The First 20 years of the A.C. field Measurement Technique

Dr Martin LUGG
TSC Inspection Systems
6 Mill Square, Wolverton Mill, Milton Keynes, MK12 5RB, UK

Abstract

The A.C. Field Measurement technique was originally developed as a non-contacting version of the A.C. Potential Drop technique, with the aim of accurately measuring the depth of surface-breaking fatigue cracks at welds underwater.

Since the publication of the modelling work that made ACFM possible in 1988, the technique has expanded into many diverse applications, both underwater and on dry land.

This paper describes the evolution of ACFM equipment from the first commercial systems produced in 1991 for underwater inspection of welded offshore structures, to the current sophisticated, semi-automated array systems for inspecting drill-string threads, storage tank welds, and rails.

Keywords: ACFM, underwater, rail, threads

1. Introduction

In the mid 1980's, oil companies working in the North Sea were looking for a technique better suited to estimating the depths of fatigue cracks found underwater at welded intersections by magnetic particle inspection (MPI). A.C. potential drop (ACPD) was one technique being used for this purpose at the time, but it was very difficult and slow to use underwater because of the need to maintain very good electrical contact between the voltage probe and the surface. A non-contacting equivalent to ACPD was required. The mechanical engineering department at University College London (UCL) had many years experience in both theoretical and practical developments in ACPD, so a group of UK oil companies approached them to develop the new technique, which became known as a.c. field measurement (ACFM).

ACFM uses induced rather than injected currents but maintains, as far as possible, the same uniform strength, unidirectional currents present for ACPD. This allowed UCL to take existing theoretical models of the effect of semi-elliptical surface breaking defects on the current flow and to extend them to predict the effect on the associated magnetic fields above the surface. By measuring components of these magnetic fields and comparing the results with the theoretical predictions, ACFM is able to determine the length and depth of a defect.

The theoretical model, and early experimental results, were published in 1988[1] and a new inspection technique was born. Over the following 20 years, ACFM has expanded worldwide into a useful addition to the NDT toolbox, particularly for inspecting painted or coated, welded steel structures.

2. The ACFM Technique.

The Alternating Current Field Measurement (ACFM) technique is an electromagnetic technique capable of detecting and sizing surface breaking cracks in metals. The basis of the technique is that an alternating, locally uniform current is induced to flow in the component under test. Because the current is alternating (with typical frequency in the order of 10^4 Hz) it flows in a thin skin close to the surface. When there are no defects present the electrical current will be undisturbed, but if a surface-breaking crack is present the uniform current is disturbed and flows around the ends and down the faces of the crack. Associated with the current flowing in the surface is a magnetic field above the surface that will also be disturbed in the presence of a defect.

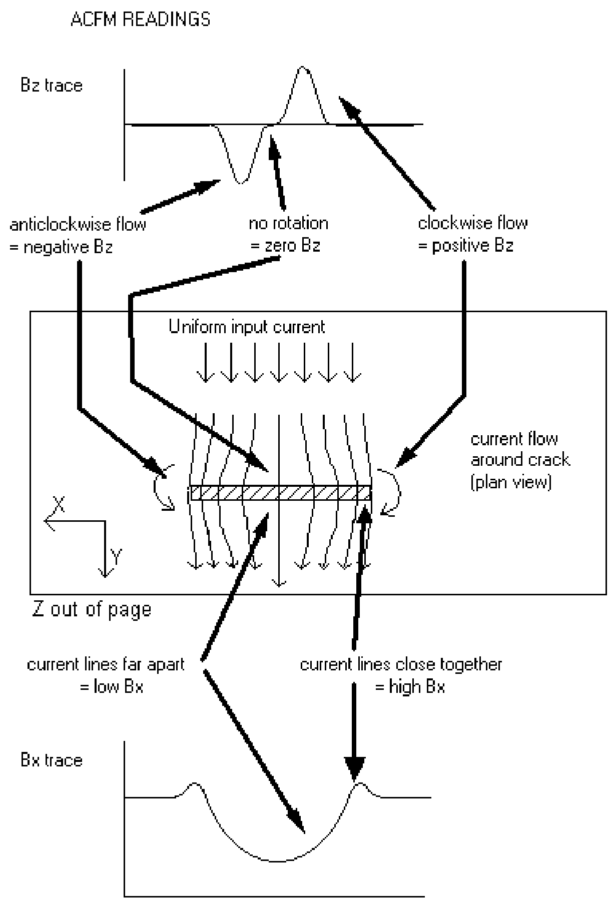

Figure 1. ACFM currents flowing around a defect

Figure 1 presents a plan view of a surface breaking crack where a uniform alternating current is flowing at right angles to the plane of the defect. The field component denoted Bz in Figure 1 (normal to the surface) is zero in a uniform field, but non-zero components are generated by circulating current flows around the ends of the crack. These flows are clockwise at one crack end and anti-clockwise at the other, producing positive and negative signals. The distance between these Bz signals is therefore indicative of crack length. The field component denoted Bx (parallel to the surface and perpendicular to the current) responds to the reduction in current surface density as the current flows around the crack and is therefore indicative of the depth of the defect. In order to estimate defect size the only two measurements required are the percentage reduction in Bx, and the distance on the component between the locations of the maximum and minimum values in Bz.

From a practical standpoint, standard ACFM probes contain a remote field induction system, usually a horizontal solenoid or yoke above the surface, together with two orthogonal magnetic field sensors close to the surface that allow measurement of the two components of magnetic field at the same point in space. The probe requires no electrical or mechanical contact with the component and can therefore be applied without the removal of surface coatings or grime. In order to collect the required data, the probe is moved over the component surface, along a line parallel to the expected defects (e.g. along a weld toe).

The use of a uniform input field provides other benefits, in addition to the ability to model the field-defect interactions. For example, signals vary relatively slowly with probe stand-off from the surface, so surface roughness or large coating thicknesses cause less of a problem than for conventional eddy current inspection. Also, by scanning parallel to the defect, rather than across it, ACFM has less of a problem inspecting at interfaces between different materials.

A standard PC is used to control the equipment and display results. The plot on the left of Figure 2 shows typical raw data from the crack end (Bz) and crack depth (Bx) sensors collected from a manually deployed probe. The right hand section of Figure 2 shows the same data presented as a so-called butterfly plot, in which Bx is plotted against Bz. In the presence of a defect, a loop reminiscent of a butterfly is drawn in the screen and the operator looks for this distinctive shape to decide whether a crack is present or not. 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.

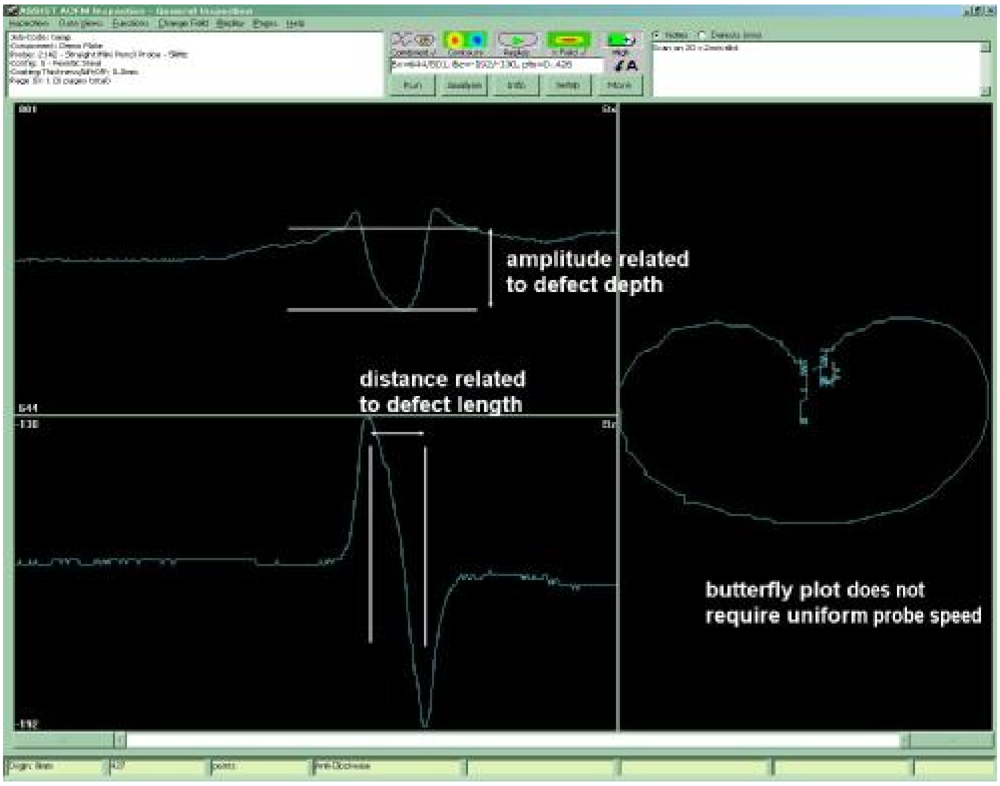

Figure 2. Typical ACFM signal response to a defect

3. Underwater ACFM

Since the ACFM technique was originally developed for sizing cracks underwater, the first practical system was an underwater one. The first subsea instrument to utilise the ACFM technique (the U11) was built in 1991. Although developed for sizing defects found by other techniques (usually magnetic particle inspection), the fact that ACFM probes work through rust and paint etc. mean that ACFM is also well suited as a detection technique. The prototype was used in a series of Probability of Detection trials on real fatigue cracks on tubular welded intersections in a diving tank at City University, London. The results demonstrated that ACFM was at least as good as MPI for detection, and with the added advantage of providing defect depth information accurate to about +/- 15% [2]. Other advantages of ACFM over MPI are that it does not require the diver to interpret the results (this is done by the topside operator), it does not require good visibility (so inspection can be done 24 hours a day or in muddy waters), it can be carried out in quite strong currents, and all results are stored for audit purposes or comparison with earlier inspections.

The U11 contained a series of separate pcbs for each circuit function. This made the subsea unit quite large. Putting this into a housing rated for 300m water depth resulted in a heavy unit as well.

In 1995, the U11 system was replaced by the U21, which took advantage of developments in electronics to reduce the size and weight of the subsea unit, while at the same time adding the ability to support probes with multiple sensors, motors and encoders. The first of these units was developed for Norske Shell to allow inspection of parts of the Draugen platform only accessible by ROV[3]. The limited dexterity of ROV manipulators means that they are generally not able to move standard probes along welds with enough precision for a reliable inspection. To get round this problem, TSC developed probes containing 2D arrays of sensors with compliance in the vertical direction to ensure good coverage of the weld even when the probe is misplaced. The probes were held on by suction to allow the ROV to let go while readings were taken. To improve the resolution of data, the whole array was scanned across the surface by an electric motor. Once the readings were taken at a given location, the ROV moved the probe along to the next location, and the whole weld was inspected in this way in a series of overlapping “snapshots”.

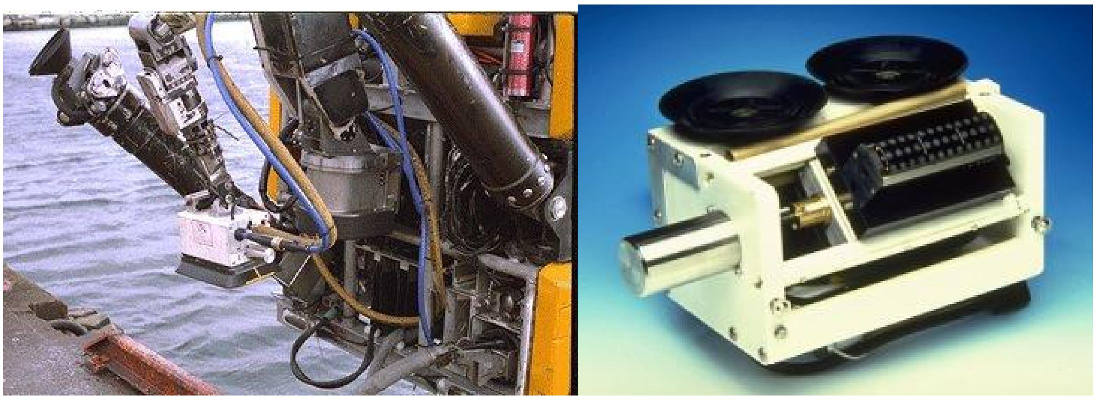

Figure 3. ACFM array probe for butt welds mounted on ROV (left); probe for fillet welds (right)

In 2002, a major advance took place with the launch of the U31 system. In this system, much lower currents are used which allows a reduction in power consumption. Also, surface-mount components replace the previous discrete ones, and the number of pcbs is reduced to two. The result is a large reduction in the size and weight of both the subsea and topside units. This makes it much easier to transport ACFM equipment offshore, and also allows deployment by smaller ROVs.

Table 1. Comparison of ACFM subsea systems

	U11	U21	U31
Subsea Unit Height	87cm	80cm	27cm
“ “ Diameter	43cm	37cm	14cm
“ “ Weight	55kg	45kg	9kg
Topside Unit Weight	15kg	11kg	3kg
Max no of channels	2	64	32

Figure 4. U11 system (top left); U21 and U31 subsea units (top right); U31 system (bottom)

4. ACFM for Drillstring Thread Inspection

Following the successful deployment of ACFM underwater, the oil industry started to look for other applications where the technique would be beneficial. One such application was the inspection of the threaded connections on drillpipe and other drillstring components. These are usually inspected by MPI, but this is difficult to do, especially on the female box threads, and it was known that MPI can miss defects in this situation, leading to the possibility of an expensive downhole failure[4]. ACFM offered the advantages of a signal response that increased with defect depth (thus having a greater probability of not missing a significant defect), no need to carry out inspections in darkened areas, and no need to rotate the drillpipe. In addition, the relatively uniform geometry found in a thread meant that background signal changes are very small which allowed the development of software that could automate detection.

Thread inspection can be carried out with conventional single sensor probes, using replaceable shoes to fit each thread form. However, inspection speed can be greatly increased by using an array probe, with sensors in each thread root, that inspects the complete thread in one 360° scan.

In 1996 group of UK oil companies funded the development of an ACFM system called ATI (Automated Thread Inspection) that inspects pin and box threads of drillstring components, giving automated detection and sizing of defects greater than 8mm long by 0.75mm deep [5].

The original ATI system was based on the U12 instrument (the topside equivalent of the U21 underwater instrument). This was fairly bulky and not particularly rugged. However, developments in the instrumentation used above water has continued to mirror the developments of the underwater equipment, and the latest ATI system uses the Amigo instrument which is IP54 rated, light and rugged and ideally suited for use in the drillpipe yard.

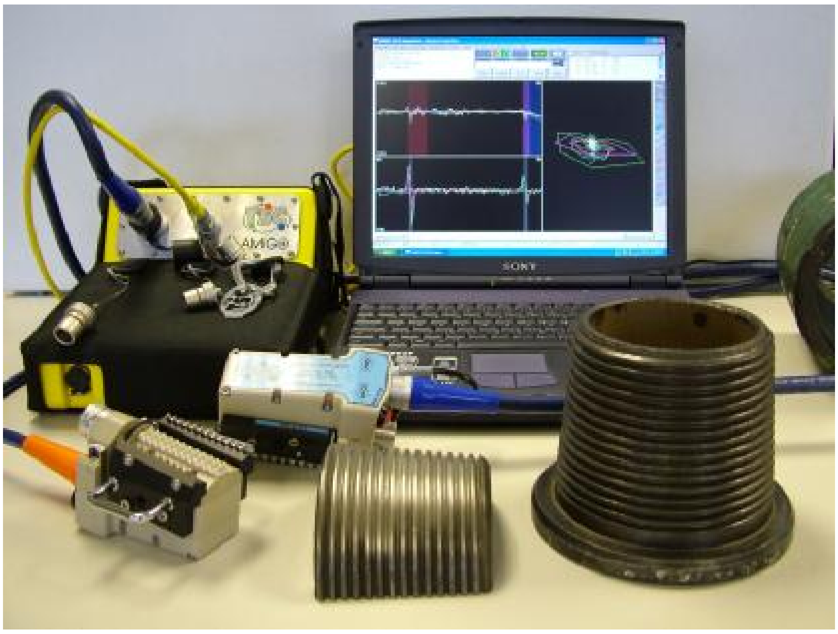

Figure 5. Amigo-based ATI system

5. ACFM in the Rail Industry

Another industry that has benefited from the ACFM technique, and in turn has driven major improvements in technology, is the rail industry.

Environmental concerns have led to recent moves towards water-based paints on bogies. This meant that it was much more difficult to remove the paint for inspection by MPI, so a leading UK train company turned to ACFM for this application. The first inspection task was on an internal weld that was accessible only by reaching in through a small port and past an internal stiffener plate, so could not be inspected by MPI. Special pencil probes were developed to inspect this and other tight geometries and short welds found on train bogies.

While the bogie application was being developed, extensive trials were also carried out on axles to demonstrate that detection results were at least as good as those obtained previously [6]. The trials showed that ACFM outperformed MPI - particularly in terms of consistency of results.

Figure 6. ACFM inspection of rails (left) and bogies (right)

Following these successes, attention was turned to the sizing of rolling contact fatigue (RCF) cracks on rails. Rail breaks from RCF cracking, particularly on bends, was a major problem in the UK in the 1990s. Inspection was conventionally carried by visual inspection and ultrasonic "walking stick" probes. Visual inspection gives no indication of the depth of any defects seen, while there was concern that ultrasonic probes were not able to depth size the deepest defect if it was closely surrounded by shallower ones.

RCF defects have very different morphology to the standard fatigue cracks for which ACFM was developed. They are generally inclined at only 30^{o} or so from the surface, but then may change direction to grow towards the surface leading to loss of part of the rail surface, or conversely may turn downwards rapidly through the rail leading to a rail break. In addition to this, the crack front will often be wider under the surface than the length on the surface, and crack depth will be large compared to surface length. All these factors mean that the theoretical sizing model developed in the 1980s does not work for RCF cracks. To overcome this, extensive calibration trials were undertaken using rail with real RCF cracks which were then broken open. Results of sizing using the new calibration procedure were subsequently compared with other defective rails and generally good agreement was found [7].

Special software incorporating the new sizing algorithm was produced. This software also included automated detection, and reporting of the deepest defect found in a given length of rail. An ACFM array probe, shaped to the rail profile, was fitted to a "walking stick" that also carried a modified high-speed Amigo instrument and laptop. Network Rail has accredited the ACFM walking stick system.

6. Conclusions

Since publication of the theory behind the technique 20 years ago, ACFM has continued to evolve to solve inspection problems in a wide variety of industries. Smaller, lighter, faster instrumentation and more sophisticated software has been developed for inspection by ROV, for automated inspection of threads, and for rail inspection. Further developments are already underway for a new generation of instrumentation that will offer even more improvement in speed and sophistication.

References

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

[2] Rudlin, J. and Dover, W.D. "Results of Probability of Detection Trials". Proceedings of International Offshore Contracting & Subsea Engineering, Aberdeen, UK, A.O.D.C., 13-16 October, 1992.

[3] Raine, G.A. and Lugg, M.C. "ROV Inspection of Welds – a Reality", INSIGHT, 38 [5], pp 346-350, 1996.

[4] Gaynor, T.M., Roberts, D.L., Holman, E. and Dover, W.D. "Reduction in Fatigue Failures through Crack Detection by Alternating Current Field Measurements" IADC/SPE 35033. Presented at IADC/SPE Drilling Conference, New Orleans, 12-15 March, 1996.

[5] Topp, D. "Use of the ACFM Inspection Method to reduce Downhole Drillstring Failures", presented at Australia Oil & Gas Conference, 2001.

[6] Howitt, M. "Bombardier brings ACFM into the Rail Industry", Insight, Vol.44, No. 6, pp 379-382, June 2002.

[7] Topp, D. and Smith, M. "Application of the ACFM inspection method to rail and rail vehicles", Insight, Vol 47, No 6, pp 354-357, 2005.