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'Fitness for Purpose' Using ACFM for Crack Detection and Sizing and FACTS/FADS for Analysis

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SUMMARY

A new a.c. field measurement technique has been developed for simultaneous crack detection and sizing. It can be used for inspection of welded joints, threads and other components, in air and underwater. The technique has been successfully tested in air and diving tank trials on fatigue cracked components. Accurate crack detection and sizing can be linked to fracture mechanics to give remaining life estimates. This paper describes the use of ACFM for welded joints and threads and how it can be linked with fracture mechanics software to give fitness for purpose or inspection schedules.

The a.c. field measurement (ACFM) technique has been developed from the a.c. potential drop (ACPD) technique (1) and (2) which was originally used for fatigue crack sizing and crack growth monitoring. The ACFM technique is simpler in operation as it depends on the measurement of the near-surface magnetic fields rather than the surface electric fields, thus requiring no electrical contact. Theoretical work carried out at the Wolfson NDE Unit in the Mechanical Engineering Department at University College London determined the relationship linking these two fields (3). Thus existing models of electric fields around cracks can be used to size cracks using magnetic field measurements. This non-contacting sizing capability relies on the use of a undirectional input current in the region under inspection, similar to that required for the ACPD technique. For the ACFM technique, the input current is induced into the specimen thus making the system fully non-contacting.

The ability to simultaneously detect and size surface breaking cracks offers significant potential benefits over existing techniques such as magnetic particle inspection, acpd and eddy currents. The use of a undirectional input current provides further practical benefits as well as allowing crack depth estimates. Firstly, the decay in the strength of the input field with probe height is relatively small so that variations in signal with probe lift-off are reduced. Secondly, the current flow is arranged normal to the crack or weld toe so that no perturbation in direction and hence no signal occurs at the interface due to the change in material permeability. A final benefit is that the technique requires no calibration. Techniques requiring calibration rely on the measurement of signal strength on a standard notched sample. For weld inspection the standard block is invariably of different material to that at the crack location leading to errors in interpretation.

The advent of NDT equipment such as acfm, allows one to employ 'Fitness for purpose' concepts. Special purpose software has been produced to size remaining life estimates for cracked components. The software for welded components (FACTS) and threaded components in drillstrings (FADS) is briefly described.

INTERPRETATION OF ACFM TO GIVE DETECTION AND SIZE

The theoretical modelling carried out for ACFM utilises a plane crack with a normally incident electric field, E_o, shown in Figure 1. The cartesian co-ordinate system used defines the y-axis as the direction of incident current flow, the x-axis lying along the crack edge, and the z-axis normal to the metal surface. The incident electric field then has one non-zero component, E_y, equal to E_o. The background magnetic field will be orthogonal to this electric field, so that the component parallel to the crack edge, B_x, will have the largest value. In the absence of a crack, the other two components B_y and B_z will be zero.

The presence of a crack diverts some of the current away from the centre of the crack and concentrates it near the crack ends, giving rise to perturbations in all three components of magnetic field. Changes in the principal component, B_x, reflect these changes in the current density so that B_x is below its background level over most of the crack length but rises above that level near the crack ends. The component B_y is determined by the current flow parallel to the crack edges and thus peaks towards the crack ends and is of opposite sign on each side of the crack. The vertical component B_z is determined by the circulation of the current around the crack ends. Since this circulation is clockwise at one crack end but counter-clockwise at the other, the B_z signal consists of a peak above one end and a trough above the opposite end of a surface breaking crack. Figure 2 shows typical traces expected for the three components.

Quantitative predictions of the perturbations to the magnetic field have been produced for a variety of surface breaking cracks of different shapes and sizes in ferritic steel and aluminium. These have been compared favourably with measured values. In practice computer programs exist to convert the a.c. field measurements to crack length and depth.

APPLICATION OF ACFM IN NDT

Welded Joints

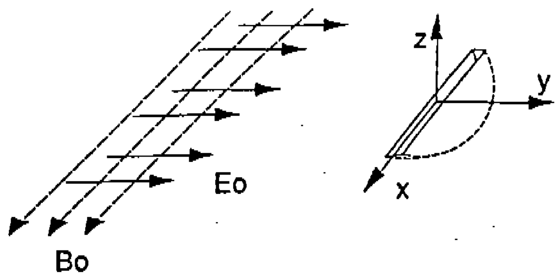


Figure 1. Coordinate definition for a surface-breaking crack in a uniform incident field

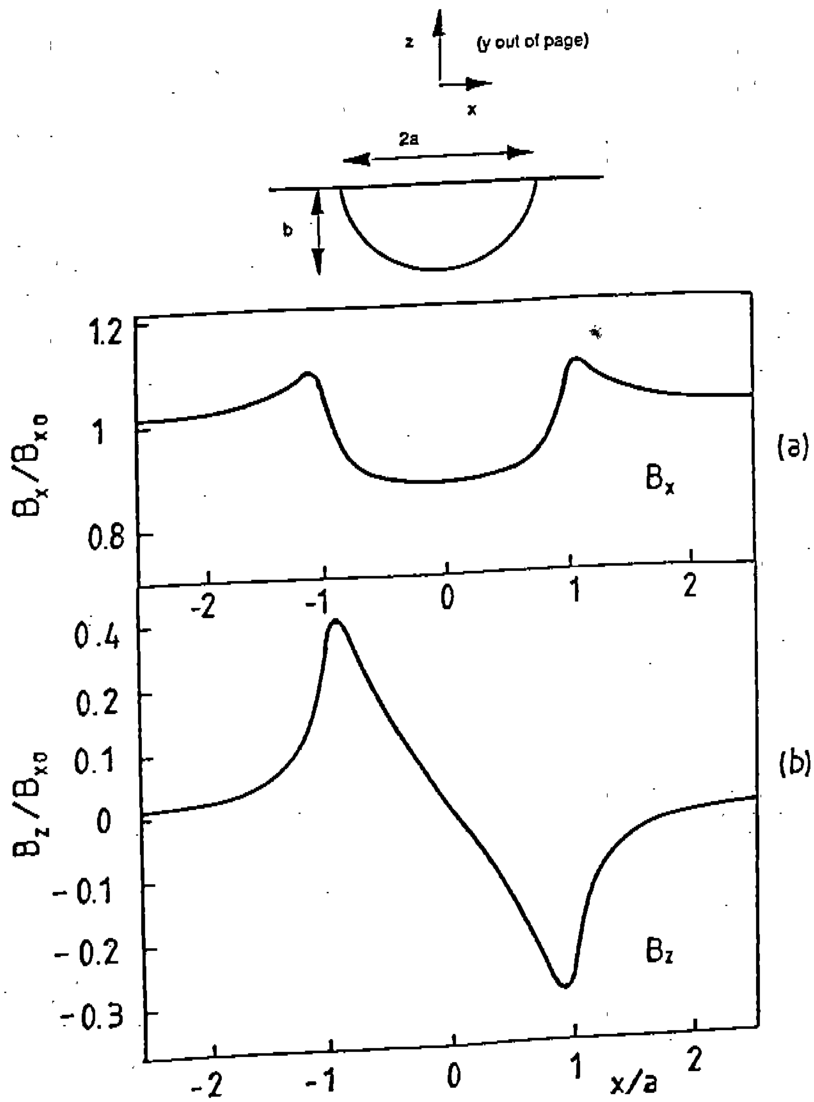


Figure 2

The theoretical modelling described in the previous section has been incorporated into an inspection system, based on the ACFM technique for crack detection and sizing. Four versions exist for laboratory use, in-service NDT, underwater inspection, and drillstring thread inspection.

One of the most widely researched application areas is that of welded joints. Particular attention has been paid to the underwater application of the techniques in the offshore industry where tubular welded connections require periodic inspection. The presence of a weld leads to high stresses at the change in geometry. Fatigue cracking generally occurs along the weld toe or between two weld beads parallel to the weld toe. This makes detection by scanning a probe along the length of a crack, much easier than scanning across a crack. The B_y component is not suitable for this application because the sign reversal across a crack, when associated with slight lateral deviations by a probe scanning along a crack, would result in large changes in signal. For the practical application of weld inspection, sensors to measure B_x and B_z are therefore used, with the latter best suited for detecting crack ends and therefore obtaining length estimates, while the former is used to obtain estimates of crack depth.

Purpose-built instrumentation shown schematically in Figure 3 has been produced for the Offshore Industry which can be used for both acfm and acpd inspection. The instrumentation has displays both topside and underwater (4). The topside unit also includes the acfm sizing algorithms described in the previous section. Probes development and trials have formed part of a Joint Industry Project funded by DEn, TSC, Shell, BP and Conoco.

The acfm underwater trials were carried out in the diving tank at the UCL Underwater NDE Centre. The two divers used had considerable North Sea experience although neither had used the acpd or acfm techniques before. Despite this, the ease of use of the system meant that good, repeatable results were possible after only a short training period.

The purpose of the trial with the prototype system was to assess the sizing capability of the technique in an underwater situation, as well as to obtain valuable feedback from the operators on aspects of probe design and procedures for efficient use. The trial could not be expected to assess the probability of detection capability of the system in the time available, so in order to maximise the information obtained a single double-X node was used which contained cracks at six of the eight saddle sites available. The approximate extents of the cracks were marked on the joint before the trial.

The procedure adopted for each crack was as follows. A mid-range gain was selected and a continuous trace from the B_z coil was recorded while the probe was swept steadily around the weld toe. The results of this trace were used to locate the crack ends more accurately and to determine the structure of the crack (i.e whether it consisted of a number of smaller cracks or contained an overlap or line contact). Having determined the approximate length of the crack it was re-inspected by recording readings from both the B_z and B_x coils at regularly spaced intervals. This interval was typically 10mm but was reduced to 5mm for short cracks (i.e. less than 50mm long). By the end of the trial, the whole inspection procedure for a given crack required only 15 minutes.

Some typical results obtained during the trials are shown in Figure 4. These show readings recorded by both sense coils above a crack estimated to be 21mm long by 2.3mm deep. This figure clearly shows features predicted by theory which were given in Figure 2. The results from all the inspections were used to determine length and depth estimates for the cracks inspected. In order to obtain these estimates two measures of the magnetic field distribution are required. Firstly, the distance between the peak and trough in the B_z signal, is required as an initial estimate of crack length. Secondly, either the amplitude of the B_z signal as a fraction of background field, $\Delta B_z/B_o$, or the amplitude of the B_x signal, $\Delta B_x/B_o$, gives an initial estimate of aspect ratio. A final iteration then produces estimates of crack size. Figure 4 illustrates the definitions of the data requirements described above. Figures 5 a,b show the sizes obtained for all the cracks inspected. Figure 5 a shows a comparison of the predicted lengths with those measured by MPI. The agreement is very good, being generally within 5mm (i.e. at least as good as the increment between successive readings). Figure 5 b shows a comparison of the predicted depths using the B_x signal amplitude with those measured by ACPD. Again the agreement is good, with the estimates agreeing to within 0.5mm. Depths estimates can also be made using only the B_z signal amplitude. Thus additional results can be used to confirm the first estimate.

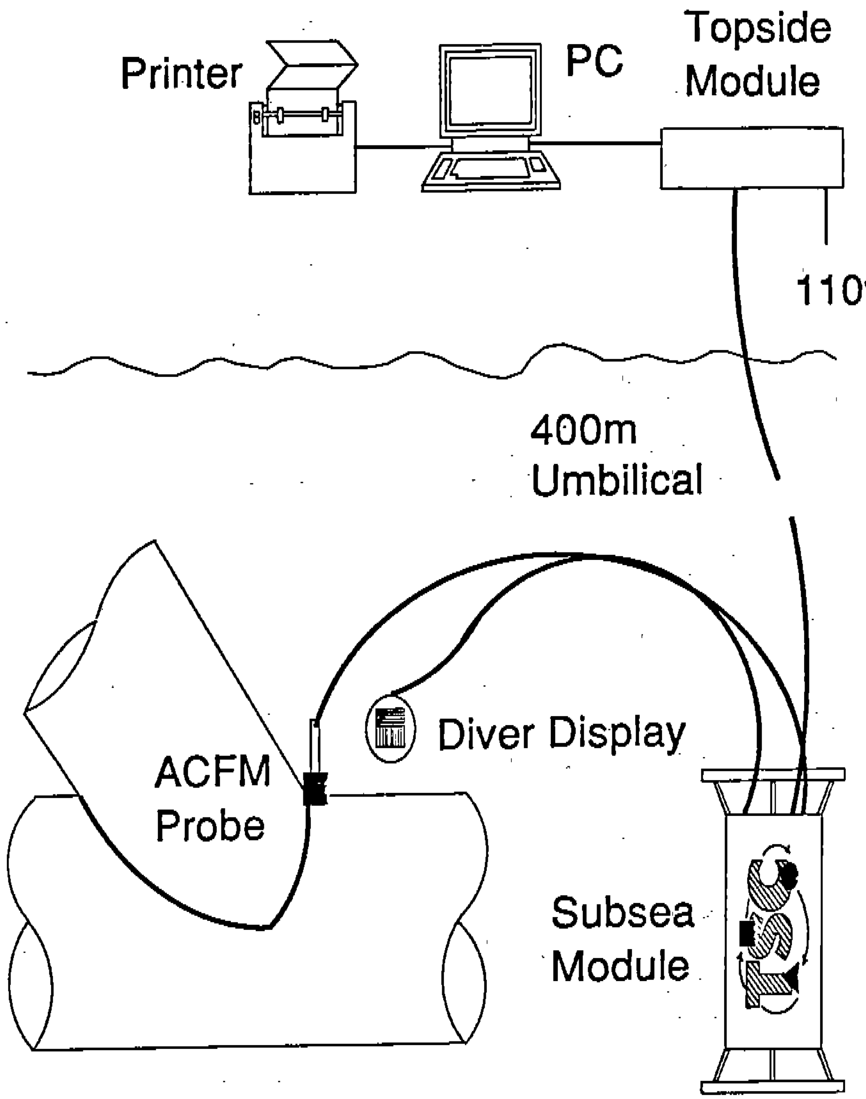
The diving trials described here proved to be very successful. Separate air trials using similar instrumentation also resulted in rapid, accurate measurements of the lengths and depths of a range of simple defects. However, it was quite clear from both of these experimental studies that acfm was extremely good for crack detection. As a consequence a full Probability of Detection trial will be conducted in early 1991. This should demonstrate the performance of acfm as a combined detection and sizing technique for welded joints. For ease of crack detection a plot of B_z versus B_x is used. This 'butterfly' plot, shown in Figure 6, gives a very distinctive crack detection signal.

DRILLSTRING THREAD INSPECTION

The problem of downhole drillstring failure, and the costs associated with such failures, have long been recognised. Reduced failure rates can be achieved using fitness for purpose assessment, based on fracture mechanics. This requires reliable in-service inspection to provide crack detection and details of crack size.

A new non-contacting automated thread inspection system has been developed (5) for this purpose. The system utilises pneumatic deployment of an array of ACFM sensors which allows all threads of a connection to be accurately and reliably inspected. ACFM readings are recorded under computer control and an automated interpretation using theoretical signal inversion is conducted. This provides simple PASS-FAIL control as well as data storage for subsequent off-line detailed analysis.

The system is completely portable and is self-contained and has been developed for use on site. All aspects of the system are controlled by an on-board microprocessor and no interpretation is required by the operator. There is therefore no subjective interpretation. The development of this new system was funded by BP.



Underwater ACFM Crack Microgauge

Figure 3

Figure 4 Magnetic fields obtained using an induced field - Crack FM1b

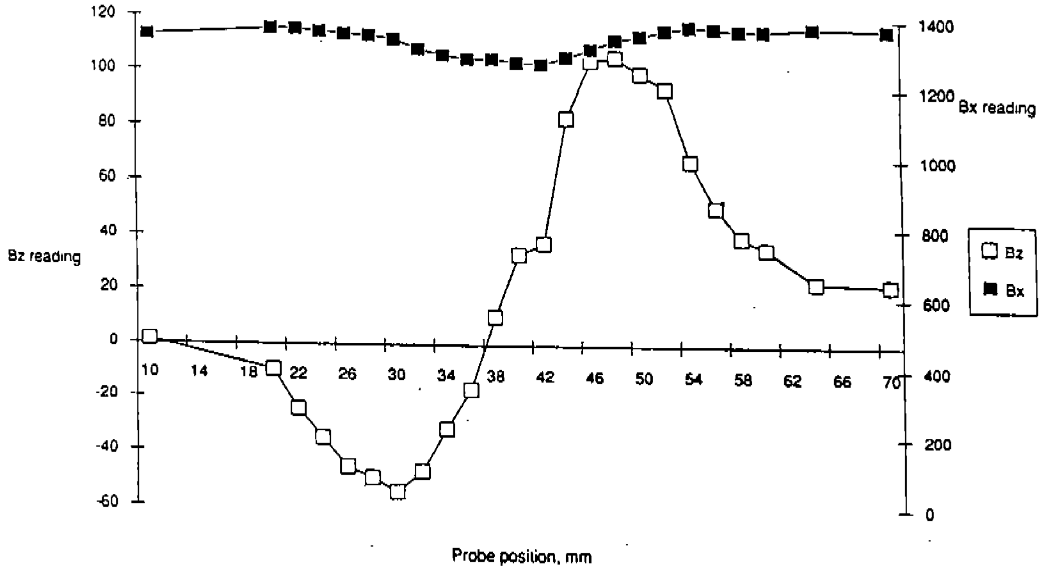


Figure 5a Comparison of estimates of crack length from Bz with MPI measurements

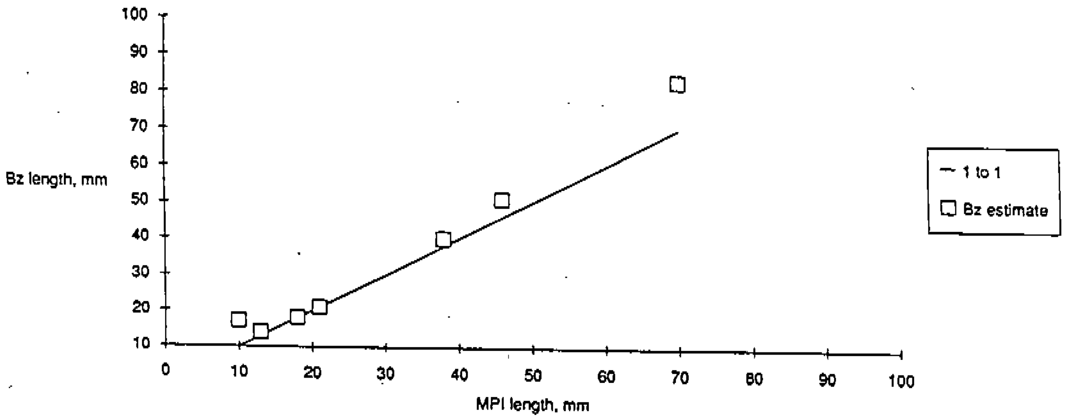


Figure 5b. Comparison of estimates of crack depth from Bx with ACPD measurements

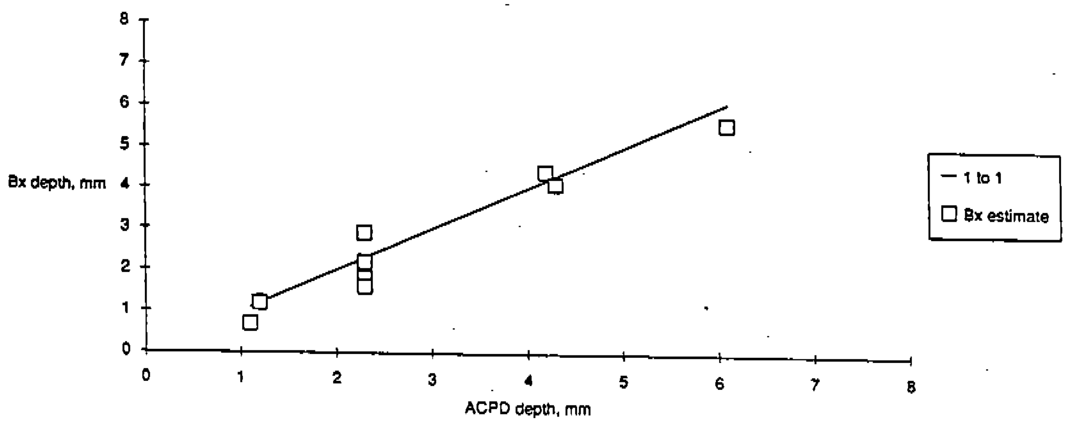
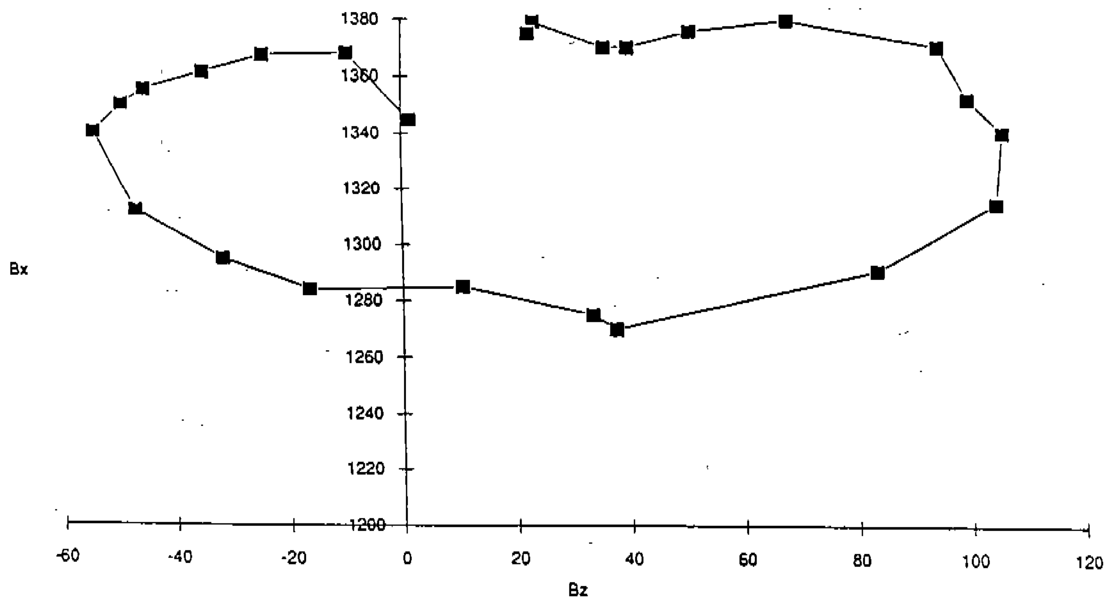


Figure 6 Butterfly plot for crack FM1b



General Arrangement

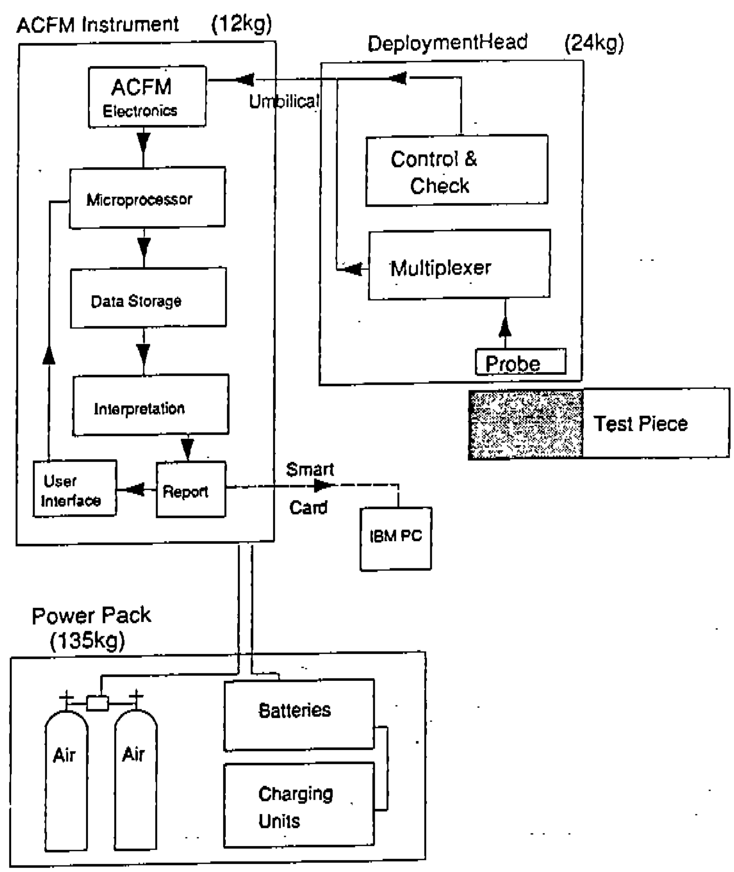


Figure 7

The acfm part of the system employs an array of sensors arranged such that each thread is interrogated by a pair of orthogonal sensors. A uniform ac field is induced into the component using an induction yoke, both sensor and yoke are non contacting devices. The array of sensors and yoke form the inspection probe which is machined to suit the thread form of the component.

The mechanical deployment system rotates the probe through 185° at a uniform speed. By using two probes diametrically opposed, this produces an overlapping scan of the whole connection. While the probe is being moved around the thread, the sensors are switched sequentially to the signal conditioning circuits at a frequency of 500Hz. During a scan, which takes around two minutes, a total of 60,000 field measurements are made.

The whole system is controlled by a microprocessor. This controls the mechanical and electronic functions of the system and then analyses and reports the results. The overall system layout is given schematically in Figure 7; the hardware setup for pin inspection is shown in Figure 8.

The prototype system has been evaluated in a series of trials by inspecting a range of defects in both pin and box. These have shown that a defect 8mm x 0.5mm can be reliably inspected. As an example, figure 9 shows scans for a defect of size 16.0mm x 3.0mm. The depth predicted by the computer for this crack (2.9mm) was in excellent agreement with the true depth. Final validation tests will be completed by the end of 1990 upon which the complete system will undergo a series of extensive field trials.

ACFM For Quality Control

Advances in the use of multiple sensor arrays plus fast modelling now mean that it is possible to use a.c. field measurements for quality control tasks. Mathematical modelling and hardware developments are underway which will allow the "electromagnetic imaging" of components. Such images can be created with input fields of different orientation and frequencies to provide detailed information about surface condition and geometry for manufactured components. It has long been recognised that there are significant advantages in using more than one inspection technique for any particular task, on the basis that complementary information from inspections based on different physical principles enhances confidence in the inspection results.

The development known as AIRES (Automated Image Reconstruction using Expert Systems) (6) employs artificial intelligence techniques to integrate data from vision systems and ACFM sensors to allow the component to be "modelled" any anomalies from the specification highlighted. The project is a collaborative venture between UK, France and Germany and is expected to be completed at the end of 1992.

FATIGUE CRACK GROWTH SOFTWARE

FACTS

Due to the complex geometry of tubular connections it is extremely difficult to analyse this type of joint. Major research programmes, both in the UK and other countries, have been mounted to provide experimental evidence on the fatigue behaviour of tubular connections. Studies have also been conducted on models to predict the fatigue behaviour of tubular joints using fracture mechanics. A substantial amount of this work was carried out at University College London and led to the development of a *rapid modelling* methodology.

One of the objectives of a recent programme (7) was to produce a software package which has all the analytical tools and databases of experimental results. This objective was met with the release of the first version of FACTS in November 1989. FACTS provides access to the most complex of fracture mechanics calculations within a user-friendly software framework. This integrated framework provides for sophisticated calculations to be performed and for results to be plotted and printed out as report quality documents. Access to the experimental database is also printed out.

The methodology to be included in the software and the development of the software was supervised by a Working Group consisting of industrial and academic experts. This group critically reviewed the various analysis methods, experimental data prior to incorporation in the software.

The analysis modules were developed by research groups at UCL and Nottingham University. These modules were implemented as stand-alone routines which could be tested individually and therefore made available to Working Group members for trial use. Once the modules were approved, they were sent to Technical Software Consultants Limited, a commercial software house, for incorporating into the overall framework.

Once the software was developed, a comprehensive validation exercise was performed by Brown and Root Vickers (BRV). The validation consisted of module level checking as well as comparing results predicted by FACTS with published analytical and experimental results. In addition, BRV compared the results produced by FACTS with in-house analysis programs.

The calculations possible with FACTS and some of the features are listed below:

Stress Analysis

- Stress concentration factor calculations using Kuang, Wordsworth and Smedley, Efthymiou and Durkin, or HCD equations.
- Stress distribution calculations using UEG or HCD equations.

Load History Assessment

- Time series generation form a specified power spectral density with rainflow and range counting.
- Input of multiple sea states through scatter diagrams.
- Calculation of a weighted average stress range from a nominal load history or stress input.
- Calculation of a weighted average stress range from load or stress exceedance diagrams.
- Closed form solutions for calculation of equivalent weighted average stress range.
- Support for Pierson-Moskowitz, JONSWAP and other user specified spectra.

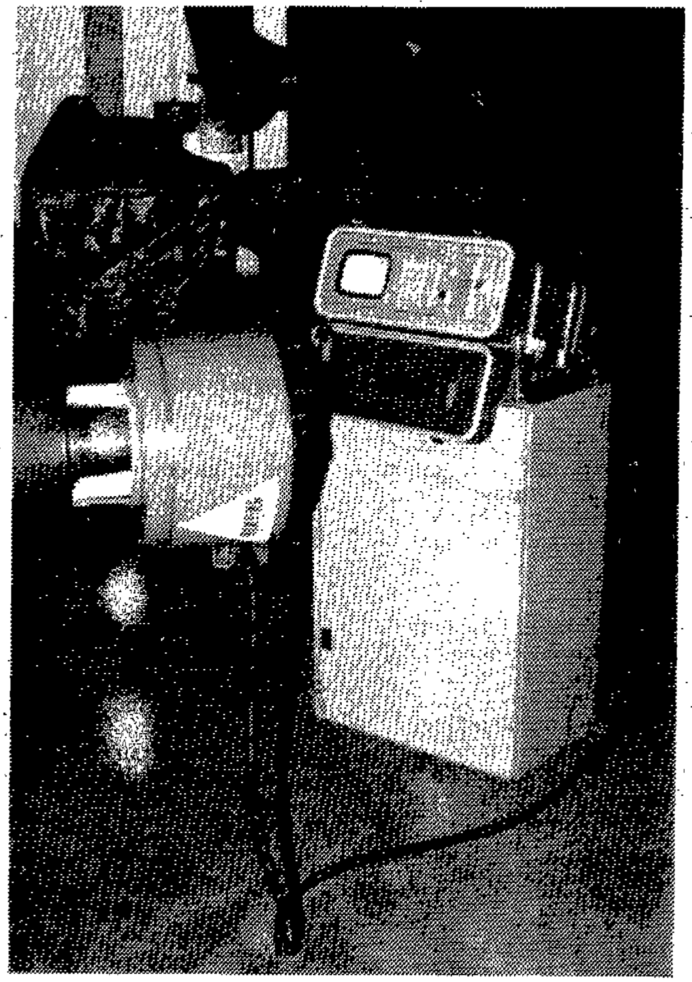
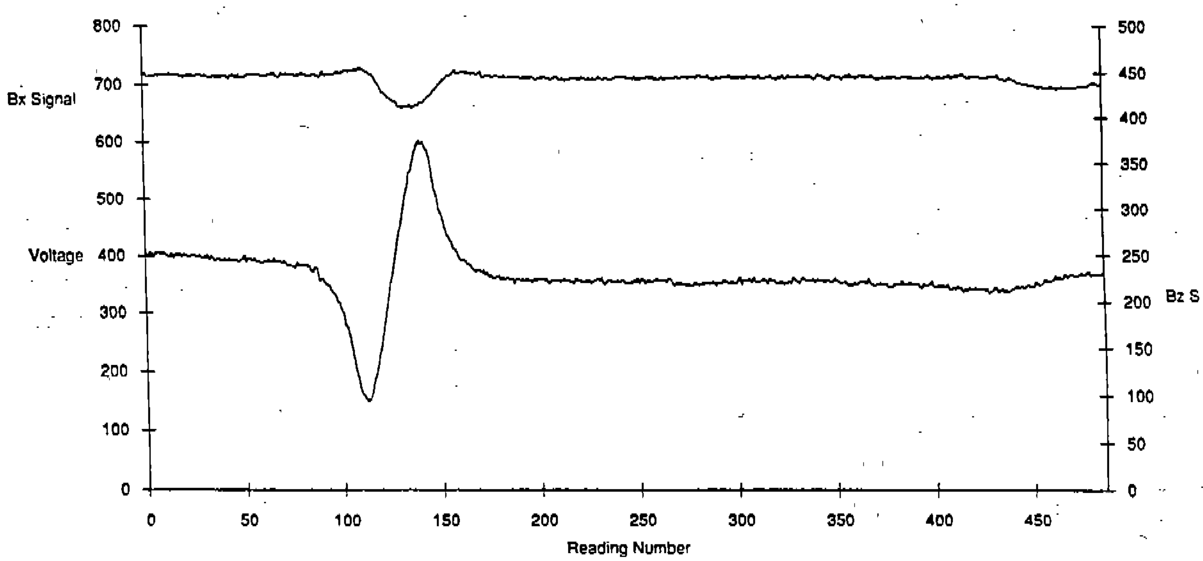


Figure 8 Pin Deployment Head
(Front Cover Removed)
Inspection and Power Supply Unit

Figure 9 Signal From a Defect 16mmLong 3.0mm Deep



Fracture Mechanics Calculations

- Crack growth rate prediction using several different analytical and empirical stress intensity factor solutions such as Newman-Raju, Holdbrook-Dover, Niu-Glinka weight function, O-integral, AVS, TPM etc.
- Remaining life calculations.
- Production of S-N curves.
- Calculation of Y-curves.
- Incorporation of linear load shedding algorithm.

Databases

- Experimental SCF and S-N database of tubular joint data accessible from the program.
- Materials database contains commonly used structural steel properties and may be extended by the user.
- dBase III® compatible database format.

Report Generation

- Publication quality tabular and graphical data may be output using a variety of hardcopy devices.
- Graphics may be customised by the user.

Ease of Use

- Unique route selection front-end guides the user through the compatible and necessary calculation options.
- A menu-structured approach with context sensitive help.

Documentation

- Comprehensive technical, programmers and user manuals for the analysis routines.
- User manual for the FACTS software.
- Validation report including all test cases.

System Requirements

- IBM PC-AT, PS/2 or compatible system.
- 640 kB memory.
- DOS 3.3.
- Minimum of 3MB free disk space.
- A maths co-processor is recommended.

The final version of FACTS has been supplied to all Sponsors together with full documentation. It is now available to non-sponsors. FACTS is a successful development of a user friendly software for the Offshore Industry. It was produced through collaboration of Operators, Designers, Universities and a Software Company.

FATIGUE ANALYSIS OF DRILLSTRINGS (FADS)

Drill strings are designed to resist fatigue failure and hence in-service failure rates are low. Unfortunately, the consequence of even a few failures is costly and the desirable failure rate is below that achievable by conventional design methods. In these circumstances an economic design with a very low failure rate requires a fatigue and fracture mechanics assessment at the design stage combined with high quality in-service inspection using NDT techniques. To achieve the greatest economics in operation, precise calculation and prediction of likely performance are required together with accurate and reliable detection and sizing of any flaws that emerge in service. Given this situation one can specify the longest service interval, for a given low failure rate, that can be undertaken between inspections.

The FADS project (8) has shown that the first objective can be achieved and the study provided an analysis for two thread geometries on one steel, AISI 4145. The main deliverable is a computer based analysis system for remaining fatigue life (FADS) based on new results that provided parametric stress equations, materials data, fatigue and fracture mechanics analysis, and validation from full scale tests.

The individual stages of the project were to produce the following individual software modules:

i Materials database

ii Parametric solutions for SCF in threaded connections

iii Initiation Life model

iv Propagation Life model

Of these, (i) and (ii) could be "stand alone" modules whereas (iii) and (iv) would both require input of material parameters and hence should logically be linked with the materials database. Thus to make best use of the modules an integrated package was developed whereby the end user was able to access all modules and cross-call between them. In this way, the user has to have access to the full facilities of the analysis package but could simply elect to use certain parts as required. The database could be used without the other modules, likewise the stress analysis module could be used without calling the others. In this way, maximum flexibility was maintained for the user.

The software package allows the output of each module to be presented in graphical form on the screen and also allows output in the form of text files. It is possible for end users to specify interaction with existing databases or spreadsheets.

In addition to output from the total package, integration of results from the individual modules is also possible. For example, the end user may wish to predict a fatigue life to failure, assuming a given flaw size, under various blocks or cyclic loading. For each block the crack growth would be determined. The results from these individual blocks would then be brought together to provide a life to failure calculation. The package will therefore contain this facility, the results of which could be used to determine inspection requirements etc.

The loading input for the basic package is restricted to cyclic loading blocks. As described above, the requirement for multiple block loading will be satisfied by considering the results from individual blocks. At a later stage, however, it may be desirable to enable service loading to be input via some kind of cycle counting method. This would be an additional exercise and could again be integrated into individual user's databases of service load listing and drill pipe records.

FADS has been validated by using it to analyse and predict fatigue crack growth in connectors subject to fatigue tests in the laboratory under controlled conditions. These tests were for both axial loading and rotating bending.

SUMMARY

The ACFM technique, and its predecessor ACPD, have been shown to have the following capabilities and features.

- Defect Detection
- Defect Sizing (length and depth of surface breaking defects)
- Require no electrical contact
- Suitable for use through coating (metallic and non-metallic)
- Requires no calibration
- Can be interpreted automatically
- Can be used in conjunction with sensor arrays

Examples have demonstrated how the two techniques have been developed for a range of industrial applications with varying degrees of sophistication. The techniques are unique in their ability to both detect and size surface breaking defects, without prior calibration or, for ACFM, any electrical contact. The applications are supported by mathematical models of the electromagnetic fields which allow signal inversion techniques to be employed to give defect characteristics. The user of sensor arrays has overcome many of the difficulties associated with component scanning and has been demonstrated in a number of industrial applications. ACFM, although relatively new is proving to be a major advance in NDT.

The advent of rapid fracture mechanics modelling and its incorporation into user friendly software has provided the opportunity in two sectors of the offshore industry, to implement 'fitness for purpose' concepts. Thus realistic inspection scheduling and extremely low failure rates are possible for offshore structures and drilling.

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LT K.T. Hays

I understand that ACPD is very weld geometry dependent and for that reason it was only used for crack sizing and length measurement basically because the software developed to model the flux was for that particular weld geometry. Has any work been done as far as with this new method of ACFS, is it as weld geometry dependent and if so is it being used for crack detection at all?

P.A. Frieze

When you say ACPD could you be more specific on that?

LT K.T. Hays

As I understand it, it has only been used for the particular node that you had shown. In other words, it hasn't been able to be used on variable geometries because in order to be used for variable geometry, you had to model the crack length and crack depth of that particular geometry in order to actually measure that from the variable geometry. It is very difficult to model that.

P.A. Frieze

ACPD and ACFM are to a certain extent geometry dependent. The basic phenomenon of the AC method in which the cement passes through the skin of the material which suggest little geometry dependence once some standard weld profiles have been investigated, eg, flat butt welds, T-butt welds, and fillet welds of various angles. For large diameter tubulars, the curvature in the direction along the crack will have little influence and flat plate results an be used. For braces at 35° and inspection in the heel region, probe design will be more heavily influenced by geometry particularly for small diameter tubulars. To date, probes have not been developed for this particular circumstance.