (PoD) of critical-sized defects. ACFM pencil probes can detect surface-breaking defects in any orientation. Nonetheless, in order to size defects, they need to lie between 0°-30° and 60°-90° to the direction of travel of the probe. This drawback is overcome in ACFM arrays by incorporating various field inducers in order to allow a field to be introduced within the inspected surface in other orientations. This is particularly useful in situations where the crack orientation is unknown or variable. In this case, additional sensors, are also incorporated in order to take full advantage of the additional input field directions.

In 2000, TSC with the support of Bombardier Transportation, begun the development of an advanced ACFM system for application in the rail industry. The objectives of this effort were to develop a highly portable ACFM system, with friendly user interface capable of detecting, automatically sizing and thresholding defects for the inspection of train wheelsets. During initial tests on previously rejected train axles either due to failure on Magnetic Particle Inspection (MPI) or because of excessive surface corrosion, the developed ACFM system achieved an 84% PoD in comparison to 44% PoD for MPI. Following the experimental work on the train axles, it became evident that an ACFM system could be deployed to both detect and size RCF cracking on rails. This led to the development of a pedestrian-operated ACFM walking stick as shown earlier in figure 6. This is a totally self contained device and capable of 8-hour long independent operation[22]. The incorporated ACFM array has been shaped to conform to the shape of the head of the rail. This allows the application of the ACFM system in both new and worn rails. The inspection across the rail head is carried out by sequentially scanning across the group of sensors enabling the uninterrupted inspection of the rail. Based on the data acquired through extensive metallographic work on rails with RCF cracking, a customised software package incorporating the appropriate defect sizing algorithms has been developed in order to enable the automated sizing of the RCF cracks that are detected with the walking stick.

By increasing sampling rates to 50kHz the walking stick system achieved scanning speeds of 0.75m/s (approximately 2-3 km of rail can be inspected within an hour). It should be stressed that sufficient data must be collected to not only detect a defect but also to determine its severity. Further experiments are currently under way in an effort to develop a high-speed ACFM sensing system for the detection and quantification of RCF in rails in collaboration with the University of Birmingham.

2.5 Rail inspection using electromagnetic acoustic transducers

Electromagnetic acoustic transducers (EMATs) may be used to generate and detect ultrasound in an electrically conducting or a magnetic material. This is achieved by passing a large current pulse through an inductive coil in close proximity to a conducting surface in the presence of a strong static magnetic field, often provided by a permanent magnet. The orientation of the magnetic field, geometry of the coil and physical and electrical properties of the material under investigation have a strong influence on the ultrasound generated within the sample. EMATs have the advantage that they operate without the need for physical coupling or acoustic matching as it is an electromagnetic coupling mechanism that generates the ultrasound within the sample skin depth. This also means that the perturbation that physical coupling causes is insignificant, and operation at elevated temperatures is possible. EMATs are therefore suitable for rail inspection. Figure 17 shows the EMAT principle.

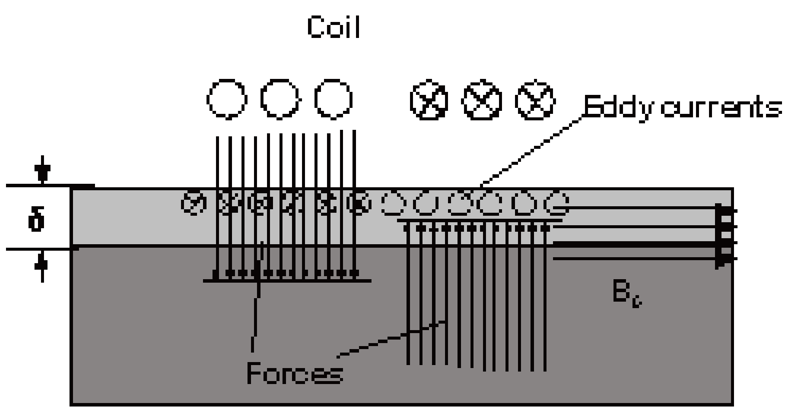

Figure 17 - Principle of electromagnetic acoustic generation

A commercial hi-rail inspection vehicle using an EMAT system has been developed by Tektrend (now NDT Olympus) in Canada[17]. The EMAT probes in the system function in the pulse-echo mode or in both the pulse-echo mode and the pitch-catch mode. Figure 18 shows the EMAT sensors deployment mechanism during rail inspection.

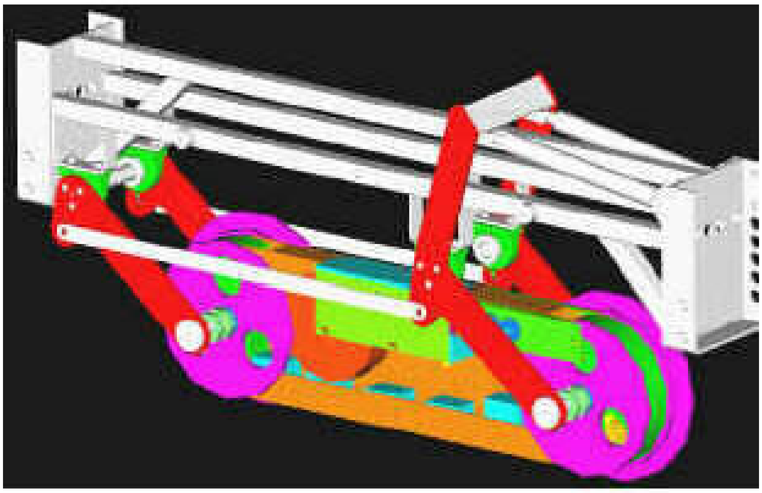

Figure 18 - Designed transducer carriage and holder.

Positioning of the transducers within this assembly was investigated to determine the design trade-offs required to optimise the inter-transducer spacing of pitch-and-catch pairs with respect to detectability, and to balance the magnetic forces of the EMAT probes. The pitch-and-catch mode requires a fixed distance separation between the receiver and emitter. The system contains two pitch-and-catch tandems, the Rayleigh waves pair and the 90° SH-wave (horizontal plan shear wave) pair. For the 90° SH-wave tandem used to inspect the railhead, a separation of 12" was established as the most effective. One single EMAT in the inspection tool is used to generate a 70° SH-wave and a 90° SH-wave. The same EMAT probe designed to generate the 90° SH- waves was configured to induce 70° SH-waves in the rail head. The two other EMATs, the 0° SH-wave radially polarized and the 35° shear wave, work independently. However, the transducers are separated with respect to the others to balance the strong magnetic attraction between the rail and the transducer, and to avoid overlap of echoes entering the receiving gates.

Each EMAT probe consists of a flat coil printed (wound or on a Kapton sheet) and a single or set of permanent magnets made of sintered Neodymium-Iron-Boron (NdFeB) stacked over the coil as shown in Figure 19. The magnet is shielded from the coil by a copper foil inserted between the coil and the magnet(s). A layer of foam material is also inserted to allow the coil to follow railhead surface irregularities. With a polymer tape, PCB material and foam, the magnet lift-off is about 2.5mm from the rail. When the coil is printed on the bottom side of the PCB material, coil lift-off corresponds to the polymer tape thickness of 0.2mm[17].

The data acquisition system has been designed to support 12 real-time acquisition channels. Each channel represents a high-power tone burst pulser/receiver card with adjustable voltage output (400-1800 Vpeak-peak). The receiver units on the system have excellent linearity, fast recovery form overload, and a good signal-to-noise ratio. Filters were also designed and manufactured to reduce the noise and to limit the high-end signal response[17].

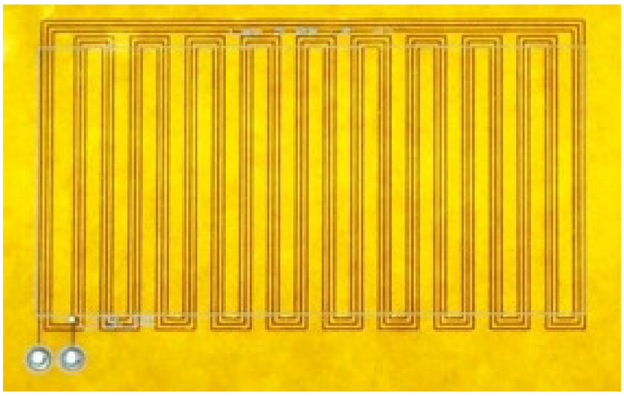

Figure 19 - Coil used for generation of shear vertical waves[17].

The detection capabilities of the system were assessed over the 45m long evaluation track at CN Taschereau Yard in Montreal. These tracks are specially designated for system test calibration and have been prepared with defects of various types, including horizontal split heads, bolt hole cracks, vertical split heads, defective welds, split webs, and bolt hole cracks. During these tests, different EMAT configurations were used to evaluate their detection performance from 10km/h to 15km/h.

Relevant work on EMAT sensor development for high-speed rail inspection is currently ongoing in the UK. The research effort is led by academic institutes (Universities of Warwick, Birmingham and Bristol) and supported by Network Rail[14-16]. The University of Warwick together with the University of Newcastle have also examined the possibility of applying a hybrid system involving the use of EMAT sensors and pulsed EC probes to increase the system's overall sensitivity on shallow cracks. Relevant research has also been on-going in Russia by NPP VIGOR[31].

2.6 Rail inspection using visual cameras

Until recently, visual inspection was carried out only by experienced personnel walking along the rail track and physically looking for defects. This potentially dangerous practice, although largely unacceptable due to the levels of subjectivity it involves, is still being employed by the infrastructure managers. Over the last few years however, various visual camera-based systems for railway applications have been implemented. These may be classified according to their functionality into four major groups: a) track inspection systems, b) train inspection systems, c) systems for maintenance and operation, and d) passenger related systems.

The concept of automated visual systems is based on the use of a high-speed camera capable of capturing video images of the rail track as the train moves over it. The captured images are then analysed automatically using customised image analysis software. Software analysis is based on identification of objects or defects detected using cross-correlation techniques while data are classified using a supervised learning scheme. Object recognition by using a learning-from-examples technique is related to computational issues. In order to achieve real-time performances the computational time to classify patterns should be small. When trying to detect smaller objects such as rail defects on the surface of the track the resolution of the captured video image needs to be higher in order to provide reliable data for analysis. However, as the resolution of the image increases, so does the amount of data acquired and hence more computational time is needed to complete the analysis. As a result the speed of the inspection needs to be adjusted to keep in pace with data analysis.

Automated visual track inspection systems can be used to measure the rail head profile and percentage of wear, rail gap, moving sleepers, absence of ballast, base plate condition in absence of ballast, pincers position, missing bolts and surface damage, including RCF and rail corrugation. The speed of operation of these systems can vary from 60 km/h to 320 km/h depending on the type of inspection carried out and the resolution required. For example, inspection for the detection of rail corrugation can be performed much faster than that for the detection of RCF cracking. Unfortunately, automated vision systems do not provide any information with regards to the presence of any internal defects and therefore cannot be used to substitute ultrasonic inspection.

SNCF in particular, operates a high speed camera inspection of its rail track network from its new “IRIS 320” car that can achieve speeds up to 320 km/h. These inspections are performed every 15 days to detect visual surface defects over high speed lines as well as high standard main line (speed ≥ 160 km/h). Figure 20 shows the principle of visual rail track inspection.

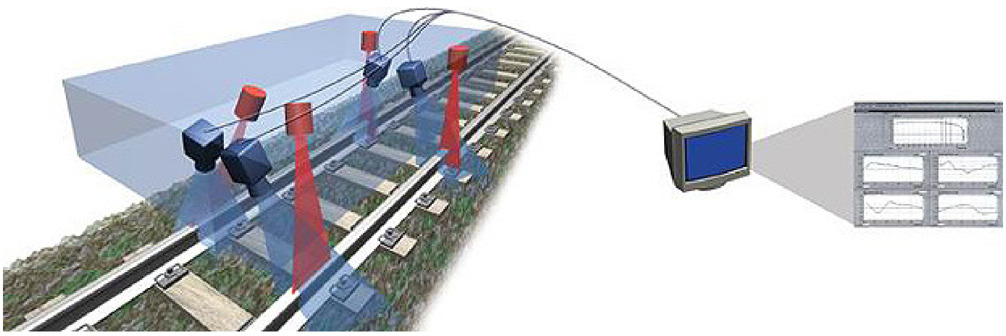

Figure 20 - Rail track inspection using visual cameras

2.7 Rail inspection using laser ultrasonics

Laser ultrasonic testing combines the sensitivity of ultrasonic inspection with the flexibility of optical systems in dealing with complex inspection problems. It works well in the testing of metals, composite materials, ceramics, and liquids. Its remote nature allows the rapid inspection of curved surfaces on fixed or moving parts. It can measure parts in hostile environments or at temperatures well above those that can be tolerated using existing techniques. Its accuracy and flexibility have made it an attractive new option in the non-destructive testing market.

Laser-based ultrasonics is a remote implementation of conventional ultrasonic inspection systems that normally use contact transducers, squirter transducers, or immersion systems. Laser ultrasonic systems operate by first generating ultrasound in a sample using a pulsed laser. When the laser pulse strikes the sample, ultrasonic waves are generated through a thermoelastic process or by ablation. As shown in the figure below, the full complement of waves (compressional, shear, surface, and plate) can be generated with lasers. When this ultrasonic wave reaches the surface of the sample, the resulting surface displacement is measured with the laser ultrasonic receiver based on an adaptive interferometer.

Transportation Technology Centre Inc. (TTCI) together with Technogamma in the U.S. developed the first laser ultrasonics system for rail inspection. Preliminary tests showed that the developed laser ultrasonic system can be used to inspect the entire rail section including rail head, web and base. The system is loaded on a hi-rail vehicle (shown in Figure 21) and can currently operate at speeds up to 32km/h. The optimum inspection speed however has been found to be between 8km/h and 15km/h[13].

Figure 21 - The TTCI-Technogamma laser ultrasonics hi-rail vehicle[13].

Due to the hazardous nature of the laser used a Nominal Hazard Zone (NHZ) needs to be established prior to inspections. The NHZ varies from 0.07m to 0.55m. During tests two different techniques are used to inject ultrasonic waves in the rail, a) point generation and b) line generation as shown in Figure 22[13].

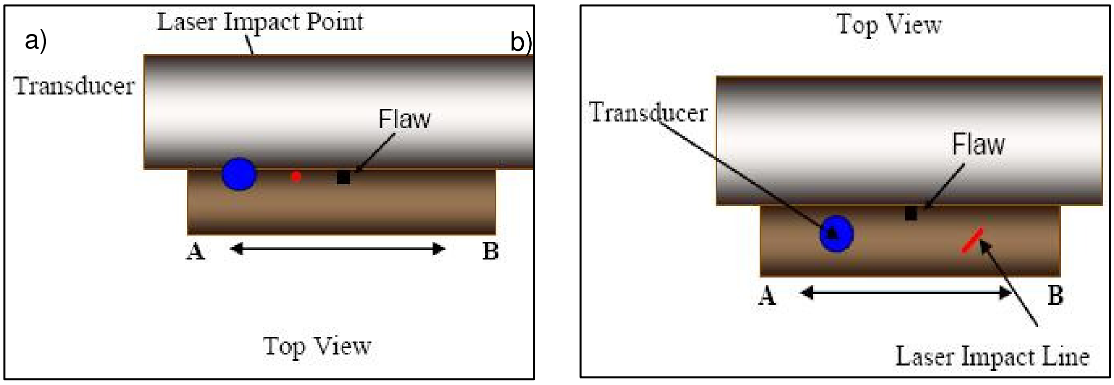

Figure 22 - Ultrasound generation using a) laser impact point and b) laser impact line[13].

It was found that ultrasound generation using laser impact line increases sensitivity and optimises the signal reception. However, it is still not clear how efficient the system is and it appears that there is still a lot of development needed.

2.8 Rail inspection using ultrasonic phased arrays

Ultrasonic phased arrays are a novel technique for non-destructive evaluation of structural components. Instead of a single transducer and beam, phased arrays use multiple ultrasonic elements and electronic time delays to create beams by constructive and destructive interference. As such, phased arrays offer significant technical advantages for weld testing over conventional ultrasonics. The phased array beams can be steered, scanned, swept and focused electronically. Beam steering permits the selected beam angles to be optimised ultrasonically by orienting them perpendicular to the predicted discontinuities, for example lack of fusion in automated welds.

Electronic scanning permits very rapid coverage of the components, typically an order of magnitude faster than a single transducer mechanical system. Beam steering (usually called sectorial or azimuthal scanning) can be used for mapping components at appropriate angles to optimise the probability of detection of discontinuities. Sectorial scanning is also useful when only a minimal footprint is possible. Electronic focusing permits optimising the beam shape and size at the expected discontinuity location, as well as optimising the probability of detection. Overall, the use of phased arrays permits optimising discontinuity detection while minimising testing time.

Research on rail inspection using ultrasonic phased arrays is currently ongoing in the U.S. (TTCI and Iowa State University), the UK (the Universities of Bristol, Warwick and Birmingham and TWI Ltd.) and France (Socomate). No practical systems involving ultrasonics phased arrays have been developed for high-speed rail inspection so far due to the problems that arise from the large amount of data that need to be analysed. The maximum inspection speeds currently achievable with ultrasonic phased arrays is approximately 5km/h[26].

A new in-parallel analysis concept (known as the Fast Automated Angle Scan Technique or FAAST) has been recently developed by Socomate to address the processing problem. The 128-channel system developed is capable of processing in real time, the data obtained from a multi-element probe in order to detect and characterise in one shot all reflectors inside the acoustic sound field of the probe. The system can achieve inspection speeds of up to 100km/h and has a control pitch of 4mm. The main inspection angles are -70°; -35°; 0°; +35°; +70°[32].

More recently, SNCF in collaboration CEA developed a phased array system to inspect arc welding repairs. This system will be used to inspect several hundred of arc welding repairs on the SNCF's high speed lines network by the end of 2007.

2.9 Rail inspection using long range ultrasonics (guided waves)

Long-range ultrasonics is an ultasonics testing (UT) technique based on transmitting ultrasound as volumetric waves along a structure such as a rail. Long-range ultrasonics may employ a range of wave modes Lamb, Plate, Rayleigh, but have become commonly known as the Guided Wave UT technique. Transducers are designed and placed so that the appropriate wave modes can be excited and transmitted in the structure. Reflections from fixed reference points, such as girth welds, can be detected as well as changes in cross sectional areas, such as cracks or corrosion. These reflections are recorded and analysed to produce information on the probability, approximate size and location of the reflections. This analysis requires suitable software in addition to trained and experienced personnel[28].

Long-Range Ultrasonics can be effective over distances up to 180m from the sensor array. However, various factors can significantly attenuate the signal to an extent that in some cases, the effective distance may only be a few metres. The wave mode and frequency selected determines the most effective inspection range. The techniques are generally sensitive to change in the cross-sectional area of the component. As such a 5% change in the cross-sectional area of the inspected structure is needed in order to produce an interpretable response indication.

Research in the field of rail inspection using long-range ultrasonics is currently on-going in the U.S., (The Pennsylvania State University), South Korea (Seoul National University of Technology) and the U.K. (TWI). A commercial guided waves hi-rail vehicle, known as Prism, has been produced by Wavesinsolids LLC in the U.S.

2.10 Rail inspection using multi-frequency eddy current sensors

Research in the field of multi-frequency eddy-current inspection of rails by the Universities of Manchester and Birmingham is still in the very early stages and only limited tests have been performed. However, early experimental results have shown that the technique has a strong potential of being used to detect and quantify near-surface and surface-breaking defects at high speeds[24].

2.11 Rail inspection using magnetic anisotropy and permeability systems (MAPS)

Most rail inspection technologies rely on detecting rolling contact fatigue at the early stages of propagation. Magnetic Anisotropy and Permeability System (MAPS) technology developed by AEA in the UK can be used to measure the residual stresses in the rail crown which has significant influence on the initiation and evolution of gauge corner cracking. Using this technology, the assessment of the residual stresses in rail can be measured and monitored. This would give an early indication of the onset of the cracking and thus preventative remedial action such as rail grinding can be undertaken. MAPS is a portable system with manual probe that can be manoeuvred over the rail with controllable penetration from 0.1 down to 5 mm[33].

Table 2 summarises of NDT techniques for the rail industry

NDT Technique	**Systems Available**	**Defects Detected**	**Performance**
Ultrasonics	Manual and high-speed systems (up to 70 km/h)	Surface defects, rail head internal defects, rail web and foot defects	Reliable manual inspection but can miss rail foot defects. At high speed can miss surface defects smaller <4mm as well as internal defects particularly at the rail foot
Magnetic Flux Leakage	High-speed systems (up to 35 km/h)	Surface defects and near surface internal rail head defects	Reliable in detecting surface defects and shallow internal rail head defects although cannot detect cracks smaller than <4mm. MFL performance deteriorates at higher speeds
Pulsed Eddy Current (including Field Gradient Imaging)	Manual and high-speed systems (up to 70 km/h)	Surface and near-surface internal defects	Reliable in detecting surface breaking defects. Adversely affected by grinding marks and lift-off variations
Automated Visual Inspection	Manual and high speed systems (up to 320 km/h)	Surface breaking defects, rail head profile, corrugation, missing parts, defective ballast	Reliable in detecting corrugation, rail head profile missing parts and defective ballast at high speeds. Cannot reliably detect surface breaking defects at speeds >4 km/h. Cannot assess the rail for internal defects
Radiography	Manual systems for static tests	Welds and known defects	Reliable in detecting internal defects in welds difficult to inspect by other means. Can miss certain transverse defects
Electromagnetic Acoustic Transducers	Low speed hi-rail vehicle (<10km/h)	Surface defects, rail head, web and foot internal defects	Reliable for surface and internal defects. Can miss rail foot defects. Adversely affected by lift-off variations
Long range Ultrasonics	Manual systems and low-speed hi-rail vehicle systems (<10 km/h)	Surface defects, rail head internal defects, rail web and foot defects	Reliable in detecting large transverse defects (>5% of the overall cross-section)
Laser Ultrasonics	Manual and low-speed hi-rail vehicle systems (<15 km/h)	Rail head, web and foot defects	Reliable in detecting internal defects. Can be affected by lift-off variations of the sensors, difficult to deploy at high speeds

NDT Technique	Systems Available	Defects Detected	Performance
Alternating Current Field Measurement	Manual systems (hi-speed system under development)	Surface breaking defects	Reliable in detecting and quantifying surface breaking defects. Cannot detect sub-surface defects. Very good tolerance to lift-off variations
Multifrequency eddy current sensors	Manual system. Static and slow speed.	Surface and near surface defects.	Limited experiments conducted. Has potential to reliably quantify defects detected.
MAPS	Manual system. Static and walking speed tests	Residual stresses	Results comparable to X-ray diffraction. Commercially available.

Table 2 - NDT techniques for the rail industry

3. Non-destructive evaluation techniques used around the world

The summary below can be used as a reference by the engineers in the field of rail inspection who wish to know of what equipment is currently available or being researched and where.

3.1 Network Rail, Ultrasonic Rail Testing

Country of Origin/Organisation: United Kingdom, Network Rail.

Category: Handheld ultrasonic rail flaw detection, automated ultrasonic rail testing unit (UTU).

Description:

Network Rail (NR) carries out rail inspection using the ultrasonic methods as described in Railtrack Line Specification RT/CE/S/055. NR uses both the man operated 070 portable equipment (shown in Figure 23) and the ultrasonic test unit vehicle (Figure 24).

Figure 23 - Ultrasonic Rail Flaw Detection (URFD) equipment.

Figure 24 - Network Rail Ultrasonic Test Unit

The portable ultrasonic shear wave testing unit (walking stick) holds a 9-channel roller search unit.

Network Rail is running a new ultrasonic test unit (UTU 5) with support given by Sperry and First Engineering. The UTU 5, using Sperry ultrasonic track inspection technology is faster, more efficient and reliable than conventional manual ultrasonic methods. The use of a train-based system gives a 40% improved performance and reliability, and a great reduction in broken rails. The Sperry UTU 5 ultrasonic test unit is a rail-road vehicle that tows along a Roller Search Unit (RSU). The liquid-filled tyre on the RSU contains nine individual transducers which combine to give ultrasonic inspection at different angles (directions). The detection capability of this device is maximised by the use of pre-determined ultrasonic beams for the detection of specific defects. The output is displayed as a B-scan, allowing the inspector to identify and classify the signature of defects on the track easily. The data, tagged with the railway mileage and GPS location, is transmitted back to Sperry's Derby office via wireless link, where it is further analysed. The RSU tyre conforms to the shape of the rail surface even on worn and deformed rail, giving more reliable inspection of rail head and bolted joints.

Ultrasonic Inspections as outlined in

- U1 Testing of Fish-plated Rail Joints
- U2 Testing of Rails not covered by U1 & U3
- U3 Testing of Full Rail Sections using 070 Rail Testing System
- U4 Crack Size Estimation in Rolled High Manganese Steel
- U5 Examination of Squats & Inspection of Rail Head Repairs
- U6 Testing for lack of fusion of Alumino Thermic Welds
- U7 Rail Measurement
- U8 Confirmation & Examination of Vertical Longitudinal Defects
- U10 Testing of Adjustment Switches (remedial grinding service available)
- U14 Detection & Sizing of Gauge Corner Cracking

In current practice, procedures U3 and U14 are employed to detect rolling contact fatigue cracks (gauge corner cracking) on the rail.

These procedures, however, do not report the defect sizes and precise location of rolling contact fatigue cracks. Only cracks within a certain angular range (15-25^{o}) from the vertical in either direction can be detected reliably using these techniques, shallower cracks (less than 5mm in depth) and cracks near to the gauge corner are unlikely to be detected. On the other hand, rolling contact fatigue cracks tend to occur in cluster and thus some deeper cracks can still be detected using these procedures. However, speed of inspection is the major set back for these techniques, as a track inspector with the 'walking stick' can only cover a small section of track a day.

3.2 'Pitch & Catch' EMATs

Country of Origin/Organisation: Canada – Tektrend, United Kingdom - Universities of Warwick, Birmingham and Bristol.

Category: EMATs, Non-contact NDT, couplant-free

Description:

Traditional ultrasonic rail testing systems are based on the pulse-echo method where reflections from defects are stored and analysed. A single ultrasonic transducer is used to transmit a short longitudinal ultrasonic pulse along the rail, and the same transducer will also act as a receiver to detect the reflected signal. However, this technique suffers from the inherent 'dead-time' caused by the finite pulse length before the transducer can start to received the reflected signal, and thus it is unable to detect near-surface defects. Earlier research has shown that low-frequency Rayleigh waves can be used to detect gauge corner cracking. High frequency ultrasonic, typically at 2.4MHz requires a separation distance of 2.5 mm between the magnet and the rail, and 0.2 mm for the inducing coil. Using low frequency ultrasonic, the distance can be further increased and thus enable the transducers to be fitted on a moving train.

Pitch-catch low frequency ultrasonic transducers (EMAT) use guided wave mode (similar to the classical Rayleigh surface waves) that propagate along the surface of the rail, penetrating to a depth of 2-15mm. The generated wideband surface wave is used to gauge the depth of the crack, by comparing the surface wave at a particular frequency that pass underneath the crack with the wave propagate through a defect free region.

3.3 North America - Sperry Rail Service Ultrasonic and Induction Cars

Country of Origin/Organisation: North America, Sperry Rail Service

Category: Ultrasonic Portable Rail Detector (PRD), Ultrasonic Roller Search Unit (RSU), Ultrasonic Testing Unit/Car.

Description:

Federal Railroad Administration (FRA), Office of Safety established a fundamental rail inspection standards and requirements for North America. The Association of American Railroads (AAR) and FRA are continuously developing new detection techniques and technologies, understanding the defect occurrence and characteristics, setting the standards and defect remedial action criteria to control the defects in track. In North America, the three major contractors for rail road inspection are Harsco Track Technologies, Sperry Rail Services and Herzog Services. The majority of the rail road vehicles used for rail testing use ultrasonic technology to achieve the purpose, however, the larger rail car units incorporate magnetic induction probes as well.

Sperry Rail Service testing cars are capable of speeds up to 65km/h in continuous operation manner. However, inspections are normally carried out at a speed of 45km/h for optimum performance. In practice, the vehicle stops regularly when a defect or a cluster of defects are detected to visually or manually verify the results reported by the rail testing car. The stopping and verification process result in an inspection speed of 10 to 14km/h on average. The system is capable of detecting rail defects in the longitudinal and the transverse direction[34].

Below are the specifications of the rail testing cars. These vehicles employ induction and/or ultrasonic testing while carrying out rail inspection. There are several different vehicle combinations as shown inFigure 25, namely:

- 100 series: Ultrasonic / Induction rail-bound cars (Chase possible)
- 800 series: Ultrasonic road rail cars (Chase possible)
- 900 series: Ultrasonic / induction road rail cars (Chase possible)
- 400 series: High speed ultrasonic
- 200 series: High speed ultrasonic

For the first three series the testing speed is generally kept around 15–25km/h. The 200 series can achieve a speed of 45km/h. These cars are equipped with Roller Search Unit (RSU), where the results are displayed on B-scan based diagram, replacing the conventional strip chart based display. Mathematical algorithms have been developed to reduce the data presented for interpretation purpose.

Most common defects in North America are transverse defects, weld defects and vertical split head defects. Since the introduction of hi-rail platform fitted with ultrasonic and induction detection transducers, there has been 50% reduction of instances rail head defect failures, detecting defects before failures and 60% in testing speed.

Figure 25 - Sperry rail services ultrasonic testing cars and railway vehicles.

Sperry Rail have developed complementary testing techniques where both ultrasonic and induction methods are used for the testing of rail flaws.

- **a. Magnetic Flux Leakage:** A high current is sent to the railhead, and the rail essentially forms part of an electrical circuit. When the current encounters a defect, the current will travel around the defect and hence distortion can be detected through a block of receivers that detects the disturbances of the magnetic field. The induction technique covers the rail head fully, including the surface, corners and fillets, thus it is able to detect difficult to detect defects such as detail fractures in the gauge corner of the railhead. Also, without the use of couplant, this technique is also suitable for testing during low temperature.
- **b. Ultrasonic:** An ultrasonic beam is sent to the rail and defects can be detected by analysing the signal spectrum received by a single or an array of transducers. Performing signal processing on the reflected ultrasonic signal (amplitude and frequency), the characteristics of the defect (e.g. crack depths and lengths) can be reliably predicted. Ultrasonic signals are sent to the rail at different incident angles (0°, 37.5°, 45°, 70°) to provide wider coverage of defect detection on the railhead, web and rail foot/base. The ultrasonic transducers are housed in fluid filled membrane measurement wheels, with three to six transducers per wheel. There are two wheels per rail, with 0°, 45° and 70° transducers mounted in the 'forward' and 'backward' positions. A slightly different configuration is the use of 0°, 37.5° and 70° transducers, oriented towards the centre, field and gauge side. A more complete configuration uses 18 ultrasonic transducers per rail to find vertical split head and under-shell defects. Under extreme low temperature condition, a special low temperature couplant is required.

Sperry rail also develops a portable rail detector (PRD) unit that contains nine ultrasonic transducers operating at 2.25MHz. A water tank is fitted on the tray to provide the couplant which is fed to the Roller Search Unit (RSU). The output is displayed in the form of A-scan.

3.4 EURAILSCOUT UST-96 & UST-02

Country of Origin/Organisation: Germany, France, Netherlands - Deutsch Bahn, SNCF, Netherlands Railways, EURAILSCOUT.

Category: Eddy current & Ultrasonic rail inspection car

Description:

The EURAILSCOUT UST-02 shown in figure 23 combines two different techniques, an ultrasonic and an eddy current measuring system. Both systems allow comprehensive analysis of through sensory registration, data processing and evaluation. A summary of both systems is provided below.

Eddy current measurement system

EURAILSCOUT UST-02 uses the eddy current measurement system shown in figure 24 to detect the defects near the surface in the running-edge area of the rail. This data is often used for the planning of rail grinding and assessment of the quality of the work. This system covers an area of approximately 0.2 to 25 mm on the running edge of the rail, using four sensors on each rail. Each rail measurement unit also has a four-channel eddy current probe wired to a data acquisition unit that allows data storage and evaluation. Incorporating the D-GPS (Global Positioning System), tacho encoders and special markers (on the track), the defect locations can be located accurately.

The eddy current probes are guided independently of the ultrasonic measurement head transmitters so as to allow the probes to follow the wear profile of the rail being scanned. An easy classification of head-checks according to the Network Rail Standard can be achieved using this system. In addition to the classification, a report on the depth of the head-checks can be obtained from the recorded amplitude of the eddy current signals. By taking into consideration the initiating crack angles, a crack depth of approximately 2-3 mm can be measured.

The system allows for an automated rail inspection without the interference of operators. As the measurements are being recorded and analysed in real time, a supervisor can easily monitor and assess the quality of the inspection. A report containing the defects is generated at the end of the run.

Ultrasonic measurement system

The Ultrasonic Measurement System built into the third generation UST 02 has the following features:

- The doubling of the ultrasonic examining channels to 32 units from the older generation, UST 96,
- The possibility of online processing of the data, and a theoretical measuring speed of 100 km/h.
- Real-time classification of the defects detected.
- The possibility of remote supervision of the systems using GPRS and UMTS / 3G technology.

The real time processing of ultrasonic measurement data requires data such as track profiles, distance travelled along the track and detected track defects are summarised to form clusters. These clusters are then further evaluated and classified, partly automatically and partly manually by the ultrasonic examiner on the rail examination train.

The detection of vertical cracks and squats in the rail-head is made possible by the integration of a second measuring bogie in the UST 02, the expansion of the ultrasonic probes to 32 units, as well as the use of new additional ultrasonic examining-heads.

The number of real-time markers (used for communication between the different measurement systems) has been increased to 32 units. Other real-time markers such as tunnels, switches or railway crossings are manually submitted by the vehicle driver. These markers are mainly used for data synchronisation between difference runs, and different measurement systems.

Figure 26 - EURAILSCOUT UST 02 Eddy Current and Ultrasonic Measuring Train (courtesy of DB)

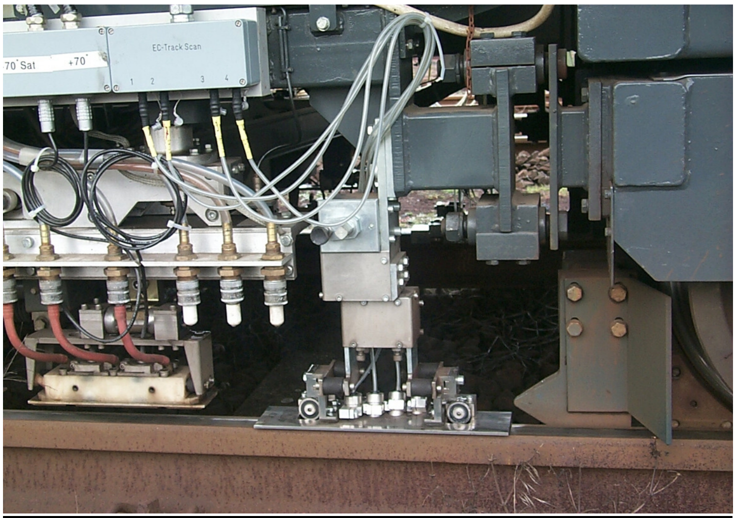

Figure 27 - The Eurailscout eddy current probe holder is seen in the middle (photo is courtesy of Mr Ronald Krull, Deutsche Bahn AG)

3.5 EVS-ScanMaster SFB-50 and SFB-100

Country of Origin/Organisation: Israel – Israel Railway, Deutsch Bahn AG - EVS-ScanMaster.

Category: Ultrasonic rail inspection car

Description:

A high-speed ultrasonic test train is also provided my EVS-ScanMaster (IRT) Ltd used by Israel's Railway. The Scanmaster SFB-100 can achieve inspection speeds of up to 100km/h and it can test the railway track in 250km long segments. SFB provides automated assessment of the defects detected with a resolution of 6mm at 90km/h. The SFB-100 uses six ultrasonic transducers for each rail with transducers oriented in 4 main angles, 0°, ±35°, ±70° and 90°

3.6 Tokimec Ultrasonic Rail Inspection Car & Ultrasonic Rail Flaw Detector

Country of Origin/Organisation: Japan, Tokimec Rail Techno Inc.

Category: Ultrasonic

Description:

Tokimec Rail Techno Inc. has a wide range of ultrasonic products for rail flaw detection. These include ultrasonic rail inspection cars shown in Figure 28, ultrasonic rail flaw detectors seen in Figure 29, and a portable ultrasonic rail flaw imager shown in Figure 30[35].

a) Ultrasonic Rail Inspection Cars URIC

The Tokimec internal flaw inspection cars detect rail defects as they travel along the track. Supported by the distance measurement system, this system is able to provide the precise location where the defects are on the track. In addition to flaw detection, the vehicle also incorporates a sectional wear measurement using image processing technology and rail corrugation measurement using lasers. The system is capable of conducting inspection at speeds up to 40km/h. The scanning results are presented in B-scan, alongside information on defect type, classification and position data. Data storing and playback enable evaluation and distinguishing a real defects from 'natural' defects such as bolt holes. In addition, A-scan display in real time is also available.

Figure 28 - Tokimec Ultrasonic Rail Inspection Car 'URIC'

b) Ultrasonic Rail Flaw detector - 'PRD-100A', 'PRD-100B'

The ultrasonic rail flaw detector 'PRD-100' is a flaw detection imager on a cart which is hand-driven. The scanning output is displayed in a cross-sectional B-scan. Two models are available, namely: Search Unit (Probe) (i) PRD-100A - Angle beam (45° front, 45° rear, 70°), straight beam (0°). (ii) PRD-100B type – Angle beam (special angle for corrosion detection, 45° front, 70°), straight beam (0°).

This device has a videocassette recorder that acquires continuous recordings of the detection image, along with the operator's comments by means of a microphone connection. The video image captured can be printed or downloaded to a personal computer for further analysis.

Figure 29 - Tokimec Ultrasonic Rail Flaw Detector

c) Portable Ultrasonic Rail Flaw Imager - SM-2R

The SM-2R is a portable ultrasonic flaw imager. The SM-2R outputs "B" mode ("B" scope) display (cross-sectional display) and "A" mode ("A" scope) display for ultrasonic digital flaw images.

The defects on the rail are displayed with a B mode cross-sectional colour image. Three types of probe at different angles (0°, 45° and 70°) can be switched intermediately to display different type of defects shown in Figure 31.

Figure 30 - The SM-2R portable ultrasonic flaw imager "Sonor Checker"

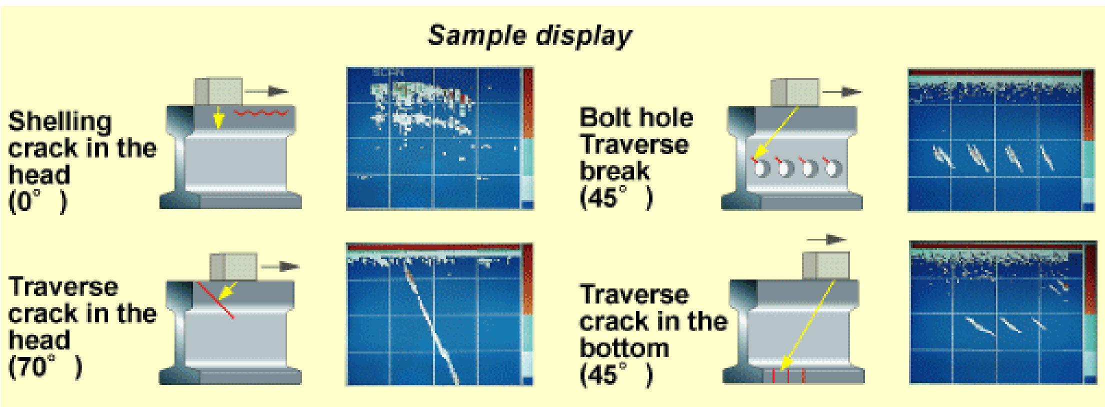

Figure 31 - Probes angled at 0°, 45° and 70° displaying different defects

3.7 Société Nationale des Chemins de fer Français (SNCF) Ultrasonic Inspection Train

Country of Origin/Organisation: France, SNCF & INRETS (French National Institute for Transport and Safety Research).

Category: Eddy current, Ultrasonic

Description:

SNCF operates the ultrasonic inspection train that is capable of scanning both rails at speeds of up to 50km/h. Figure 32 and Figure 33 show the SNCF ultrasonic inspection train, and the ultrasonic probes mounting. On each side of the rail, three ultrasonic probes (one vertical probe looking for longitudinal cracks, two angled probes looking for transverse cracks) are triggered at constant space, governed by the running speed of the train. This is as illustrated in figure 31. One of these inspection trains will be replaced in 2008 by purchasing an US 6.1 Speno car. SCNF test trains are periodically calibrated on a test site which is equipped with rails affected by known and referenced defects.

Figure 32 - SNCF ultrasonic inspection train

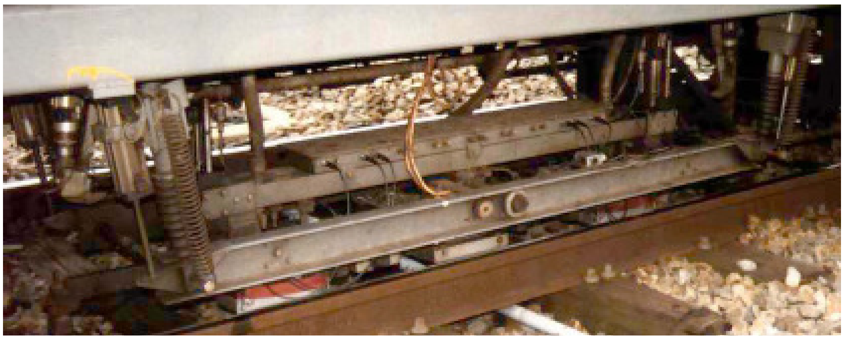

Figure 33 - Ultrasonic probes mounting

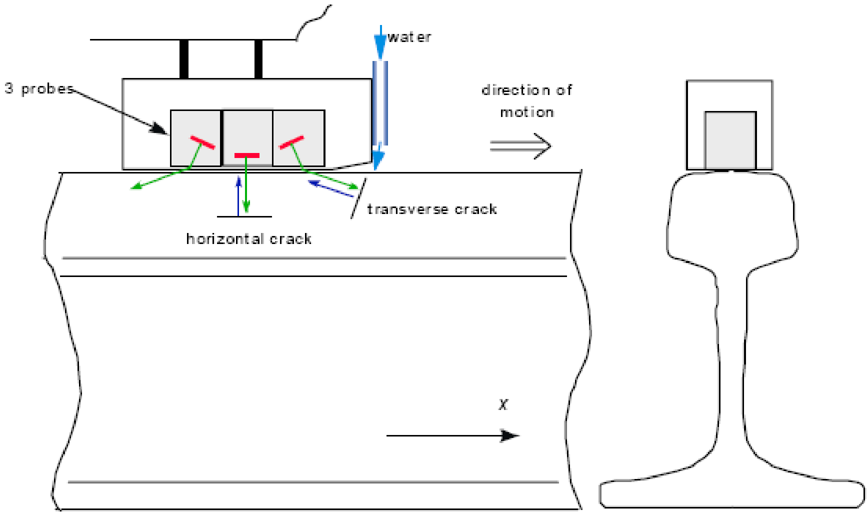

Figure 34 - Three ultrasonic probes, vertical probe for horizontal/longitudinal cracks detection, angled probes for transverse cracks detection.

3.8 Speno International – Geneva, Switzerland

Country of Origin/Organisation: Switzerland, Speno International S.A.

Category: Ultrasonic rail inspection car

Description:

Speno International offers ultrasonic rail testing vehicles for sale and contract hire in Europe. The ultrasonic vehicle, US 6-1 inspection car shown in Figure 35, uses ultrasonic probes at the following angles to detect the rail internal defects:

- 0° for detection of horizontal cracks (covers rail head, web-head fillet radius, web-base fillet radius).
- 30° for longitudinal-vertical cracks
- 35° for bolt-hole cracks.
- 70° for transverse railhead cracks.

Figure 35 - Speno US 6-1 Ultrasonic Rail Testing Vehicle.

The testing trolley on a US 6-1 is mounted underneath the test vehicle, and consists of two sliding shoes that house the ultrasonic rollers and feeler wheel. The feeler wheel is maintained in permanent contact with the gauge face of the railhead by pneumatic actuators. These frames can be lifted automatically when the test vehicle travels over switches and crossings. Water is injected between the probes and the running surface of the rail to ensure good coupling of transmitted ultrasonic waves and the reflected signal. A set of dummy wheel steel probes are installed in front of the measuring probes to clear the 'path' and displace any obstacles that may impede the measurement operation. The test vehicle is also equipped with an automatic probe position system that aligns the slide shoe probes with the longitudinal axis of the rail so as to minimise the effects due to changing rail profile, wear and curvature.

The testing car also records the distance travelled using a pulse generator, where as proximity detectors are used to indicate the type of rail component (either pearlitic rail steel or the non-magnetic austenitic manganese steel. Infrared and ultrasonic sensors detect the fishplates at rail joints. The signal from ultrasonic probes are analysed in real time, and when a defect is detected, the electronic signature/pattern of the signal is recorded and a paint spraying gun is used to mark the location of the defect. This test vehicle has an average testing speed of 60km/h.

3.9 Banverket (Sweden)

Country of Origin/Organisation: Sweden, Banverket

Category: Ultrasonic test train and handheld device.

Description:

Banverket of Sweden uses both manual and automatic ultrasonic technique for rail testing. Manual testing involves a ultrasonic transducer trolley pushed by an operator, who is able to cover 4.5 to 7km per day. Automated testing is achieved by an ultrasonic test train covering a distance of 150 to 300km per days. Defects found by the test train are frequently followed by manual inspection to further verify the result. The equipment use generally have a 0° probe to cover the railhead to the rail foot for horizontal defects, where as the probes angled at 70° check for transverse defects. Ultrasonic waves in the frequency range of 2 to 4MHz are often used.

3.10 MÁV Co's rail diagnostic train

Country of origin /organisation: Hungary/ MÁV Central Rail and Track Inspection Ltd

Category: Ultrasonic measurement, video inspection

Description:

MÁV Central Rail and Track Inspection Ltd operates such a rail diagnostic measuring train, which is able for the ultrasonic inspection of the rails, for measurement of the rail profile, and rail corrugation at the same time.

Figure 36 - MÁV Co's rail diagnostic measuring coach (in the middle)

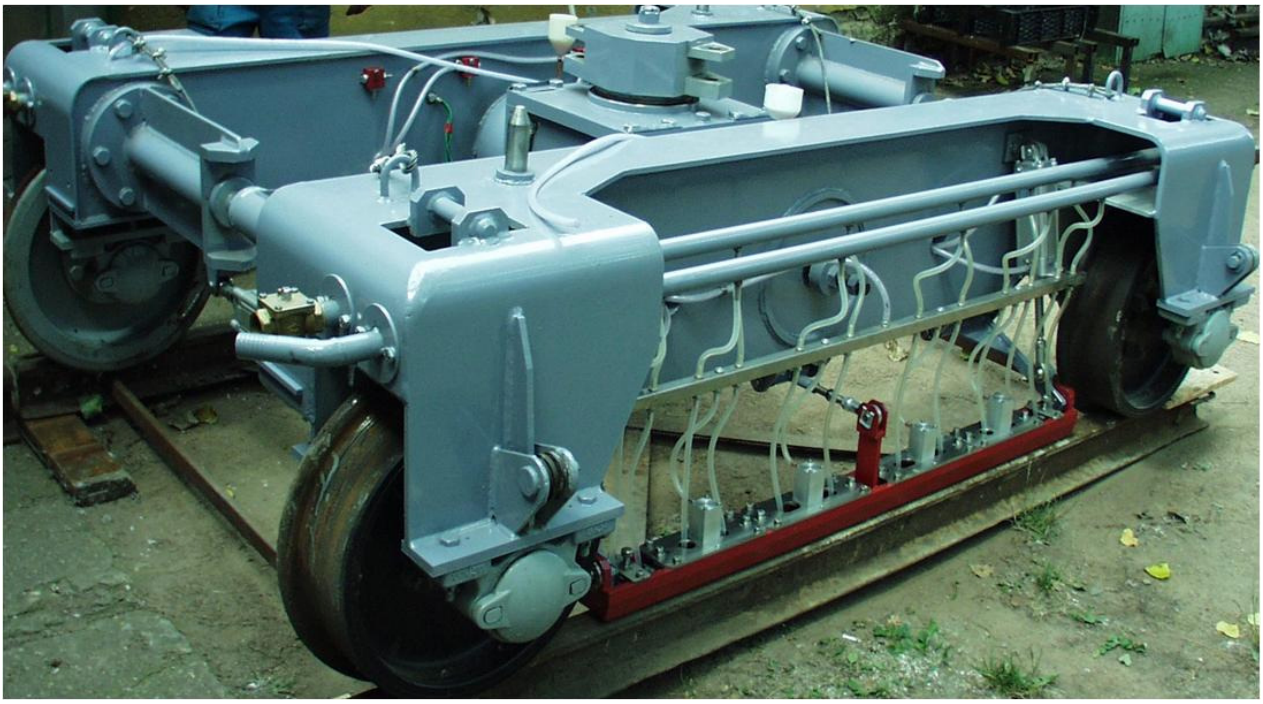

Figure 37 - Special measuring bogie for ultrasonic rail investigation

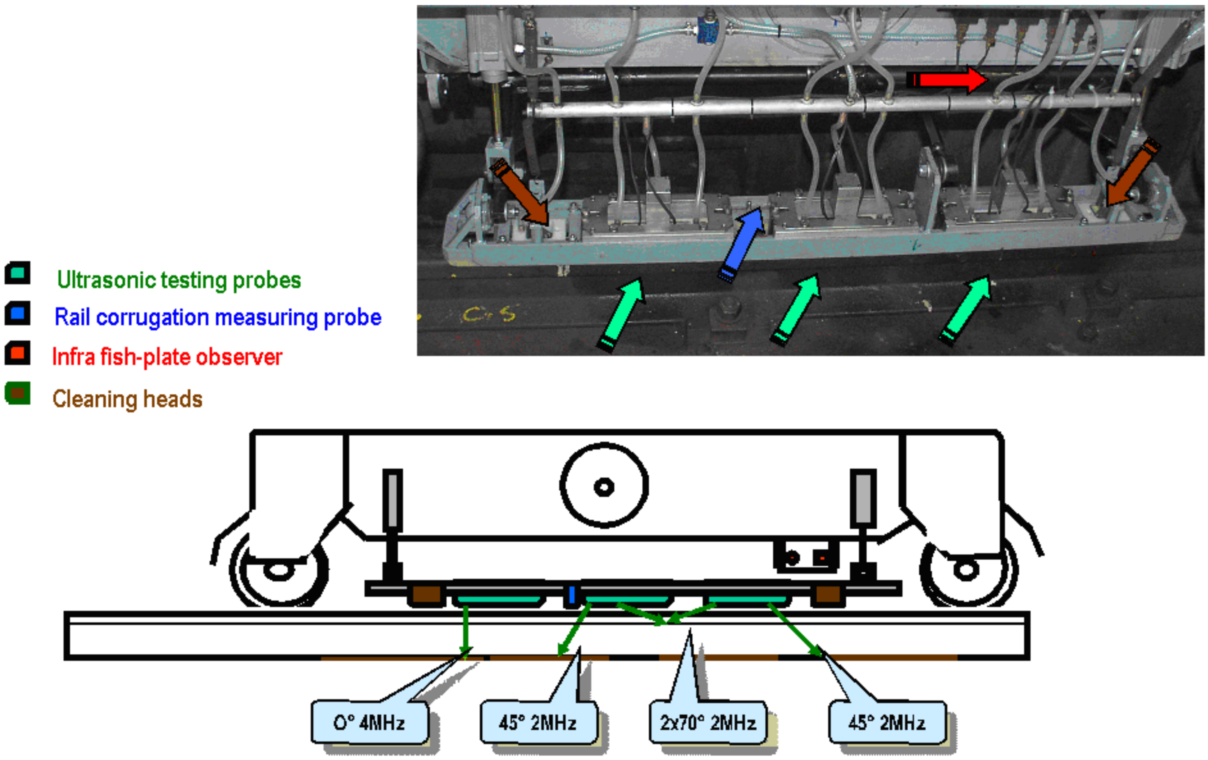

Figure 38 - Ultrasonic head arrangement of MÁV Co's rail diagnostic measuring coach

MÁV Co's manual ultrasonic tester

It carries out the examination of one rail in 3 radiation places with the arrangement of probes of 70°-70°-0°. For examination of welds probes with arrangements of 45°-45°-0° also can be used. (Probes can be produced for the required radiation angle). Equipment is applicable for detection of every lack of material in the rail (head, web) horizontal, and transversal (diagonal). Equipment can be used for every rail type.

Measuring heads (probes) and their technical data

- 1 pcs. Perpendicular S-E type (transmitter-receiver) longitudinal probe with frequency of 4 MHz. Diameter of the oscillating crystal is 20 mm, from 2 types of crystals.
- 2 db. Angle-emitter S -E (transmitter-receiver) transversal probe with frequency of 2 MHz. Size of the oscillating crystal is 10x15 mm.
- The arrangement of the probes is so, that the longitudinal running times in the plexi-glass in front of the oscillating crystals are the same.
- This is a pre-requisition of the display of the 3 systems on one screen. The The probes don't contain the joints of transmission and reception, these are parts of pre-amplifier.
- Probes are in a plastic house, which ensures the good sliding on the rail and wear resistance.

Figure 39 -USK-002 manual ultrasonic testing instrument

3.11 Alternating Current Field Measurement (ACFM)

Country of origin/organisation: UK – TSC, Bombardier and Network Rail

Category: Electromagnetic

Description:

In 2000, TSC with the support of Bombardier Transportation, begun the development of an advanced ACFM system for application in the rail industry. The objectives of this effort were to develop a highly portable ACFM system, with friendly user interface capable of detecting, automatically sizing and thresholding defects for the inspection of train wheelsets. During initial tests on previously rejected train axles either due to failure on Magnetic Particle Inspection (MPI) or because of excessive surface corrosion, the developed ACFM system achieved an 84% PoD in comparison to 44% PoD for MPI. Following the experimental work on the train axles, it became evident that an ACFM system could be deployed to both detect and size RCF cracking on rails. This led to the development of a pedestrian-operated ACFM walking stick as shown in figures 3a and 3b. The incorporated ACFM array has been shaped to conform to the shape of the head of the rail. This allows the application of the ACFM system in both new and worn rails. The inspection across the rail head is carried out by sequentially scanning across the group of sensors enabling the uninterrupted inspection of the rail.

3.12 Laser Ultrasonics

Country of origin/organisation: U.S. – TTCI, Technogamma, American Railway association

Category: Ultrasonics

Description:

Transportation Technology Centre Inc. (TTCI) together with Technogamma in the U.S. developed the first laser ultrasonics system for rail inspection. Preliminary tests showed that the developed laser ultrasonic system can be used to inspect the entire rail section including rail head, web and base. The system is loaded on a hi-rail vehicle (shown in figure 18) and can currently operate at speeds up to 32km/h. The optimum inspection speed however has been found to be between 8km/h and 15km/h.

3.13 Long-range Ultrasonics (Guided waves)

Country of origin/organisation: U.S. – Wavesinsolids LLC

Category: Long-range ultrasonics

Description:

Transducers are used to generate the longitudinal guided waves. The generated waves propagate into the rail and the presence of transverse defect can be deduced from the reflected signal.

Research in the field of rail inspection using long-range ultrasonics is currently on-going in the U.S., (The Pennsylvania State University), South Korea (Seoul National University of Technology) and the U.K. (TWI). A commercial guided waves hi-rail vehicle, known as Prism, has been produced by Wavesinsolids LLC in the U.S. The system can detect a transverse defect involving 20% reduction in the cross-section area at a distance of 1.8m.

3.14 Automated Visual Inspection

Country of origin/organisation: Germany – Bildverarbeitungssysteme GmbH, Italy – MERMEC Group

Category: Automated visual inspection

Description

Bildverarbeitungssysteme GmbH in Germany has developed advanced visual inspection systems for track maintenance. The visual inspection systems combine precise error detection with high processing speeds. Imposing virtually no restrictions on scheduled rail traffic, these systems provide regular and economic track inspection. Damage is therefore discovered very early, making it possible to substantially extend the lifecycle of tracks through preventative measures. Visual cameras can be used for the inspection of the entire surface track system for safety relevant inconsistencies. Defects on track are detected just as reliably as missing fasteners, sleeper and ballast defects. Similar systems are available by MERMEC in Italy.

3.15 Ultrasonic Phased Arrays

Country of origin/organisation: France – Socomate, U.S – Pennsylvania State University, South Korea – Seoul Technical University, UK – Universities of Bristol, Warwick and Birmingham.

Category: Ultrasonics

Description:

Research on rail inspection using ultrasonic phased arrays is currently undergoing in the U.S. (TTCI and Iowa State University), the UK (the Universities of Bristol, Warwick and Birmingham and TWI Ltd.) and France (Socomate). No practical systems involving ultrasonics phased arrays have been developed for high-speed rail inspection so far due to the problems that arise from the large amount of data that need to be analysed. The maximum inspection speeds currently achievable with ultrasonic phased arrays is approximately 5km/h.

A new in-parallel analysis concept (known as the Fast Automated Angle Scan Technique or FAAST) has been recently developed by Socomate to address the processing problem. The 128-channel system developed is capable of processing in real time, the data obtained from a multi-element probe in order to detect and characterise in one shot all reflectors inside the acoustic sound field of the probe. The system can achieve inspection speeds of up to 100km/h and has a control pitch of 4mm. The main inspection angles are -70°; -35°; 0°; +35°; +70°.

4. Conclusions

The rail testing industry is facing a new challenge to further improve the reliability of rail testing techniques, while seeking for new and emerging technologies in magnetic induction or ultrasonic transducers that aid the detection of rail defects. With the ultrasonic testing equipment, focus has been on better understanding of the propagation waves and the interaction of ultrasonic waves with the defects through the reflected signal. Further results, such as the crack location, depth, type etc. can be deduced through the analysis of the transducers signal.

Ongoing work is under way to develop improved automated rail testing techniques, mostly in the field of employing the ultrasonic technology. Development of new processing algorithms (e.g. pattern/signature recognition) to detect defects has become the major focus of most research activities to detect defects quickly and reliably, aiming to reduce the incidents of false alarms.

In most cases, data recording capability of the rail testing equipment allows the inspector to download the data for off-line signal analysis. Such facilities should significantly reduce the amount of time required to stop the testing to hand verify the defects on the spot. This should also help the inspector to prioritise defects by severity and carry out the risk assessment, and thus also help to plan and schedule the maintenance of the defective rails.

With more reliable defect detection through the use of newly-developed ultrasonic sensors and eddy current transducers, it is possible to further improve the operation of railway network, guaranteeing safe passage of vehicles transversing on the track.

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