APPLICATION OF THE ACFM INSPECTION METHOD TO RAIL AND RAIL VEHICLES

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Abstract: The ACFM inspection technique is an electromagnetic inspection method, which is widely used in the Oil and Gas industry for the detection and sizing of surface breaking cracks. It provides a number of advantages over conventional inspection methods, particularly in the ability to inspect without removing coatings or grease, and has recently been adapted for a number of rail specific applications. The technique has now been accredited in the UK for use on vehicle wheelsets and for the inspection of plain rail.

This paper describes the background to the ACFM technique and its application to in-service inspection. The development of a new 'Walking Stick' for inspection of the rail head is described, together with some of the challenges of inspecting the complex crack geometries associated with cracks generated by rolling contact fatigue (RCF). ACFM has also been applied to both plain and driven axles, examples of these applications together with its use on bogies are also given.

This paper also considers some of the challenges faced when moving technology from one industry to another. Operator training has to be considered as well as the validation requirements for acceptance of a new technique. Validation often requires comparison with existing technologies in blind trials but these are not necessarily quantitative in terms of performance. Destructive sectioning provides an absolute measure of system capability and was also used during these developments. Results from both destructive and non-destructive trials are discussed.

Introduction: The Alternating Current Field Measurement (ACFM) technique is an electromagnetic inspection method capable of surface crack detection and sizing. The technique does not require coating removal and was originally developed in the late 1980s for use in the Oil Industry, where there was a requirement for improving the reliability of subsea inspection. The first application of ACFM in the rail industry was for the inspection of axles. This came about from a review of available crack detection methods conducted by the Engineering Link following a fatal accident involving the failure of an axle. This review, which looked beyond those methods traditionally used in the rail industry, was followed up by a series of blind trials[1] in which the ACFM technique was found to outperform conventional Magnetic Particle Inspection (MPI) and an advanced eddy current method. These results then generated further interest in the technique and in particular whether it could be used for the inspection of rails. At the time, the UK had experienced a major accident involving a rail break, which identified a problem in the network infrastructure from Head Checking. More specifically, gauge corner cracking (GCC) was identified as a potential problem and significant effort was put into addressing this problem, both in terms of identifying the causes and controlling the rail condition once cracks were known to exist. The ACFM method was developed for this particular application in an effort to identify the severity of the defects, this meant categorising the defects in terms of their depth. Although the crack morphology was complex, good performance was achieved from the system, which is now in use on the UK network.

Another application, which has been developed recently, is the inspection of bogies. Like axles, these are traditionally cleaned to bright metal before inspection using MPI. The use of ACFM reduces the cleaning requirement and provides auditable data recording of the results. This application was pioneered by Bombardier Transportation UK Ltd[2], and has recently achieved accreditation in the UK.

The ACFM Method: The Alternating Current Field Measurement (ACFM) technique is an electromagnetic technique capable of both detecting and sizing (length and depth) surface breaking cracks in metals. The basis of the technique is that an alternating current can be induced to flow in a thin skin near the surface of any conductor. By introducing a remote uniform current into an area of the component under test, when there are no defects present the electrical current will be undisturbed. If a crack is present the uniform current is disturbed and the current flows around the ends and down the faces of the crack. Because the current is an alternating current (AC) it flows in a thin skin close to the surface and is unaffected by the overall geometry of the component.

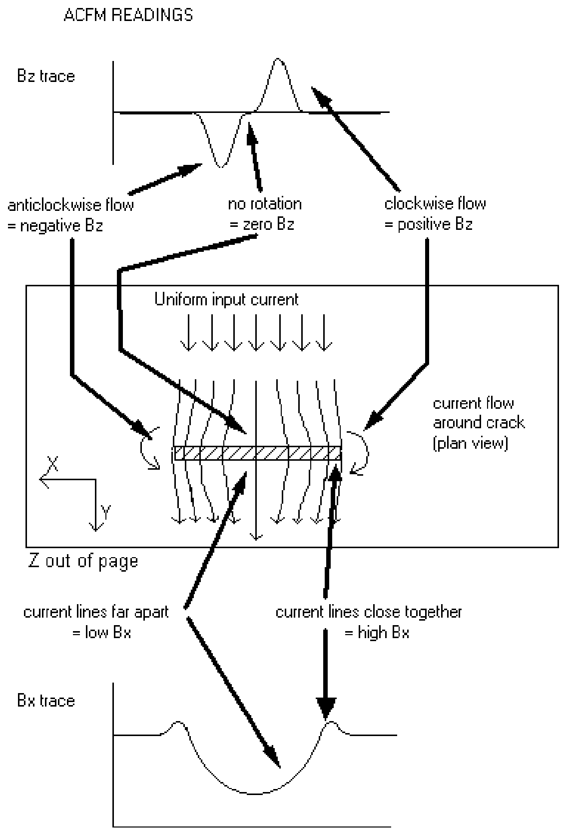

Figure 1. ACFM currents flowing around a defect

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 studies at University College London, which provided mathematical modelling of the magnetic field rather than electrical fields, and advances in electronics and sensing technology.

Although 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 1 presents a plan view of a surface breaking crack where a uniform ac current is flowing. The field component denoted Bz in figure 1 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 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 so for a shaft or axle subjected to fatigue, the current would be introduced in an axial direction to be disturbed by cracks in a circumferential direction.

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.

The mathematical modelling of current disturbances[3] showed good correlation between theoretically predicted magnetic field disturbances and those measured, hence providing the ability to make quantitative measurement of the magnetic field disturbances and to relate them directly to the size of the defect that will have caused such a disturbance. Note that the modelling was restricted to planar defects with a semi-eliptical shape, as usually encountered with fatigue cracking. The aspect ratio was not fixed, allowing, for any particular length of defect, a range of depths up to one half of the defect length (semi-circular) to be sized. Defects that deviate from this morphology may lead to error in the predicted depth.
From a practical standpoint, the technique can be applied using a single probe that can be manually moved along a component. Experience showed that with earlier electromagnetic inspection systems, for example eddy current devices, there were a number of drawbacks when used in practical situations. Many of these arose from signals from features other than cracks, leading to difficult interpretation of the signals. For example, even small amounts of probe lift off from the surface can cause large changes in a standard eddy current response. The ACFM technique has virtually eliminated this and other related problems by use of the uniform field together with careful probe and electronics design, but in particular by utilising special displays of the data. A standard PC is used to control the equipment and display results. ACFM is unique in the way data is displayed.
The plot on the left of figure 2 shows typical raw data from the crack end and crack depth sensors collected from a manually deployed probe. The right hand section of figure 2 shows this presented as a butterfly plot. In the presence of a defect, the butterfly loop is drawn in the screen and for manual operation the operator looks for this distinctive shape to decide whether a crack is present or not. Having detected a defect, the data can be subsequently interrogated to determine the depth of the crack *without calibration*. All data is stored by the system and is available for subsequent review and analysis. This is particularly useful for audit purposes and for reporting.
Because ACFM uses a remote uniform field, it is possible to make a number of field measurements at different positions in the same field. This concept is used for both axles and rail inspection by producing a probe, profiled to the component and containing multiple field sensors. This 1D array of sensors can then be swept along or around surface to provide inspection of the scanned area.

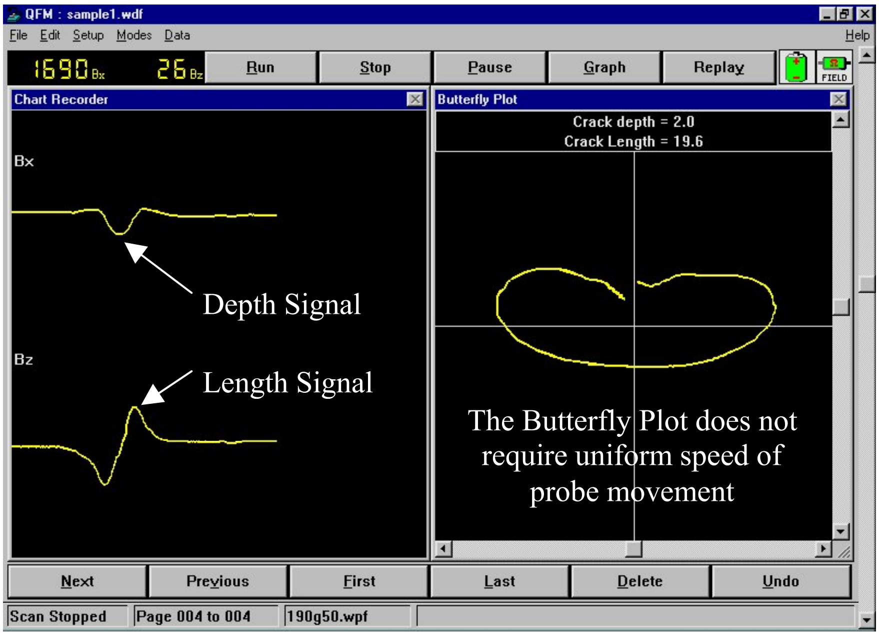

Figure 2. Typical ACFM signal response to a defect

Application of ACFM to Axles: Following its successful performance in the Engineering Link axle trials, ACFM has been gradually introduced for the surface inspection of railway axles as a replacement for MPI. Due to its ability to operate through coatings, ACFM inspection can be conducted on painted axles without the need to strip and re-paint. This can provide a major saving in time and costs as well as aiding in corrosion integrity by not disturbing the original coating. Because the ACFM technique records all inspection data, there is a permanent record of the inspection available should an axle fail in service.

Axles can be inspected either on or off the vehicle. In the latter case, it is usually most convenient to mount the axle in an engineering lathe and to mount the ACFM probe onto a toolpost that can be scanned along the length of the axle while it is rotated. In this way, the whole axle body can be inspected in a continuous helical scan.

If the axle is to be inspected on the vehicle then it is usual to use an array probe. These are larger probes which contain multiple sensors and can inspect a much wider area that standard probes. Each of the sensors is sampled as the probe is moved and an integral encoder logs the distance travelled into the software. The axle is inspected in overlapping bands as the probe is scanned around the axle.

One application area that was proving difficult to inspect using conventional techniques was the section of axle under the Earth Return Brush (ERB) on an in-service power axle. Access to the area could be achieved by removing the brush and its holder leaving a small circular aperture approximately 90mm (3.5inches) in diameter and 50mm (2.0") deep. MPI was not considered suitable due to the restricted access and the problem with the use of contaminating fluids on an in-service box. Due to axle geometry, Ultrasonic inspection was also not possible.

A custom ACFM array probe was designed and manufactured to fit through the access hole and inspect the axle under the brush with the axle in place on the train. Figure 3 shows the probe which contains 8 sensors covering an area of 70mm (2.8inches).

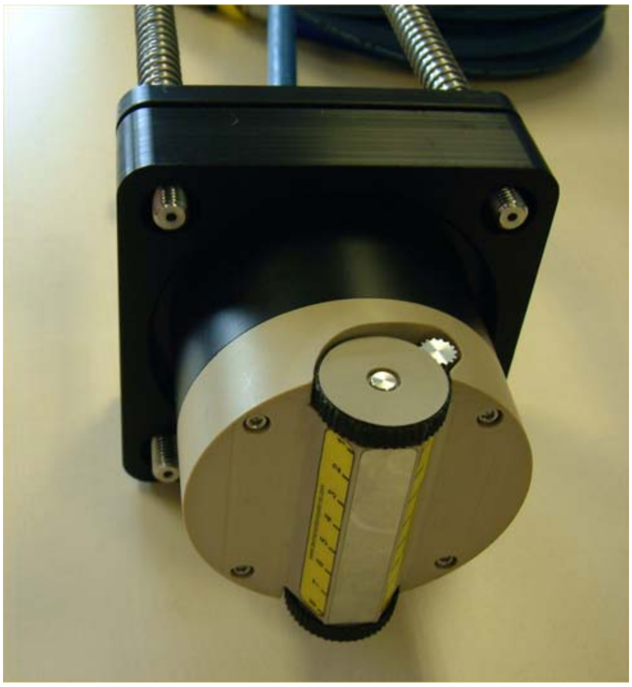

Figure 3. ERB ACFM array probe

Deployment was carried out by jacking the appropriate bogie to raise the wheels off the rails, then rotating the wheel while data was collected. In this way, the entire inspection site could be inspected with just one rotation of the axle.

Application of ACFM to rails: As described above, the ACFM method was originally developed for manual inspection of welds. Here the requirements are very specific, generally the inspection area is a narrow strip near the weld toes and, because the inspections are carried out manually, the scan speed can be relatively slow, perhaps 10mm per second for short periods. The requirement for rail inspection was very different. There was a requirement to inspect a wider area, covering the gauge face, gauge corner and across the head towards to field side. The speed of inspection needed to be as high a possible, in order to achieve acceptable throughput. It was also desirable to have automated interpretation of the results. Another major challenge was in the crack morphology. Typically GCC comprises multiple, closely spaced cracks at a large angle to the running direction. The cracks are often inclined to the surface, penetrating initially at an angle of approximately 30 degrees until they break through the compressive layer, about 5mm (0.2 inch) below the surface, when the angle increases to approximately 60 degrees. The ultrasonic testing, that was conventionally being carried out, suffered from "crack shielding" whereby shallower defects could mask deeper defects and thereby undersize the greatest defect depth. Shallow cracking was also difficult for ultrasonics to identify and categorise. There is a poor correlation between crack surface length and penetration depth of the cracks and even short cracks can be deep. However, due to the limitations of the then available techniques, the UK inspection standards dictated that GCC should be classified according to the greatest surface length rather than the depth – which is the more crucial in engineering terms.

Coverage of the rail head was achieved by use of a sensor array, shaped to the head of the rail. In fact the probe was designed to take the shape of a wheel in order to optimise the location of the probe even on worn rail. The inspection across the rail head is carried out by sequentially scanning across the group of sensors. By doing this, a continuous scan of the rail head is achieved as the probe is pushed along the rail.

Speed was initially limited by the sampling rates achievable for a 5kHz input signal. For this application, this was increased to 50kHz and scanning speeds of 2-3km (1.3-1.9 miles) per hour have been achieved. It must be recognised that this is a quantitative inspection method and that sufficient data must be collected to not only detect, but also determine the severity of the cracking.

The system has been packaged into a pedestrian 'Walking Stick' (figure 4) which is totally self contained and capable of operating for at least 8 hours from its own power source. The walking stick display is a ruggedised PC which controls the system and displays analysed data in a readily useable form for the operator. Very little operator interpretation is required.

The ACFM method relies on predication of AC current flows on the surface of a component and the modelling has focussed on the planar semi elliptical cracks, typical of fatigue damage. The sizing models therefore didn't apply to the complex crack shapes synonymous with GCC. In order to provide real time crack sizing it was necessary to consider the mathematical modelling and its relevance to the GCC crack form. It was decided that the existing models would be used as a starting point and that empirical correction factors would be applied to take account of the crack type. This obviously required a large amount of data on crack growth behaviour and that is difficult to achieve with any existing non-destructive testing methods. For this reason, it was decided to embark on a programme of destructive testing, which could be used to characterise the crack shape and at the same time to validate the results of blind trials using the ACFM method.

Figure 4. ACFM Rail Walking Stick

A number of samples of cracked rail from the network were collected and after inspection with the Walking Stick were sectioned to determine the crack size and shape. This information was then used to develop empirical corrections to the sizing models (see figure 5).

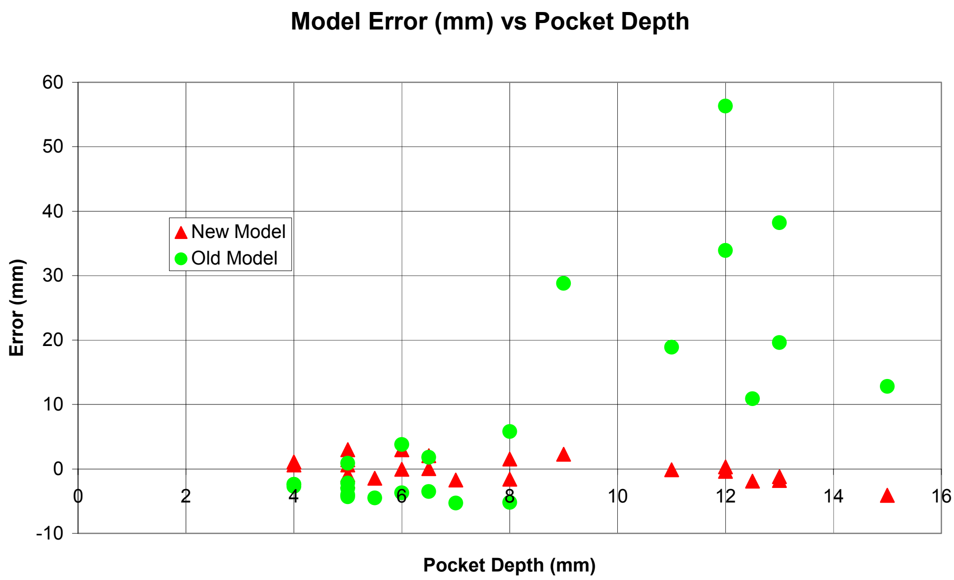

Figure 5. Comparison of errors using old and new models

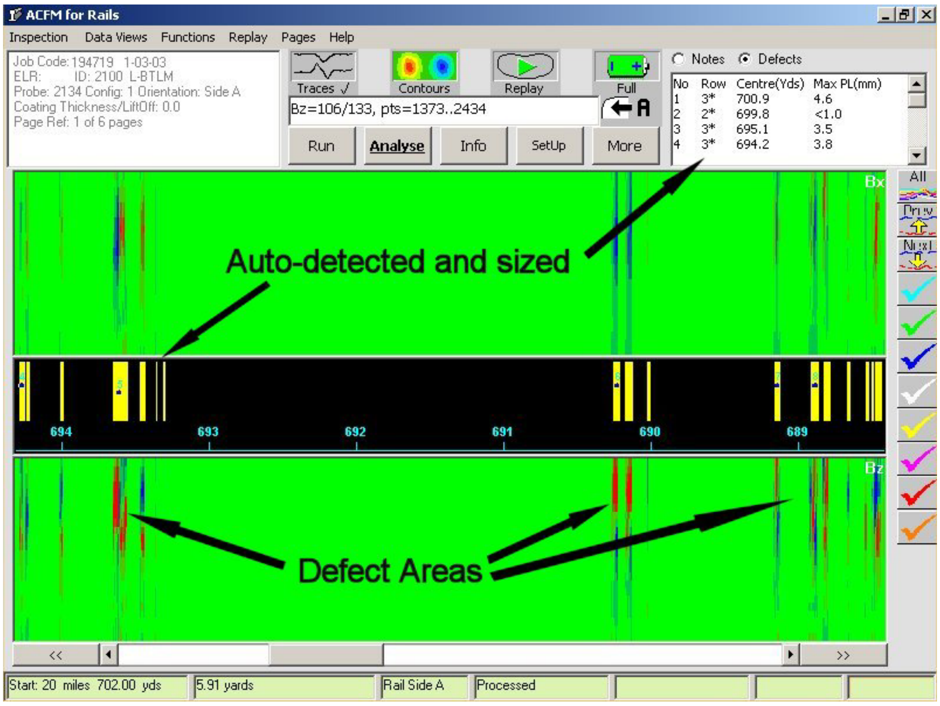

Figure 6. Walking Stick screen layout showing defective rail

Another part of the accreditation process involved EMC testing to both industrial standards[4] and railway specific standards[5]. This work was supplemented by third party reviews to assess the likelihood of interference with specific trackside signalling equipment[6]. This has led to product approval by Network Rail for use even on operational track (Red Zone working).

Application of ACFM to bogies: Railway bogies are currently inspected using a combination of visual, MPI and Ultrasonic techniques. This requires bogies to be thoroughly cleaned and, in the case of MPI, to be stripped of all paint in the inspection areas. In addition, when the bogie is in service, many areas are not open to inspection.

Although it is not possible to gain access to all areas of an in-service bogie, many areas not accessible for MPI can be inspected using ACFM and the ability to operate through coatings reduces the cleaning costs. In addition ACFM can provide a quantitative assessment of the defect depth, and hence severity.

Bombardier Transportation, UK recognised the potential for using ACFM to inspect bogies both at overhaul and in-service and launched a program to introduce ACFM into this sector of the rail industry. TSC developed equipment (figure 7) and probes to meet their target defect size of 5mm long x 0.5mm deep and to simplify inspection for the operator. Automated defect detection and sizing was introduced along with other operator aids to simplify and speed up the inspections. In order to provide an auditable and comprehensive report format for end clients, a semi-automated summary report scheme was introduced which could combine the results from all inspections on a particular bogie.

To evaluate the performance of the technique and to certify its use for this application, Bombardier Transportation's Conformance Certification Body (CCB) and Vehicle Acceptance Body (VAB) conducted an extensive and detailed study. This study involved a literature search on all past papers, applications and performance reports, a full risk assessment, selective laboratory experiments and field trials. This culminated in a qualification dossier[7] which was endorsed by The Engineering Link and The Welding Institute.

One initial application was the inspection of a UK type 91 bogie which had a previously inaccessible weld on the inside of a box section. Access was at arm's length through a small hole in the section enabling a probe to be deployed along the weld toes.

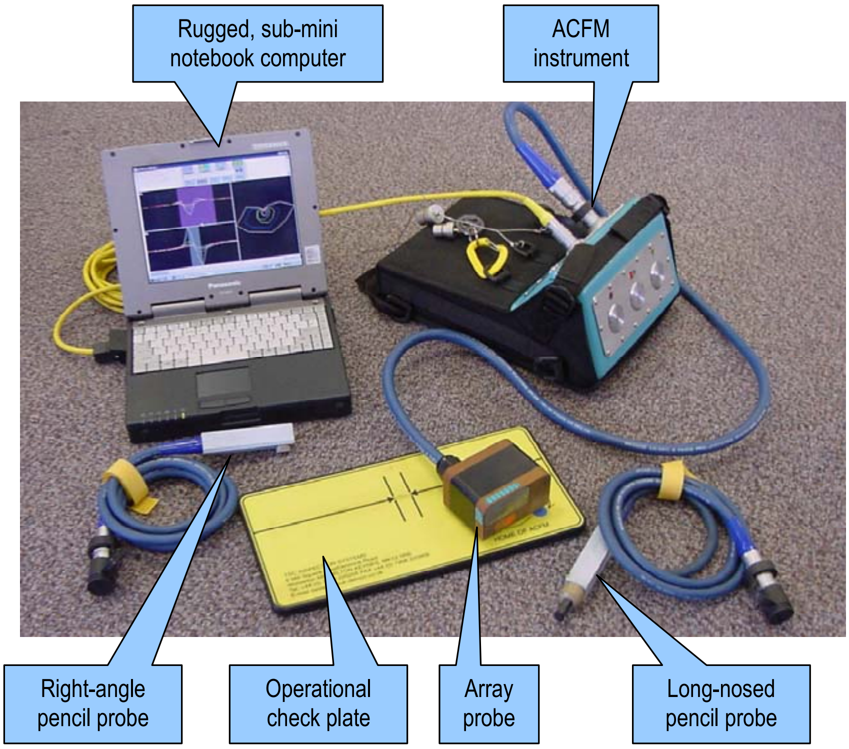

Figure 7. ACFM inspection equipment for Bombardier Transportation

Training: As with any inspection method, it necessary to ensure that operatives are properly trained and certified to operate the equipment. Special training courses have been developed together with operator certification, compliant with EN473. These have been developed for both Axle Inspection and Rail Inspection under the CSWIP certification Scheme[8].

Conclusions: Introducing new inspection techniques into the rail industry is a challenge that involves many aspects of accreditation and approvals. It is also necessary to consider the skills level of operators and training requirements specific to that industry. This paper has shown how inspection technology originally developed for the Oil and gas Industry has met these challenges and been accepted for a number of different applications within the UK.

References: [1] "Evaluation of Electro-Magnetic Non-Destructive Testing Techniques" (Executive Summary and Recommended Way Forward), Dr M Pollard & J.D. Walker, The Engineering Link, December 2000.

[2] "Bombardier Brings ACFM into the Rail Industry", M. Howitt, INSIGHT (Journal of the British Institute of Non-Destructive Testing) Vol 44 No.6, June 2002.

[3] "Thin-skin electromagnetic fields around surface-breaking cracks in metals", Lewis, A.M., Michael, D.H., Lugg, M.C. and Collins, R. , J.Appl.Phys. 64 (8), pp 3777-3784, 1988.

[4] EU EMC Directive 89/336/EEC.

[5] UK Rail regulations SI 2372 1992.

[6] Atkins Rail, Document No. 4340050-L-EC-003

[7] "Alternating Current Field Measurement (ACFM) Qualification Dossier", Stephen Ford, Vehicle Acceptance Body, Bombardier Transportation UK Ltd, August 2001.

[8] Document No. CSWIP-ISO-NDT-11/93R (Requirements for the Certification of Personnel Engaged in Non-Destructive Testing), 3rd edition, September 2001.

Acknowledgement: Support from Network Rail in the development and accreditation of the Walking Stick is acknowledged.