New EMAT solutions for the railway industry

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Abstract

With the constant increase of rail traffic, travelling speeds and rail car loads, the use of the appropriate NDT method to assess the integrity of railcar and rail track components is becoming more and more critical. These factors cause increased wear and degradation in railway assets meaning enhanced inspection requirements where optimization of inspection time becomes a crucial factor.

EMATs have the ability to perform couplant-free inspection making them ideal for a variety of rail industry applications where the existence of liquids is not convenient or even acceptable having better tolerance to surface conditions and allowing for faster inspection of components without compromising reliability.

Recent advances in the development of solutions for inspection of railway components carried out by Innerspec Technologies using EMATs are presented in this document. These include inspection or rail track and rolling stock components using Innerspec´s portable inspection equipment.

1. Introduction

Last developments of high-speed trains put more pressure on enhancing safety inspection procedures for both train components and railway infrastructure. This increases the need for introducing new complementary inspections methods.

Material defects, including cracks, holes or voids, may appear during either manufacturing process or in-service operation of railway infrastructure. As time goes by, railway materials start to deteriorate as they are subjected to extreme conditions such as high speed, high temperatures due to braking forces and harsh environmental conditions. Furthermore, it is critical to control residual stress levels in order to avoid catastrophic failure. The presence of defects and lack of control in residual stress levels is a major threat to the safe operation of the railway system. So much so that railway standards such as EN 13262:2011 and German Standard VPI 09 establish maximum stress levels for in-service rail wheels.

EMAT (Electro Magnetic Acoustic Transducers) is an ultrasonic NDT testing method which does not require any couplant to perform the inspection, as the ultrasound is generated directly within the material adjacent to the transducer.

While the conventional UT requires a piezo transducer to generate the ultrasound and uses a couplant gel to transmit it to the material, EMAT ultrasound generation is based on the interaction between the magnetic field created by a magnet and the Eddy currents induced by a coil in the test piece. The combination creates a Lorentz force within the material, which is responsible of the vibration of the material's lattice and so of the ultrasonic waves. EMAT is a non-contact technique with lift-off capabilities and it is especially suited for automated inspection and for hot, cold, painted, coated or dirty parts.

EMAT transducers are energy consuming circuits thus requiring the use of High Power instrumentation which has to provide instant currents in the range of 100A. Such demanding tasks have historically put a barrier on the development of stand-alone EMAT pulse-receivers. Recent advances in efficient energy management systems and low consumption EMAT electronics carried out by Innerspec Technologies have made possible the development of the first range of hand-held battery powered EMAT instruments which are capable of generating up to 1200V with 8kW of peak power at speeds of up to 300Hz.

Sections 2-4 below showcase three novel railway applications where EMAT technology has been proven to provide outstanding results.

2. Application 1: Residual Stress Measurement in Railway Wheels

In rail wheels, the presence of tensile residual stresses is generally harmful since they can contribute to, and are often the main cause of fatigue failure and cracking. Compressive residual stresses are generally induced in the wheel material during manufacturing process as these are beneficial since they prevent origination and propagation of fatigue cracks and increase wear and corrosion resistance. It is also important to maintain compressive stress levels within specific safety limits in order to avoid compression stresses in excess of yield limit which would lead to inhomogeneous plastic deformations.

2.1 Stress measurement technique

Ultrasonic bulk waves are used to determine the presence and degree of stress in metal samples. In a stress-free metal that does not appear to have any crystallographic texture or anisotropy due to the average alignment of grains within that metal, horizontally polarized shear waves will pass through the material with a constant velocity regardless of the direction of polarization. The application of in-plane stress will make the metal behave anisotropically and each polarized shear wave will have a slightly different velocity. By measuring the difference between these velocities, the material stress levels can be obtained.

Temperature variations will change the velocity of both polarizations by the same amount to a first order approximation, and so by measuring the relative difference of the shear wave velocities, the stress measurement is not affected by variations in temperature or even sample thickness.

EMAT is especially well suited for this application because it can generate shear waves with different polarizations and do not mechanically load the surface under test allowing a greater precision of measurement of ultrasonic arrival time variation. Furthermore, EMAT does not suffer from "beam steering" errors caused by misalignment of the transducer with the surface because they electromagnetically couple energy into and out of the material under test. [1]

2.2 Ultrasonic birefringence measurement

A stress change in a material results in a change in the speed of ultrasonic waves passing through that part. The difference in the wave speeds in the hoop (circumferential) and radial directions allows for calculation of the stress state of the rim.

The technique requires using two linearly polarized shear waves oriented orthogonally from each other as presented in Figure 1.

$$Stress = K \cdot B + \sigma_0$$

$$B\ (‰) = \frac{(T_{Sc} - T_{Sr})}{\left\{\frac{(T_{Sc} + T_{Sr})}{2}\right\}} x\ 1.000$$

Where T_{Sc} and T_{Sr} are the time of flight of each of the orthogonally polarized shear waves, σ_0 is the initial stress, and K is a constant of proportionality which depends on the material, known as acoustic-elastic constant, which can be determined empirically.

B_0 represents the unstressed state birefringence due to material texture.

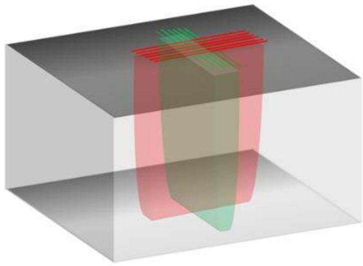


Figure 1. Disposition of the orthogonal wave beams

2.3 Measurement procedure

In contrast with alternative systems, the dual EMAT sensor allows for instant acquisition of stress values avoiding transducer rotation and facilitating user intervention.

When using Innerspec's Stress Measurement system, the acoustic-elastic constant, K, can be either entered manually or calculated empirically by performing Time of Flight (TOF) measurements for a range of known load values by means of a mechanical test.

Measurements can be performed only in the areas where the rim faces are parallel, starting from the rolling surface up to the inner rim diameter. Measurement region ends in the areas where ultrasonic signal scatter or diffract due to varying geometry.

Stress measurement system allows for storage of wheel specific configuration parameters which facilitate user intervention. In addition, inspection results are reported automatically and linked to the used configuration parameters for data reporting.

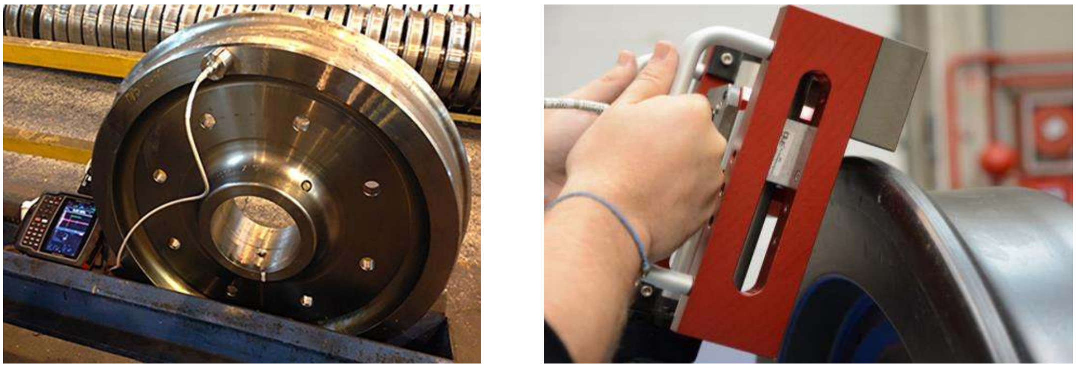
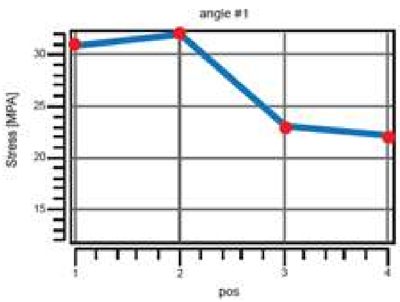


Figure 2. Innerspec PowerBox H performing Stress Measurement on rail wheel a) without positioner b) with positioner

2.4 Results

The residual stress measurement system performance was validated on sample cast steel rail wheels after manufacturing process. These wheels had not been in operation and therefore presented stress values within the standard margins. As can be seen in Figure 3, inspection results are reported automatically in a document which includes inspection parameters, table of results and graphs. These results are presented in standard form to secure wheel compliance with railway standards.



STRESS RESULTS

angle

pos

Units = MPa	1	2	3
1	31	18	-
2	32	-	22
3	23	17	31
4	22	12	-

Figure 3. Stress measurements results

3. Application 2: Axle surface inspection using Rayleigh waves

Securing wheelset axles integrity is a crucial element for both the safety and economic performance of trains. This component deteriorates through its lifetime by means of fatigue and corrosion mechanisms. For this reason, axles tend to crack either in mid-span or under or close to the wheel seats. Thus, periodic inspection must be performed to ensure that these mechanisms do not compromise the axle safety.

Axles can be inspected either in the depot (while still on a train) with limited access or at overhaul when worn wheels are removed and there is good access to surface. [3] EMAT generated Rayleigh Waves are capable of performing accurate surface inspection of rail axles in a fast and reliable manner.

3.1 Axle inspection with EMAT

Rayleigh Waves or Surface Waves are the simplest case of Guided Waves. They are confined within a wavelength of the surface along the direction of propagation. Surface Waves combine both a longitudinal and transverse motion to create an elliptic orbit motion.

Surface Waves can be used to inspect areas that other waves might have difficulty reaching. In contrast with alternative technologies, EMAT can very easily generate surface waves on both ferromagnetic and non-ferromagnetic materials.

Rayleigh waves offer several advantages for axle inspection including their ability to follow curved surfaces as well as their fast screening capabilities while maintaining high sensitivity.

Whilst conventional UT needs, at least, two operators to inspect one single disassembled axle in 40 minutes, EMAT inspection can be performed by one operator and minimizes the inspection duration up to 10 times. Furthermore, conventional UT requires use of couplant which makes the inspection more complex than with EMAT technique, as the couplant needs to be homogeneously distributed on the surface. In addition, conventional UT depends on the operator's precision as the probe must be accurately positioned on the material surface whilst the EMAT sensor is magnetically attracted to the metallic part.

3.2 Test procedure

The Rayleigh wave depth of penetration is directly related to the wavelength (pitch of the EMAT coil) and the frequency, with 97% of energy concentrated within a single wavelength depth from the top wall. This feature allows the user to decide the inspection depth within the material in order to adjust the acceptance and rejection criteria.

Based on application specific requirements, penetration depth for the surface wave is adjusted. The corresponding EMAT coil and inspection settings are defined to achieve optimum results.

3.3 Results

EMAT surface inspection in rail axles was validated in two disassembled samples. Although EMAT Rayleigh Waves are able to spot surface notches or cracks with less than 1 mm depth, results presented below are for the minimum defect required for this application which was 5 mm deep by 30 mm long.

Innerspec benchmarked the results obtained with 274A0093-M00 and 274A0244 sensors as can be seen in Figure 4. Flaw reflections were sought by using a Pulse-Echo configuration in order to find the defective areas. Found defects were present in the critical areas of the axles (in mid-span or under or close to the wheel seats) where they tend to break.

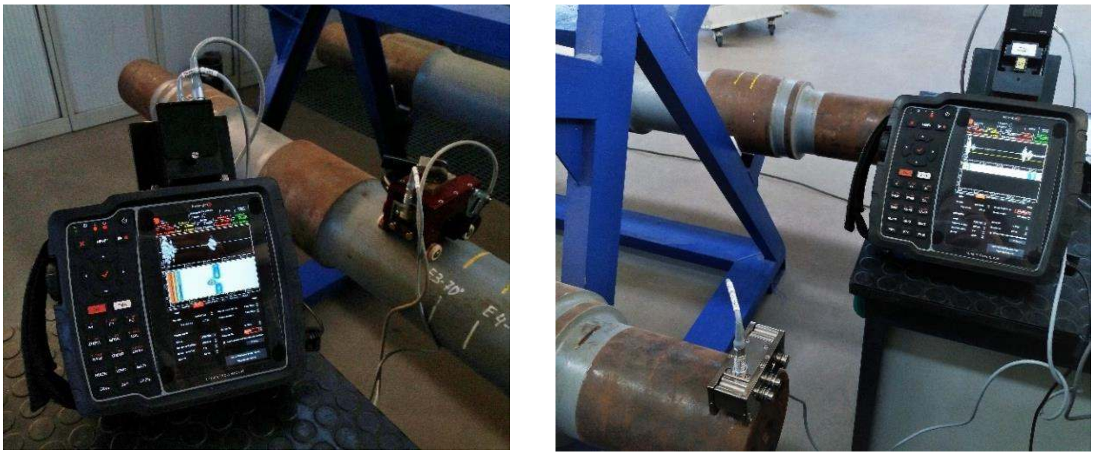


Figure 4. Axle inspection with Innerspec PowerBox H using a) 274A0093-M00 sensor b) 274A0244 sensor

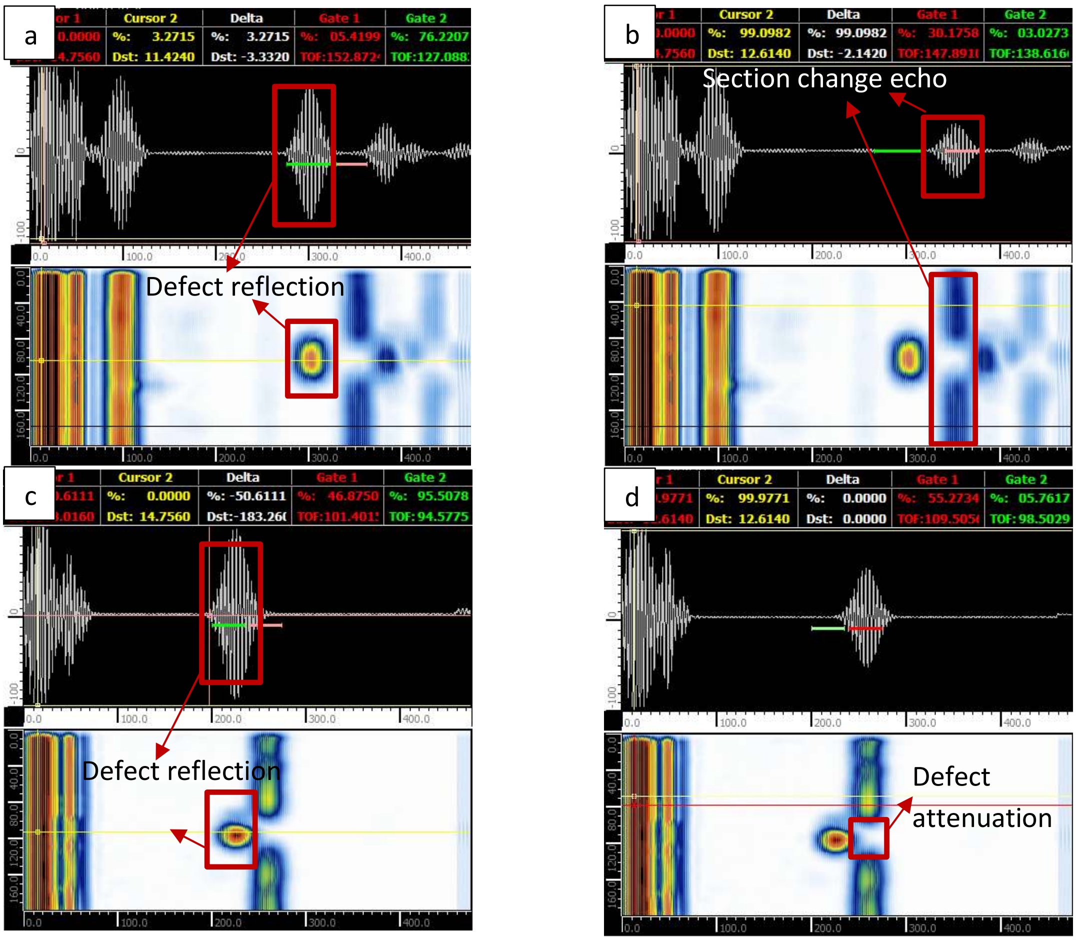


Figure 5. Rail axle inspection results a) 274A0093-M00 sensor with defect b) 274A0093-M00 without sensor defect c) 274A0244 sensor with defect d) 274A0244 sensor without defect

The furthest echo showcases the change in diameter of the train axle (change of section echo in Figure 5a). This echo is used as a reference and any defect located between the sensor and this change of section will appear earlier in the B-scan (as shown in Figure 5). The detection of surface defects is based on reflections and attenuations. When there is a defect, a reflection from the flaw emerges. Besides, the change of section echo used as a reference is attenuated as indicated in Figure 5c.

As depicted in Figure 5 above, both sensors are able to spot axle cracks with a high amplitude reflection levels (76-96%) compared with 3-5% amplitude in non-defective areas. This turns into a 25:1 SNR for the 274A0093-M00 and a 17:1 SNR for the 274A0244 sensor. However, Innerspec recommends to use the 274A0244 for inspecting rail axles with assembled wheels as the inspection area is more limited.

EMAT technique for flaw detection in rail axles was proved to be highly suitable and straightforward when using Innerspec PowerBox H. Due to this, inspection duration can be reduced to less than 10% compared with alternative UT solutions.

4. Application 3: Rail head inspection using EMAT guided waves

Rails are exposed to hard operational conditions such as high speeds, cycling loads as well as harsh environments. Defects can be initiated within the rail either during manufacturing process or, what is more frequent, due to fatigue and other failure mechanisms during operation. If no recovery actions are undertaken to secure rail integrity, surface or internal cracks can propagate causing complete rail breakage, which could lead to train derailment. [4]

4.1 Rail head inspection with EMATs

Ultrasonic Guided Wave Testing is a Non-Destructive technique that employs elastic waves that propagate along a structure while guided by its boundaries. Guided waves permit covering long distances from a single point with a limited number of sensors, making it very effective for rapid scanning of rails and other long-type structures.

Lamb Guided Waves travel throughout the material with both vertical and forward motion in an elliptical pattern. Although there are an infinite number of modes associated to Lamb waves, the mode selected for this application focuses most of the energy on the surface to detect small surface cracks and defects.

EMAT technology is contactless and ideally suited for high speed inspection of surface and near surface defects due its permissibility to rough surface conditions and lack of couplant. Furthermore, EMATs are capable of generating unique wave modes, performing a clean frequency selection during excitation.

4.2 Test procedure

For these trials, transmit and receive coils were configured in Pitch-Catch. Both channels of the transmitter coils were excited phasing the energy to propagate only in one direction. The phasing of energy using dual coils needs to be carried out in order to avoid reflections from the back edge.

A Guided Wave was generated using 185 kHz and 0.646” coil which provides indications about the rail surface defects. The energy tends to remain concentrated on the surface of the rail head. The rail was machined with a notch perpendicular to the axial direction.

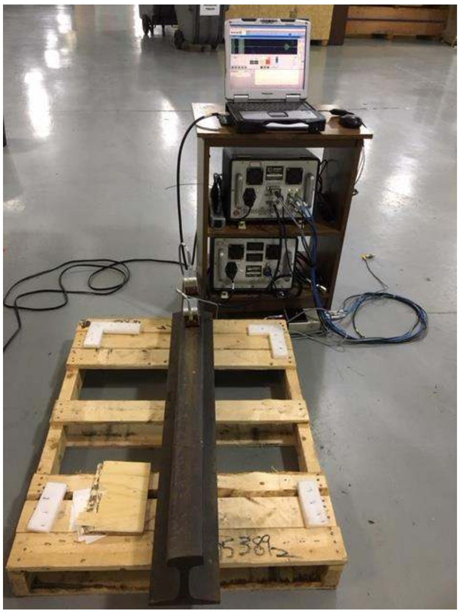
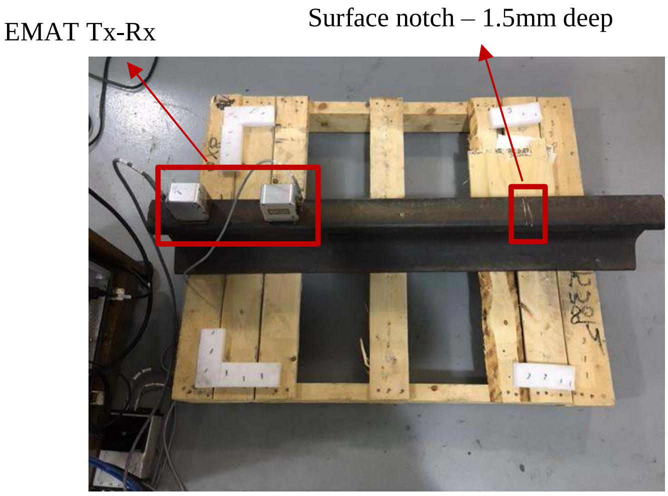


Figure 6. Laboratory setup working in Pitch Catch configuration using Innerspec PowerBox 2

4.3 Results

The use of EMAT generated guided waves allows for reliable rail head surface inspection. The ability to normalize ultrasonic signals induced into the rail head is a key advantage if a dynamic or automatic inspection needs to be performed. The use of a normalized reflection secures that a defect response remains constant even if the lift-off between the EMAT transducer and the rail head surface varies. In these tests, Innerspec was able to detect a rail head surface notch perpendicular to the axial direction with a depth of 1.5 mm. A 5:1 signal to noise ratio (SNR) was achieved in contrast with a clean surface area at a distance of 610 mm (22 inches), as can be seen in Figure 7 below.



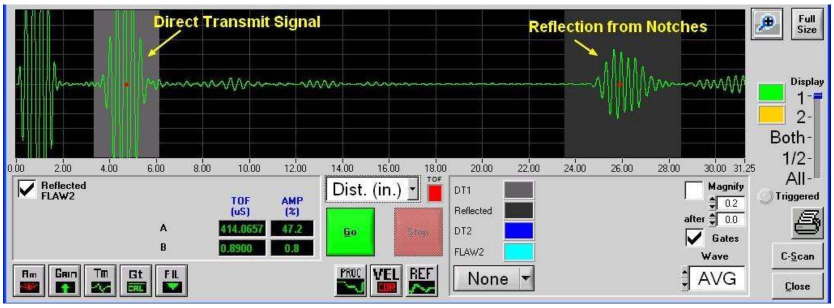


Figure 7. Reflection from Rail Head notch in Pitch - Catch mode. A-Scan View

5. Conclusions

The capabilities of EMAT technology for defect detection in train axles, rail heads and control of residual stress levels in rail wheels were demonstrated.

For residual stress measurement, the use of Innerspec PowerBox H was proved to be reliable, performing accurate readings in accordance with regulatory standards. Furthermore, the PowerBox H allows for in-service quality control of train wheels due to its portability.

The use of EMAT generated Rayleigh waves for train Axle evaluation facilitates the inspection process, reducing operators time to approximately 10% compared to conventional UT alternatives. Furthermore, standard defects required to comply with customer needs were clearly recognised, achieving a 25:1 SNR when using the 274A0093-M00 sensor and a 17:1 SNR when the 274A0244 sensor was used.

Finally, regarding rail head inspection, the tests carried out on a rail sample showed that EMAT Guided Waves are able to detect surface notches maintaining detectability even if the sensor lift-off with the part varies. This makes EMAT an ideal candidate to perform automatic and semi-automatic rail head inspection due to its permissibility to variable surface conditions.

6. Acknowledgments

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7. References

[1] J. Jimenez, V. García, C. Boyero. “Handheld solutions for measurement of residual stresses on railway wheels using EMATs”, European Congress Non-Destructive Testing, 2016.

[2] Innerspec Technologies Inc, “www.innerspec.com“ [online]. Available: https://www.innerspec.com/2018/01/25/residual-stress-measurement-in-train-wheels.html

[3] J. Rudlin, A. Raude, U. Völz y A. Lo Conte, "New Methods of Rail Axle Inspection and Assessment", 18th World Conference Nondestructive Testing Conference Proceedings, 2012.

[4] F. Fadaeifard, M. Toozandehjani, F. Mustapha, K. Matori, M. Ariffin, N. Zahari y A. Nourbakhsh, "Rail inspection technique employing advanced nondestructive testing and Structural Health Monitoring (SHM) approaches," Conference: Malaysian International NDT conference and Exhibition (MINDTCE 13), At Kualalampur, 2013.