INTERAIL: Development of a Novel Integrated Inspection System for the Accurate Evaluation of the Structural Integrity of Rail Tracks – Implementation of the ACFM Rail Inspection Module

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Abstract
The continuous increase in train traffic, axle loads and operating speeds means that the catastrophic failure of a rail section may result in very serious derailments, such as the one that took place in Hatfield, UK, in 2000, causing loss of life, injuries, severe disruption in the operation of the network, unnecessary costs, and loss of confidence in rail transport by the general public. Reliable and cost-effective inspection of rail tracks is therefore of paramount importance to ensure the safe travel of passenger and freight rolling stock. Tests carried out using Alternating Current Field Measurement (ACFM) sensors proved their capability in detecting Rolling Contact Fatigue (RCF) damage at high speeds even when measurable lift-off is involved. This paper summarises the results related to the implementation of the ACFM technology as part of the INTERAIL inspection platform.

1. Introduction
The ever growing need for the society to employ more environmentally friendly transportation policies is expected to further underline the economic and societal role of rail transport in achieving sustainable mobility across Europe in the years to follow. Today, the European rail network is continuously 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. A significant number of infrastructure related accidents in the rail industry is due to rail failure. The continuous increase in train traffic, axle loads and operating speeds means that the catastrophic failure of a rail section may result in very serious derailments, such as the one that took place in Hatfield, UK, in 2000 (figure 1), causing loss of life, injuries, severe disruption in the operation of the network, unnecessary costs, and loss of confidence in rail transport by the general public.

The work presented in this paper is carried out as part of the INTERAIL project. INTERAIL (www.interailproject.eu) is a major European collaborative research project which is led jointly by ISQ and the University of Birmingham with the support of the European Commission (contract number SCP8-GA-2009-234040). The project launched officially in October 2009 and will result in the implementation and demonstration of the advanced INTERAIL high-speed inspection system under actual operational conditions by 2012. The project involves thirteen partners across Europe with strong participation from the rail industry.

The main objective of INTERAIL is to minimise the number of rail failures by developing and successfully implementing an integrated high-speed system based on modular design for the fast and reliable inspection of rail tracks. The application of the high-speed system will be complemented through the implementation of novel semi-automated testing equipment which will be deployed for the in-situ verification and evaluation of the defects detected during high-speed inspection.

Figure 1: The Hatfield rail track site following the accident [taken from Ref. 1].

2. Concept of the INTERAIL Inspection Platform

In recent years, rail infrastructure managers have shown strong interest in the development of novel high-speed techniques for the reliable and accurate evaluation of rails in order to improve the efficiency of preventative maintenance and reduce the need for reactive maintenance to the lowest possible level. Within Europe, the European Commission has set new safety targets and stricter procedures for the rail industry as part of the plan for reform and integration of national member-state rail networks in a Pan-European single network. Safety aspects of rail transport have been particularly highlighted by the European Commission in an effort to increase public confidence in train travel.

The INTERAIL consortium partners are currently involved in the development and implementation of an integrated high speed inspection system based on a modular design, which will enable the fast and reliable inspection of rail tracks at speeds up to 320 km/h depending on the system's mode of operation. The INTERAIL system combines the use of automated visual inspection with ACFM and ultrasonics probes into a single high-speed inspection vehicle. Each module will provide information for different aspects of the condition of the rail track. The automated visual inspection module will provide information on levels of corrugation, rail head profile, missing parts, and defective slippers. The ACFM module will detect and quantify the severity of RCF damage including head checks and squats, whilst the ultrasonics module will detect and evaluate any internal defects that may be present in the rail. Integration of the three aforementioned modules will allow the full assessment of the condition of the rail track in a single run, resulting in a noteworthy reduction of inspection times when compared with existing state of the art high-speed NDT systems. Furthermore, through the combined analysis of the data obtained through the different inspection modules, it is made possible to minimise the occurrence of false defect indications leading to further reductions in inspection times, cost and personnel effort, while rail inspection reliability is significantly enhanced.

The high-speed INTERAIL system will be complemented through the development of defect verification and evaluation techniques which will also be applicable for the inspection of welds, switches and crossings. Welds, switches and crossings are particularly difficult to inspect with existing equipment due to the technical limitations involved. The consortium will develop three different techniques for this purpose, including ACFM for the evaluation of surface-breaking defects, ultrasonic phased arrays for detection and assessment of internal defects and high-frequency vibration analysis. The schematic in Figure 2 shows a simplified outline of the concept of the INTERAIL inspection platform.

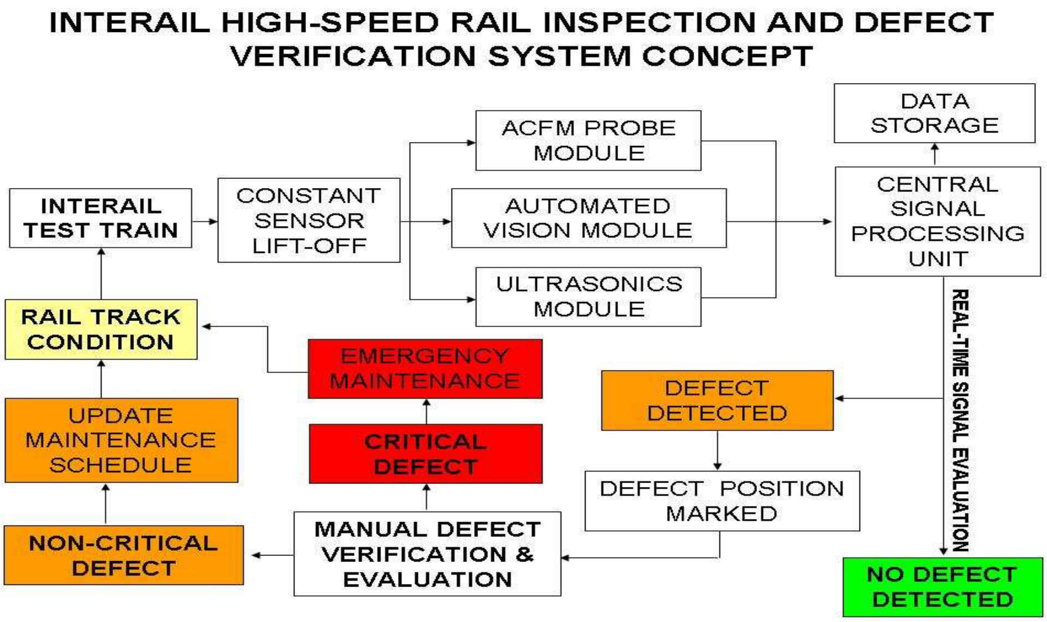

Figure 2: Simplified schematic showing the overall concept of the INTERAIL high-speed rail inspection and defect verification platform [after M. Papaelias, Ref. 2].

The technical results presented herewith are related to the effort associated with the development and implementation of the high-speed ACFM module.

3. The ACFM Principle

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. 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 3 demonstrates the theory behind the operation of the ACFM sensor. Increases in inspection speeds, application to non-planar crack morphologies and extension of sizing models to accommodate different crack types have either been achieved or being investigated further [3-6]

The ACFM technique is capable of both detecting and sizing (length and depth) surface breaking cracks in metals based on the thin-skin theory developed by Lewis, Michael, Lugg, and Collins (LMLC theory) [3]. Under certain conditions ACFM can be applied for the detection of near-surface defects, however, this strongly depends on the electromagnetic properties of the metal under inspection. Typically, the maximum skin depth achieved with ACFM systems varies from 0.1mm for carbon steels to 6mm for stainless steel.

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.

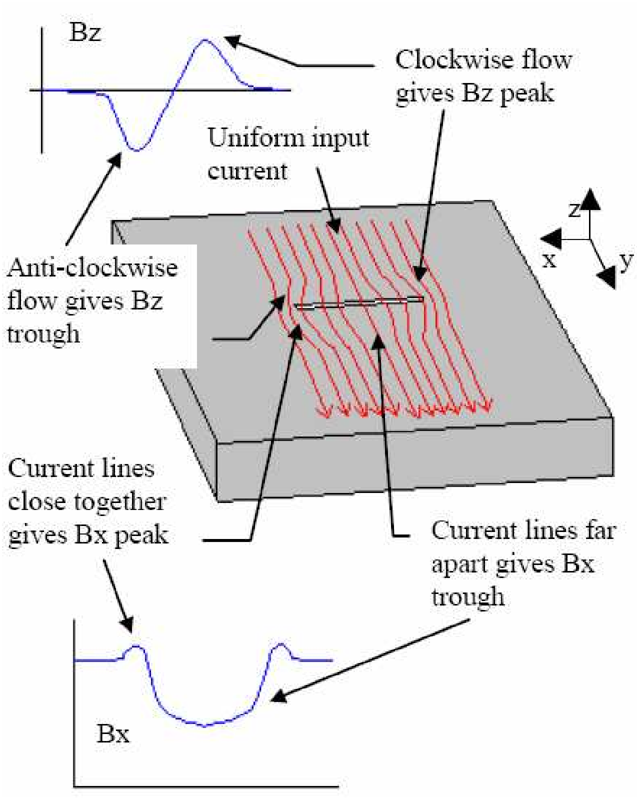

Figure 3: Definition of field directions and co-ordinate system used in ACFM.

Associated with the current flowing in the surface is a magnetic field above the surface which, like the current in the surface, will be disturbed in the presence of a defect. An important factor of the ACFM technique is its capability to relate measurements of the magnetic field disturbance to the size of defect that caused that disturbance. The breakthrough came from a combination of research studies, which provided mathematical modelling of the magnetic field rather than electrical fields, and advances in electronics and sensing technology [7-8]. Despite the fact that the magnetic field above the surface is a complex 3D field, it is possible, by choosing suitable orthogonal axes, to measure components of the field that are indicative of the nature of the disturbance and which can be related to the physical properties of any cracks present. Figure 3 presents a plan view of a surface breaking crack where a uniform AC current is flowing. The field component denoted Bz responds to the poles generated as the current flows around the ends of the crack introducing current rotations in the plane of the component. These responses are principally at the crack ends and are indicative of a crack length. The field component denoted Bx responds to the reduction in current surface density as the current flows down the crack and is indicative of the depth of the defects. Generally, the current is introduced perpendicular to the expected direction of cracking. In practice, special probes have been developed which contain a remote field induction system, for introducing the field into the component, together with special combined magnetic field sensors that allow accurate measurement of the components of the magnetic field at the same point in space. The probe requires no electrical contact with the component and can therefore be applied without the removal of surface coatings or grime.

In contrast to conventional eddy current sensors that require 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 at small lift-off 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.

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 0º-30º 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, denoted By, are also incorporated in order to take full advantage of the additional input field directions.

To make best use of an array probe, it is necessary to switch through the sensors as quickly as possible in order to allow rapid inspection. However, there are inherent limitations to this including switching settling times, data transfer rates and limitations in the sampling of a 5kHz signal. With conventional analogue electronics these factors limit the speed of scan for array probes to around 0.15m/s for a single field 16-channel array. In order to improve the applicability of the ACFM array probes a high-speed instrument has been developed which allows scanning speeds 4-5 times faster than with a conventional ACFM instrument. This has been achieved by increasing the energising frequency from 5kHz to 50kHz together with modifications to the signal processing electronics.

4. ACFM Experiments

In the experiments reported herewith, inspection speeds of up to 121.5km/h were carried out using a turning lathe test rig and a high-speed single channel micro pencil probe manufactured by TSC Inspection Systems. The pencil probe operated at a frequency of 50kHz and was driven by a commercial TSC AMIGO instrument [9]. The data obtained were logged using customised software on a PC which incorporated a high-speed data acquisition board. The data acquisition rate during tests was 1MHz.

To test the overall capability and performance of the ACFM system at high inspection speeds under controlled experimental conditions a special rotary test piece was manufactured as shown in figure 4. The material used for manufacturing the rotary test piece was a 0.9 wt % C steel to make sure that the microstructure, as well as the relative magnetic permeability and electrical conductivity are similar to those exhibited by conventional 260 rail steel grade (typically 0.7-0.8 wt % C), with both steels having a predominantly pearlitic microstructure. The rotary test piece had a 230mm diameter and was 60mm thick with a bore in the centre 210mm in diameter and 50mm deep.

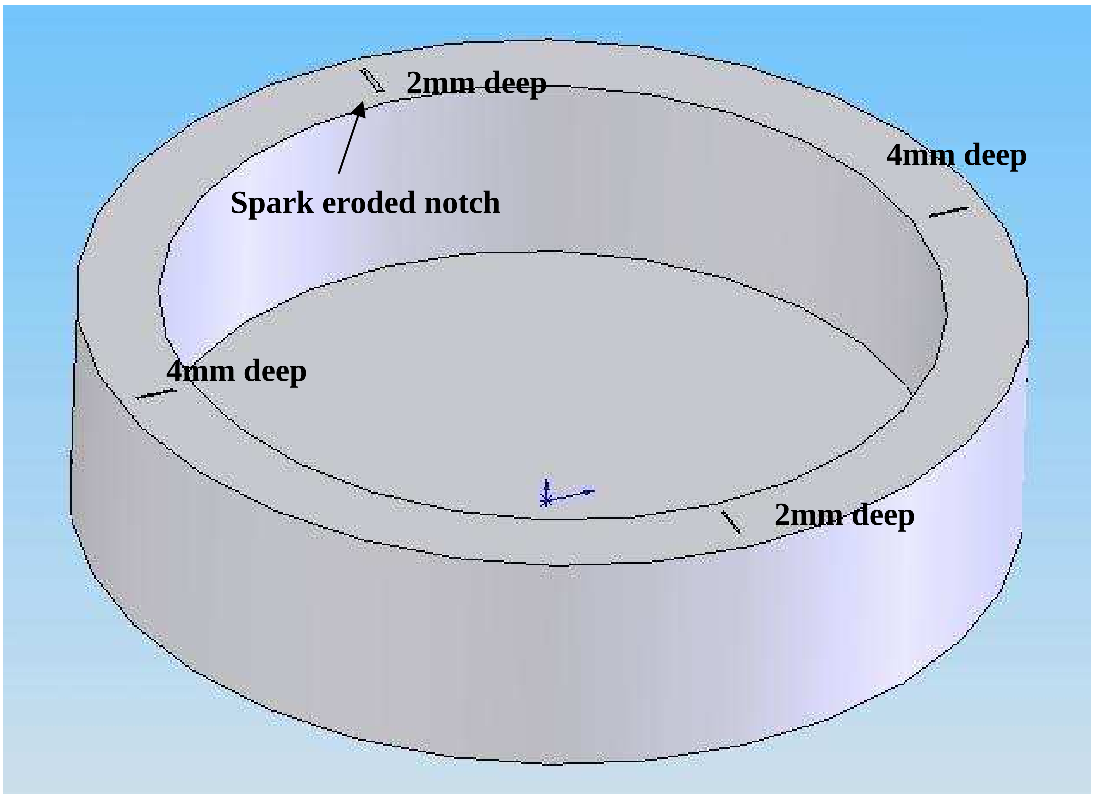

Figure 4: Schematic diagram of the rotary test piece with four spark eroded notches.

Four transverse notches (2 x 2mm and 2 x 4mm deep with a flat profile) were spark eroded at the centre of the 20mm wide rim of the sample. Each notch was 10mm long and 0.5mm wide. The sample was placed in a turning lathe capable of rotating the test piece between 1 to 3000 revolutions per minute (rpm). The rotational speed of one rpm for this experimental setup corresponded to the equivalent of a surface speed of 0.0405km/h at the centre of the notch (i.e. 10mm away from the edge of the rim) and hence at 3000 rpm the surface speed of the sample at the centre of the notches was 121.5km/h. The ACFM probe was positioned opposite to the centre of the notches and at a 0° angle with reference to their surface orientation as shown in figure 5. The initial constant lift-off of the ACFM probe with regards to the surface of the rotating sample was 0.8mm. Tests were carried out with a lift-off of up to 5mm in order to evaluate the effect of increasing distance between the surface of the inspected sample and the probe on the ACFM signal.

During experiments, the data were logged on the PC and then plotted using customised software. Further development of the software used is currently under way to enable plotting of the data in real time. The data logged during these tests were the ACFM probe signal (i.e. Analogue to Digital Conversion of probe voltage) with time. Data were collected for various speeds, starting from equivalent surface speeds of 4.5km/h (at 100 rpm) up to 121.5km/h (at 3000 rpm) as discussed next.

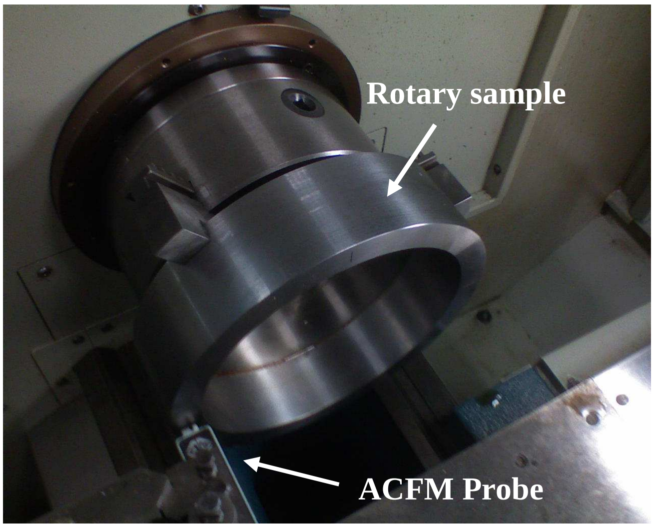

Figure 5: Experimental setup for the turning lathe tests using the rotary test piece.

Although, the prime objective of the turning lathe experiments was to evaluate the applicability of the ACFM probe for high-speed detection and not the accurate quantification of depth and surface length of the spark eroded notches, through the sensor configuration employed it was possible to obtain correct rankings for each notch in terms of its depth as shown from the data plots presented herewith.

Tests were carried out initially at a relatively slow speed of 4.5km/h (100 rpm) and 0.8mm lift-off in order to ascertain that the ACFM micro-pencil probe was capable of detecting all four notches. After verifying that the notches were detected by the ACFM system, the inspection speed was increased progressively up to 121.5km/h while maintaining a constant lift-off. The plot in figure 6 shows the changes in the probe signal caused by the presence of the notches versus time at an inspection speed of 81km/h. It is evident that the data pattern repeats itself during each revolution signifying that this experimental setup provides a suitable platform for reproducible inspection conditions which allows the repeatability of the ACFM tests to be assessed. Moreover, the signal intensity arising from the presence of a 2mm notch can be clearly distinguished from that of a 4mm notch, hence offering a measure of quantification.

Comparison of the data acquired at various inspection speeds while maintaining a 0.8mm lift-off showed that the amplitude of the signal remains unaltered. As shown in figure 7, at an inspection speed of 20.25km/h the amplitude of the signal is virtually the same with that acquired at a speed of 121.5km/h (any variations seen are within the noise level of the measurement). In addition, noise levels in the obtained signal are also similar throughout the inspection speed range of these tests.

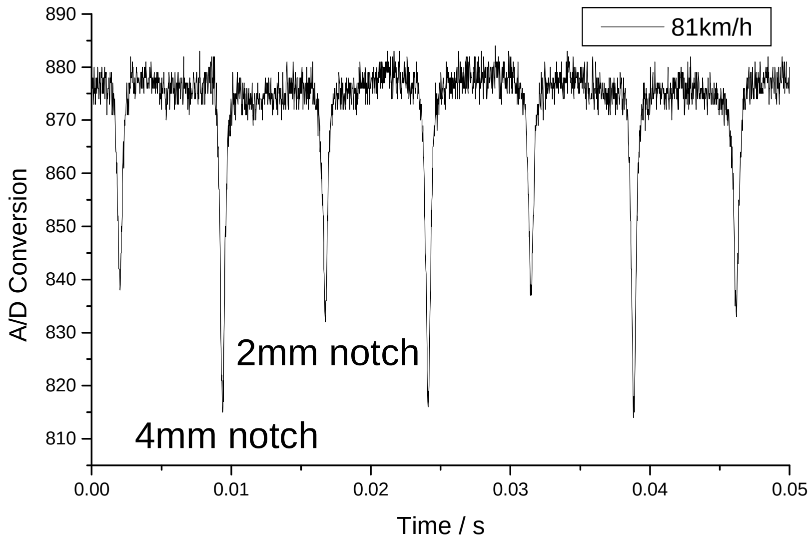

Figure 6: ACFM data plot at 81km/h with 0.8mm probe lift-off.

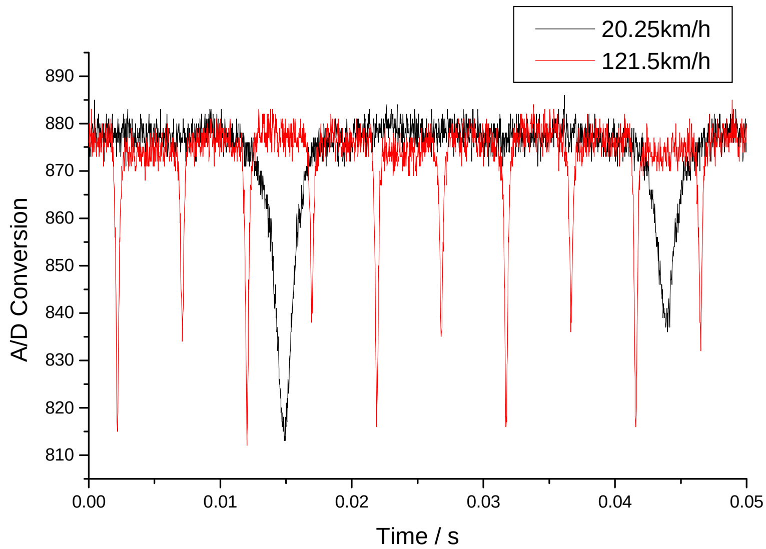

Figure 7: ACFM data plots showing the resulting signals at 20.25km/h and 121.5km.h with 0.8mm lift-off.

Further tests carried out with increasing lift-offs (2mm, 3mm, 4mm and 5mm) at the same inspection speed range (4.5–121.5km/h) showed a square reduction in the ACFM defect signal amplitude as expected. Therefore, as seen from the normalised plots in figure 8 for an inspection speed equal to 81km/h, the signal arising for a 2mm notch at 0.8mm lift-off is comparable to that arising for a 4mm notch at 2mm lift-off. Similarly, the signal acquired due to the presence of a 4mm notch at a probe lift-off of 3mm is comparable to the signal obtained for a 2mm notch for a 2mm probe lift-off. Although the test notches were detectable at all lift-offs used, the results obtained in these experiments suggest that probe lift-off during inspection under field conditions is a significant factor which needs to be controlled and taken into account if accurate quantification of RCF cracking is to be achieved. Another interesting feature in the plots of non-normalised raw data is that the overall ACFM signal decreases with increasing lift-off. Therefore, by quantifying the reduction in the overall ACFM signal it may be possible to evaluate any lift-off variations that may occur during actual inspection.

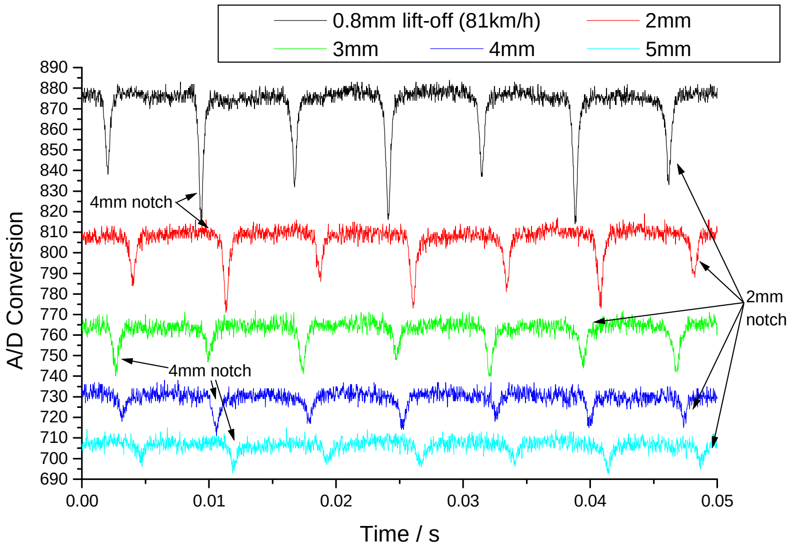

Figure 8: Normalised ACFM data plots for various lift-offs at 81km/h.

5. Experiments and results using the spinning rail rig

A 3.6m diameter spinning rail rig capable of rotating at speeds between 1-80km/h (shown in figure 9) was used to assess the ACFM technique using idealised defects on rails. A special set of eight 1.41m long curved rails containing artificially induced notches were produced, including half-face slots machined normal to the railhead surface, clusters of angled slots, and pocket-shaped defects more typical of actual RCF defects.

Figure 9: The spinning rail rig at the University of Birmingham.

The notches were spark eroded in the test rails using a 0.7mm thick wire. The shapes and sizes of the induced defects were chosen in such a way as to enable their use as calibration samples for various NDT technologies. The depth of the notches varied between 2 and 15mm, while for more realistic representation of RCF cracking certain notches were angled with respect to the surface normal and the rail edge and the railhead surface. RCF head checks detected in rails, are often inclined to the surface, penetrating initially at a shallow angle of approximately 15° - 30° until they reach a characteristic depth and turn down into the railhead at an angle of approximately 60° [10-11]. Figure 10 shows a plan view schematic of sample rails and induced notches. The induced artificial pocket shaped defects contained in rail samples designated #7 and #8 are the ones that more closely resemble actual RCF cracks.

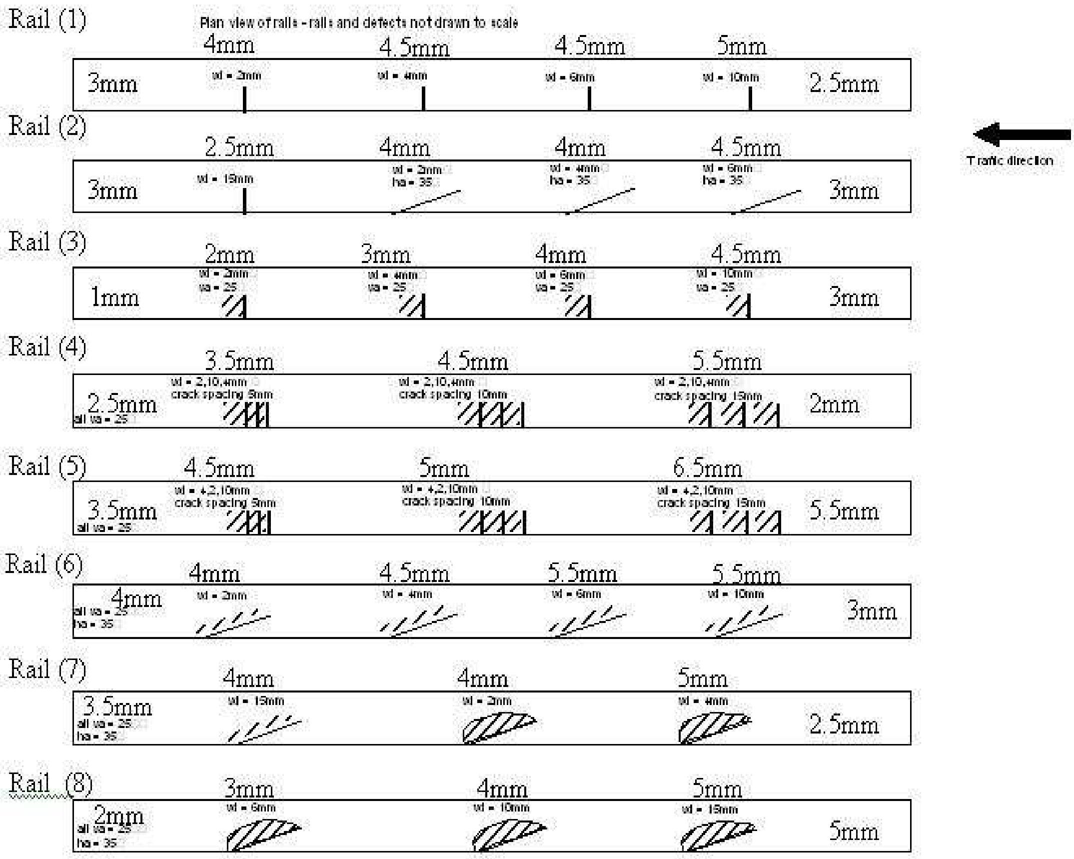

Figure 10: Schematic showing the test rails for the rail rig tests. Vd = vertical depth of the notch in mm, ha = horizontal angle of orientation in degrees, va = vertical angle of orientation in degrees. The values in mm shown on top and at the ends of each rails illustrate the probe lift-off at that particular section during the rig tests

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During the ACFM tests with the spinning rail rig, the micro pencil probe used for the turning lathe tests was installed on a customised trolley. It was found that the probe lift-off varied between 1mm to 6.5mm during a complete rotation of the rig. The fact that lift-off variations existed within each test rail due to bowing, affected the ACFM measurements since the trolley used was designed to compensate for lift-off variations from rail to rail and not within each rail. Lift-off occurring due to bowing in the individual test rails meant that the probe stand-off was highest at the centre of each rail where the notches were present. This sort of lift-off variation is not expected in real life inspection of rails.

ACFM tests were carried out initially with the pencil probe at a slow speed (manual tests at 0.1km/h) and zero lift-off to verify that the system could detect every notch induced on the test rails. Following these tests, the probe was installed on the customised trolley and the rig was rotated at 1.6km/h, progressively increasing the speed of the spinning rig up to 48km/h.

The probe was positioned in such a way that the induced current flowed in the longitudinal direction of the rail head. As shown in figure 10, the notches to be inspected are at a 0° or 35° surface angle with respect to the probe orientation and 90° or 25° to the railhead surface. Although the main objective of these tests was to verify the capability of detection of the ACFM probe at high speeds under simulated rail inspection conditions, for these orientations, the ACFM system used should also be able to offer a quantitative measure of the depth of the notches detected. However, due to lift-off variations that occurred during testing it was impossible to obtain correct rankings for all inspected notches, while certain notches were not positively detected.

The plot in figure 11 show the data obtained for rails #5 and #3 at a speed of 2.3km/h. The effect of lift-off variation can be clearly seen by the changes in the overall ACFM signal plot. However, the induced notches were clearly detected in both rails. Rail #5 contained three groups of clustered notches (notches with depths 2mm, 10mm and 4mm) as demonstrated in figure 10. Each clustered group of notches had a different spacing between the notches of the cluster of 5mm, 10mm and 15mm respectively. The reason for using clustered notches was to assess the capability of the sensor in resolving the presence of individual defects when clustered. As seen in the ACFM data plot in figure 11, despite the fact that all three clusters of induced notches have been detected, it has not been possible to resolve individual notches within the clusters due to the high probe lift-off involved during the experiments (more than 4mm). The plot in figure 12 shows the ACFM data acquired for rails #5 and #3 at an inspection speed of 32km/h. The data acquired at an inspection speed of 2.3km/h is virtually identical to that obtained at 32km/h as expected from the lathe tests.

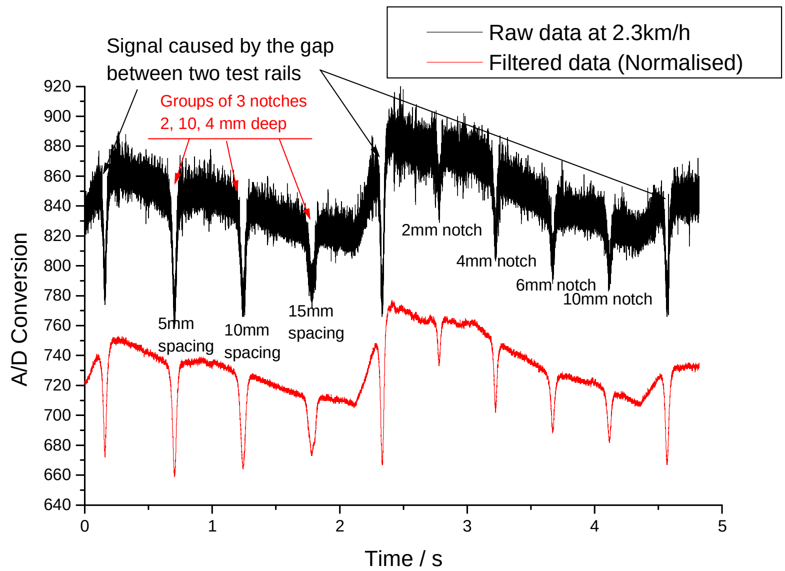

Figure 11: Raw and normalised filtered data plots for test rails #5 and #3 at 2.3km/h.

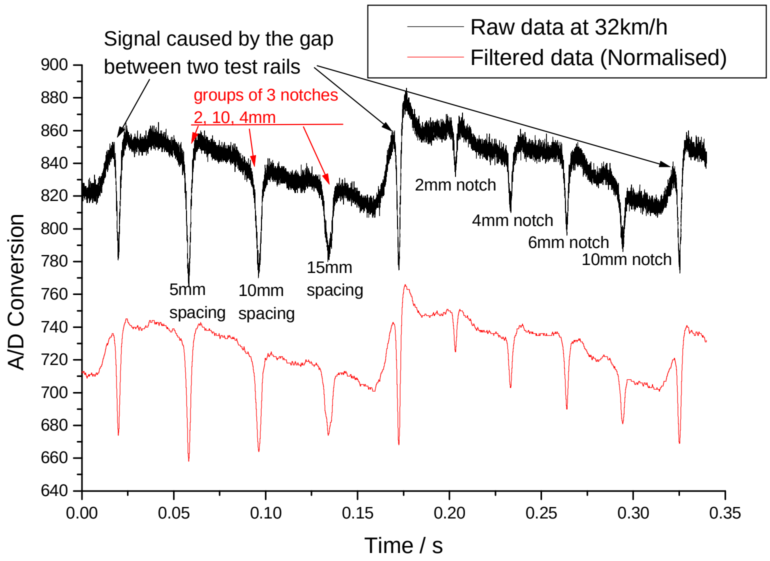

Figure 12: Raw and normalised filtered data plots for test rails #5 and #3 at 32km/h.

6. Conclusions

High-speed ACFM tests were carried out using a micro pencil ACFM probe that was driven by a TSC Amigo crack microgauge system. Tests were carried out initially using a rotary test piece containing spark eroded notches which were 2mm and 4mm deep. A turning lathe was used to rotate the rotary test piece at speeds up to 121.5km/h (at 3000rpm). This experimental configuration provided controlled inspection conditions as well as easy repeatability of the tests. It was found that the probe could successfully detect the induced notches at 121.5km/h and that the ACFM signal remained largely unaffected by the increases in speed under constant lift-off. Tests using different lift-offs revealed that the intensity of the signal obtained for a given notch was reduced by the square as the lift-off increased as expected.

In order to simulate actual rail inspection conditions at high speed, further tests were carried out using the spinning rail rig at the University of Birmingham. The ACFM micro pencil probe was installed on a special trolley, however, under this experimental configuration it was impossible to compensate for lift-off variations that occurred during the spinning rail rig tests due to the limitations in the design of the trolley used. Data analysis of the results obtained, showed that the ACFM sensor detected all induced notches. It was also found that the variations in the lift-off made it impossible to obtain correct rankings for all the detected defects. Comparison of the ACFM data at various inspections speeds showed that the signal remained largely unaffected with increasing velocity up to 48km/h. Unfortunately, lift-off variations during the experiments did not permit a more accurate evaluation of the capability of the ACFM micro-pencil probe. However, the implications that arise from the fact that there is virtually no loss of signal with increasing speed is extremely important for the application of ACFM technology as an alternative means of high-speed inspection of rails. The performance of the ACFM technique at inspection speeds up to 80km/h and constant lift-off is currently under investigation using a new trolley design. Modelling work is also underway to evaluate the interaction of RCF cracks with the AC and electromangnetic fields induced.

Further development will also concentrate in the integration of the ACFM module with the automated vision and ultrasonics module as part of the complete INTERAIL high speed inspection system.

7. Acknowledgements
The authors are indebted to Mr Andy Robertson and Mr Andy Tancock from Network Rail for their kind contribution to this work. The assistance of Dr John Garnham from the Birmingham Centre for Rail Research and Education is also gratefully acknowledged. The authors wish to thank the Rail Research Centre at the University of Birmingham and TSC Inspection Systems for the provision of facilities and equipment. Finally, the authors would like to express their gratitude to the European Commission for partially funding this work through contract SCP8-GA-2009-234040.

8. References

1. **Grassie, S. L.** Rolling Contact Fatigue on the British railway system: treatment, Wear, 2005, 258, 1310-1318.
2. **INTERAIL Project** "Description of Work", SCP8-GA-2009-234040, October 2009.
3. **Lewis, A. M., Michael, D. H., Lugg, M. C., Collins, R.** Thin-skin electromagnetic fields around surface-breaking cracks in metals, J. Appl. Phys., Vol. 64, No 8, pp. 3777-3784, October 1988.
4. **Dover, W. D., Collins, R., Michael, D. H.** The use of AC-field measurements for crack detection and sizing in air and underwater, Phil. Trans. R. Soc. Lond., Vol. 320 A, pp. 271-283, 1986.
5. **Lugg, M. C. and Collins, R.** Proc. 21st Ann. Br. Conf. Non-Destructive Testing, ed. P. J. Emerson and G. Oates, pp. 533-540, 1986.
6. **Lugg, M. C., Shang, H. M., Collins, R., Michael, D. H.** The measurement of surface crack inclination in metals using AC electric fields, J. Phys. D: Appl. Phys., Vol 21, pp. 1814-1821, 1988.
7. **Topp, D. and Smith, M.** Application of the ACFM Inspection Method to Rail and Rail Vehicles', In the Proceedings of ENCDT 2005.
8. **Lugg, M., Topp, D.** Recent developments and applications of the ACFM inspection method and ACSM stress measurement method, Proceedings of ECNDT 2006, Berlin, Germany, 2006.
9. TSC Inspection Systems, ACFM Crack Microgauge AMIGO Model User guide, 2001.
10. **Garnham, J. E., Franklin, F. J., Fletcher, D. I., Kapoor A., Davis, C. L.** Predicting the life of steel rails, Proc. IMechE, Part F: J. Rail and Rapid Transit (Special Issue), Vol. 221, No. 1, pp. 45-58, 2007.
11. **Eden, H. C., Garnham, J. E., Davis, C. L.** Influential microstructural changes on rolling contact fatigue initiation, in pearlitic rail steels, Materials Science and Technology, Vol. 21, No. 6, pp. 623-629, 2007.